Наставном већу Института за физику Београд
Београд, 30.11.2020. године

Предмет:
Молба за покретање поступка за избор у звање научни сарадник

С обзиром да испуњавам критеријуме прописане од стране Министарства просвете, науке и технолошког развоја за стицање звања научни сарадник, молим Научно веће Института за физику у Београду да покрене поступак за мој избор у наведено звање.

У прилогу достављам:

1. Мишљење руководиоца са предлогом чланова комисије за избор у звање
2. Стручну биографију
3. Преглед научне активности
4. Елементе за квалитативну и квантитативну оцену научног доприноса са доказима
5. Списак објављених научних радова и њихове копије
6. Податке о цитираности
7. Уверење о одбрањеној докторској дисертацији

С поштовањем,

др Јелена Марјановић

Јелена Марјановић

Наставном већу Института за физику Београд
Београд, 30.11.2020. године

Предмет:
Мишљење руководиоца Центра о избору др Јелене Марјановић у звање научни сарадник

Јелена Марјановић је запослена у Лабораторији за неравнотежне процесе и примену плазме (раније Лабораторија за гасну електронику) под руководством др Гордане Маловић у оквиру Националног центра изузетних вредности за неравнотежне процесе Института за физику у Београду. Јелена Марјановић се бави експерименталним истраживањем пробоја и карактеристика неравнотежних пражњења на ниском притиску у парама течности. Колегиница Марјановић је аутор и коаутор четири научна рада која су објављена у међународним часописима категорија М21а, М21, М22 и М23. Резултати њених истраживања су презентовани на великом броју међународних конференција. Била је коаутор већег броја предавања по позиву (19) и већег броја радова штампаних у изводу (20) и целини (12).

С обзиром да испуњава све предвиђене услове у складу са Правилником о поступку, начину вредновања и квантитативном исказивању научноистраживачких резултата истраживача МПНТР, сагласна сам са покретањем поступка за избор др Јелене Марјановић у звање научни сарадник.

За састав комисије за избор др Јелене Марјановић у звање научни сарадник предлажем:

1) др Драгану Марић, научног саветника Института за физику у Београду
2) др Николу Шкора, вишег научног сарадника Института за физику у Београду
3) др Гордану Маловић, научног саветника Института за физику у Београду
4) проф. др Срђана Буквића, редовног професора Физичког факултета Универзитета у Београду

Руководилац Лабораторије за
неравнотежне процесе и примену плазме

Др Гордана Маловић, научни саветник

Биографија др Јелене Марјановић

Јелена Марјановић (рођена Сивош) је рођена 23.01.1983. године у Крушевцу.
Физички факултет Универзитета у Београду – смер Примењена физика и информатика је уписала школске 2002/2003. године и завршила са просечном оценом 8,34. Дипломирала је 29.12.2010. године са темом „Пробој и струјно–напонске карактеристике пражњења у воденој пари" са оценом 10 под менторством др Драгане Марић.

Докторске студије на Физичком факултету Универзитета у Београду – смер Физика јонизованог гаса и плазме уписала је 2011. године. Положила је све изборне испите са просечном оценом 10,00. Предлог теме је успешно одбранила пред Колегијумом докторских студија на Физичком факултету 27.06.2018. године, а на седници Наставно–научног већа Физичког факултета одржаној 21.11.2018. године усвојен је Извештај Комисије за оцену испуњености услова и оправданост предложене теме за израду докторске дисертације под менторством др Драгане Марић научног саветника у Институту за физику. Докторску дисертацију под називом „Пробој и особине неравнотежних DC пражњења на ниском притиску у парама течности" одбранила је 27.11.2020. године на Физичком факултету у Београду.

Јелена Марјановић је у радном односу од 1.01.2011. године у Институту за физику у Београду у Лабораторији за гасну електронику (сада Лабораторија за неравнотежне процесе и примену плазме) под руководством проф. др Зорана Љ. Петровића. На седници Научног већа Института за физику одржаној 23.09.2014. године изабрана је у звање истраживач сарадник, а реизабрана у исто звање на седници Научног већа Института за физику одржаној 18.07.2017. године.

Аутор и коаутор је четири научна рада која су објављена у међународним часописима категорија М21а, М21, М22 и М23. Резултати њених истраживања су презентовани на великом броју међународних конференција у виду предавања по позиву (19) и радова штампаних у изводу (20) и у целини (12).

Преглед научне активности др Јелене Марјановић

Кандидат Јелена Марјановић се бави истраживањима која спадају у област физике јонизованих гасова и плазми у Лабораторији за неравнотежне процесе и примену плазме под руководством др Гордане Маловић (раније Лабораторија за гасну електронику коју је водио академик Зоран Љ. Петровић) у Институту за физику у Београду. Главна тематика њеног рада јесте експериментално истраживање DC пробоја и неравнотежног пражњења на ниском притиску у парама течности. Фокус рада је на проучавању елементарних процеса, њихове кинетике и феноменологије пробоја и различитих режима пражњења које је до сада обухватило водену пару и паре алкохола: метанола, етанола, изопропанола и бутанола. Циљ овог рада је да се обезбеде подаци неопходни за разумевање процеса који одређују пробој и особине пражњења у парама и течностима које се користе у многобројним применама – у медицини, нанотехнологији, обради и синтези материјала, заштити животне средине.

Истраживачки рад и научни резултати које је до сада остварила др Јелена Марјановић су обезбедили основу за описивање пробоја у парама течности и омогућили постављање елементарних benchmark тестова, пре преласка на моделовање пробоја и пражњења изнад течности, у мехурићима у течности и директно у течности.

Први корак у њеном раду је био да постојећи експериментални уређај надогради и прилагоди раду са парама органиских течности. При томе су паре органских течности, као што су истраживани алкохоли, представљале посебан изазов у раду на ниским притисцима, због формирања угљоводоничних нечистоћа (полимерних филмова и прашине). Др Јелена Марјановић је успешно прилагодила експериментални уређај и процедуре припреме и тестирања система, што је обезбедило неопходну поузданост и репродуцибилност мерења. Захваљујући томе, резултати њених истраживања су инкорпорирани и у базу референтних података за пробој и неравнотежна пражњења центра изузетних вредности „Центар за неравнотежне процесе“, који је већ дуги низ година познат као најпоузданији извор података за електрични пробој. Део ових резултата је и објављен у прегледном раду:

- Gas breakdown and secondary electron yields, D. Marić, M. Savić, **J. Sivoš**, N. Škoro, M. Radmilović-Radjenović, G. Malović and Z. Lj. Petrović, *European Physical Journal* D, **68** (6) (2014) 155 (7pp).

Мерења пробојних напона (Пашенових кривих), јонизационих коефицијената, приноса секундарних електрона, спектрално разложена снимања просторне структуре пражњења, временски разложена снимања формирања и развоја пражњења и снимања струјно–напонских карактеристика обезбедило је податке за:

1) формирање база за моделовање пробоја у парама течности, конкретно у воденој пари и парама горе поменутих алкохола и

2) нормирање сетова података за сударне пресеке (енг. cross sections) и за прорачун транспортних коефицијената електрона, позитивних и негативних јона и брзих неутрала у испитиваним парама.

Оригинални доприноси научне активности др Јелене Марјановић су следећи:

- У случају алкохола метанола и етанола измерени јонизациони коефицијенти су проширили интервал већ постојећих резултата у литератури, док су у случају изопропанола и бутанола, по нашем сазнању, ово прва мерења те врсте.
- Одређен је принос секундарних електрона у парама алкохола за које до сада није било података у доступној литератури.
- У случају водене паре, започет је рад на проучавању утицаја формирања капљица на пробој и одређена су времена прелета јона и дрифт брзине, о којима има врло мало података у литератури и који углавном леже на врло ниским вредностима редукованог електричног поља *E/N*.

Резултати ових истраживања су до сада објављени у три рада у међународним научним часописима, у којима је колегиница Марјановић први аутор, са кључним доприносом у реализацији:

- Breakdown and dc discharge in low-pressure water vapour, **J. Sivoš**, N. Škoro, D. Marić, G. Malović and Z. Lj. Petrović, *Journal of Physics D: Applied Physics*, **48** (42) (2015) 424011 (9pp)
- DC discharge in low-pressure ethanol vapour , **J. Sivoš**, D. Marić, N. Škoro, G. Malović and Z. Lj. Petrović, *Plasma Sources Sci. Technol.*, **28** (2019) 055011 (8pp)
- Low-pressure DC breakdown in alcohol vapours, **J. Sivoš**, D. Marić, G. Malović, and Z. Lj. Petrović, *European Physical Journal* D, **74**, (2020) 64 (10 pp)

Треба истаћи да је специфичност коришћене експерименталне технике, у односу на типичне експерименте са роjевима доступне у другим лабораторијама, у томе што омогућава нормирање и верификацију пресека у области већих вредности редукованог електричног поља *E/N* (~ kTd) које су најчешће заступљене у практичним применама. Подаци добијени у досадашњим мерењима у пражњењима у парама течности представљају и основу за будући рад у оквиру ког би се применили у истраживању и моделовању комплекснијих система као што су област (енг. Interface) између гасовите и течне фазе и сама течност.

Елементи за квалитативну оцену научног доприноса др Јелене Марјановић

1. Квалитет научних резултата

1.1 Значај научних резултата

Др Јелена Марјановић се у току досадашњег рада бавила експерименталним истраживањем DC пробоја и неравнотежног пражњења на ниском притиску у парама течности, где је посебна пажња усмерена на проучавање елементарних процеса, њихове кинетике и феноменологије пробоја и различитих режима неравнотежног пражњења. Урађена је провера и прилагођење постојећих експерименталних техника раду са парама течности, а посебна пажња је посвећена контроли чистоће паре, раду на стабилном притиску, добијању поузданих и репродуцибилних резултата, снимању спектрално разложене просторне структуре пражњења и остваривању високих притисака ради проучавања утицаја формирања капљица на пробој у пари течности. Идентификовани су доминантни процеси у пробоју и пражњењу, као и врсте честица које имају значајну улогу у овим процесима. Спроведена су детаљна мерења, како у слабострујној области, тако и на јаким струјама, у парама метанола, етанола, изопропанола и бутанола, која су дала податке неопходне за омогућавање постављања benchmark тестова, док је у случају водене паре урађена детаљнија анализа којом је проширен сет постојећих података: брзина дрифта и време прелета јона, оптички емисиони спектри и спектрално разложена мерења, просторно–временска анализа развоја абнормалног пражњења којом је посматрана кинетика процеса који доводе до формирања катодног пада и добијена информација о улози различитих врста честица (електрона и тешких честица) у формирању абнормалног пражњења, утицај формирања капљица на пробој. Током рада на овим пражњењима уочени су и детаљно проучени феномени као што су појава двоструких констрикованих канала пражњења и нагле промене режима пражњења у области јаких струја, који представљају добру основу да се детаљним моделовањем објасни промена режима рада пражњења као и особине у појединим режимима.

1.2 Параметри квалитета часописа

Кандидат др Јелена Марјановић је објавила укупно 4 рада у међународним часописима и то:

- 1 рад у међународном часопису изузетних вредности (M21a) Plasma Sources Science and Technology (IF= 4.220 SNIP= 1.632 (вредности за 2019. годину))
- 1 рад у врхунском међународном часопису (M21) Journal of Physics D: Applied Physics (IF= 3.170 SNIP= 1.329 (вредности за 2015. годину))

- 1 рад у међународном часопису (М23) European Physical Journal D: Atomic, Molecular, Optical and Plasma Physics (IF= 1.290 SNIP= 0.725 (вредности за 2019. годину))
- 1 рад у међународном часопису (М22) European Physical Journal D: Atomic, Molecular, Optical and Plasma Physics (IF= 1.240 SNIP= 0.712 (вредности за 2014. годину))

Укупан импакт фактор објављених радова др Јелене Марјановић износи 9.92.

Додатни библиометријски показатељи према упутству о начину писања извештаја о изборима у звања које је усвојио Матични научни одбор за физику су:

	ИФ	М	СНИП
Укупно	9.92	26	4.398
Усредњено по чланку	2.48	6.5	1.0995
Усредњено по аутору	1.9776	5.0643	0.87515

1.3. Позитивна цитираност научних радова кандидата

Према бази Google Scholar Citations радови др Јелене Марјановић су цитирани 59 (без цитата коаутора и аутоцитата 45 цитата) пута, а Хиршов индекс је 3. Према бази Web of Science радови др Јелене Марјановић су цитирани 45 пута (без цитата коаутора и аутоцитата 39 цитата). Према овој бази Хиршов индекс кандидата је 3.

1.4. Међународна сарадња

- 2013-2017 учешће у европској COST акцији (European Cooperation in Science and Technology): „TD1208 - Electrical discharges with liquids for future applications”
- Учешће у школи одржаној у Љубљани у фебруару 2014. године – Training School in Ljubljana, Slovenia под називом *Chemistry initiated by electrical discharges with liquids* у оквиру COST акције TD1208 Electrical discharges with liquids for future applications
- Учепће у школи одржаној у Београду у септембру 2016. године – *3rd Training School: Advanced Diagnostics of Discharges with Liquids and Plasma Treated Liquid Phase* у оквиру COST акције TD1208 Electrical discharges with liquids for future applications

1.5. Остали показатељи успеха у научном раду

Др Јелена Марјановић је одржала предавање, у оквиру секције усмених презентација, под називом „DC breakdown in vapours of liquids" (*Oral sessions*) на међународној конференцији 42nd IEEE International Conference On Plasma Science (ICOPS 2015) одржаној од 24. до 28. маја 2015. године у Белеку, Анталија, Турска.

Др Јелена Марјановић је одржала предавање (*Oral contributions*), у оквиру секције усмених презентација, под називом „Discharges in Alcohol Vapours at Low Pressures" на међународној конференцији 22nd International Conference on Gas Discharges and Their Applications (GD 2018) одржаној од 2. до 7. септембра 2018. године у Новом Саду, Србија.

Др Јелена Марјановић је одржала предавање по позиву (*Progress invited talk*) под називом „Breakdown and characteristics of non–equilibrium low–pressure DC discharges in vapours of liquids" на међународној конференцији 30th Summer School and International Symposium on the Physics of Ionized Gases (SPIG 2020) одржаној од 24. до 28. августа 2020. године у Шапцу, Србија.

2. Нормирање броја коауторских радова

Сви публиковани радови др Јелене Марјановић спадају у радове експерименталне природе. Према Правилнику о поступку и начину вредновања и квантитативном исказивању научноистраживачких резултата истраживача у случају екпериментални радова предвиђено је до 7 коаутора. Укупан ненормиран број бодова је 96.5, док је нормиран број М бодова 91.238 што је знатно више у односу на захтеваних 16 бодова за избор у научног сарадника.

3. Учешће на пројектима МПНТР Републике Србије

Др Јелена Марјановић је учествовала на следећим пројектима Министарства просвете, науке и технолошког развоја:

2010–данас: „Фундаментални процеси и примене транспорта честица у неравнотежним плазмама, траповима и наноструктурама" (ОИ171037).

2010–данас „Примене нискотемпературних плазми у биомедицини, заштити човекове околине и нанотехнологијама" (ИИИ41011).

4. Активности у научним и научно-стручним друштвима

4.1. Организација научних скупова

Др Јелена Марјановић је била у локалном организационом комитету за конференцију 27th Summer School and International Symposium on the Physics of Ionized Gases, од 26. до 29. августа 2014. године у Београду, Србија.

Др Јелена Марјановић је била у локалном организационом комитету за конференцију 22nd International Conference on Gas Discharges and Their Applications, од 2. до 7. септембра 2018. године у Новом Саду, Србија.

Др Јелена Марјановић је била у локалном организационом комитету за конференцију 20th International Workshop on Low-Energy Positron and Positronium Physics and 21st International Symposium on Electron-Molecule Collisions and Swarms, од 18. до 20. јула 2019. године у Београду, Србија.

5. Утицај научних резултата

Утицај научних резултата се огледа у броју цитата који су наведени у тачки 1.3. овог одељка, а значај резултата је описан у тачки 1. Пун списак радова и подаци о цитираности из *Scopus* базе су дати у прилогу.

6. Конкретан допринос кандидата у реализацији радова у научним центрима у земљи и иностранству

Кандидат је своју истраживачку и научну активност реализовала у Институту за физику у Лабораторији за гасну електронику под руководством академика Зорана Љ. Петровића (сада Лабораторија за неравнотежне процесе и примену плазме под руководством др Гордане Маловић). Њен допринос се огледа у експерименталним мерењима неопходним за комплетирање базе сетова података за пробој и неравнотежна пражњења у гасовима, а посебно за пробој и пражњења у парама течности. Дала је кључан допринос у свим фазама реализације радова на којима је потписана као први аутор – у експерименталним мерењима, обради, анализи и интерпретацији резултата, као и у писању научних радова и комуникацији са уредницима и рецензентима часописа.

Елементи за квантитативну оцену научног доприноса др Јелене Марјановић

Остварени М–бодови по категоријама публикација

Категорија	М–бодова по публикацији	Број публикација	Укупно М–бодова	Нормирани број М–бодова
M21a	**10**	**1**	**10**	**10**
M21	**8**	**1**	**8**	**8**
M22	**5**	**1**	**5**	**5**
M23	**3**	**1**	**3**	**3**
M31	**3.5**	**7**	**24.5**	**21.333**
M32	**1.5**	**12**	**18**	**14.405**
M33	**1**	**12**	**12**	**12**
M34	**0.5**	**20**	**10**	**10**
M70	**6**	**1**	**6**	**6**

*Нормирање је урађено у складу са Прилогом 1 Правилника.

Поређење оствареног броја М–бодова са минималним условима потребним за избор у звање научног сарадника

	Потребно	Остварено	Остварено (нормирано*)
Укупно	**16**	**96.5**	**91.238**
M10+M20+M31+M32+M33+M41+M42	**10**	**80.5**	**73.738**
M11+M12+M21+M22+M23	**6**	**26**	**26**

*Нормирање је урађено у складу са Прилогом 1 Правилника.

Списак радова др Јелене (Сивош) Марјановић

Рад у међународним часописима изузетних вредности (М21а):

1.**Jelena Sivoš**, Dragana Marić, Nikola Škoro, Gordana Malović and Zoran Lj Petrović
DC discharge in low-pressure ethanol vapour
Plasma Sources Sci. Technol., **28**, 055011 (8pp), 2019, IOP Publishing Ltd
ISSN: 0963-0252, doi: 10.1088/1361-6595/ab0952
IF: 4.220
Број хетероцитата: 1

Рад у врхунским међународним часописима (М21):

1.**Jelena Sivoš**, Nikola Škoro, Dragana Marić, Gordana Malović and Zoran Lj Petrović
Breakdown and dc discharge in low-pressure water vapour
Journal of Physics D: Applied Physics, **48** (42), 424011 (9pp), 2015, IOP Publishing Ltd
ISSN 0022-3727, doi: 10.1088/0022-3727/48/42/424011
IF: 3.170
Број хетероцитата: 6

Рад у истакнутим међународним часописима (М22):

1.Dragana Marić, Marija Savić, **Jelena Sivoš**, Nikola Škoro, Marija Radmilović-Radjenović, Gordana Malović, and Zoran Lj. Petrović
Gas breakdown and secondary electron yields
European Physical Journal D, **68** (6), 155 (7pp), 2014, Springer-Verlag
ISSN 1434-6060, doi: 10.1140/epjd/e2014-50090-x
IF: 1.240
Број хетероцитата: 33

Рад у међународним часописима (М23):

1.**Jelena Sivoš**, Dragana Marić, Gordana Malović, and Zoran Lj. Petrović
Low-pressure DC breakdown in alcohol vapours
European Physical Journal D, **74**, 64 (10pp), 2020, Springer-Verlag
ISSN 1434-6079, doi: 10.1140/epjd/e2020-100540-3
IF: 1.290
Број хетероцитата: 1

Предавање по позиву са међународног скупа штампано у целини М31

1. Zoran Lj Petrović, **Jelena Sivoš**, Marija Savić, Nikola Škoro, Marija Radmilović Rađenović, Gordana Malović, Saša Gocić and Dragana Marić

New phenomenology of gas breakdown in DC and RF fields
18th International Summer School on Vacuum, Electron and Ion Technologies

Journal of Physics: Conference Series 514 (2014) 012043 (9pp)
Published by: IOP Publishing
ISSN 1742-6588, doi:10.1088/1742-6596/514/1/012043

2. Zoran Lj. Petrović, Nevena Puač, Dragana Marić, Dejan Maletić, Kosta Spasić, Nikola Škoro, **Jelena Sivoš**, Saša Lazović and Gordana Malović
Development of Biomedical Applications of Nonequilibrium Plasmas and Possibilities for Atmospheric Pressure Nanotechnology Applications
28th International Conference On Microelectronics (MIEL)
PROC. 28th International Conference On Microelectronics (2012) 31-38
Published by: Electron Devices Society of the Institute of Electrical and Electronics Engineers, INC & IEEE, 345 E 47TH ST, NEW YORK, NY 10017 USA
ISBN 978-1-4673-0238-8, ISSN: 2159-1660, doi: 10.1109/MIEL.2012.6222791

3. Zoran Lj. Petrović, Vladimir Stojanović, Nikola Škoro, Željka Nikitović, Gordana Malović, **Jelena Sivoš** and Dragana Marić
Development of Fast Neutral Etching for Integrated Circuits and Nanotechnologies Fast Neutrals in Gas
29th International Conference on Microelectronics (MIEL)
PROC. 29th International Conference on Microelectronics (2014) 17-24
Published by: IEEE, 345 E 47TH ST, NEW YORK, NY 10017 USA
ISBN: 978-1-4799-5296-0, ISSN: 2159-1660, doi: 10.1109/MIEL.2014.6842079

4. Zoran Lj. Petrović, **Jelena Sivoš**, Konstantin Karajović, Gordana Malović and Dragana Marić
Electrical breakdown in water vapor and ethanol
69th Iuvsta Workshop On Oxidation Of Organic Materials By Excited Radicals Created In Nonequilibrium Gaseous Plasma
December 9-13,2012, Crklje na Gorenjeskem, Slovenia, p. 55-58
Published by: Siovenian Society for Vacuum Technique (DVTS Drustvo za vakuumsko tehniko Siovenije), Teslova 30, SI-l000 Ljubljana, Slovenia)

5. Dragana Marić, **Jelena Sivoš**, Nikola Škoro, Gordana Malović, Thomas Kuschel, Ilija Stefanović, Joerg Winter and Zoran Lj. Petrović
Breakdown and Discharge Development in Various Gases and Electrode Configurations
19th Symposium on Application of Plasma Processes Workshop on Ion Mobility Spectrometry
January, 26-31, 2013, Vrátna, Slovakia, p. 33-41
Published by: Department of Experimental Physics, Faculty of Mathematics, Physics and Informatics, Comenius University in Bratislava (Slovakia); Society for Plasma Research and Applications in cooperation with Library and Publishing Centre CU, Bratislava, Slovakia

6. Dragana Marić, **Jelena Sivoš**, Nikola Škoro, Vladimir Stojanović, Srđan Marjanović, Ana Banković, Saša Dujko, Gordana Malović and Zoran Petrović
Atomic and Molecular Processes of Interest for Modeling of Discharges in Liquids
6th Conference on Elementary Processes in Atomic Systems (CEPAS)
July, 9-12, 2014, Bratislava, Slovakia, p.121-122
ISBN 978-80-8147-021-9

7. **Jelena Sivoš**, Nikola Škoro, Dragana Marić, Gordana Malović and Zoran Lj. Petrović
Discharges in alcohol vapours at low pressures

22nd International Conference on Gas Discharges and their Applications (GD)
September 2-7, 2018, Novi Sad, Serbia, p. 327-330
Published by: Serbian Academy of Sciences and Arts, Kneza Mihaila 35, Belgrade, Serbia
ISBN:978-86-7025-781-8

Предавање по позиву са међународног скупа штампано у изводу М32

1. Zoran Lj. Petrović, Dragana Marić, Nikola Škoro, Marija Savić, **Jelena Sivoš**, Marija Radmilović Rađenović, Milovan Šuvakov and Gordana Malović

New phenomenology in description of Townsend discharges and gas breakdown: from standard size to micro discharges
The 4th International Conference on PLAsma-Nano Technology & Science (IC-PLANTS)
March, 10-12, 2011, Gifu, Japan, I-07
Published by: Plasma Nanotechnology Research Center

2. **Jelena Sivoš**, Nikola Škoro, Dragana Marić, Gordana Malović and Zoran Lj. Petrović
Electrical breakdown in low-pressure ethanol vapour
16th International Conference on Plasma Physics and Applications
June, 20-25, 2013, Magurele-Bucharest, Romania, p. O18-50
Published by: INFLPR, Str. Atomistilor, Nr. 409, Magurele, Bucharest, Romania, Eds. B. Mitu and G. Dinescu
ISSN 2344-0481

3. Zoran Lj. Petrović, Saša Dujko, Jasmina Mirić, Danko Bošnjaković, Ana Banković, Srđan Marjanović, Dragana Marić, **Jelena Sivoš**, Nikola Škoro, Marija Savić, Olivera Šašić and Gordana Malović
Cross Sections for Scattering of Electrons and Positrons in Modeling of Ionized Gases and Non-Equilibrium Plasmas
International Symposium on Non-equilibrium Plasma and Complex-System Sciences (IS-NPCS)
February, 26-28, 2014, Icho Kaikan, Osaka University, Osaka, Japan, 106

4. **Jelena Sivoš**, Dragana Marić, Nikola Škoro, Gordana Malović and Zoran Lj Petrović
DC Breakdown in Vapours of Liquids
42nd IEEE International Conference on Plasma Science (ICOPS)
May, 24th- 28th, 2015, Belek, Antalya, Turkey, 4E-1 (1 pp)
Published by: Suleyman Demirel University, Isparta, Turkey, Sandia National Laboratories, University of New Mexico, IEEE

5. Nikola Škoro, Dragana Marić, Vladimir Stojanović, **Jelena Sivoš**, Gordana Malović and Zoran Lj. Petrović
Heavy-particle collisions in water vapour discharges at low pressures
23rd Europhysics Conference on the Atomic and Molecular Physics of Ionized Gases (ESCAMPIG)
July, 12-16, 2016, Bratislava, Slovakia, p. 406-409
Published by: European Physical Society
ISBN: 979-10-96389-02-5

6. Nikola Škoro, Dragana Marić, Vladimir Stojanović, **Jelena Sivoš**, Gordana Malović and Zoran Lj. Petrović
Heavy-Particle Processes in Low-Pressure Water Vapour Discharge
28th Summer School and International Symposium on the Physics of Ionized Gases (SPIG)
August 29–September 2, 2016, Belgrade, Serbia, p. 456
Published by: University of Belgrade, Faculty of Physics, Belgrade, Studentski trg 12, P. O. Box 44, 11000 Belgrade, Serbia
ISBN: 978-86-84539-14-6

7. Zoran Lj. Petrović, Antonije Đorđević, Jana Petrović, **Jelena Sivoš**, Marija Savić, Gordana Malović and Dragana Marić
RF Breakdown as a Swarm Experiment
82nd IUVSTA Workshop
December 4-7. 2017, Bankoku Shinryokan, Okinawa, Japan, p. O-2
Published by: Osaka University, Japan

8. Dragana Marić, **Jelena Sivoš**, Nikola Škoro, Vladimir Stojanović, Srđan Marjanović, Ana Banković, Saša Dujko, Gordana Malović and Zoran Lj. Petrović
Atomic and Molecular Processes of Interest for Modelling of Discharges in Liquids
Gordon Research Conference on Plasma Processing Science: Plasmas with Complex Interactions – Exploiting the Non-Equilibrium
July 24-29. 2016, Proctor Academy in Andover NH, United States

9. Zoran Lj. Petrović, Saša Dujko, Dragana Marić, Gordana Malović, Nevena Puač, Danko Bošnjaković, Olivera Šašić, Marija Puač, **Jelena Sivoš**, Milovan Šuvakov and Nikola Škoro
Non-Equilibrium in Ionized Gases Determined by Charged Particle Collisions with Molecules
XX International Workshop on Low-Energy Positron and Positronium Physics, XXI International Symposium on Electron-Molecule Collisions and Swarms, V Workshop on Non-Equilibrium Processes
July 18–21, 2019, Belgrade, Serbia, p. 5
Published by: Serbian Academy of Sciences and Arts and Institute of Physics Belgrade
ISBN: 978-86-7025-819-8

10. **Jelena Sivoš**, Dragana Marić, Nikola Škoro, Gordana Malović and Zoran Lj. Petrović
Breakdown and Discharges in Low-Pressure Alcohol Vapors
10th International conference on plasma nanoscience (iPlasmaNano-X)
September 15–20, 2019, Poreč, Croatia, p. T–12
Published by: University of Orleans, Orleans, France

11. Zoran Lj. Petrović, Antonije Đorđević, Marija Puač, Jana Petrović, **Jelena Sivoš**, Gordana Malović and Dragana Marić
Measurements and simulations of RF breakdown in gases
7th ICAPT International Conference on Advanced Plasma Technologies
February 24–March 1, 2019, Hue, Vietnam, p.45
Published by: Plasmadis, Ljubljana, Slovenia

12. **Jelena Marjanović**, Dragana Marić, Gordana Malović and Zoran Lj. Petrović
Breakdown and Characteristics of Non-Equilibrium Low-Pressure DC Discharges in Vapours of Liquids

30th Summer School and International Symposium on the Physics of Ionized Gases (SPIG)
August 24 -28, 2020, Šabac, Serbia, Publ. Astron. Obs. Belgrade No. **99** (2020), p.148
Published by: Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia
ISBN: 978-86-80019-94-9; ISSN 0373-3742

Саопштење са међународног скупа штампано у целини М33

1.Nikola Škoro, Jelena Sivoš, Dragana Marić, Gordana Malović and Zoran Lj. Petrović
Volt-Ampere Characteristics of Water Vapour Discharges
30th International Conference on Phenomena in Ionized Gases (ICPIG)
August 28th – September 2nd 2011, Belfast, Northern Ireland, UK, C8-153 (4pp)
Published by: Queen's University Belfast, University Road, Belfast BT7 1NN, Northern Ireland, UK

2. Nikola Škoro, Dragana Marić, **Jelena Sivoš**, Gordana Malović, William Graham and Zoran Lj. Petrović
Breakdown and low current discharges in water vapour
ECM 112 and 4th ICAPT
September, 9-13, 2011, Strunjan, Slovenia, p. 164-167
Published by: Siovenian Society for Vacuum Technique (DVTS Drustvo za vakuumsko tehniko Siovenije), Teslova 30, SI-l000 Ljubljana, Slovenia
ISBN 978-961-92989-3-0

3. **Jelena Sivoš**, Nikola Škoro, Dragana Marić, Gordana Malović and Zoran Lj. Petrović
Volt-Ampere Characteristics of Low Pressure DC Discharges in Water Vapor
26th Summer School and International Symposium on the Physics of Ionized Gases (SPIG)
August 27-31, 2012, Zrenjanin, Serbia, p. 273-276
Published by: University of Novi Sad, Faculty of Sciences Department of Physics, Trg Dositeja Obradovića 3 21000 Novi Sad, Serbia
ISBN 978-86-7031-242-5

4. Vladimir Stojanović, **Jelena Sivoš**, Dragana Marć, Nikola Škoro and Zoran Lj. Petrović
Monte Carlo simulation of electron transport in H_2O vapour
26th Summer School and International Symposium on the Physics of Ionized Gases (SPIG)
August 27-31, 2012, Zrenjanin, Serbia, p. 35-38
Published by: University of Novi Sad, Faculty of Sciences Department of Physics, Trg Dositeja Obradovića 3 21000 Novi Sad, Serbia
ISBN 978-86-7031-242-5

5. Dragana Marić, **Jelena Sivoš**, Nikola Škoro, Gordana Malović and Zoran Lj. Petrović
Low-Pressure Breakdown in Ethanol Vapour
31st International Conference on Phenomena in Ionized Gases (ICPIG)
July, 14-19, 2013, Granada, Spain, p. PS4-048 (4pp)
Published by: Spanish National Research Council (CSIC)

6. **Jelena Sivoš**, Dragana Marić, Nikola Škoro, Gordana Malović and Zoran Lj. Petrović
Breakdown in water vapour and ethanol vapour: heavy particle processes

3rd National Conference on Electronic, Atomic, Molecular and Photonic Physics
August 25th, 2013, Belgrade, Serbia, 21-24
Published by: University of Belgrade, Faculty of Physics, Studentski trg 12, 11000 Belgrade, Serbia, Ed. by B.P. Marinković, G.B. Poparić
ISBN 978-86-84539-10-8

7. **Jelena Sivoš**, Dragana Marić, Nikola Škoro, Gordana Malović and Zoran Lj. Petrović
Abnormal Glow Discharge in Ethanol Vapour
27th Summer School and International Symposium on the Physics of Ionized Gases (SPIG)
August, 26 – 29, 2014, Belgrade, Serbia, p. 387-390
Published by: Institute of Physics,Belgrade, Pregrevica 118, P. O. Box 68 11080 Belgrade, Serbia and Klett izdavačka kuća d.o.o. Maršala Birjuzova 3-5, IV sprat 11000 Belgrade
ISBN 978-86-7762-600-6

8. **Jelena Sivoš**, Dragana Marić, Nikola Škoro, Gordana Malović and Zoran Lj. Petrović
Electrical Breakdown in Low-Pressure Methanol Vapour
27th Summer School and International Symposium on the Physics of Ionized Gases (SPIG)
August, 26 – 29, 2014, Belgrade, Serbia, p. 391-394
Published by: Institute of Physics,Belgrade, Pregrevica 118, P. O. Box 68 11080 Belgrade, Serbia and Klett izdavačka kuća d.o.o. Maršala Birjuzova 3-5, IV sprat 11000 Belgrade
ISBN 978-86-7762-600-6

9. **Jelena Sivoš**, Nikola Škoro, Dragana Marić, Gordana Malović and Zoran Lj. Petrović
Low-pressure DC discharge in vapour of Methanol and Ethanol
32nd International Conference on Phenomena in Ionized Gases (ICPIG)
July, 26-31, 2015, Romania, Iasi, P2.53 (4 pp)
Published by: Alexandru Ioan Cuza University, Faculty of Physics Iași, Plasma Advanced Research Centre (IPARC)

10. **Jelena Sivoš**, Nikola Škoro, Dragana Marić, Gordana Malović and Zoran Lj. Petrović
Analysis of Transit Time of Ions in Low - Current DC Discharge in Water Vapour
28th Summer School and International Symposium on the Physics of Ionized Gases (SPIG)
August 29- September 2, 2016, Belgrade, Serbia, p. 316-319
Published by: University of Belgrade, Faculty of Physics, Belgrade, Studentski trg 12, P. O. Box 44, 11000 Belgrade, Serbia
ISBN: 978-86-84539-14-6

11. Vladimir Stojanović, Nikola Škoro, **Jelena Sivoš**, Gordana Malović, Dragana Marić and Zoran Lj. Petrović
Modeling Emission from Water Vapor DC Discharge at Low Pressure
28th Summer School and International Symposium on the Physics of Ionized Gases (SPIG)
August 29- September 2, 2016, Belgrade, Serbia, p. 328-331
Published by: University of Belgrade, Faculty of Physics, Belgrade, Studentski trg 12, P. O. Box 44, 11000 Belgrade, Serbia
ISBN: 978-86-84539-14-6

12. **Jelena Sivoš,** Dragana Marić, Nikola Škoro, Gordana Malović and Zoran Lj. Petrović
Volt-ampere characteristics and abnormal glow discharges in methanol and ethanol vapours
29th Summer School and International Symposium on the Physics of Ionized Gases (SPIG)

August 28- September 1, 2018, Belgrade, Serbia, p. 222-225
Published by: Vinča Institute of Nuclear Sciences, University of Belgrade, P.O. Box 522, 11001 Belgrade, Serbia
ISBN: 978-86-7306-146-7

Саопштење са међународног скупа штампано у изводу М34

1. **Jelena Sivoš**, Nikola Škoro, Dragana Marić, Gordana Malović and Zoran Lj. Petrović
Axial emission profiles of Townsend discharge in water vapour
XXI Europhysics Conference on Atomic and Molecular Physics of Ionized Gases (ESCAMPIG)
July, 10-14, 2012, Viana do Castelo, Portugal, p. 9 (2pp)
Published by: European Physical Society
ISBN 2-914771-74-6

2. Zoran Lj. Petrović, **Jelena Sivoš**, Dragana Marić, Nikola Škoro and Vladimir Stojanović
Kinetics of Electrons in H_2O at High Values of Reduced Electric Field
65th Annual Gaseous Electronics Conference (GEC)
October 22nd–26th, 2012, Austin, Texas, USA
Bulletin of the American Physical Society, vol. **57**, no. 8, PR1.00032
Published by: American Physical Society
ISSN: 0003-0503

3. **Jelena Sivoš**, Nikola Škoro, Dragana Marić, Gordana Malović and. Zoran Lj. Petrović
Breakdown in ethanol vapour
5th Central, European Symposium on Plasma Chemistry
August, 25-29, 2013, Balatonalmádi, Hungary, P-FUN6, p.113
Published by: Research Centre for Natural Sciences, Hungarian Academy of Sciences H-1025 Budapest, Pusztaszeri út 59-67., Wigner Research Centre for Physics, Hungarian Academy of Sciences H1121 Budapest, Konkoly Thege Miklós út 29-33., Diamond Congress Ltd., Conference Secretariat H-1012 Budapest, Vérmezó út 8, HUNGARY
ISBN 978-615-5270-04-8

4. Zoran Lj Petrović, **Jelena Sivoš**, Nikola Škoro, Gordana Malović, Dragana Marić
DC breakdown in ethanol vapor
66th Annual Gaseous Electronics Conference
September 30th – October 4th, 2013, Princeton, New Jersey, USA
Bulletin of the American Physical Society, vol. 58, no. 8, HW1 35, p.54
Published by: American Physical Society
ISSN: 0003-0503

5. Zoran Lj Petrović, **Jelena Sivoš**, Marija Savić, Nikola Škoro, Marija Radmilović Radenović, Gordana Malović and Dragana Marić
New Phenomenology of Gas Breakdown in DC and RF Fields
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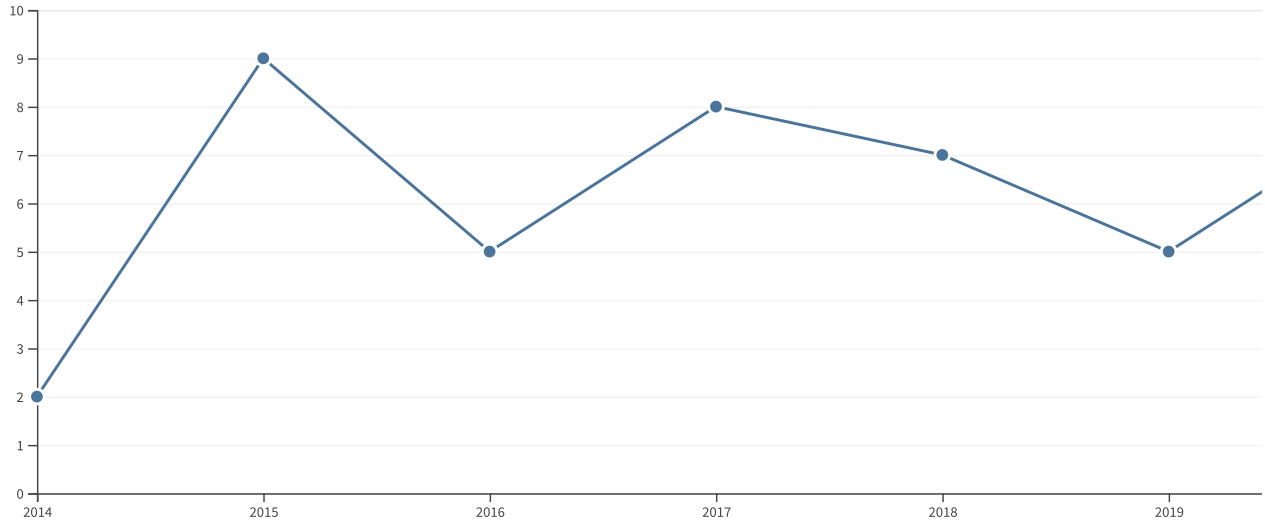

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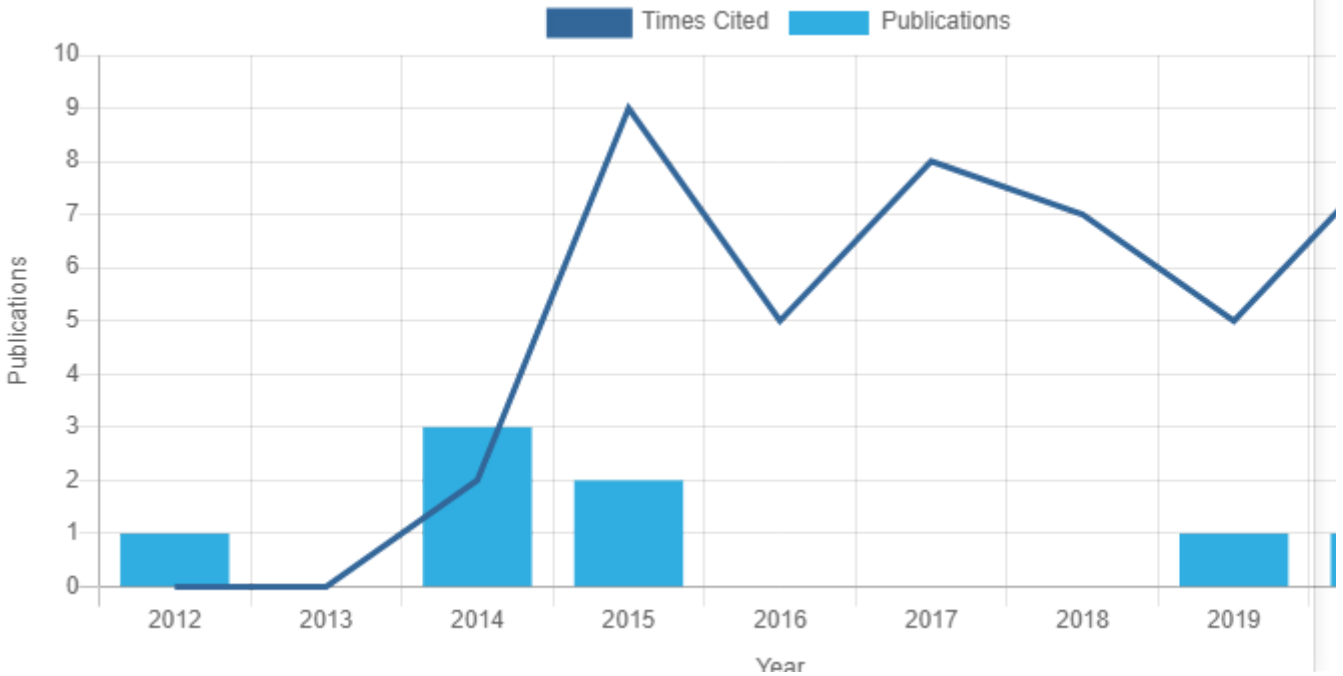

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Effects Of Electrons and Heavy Particles On Halpha Emission In Pure H_2O DC Discharge At High E/N (E-Electric Field, N-Gas Density) Z Petrovic, V Stojanovic, N Skoro, J Sivos, D Maric, G Malovic APS, MW6. 047		2016
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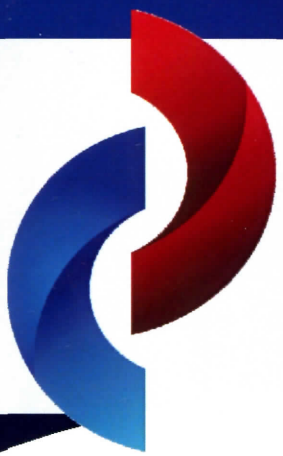

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30th Summer School and International Symposium on the Physics of Ionized Gases

Dr Jelena Marjanović

Belgrade, 10 December, 2019

Dear **Dr Jelena Marjanović,**

On behalf of the Scientific and Organizing Committees, we have a pleasure to invite you to attend the *30th Summer School and International Symposium on the Physics of Ionized Gases* (SPIG 2020) and present a **Progress invited talk**.

The SPIG 2020 will be held from August 24th to 28th, 2020 in Šabac, Serbia. The details of the conference are available at official website: http://www.spig2020.ipb.ac.rs/
Please note that due to the limited conference budget, the SPIG2020 organizers will try to provide partial support to students and early stage researchers, as well as colleagues from economically less privileged countries. Thank you for your understanding and support.

We look forward to welcoming you to Šabac.

Yours sincerely,

Luka Č. Popović
(Co-Chair of the Scientific Committee)

Dragana Ilić
(Co-Chair of the Loc. Org. Committee)

Duško Borka
(Co-Chair of the Scientific Committee)

Vladimir Srećković
(Co-Chair of the Loc. Org. Committee)

SPIG 2020 Organizer:
University of Belgrade, Faculty of Mathematics, Department of Astronomy

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University of Belgrade, Institute of Physics
Astronomical Observatory of Belgrade

30th Summer School and International Symposium on the Physics of Ionized Gases

SPIG 2020

Dr Jelena Marjanović

Belgrade, September 1st, 2020

We certify that Dr Jelena Marjanović has presented a Progress invited talk 'Break-down and characteristics of non-equilibrium low-pressure DC discharges in vapours of liquids' in the 30th Summer School and International Symposium on the Physics of Ionized Gases held in virtual format, August 24-28, 2020 (http://spig2020.ip-b.ac.rs/).

Yours sincerely,

Luka Č. Popović
(Co-Chair of the Scientific Committee)

Dragana Ilić
(Co-Chair of the Loc. Org. Committee)

Duško Borka
(Co-Chair of the Scientific Committee)

Vladimir Srećković
(Co-Chair of the Loc. Org. Committee)

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30th Summer School and International Symposium on the Physics of Ionized Gases

Šabac, Serbia,
August 24 -28, 2020

CONTRIBUTED PAPERS

&

ABSTRACTS of INVITED LECTURES, TOPICAL INVITED LECTURES and PROGRESS REPORTS

Editors:
Luka Č. Popović, Duško Borka,
Dragana Ilić and Vladimir Srećković

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S P I G 2020

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Faculty of Mathematics
(Department of Astronomy)
Astronomical Observatory
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Institute of Physics,
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Belgrade, 2020

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SPIG 2020

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BREAKDOWN AND CHARACTERISTICS OF NON-EQUILIBRIUM LOW-PRESSURE DC DISCHARGES IN VAPOURS OF LIQUIDS

JELENA MARJANOVIĆ[1], DRAGANA MARIĆ[1], GORDANA MALOVIĆ[1] and ZORAN LJ. PETROVIĆ[1,2]

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Abstract. The study of non-equilibrium discharges in liquids and their vapors have become very popular due to a variety of possible applications, such as in nanoscience for the synthesis of nanographene layers and fast growth of carbon nanotubes (Hagino et al. 2012), for the treatment of materials and surfaces (Fumagalli et al. 2012), in biomedicine (Stalder et al, 2006), for polymerization processes and thin-film synthesis (Brunet et al. 2017), in fuel industry - sources of hydrogen (Petitpas et al. 2007), for purification and decontamination (Kitano et al. 2006), etc. However, emergence of new devices demands knowledge on elementary processes and their balance in discharge that can be obtained from studies of breakdown and electrical characteristics of discharges. Here we present results of the comprehensive experimental investigation of breakdown properties, spectra, spatial and spectrally resolved emission and V-A characteristics in low-pressure discharges in vapours of methanol, ethanol, isopropanol, n-butanol and water that provide sets of data for different operating regimes (Sivoš et al. 2015, 2019). Furthermore, we performed a detailed analysis of unusual behaviour of the discharge observed at the transition from normal to abnormal glow regime in methanol and ethanol vapour and the existence of double channels of the discharge observed in Townsend and normal glow regime in water vapour. Therefore, this paper aims to give an overview of breakdown data and data for Volt-Ampere (V-A) characteristics of discharges in vapours of studied liquids; and to emphasize some of the issues that can be important in the analysis and interpretation of results.

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SPIG2020 - Program by day

Monday, Aug 24th (Day 1)

- Organized bus transfer* for SPIG2020 - time (TBA)
- 17:30 Opening ceremony
- 18:00 Session dedicated to 30th jubilee of SPIG conferences
- 20:00 Welcome cocktail* with the concert of traditional music and dance

Tuesday, Aug 25th (Day 2)

- 9:00-19:30 SPIG 2020

Wednesday, Aug 26th (Day 3)

- 9:00-18:00 SPIG 2020
- 18:00 Organized bus transfer to Belgrade*

Thursday, Aug 27th (Day 4) – ONLY VIRTUAL (through Webex Event)

- 9:00-20:00 SPIG 2020

Friday, Aug 28th (Day 5) – ONLY VIRTUAL (through Webex Event)

- 9:00-14:00 SPIG 2020

*IMPORTANT NOTE:

In the case of unfavorable epidemic situation in Serbia, SPIG2020 will be shifted to fully virtual conference. This will be announced in the Final Announcement on August 1, 2020.

SPIG 2020 PROGRAMME

Šabac, Serbia, August 24 – 28, 2020

Monday 24th August 2020 **SPIG 2020 (day 1)**	**REGULAR**	
PL *– Plenary lecture: 35+10 min*	***TL*** *– Topical lecture: 25+5 min*	***PR*** *– Progress Report: 15+5 min*
16:00-17:30	***Arrival and registration***	
17:30-18:15	***Opening ceremony***	
	Plenary Session 1, Hall A, *Chair: L. Č. Popović*	
18:15-19:00	**Zoran Petrović** (Serbia): Review talk on History and Importance of SPIG (dedicated to the 30th jubilee)	
20:00-22:00	*Welcome Cocktail*	

Tuesday 25th August 2020 **SPIG 2020 (day 2)**	**REGULAR+VIRTUAL**	
	Plenary Session 2, Hall A, *Chair: Z. Petrović*	
09:00-09:45	**Jean-Paul Booth** (France): A new look at oxygen plasmas - quantitative spectroscopy for rigorous testing of models *(Virtual)*	
09:45-10:30	**Tőkési Károly** (Hungary): Multiple electron scattering in atomic and surfaces collisions *(Virtual)*	
10:30-11:00	*Coffee break*	
	Plenary Session 3, Hall A, *Chair: A. Milosavljevic*	
11:00-11:45	**Oskar Asvany** (Germany): High-resolution spectroscopy of cation-helium complexes at low temperature (*Virtual*)	
11:45-12:30	**Tony Donne** (Germany): Challenges and Progress on the path towards Fusion Electricity *(Virtual)*	
12:30-14:30	*Lunch break*	
	Hall A - Parallel Session: Collisions (devoted to R. Janev) *Chair: N. Simonović*	***Hall B - Parallel Session*** *Chair: B. Obradović*
14:30-15:00	**Tasko P. Grozdanov** (Serbia): Dynamical adiabatic theory of atomic collisions	**Mario Janda** (Slovakia): The transient spark discharge driving circuit optimizations for enhanced NOx generation
15:00-15:30	**Nataša N. Nedeljković** (Serbia): Two-state vector model for the ion-surface interaction: foundation and application	**Eric Griglio** (France): Ion transport through insulating capillaries: Self-organized focusing revealed

15:30-16:00	**Ronald McCarroll** (France): Adiabatic Representation of Atomic Collision Processes *(Virtual)*	**Suvasthika Indrajith** (France): Effects of ionizing radiations on the reactivity inside clusters of linear hydrocarbons: polymerization vs. cyclization **[15:30-15:50]**
16:00-16:30	**Roberto Celiberto** (Italy): Electron-molecule collisions in fusion plasmas: a long-standing collaboration with Professor Ratko Janev *(Virtual)*	**Dragan M. Pavlović** (Serbia): Plasma channel evolution in the triggered lightning discharges **[15:50-16:10]**
		Aliaksandra Kazak (Belarus): The atmospheric pressure air plasma jets for innovative medical applications **[16:10-16:30]**
16:30-17:00	*Coffee break*	
	Hall A - Parallel Session Collisions (devoted to R. Janev) *Chair: T. Grozdanov*	***Hall A - Parallel Session*** 4. GENERAL PLASMAS *Chair: I. Savić*
17:00-17:30	**Song Bin Zhang** (China): Quantum collision dynamics involving plasma shielding effects with Prof. Ratko Janev *(Virtual)*	**Miroslava Vukčević** (Serbia): Soliton structures in different astrophysical systems **[17:00-17:20]**
17:30-18:00	**Yue Ying Qi** (China): Atomic structure and dynamic process in ideal and non-ideal plasma with Prof. Ratko Janev *(Virtual)*	**Nikola Veselinović** (Serbia): Correlation analysis of solar wind parameters and secondary cosmic rays flux **[17:20-17:40]**
18:00-18:30	**Predrag Krstic** (USA): Vibrationally resolved collisions of hydrogen ions and molecule *(Virtual)*	**Đorđe Savić** (Serbia): Modeling broad line polarization in active galactic nuclei **[17:40-18:00]**
18:30-20:00	***Poster session (1)*** □ Regular and virtual poster presentation [*Optional: 3min presentation of posters]	
20:00	***Conference dinner***	

Wednesday 26th August **SPIG 2020 (day 3)**	**REGULAR+VIRTUAL**	
PL *– Plenary lecture: 35+10 min*	***TL*** *– Topical lecture: 25+5 min*	***PR*** *– Progress Report: 15+5 min*
	Plenary Session 4, Hall A, *Chair: B. Marinković*	
09:00-09:45	**K.-D. Weltmann** (Germany): Physical Applications in Life Science *(Virtual)*	
09:45-10:30	**Nigel Mason** (UK): New frontiers in Atomic and Molecular Physics *(Virtual)*	
10:30-11:00	*Coffee break*	
	Hall A - Parallel Session 3. LOW TEMPERTURE PLASMAS *Chair: G. Poparić*	***Hall B - Parallel Session*** 1. ATOMIC COLLISION PROCESSES *Chair: M. S. Dimitrijević*
11:00-11:30	**Nikša Krstulović** (Croatia): Cavity Ring-Down Spectroscopy as a Tool for Plasma Diagnostics *(Virtual)*	**Miloš Ranković** (Czech Republic): Electron collisions with dielectric gases considered as SF6 replacement

11:30-12:00	**Daiji Kato** (Japan): Compact electron beam ion trap for spectroscopy of multiple charged ions *(Virtual)*	**Nikolay Shvetsov-Shilovskiy** (Germany): Semiclassical two-step model for strong-field ionization: Further developments and applications
12:00-12:20	**Sanja Živković** (Serbia): Analytical capabilities of TEA CO2 laser based LIBS setup	**Dejan Miličević (Serbia);** Study of structural modifications in poly(L-lactide) (PLLA) induced by high-energy radiation
12:30-14:30	*Lunch break /SPIG Committee meeting at 13h*	
	Hall A - Parallel Session 4. GENERAL PLASMAS *Chair: D. Marić*	
14:30-15:00	**Gregor Primc** (Slovenia): Probing neutral oxygen atoms by laser-optic catalytic sensor	
15:00-15:20	**Ivan Krstić** (Serbia): Spectroscopic investigation of discharge and afterglow phase of microsecond pulsed glow discharge	
15:20-15:40	**Jelena Marjanović** (Serbia): Breakdown and characteristics of non-equilibrium low-pressure DC discharges in vapours of liquids	
16:00-18:00	*Excursion (visit of the city museum)*	

Thursday 27th August 2020 **SPIG 2020 (day 4)**	**ONLY VIRTUAL**	
PL *– Plenary lecture: 35+10 min*	***TL*** *– Topical lecture: 25+5 min*	***PR*** *– Progress Report: 15+5 min*
	Plenary Session 5, Room A*, Chair: A. Ivković*	
09:00-09:45	**Masaharu Shiratani** (Japan): Materials Processing with Low Pressure Plasma: Present Issues and Possible Solutions	
09:45-10:30	**Sibylle Günter** (Germany): The two concepts of magnetic confinement: tokamak and stellarator	
10:30-11:00	*Coffee break & Chat Room*	
	Plenary Session 6, Room A, *Chair: D. Ilić*	
11:00-11:45	**Netzer Hagai** (Israel): Following Supermassive Black Holes Over Cosmic Time	
11:45-12:30	**Dimitri Batani** (France): Current status of the laser fusion research and the shock ignition approach	
12:30-14:00	*Lunch break*	
	Room A - Parallel Session 4. GENERAL PLASMAS *Chair: M. Škorić*	***Room B - Parallel Session*** 3. LOW TEMPERATURE PLASMAS *Chair: M. Kuraica*
14:00-14:30	**Alicja Domaracka** (France): Ion processing of astrophysical ices	**Andrew Gibson** (Germany): Numerical simulation-based optimisation of plasma sources for medical applications

14:30-15:00	**Sebastijan Brezinsek** (Germany): Plasma-wall interaction in W7-X operating with graphite divertor	**Marie-Lise Dubernet** (France): VAMDC – Results and Perspective
15:00-15:20	**Damir Devetak** (Germany): Dissipative phenomena in QCD plasma state created in heavy ion collisions	**Željko Mladenović** (Serbia): Atmospheric pressure helium plasma jet propagating in humid air - influence of water vapour on chemical composition and plasma parameters
15:20-15:40	*Coffee break & Chat Room*	
	Room A - Parallel Session 4. GENERAL PLASMAS *Chair: S. Tošić*	***Room B - Parallel Session*** 2. PARTICLE AND LASER BEAM INTERACTION WITH SOLIDS *Chair: Z. Mišković*
15:40-16:10	**Joël Rosato** (France): Spectroscopic modeling for the investigation of magnetic fusion plasmas and stars with magnetic field	**Régis Bisson** (France): Simulating plasma-wall interaction in fusion reactors with beam-surface experiments
16:10-16:40	**Masanori Nunami** (Japan): Turbulence simulations for stellarator plasma transport	**Kamran Akbari** (Spain): Relativistic Theory of the Interaction of Two-Dimensional Materials with Moving Charged Particles **[16:00-16:20]**
16:40-17:00	*Coffee break & Chat Room*	
	Room A - Parallel Session 3. LOW TEMPERATURE PLASMAS *Chair: S. Djurović*	***Room B - Parallel Session*** 1. ATOMIC COLLISION PROCESSES *Chair: I. Mančev*
17:00-17:30	**Augusto Stancampiano** (France): Plasma jets and multijets in contact with liquids in biomedical experiments: electro fluid dynamic and reactive species distribution	**Dmitry Voloshin** (Russia): PIC MCC and fluid simulation of processing plasmas: collision radiative models and ion energy distribution functions
17:30-17:50	**N. Ben Nessib** (Saudi Arabia): The Fully Relativistic Multiconfiguration Dirac-Hartree-Fock Method for Atomic Structure Calculations for Multiply Charged Ions: The Example of Ca XV	**Ramón L. Panadés-Barrueta** (France): On the automatic computation of global (intermolecular) potential energy surfaces for quantum dynamical simulations
17:50-18:10	**Aleksandra Nina** (Serbia): Propagation of electromagnetic waves in perturbed lower ionospheric plasma	**Luca Vialetto** (Netherlands): Monte Carlo flux modelling of electron kinetics in CO2
18:10-20:00	**Poster session (2)** - Virtual presentation of posters [*Optional: 3min presentation of posters]	

Friday 28th August 2020 **SPIG 2020 (day 5)**		**ONLY VIRTUAL**
PL *– Plenary lecture: 35+10 min*	***TL*** *– Topical lecture: 25+5 min*	***PR*** *– Progress Report: 15+5 min*
	Room A - Parallel Session 4. GENERAL PLASMAS *Chair: V. Srećković*	***Room B - Parallel Session*** 1. ATOMIC COLLISION PROCESSES *Chair: M. Trtica*
9:00-9:30	**Jovan Milošević** (Norway): Quark gluon plasma in an early phase of the Universe and in the laboratory	**Tiago Silva** (Portugal): A detailed reaction mechanism set for vibrational chemistry in CO2 plasmas
9:30-9:50	**Andjelka Kovačević** (Serbia): Rise of LSST - detection of oscillations in AGN emission light curves at different cosmological scales	**Jasper Peschel** (Sweden), Dissociation dynamics of the diamondoid adamantane upon photoionization by XUV femtosecond pulses
9:50-10:10	**Jelena Petrović** (Serbia): The evolution of stellar interiors in massive binary systems	**Ilija Simonović** (Serbia): Kinetic and fluid modelling of non-equilibrium transport of charged-particle swarms in neutral gases and nonpolar liquids
10:10-10:30	**Aleksandra Ćiprijanović** (Serbia): Multi-messenger studies of cosmic ray acceleration in galaxy cluster accretion shocks	**Ana Silva** (Netherlands): A reaction mechanism for vibrationally cold CO2 plasmas
10:30-10:50	**Nikolai Bezuglov** (Russia): Penninning ionization processes involving cold Rydberg alkali metal atoms	**Abeer Almodlej** (Saudi Arabia): The Modified Semi-Empirical Stark Broadening method of calculations: The example of Alkali like ions
11:00-11:30	*Coffee break & Chat Room*	
	Plenary Session 7, Room A, *Chair: D. Borka*	
11:30-12:15	**Dragan Huterer** (USA) Dark Matter and Dark Energy: Gases that Dominate the Universe	
12:15-13:00	**Jaime de Urquijo** (Mexico) The measurement of electron and ion swarms transport and reactivity: Current state and future challenges	
13:00-13:30	*Discussion and Chat Room (D. Ilić, V. Srecković)*	
13:30-14:00	***Closing of the conference***	

LIST OF POSTERS

Maximum dimensions of your poster should be 60cm (width) x 90cm (height).

No	Session	Title	Author
1	1.1.	A DFT study of dissociative electron attachment to C5XH4N and C4XH3N2 (X=H,Cl,Br) aromatic molecules	N. Tańska
2	1.1.	Excitation of the (001) mode of CO2 IN 2.45 GHz microwave E field and DC B field	M. M. Vojnović, V. V. Stanković, M. M. Ristić, G. B. Poparić
3	1.1.	Rates for excitation of the CO2 Fermi resonance members in rf electric field	V. V. Stanković, M. M. Vojnović, M. M. Ristić, G. B. Poparić
4	1.1.	Cross sections calculations for electron scattering from rhodanine and cyanoacetic acid	B. Zywicka, P. Mozejko

ACKNOWLEDGEMENT

30th SUMMER SCHOOL AND INTERNATIONAL SYMPOSIUM ON THE PHYSICS OF IONIZED GASES

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Sunday, September 2nd

	MASTER CENTER 1ST FLOOR HALL
18.00-20.00	Registration
	MASTER CENTER RESTAURANT-1ST FLOOR
19.00-20.30	Welcome cocktail

Monday, September 3rd

8.15-9.00	Registration	
	HALL A	
9.00-9.15	**Opening ceremony**	
	Plenary session I1 **Chair: Z. Lj. Petrović**	
9.15-10.00	**IL4:** *Controlling plasma surface interactions when challenged by statistics and equilibrium* **M. J. Kushner**, MIPSE University of Michigan, USA	
10.00-10.45	**IL2:** *Nonequilibrium kinetics in CO_2 plasmas* **V. Guerra**, IST Universidade de Lisboa, Portugal	
10.45-11.15	Coffee break	
	Parallel session O1, HALL A **Chair: J. E. Jones** (Oral contributions 12")	**Parallel session O2, HALL B** **Chair: K. Hidaka** (Oral contributions 12")
11.15-11.27	**A1** *The Effect of Lorentz Force on Nozzle-Arc Characteristics ove* **Sumedh Pawar** an 	**C1** *ICCD-imaging of a plasma glow during the prebreakdown stage of nanosecond discharges in different gases at both polarities of voltage* **Victor Tarasenko**, Dmitry Beloplotov, Mikhail Lomaev and Dmitry Sorokin
11.28-11.40	**A2** *Calculation Model Development of PTFE Nozzle Ablated Mass and Pressure Changes in High-Voltage Circuit Breaker* **Motohiro Sato,** K. Horinouchi, S. Hiza, Y. Nakamura, Y. Yoshitomo, Y. Shimizu and Y. Yokomizu	**C2** *Flashover of metallic-particle polluted insulators in compressed SF_6 under different voltage waveforms* **Valeria Teppati**, Martin Seeger, Torsten Votteler and Angelos Garyfallos
11.41-11.53	**A6** *Determination of the Voltage Recovery Process for VSC HVDC Systems after transient Single-Pole to Ground Faults* **Maximilian Stumpe**, Armin Schnettler and Ankur Garg	**C3** *Experimental Characterization and Modeling of the Dielectric Breakdown Strength for Technical Surfaces in F-gas Free High-Voltage Switchgear* Svetlana Gossmann, Bernhard Lutz, Andreas Geisler and **Paul Gregor Nikolic**

11.54-12.06	**A8** *Study of simple substituted test method for evaluating protective ability of face shield against hazards of electric arcs* **Shizue Furukawa**, Tomo Tadokoro and Michiharu Ichikawa	**C4** *Objectives and setup to study electrical breakdown in CO_2 as an alternative to SF_6* **Siddharth Kumar** and Tom Huiskamp
12.07-12.19	**A9** *Enhanced Low Voltage DC Switching Using a Permanent a Magnet* **John Shea**	**C5** *Breakdown phenomenon across mm-scale gap with thin cavity* **Hiroyuki Iwabuchi**, Yuya Nakaso and Tsutomu Oyama
12.20-12.32	**A10** *Optical Emission Spectroscopy of Ablation-Dominated Arcs during High-Current Phase and around Current Zero* **Klaus-Dieter Weltmann**, Ralf Methling, Nicolas Götte, Sebastian Wetzeler and Dirk Uhrlandt	**C9** *Discharges in alcohol vapours at low pressures* **Jelena Sivoš**, Nikola Škoro, Dragana Marić, Gordana Malović and Zoran Lj. Petrović
12.33-12.45	**A11** *Evaporation-determined model for cathodic heating in GMA welding* Oleg Mokrov, **Marek Simon**, Alexander Schiebahn and Uwe Reisgen	**C11** *Modeling of radio-frequency breakdown by a Monte Carlo technique* **Marija Puač** and Zoran Lj. Petrović
12.45-14.30	Lunch break	
	Parallel session O3, HALL A **Chair: J. M. Bauchire** (Oral contributions 12”)	**Parallel session O4, HALL B** **Chair: M. Seeger** (Oral contributions 12”)
14.30-14.42	**G1** *Detachment of metallic microparticle from electrode erosion in high-voltage switch* **Wei Zhong**, Guoliang Zhang, Ao Xu and Xingwen Li	**L2** *Mobility Measurement in Different Purities O_2 Using High-Pressure Ion Drift Tube* **Yui Okuyama**
14.43-14.55	**G2** *Influence of polarity to plasma evolution characteristic in three-electrode gas spark gaps* **Ao Xu**, Lin Yang, Wei Zhong, Dazhi Jin and Lei Chen	**L3** *Relation between third-order transport coefficient D_3 and α parameters* **Satoru Kawaguchi**, Kazuhiro Takahashi and Kohki Satoh
14.56-15.08	**G3** *Comparative Studied of Rarefied Deuterium Z-pinch Plasma Shell Discharge by PIC and MHD Simulations* **Cheng Ning**, Zhixing Feng, X. Q. Zhang, Chuang Xue and B. W. Li	**L5** *Calculation of rate constants of some chemical reactions of C5-PFK decomposition* **Li Chen**, Xingwen Li and Jiayu Xiong
15.09-15.21	**G4** *Computer Simulation of B-Field Flux Concentrators for Rotary Arc Current Interruption* **Leonid Shpanin**, Gordon Jones and Joseph Spencer	**L7** *Electron transport in strongly attaching gases in radio-frequency electric and magnetic fields* **Jasmina Atic**, Danko Bosnjakovic, Zoran Petrovic and Sasa Dujko

Proceedings of the 22nd International Conference on Gas Discharges and Their Applications

Novi Sad — Serbia
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Volume 1

Serbian Academy of Sciences and Arts

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- VOLUME 1 -

2nd - 7th September 2018

Novi Sad, SERBIA

Serbian Academy of Sciences and Arts
&
Institute of Physics, University of Belgrade

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TOPICS

Volume 1

A. Arcs

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J. Lightning

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L. Fundamental Processes and Cross-Sections

M. Emerging and Topical Applications of Gas Discharges

N. Measurement Techniques

DISCHARGES IN ALCOHOL VAPOURS AT LOW PRESSURES

J. SIVOŠ[1*], N. ŠKORO[1], D. MARIĆ[1], G. MALOVIĆ[1] AND Z. LJ. PETROVIĆ[1,2]

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ABSTRACT

The basic properties of a breakdown in alcohol vapours (methanol, ethanol, isopropanol and n-butanol), Paschen curves and the corresponding distributions of emission intensities in Townsend regime of discharge were recorded in the range of *pd* (pressure x electrode gap) in the region of Paschen minimum. We obtained effective ionization coefficients of alcohols for the *E*/*N* range 1 kTd–5 kTd from the experimental profiles of emission. Recorded profiles of emission enabled us to identify conditions where processes induced by heavy particles (ions and fast neutrals) are dominant in inducing emission from the discharge.

1. INTRODUCTION

Rapid growth in diversity of potential applications of plasmas in and in contact with liquids brought a need to resolve the issues addressed to mechanisms and elementary processes in these discharges. The idea is to answer at key challenges in this field which regard to transport, chemistry, availability/lack of fundamental reaction rates and cross sections. Interactions of non-equilibrium plasmas with liquids are interesting due to broad domain of applicability from material processing [1] to health care [2] and environmental remediation [3]. Recently, studies of discharges involving alcohols and their vapours draw attention to their application in biomedical field, food industry, environmental technology, material synthesis – fast growth of carbon nanotubes, production of graphene layers and nanoparticles [4-6], in fuel industry for production of hydrogen [7] and for mixtures of gases in high energy particle detectors [8]. The technical advances in the design of new devices are not sufficient in development of applications. Detailed analysis of phenomena which take part in these discharges can be conducted through measurements of elementary properties of the discharge regarding breakdown, operating regimes, discharge structure etc.

In this work, we show measurements of breakdown properties of several alcohol vapours at low pressure. All measurements of electrical properties are supported with recordings of axial discharge structure by an ICCD camera.

2. EXPERIMENTAL SET–UP

The breakdown is achieved between plane cathode made of copper and flat quartz window with a deposited thin platinum film that served as an anode. Diameter (2*r*) of electrodes is 5.4 cm, while the gap is variable. In this paper we show results obtained at two different distances *d*: 1.1 cm and 3.1 cm. The electrode system is placed inside a tight quartz tube, to prevent long-path breakdown. The vapours were evaporated from liquid samples of 99% (methanol, isopropanol and n - butanol) and 95% ethanol. During measurements, the pressure is kept well below the vapour pressure to prevent the formation of liquid droplets. The electrical circuit (fig. 1) allows igniting the discharge in the low-current dc regime using a large series resistance R_0 to limit the current. The breakdown voltage is determined by extrapolating discharge voltages to the zero current. Profiles of the discharge are recorded by an intensified charge-coupled device (ICCD) camera (Andor IStar DH720-18U-03) equipped with a photographic lens. Emission profiles are acquired integrally, in visual range of spectra, and by using optical filters for CH band at 431 nm and Hα line at 656 nm.

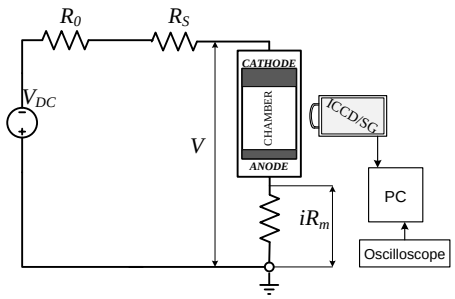

Fig. 1 Experimental set-up scheme

Spectra of emission are also recorded, by spectrograph ORIEL MS127i with a focal length of 138 mm. A detailed description of our experimental technique is given in [9].

3. RESULTS AND DISCUSSION

Breakdown voltage dependence on *pd* (pressure times electrode gap) is measured at two electrode gaps: 1.1 cm (fig. 2a)) and 3.1 cm (fig. 2b)) for four selected alcohol vapours (methanol, ethanol, isopropanol and n-butanol).

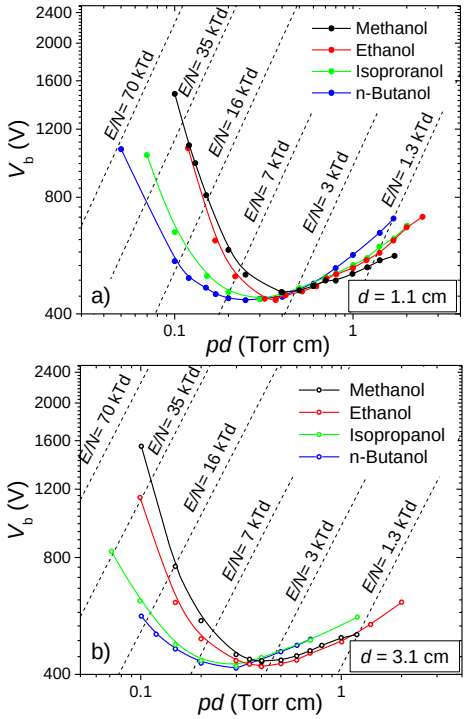

Fig. 2 Paschen curves of discharge in alcohol vapours at two electrode gaps: a) 1.1 cm and b) 3.1 cm

Curves are recorded for *pd* range from 0.06 Torr cm to 2 Torr cm. The reduced electric field *E*/*N* (*E* – electric field, *N* – gas density) is indicated in the plot by several dashed lines representing constant *E*/*N* values. Recorded Paschen curves show that minimum shifts towards the lower pressures for more complex alcohols. For each point of the Paschen curves, spatial profiles of the discharges operating in low-current limit were recorded.

In addition, we have made measurements of emission spectra for methanol, ethanol (fig. 3), isopropanol and n-butanol vapours, that enabled identification of species that participate in these discharges. All four alcohols in the spectral range from 300 nm to 900 nm exibit emission from OH (at 306 nm), CH (431 .nm) and Hα (656 nm). So, according to the measured spectra, we can assume that the most prominent heavy particles that participate in processes of collisional excitation and ionization are H atoms and some heavier dissociation fragments (OH and/or CxHy species) that are produced in vapour dissociation [10].

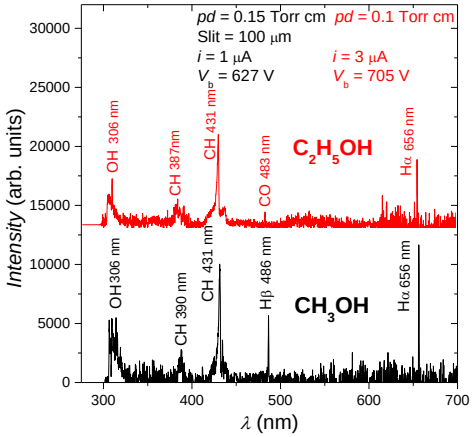

Fig. 3 Emission spectra of alcohol vapours discharges: methanol (black) and ethanol (red)

Since emission is the most intense at 656 nm and 431 nm, we chose Hα and CH band-pass optical filers for spectrally resolved recordings of emission from discharge.

In figure 4 we illustrate how the change of *pd* (*E*/*N*) influences the structure and basic processes in the discharge. We show profiles of emission scaled by the *pd* parameter (*d* is the distance from the cathode), so we may compare emission intensity distributions at different electrode gaps/pressures, i.e different *E*/*N*. At low *pd*-s and high *E*/*N*, heavy particles, ions and neutrals, gain enough energy to perform excitation and even ionization. At *pd* = 0.2 Torr cm heavy-particle processes dominate over electron processes, which is revealed through emission profile peaking close to the cathode (fig. 4a)). The most probable candidates for inducing such high emission in the cathode region are CH radicals and hydrogen fast

atoms. In the right-hand branch of the Paschen curve, at *pd* = 0.6 Torr cm, we observe two peaks of emission intensity, smaller at the cathode and higher at the anode, which indicates excitation by electrons (fig. 4b)). A small peak of emission at the cathode is due to the processes induced by CH radicals. In the case of Hα profile, we observe a typical, exponential, increase of emission intensity from the cathode to the anode, which indicates excitation by electrons, with distinct non-hydrodynamic region close to the cathode [11,12]. The data presented on fig. 4 also indicate that basic processes governing breakdown and low-current discharges stay the same for the same *pd*, for the range of gaps covered here, so the discharge structure remains unchanged.

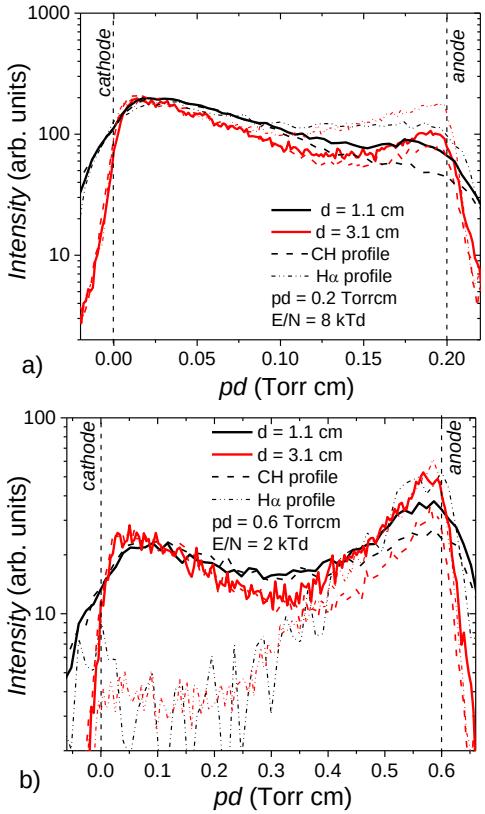

Fig. 4 Axial profiles of emission from Townsend discharge in methanol vapour taken in the a) left branch (pd = 0.2 Torr cm) and b) in the right branch (pd = 0.6 Torr cm) of the Paschen curve. At x-axis the distance from the cathode d is multiplied by p to enable comparisons of profiles recorded at the same pd at different electrode gaps. Full lines represent profiles integrated in visual spectra, the dashed profiles are recorded through a band-pass CH filter and dash-doted profiles are recorded through a Hα filter

Based on experimentally recorded emission profiles for the low current limit (no space charge effect) of the discharges in the Townsend/diffuse regime (breakdown conditions) we were able to determine effective ionization coefficients for studied alcohols. Basically, when the discharge is running in the low-current limit, the emission profile reflects electron multiplication between the electrodes (best observed if plotted in the semi-log scale) and the slope corresponds to the ionization coefficient once equilibrium with the local field is reached [11]. However, at high E/N emission in front of the cathode coming from heavy-particle excitation mask electron excitation profile. Thus, in fig. 5 we show effective ionization coefficients from our experimental data for the range of *E/N* from 1 kTd to 5 kTd. We also show results for ionization coefficients from the literature [13-15] for comparison.

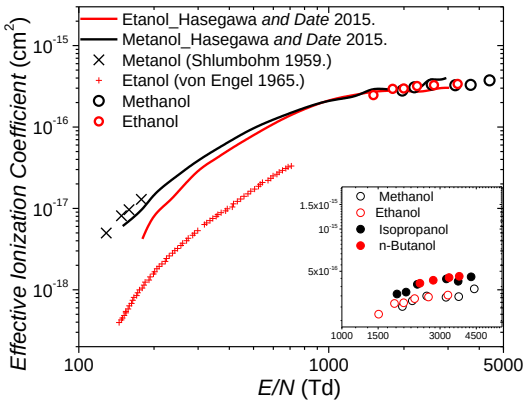

Fig. 5 The dependence of reduced effective ionization coefficient (α_{eff}/N) on the reduced electric field (E/N). Results obtained from our experiment for methanol (open black circles) and ethanol (open red circles) are compared with data for methanol from Hasegawa and Date [13] (black line) and Shlumbohm [14] (black X) and with data for ethanol from Hasegawa and Date [13] (red line) and von Engel [15] (red crosses). The inset shows results from our experiment for methanol, ethanol, isopropanol and n-butanol

Our results agree well with Hasegawa and Date [13] in the range of *E/N* > 1 kTd. Due to experiment limitations and instability of discharge operation we couldn't obtain data for the range of *E/N* < 1 kTd.

4. CONCLUSION

In this paper, we present the data from experimental studies of the dc breakdown in four alcohol vapours: methanol, ethanol, isopropanol and n-butanol. The measured data provide the basis to describe the breakdown in alcohol vapours, to identify species and elementary processes that participate in these discharges. The results also provide basis for further progress in modelling of the breakdown in alcohols.

ACKNOWLEDGEMENTS

This work is supported by the Serbian MESTD under project numbers ON 171037 and III 41011.

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Monday *25-May-15*	Tuesday *26-May-15*	Wednesday *27-May-15*	Thursday *28-May-15*	Friday *29-May-15*
9:00 - 10:30 welcome & awards (30 min) Plenary PL1 (1 hr) **Sinars** *Citrine II-III*	9:00-10:00 Plenary PL3 **Chen** *Citrine II-III*	9:00-10:00 Plenary PL5 PSAC Winner **Velikovich** *Citrine II-III*	9:00-10:00 Plenary PL7 **Lu** *Citrine II-III*	**MINICOURSE** *Amphitheater* **9am - 6pm**
BREAK 10:30-11:00	BREAK 10:00-10:30	BREAK 10:00-10:30	BREAK 10:00-10:30	
11:00 - 1:00 1A **1.3 Space Plasmas** *Opal I*	10:30-1:00 3A **1.1 Basic Phenomenon I** *Opal I*	10:30-1:00 5A **1.2 Computational Plasma Physics** *Opal I*	10:30-1:00 7A **1.1/1.2 Basic Phenomenon II / Computational Plasma Physics II** *Opal I*	
11:00 - 1:00 1B **4.1 Fusion** *Opal II*	10:30-1:00 3B **2.1 Intense Beam Microwave Generation** *Opal II*	10:30-1:00 5B **2.2 / 2.3 Fast Wave Devices / Slow Wave Devices** *Opal II*	10:30-1:00 7B **4.2 / 4.3 Particle Acceleration with Lasers and Beams / Radiation Physics and X-ray Lasers** *Opal II*	
11:00 - 1:00 1C **2.6 / 2.8 Non-Rusion Microwave Systems / THz Sources, Radiation & Applications** *Onyx*	10:30-1:00 3C **4.6 Z Pinches** *Onyx*	10:30-1:00 5C **3.1 Plasma, Ion, and Electron Sources** *Onyx*	10:30-1:00 7C **7.4 Compact Pulsed Power and Applications** *Onyx*	
11:00 - 1:00 1D **7.2 / 7.3 Switching / Generators & Networks** *Quartz*	10:30-1:00 3D **6.1 / 6.2 / 6.3 Diagnostics** *Quartz*	10:30-1:00 5D **5.4 Plasma for Lighting, Displays, and Microdischarges** *Quartz*	10:30-1:00 7D **4.6 Z Pinches** *Quartz*	
11:00 - 1:00 1E **5.1 / 5.2 Nonequilibrium Plasma Applications / High-Pressure and Thermal Plasma Processing** *Topaz*	10:30-1:00 3E **5.5 Environmental and Industrial Applications** *Topaz*	10:30-1:00 5E **5.1 Nonequilibrium Plasma Applications** *Topaz*	10:30-1:00 7E **5.5 Environmental and Industrial Applications** *Topaz*	
LUNCH 1:00 - 2:00	LUNCH 1:00 - 2:00	LUNCH 1:00 - 2:00	END	
2:00-3:00 Plenary PL2 **Krasik** *Citrine II-III*	2:00-4:00 4A **1.5 Dusty Plasmas** *Opal I*	2:00-3:00 Plenary PL6 **Inan** *Citrine II-III*	**MINICOURSE** *Amphitheater* **1pm - 6pm**	
Poster Session 3:00 - 4:30 1P **1.1, 1.2, 1.5, 2.1, 4.4, 4.6, 5.1, 5.6, 7.1** *Citrine I*	2:00-4:00 4B **2.5 Codes and Modeling** *Opal II*	*Poster Session* 3:00 - 4:30 3P **1.6, 2.2, 2.3, 2.5, 3.1, 3.2, 4.1, 4.2, 4.3, 5.5, 6.1, 6.2, 6.3** *Citrine I*		
BREAK 4:00-4:30	2:00-4:00 4C **4.1 Fusion** *Onyx*	BREAK 4:00-4:30		
4:30-6:30 2A **1.4 Partially Ionized Plasmas** *Opal I*	2:00-4:00 4D **5.6 Plasma Medicine** *Quartz*	4:30-6:30 6A **2.7 Microwave Plasma Interaction** *Opal I*		
4:30-6:30 2B **1.6 Plasma Chemistry** *Opal II*	2:00-4:00 4E **7.1 Insulation and Dielectric Breakdown** *Topaz*	4:30-6:30 6B **1.6 Plasma Chemistry** *Opal II*		
4:30-6:30 2C **3.1 / 3.2 Plasma, Ion, and Electron Sources / Intense Electron Ion Beams** *Onyx*	BREAK 4:00-4:30	4:30-6:30 6C **4.7 Plasma Materials** *Onyx*		
4:30-6:30 2D **4.5 Laser Produced Plasmas** *Quartz*	*Poster Session* 4:00-5:30 2P **2.7, 2.84.5, 4.7, 5.2, 5.3, 5.4, 5.5, 7.2, 7.3, 7.4** *Citrine I*	4:30-6:30 6D **4.4 High Energy Density Plasmas** *Quartz*		
4:30-6:30 2E **5.6 Plasma Medicine & Biological Effects** *Topaz*	5:30-6:30 Plenary PL4 Curie Winner **N. Hershkowitz** *Citrine II-III*	4:30-6:30 6E **5.3 Plasma Thrusters** *Topaz*		

Plenary Session
Oral Sessions
Poster Session

Program 5/18/15

Session PL0: Welcome Session

Monday, May 25 09:00-09:30, Citrine II-III

Session Chair: Lutfi Oksuz, Suleyman Demirel Universitesi

Session PL1: Plenary PL1

Monday, May 25 09:30-10:30, Citrine II-III

Session Chair: David A. Hammer, Cornell University

9:30 PL1-1 MAGNETO-INERTIAL FUSION RESEARCH IN THE UNITED STATES: A PROMISING PROSPECT
D. B. Sinars
Sandia National Laboratories, Albuquerque, NM, USA

Session 1A: Space Plasmas

Monday, May 25 11:00-13:00, Opal I

Session Chair: Peter H Yoon, University of Maryland, College Park

11:00 1A-1 (invited) WEAK TURBULENCE IN RADIATION BELTS
G. Ganguli[1], C. Crabtree[1], M. Mithaiwala[1], L. Rudakov[2]
[1]*Plasma Physics Division, Naval Research Laboratory, Washington, DC, United States*
[2]*Icarus Inc., Bethesda, MD, US*

11:30 1A-2 (invited) ABSORPTION AND EMISSION SPECTROSCOPY REVEALING ASTROPHYSICAL PLASMA PROPERTIES IN AT-PARAMETER LABORATORY EXPERIMENTAL SIMULATIONS
M. E. Koepke[1], G. A. Rochau[2], G. P. Loisel[2], J. E. Bailey[2], D. Liedahl[3], T. Nagayama[2], R. Mancini[4], T. S. Lane[1], M. K. Flaugh[1]
[1]*West Virginia University, Morgantown, WV, USA*
[2]*Sandia National Laboratories, Albuquerque, NM, USA*
[3]*Lawrence Livermore National Laboratory, Livermore, CA, USA*
[4]*University of Nevada, Reno, NV, USA*

12:00 1A-3 WHISTLER WAVES IN MAGNETOSHEATH WITH OBSERVED FLAT TOP DISTRIBUTIONS
M. N. S. Qureshi
Physics, GC University, Lahore, Pakistan

12:15 1A-4 (invited) IONOSPHERIC MODIFICATIONS USING MOBILE, HIGH POWER HF TRANSMITTERS BASED ON HPM TECHNOLOGY
K. Papadopoulos
Physics, University of Maryland, College Park, MD, United States

12:45 1A-5 ASYMPTOTIC THEORY OF SOLAR WIND ELECTRONS
P. H. Yoon
IPST, University of Maryland, College Park, College Park, MD, United States

Session 1B: Inertial and Magneto-Inertial Fusion

Monday, May 25 11:00-13:00, Opal II

Session Chair: Daniel B Sinars, Sandia National Laboratories

15:30 4D-6 CHARACTERISTICS OF A SURFATRON-PRODUCED ATMOSPHERIC-PRESSURE PLASMA JET AT LOW PLASMA TEMPERATURES
T. Doll, C. M. Oeguen, R. Kling
Light Technology Institute, Karlsruhe Institute of Technology, Karlsruhe, Germany

Session 4E: Insulation and Dielectric Breakdown

Tuesday, May 26 14:00-16:00, Topaz

Session Chair: Zoran Petrovic, Univ. of Belgrade

14:00 4E-1 DC BREAKDOWN IN VAPOURS OF LIQUIDS
J. Sivos, D. Marić, N. Skoro, G. Malović, Z. L. Petrović
Institute of Physics Belgrade, Belgrade, Serbia

14:15 4E-2 PREBREAKDOWN PROCESSES IN WATER WITH SCREENED ELECTRODES AND POSSIBILITY OF PULSE ELECTRICAL STRENGTH INCREASE
S. M. Korobeynikov[1], A. V. Melekhov[2]
[1]*Power Engineering, Novosibirsk State Technical University, Novosibirsk, Russian Federation*
[2]*Laser Plasma, Institute of Laser Physics, Novosibirsk, Russian Federation*

14:30 4E-3 TWO-DIMENSIONAL SIMULATIONS OF GAS DISCHARGE IGNITION IN SHORT GAPS AT VOLTAGE VALUES BELOW PASCHEN MINIMUM
V. Y. Kozhevnikov[1], A. V. Kozyrev[1], L. A. Zjulkova[2], N. S. Semeniuk[2]
[1]*Faculty of Physics, Tomsk State University, Tomsk, Russian Federation*
[2]*Institute of High Current Electronics, Tomsk, Russian Federation*

14:45 4E-4 DIELECTRIC WITHSTAND OF MULTI BARRIER ARRANGEMENTS IN AIR SUBJECT TO A LIGHTNING IMPULSE VOLTAGE PULSE
J. Ekeberg
Corporate Research, ABB Schweiz AG, Baden-Daettwil, Switzerland

15:00 4E-5 STUDY ON SPOTS ON ELECTRODES AND POLARITY EFFECT INVERSION IN A NANOSECOND-PULSE GAS BREAKDOWN
C. Zhang[1,2], V. F. Tarasenko[3], R. Wang[1,2], T. Shao[1,2]
[1]*Institute of Electrical Engineering, Chinese Academy of Sciences, Beijing, China*
[2]*Key Laboratory of Power Electronics and Electric Drive, Chinese Academy of Sciences, Beijing, China*
[3]*Institute of High Current Electronics, Russian Academy of Sciences, Tomsk, Russia*

15:15 4E-6 NANOSECOND HIGH POWER MICROWAVE WINDOW BREAKDOWN DIANOSTIC AND ITS MECHANISM
C. Chang[1,2], Y.D. Li[2], J. Verboncoeur[3], C. Chen[1]
[1]*Laboratory on Science and Technology of High Power Microwave, Xi'an, Shaanxi, China*
[2]*Key Laboratory of Physical Electronics and Devices of the Ministry of Education, Xi'an Jiaotong University, Xi'an, Shaanxi, China*
[3]*Department of Electrical and Computer Engineering, Michigan State University, East Lansing, Michigan, United States*

15:30 4E-7 STREAMER DISCHARGES ALONG DIELECTRIC SURFACES - EXPERIMENTAL INVESTIGATIONS
A. Chvyreva[1], A. J. M. Pemen[1], T. Christen[2]
[1]*Electrical Engineering, Eindhoven University of Technology, Eindhoven, Netherlands*
[2]*Corporate-Research, ABB Switzerland Ltd., Baden, Switzerland*

15:45 4E-8 POLARITY EFFECTS ON BREAKDOWN STRENGTH FOR HIGH ENERGY STORAGE LIQUID DIELECTRICS IN MICROSECOND REGIME
W. Zhen[1], Z. Zicheng[1], Z. Jiande[1], S. Zuyin[2]
[1]*College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha, China*
[2]*Military Delegate of Air Force Resident Office in Hunan Province, Changsha, China*

Session PL4: Plenary PL4

Tuesday, May 26 17:30-18:30, Citrine II-III

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Abstract Book

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Belek, Antalya, Turkey

DC BREAKDOWN IN VAPOURS OF LIQUIDS*

Jelena Sivoš, Dragana Marić, Nikola Škoro, Gordana Malović and Zoran Lj. Petrović
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Research of discharges in liquids and their vapours has opened many possibilities for novel applications of non-equilibrium discharges in medicine, fuel and sensor industry, food industry and nanotechnology[1,2]. As breakdown in liquids is a quite complex phenomenon, research on the breakdown in vapours of relevant liquids can provide initial information necessary to study elementary processes in the gas phase and at surfaces[3].

Breakdown measurements in vapours of water, methanol and ethanol presented here are done between plane-parallel electrodes, separated by 1.1 cm and biased by a DC voltage. Vapours are obtained from bi-distilled de-ionized water, 99 % methanol and 95 % ethanol. Determination of breakdown voltages and recording of Paschen curve is enabled by the electrical circuit with high resistance which provided highly reproducibility and reliability of data. Cylindrical quartz chamber allows recording of axial (side-on) discharge profiles with ICCD camera, integrated in visible spectra and with narrow band-pass filters: at 656 nm (Hα) for all vapours and at 431 nm (CH band) in alcohols.

Breakdown voltages and spatial profiles of low-current discharge are measured in the range of pressures from 0.07 to 4.5 Torr, well below the vapour pressure to avoid droplet formation. Spectrally resolved measurements of emission profiles indicate importance of heavy particles[4] formed in dissociation of vapour molecules. In water vapour, heavy-particle processes are dominant only at high *E/N* (above 6 kTd), while in methanol and ethanol vapours significant contribution starts from 3 kTd. In the right-hand branch of the Paschen curve (lower *E*/*N*), electron induced excitation becomes significant. In this range of conditions, it is possible to determine ionization coefficients and secondary electron yields from Paschen curves and emission profiles of the discharge. Still, this range is quite narrow for the vapours that we studied, as instabilities, streamer mechanism of breakdown and condensation impede reliable measurements.

1 K. R. Stalder et al, “Spatial and temporal variation of repetitive plasma discharges in saline solutions”, J. Phys. D 39 (2006) 3457.
2. T. Hagino et al. “Ultrahigh-Speed Synthesis of Nanographene Using Alcohol In-Liquid Plasma”, Appl. Phys. Express 5 (2012) 035101.
3. D. Marić et al. “Gas breakdown and secondary electron yields”,Eur. Phys. J. D. 68(6) (2014) 155.
4. D. Marić et al. “Axial emission profiles and apparent secondary electron yield in abnormal glow discharges in argon”, Eur. Phys. J. D 21 (2002) 73.

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THE EUROPEAN PHYSICAL JOURNAL D

Regular Article

Low-pressure DC breakdown in alcohol vapours*

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Abstract. The results covered in this paper provide breakdown data represented by Paschen curves for methanol, isopropanol and n-butanol, along with the corresponding axial profiles of emission in Townsend regime of the discharge and including the optical emission spectra. Paschen curves were recorded in the range of *pd* (pressure x electrode gap) from 0.10 to 3.00 Torr cm. The optical emission spectra (OES) are recorded for wavelength range from 300 to 900 nm, for discharges in all studied alcohols. The recorded spectra enabled identification of species that participate in these discharges. All three alcohols exhibit emission from excited radicals OH (at 306.4 nm), CH (at 431.2 nm) and Hα (at 656.4 nm) produced mostly in dissociative excitation by electrons. Recorded profiles of emission enabled us to identify conditions where processes induced by heavy particles (ions and fast neutrals) are dominant in inducing emission from the discharge.

1 Introduction

Alcohols are organic compounds that are widely used in numerous applications. In recent years, with increasing public awareness of the need for environmental protection, and the reduction of greenhouse gas emissions in the fight against global warming, eco-friendly and renewable energy sources have attracted attention. Certainly, hydrogen is one of the most promising fuels and clean energy sources, however, the main problem is its storage, due to the low density. One of the solutions is to obtain it directly on-site from other compounds. Alcohols have proven to be particularly attractive and suitable for hydrogen production using low-temperature non-equilibrium plasmas [1–4]. It has been proposed that Direct Alcohol Fuel Cells (PEMFC fuel cells) may be used in vehicles, but also in other portable electric or electronic devices [5–8]. In relation to the use of alcohols as a fuel or as its precursor, studies of combustion and initialization of the discharge are needed.

Further development of environmentally friendly energy sources requires an improvement of existing materials and obtaining new ones with enhanced characteristics such as technologies to prepare materials required to grow nanostructures for fuel cells (for example [8–10]). Carbon nanomaterials, such as nanotubes and graphene, are very interesting for a wide variety of applications due their unique structure and exceptional electrical, physical and morphological properties. Specifically, one of the most prominent features of graphene is its high conductivity, which makes it attractive as a material for channels in the next generation of ultra-fast transistors and for transparent electrodes in solar cells. Many studies have shown that plasmas in alcohols can be used as a carbon source [11–15]. It turns out that hydroxyl groups and oxygen atoms from alcohol play an important role in crystallization and formation of nanographene layers [14].

Another important application within the context of gas discharges is in elementary particle/ionizing radiation detection, where alcohol vapours and other hydrocarbon gases are used as quenchers [16–19]. In some cases, alcohols are also applied to suppress aging of detectors [20]. Even though alcohols are used in small percentages in gaseous detectors, in mixtures with atomic buffer gases, they have a critical influence on the shape of electron energy distribution and transport coefficients, due to large vibrational excitation cross sections [21,22].

Thus, there is a versatile field of application of these non-equilibrium discharges, both in liquid state or as a vapour. The development of future and improvement of existing applications are based on a good understanding of elementary processes that take place in the discharges. A special challenge is to extend the techniques and understanding of the gas phase discharges into the realm of discharges in liquids, liquid-gas interfaces and gas mixtures involving vapours [23]. The information, on fundamental

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processes, can be obtained from measurements of elementary properties of discharges such as breakdown, operating regimes, discharge anatomy, etc. Hence, the importance of breakdown studies lays in the fact that they can reveal information on individual processes and their balance in discharges [24–30].

Back at the beginning of the twentieth century, Townsend had formulated the theory of initiation of electrical breakdown in a gas [29,30], which predicts that the breakdown voltage (V_b) scales with the pd product, where d represents the length of the electrode gap and p is the pressure. Product pd is proportional to the number of collisions that one particle makes while covering some distance. A Paschen curve (plot of the breakdown voltage dependence on pd), is unique to each gas or gas mixture and provides information for a better understanding of the underlying processes in electrical breakdown. Our research aims at providing some of the basic data on a breakdown and various operation regimes of low-pressure DC discharges in vapours of liquids (water and alcohols) [27,28,31]. The lack of such data in the literature is one of the key reasons why it is necessary to address this type of research.

In this paper, we present measurements of the Paschen curves obtained for the discharges in the vapours of primary alcohols (methanol and n-butanol) and secondary alcohol (isopropanol) at low–pressures and compared to previously published results for ethanol [31]. All measurements of electrical properties are supported by recordings of axial discharge profiles by an ICCD camera. Therefore, our study of low–pressure discharges in alcohol vapors provides a complete set of breakdown data together with spatial emission profiles of the low–current discharges. Such sets may be the basis for further analysis or may be employed directly (e.g. ionization coefficients) [22,24,32]. The present measurements can also provide new or give additional insight into the understanding of relevant atomic and surface processes associated with electrical breakdown [24,33,34].

2 Experimental setup

The electrode system consists of two flat electrodes 5.4 cm in diameter and is placed inside a tightly fitted quartz tube. The distance between electrodes is adjustable and the present measurements were performed in a plane-parallel electrode geometry, at two different electrode distances: 1.1 and 3.1 cm. The cathode is made of copper, while the anode is a quartz window with a deposited thin, transparent, conductive platinum film. A simplified schematic of the experimental set-up is provided at Figure 1.

The discharge chamber construction allows side–on recordings and we used two setups to register emission coming from the discharge. In the first case, the camera was equipped with a glass lens allowing us to acquire axial discharge profiles of the spectrally integrated emission in the visible range of spectra, defined by the transparency of the lens and the quantum efficiency of the ICCD photocathode. For spectrally resolved measurements we used

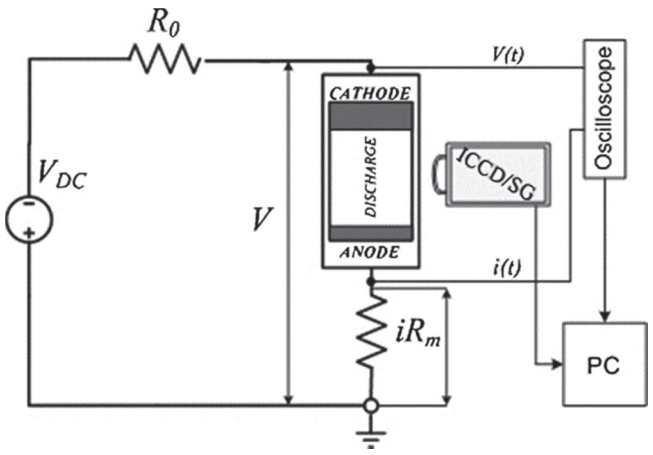

Fig. 1. Schematics of the experimental setup and the electrical circuit used in measurements. All the recordings were made with an ICCD camera mounted with an objective lens, a filter or a spectrograph (SG). The series resistor R_0 is used to limit current and keeps it as low as possible for measurements in the Townsend discharge. R_m is the "monitoring" resistor used to measure discharge current.

band–pass optical filters in front of the lens thus enabling recordings of emission profiles for a narrow range of wavelengths. In another setup, optical spectrum of emission from alcohol vapour discharges was recorded by focusing light from the discharge to a 100 μm entrance slit of the ORIEL MS127i spectrograph. In both cases sensitive ICCD camera (Andor IStar DH720-18U-03) was used to detect the signal. The spectrograph is equipped with a ruled grating with a wavelength range from 200 to 1200 nm with spectral resolution 0.22 nm. A more detailed description of the experimental procedure is given in [31]. The requirements of the experiment (very small currents, steady state Townsend discharges) dictated the need to limit the resolution in order to increase the sensitivity.

The vacuum chamber is pumped down to the base pressure of below 10^{-6} Torr. Prior to the measurements, the surface of the cathode is treated by a relatively high current discharge in hydrogen (30 μA), approximately 30 min, until a stable voltage is achieved. The cathode surface treatment can remove oxide layers and impurities from the cathode, up to an extent where the surface becomes stable during the long periods of measurements. This procedure has been proven to provide reliable and reproducible breakdown data [24,33]. After the cleaning of the cathode, the discharge chamber is again vacuumed to the pressure of around 10^{-6} Torr. Both, treatment in hydrogen discharge and measurements in alcohol vapours are done in a slow flow regime, to ensure that possible impurities formed in the discharge chamber are continuously removed.

We have performed measurements for three primary alcohols: methanol, ethanol (see our earlier paper [31]) and n-butanol, and one secondary alcohol – isopropanol (2–propanol). The vapours are obtained from 99.5% purity methanol, isopropanol, and n-butanol. Water is an abundant impurity in alcohols (max. 0.2%), while other volatile impurities such as acetone, aldehydes and formic acid (max. 0.002%) are present in small quantities. Also, iron

(0.0005%) and some non-volatile substances (<0.001%) are present only in traces. Therefore, a small percentage of water vapour may be found in the discharge. Effects of inherent gas impurities can be critical in two cases. First, it is known that breakdown data in atomic gases are sensitive to molecular impurities, due to significant vibrational energy losses introduced by molecular gases. Second, the attachment to impurities may strongly affect discharges in gases that are not subject to attachment. In that respect dissolved oxygen would be the most important impurity. However, neither of the two possible processes are expected to affect strongly the results for gas discharges where ionization is a key process and is dominated by the most abundant gas. Therefore, water will not affect the results strongly (beyond its percentage abundance) through either of the two effects and the same is true for all other present components. Also, it should be stated that even without evaporating the dissolved oxygen it would not affect the breakdown potential and other properties of the discharge as the operating point is defined by the ionization to the most abundant gas i.e. alcohols.

The alcohol vapour is introduced into the discharge chamber from a test tube with a liquid sample, through a pressure regulating valve. Immediately after opening the valve, alcohol begins to boil due to the pressure difference above its surface (10^{-6} Torr) and the pressure of dissolved gases in the sample itself. In this way, alcohol becomes devoid of dissolved volatile constituents. The impurities are reduced in the liquid sample to a minimum throughout the boiling and vacuuming processes. Boiling stops when a significant part of volatile impurities evaporates. After boiling has ceased vapour is maintained at a moderate pressure (lower than the vapour pressure) in the chamber for period of 1–2 h in order to saturate the electrodes and the chamber walls. The vapour pressures of methanol, isopropanol and n-butanol at room temperature (25°C), are around 127, 44 and 7 Torr, respectively [35], so during the measurements operating pressures are kept well below these values to avoid the formation of liquid droplets.

The electric circuit is designed (as explained in greater detail in our previous papers [28,31,36]) to provide stable operation of the discharge near the breakdown conditions. The breakdown voltage for each *pd* is determined from the low–current limit of the discharge, by extrapolating the discharge voltage to zero current in the dark Townsend discharge mode [31,33,37].

3 Results and discussion

3.1 Paschen curves–breakdown data

Figure 2 shows breakdown voltage as a function of *pd*, where p is the pressure, and d is the electrode gap size. These measurements have been performed at two inter-electrode distances: 1.1 and 3.1 cm and cover the range of *pd*s from 0.10 to 3.00 Torr cm overlapping with the minimum of the breakdown voltage in all cases. The dashed lines in the graphs indicate the values of the reduced electric field E/N ($1\,\mathrm{Td} = 10^{-21}\,\mathrm{Vm}^2$). Shapes of Paschen curves for all alcohols are typical for gaseous low-pressure DC discharges [33]. Electrode gaps are measured to better than 2% uncertainty, pressure and voltage to better than 1%, which makes them too small to be presented in graphs.

The minimum of Paschen curve, in the case of methanol for the gap of 3.1 cm lies at 0.40 Torr cm, while breakdown voltage is 433 V. At the same gap, for isopropanol and n-butanol, the minimum lies at 0.30 Torr cm and breakdown voltages are 420 V and 415 V respectively. When distance between electrodes is 1.1 cm minimal breakdown voltages are: 455 V at 0.40 Torr cm for methanol, 436 V at 0.30 Torr cm for isopropanol, and 434 V at 0.25 Torr cm for n-butanol. Breakdown in ethanol vapour has been presented in detail in [31]. In Figure 2d we compare Paschen curves for ethanol with other studied alcohols. One may notice a general trend that the minimum of the Paschen curves shifts to lower voltages and lower *pd*, as one goes from simple to more complex alcohols. As molecule becomes more complex (more atoms) there are more modes for vibrational excitation (and vibrational excitation is the dominant process controlling the mean energy of the discharge) and thus losses are likely to be greater requiring breakdown at higher E/N. To the right of the Paschen minimum one can reach greater E/N by increasing the breakdown voltage and as a result the Paschen curve for the most complex molecule is above those that are less complex. To the left of the Paschen minimum the more efficient way to reach higher E/N (ie mean energy) is to shift the minimum to the lower values of *pd* as the values of the voltages for the minimums are similar. Thus the most complex molecule has the lowest breakdown voltage to the left of Paschen minimum.

Paschen curves (Fig. 2) obtained at different electrode gaps show good agreement at low E/N values (the right-hand branch of the Paschen curve). At higher E/N (the left-hand branch of the Paschen curve), some discrepancies in breakdown voltages at different electrode gaps are noticeable. The differences in breakdown voltages at different gaps may originate from slight pressure variations, which can have a large impact in a region of the steep rise of the curve. More importantly, processes at surfaces (secondary electron emission) have a stronger effect at high E/N, while low E/N breakdown is dominated by gas phase processes [24]. Even the slightest changes at cathode surface between two sets of measurements can be detected through differences in the left-hand branch of the Paschen curve. The applied experimental technique, in our measurements, is designed to ensure minimal discrepancies between different sets of measurements.

After the breakdown, discharge is stable at low-current (around $1\,\mu$A) up to $pd = 0.70$ Torr cm, except for n-butanol where the boundary is at 0.40 Torr cm. Above these values discharge ignites into oscillations. At higher *pd* we obtain periodic relaxation oscillations from which we can determine the breakdown voltages [38–41]. In the case of alcohol discharges these periodic relaxation oscillations have frequencies between 250 and 890 Hz. However, above 3.0 Torr cm, it becomes difficult to control the discharge, oscillations become random and we cannot use them to establish breakdown voltage with reasonable accuracy. At

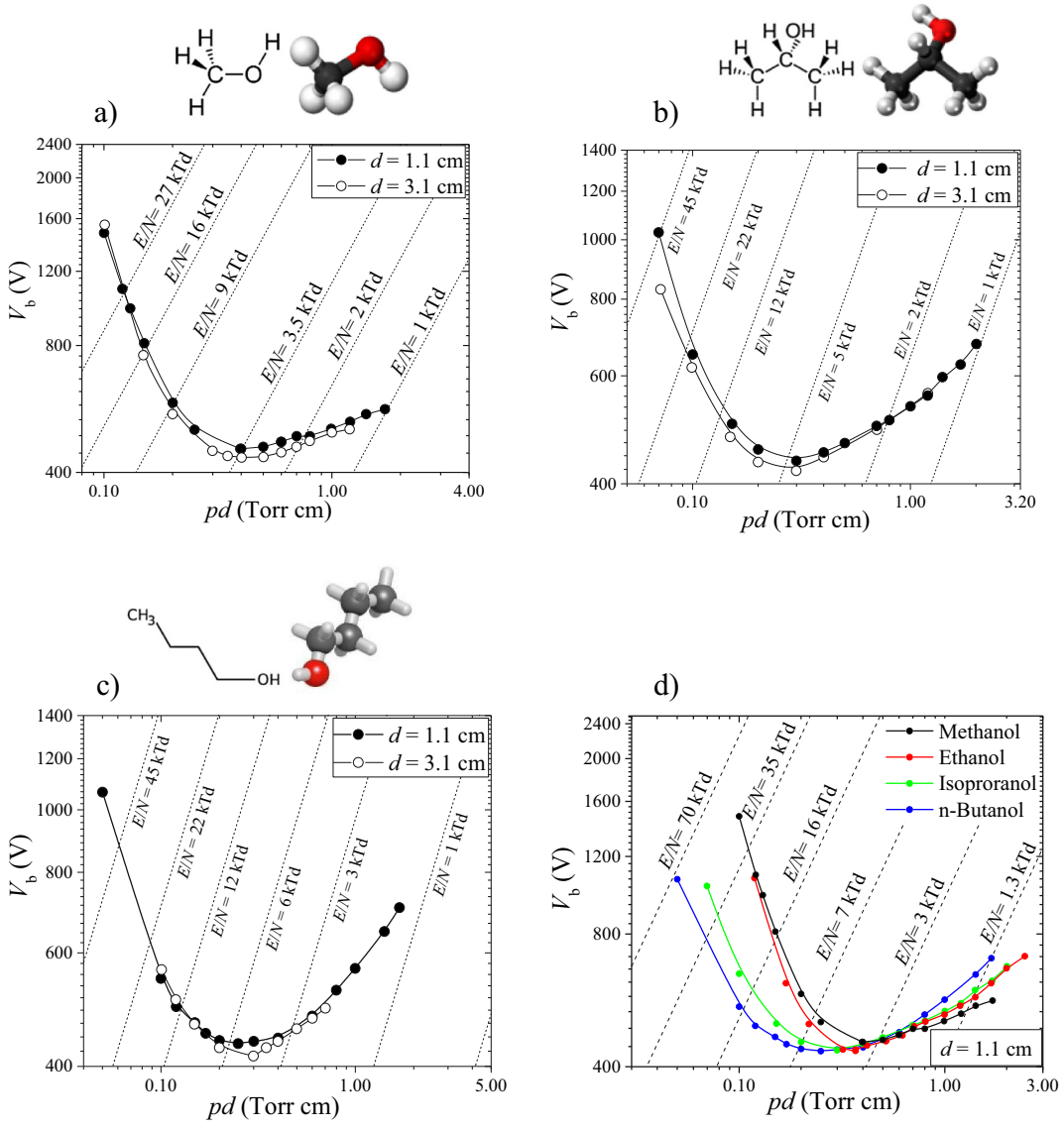

Fig. 2. Paschen curves for discharges in vapours of alcohols, at various reduced electric field (E/N) indicated by dashed lines [$1\,\mathrm{Td} = 10^{-21}\,\mathrm{Vm}^2$ and $1\,\mathrm{Torr} = 133.32\,\mathrm{Pa}$]. (a) Methanol vapour at $d = 1.1\,\mathrm{cm}$ (full circles) and at $d = 3.1\,\mathrm{cm}$ (open circles), (b) isopropanol vapour at $d = 1.1\,\mathrm{cm}$ (full circles) and at $d = 3.1\,\mathrm{cm}$ (open circles), and (c) n-butanol vapour at $d = 1.1\,\mathrm{cm}$ (full circles) and at $d = 3.1\,\mathrm{cm}$ (open circles), and (d) comparison of Paschen curves for alcohols that we studied at $d = 1.1\,\mathrm{cm}$. Paschen curve for ethanol is taken from our previous publication [31].

the same time we did not pursue adjustments of the innermost impedance that would require redesigning the experiment to stabilize the discharge [42,43]. Spatial profiles of emission from the discharges recorded along with breakdown data confirm that even at the highest pressures for the *pd*s covered here there is no evidence of a transition to the streamer discharge.

3.2 Axial profiles of emission

We have recorded axial distributions of light intensities integrated over the visible spectral range at different values of *pd* – from 0.10 Torr cm to 0.70 Torr cm. Axial distributions of emission in the low-current limit of the $V - A$ characteristics ($\sim 1\,\mu\mathrm{A}$) are shown in Figure 3 for the two electrode gaps 1.1 and 3.1 cm for methanol (Fig. 3a) and for 3.1 cm for discharges in isopropanol and n-butanol (Fig. 3b). Profiles are obtained from 2D side-on images of the discharge (Fig. 3a).

It has been often stated that the anatomy of discharges may be used to reveal information on overall particle kinetics at different conditions [44–48]. In discharges in alcohol vapours as it can be seen in emission profiles in Figure 3, electron induced excitation is responsible for the shape of emission distribution with the typical exponential increase in intensity towards the anode, at highest *pd*s (lowest E/Ns) covered by our measurements. At lower *pd* i.e. higher E/N, even ions may gain enough energy for excitation. Furthermore, charge exchange with neutral

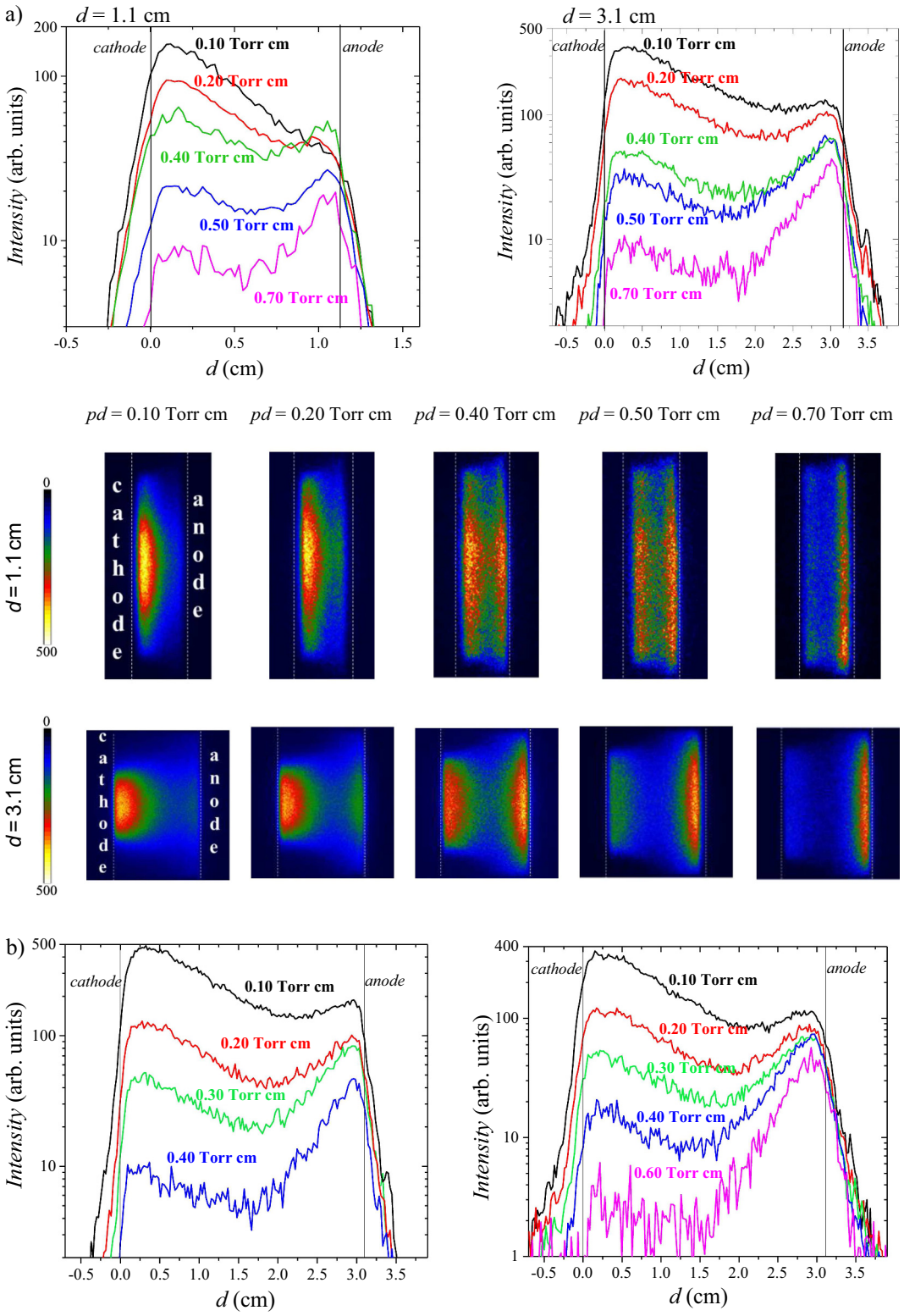

Fig. 3. (a) Axial profiles of emission from discharge in methanol vapour for different values of *pd* (pressure x electrode gap) at electrode gaps: $d = 1.1$ cm and $d = 3.1$ cm. Below the graphs are presented 2D false–colour images of the discharge that correspond to *pd* values at the given electrode gaps showed above. (b) Axial profiles of emission from discharge in isopropanol (left), and n-butanol (right) vapours for different values of *pd* (pressure x electrode gap) at electrode gap $d = 3.1$ cm.

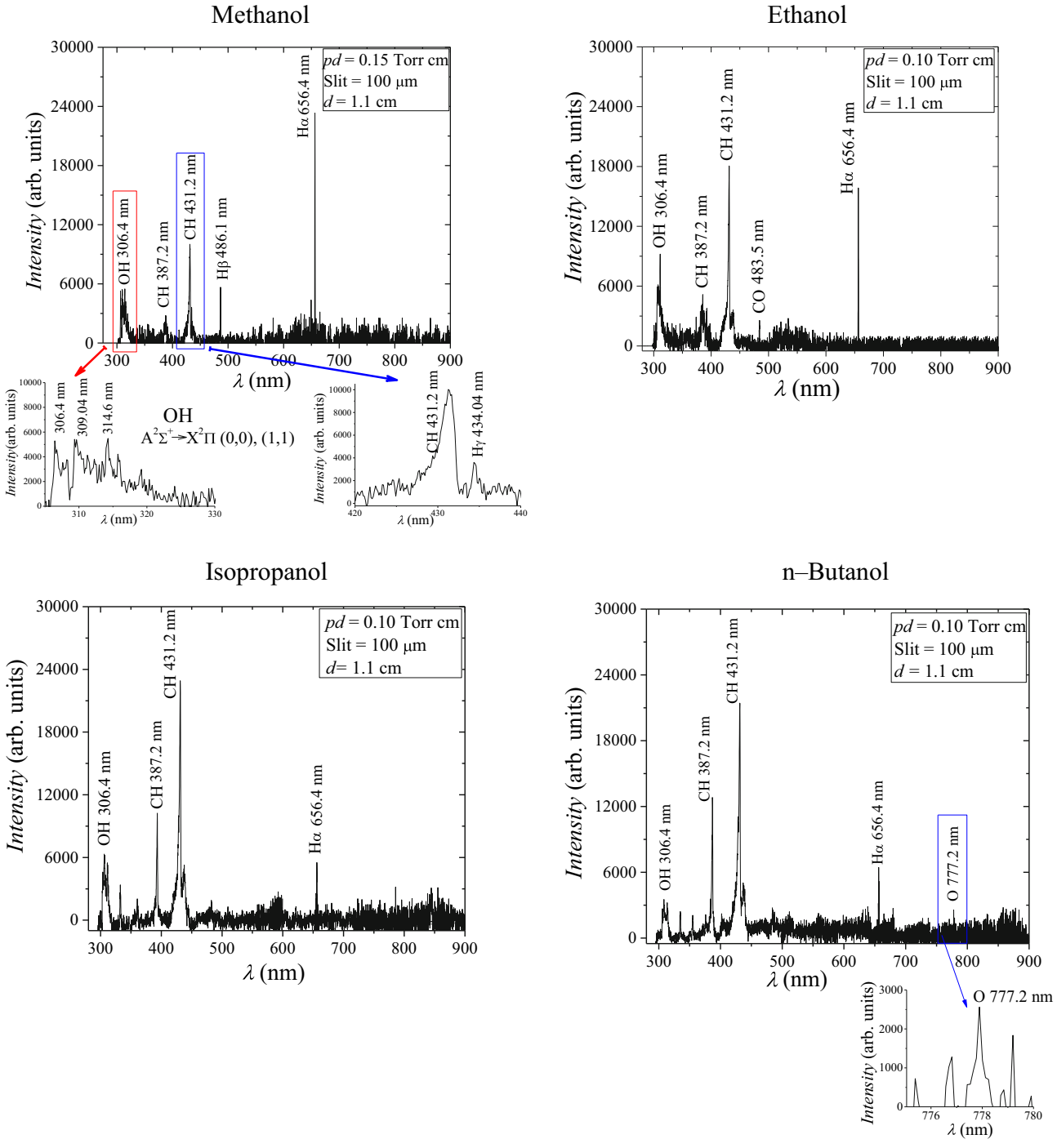

Fig. 4. Emission spectra of discharge in alcohol vapours at low pressure (in the left–hand branch of Paschen curve) and $d = 1.1$ cm. The width of the spectrograph slit was 100 μm.

atoms and molecules may be very efficient, as it has been seen in [45,49,50], so fast neutrals play an important and even dominant role at high E/N. With further increase in E/N contribution of heavy particles increases, which is clearly revealed in Figure 3 through the rising peak of emission close to the cathode. In the range of Paschen minimum, the contribution of heavy particles to excitation is almost the same as the contribution of electrons for all vapours of alcohols presented here. At even lower pressures heavy particles become dominant.

3.3 Spectrally and spatially resolved emission

Optical emission spectra (OES) for discharges in selected alcohols are presented in Figure 4. Here, we repeat the

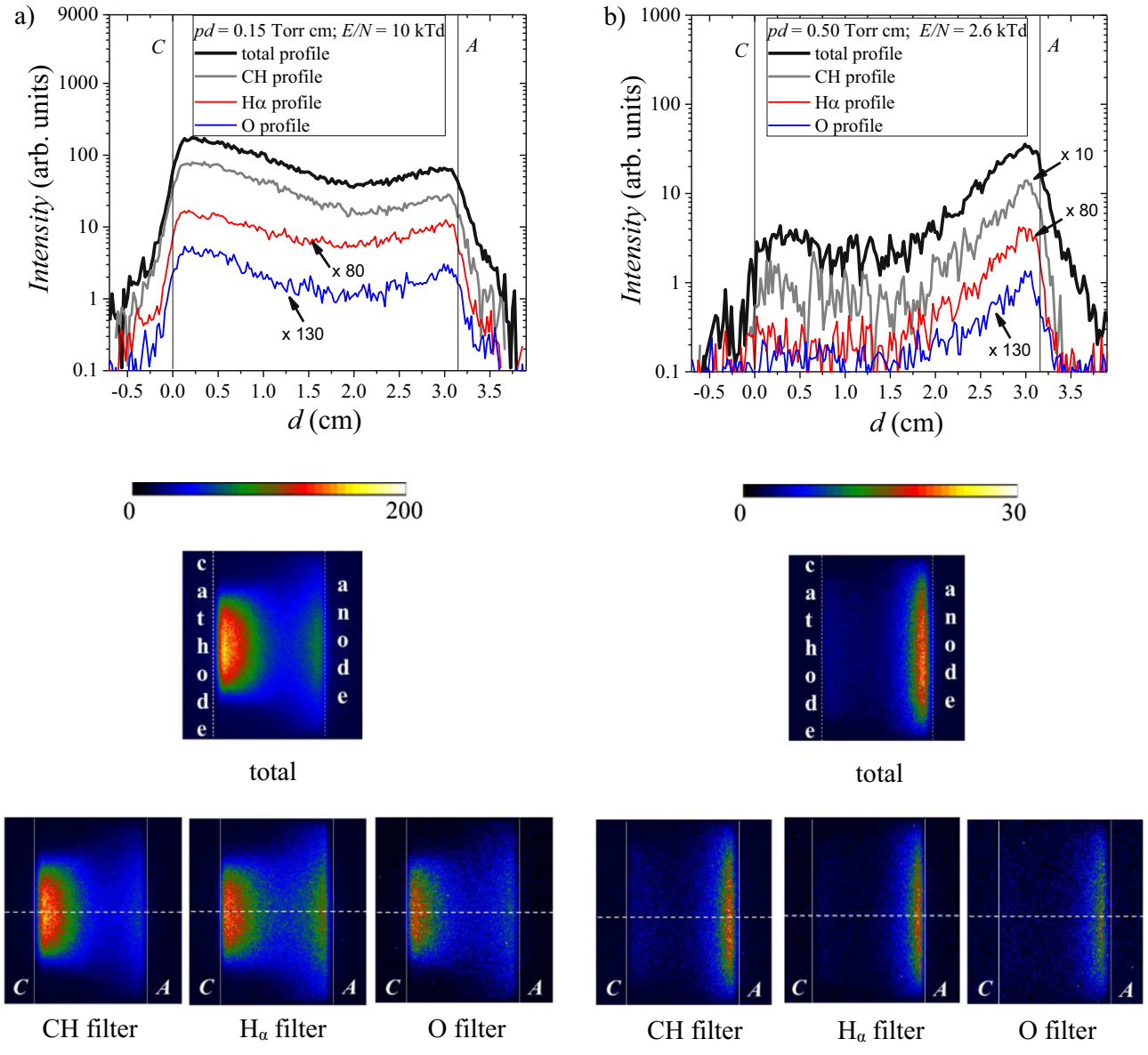

Fig. 5. Axial profiles of emission from discharge in n-butanol vapour at electrode gap $d = 3.1$ cm for two values of pd (pressure x electrode gap): (a) 0.15 Torr cm and E/N (reduced electric field) 10 kTd and (b) 0.50 Torr cm and $E/N = 2.6$ kTd. Emission intensity of selected lines is corrected for the filter transparency and presented at the same intensity scale. Some of the profiles are multiplied by the scaling factor for easier comparison of results. Letters C and A indicate positions of cathode and anode. Axial emission intensity distributions are obtained by extracting the intensities along the horizontal axis shown by the dashed line in 2D images.

ethanol emission spectrum from [31] for comparison with the alcohol spectra presented in this paper.

The spectra were obtained for conditions in the left-hand branch of the Paschen curve, or in other words, at low pressures and at high E/N. All recordings were done at low currents (1 to 3 μA), i.e. for the discharge operating in the Townsend regime, where space charge effects can be neglected. The strongest line for simpler alcohols is H_α, while for the more complex alcohols, that line is subdued, and CH emission is the strongest.

Optical emission spectra measurements were performed in the spectral range from 300 to 900 nm, in which the most intense emissions belong to OH and CH radicals and atoms O and H (Balmer series lines). The detected emission stems from the excited species produced in dissociative excitation of the parent molecule producing H atoms and some heavier excited dissociation fragments (OH, CO and/or CxHy) [31,51–55]. The optical emission spectrum of ethanol vapour discharge was described in detail in [31]. If we look at all recorded OES, it is obvious that emissions originated from OH, CH, and H_α, are the most prominent in the herein studied discharges of alcohol. The emission at 306.4 nm originates from OH radicals [54–57]. On the other hand, the emission of CH radicals comes from two

dominant systems: (1) the $A^2\Delta \rightarrow X^2\Pi$ system, with the band-head at 431.2 nm, and (2) the $B^2\Sigma^- \rightarrow X^2\Pi$ system, with the band-head at 387.2 nm [50–54]. The isopropanol and n-butanol have more carbon content than methanol and ethanol do and contain many more C–H bonds, so CH emission has the highest intensity in these discharges [58].

The recorded optical emission spectra were used to select the appropriate band-pass optical filters for spectrally resolved recordings of spatial emission distributions from discharges. In the case of n-butanol, we used optical filters for extracting emissions at three selected wavelengths: 431.2 nm (CH), 656.4 nm (Hα), and 777.2 nm (O). Figure 5 shows axial profiles of emission from the discharge in n-butanol vapour, obtained for electrode gap of 3.1 cm, in the left part of the Paschen curve at $pd = 0.15$ Torr cm and $E/N = 10$ kTd, and in the right-hand branch of the Paschen curve at $pd = 0.50$ Torr cm and $E/N = 2.6$ kTd. Axial emission profiles are extracted along the horizontal discharge axis from 2D images (white dashed line in Fig. 5).

At $pd = 0.15$ Torr cm (Fig. 5a) the dominant part of emission originates from excitation induced by heavy particles (ions, fast neutrals and metastables but presumably mostly fast neutrals – see Phelps Petrović [45]). That is indicated through the peak of emission close to the cathode [46,47]. Axial profiles of CH (grey line), H_α (red line) and O (blue line) emission follow the integrated emission profiles (black line) (Fig. 5a). The most significant contribution to fast neutral induced emission (i.e. at low pressures and high E/N) comes from the excited CH radical. A less significant contribution to the heavy-particle excitation belongs to O and H species.

With an increase in pressure, (e.g. at $pd = 0.50$ Torr cm, Fig. 5b), the maximum of emission in front of the anode becomes a dominant feature in the profile. The peak of the total emission (black line) near the anode is due to the excitation in electron–neutral collisions. Also, the shapes of CH, H_α, and O profiles (at 0.50 Torr cm, Fig. 5b), reveal that these emissions are the consequence of the electron excitation. On the other hand, at 0.15 Torr cm (Fig. 5a) H and O atoms, and CH radical are excited in collisions with heavy particles.

4 Conclusions

Non-equilibrium discharges in alcohols, either in the liquid or gas phase, have become a very popular area of research, largely because of their wide field of application [1–14,23]. The main obstacles to further understanding of these complex systems lie in the incompleteness and lack of relevant data on elementary processes that exist in the literature [23]. Therefore, we aim to provide information necessary for understanding some of the properties of DC breakdown, low–current and glow discharges in alcohol vapours.

In this paper we present data from experimental studies of the DC breakdown in three alcohol vapours: methanol, isopropanol and n-butanol, at low pressure. Paschen curve that has the lowest breakdown voltage, i.e. the lowest minimum is for n-butanol, at both electrode distances: 1.1 and 3.1 cm. On the other hand, methanol vapour has the highest breakdown voltages. Also, recorded Paschen curves show that minimum shifts towards the lower pressures, higher E/N, for more complex alcohols. The complexity is proportional to the number of atoms in a molecule so with increase in complexity there are more modes for vibrational excitation that causes greater losses requiring breakdown at higher E/N. To the right of the Paschen minimum this is satisfied by increasing the breakdown voltage but to the left of the Paschen minimum the more efficient way to reach higher E/N (i.e. mean energy) is to shift the minimum to the lower values of pd. Thus, the most complex molecule has the higher breakdown voltages to the right of Paschen minimum and the lowest breakdown voltage to the left of Paschen minimum. The dependence of our results on the complexity must have some relationship to the photon induced processes as the dissociation must proceed along the same basic molecular potential curves. However, we were not able to identify the relationship. One could perhaps pursue the relationship between photon induced dissociation/ionization processes and their energy dependence with our observations and see whether some deeper relationship may be defined. In any case such a study should be based on distribution functions and electron scattering cross sections on the side of Paschen curve modelling and understanding of molecular potential curves for photon processes.

Recorded axial profiles of emitted light from low–current discharge reveal that heavy–particles make a significant contribution to breakdown in alcohol vapours, in a wide range of values of pd i.e. E/N. Even at moderate values of reduced electric field E/N, from 3 to 5 kTd, heavy–particle induced processes have a significant role in the discharge. For higher values of E/N they become dominant.

Spatially resolved emission measurements with optical filters show that most of the emission in visible spectral range originates from CH radicals, O, and H atoms, probably mostly through dissociative excitation rather than ground state excitation [59]. Measurements of OES reveal that OH band (head at 306.4 nm), CH band (head at 431.2 nm) and H_α line (656.4 nm) have the largest share in the emission spectrum in the range from 300 to 900 nm, for discharges in all alcohols studied here, while CO (also detected in ethanol discharge), C, and O lines are visible in isopropanol and n-butanol discharges. The measured data provide the basis to describe the breakdown in alcohol vapours, to identify species and elementary processes that participate in these discharges. The obtained results also can enable further progress in modelling of the breakdown in alcohols.

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Author contribution statement

Jelena Sivoš – performed experimental measurements and calculations, analyzed the results and wrote the draft of the manuscript. Dragana Marić – led the studies and interpretation of the results, participated in analysis and discussion of the raw data and the results and participated in revising and writing the paper. Gordana Malović – helped in the analysis of data pertaining to emission properties of studied discharges, in the discussion of the results and in the editing of the manuscript. Zoran Lj. Petrović – defined the plan of research and development of the experimental procedure. He supervised the studies and analysis of the results, organization and finalization of the manuscript.

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PAPER

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DC discharge in low-pressure ethanol vapour

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Abstract

In this paper, we present data from experimental studies of the DC breakdown in ethanol vapour at low pressure as well as electrical and optical measurements of DC discharge parameters from low-current to high-current regimes. A Paschen curve and the corresponding distribution of emission intensities at low-current were recorded in the range of *pd* (pressure x electrode gap) from 0.10 Torr cm to 3.00 Torr cm, covering the region of Paschen minimum. Recorded axial profiles of emitted light from low-current discharge reveal that heavy particles make up a significant part in ethanol vapour breakdown in a wide range of values of *pd* i.e. E/N, for values $E/N > 3$ kTd they become dominant. Also, we recorded volt–ampere characteristics at working conditions close to the minimum of the Paschen curve, together with spatial profiles of low-current discharge. In the region of transition from normal to abnormal glow, sudden changes of the regime of operation were observed.

Keywords: plasmas in liquids, electrical gas breakdown, DC discharges, alcohol vapour, volt–ampere characteristics

1. Introduction

Non-equilibrium plasmas are an indispensable part in the development of material processing and sputtering techniques, in microelectronics for fabrication of large-scaled integrated devices (LSI) and in the light sources industry [1]. Applications of non-equilibrium electrical discharges in organic liquids and their vapours is of interest for environmental technologies, sensor industries [2], nanotechnologies and biotechnologies [3, 4]. For instance, organic molecules (containing carbon and hydrogen atoms) play an important role in the production of graphene layers [5] and in the growth of nanotubes [6]. For a long time discharges in mixtures of gases involving alcohols have been used for elementary particle detectors [2, 7–9].

Recently, studies of discharges in ethanol (and other alcohols) began drawing attention because of their application in production of ecologically friendly sources of energy (biofuels for internal-combustion engines, PEMFC fuel cells) [10, 11], in nanoscience for fast growth of high purity carbon nanotubes (CNT's) and nanoparticles [12, 13], in the food industry, biomedicine etc. One of the main advantages of applications of plasma operating in alcohols/alcohol vapours is the simplicity of experimental design allowing for fast emergence of new devices. However, development of applications cannot be based only on empirical technical advances in the design of devices. Key knowledge required for further advances is the understanding of discharges in liquids and their vapours and information about elementary processes taking part in the discharge [14].

One direction that research should take are measurements of elementary properties of the discharge regarding breakdown, operating regimes and discharge structure etc. Breakdown studies can reveal information on processes and their balance in discharges. Moreover, secondary electron production is an important parameter of the discharge and to obtain it, and consequently to develop realistic models of discharges, it is not sufficient to only model the Paschen curve, but also the volt–ampere (VA) characteristics of the discharge [15].

In this paper we present measurements in low pressure ethanol vapour of a Paschen curve, showing the dependence of breakdown voltages (V_b) as a function of the product of pressure and electrode distance (*pd*). Besides, we recorded

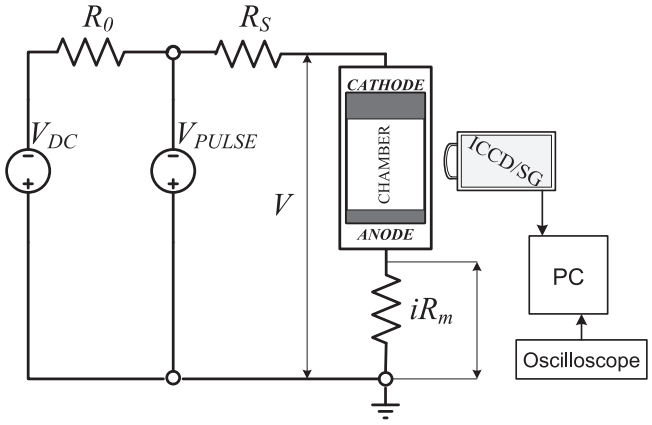

Figure 1. Schematic of the experimental setup and the electrical circuit used in measurements. Recordings are obtained with an ICCD camera with an objective lens and a spectrograph (SG).

VA characteristics at working conditions close to the minimum of the Paschen curve. We also noticed and performed a detailed analysis of the unusual behaviour of the discharge regime switching, observed in the abnormal glow. All measurements of electrical properties are supported with recordings of axial discharge structure by an ICCD camera. Hence, our study of low pressure discharges in ethanol vapour provides a complete set of breakdown data together with spatial profiles of low-current discharge as well as thorough investigation of electrical and optical properties of the discharge operating in a wide range of currents in the VA characteristics.

2. Experimental setup

Figure 1 shows a simplified schematic of the experimental setup. Discharge is initiated between two parallel-plate electrodes, placed inside a tightly fitting quartz tube. Each of electrodes is 5.4 cm in diameter. The cathode (C) is made of copper, while the anode (A) is made of quartz covered by a thin, transparent, conductive platinum film. The distance of electrodes can be adjusted and for this experiment it was set to 1.1 cm.

Construction of the discharge chamber allows side-on recordings and we used two setups to register emission coming from the discharge. In the first case, the camera was equipped with an objective lens allowing us to acquire axial discharge profiles of spectrally integrated emission in the visual range of spectra, defined by the transparency of the objective and the quantum efficiency of the ICCD photocathode. Additionally, placing band-pass optical filters that have maximum transparency at 431 nm (region of hydrocarbon CH radical emission band , the $^2\Delta$ -> $^2\Pi$ transition) and at 656 nm (region of Hα line emission, the n = 3 to n = 2 transition) in front of the objective lens allowed us to record the profiles of emission at quoted wavelengths. In another setup, to obtain a spectrum of emission of ethanol discharge we focused light from the discharge volume to a 100 μm entrance slit of spectrograph ORIEL MS127i. In both cases, a sensitive ICCD camera (Andor IStar DH720-18U-03) was used for detecting the signal. The spectrograph is equipped with a ruled grating with a wavelength range from 200 to 1200 nm and spectral resolution 0.22 nm.

In order to obtain reproducible results, it is necessary to perform preparations before every measurement. In the beginning, the system is pumped down to an initial pressure of the order of 10^{-6} Torr. Before the measurements, the cathode surface is conditioned in a hydrogen discharge with a current around 30 μA (for approximately 40 min), until the operating voltage stabilizes. Hydrogen is chosen because it is lightweight, so no cathode material is dispersed. At the same time, this treatment effectively removes chemical oxides and adsorbed layers of impurities from the cathode surface and thus produces the same surface conditions for each measurement.

Additionally, values of pressure are measured to better than 1% uncertainty. As for the gap d it is also of the order of 2% uncertainty but it is fixed for all measurements as it does not change from one pressure to another. The critical issue is the changes in the surface conditions and there we needed to ascertain the reproducibility of results. For argon, the reproducibility is excellent (better than 1% over long time periods) but for gases such as ethanol the reproducibility is not as good as there is always a possibility of deposition. Thus, we repeated cleaning cycles and checked for the reproducibility over the period of measurements. Changes in the breakdown voltage were taken as an indication that surface of the cathode has been conditioned (deposition or possibly cleaning) and we repeated cleaning that always produced results within narrow margins (to one volt). Thus, one may conclude that the uncertainty of measurements of the voltage is less than 1%, the current is accurate to several percent but bearing in mind extrapolation to the zero current uncertainty is mainly defined by the uncertainty of the voltage measurements, while uncertainties in current average out if results were obtained carefully. The experimental uncertainty is of the order of the size of the points or less.

Ethanol vapour is obtained from 95% ethanol (C_2H_5OH) ($M = 46.07$ g mol^{-1}). The main impurity in ethanol is water, while other impurities, such as acetone, methanol, aldehydes, formic acid are present only in traces (<0.001%). Therefore a small percentage of water vapour is present in the discharge. Typically, molecular gas impurities produce a very large effect on the discharges in atomic gases due to lack of vibrational energy losses in the former. Another strong effect arises from the attachment to impurities that may strongly affect the gases that are not subject to attachment. However, neither of the two effects are important in the ethanol vapour and they will not affect the results strongly. We could not clean the samples any further by freezing and evacuating the liquid as the freezing of ethanol occurs at a very low temperature. The vapour is introduced into the chamber at low pressure from a container with a liquid sample, through a pressure regulatory valve at a low flow rate. Immediately after opening the valve alcohol begins to boil due to the pressure difference over its surface and the pressure of gases dissolved in the sample itself. Throughout this process alcohol becomes

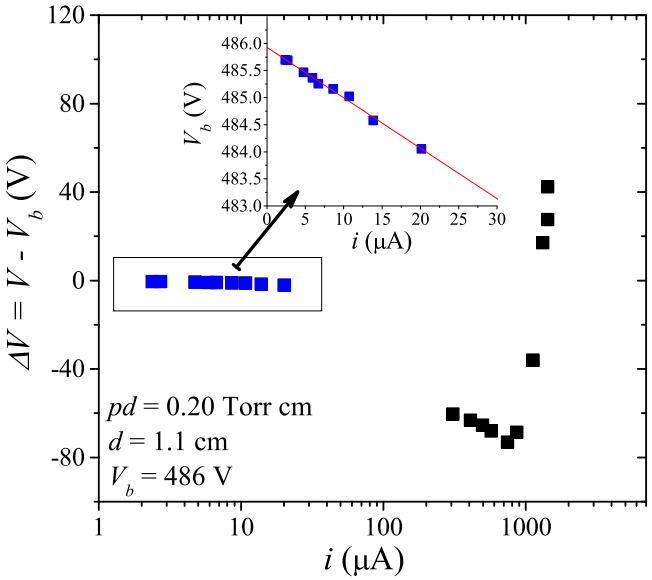

Figure 2. Example of VA characteristics of ethanol vapour discharge at $pd = 0.20$ Torr cm and $d = 1.1$ cm, with an illustration of breakdown voltage determination in the inserted graph.

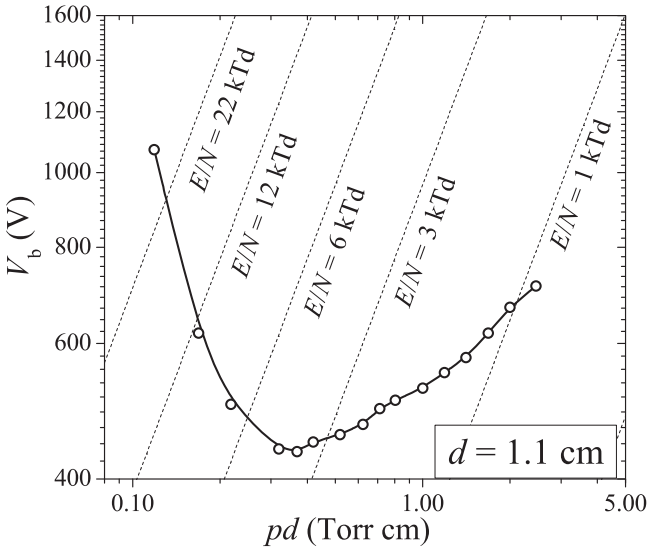

Figure 3. Paschen curve for discharges in ethanol vapour at $d = 1.1$ cm, at various reduced electric field (E/N) indicated by dashed lines [1 Td = 10^{-21} Vm^2 and 1 Torr = 133.32 Pa].

devoid of dissolved volatile constituents and after few seconds the sample surface becomes still. After that, the vapour is maintained at moderate pressure (~20 Torr) in the chamber for periods of 1–2 h in order to saturate the electrodes and the chamber walls. The vapour pressure of ethanol, at room temperature, is around 45 Torr [16], so during the measurements operating pressure is kept well below this value to avoid the formation of liquid droplets.

The electric circuit is designed to provide operation of the discharge both at breakdown conditions (i.e. low-current limit) and at higher currents. The breakdown voltage for each pd is determined from the low-current limit of the discharge, by extrapolating the discharge voltage to zero current in the dark Townsend discharge mode [15, 17]. In figure 2 we show VA characteristics with the low-current limit enlarged and inserted in a separate graph in order to illustrate determination of the breakdown voltage. One should pay attention to the linear extrapolation with small changes of voltage from the lowest current points to the zero current limit. Usually we limit ourselves to below 10 μA currents.

The discharge current is determined by measuring voltage drop on the resistor R_m. Recording of VA characteristics is accomplished in a pulsed regime, by imposing a short pulse of voltage in addition to running discharge at a small DC current (~1 μA). Pulses last long enough to allow the formation of the steady-state discharge and measurement of constant values in voltage and current signals. Pulsed mode of operation prevents the heating and conditioning of the cathode surface during the measurements, while a small DC current is also used to eliminate the breakdown delay time [18, 19]. The pulses are synchronized with the ICCD camera so electrical measurements and recording of emission can be acquired simultaneously.

3. Results and discussion

3.1. Paschen curve

The Paschen curve for the discharge in ethanol vapour at an electrode gap of 1.1 cm is shown in figure 3. Breakdown voltage dependence on pd, where p is pressure and d is electrode gap, cover a range from 0.10 Torr cm to 3.00 Torr cm.

The shape of the Paschen curve is typical for low pressure DC discharges [15]. The minimum breakdown voltage of 435 V occurs at around $pd = 0.35$ Torr cm, which corresponds to the reduced electric field value of $E/N = 4$ kTd. After breakdown, the discharge operates stably at low-currents up to $pd = 0.70$ Torr cm, but above this value discharge ignites into oscillations. For pds in the range between 0.70 and 3.00 Torr cm, we could not operate the discharge outside the oscillatory regime- the oscillations are the same as the oscillations annotated in the VA characteristics, and we have chosen the modes that allowed us to determine the breakdown voltage most accurately [20, 21]. There are periodic relaxation oscillations with frequencies between 250 and 800 Hz. However, above 3.00 Torr cm, it becomes difficult to control the discharge, oscillations become random and we cannot use them to establish a breakdown voltage with reasonable accuracy. Spatial profiles of emission from the discharge recorded along with breakdown data confirm that even at the highest pressures covered here, there is no evidence of transition to the streamer discharge in the range of pd covered here.

3.2. Spectrally and spatially resolved measurements

Measurement of emission spectra enables identification of species existing in the discharge. In figure 4 we present optical emission spectrum for ethanol vapour discharge recorded at $pd = 0.10$ Torr cm at low current, i.e. for the

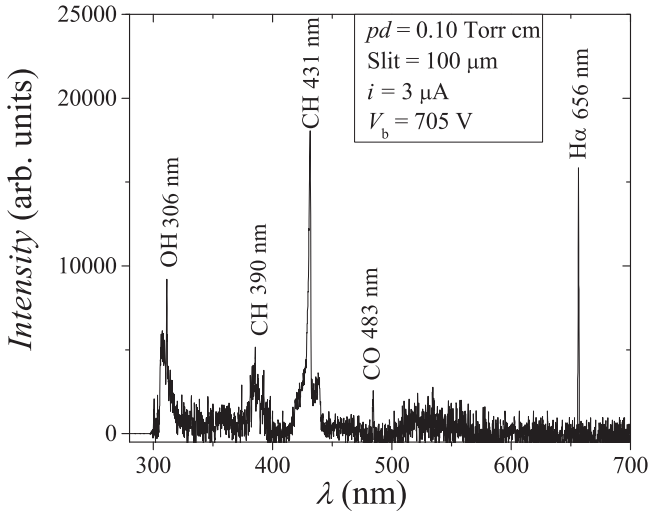

Figure 4. Emission spectrum of discharge in ethanol vapour at $pd = 0.10$ Torr cm and $d = 1.1$ cm. The width of the spectrograph slit was 100 μm.

discharge operating in Townsend regime. Very few lines are observed because of the very small current of 3 μA.

In the spectral range 300–700 nm, we detected OH, CO, CH, and Hα (Balmer series line) emission. All observed emission stems from excited species produced in dissociative excitation of the parent molecule [22–25] producing H atoms and some heavier excited dissociation fragments (OH, CO and/or CxHy). As previously observed in ethanol discharges [6, 23, 25], it is possible to form CO from the molecule of ethanol either in collisions with electrons or radicals/H_2O molecules. Additionally, the spectra baseline features a broad peak at wavelengths between 500 nm and 600 nm which can be caused by CO_2 continuum [26], CO band emission [27] or C_2 Swan band emission [26].

Besides measurements of emission spectra we also recorded spatially resolved emission. These recordings include spatial profiles of the total emission in a visual spectral range and spatial distribution of emission in a narrow wavelength interval around the most intense lines in the visible part of the spectrum (431 nm and 656 nm). Axial emission profiles shown in figure 5 are extracted along the discharge axis from 2D images obtained for emission spectrally integrated in visual spectra and filtered by CH and Hα band-pass optical filers.

Profiles for different pd values between 0.10–0.60 Torr cm present how the change of E/N (pd) influences the structure and basic processes in the discharge. Since during these recordings discharge operates at a low-current limit i.e. in the Townsend regime, where the density of space charge is insignificant so electric field between electrodes is nearly homogeneous [18], one would expect an exponential rise of emission towards the anode as electrons gain enough energy for excitation processes in electron–neutral collisions. However, presented integrated profiles (solid lines) for all pd values reveal a strong emission peak in front of the cathode. The work of Phelps and colleagues has shown that heavy-particle (fast neutral) excitation is the dominant cause of the emission in front of the cathode [19, 28]. While CH emission singled out from the discharge (dashed lines) follows the integrated profiles in shape, Hα emission (dash dotted lines) exhibit dissimilar shape and a much lower emission intensity as compared to the CH emission.

At the 0.10 and 0.20 Torr cm (figures 5(a) and (b)), in the left-hand branch of the Paschen curve, predominate emission comes from the wavelength range covered by the CH filter suggesting that CH species have the most important role in heavy-particle excitations. With the increase of pressure, at $pd = 0.60$ Torr cm (figure 5(d)), CH emission partakes less in the total emission. The peak of the total emission near the anode, that emerges at $pd = 0.20$ Torr cm (figure 5(b)) and exceeds maximum of emission in front of the anode at $pd = 0.60$ Torr cm at the highest values of pd (lowest E/N) (figure 5(d)), is created due to excitation processes in electron–neutral collisions. In this case, the Hα emission intensity (dash dotted lines) is also much higher. The shape of Hα profile in the range from 0.20 Torr cm to high pd values suggest that only electron excitation plays role in the case of H atom in that range. However, at low pd (high E/N) H atoms are also excited in collisions with heavy particles.

3.3. Volt–ampere characteristics

For a complete picture of ethanol vapour discharge properties, along with the breakdown and low-current recordings, it is also necessary to obtain VA characteristics. In figure 6 we show VA characteristics of ethanol vapour discharge at $pd = 0.20$ Torr cm measured in the range of discharge currents from $\sim$1 μA to several mA together with 2D images of typical operating regimes for low pressure DC discharges [29, 30]. These regimes are clearly distinguished [28, 29].

In the diffuse Townsend regime (up to 20 μA), VA characteristics shows a slightly negative slope, with a negative differential resistance of $R_D = -84$ kΩ. The negative differential resistance, jointly with the breakdown data, is important in the analysis of secondary electron yields [15, 31]. Between Townsend and normal glow regime, for currents from 20 μA to 300 μA, is a region of free-running oscillations characterized by a more rapidly decreasing voltage.

After this region, the discharge becomes constricted and operates in a stable regime of normal glow. With a further increment of the current, discharge becomes diffuse again and runs in an abnormal regime that is characterized by a very steep positive slope in VA characteristics for currents above 740 μA. In 2D images recorded for all discharge regimes, i.e. at all discharge currents investigated, there is a peak of emission in front of the cathode. As for the low-current case discussed before, it has been shown that the peak of emission at the cathode in higher current regimes is a result of fast neutral excitation. These fast neutrals are mainly produced by fast ions going through charge–transfer collisions with molecules of the background gas [19, 32]. These processes are prone to occur at lower pressures since the ion energy gain has smaller dissipation in collisions. Lower pressures

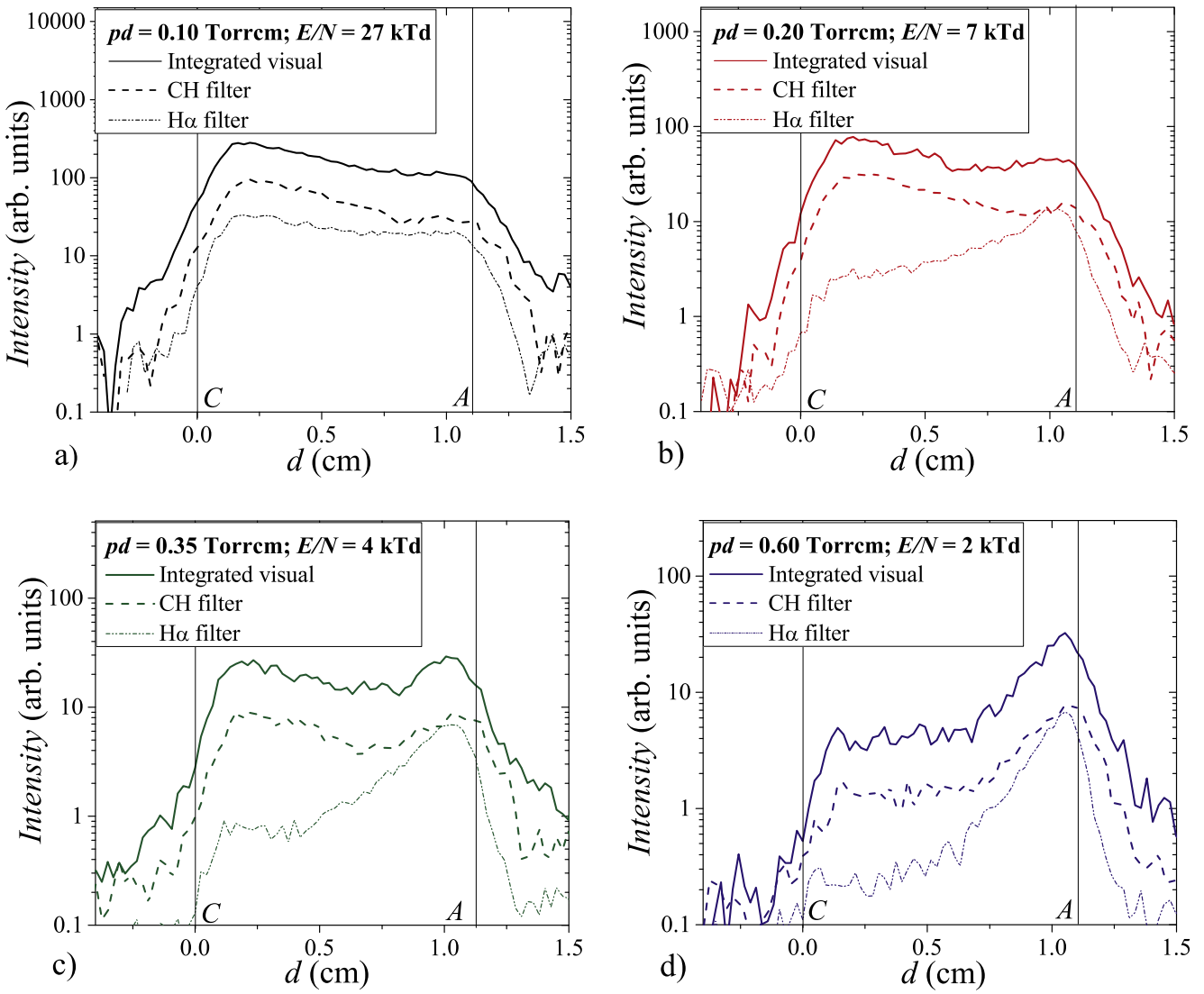

Figure 5. Axial profiles of emission from discharge in ethanol vapour for different values of *pd* (pressure x electrode gap) and E/N (reduced electric field) at electrode gap $d = 1.1$ cm. Filtered emission is recorded at the same intensity scale and corrected for the filter transparency. Letters *C* and *A* indicate the positions of the cathode and anode.

typically correspond to the conditions at the left-hand side of the Paschen curve, where the E/N-s are high enough, which is the case for the VA characteristics shown in figure 5. Particularly, for ethanol vapour the most probable candidates for heavy particles that participate in excitation and ionization are fast H atoms and some heavier dissociation fragments (OH, CO and CH species).

During our investigation of normal glow, sudden changes in the operating conditions (even in regime) were observed. Measurements reveal changes in the steady-state current and voltage values within a single voltage pulse. Changes in discharge operating modes have been noticed before, in the case of a normal glow in argon [17] and in the case of hollow cathode discharges [33, 34], where a sudden increase of current is followed by a decrease of operating voltage within a single pulse. However, in the present study the discharge operates at the lower current and higher voltage after the transition.

In figure 7 we show two examples of the effect where current and voltage waveforms have pronounced step-like shapes due to the mode change. The transition effect is present in the current range from around 860 μA (beginning of positive slope of the VA characteristics) to around 1430 μA. In the first example, at lower current shown in figure 7(a) the transition in operation mode occurs approximately 2 ms after the pulse ignition. During the transition, the discharge switches to a $\sim$40 V higher voltage and $\sim$130 μA smaller current.

The transition is smooth and lasts around 15 μs. In the second example, shown in figure 7(b), the same effect is present at a higher initial current of $\sim$1680 μA, but the transition here happens only 30 μs after the initial time interval of stable operation. The transition lasts around 3 μs, and the discharge switches to $\sim$70 V higher voltage and $\sim$320 μA smaller current. It appears that the transition happens earlier within the pulse for higher initial currents. At given conditions, mode change in consecutive pulses is very

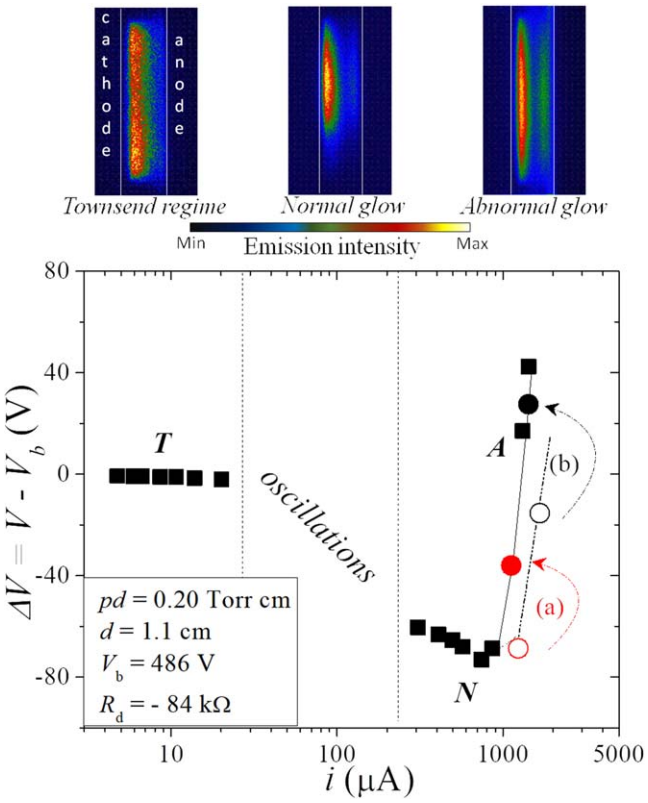

Figure 6. VA characteristics of ethanol vapour discharge at $pd = 0.20$ Torr cm and $d = 1.1$ cm. The voltage is shown as a difference between discharge (V) and breakdown voltage (V_b). Capital letters (T, N, A) correspond to 2D false colour images of the discharge running in different regimes. Circles and arrows indicate transitions in operating regimes shown in figure 7 (please see text for details).

reproducible, it always occurs at the same time after the beginning of the pulse. The transition is always smooth and there are no instabilities or oscillations in the voltage and current waveforms.

Together with the waveforms, recordings of light emission from the discharge are taken several times during one pulse. Figure 8 shows axial profiles of emission recorded with short exposure time (0.2 μs) at time points marked in figure 7(b). Generally, in both profiles, a significant influence of heavy particles in excitation and ionization is present, judging by the peak of emission near the cathode. Although the discharge current drops after the step, the overall intensity of emission is higher. However, ratios of maximum intensities of profiles near electrodes obtained for both cases, before the step (open circles) and after the step (full circles), are the same (around 3). Moreover, from 2D images of the discharge taken before and after the transition, we estimated that in the radial direction both profiles have the same width and therefore the same effective discharge area [35]. One significant difference between profiles is in the position of emission peak that corresponds to the negative glow i.e. coincides with the edge of the cathode fall [36]. The edge of the cathode fall region shifts closer to the cathode after the transition.

This kind of behaviour is very unusual, as one would expect that the length of the cathode fall would increase with the decrease of current [36]. The cause for such change in electric field distribution, discharge current and voltage is not clear. Bearing in mind that the timing of the effect is reproducible in consecutive pulses, we cannot attribute the effect to deposition or sputtering. Gas or electrode heating should not have a significant influence, as the discharge pulses are kept short and the discharge operates in slow flow regime to avoid those effects. Furthermore, one would expect the effect to be more significant at higher currents. From the estimates based on the complete sets of cross sections for similar gases for which such sets exist, the degree of dissociation does not affect the results. The observed behaviour is probably connected to changes in the balance of charged or excited species: ions or electronically and vibrationally excited dissociation products and adsorbed species created in discharges [22]. Thus, in some time intervals, after the pulse application, the dominant gas species produced in the discharge may be changed and consequently influence the balance of charged and excited species. In order to clarify and explain the mechanism behind the transition, additional experimental measurements and modelling should be performed.

4. Conclusions

Discharges in vapours and liquids, especially organic ones, have become a very popular area of research due to a wide range of applicability [4, 14]. However, lack of relevant and complete existing data on elementary processes have become important obstacles to further understanding of these complex systems [37–41]. By measuring properties of DC breakdown, low-current and glow discharges in ethanol vapour we aim to provide information necessary for the understanding of this kind of non-equilibrium discharge.

In this paper we present data from experimental studies of the DC breakdown in ethanol vapour at low pressure as well as electrical and optical measurements of DC discharge parameters from low-current to moderately high-current regimes. A Paschen curve in ethanol vapour has a minimal breakdown voltage of 435 V at $pd = 0.35$ Torr cm. Recorded axial profiles of emitted light from low-current discharge reveal that heavy particles make a significant contribution to ethanol vapour breakdown in a wide range of values of pd i.e. E/N. For $E/N > 3$ kTd they become dominant. Spatially resolved emission measurements with optical filters show that most of the emission in visible spectral range originates from CH radicals and H atoms, probably mostly through dissociative excitation rather than ground state excitation [42]. Spectrally resolved measurements reveal that OH band (head at 306 nm), CH band (head at 431 nm) and Hα line have the largest share in the emission spectrum in the range from 300 to 700 nm, while CO lines are also visible. The measured VA characteristics at $pd = 0.20$ Torr cm has the shape typical for low pressure discharges.

Measurements in a narrow current range in the abnormal glow part of the VA characteristics reveal sudden transitions while operating in a stable discharge regime. Without any

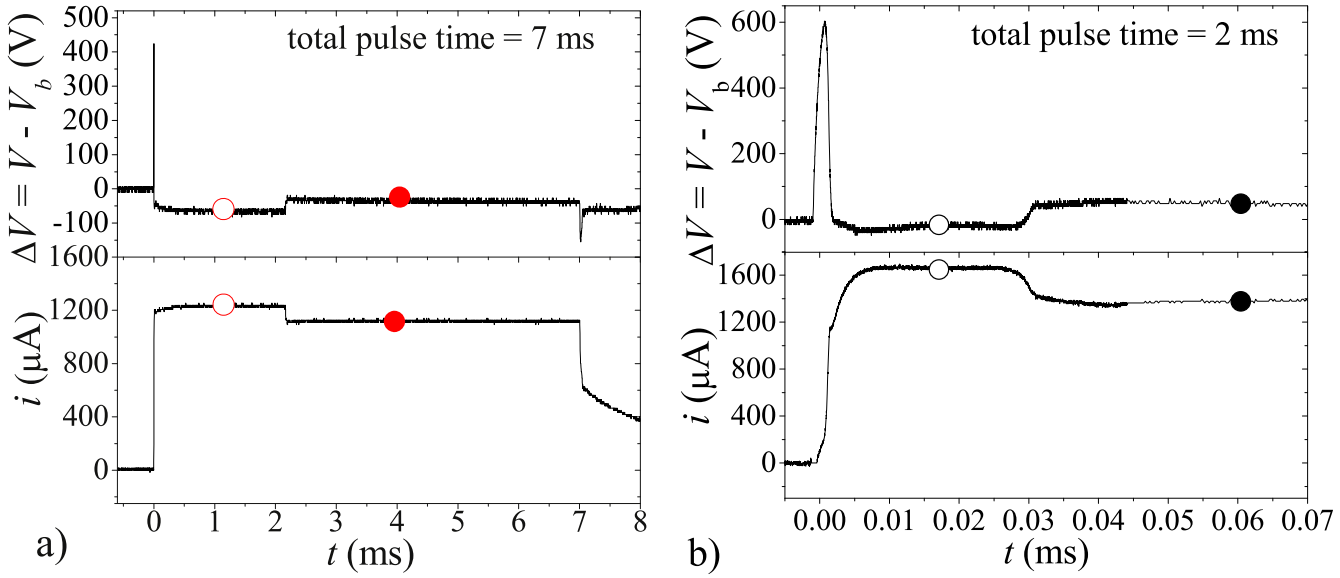

Figure 7. Waveforms of voltage and current obtained (a) at lower current (initially $i_d \approx 1240\ \mu$A) and (b) higher current (initially $i_d \approx 1680\ \mu$A) with the transition effect within a pulse. Voltage is presented as a difference between breakdown voltage ($V_b = 486$ V) and operating voltage. Values before and after the transition are shown as open and closed circles respectively are plotted in figure 6.

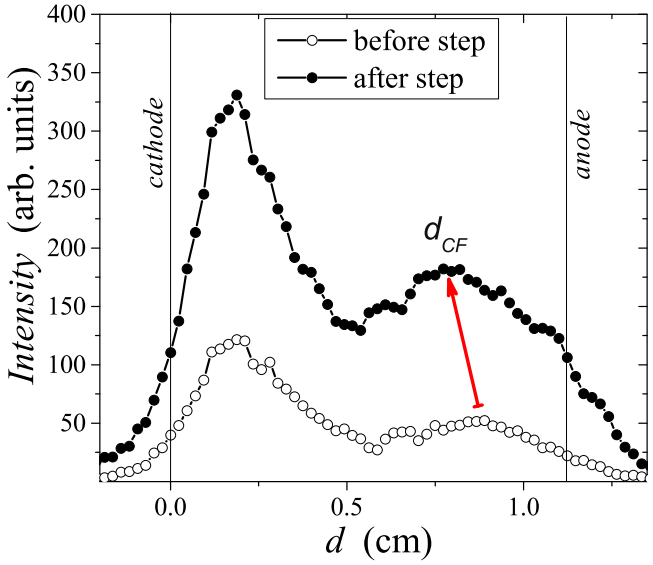

Figure 8. Profiles of emission taken along the axis of 2D images of the discharge recorded before (open symbols) and after (full symbols) the step at time points marked in figure 7(b). Change of the initial steady-state values of current and voltage after the step are: $\delta i = -320\ \mu$A, δV = 70 V. Cathode fall length is indicated with d_{CF}.

instabilities or oscillations and with no significant change in the externally observed spatial structure, the discharge switches between steady-state modes of operation changing from higher to lower current and from lower to higher voltage within a single voltage pulse. The transition into a more preferable operating mode, after some time of stable operation, is probably due to changes in the balance of charged and excited species, dissociation products and adsorbed species created in the discharge. The effect is interesting from the point of view of fundamental discharge properties and from the point of view of applications that work in pulsed or high frequency glow regime.

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Breakdown and dc discharge in low-pressure water vapour

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Breakdown and dc discharge in low-pressure water vapour

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Abstract

In this paper we report studies of basic properties of breakdown, low-current Townsend discharge and high-current discharge regimes in water vapour. Paschen curves and the corresponding distributions of emission intensities at low current were recorded in the range of *pd* (pressure x electrode gap) from 0.1 to 10 Torrcm covering the region of Paschen minimum. From the experimental profiles we obtained effective ionization coefficient of water vapour for the *E*/*N* range 650 Td–7 kTd and fitted the results by using the extended Townsend analytical formula. Using the obtained ionization coefficient, we calculated the effective yield of secondary electrons from the copper cathode. Results of the measurements of Volt-Ampere characteristics in water vapour were presented together with the images of the axial structure of the discharge in a wide range of discharge currents for two *pd* values. Recorded profiles showed development of the spatial structure of the discharge in different operating regimes. We were able to identify conditions where processes induced by heavy particles, probably fast hydrogen atoms, are dominant in inducing emission from the discharge. Finally, standard scaling laws were tested for low current and glow discharges in water vapour.

Keywords: plasmas in liquids, electrical gas breakdown, volt-ampere characteristics, ionization coefficients, secondary electron yields, scaling laws

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent years, an increasing interest in discharges in liquids and vapours of liquids has opened new options and motivation to study non-equilibrium plasmas [1, 2]. Development of different sources operating at low or atmospheric pressures or even in the liquid was mostly driven by several applications [3, 4] of such plasmas in medicine [5, 6], surface treatment [7, 8], nanotechnologies [9–11], light sources [12] and environmental remediation [13, 14]. A common feature of all applications is the complex operation environment. At low pressure it usually consists of mixtures of gas and vapour(s) and for atmospheric pressure discharges water vapour is present in humid air or discharge is run in vapour saturated atmosphere obtained either by evaporating the liquid electrode [15] or by creating a mist [16]. In case of discharges operating in the liquid, the operation environment is often a heterogeneous liquid–air bubble system [17].

Taking into account that in devices used for applications one has to handle the non-equilibrium properties of the discharge itself and that complicated electrode geometry sources are usually being used, unravelling all processes taking place in the discharge is an arduous task. On the other hand, studies of non-equilibrium plasmas, even when directly motivated by a very specific application, lead to unravelling some of the very fundamental principles. Those are both numerous in such plasmas and necessarily connected with the need to have sufficient range and depth of data and a phenomenology, that is well tested by quantitative comparisons with experiments. In other words, the fundamental nature of the scientific studies of non-equilibrium plasmas stems from the way in which the more detailed atomic and molecular and surface processes are combined to build a complex picture of the discharge itself.

Our investigation aims at providing some of the basic data on breakdown and low-pressure operation regimes in a wide range of discharge currents in water vapour. Such data are scarce in

the literature. Contrary to complex geometries employed for devices used in applications, fundamental processes are best elucidated in a quantitative fashion in a simple geometry. Thus, measurements in non-equilibrium parallel-plate dc discharge in water vapour ignited at different conditions aim to provide a comprehensive reference set of data that can be used in interpreting and modelling more complex discharges [18–23]. While limiting ourselves to the breakdown and low current regimes of dc discharge may seem to be a limitation that is not necessary, it is done so that by using exact calculations we may determine observables and thus produce data on some of the elementary processes that are of universal importance in all regimes of operation—such as ionization rate, secondary electron yield and fast neutral excitation rates and cross sections.

In our earlier paper [24] we presented measurements of breakdown voltages and spatial profiles of low-current dc discharges in water vapour obtained from two types of water samples of different purity. We have shown that breakdown parameters are not dependent on purity of water vapour, presumably since at high *E*/*N* all impurities have similar energy loss cross sections and ionization cross section. This is in contradiction of some earlier studies of low energy transport in water vapour [25] where dependence of the diffusion on oxygen content proved to be strong due to the effect of resonant attachment to oxygen molecule at low energies.

In this paper we start from the data presented by [24] and present breakdown voltages, ionization coefficient and secondary electron yields which are obtained consistently from the breakdown data (i.e. Paschen curves and spatial profiles of low-current discharge). In addition we compare our data to the few existing experimental results. We also show measurements of Volt-Ampere (*V-A*) characteristics at two different pressures, which are necessary for a complete analysis of secondary electron production in addition to the breakdown data [26, 27]. Along with *V-A* characteristics recorded in a wide range of discharge currents, we register profiles of emission coming from the discharge for several distinctive operating conditions. This allows us to have a view on different discharge regimes and link the shape of the *V-A* characteristics to the spatial profiles of the discharge, i.e. to the relevant processes under those circumstances [28, 29].

2. Experimental setup

In our experiment, the discharge is established in a parallel-plate system of electrodes, placed within a tightly fitting quartz tube. Separation between electrodes is adjustable. The cathode is made of copper, while the anode is a transparent film of platinum deposited on a quartz window, both 5.4 cm in diameter. Such a construction of the discharge chamber allows us to record axial and radial profiles of emission while preventing a long path breakdown at low *pd* (*p* is the pressure and *d* gap between electrodes).

Water vapour is obtained from bi-distilled de-ionized water and introduced into the vacuum system at a slow flow rate (even though it was shown as stated above that this measure is not necessary for the breakdown and other high *E*/*N* studies). After the initial period of boiling, water in the tube becomes still and devoid of dissolved oxygen and other volatile constituents. In order to achieve saturation of all surfaces in the chamber, the vapour is allowed into the system for several hours before measurements and after that, the pressure is kept below 20 Torr to avoid condensation [24].

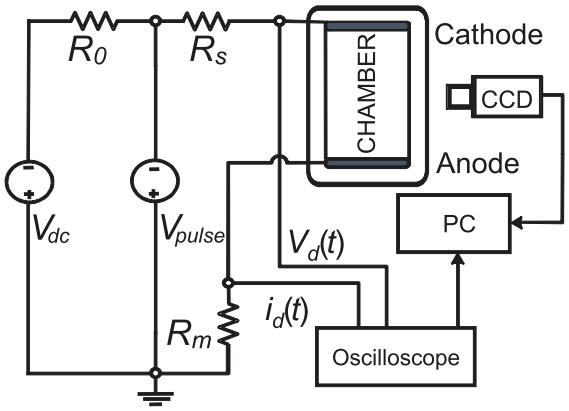

Figure 1. Schematic of the experimental setup.

The electrical circuit (figure 1) allows igniting the discharge in the low-current dc regime using a high series resistance R_0 to limit the current. Higher current pulses are generated by using a pulse which is superimposed onto a running (very low current) discharge by the pulsing circuit. Resistance R_S limits the current pulse. This permits operation at high currents during a limited period of time (usually several ms), sufficient to stabilize the discharge and allow for recording while still being too short to allow continuous damage to the electrode. The breakdown voltage is determined by extrapolating discharge voltages from the discharge operating at the lowest possible currents (~1 μA) to the zero current. For this to be a valid procedure one needs to operate in the Townsend's regime where space charge perturbation on the *V-A* characteristics is linear and small. The *V-A* characteristic in a broader range of currents is obtained by switching from the low-current to the high-current discharge regimes during pulses and taking steady-state values of the discharge current and voltage when there are no oscillations [30].

Profiles of the discharge are recorded by a sensitive intensified charge-coupled device (ICCD) camera (Andor IStar DH720-18U-03) equipped with a photographic lens. The beginning of the ICCD camera recording can be synchronized with the pulse by setting an appropriate delay in order to record profiles of the steady-state part of the pulse. The profiles are recorded with the emission integrated in visual spectra and also by using an interference band-pass Hα filter with 5% of transparency around 656 nm.

Further details of the measurements are described elsewhere [31, 32].

3. Results and discussion

3.1. Breakdown and low-current discharge profiles

The Paschen curve for water vapour is shown in figure 2. Breakdown voltage dependence on *pd* (pressure times electrode gap) ranging from 0.1 to 10 Torrcm is measured at two

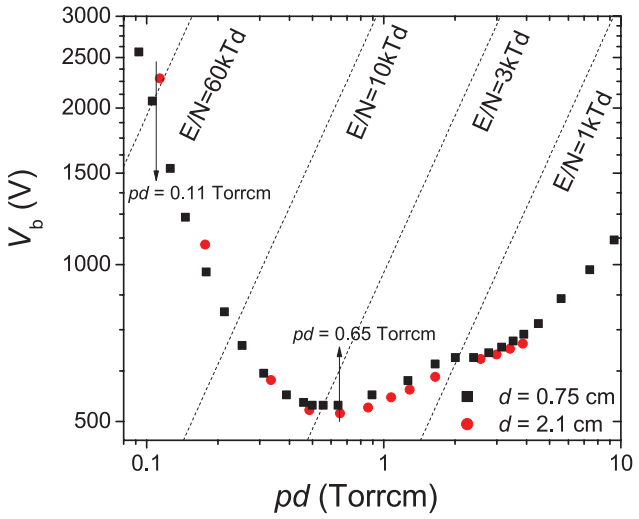

Figure 2. Paschen curves measured for two electrode gaps: 0.75 cm and 2.1 cm. Arrows mark discharge working points shown in figure 3. This figure contains some data already shown in [24] and repeated here for comparison and completeness.

electrode gaps: 0.75 and 2.1 cm. The reduced electric field (*E*/*N*) is indicated in the plot by several dashed lines representing constant *E*/*N* values. Recorded curves agree well within the whole *pd* range. Differences in breakdown voltages existing at low *pd*, i.e. in the left branch of the curve, may come both from pressure instabilities due to the steep rise of the curve and from different diffusion losses that are affected by differences in electrode gap to diameter ratio for the two measurements [33, 34]. A small inflection around 2 Torrcm is present in the right-hand part of the curve recorded for d = 0.75 cm. The minor perturbation of the curve may be due to the proximity of the dew point for water vapour [24] but its origin has not been established yet as well as whether it is present for all conditions.

For every point of the Paschen curves, spatial profiles of the discharges operating at low-current limit were recorded. At low currents, i.e. in the Townsend regime, density of space charge is insignificant and therefore the electric field between electrodes is almost homogeneous [35]. Several emission profiles are presented in figure 3. We selected profiles (of integrated emission as well as Hα emission) at pd = 0.11 Torrcm (figure 3(a)) and pd = 0.65 Torrcm (figure 3(b)) to illustrate how the change of *pd* (*E*/*N*) influences the structure and basic processes in the discharge. We show profiles scaled by the *px* parameter (x is distance from the cathode), so we may compare emission intensity distribution taken at different electrode gaps/pressures. At the same time, this may serve as an additional test of the validity of scaling with the *pd* parameter [36, 37].

In the region of the minimum of the Paschen curve, i.e. for pd = 0.65 Torrcm, we observe a typical, exponential, increase of emission intensity from the cathode to the anode, which indicates excitation by electrons (figure 3(b)). The beginning of the steady increase in the emission intensity is shifted from the cathode, leaving some space for the non-hydrodynamic region next to the cathode [38–40]. A small peak of emission at the cathode edge is due to the optical reflection. From the slope of the profile we can determine the ionization coefficient of water vapour (see section 3.2).

On the other hand, at low *pd*-s and high *E*/*N*, heavy particles, ions and neutrals, gain enough energy to perform excitation and even ionization. At pd = 0.11 Torrcm heavy-particle processes dominate over electron processes, which is revealed through emission profile peaking close to the cathode (figure 3(a)). Hydrogen fast atoms are the most probable candidate for inducing such high emission in the cathode region [41, 42]. Excellent agreement of the shape of integrated emission profiles (full lines) with the profile recorded using H_α filter (with the intensity scaled by 70 for easier comparison) (dashed line) supports this assumption. Additionally, a good overall agreement of the profiles integrated in the visual spectrum that are recorded for different electrode gaps confirms the validity of scaling laws. The basic processes governing breakdown and low-current discharges stay the same for the same *pd* for the range of gaps covered here so the discharge structure remains unchanged.

A large number of recorded spatial profiles need not be presented here but it is worth stating that they cover continuously the transition between the two regimes. If calibrated by some technique those profiles may be used to obtain quantitative data on heavy particle collisions in water vapour.

3.2. Effective ionization coefficient and secondary electron yield

One way to obtain binary collision data for the gas phase and for the collisions with surfaces is to employ swarm experiments and low-current discharges operating in the low current limit (zero space charge effect). Such conditions, which are part of the definition for swarms, also apply for breakdown itself (as the initial stages go through growth of electrons dictated by the external fields) and for the low current limit of the discharges in the dark (Townsend) or the low current diffuse regime [26, 27, 43]. Basically, when the discharge is running in the low-current limit, the emission profile reflects electron multiplication between the electrodes (best observed if plotted in the semi-log scale). Accordingly, the slope corresponds to the ionization coefficient once equilibrium with the local field is reached [38, 39, 44].

In figure 4 we show effective ionization coefficients in water vapour discharge determined from the fit to experimentally recorded emission profiles of a low-current dc discharge, recorded in the range of reduced electric fields (*E*/*N*) between 650 Td and 7 kTd. We also show results for ionization coefficients from the literature [45–48] for comparison. These sets seem to agree well in the range of low *E*/*N* where Prasad and Craggs [46] results exist. Moreover, results of Hasegawa *et al* [45] and de Urquijo *et al* [47, 48] agree well throughout the entire available range (150–650 Td). Our results are systematically lower than Hasegawa *et al* data in the range of overlap of *E*/*N*. The difference may stem from the different nature of experiments, but possibly also due to fast neutral contribution. In Hasegawa *et al* [45] authors obtain ionization and the attachment coefficient by fitting the Townsend's theoretical equation for the current growth to the experimentally

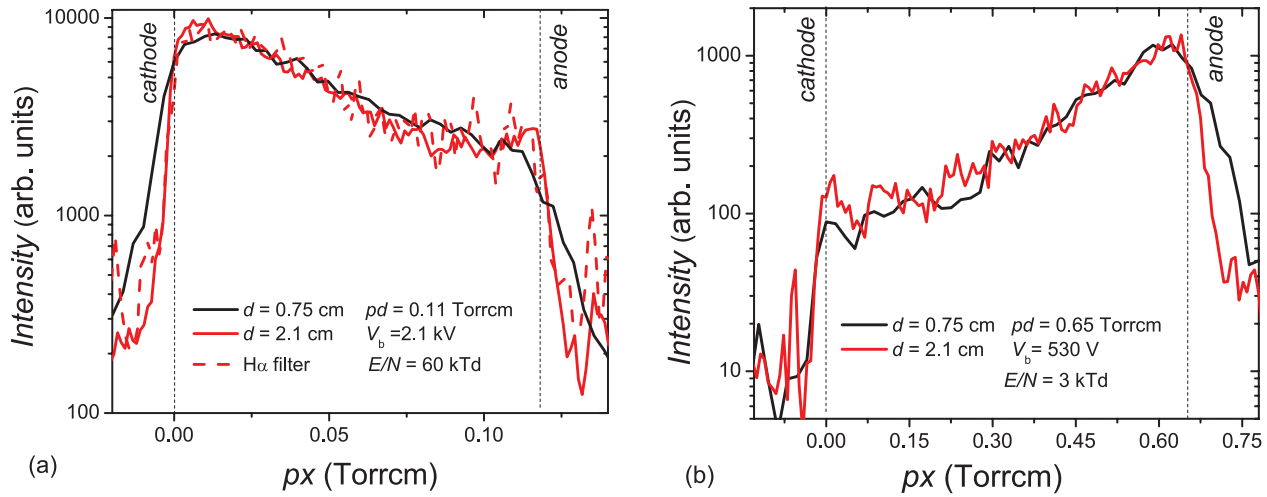

Figure 3. Axial profiles of emission from Townsend discharge in water vapour taken (a) in the left branch ($pd = 0.11$ Torrcm) and (b) in the minimum ($pd = 0.65$ Torrcm) of the Paschen curve. Distance from the cathode x is multiplied by p to enable comparisons of profiles recorded at the same pd at different electrode gaps. Full lines represent profiles integrated in visual spectra, the dashed profile is recorded through a band-pass Hα filter.

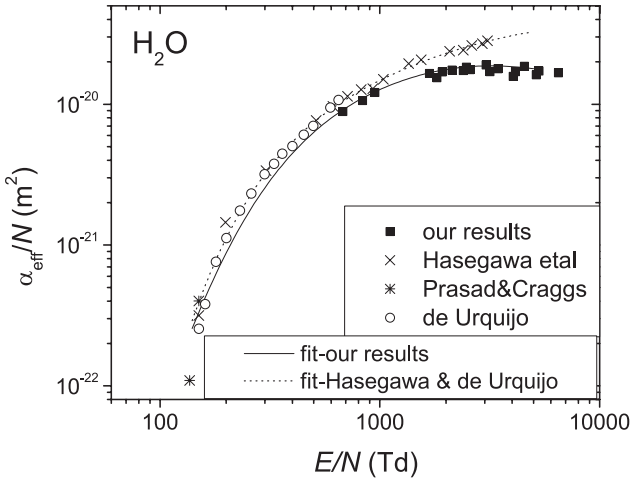

Figure 4. The dependence of reduced effective ionization coefficient (α_{eff}/N) on reduced electric field (E/N). Results obtained from our experiment (squares) are compared with data from Hasegawa *et al* [45] (crosses) and Prasad and Craggs [46] (stars) and de Urquijo *et al* (circles) [47, 48]. Lines represent fits of the ionization coefficient by analytical formula as given in the table 1.

obtained current growth in a steady state Townsend experiment. Different vapour purities (degrees of contamination) may explain some of the difference, but that is not very likely to have a considerable effect. Our own tests indicate that for the high E/N effect of water purity is very small on the breakdown voltage due to large mean electron energies and large cross sections in all gases in the relevant energy range. While the same may be said for the ionization coefficient it is likely to be more affected than the breakdown voltage itself. Nevertheless, we can state that the differences are compatible with the combined experimental and possible systematic uncertainties of the two experiments. While one may find an advantage for one set of data or the other, the analysis of our experiment should proceed using our ionization coefficient as it represents directly the multiplication in our system which is required for the calculation of the secondary electron emission yields.

In figure 4 we also show two fits by the modified Townsend's analytical formula to our experimental data and the data compiled of Hasegawa *et al* [45] and de Urquijo [47, 48]. The semi-empirical formula proposed by Phelps and Petrović [26, 49] and further evaluated for a number of gases in [50] has several terms identical to the Townsend's formula for ionization coefficient but the values of parameters are different. Physical meaning for using the multi-term formula can be found in the existence of several groups of electrons in the discharge, with the coefficient B_i showing the range where the term i is significant and A_i giving the maximal contribution of the particular term [50]. Moreover, the dominant term in the multi-term formula should be similar to the standard Townsend single term formula fit for the same gas. Coefficients obtained by fitting the experimental data by the 3-term analytical formula are given in table 1. In the table we also provide the E/N region where the fits are valid. It should be noted that the negative Ai coefficient in the formula allows adjustment of the fit to represent decreasing of α/N with E/N due to a decrease of the ionization cross section at higher electron energies [50]. Fitting coefficients obtained for the present experimental results are valid for our range of measurements (650 Td–7 kTd), but they also follow the trend of Hasegawa and de Urquijo in the lower range of E/N.

Furthermore, taking experimentally determined ionization coefficient (multiplication) obtained from the spatial emission profiles, we may calculate secondary electron yields using the condition for self-sustaining discharge [38, 39, 44, 51]. Such an approach has an advantage as it takes into account often difficult to represent non-hydrodynamic effects close to the cathode and possible effects of impurities thus giving the actual electron multiplication in the experiment [26]. A disadvantage of this technique is that it produces results of somewhat lower accuracy than pulsed discharge integration techniques. In the case of water vapour, at lower E/N resolving

Table 1. Coefficients of the Townsend formula fit in the *E*/*N* range 130 Td–7 kTd.

Formula $\frac{\alpha}{N} = \sum_{i=0}^{2} A_i \exp\left(\frac{-B_i}{E/N}\right)$	Range [Td]	A_0 [V · m]	B_0	A_1 [V · m]	B_1	A_2 [V · m]	B_2
Our results	650–7000	$0.2 \cdot 10^{-20}$	370	$2.4 \cdot 10^{-20}$	750	$-2.0 \cdot 10^{-20}$	7300
Hasegawa *et al* [46]	130–3500	$0.01 \cdot 10^{-21}$	250	$2.6 \cdot 10^{-20}$	630	$1.8 \cdot 10^{-20}$	3000

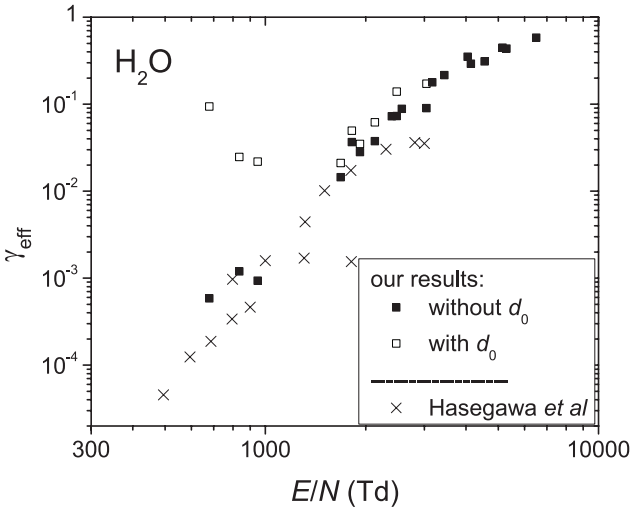

Figure 5. The dependence of the effective secondary electron coefficient (γ_{eff}) on the reduced electric field (*E*/*N*). Full symbol data was calculated disregarding the equilibration length d_0, open symbols—with d_0. Our results (squares) were obtained with copper cathode, Hasegawa *et al* [32] results (crosses)—with stainless steel cathode with gold-plated quartz inset.

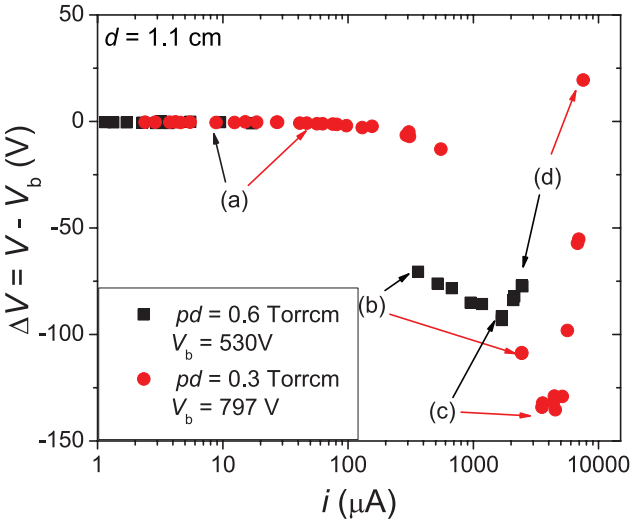

Figure 6. *V-A* characteristics for two different *pd*-s (0.6 Torrcm and 0.3 Torrcm) at fixed gap *d* = 1.1 cm. Labels (a)–(d) indicate different characteristic regimes of the discharge where the side-on images are presented in figure 6.

the length of non-hydrodynamic region at the cathode (d_0) can be elusive due to the shape of the profile next to the cathode. At higher *E*/*N*, fast heavy particles make excitations in the cathode region, preventing determination of d_0. At high *E*/*N* (low *pd*) this is not critical, as overall multiplication is small, so d_0 does not influence determination of the secondary yield considerably. Nevertheless, measurements presented here give us a consistent set of key parameters that determine breakdown in water vapour.

The effective secondary electron yield presented in figure 5 was calculated using the experimentally obtained Paschen curve and ionization coefficient. The secondary electron yield was calculated taking into account the equilibration length (d_0) where it was possible (open symbols) and without the d_0 length (full symbols). A major difference in the coefficients is observed only for lower *E*/*N* fields, i.e. for the values obtained from the right branch of the Paschen curve, where accounting for the equilibration length has the largest effect [26, 39, 40]. Additionally, in figure 5 we also plot results of Hasegawa *et al* [45] obtained with a cathode made of stainless steel with a gold-plated quartz inset entrenched in the central area [52]. Results by Hasegawa *et al* do not take into account the equilibration length. Compared to the corresponding results from our experiment, the agreement is very good, bearing in mind the different cathode materials.

3.3. Voltage–current characteristics and structure of the discharge

In figure 6 we show *V-A* characteristics of the discharge at the fixed electrode gap (*d* = 1.1 cm) and at two different pressures. We have selected conditions around the minimum of the Paschen curve (*pd* = 0.6 Torrcm) and in the left-hand branch (*pd* = 0.3 Torrcm). In the right-hand branch, above 0.7 Torrcm, the discharge instabilities impede the measurements. Oscillations of the discharge, streamer formation [24] and multiple-channel discharge [53] take place. In this paper we present only the steady-state measurements. Along with the voltage and current measurements (figure 6), we record axial images of the steady-state regimes by the ICCD camera (figures 7 and 8). Composite data containing the *V-A* characteristics and axial images of the discharge reveal the connection between the shape of the characteristics and the structure of the discharge. *V-A* characteristics and corresponding side-on images of the discharge demonstrate regimes typical of non-equilibrium low-pressure discharges [29, 31–33, 35, 49]: (a) Townsend discharge; (b) beginning of the normal glow, with distinct radial constriction of the discharge; (c) higher-current normal glow; (d) abnormal glow.

In the diffuse low-current (Townsend) discharge (labelled by (a) in figures 6 and 7) operating voltage lowers as current increases, resulting in a negative slope of the *V-A* characteristics. The negative differential resistivity of the discharge in the case of *pd* = 0.6 Torrcm is around 60 kΩ, while for *pd* = 0.3 Torrcm is around 15 kΩ. The negative differential resistance in the Townsend regime plays an important part in the

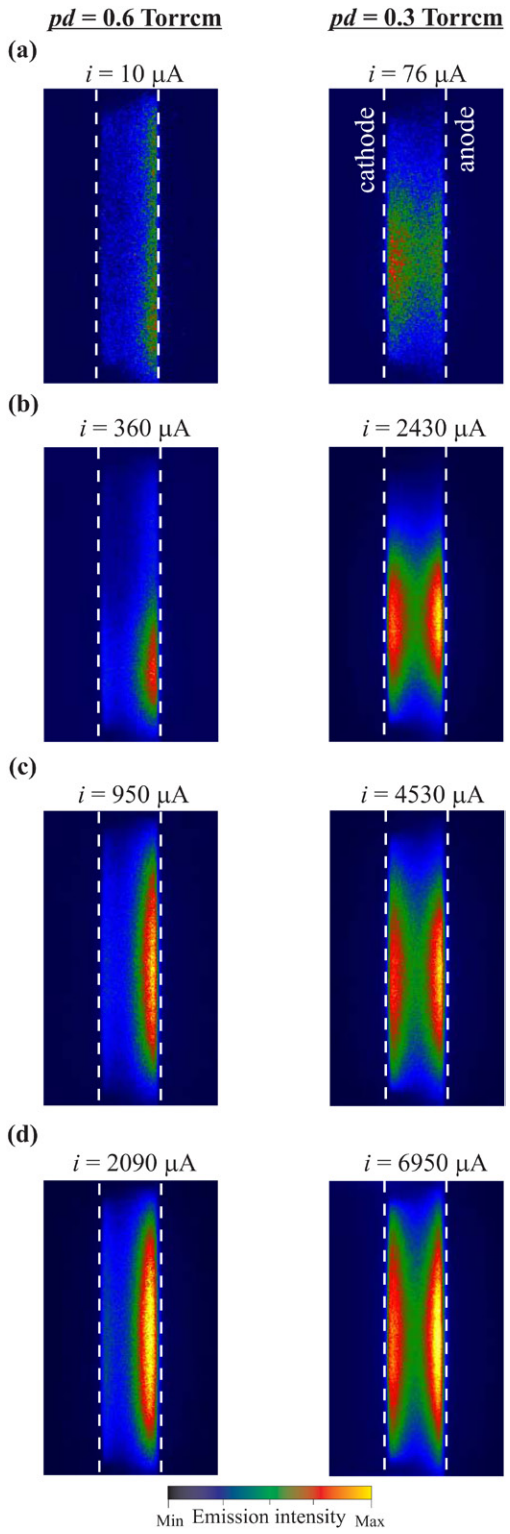

Figure 7. 2D images of the characteristic regimes of the discharge, taken with the ICCD camera in side-on view. Dashed lines indicate position of electrodes. The column at the left hand-side shows the discharge structure at $pd = 0.6$ Torrcm, while the right hand-side column is for $pd = 0.3$ Torrcm. The electrode gap is $d = 1.1$ cm in both cases. Labels (a)–(d) correspond to labels in figure 6.

analysis of secondary electron yields [27, 54]. We will leave the comprehensive analysis of the secondary electron yields in water to some further study which would involve all particles able to produce secondary electrons from the cathode surface. That goal, however, will have to involve several species of ions and fast neutrals [19–22]. The cross section set for those is being developed [55, 56]. An important part in the cross section analysis would be calculations of spatial emission profiles in the Townsend region and achievement of quantitative agreement with the measured data.

At the beginning of the normal glow (label (b) in figures 6 and 7) a distinct constriction of the discharge is formed. This kind of behaviour is typical for the normal glow [28, 29, 35, 57], although one would expect a less distinct constriction at the lower pressures. Still, since at the lower pressure the diffusion losses become important [28, 33, 34], the effective diameter of the discharge is likely to be smaller [29]. Such behaviour is also apparent through the development of the abnormal glow regime (labelled by (d) in figures 6 and 7), as the full diameter of electrodes at lower *pd*-s is achieved by the discharge at much higher currents.

At $pd = 0.3$ Torrcm, as under the breakdown conditions observed in figure 2, an additional peak of emission near the cathode can be seen throughout all regimes of the discharge. It has been well established in the literature that the cathode peak of emission is a result of fast neutrals produced by fast ions going through charge exchange collisions with almost stationary molecules of the background gas [42, 58, 59]. Such processes appear at lower pressures resulting from the energy gain of ions without much dissipation in collisions. In other words these processes are typically observed at the left-hand side of the Paschen curve, when the reduced electric field (E/N) is high enough. For example for hydrogen it has been shown that the fast neutral peak is produced mainly by fast hydrogen atoms [42]. Also, in fluorocarbons cathode peaks have been found mostly in the gases which include hydrogen atoms [60] although it is not impossible to observe the effect in other gases. In the case of water vapour, the most probable candidates for heavy-particles that participate in excitation and ionization are thus fast hydrogen atoms created in the discharge.

In figure 8 we show profiles of emission extracted from two-dimensional (2D) images presented in figure 7. The profiles are drawn along the discharge axis. Profiles are recorded as integrated in total visual spectra and with a band-pass filter of Hα line. The shape of the band-pass filter profiles closely follow the shape of the profiles obtained in full visual spectra for both *pd* values and in all regimes. Thus, excited hydrogen atom emission dominantly contributes to the overall emission within the wavelength range from ~400–800 nm. Importantly, the spatial scans maintain relative scaling of detection efficiency and thus may be put on the absolute scale by normalizing the profiles for the electron dominated peak at lower E/N as done in [38]. Thus one can unfold the data to obtain the absolute heavy particle excitation cross sections (as done by Phelps *et al* for other molecules [42, 61]).

3.4. Scaling of voltage–current characteristics

Scaling of discharge properties is an important issue that reveals whether higher order processes or non-linearities affect

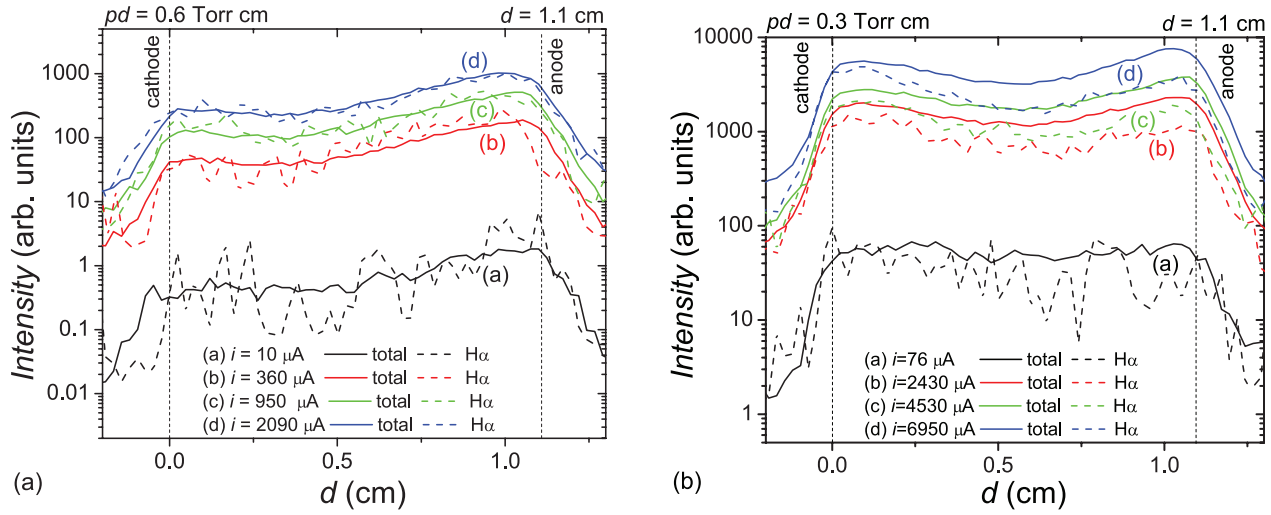

Figure 8. Axial profiles of emission for $pd = 0.6$ Torr cm (left) and $pd = 0.3$ Torr cm (right) at $d = 1.1$ cm. Hα profiles of emission are normalized with factor 80 for $pd = 0.6$ Torr cm and with factor 100 for $pd = 0.3$ Torr cm in order to compare them with profiles of total emission in visual spectra (solid lines).

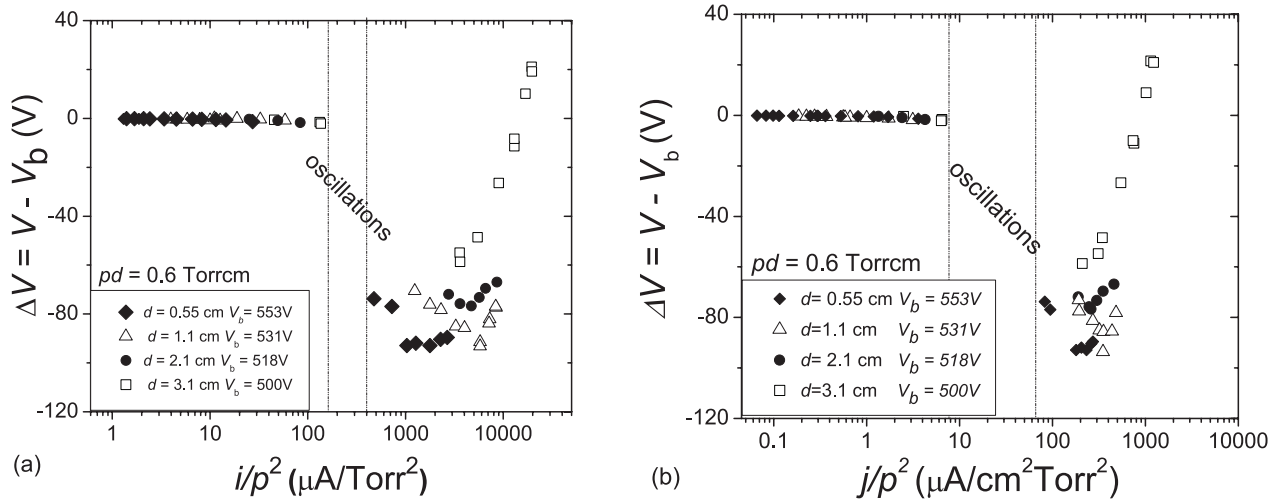

Figure 9. *V-A* characteristics for low-current discharges in water vapour, scaled by parameters (a) i/p^2 and (b) j/p^2, at $pd = 0.6$ Torrcm and different values of d. V is discharge voltage, while V_b denotes the breakdown voltage.

the overall kinetics. It is also an issue that has been often overlooked and generally *V-A* characteristics are shown as a function of current. Even if current density is used the area that is assumed for normalization is the entire area of the discharge. It has been often pointed out by Phelps and co-workers and other authors as well that realistic surface area has to be taken into consideration. Only with the development of transparent yet sufficiently conducting electrodes has it become possible to perform realistic scaling tests. One such test has been made in [29]. It revealed that, as theoretically predicted, current density throughout the normal glow remains constant and thus the whole normal glow region collapses to a single j/p^2 point. On the other hand scaling by p^2 which is due to space charge effects and should strictly work only for the Townsend's dark discharge region enables us comparisons across large discharge gaps from standard to micro discharges. In another study of this type it has been established that essentially the same physics controls standard size and micro discharges well down to 50 μm gaps [37]. Thus we proceed to test the scaling of *V-A* characteristics in water vapour.

V-A characteristics of the water vapour discharge have been measured for four different electrode gaps (0.55 cm, 1.1 cm, 2.1 cm and 3.1 cm) at several *pd* values. We have focused our attention to the *pd*-s that correspond to the minimum of the Paschen curve and to the left-hand branch, as water vapour discharges have not been studied so far under those conditions. In figure 9, V-A characteristics of the water vapour discharges at different electrode gaps (d) and at the same *pd*, are shown. The choice of $pd = 0.6$ Torrcm is right in the range of the minimum of the Paschen curve. Voltage is shown as a difference between discharge (V) and breakdown (V_b) voltage, allowing small variations of the breakdown voltage during the measurements. In figure 9, we show both i/p^2 and j/p^2 normalized results [29]. The effective area of the discharge was determined from the side on measurements by using Abel inversion.

It is worthwhile to comment on the discharge behaviour in this view, at least in the Townsend regime, which is radially diffuse, and in the abnormal glow regime, which is practically 1D as it occupies the entire electrode area.

As discussed before, we can distinguish several regions in *V-A* characteristics: the low-current Townsend regime, normal and abnormal glow. There is also a region between the Townsend discharge and normal glow, where free-running oscillations occur and it is not possible to obtain steady state values of the voltage and current.

Figure 9 shows that discharges at different gaps scale well, in the range of low-current Townsend discharge. This indicates that no processes, which would lead to the breakdown of scaling, participate in our discharge (gas or electrode heating, stepwise processes of excitation and ionization, three-body collisions etc.) [33, 36]. Variations in breakdown voltages can be contributed to variations in cathode surface conditions. It is difficult to compare voltages in the abnormal glow mode, since we have only limited available data in high current range at shorter gaps. However, it is obvious that voltages are elevated at longer gaps, i.e. lower pressures. Based on our previous studies of the scaling [33], this kind of behaviour could be attributed to additional diffusion losses. When the electrode separation becomes comparable to the diameter of the discharge, radial losses of charged particles become more important. Also, at lower pressures, losses due to a specific electric field distribution around the edges of the cathode can be important [33, 62]. Nevertheless one does not expect scaling to work perfectly for the abnormal discharge regime. Most importantly, however, the normal glow collapses practically to a single point on the j/p^2 scale thus indicating a constant current density throughout the region before the development of the abnormal glow.

4. Conclusions

Different regimes studied here are optimal for operation of non-equilibrium discharges and thus are sought for numerous applications, most importantly in treatment of thermally unstable materials, even the living tissue or organisms. In that respect, as biology often coincides with released water vapour or liquid environment that is part of the reason why discharges in liquids have become so interesting and topical in recent years. The measured data provide the basis for describing breakdown in water vapour with all data issues cleared and allow to establish a basic benchmark before one progresses to modelling of the breakdown above the water, where water may be one of the electrodes and breakdown in bubbles or even liquid water. Each of these steps requires a range of assumptions and adding to these uncertain basic processes would render modelling of such a discharge untraceable.

In this paper we present a broad range of data sampled from the experimental studies of the dc breakdown in water vapour and from low to moderate current discharges. The entire range of the operating conditions shows validity of the standard scaling laws, which proves that the three body and higher order processes do not contribute significantly to the breakdown at these pressures. We show only some of the examples of the recordings that were taken to study a whole range of standard conditions close to the minimum of the Paschen curve.

Effective ionization coefficients of water vapour are obtained from spatial profiles of emission in the *E*/*N* range of 650 Td–7 kTd. This range of reduced electric fields corresponds to mean electron energies larger than 20 eV [63], which opens a possibility to use the results for normalization of cross sections [64] for interaction of electrons with water molecules at high energies. To our knowledge, transport data at such high *E*/*N* are not available in the literature.

With the obtained ionization coefficients and measured Paschen curves, effective secondary electron yields are calculated. Special attention is given to the analysis of non-hydrodynamic development close to the cathode. One should note that the secondary electron yield here is determined for a metallic surface saturated with water vapour. It is of great interest to extend these studies to discharges with liquid electrode(s), especially to explore a possibility to extract electrons or hydrated electrons from the surface.

The next step is to couple the breakdown data to those of the low current *V-A* characteristics thus providing a chance to determine the energy (effective *E*/*N*) dependence of the secondary yield [26]. Finally the fitting of the entire *V-A* characteristics by a model that can handle both glow discharge with a self consistently determined field profile and low current uniform field limit (exactly) will provide knowledge on how to treat the secondary electron yield (as in the case of argon [31, 33]) at higher currents. We would have to first complete a study of the contribution of all the pertinent processes (ions, metastables, photons, electrons, fast neutrals etc.) and then test whether any of these processes or any other process entering the round the loop multiplication become controlled by multi step processes (such as three body ion formation or photon emission). Only then can one test the models of higher current discharges to check whether the breakdown of the scaling may mean the increased importance of some more complex processes. In particular it would be interesting to check for the effect of cluster formation around the ions and electrons and how those affect the overall performance of the discharges in water vapour.

Our study overlaps with the region of high *E*/*N* where electrons and ions may be in runaway [65]. This region is also of interest for possible breakdown in pure liquids under the effect of fast rise nanosecond pulses. Finally, as stated above we can produce absolute cross sections for fast neutral excitation by fitting the spatial profiles of emission put to the absolute scale by normalizing to excitation coefficient for electrons at the anode.

When one wishes to discuss transport and breakdown in liquids hydration of electrons (and ions) will dramatically change the kinetics of breakdown, discharge formation and how such processes develop is still an open question. Still it is expected that two interface regions exist between the gas phase and the liquid phase. Our quantitative data will be relevant for the gas phase interface where water vapour dominates over the buffer gas. In that region ions and other active particles will be formed that penetrate the liquid as well.

Acknowledgments

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Topical Review

Gas breakdown and secondary electron yields*

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Abstract. In this paper we present a systematic study of the gas breakdown potentials. An analysis of the key elementary processes in low-current low-pressure discharges is given, with an aim to illustrate how such discharges are used to determine swarm parameters and how such data may be applied to modeling discharges. Breakdown data obtained in simple parallel-plate geometry are presented for a number of atomic and molecular gases. Ionization coefficients, secondary electron yields and their influence on breakdown are analyzed, with special attention devoted to non-hydrodynamic conditions near cathode.

1 Introduction

It is often said that atomic and molecular collisions define the physics of non-equilibrium (so-called low-temperature) plasma. However, in plasma modeling, where space charge and field profile effects intervene with atomic and molecular collisions, often it is claimed that the collisional cross sections, rate coefficients and swarm transport data do not need to be very accurate as the processes are so complicated that high accuracy is not required. Gas breakdown, on the other hand, is the point where inaccuracies of the atomic collision and swarm data are amplified and at the same time the conditions for the breakdown often define the operating conditions for the plasma. To illustrate this we may give an example that ionization rate enters the breakdown condition in exponent and also that rate is often exponentially dependent on the gas density normalized electric field E/N. The mean energy and the shape of the distribution function that define the rate (together with the cross section for ionization) are on the other hand strongly dependent on all relevant inelastic processes. Breakdown under DC fields and slowly varying AC fields also depends on surface collisions of ions and atoms. Thus, breakdown condition is a very sensitive projection of atomic and molecular collision and swarm transport physics onto the realm of plasma physics.

Gas breakdown has been studied over 100 years and yet many open issues still remain. In DC discharges, the breakdown is usually described by the standard Townsend's theory [1]. Within the past 20 years, with development of experimental and modeling techniques, it became clear that the standard (basic Townsend's theory as depicted in the textbooks) theory of breakdown and low-current discharges (the so-called Townsend's regime) requires improvement. Phelps and coworkers [2–5] initiated a comprehensive revision of the theory in all its aspects.

This revision in the lowest current limit (breakdown) included taking into account the contribution of all feedback mechanisms and space-charge effects in breakdown and low-current discharges [5]. These authors only covered one gas (argon) with detailed analysis. This is why we felt that a survey of the existing well documented breakdown data would be of value as the basis for further study on the data and elucidation of the issues in use of secondary electron yields in plasma modeling. All of the presented results were obtained in our laboratory and an utmost care has been invested to avoid the usual problems in determining the breakdown data (often depicted as Paschen curves). Those include variable surface conditions, jumping straight into the glow discharge mode, recording the operating conditions for the glow discharge and also the uncertainties that arise from the long statistical delays in initiation of gas discharges.

For many years swarm experiments have represented the primary source of data for gas discharge modeling, which, on the other hand, was based on the transport theory for swarms. With only very few exceptions, the models are based on the hydrodynamic (in equilibrium with the electric field and spatially uniform) transport data. This is however not applicable in most breakdown experiments as the early stages of the breakdown occur before equilibration of the electron swarm. Thus we present also an analysis of electron excitation cross sections and studies of spatial profiles of emission to separate excitation by electrons and fast neutrals [6]. Our results also allow us to determine the width of the non-hydrodynamic region close to the cathode and the effective multiplication as

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well as the approximate determination of the field distribution in dark Townsend discharges. These data all need to be applied to determine the secondary electron yields and in modeling of plasmas.

Over the past two decades determination of the secondary electron yields [6,7] has had renewed interests, for two reasons. First, a systematic survey [5] has been made of all the processes that participate to secondary electron production and it was shown that the basic assumption of Townsend's theory that ions produce the secondary electrons is correct only in a very narrow range of conditions, while photons and gas phase ionization by neutrals contribute to the secondary electron production in a much wider range of E/N. Most importantly, it became possible to model the observed secondary electron yields in the breakdown by using binary collision (beam to surface) data.

It was shown that it is not possible to use directly the binary collision (beam-surface) data for the analysis of gas discharges and low temperature plasmas as those would have specific distributions of all the relevant fluxes that otherwise might be connected through nonlinear relations. The analysis performed for the breakdown (where all fluxes are in linear relation to the initial flux of electrons) proved to be quite robust and still fit most of the data for the glow discharges [8,9]. Nevertheless, it is possible that for some gases or some plasmas, nonlinearities may prevail and the required model may depart from the breakdown model.

In this paper we present the data on breakdown voltages (shown as Paschen curves) for a large number of gases, we show some examples on how these data are coupled with Volt-Ampere (V-A) characteristics, and we proceed to determine secondary electron yields for rare gases (assuming ions to be the primary agent producing secondary electrons) with the inclusion of the effects of equilibration and proper determination of the ionization growth coefficient.

2 Breakdown voltages and Paschen curves

Breakdown is usually represented by a Paschen curve i.e. dependence of the breakdown V_b voltage on the pd (pressure $p \times$ gap d). Parameter pd is a scaling parameter proportional to the number of collisions over a unit distance. In this respect, a typical sharp increase of the breakdown voltage at low pd-s can be explained by the need to compensate for a small number of collisions. On the other hand, at high pd-s, due to a large number of collisions, breakdown voltage is increased in order to enhance energy gain between collisions, when mean free path is getting shorter and the energy gained between two collisions becomes smaller. In the range of the Paschen minimum, production of charges by ionization and secondary electron emission and losses by attachment, diffusion and drift are well balanced.

In Figure 1 Paschen curves for several atomic and molecular gases are presented. Measurements with H_2, SF_6, CF_4, H_2O and C_2H_5OH vapours are taken with the copper cathode, with 1 cm electrode gap and 5.4 cm diameter [10,11]. For all other gases, stainless steel cathode was used in measurements in 2.9 cm gap and 8 cm electrode diameter [6,12]. Some of the data had preliminary presentation in the second edition of the textbook by Lieberman and Lichtenberg [13].

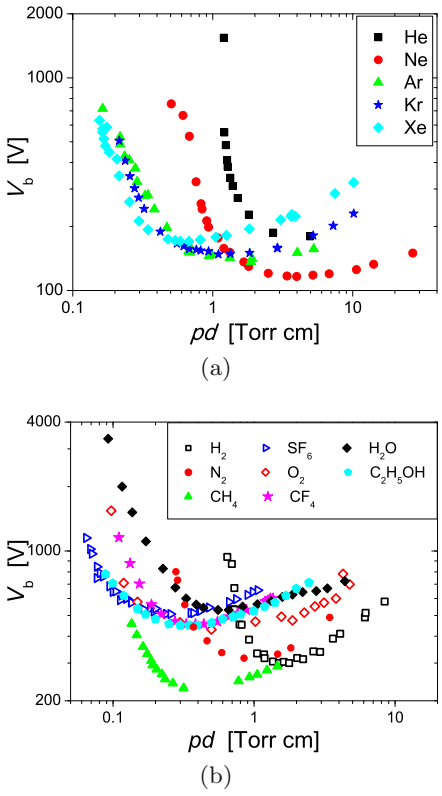

Fig. 1. Paschen curves for (a) atomic gases: Ar, He, Ne, Xe, Kr [6] and (b) molecular gases H_2, SF_6, O_2, CH_4, N_2 [12], CF_4 [10], and H_2O [11] and C_2H_5OH vapours. Measurements with H_2, SF_6, CF_4, H_2O and C_2H_5OH vapours were obtained with copper cathode, for other gases stainless steel cathode was used.

For most of the gases Paschen minimum is situated at pd of the order of 1 Torr cm and breakdown voltages are of the order of several hundred volts. In the case of electronegative gases, it is usually shifted towards smaller pd-s and higher voltages. This can be understood from the point of view of the balance of production and losses of charged particles. In electronegative gases, at low E/N i.e. high pd, attachment becomes important. As a loss mechanism for electrons, it will increase the breakdown voltage and shift the Paschen minimum to lower pressures as an even higher E/N is required to provide sufficient ionization.

There are several issues that one has to be aware of in breakdown measurements. Breakdown voltage depends on the gas mixture through identities of ions and on the cathode material. Even more important than the cathode material is the state of the cathode surface – roughness or possible oxide layers and other impurities deposited on its surface either by exposing the cathode to the laboratory environment or during the discharge operation. Sometimes

the state of the cathode surface has larger influence on the Paschen curve than the material of the cathode itself. For this reason, in our experiments cathode surfaces are treated in low-current (∼30 μA) hydrogen discharge prior to the breakdown measurements. This procedure proved to give stable conditions during measurements and reproducible results over large periods of time. Even when basic breakdown voltage varies due to surface conditions, the Paschen curve (and also the V-A characteristics) maintain their shape and so normalization onto the breakdown voltage is a good way to analyze the data [5,14].

Another issue that has to be taken into account in experiments is the regime in which the discharge ignites. Breakdown voltage should not be confused with the operating voltage. The point where the discharge operates is at the crossing of the circuit load-line and the Volt-Ampere characteristics. Quite often, especially with a small series resistance and sufficiently large overvoltages, this is in the regime of a glow discharge, where voltage can be significantly smaller than the breakdown voltage. Actual breakdown voltage, in the sense that is represented by the Paschen law, can only be found by extrapolating Volt-Ampere characteristics to zero current in the dark Townsend discharge mode. An alternative technique is to study the pre-breakdown currents [15,16]. Sometimes it is even necessary to record the spatial profile of the discharge in order to confirm the exponential increase of emission from the cathode all the way to the anode, which is typical for low-current Townsend discharge.

It is important to emphasize that, besides the Paschen curves, Volt-Ampere characteristics are essential in understanding the process of breakdown. These data are needed to establish the electric field/energy dependence of the secondary electron yields and as a consequence the slope of the V-A characteristics in the Townsend regime is defined. The slope of the characteristics is typically negative in the low-current region and it reveals the ion energy dependence of the secondary electron yield and field distortion due to the initial growth of space charge [2,3,17]. In practice, for a full description of the discharge a 3D plot should be constructed [18], such as the one shown in Figure 2, with discharge voltage (V), pressure × electrode gap product (pd) and discharge current (i) presented at the axes.

Low-current limit represents Paschen curve and in this case it is projected onto 1 μA as further changes of voltage at even lower currents would be negligible. Measurements are taken in a parallel-plate electrode system, with 1 cm gap, 5.4 cm electrode diameter and copper cathode. Considerable difference between the glow regime and Townsend regime voltages is clearly seen from the characteristics.

3 Model of the gas breakdown and secondary electron yields

Secondary electron emission is one of the key mechanisms of DC breakdown and operation of discharges. Still, there

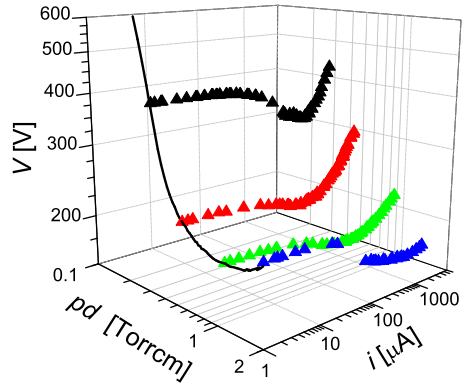

Fig. 2. Experimental V-A-pd characteristics for argon.

is a great confusion in literature in respect to the meaning of the data entering the breakdown condition. In fact, the secondary electron yield data obtained from the gas breakdown have always failed to match the direct measurements in the binary beam-surface experiments. As Phelps and Petrović [5] confirmed in the case of argon, the basic phenomenology of Townsend's theory required extension. Almost constant secondary yield of around 8% for argon ions that has been obtained by ion beams on surfaces cannot be applied to model even the basic low pressure breakdown. While one could justify a greater secondary yield due to additional processes, in the main section of mean energies the yield is actually ten times smaller than that from beam measurements. Phelps and Petrović developed a comprehensive model for argon that included all possible feedback mechanisms – secondary emission by ions, metastables, fast neutrals and photons. They also included back-diffusion of electrons and discussed conditions at the surface where standard gas discharge experiments cannot reach the conditions defined for atomically clean surfaces in ultra-high vacuum. Their study showed that one has to take into account energy dependent yields for each of the species from binary experiments in order to be in accordance with results of direct breakdown measurements. Here, we shall follow the standard procedure to determine secondary yields from the breakdown data and we shall also try to correct some of the problems and provide the data required for such corrections.

Under the conditions of the breakdown and low-current Townsend discharges, the effective secondary emission yield (γ) is related to the ionization coefficient (α) in accordance with the Townsends self-sustaining condition:

$$\gamma = \frac{1}{e^{(\alpha/N)\times Nd} - 1} \tag{1}$$

where N represents the gas number density and d is the gap between the electrodes. $\gamma(E/N)$ may be deduced from Paschen curves by using $\alpha/N(E/N)$ data from the literature [19] as was done in [6]. One may also use an analytic form of $\alpha/N(E/N)$, e.g. Marić et al. [20], as it was shown in [21]. This procedure is the standard one. Perhaps the most important problem in the procedure is that

the non-hydrodynamic region close to the cathode (d_0) affects the total multiplication, and therefore the secondary electron yield obtained from the Paschen curve. The second problem is that the ionization rate taken from the literature may give quite different multiplication as compared with the actual experiment. Even small errors in ionization coefficient result in large discrepancies of the secondary electron yield.

4 Determination of the equilibration distance

It is well-known that hydrodynamic conditions are characterized by transport coefficients that are constant in space and time [22]. However, in low-current electrical discharges at low pressures electrons do not reach the equilibrium state immediately after leaving the cathode. Only at a certain distance from the cathode electrons establish equilibrium with the gas and parameters of electron transport become spatially independent [23,24]. In a simplified approach the width of the non-hydrodynamic region may be used to separate discharge into two regions: one that can be referred to as the non-equilibrium region, with no ionization and the other where ionization behaves as if electrons are in hydrodynamic equilibrium. The problem is then how to determine the delay distance from independent measurements, by using semi-empirical formula such as the one suggested by Phelps and Petrović [5] or by kinetic calculations.

It was shown that inclusion of the effect of equilibration causes a large difference in secondary electron yield data [5], but most authors in the available literature obtain the secondary electron yields from the breakdown data without paying attention to this correction. The role of the equilibration length in determination of the secondary electron yield was studied by Folkard and Haydon [24]. A more detailed discussion of the application of the delay distance and correct determination of the effective electron yield have already been published for the case of argon [6] and for nitrogen [21].

The appropriate form of multiplication factor under Townsend's breakdown conditions is [5]:

$$\gamma = \frac{1}{e^{\alpha(d-d_0)} - 1} \tag{2}$$

where d is the gap between electrodes, and d_0 is the delay distance which has to be passed before electrons reach hydrodynamic equilibrium allowing avalanching characterized by the equilibrium ionization coefficient α. As there is a great need to determine accurate yield coefficients for plasma modeling, there is also a need to establish procedures to determine the equilibration distance.

In our experiments it is possible to obtain equilibration distances from spatial scans of emission. The width of the non-hydrodynamic region d_0 may be used to separate the discharge into two regions. Figure 3 shows two examples of spatial profiles of emission which illustrate the procedure for determination of the equilibration distance and ionization coefficients. In the case of xenon, the non-hydrodynamic width is exhibited as a flat region close to the cathode followed by exponential growth of emission. In the case of neon, there is even a sudden jump of emission just after the equilibration distance. It is still not clear what is the origin of emission in the region next to the cathode [25], as one would expect that there is no emission in non-equilibrium region. Growth of emission in hydrodynamic region is determined by a single exponential that is in excellent agreement with the equilibrium ionization coefficient [26]. While this is not the most accurate method to determine ionization coefficients, it is useful in some situations when the data are lacking and also to indicate the realistic conditions in a particular system which may be affected strongly by the contamination of the gas. Finally, this is the only direct way to obtain total multiplication as required by the breakdown theory.

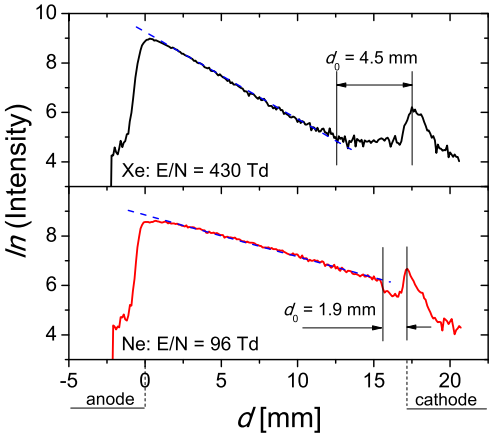

Fig. 3. Examples of the spatial emission profiles in xenon (upper plot) and neon (lower plot), with non-hydrodynamic regions indicated.

When the spatial scans of emission are not available in the experiment that is being analyzed but were available for other experiments, the delay distance d_0 can also be determined by using semi-empirical formulas such as that given in [5] through the expression for the effective value of the electrode potential difference before the exponential growth of the current:

$$V_0 = 16\sqrt{1 + \left(\frac{E/N}{1000}\right)^2}. \tag{3}$$

Probably the best method to produce delay distances is by using Monte Carlo simulations. In this paper we apply a Monte Carlo code that has been well documented in previous publications (details can be found in [27,28]), so only a brief description will be given here. The code is based on generalized null-collision technique [29]. In the code we follow electrons released at the cathode until they reach the anode. The set of cross sections that is used involves inelastic (excitation) processes, ionization and elastic scattering. Each of these processes has associated differential cross sections that are necessary only to establish the angle of scattering. The probability of scattering is determined on the basis of the total cross section. From the simulation of the spatial profile of excitation, one may observe a region

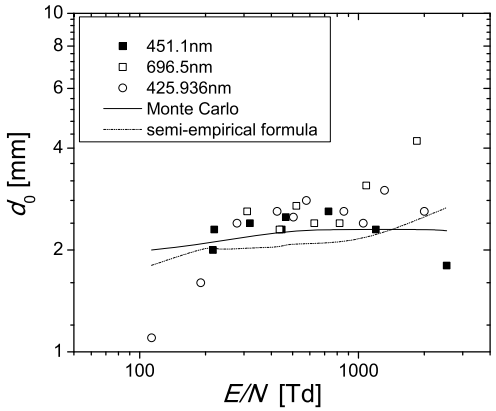

Fig. 4. The dependence of the delay distance d_0 on the reduced field E/N for argon. The delay distances were obtained by three different techniques. Calculations were performed assuming isotropic angular distribution of electrons, the gap between the electrodes of 1.72 cm.

next to the cathode where excitation is zero, followed by an exponential growth of emission and finally a growth with the hydrodynamic ionization coefficient. The hydrodynamic region is extrapolated to the zero value and that point determines the distance as applied in equation (2).

In Figure 4 we compare results for the equilibration distance as a function of the reduced field E/N in argon obtained by experiment (symbols), Monte Carlo simulation (solid line) and semi-empirical formula (dashed line). The results obtained by using three different techniques show good agreement, except for the lowest and highest values of the reduced field. It is necessary to consider here the accuracy of experimental determination of the distance d_0 at those values of E/N. At low values of E/N multiplication is very high and it is not so sensitive on the accuracy of determination of d_0 which is small anyway. On the contrary, at high E/N i.e. low pressures, overall multiplication is small, so inclusion of d_0 does not make significant difference. We may say that the agreement between the experimental data, semi-empirical formula and Monte Carlo simulations is excellent for the purpose of determining the secondary yield coefficients. Still, in experiment, due to reflection from the cathode and scatter of light, the results can be significantly scattered, as it is shown in Figure 4, so for the purpose of determination of secondary electron yields, we use results of Monte Carlo simulations when possible.

While Figure 4 shows results for equilibration distance along the Paschen curve, further on, we explore d_0 behavior for the general non-self-sustained conditions. Pressure dependence of d_0 at a fixed E/N is shown in Figure 5a and the E/N dependence at a fixed pressure in Figure 5b. In both cases, we present the results obtained using our Monte Carlo simulation code (curve) and semi-empirical formula (symbols). For a fixed reduced field, the delay continuously decreases as the gas number density (pressure) increases. On the other hand, the E/N dependence of the equilibration distance for a fixed gas number density (pressure) shows that the equilibration distance becomes

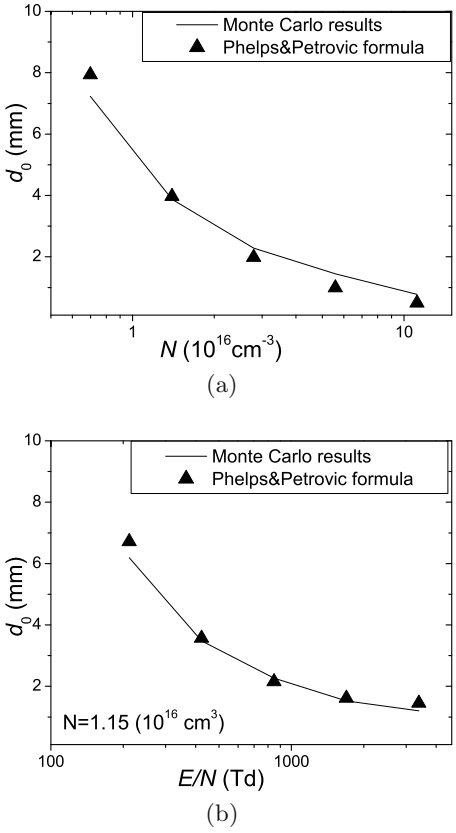

Fig. 5. The dependence of the delay distance on: (a) the gas number density for a fixed reduced field for argon; (b) the reduced field for a fixed gas number density for argon.

smaller as the reduced field increases (for a fixed gas number density). In both cases, the results obtained by semi-empirical formula and the Monte Carlo simulations are in satisfactorily agreement. The experimental measurements are in fact less reliable than the simulation due to limited spatial resolution and possible scattering of light. Thus we really seek a general agreement and put our confidence in simulations. On the contrary, the measured exponential growth, if defined well and if not overlapping with the contribution of fast neutrals, provides better representation of multiplication in the actual experiment. Agreement between results proves that scaling for the equilibration employed in the development of the semi-empirical formula is appropriate.

In Figure 6 we show calculated equilibration distances for different gasses. We have performed analysis mainly for the rare gases and in a limited sense as compared to Phelps and Petrović [5]. Partly, the reason is that experimental determination of the delay distance in molecular gases is very difficult due to several sources of emission and complex quenching. In those gases we recommend Monte Carlo simulation of the whole system both the delay gap and the exponential growth. In Figure 6 it can be seen that the equilibration distance increases with the atomic mass; however it does not change much for a specific gas in the range of E/N-s investigated here.

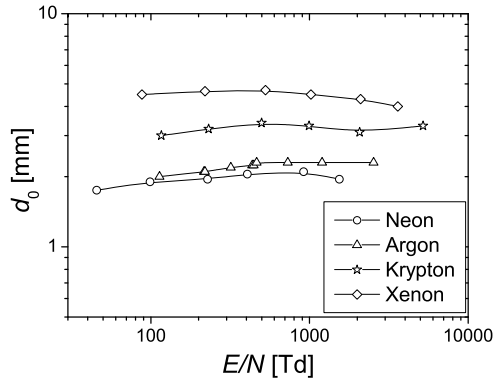

Fig. 6. Equilibration distances for different gases.

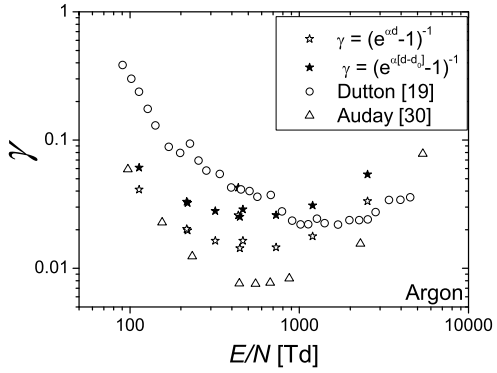

Fig. 7. Comparison of secondary electron yields for argon obtained with different data for ionization coefficients. The first three sets of data were obtained using our Paschen curve, the first two (stars) with our multiplication coefficient without and with the inclusion of the delay distance d_0 in the analysis. The third set (circles) was obtained by using the ionization coefficients from [19] to determine the multiplication. The same ionization coefficients were used in the fourth set [30] but the basis for the results was their measurements of the Paschen curve.

5 Determination of the secondary electron yields and the role of ionization rate

As discussed in previous subsection, the non-hydrodynamic region near the cathode does not necessarily have a significant influence at very low and very high E/N. However, not taking into account the existence of non-equilibrium region can significantly change results for secondary electron yields in medium range of reduced electric fields. In Figure 7 we compare the secondary electron yields in argon obtained by taking into account and not taking into account the equilibration length d_0 (solid and open stars respectively). $\alpha/N(E/N)$ data obtained directly from the experiment are used here to determine γ. As expected, taking equilibration length into account has the largest effect close to the minimum and in the right branch as compared to the left branch. Yet, towards both ends the differences induced by including d_0 diminish. The largest difference between the secondary yields with and without d_0 is a factor of two and it coincides with the minimum of the Paschen curve.

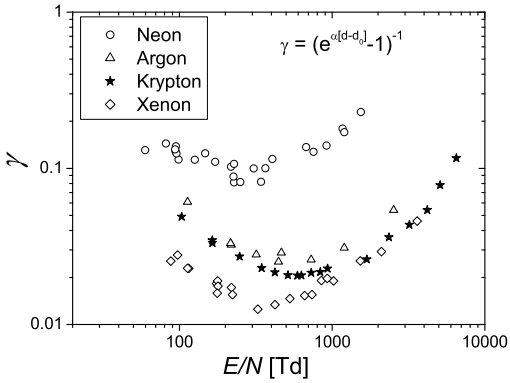

Fig. 8. Secondary electron yields for several different gasses, with the same cathode surface (stainless steel).

Taking the ionization rate from the literature may give a quite different multiplication as compared with the actual experiment and even small errors in the ionization coefficient result in large discrepancies of the secondary electron yield. In Figure 7 we also show secondary electron yields obtained from our Paschen curves by using ionization coefficients from the review [19] which are mostly based on experiments of Kruithiof (circles). These results are up to a factor of 10 different from our data mostly at high E/N.

We also show results of Auday et al. [30] who have analyzed their Paschen curve with the ionization rates from Dutton (triangles). Although those two sets of Paschen curves are apparently quite similar, the differences of yields are considerable, as large as a factor of 10.

For the low values of E/N, γ in our experiment rises more strongly than those obtained by using values of α/N from the literature. This can be explained by the fact that secondary emission of electrons can be due to any combination of numerous mechanisms of varying importance depending on the value of E/N. In the case of small values of E/N, dominant mechanism is the photoelectron emission.

Finally, a similar analysis for the secondary electron yields has been carried out for several other gases. In Figure 8 we show only final results obtained by using the most complete (correct) procedure. As expected the yield increases presumably proportional to potentials of the ion and the metastable states.

6 Conclusions

Measurements of properties of low-current discharges which include Paschen curves, Volt-Ampere characteristics and spatial profiles of emission proved to be a fertile basis for modeling of plasmas and discharges. In this paper we gave a short overview of the results of our breakdown studies covering five rare gases and eight molecular gases. We pointed out the most important issues in deducing secondary electron yields from the breakdown and swarm

experiments, compared results obtained by employing different procedures and we presented results for secondary yields for several rare gases obtained by a proper procedure. One should bear in mind that in this analysis the effective coefficients are attached to ion fluxes and a more thorough analysis along the same lines as done by Phelps and Petrović [5] should be performed for all gases together with an analysis of the applicability of the data in higher current discharges.

In conclusion, we may say that the treatment of electron non-equilibrium motion near the cathode includes determination of the delay in reaching the hydrodynamic rates of electron excitation and ionization. The results obtained when the equilibration distance is accounted for allow us to conclude that not taking into account the non-equilibrium region and correct values of ionization coefficients one may make quite large errors in obtaining secondary yields for the relevant particles in the discharge. These differences between the γ coefficients may result in some of the discrepancies between the swarm and the binary collision technique data for γ coefficients, which remains yet to be analyzed.

Monte Carlo simulation provides complete representation of non-equilibrium effect and influence of the electrodes and it is exact representation of breakdown itself, so it should be employed for modeling. A satisfactory agreement between the experimental data and the results obtained using Monte Carlo simulation code and semi-empirical formula proves that our treatment of the electron non-equilibrium behavior close to the cathode is accurate. It also became possible to make more direct comparisons between the secondary electron yields obtained from Paschen's law and from experiments consisting of a beam of ions hitting the surface under high vacuum conditions and separate detailed analyses should be made for all gases that are of interest.

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New phenomenology of gas breakdown in DC and RF fields

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New phenomenology of gas breakdown in DC and RF fields

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Abstract. This paper follows a review lecture on the new developments in the field of gas breakdown and low current discharges, usually covered by a form of Townsend's theory and phenomenology. It gives an overview of a new approach to identifying which feedback agents provide breakdown, how to model gas discharge conditions and reconcile the results with binary experiments and how to employ that knowledge in modelling gas discharges. The next step is an illustration on how to record volt-ampere characteristics and use them on one hand to obtain the breakdown voltage and, on the other, to identify the regime of operation and model the secondary electron yields. The second aspect of this section concerns understanding the different regimes, their anatomy, how those are generated and how free running oscillations occur. While temporal development is the most useful and interesting part of the new developments, the difficulty of presenting the data in a written form precludes an easy publication and discussion. Thus, we shall only mention some of the results that stem from these measurements. Most micro discharges operate in DC albeit with complex geometries. Thus, parallel plate micro discharge measurements were needed to establish that Townsend's theory, with all its recent extensions, is still valid until some very small gaps. We have shown, for example, how a long-path breakdown puts in jeopardy many experimental observations and why a flat left-hand side of the Paschen curve often does not represent good physics. We will also summarize a kinetic representation of the RF breakdown revealing a somewhat more complex picture than the standard model. Finally, we will address briefly the breakdown in radially inhomogeneous conditions and how that affects the measured properties of the discharge. This review has the goal of summarizing (rather than developing details of) the current status of the low-current DC discharges formation and operation as a discipline which, in spite of its very long history, is developing rapidly.

1. Introduction: Townsend's theory and low-current DC discharges - 100 years ago and now

With the development of basic phenomenology and theory of gas breakdown, Townsend's theory was forged some 100 years ago [1-3]. In this paper we shall give a review of how in the past 20 years the basic Townsend's theory and phenomenology have been revived, extended, revitalized and put in perspective of modelling higher current technological discharges and plasmas. This was primarily done by the groups of Art Phelps and the Gaseous Electronics Laboratory in Belgrade.

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Recent advances in diagnostics and modelling of complex plasma systems opened an opportunity to revisit the breakdown in gases both in DC and RF fields and also for micro gaps. We shall first discuss the experimental techniques to determine the breakdown voltage. Typical errors, such as neglecting the long-path breakdown on the left-hand side of the Paschen minimum, conditioning of the electrode and measuring properties within an unstable (oscillating) regime, will be covered briefly. In addition, we shall describe a proper methodology to establish volt-ampere (*V-I*) characteristics and how to use those with the goal of determining the breakdown voltage and the secondary electron yields.

Time-resolved imaging [4] provides us with information on the development of the anatomy of the discharge and its different modes. Using the spatial profile one may decide which of the mechanisms dominate the discharge. The Townsend regime is the low-current diffuse discharge with exponential growth towards the anode [5]. It is necessary to observe such a profile to ascertain that the discharge operates in the Townsend regime where Townsend's theory may be used to establish the condition for breakdown and effective secondary electron yield. The temporal development of the normal glow or abnormal glow following the breakdown reveals transient multi-regime operation that requires a new paradigm.

When considering volt-ampere characteristics, one may first observe the negative differential resistance in the Townsend regime which may be explained by a combination of space-charge effects and an energy-dependent secondary electrons yield. Thus, *V-I* characteristics should be used in addition to the Paschen curve to determine the secondary electrons yields. With the newly found field of discharges in and above liquids, we have also analyzed breakdown in water vapor and ethanol [6,7].

RF and microwave breakdowns have a different phenomenology as the secondary ions production of electrons at the cathode may not be necessary. Yet the RF breakdown is prone to phenomena not often observed in DC breakdowns, like S shaped (double valued) Paschen-like curves, frequency/gas number density scaling and additional mechanisms like multipactors. The principal experimental problem with the RF breakdown is the magnitude of the displacement current that thwarts the measurement of the conduction current making it difficult to ascertain the initiation of the discharge.

2. Gas breakdown, feedback mechanism, secondary electron yields and how to use them

Traditionally, the gas breakdown is characterized by Paschen curves. In figure 1 we show one such example of Paschen curves for the topical water vapor and ethanol vapor [6,7].

While most people will argue (including the present authors) that the Paschen law itself is developed with limiting assumptions

$$V_b = \frac{Bpd}{\ln(Apd) - \ln\left[\ln\left(1+\frac{1}{\gamma}\right)\right]}, \qquad (1)$$

the breakdown equation from the Townsend's law is in principle exact if the assumptions of the primary feedback through ions are correct:

$$\gamma(E/N)\left(e^{\alpha(E/N)d} - 1\right) = 1. \qquad (2)$$

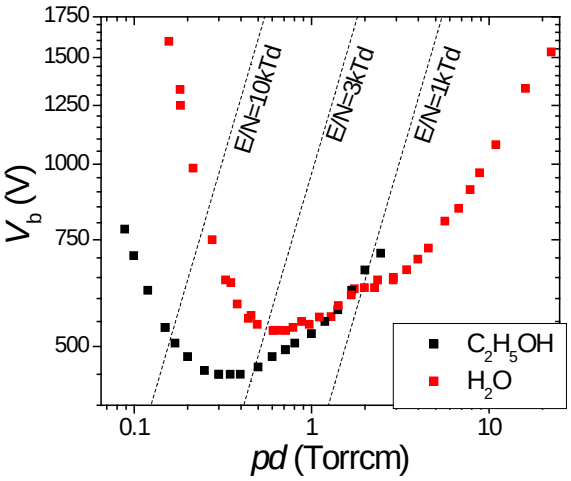

Figure 1. Paschen curves for water [6] and ethanol vapor [7].

Different forms of analytical laws have been employed for the DC breakdown in order to provide some insight [8,9], but one needs to be aware of the approximate nature of some of the basic formulae. Still, the same limitations that enter the analytical form of Paschen law may enter the implementation

of equation (2). Over the years, a large amount of data on γ have been accumulated, yet seldom those have been compared and systematically collected. Even more importantly, comparisons to binary collision (beam-surface) experiments [10] have been almost avoided in the literature presumably due to poor agreement (both qualitative and quantitative). One example where both systematic collection of data and comparisons to binary experiments have been made is the paper of Phelps and Petrović [3].

In figure 2 we show a comparison of the secondary electron yields obtained from Paschen curves in argon for a range of experiments [3]. These should be compared with a constant yield of 0.08 obtained by beam experiments with an atomically clean surface [10] or to the dot-dash line obtained for the same conditions of the cathode as found in discharge experiments. Discharge results are one order of magnitude too high at higher *E/N*, one order of magnitude lower at moderate *E/N* and two orders of magnitude higher at the lowest *E/N*. Phelps and Petrović managed to reconcile the binary collision data and the discharge results by including the following:

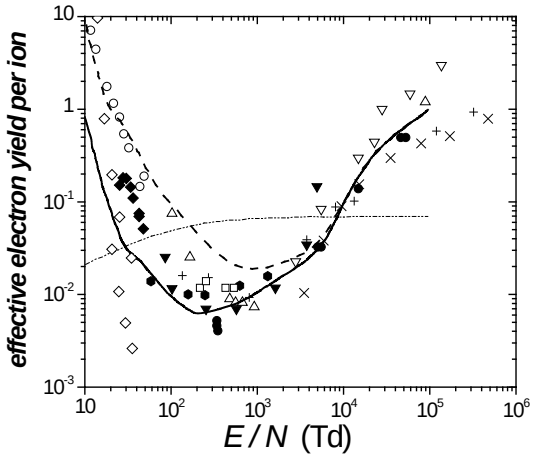

Figure 2. Effective secondary electron yield γ for argon obtained from breakdown data [3]. The different types of points indicate different experiments - see [3]. The dot-dash curve shows binary collision experiment data.

- ionization coefficient fitted in a wide range of *E/N*;
- a region close to the cathode where electrons gain energy and become in equilibrium with the local field, the simplest way of representing this being using a delay distance d_0;
- ion-induced yields at the cathode, modified to represent surfaces that are not atomically clean;
- back-diffusion, i.e. the return of newly emitted electrons back to the cathode;
- secondary electron production by metastables;
- secondary electron production by fast neutrals;
- secondary electron production by resonant radiation – the photo effect;
- trapping of resonant radiation;
- secondary electron production by fast neutrals;
- secondary production due to molecular emission.

The solid and dashed lines in figure 2 indicate the model predictions based on binary collision data (for two limits of possible contributions by molecular radiation). These two lines encompass most of the available experimental data. The good agreement with the experiments shows that all pertinent processes have been included. It also shows that the process of secondary yields modelling may be quite complex and quite challenging due to the need for a wide range of data.

The fact that Townsend's theory could associate all the yields with the flux of ions is because all fluxes are proportional to the electron flux and the system is linear in the breakdown-Townsend discharge phase. On the other hand, one cannot expect linearity to hold for higher current modes, such as glow discharges. For those, one is left with fitting the experimental data. Thus, we compared the fitting procedure with one based on the breakdown data from Phelps and Petrović [3]. We found [11] that fitting of the glow discharge is well represented by the procedure recommended for the breakdown data [3], except when *pd* is quite low and fast neutral effects become dominant. Yet, for RF discharges, for example, or for some more complex geometries, one needs to provide a clear guidance as to how the secondary electron yield may be modelled. Also, we need a considerable effort to provide the data for a number of relevant gases, as argon is the only gas covered so far by the detailed analysis.

3. Volt-ampere characteristics and spatial emission profiles

There are two ways to determine the breakdown voltage. The first option is very accurate albeit very difficult – one can extrapolate pre-breakdown currents. The second one, favored by our group, is to establish a self-sustained discharge in the low-current diffuse, i.e. Townsend, discharge and then extrapolate the measurements to zero current. All other techniques suffer from arbitrariness, either induced by the long statistical time lags or by a direct transition to the glow regime. The Townsend's regime is recognized by an exponential growth peaking at the anode and a normally broad diffusion-determined profile over the entire surface [5,12], as can be seen in figure 3.

In conducting such measurements, we (re)established that in the Townsend regime one has a negative differential resistance. As the effective resistance of the discharge is negative, sometimes, coupled with the external circuit, the overall loop resistance may become negative and oscillations may occur [13,14]. As it turns out, the space charge due to ions increases the field in front of the cathode, which increases the electron production allowing a lower field elsewhere and thus the overall voltage is reduced [14,15]. Thus, the dependence of γ on the mean energy is the reason for the negative differential resistivity, brought about by space charge induced electric field and represented as a current dependence of γ. As the discharge approaches constriction, non-linearities become important [16] and a sudden transition eventually takes place. It has also been shown that if γ were constant, the slope of the *V-I* characteristics in Townsend's regime could become positive [16]. Thus one may conclude that for the full representation of the secondary electron yield one needs to fit not only the Paschen curve but also the *V-I* characteristics. The realm of oscillations often precludes us from achieving stable operation in Townsend's regime but it is also a source of information on important processes. Thus, fitting of the induced damped or free running oscillations may reveal identity of the dominant ionic species, multiplication and may be related to basic transport properties of relevant particles.

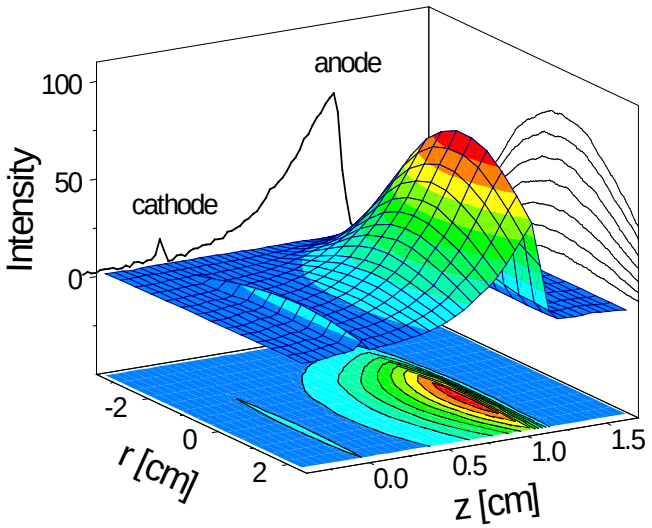

Figure 3. Spatial profile of the Townsend's regime low-current diffuse discharge [12].

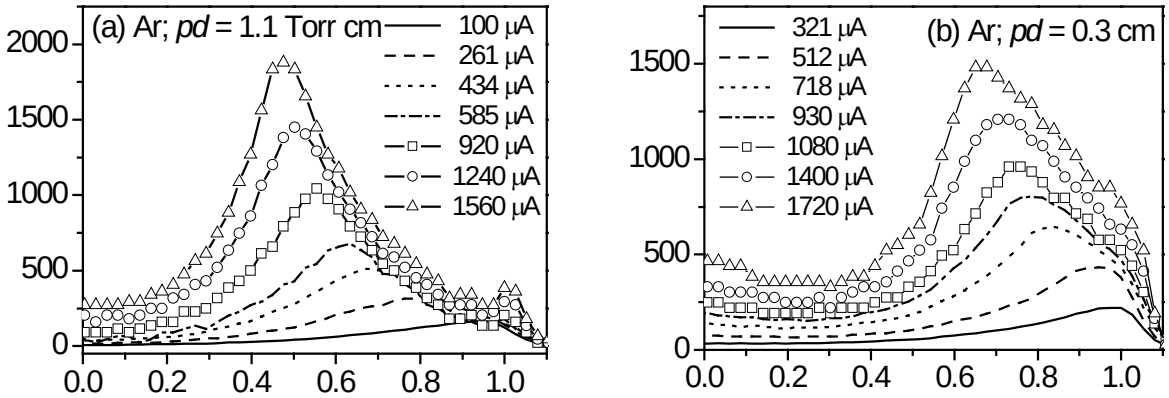

Figure 4. Axial profiles of higher current discharge regimes in argon, at (a) *pd* = 1.1 Torr cm (close to the Paschen minimum); (b) *pd* = 0.3 Torr cm (in the left-hand branch of the Paschen curve).

Another important aspect that stems from figure 3 is that spatial profiles not only give us information on the regime of operation (see figure 4 – the peak in front of the anode is for Townsend's low current discharges, the peak in the bulk corresponds to the glow discharge) but also (if put on an absolute scale) a basis to establish absolute cross sections and even profile of the field. It also shows whether and to what extent is equilibrium (with the field) developed or whether fast neutral excitation is important as recognized by the peak right in front of the cathode.

4. Scaling of the basic properties of micro discharges

Micro discharges were basically developed to take advantage of the non-equilibrium plasma that is formed around the Paschen minimum, but at a much higher pressure. Atmospheric pressure would require a 10 μm gap. On the other hand, to achieve a stable operation at high pressures one needs to use complex geometries as it proved very difficult to operate parallel plate micro discharges. Yet, many authors have assumed parallel plate geometries with narrow strips crossing at small distances and assumed that the breakdown occurs at the shortest distances. This has led to a number of papers where the left hand side of the Paschen curve showed no or little variation that could be erroneously interpreted as the onset of field emission (that was predicted to occur only for $d < 10$ μm [9]). We have made an effort to perform measurements in well defined and contained parallel plate discharges, to test the applicability of Townsend's phenomenology at small gaps [17].

Before proceeding to any modelling, we needed to test the laws of scaling, which for low pressure collision dominated discharges are E/N, pd and jd^2 (and also ω/N and B/N for time varying fields and for magnetic fields). The critical scaling is due to the current density j. Rarely are the *V-I* characteristics represented through j (as it should be) and even then it is not stated that j is actually determined by dividing the current by the entire area of the electrodes. In reality, however, constriction dominates in the glow regime. Even in the Townsend's and in the abnormal glow regimes the radial profile is quite different and so is the effective area. Taking advantage of transparent yet conducting materials for electrodes and also of ICCD cameras, we were able to record *V-I* characteristics and scale them to the real current density even in cases of complex constricted modes. First, we established that in the normal size discharges, when the current density is properly determined, it remains constant throughout the glow regime (so it is represented by a single point in *V-I* characteristics [18].

Secondly, we have been able to show that for discharges bordering on micro discharges (0.5 and 1 mm gaps) the jd^2 scaling works and finally we have extrapolated those findings (by using pD scaling where D is the diameter of the constricted region) to smaller gaps where we could not easily record the current profiles [17]. It was found, as can be seen in figure 5, that a Townsend type of scaling holds at those gaps until perhaps some smaller geometries where field emission really comes into play [19]. We have even shown that the spatial profiles scale well so that the ionization coefficient could be determined rather accurately from the axial emission profile of micro discharges [20].

It was also shown that the Paschen curves obtained for micro discharges (and sometimes even for the standard size discharges) that do not show a change of voltage on the left hand side beyond the minimum are due to an incorrectly assumed shortest distance for the gap when long path breakdown was allowed [21]. Reducing the chances for the long path breakdown brings back the Paschen curve to agreement with that obtained for standard dimensions/pressures.

The fact that we proved scaling and also were able to obtain accurate readings of ionization coefficients proves that it is possible to apply Townsend's phenomenology and even to some degree theory to micro discharges. The jd^2 scaling allows Townsend regime to operate at considerably higher current densities.

5. Time resolved measurements

A preliminary publication of our results on time dependent recordings of the development of the breakdown and DC discharge regimes was given in [9,22], while the majority of the data remain unpublished. The results may be summarized as follows. During the initial stage, the discharge passes through the Townsend regime and, as the current increases, glow and abnormal glow regimes are visited. During the minimum of oscillations, the discharge almost immediately returns to the

Townsend regime and then changes occur again and again following oscillations in current. Studies such as this one performed for a parallel plate geometry are needed to provide the background for understanding developments in more complex geometries [23] and different scales.

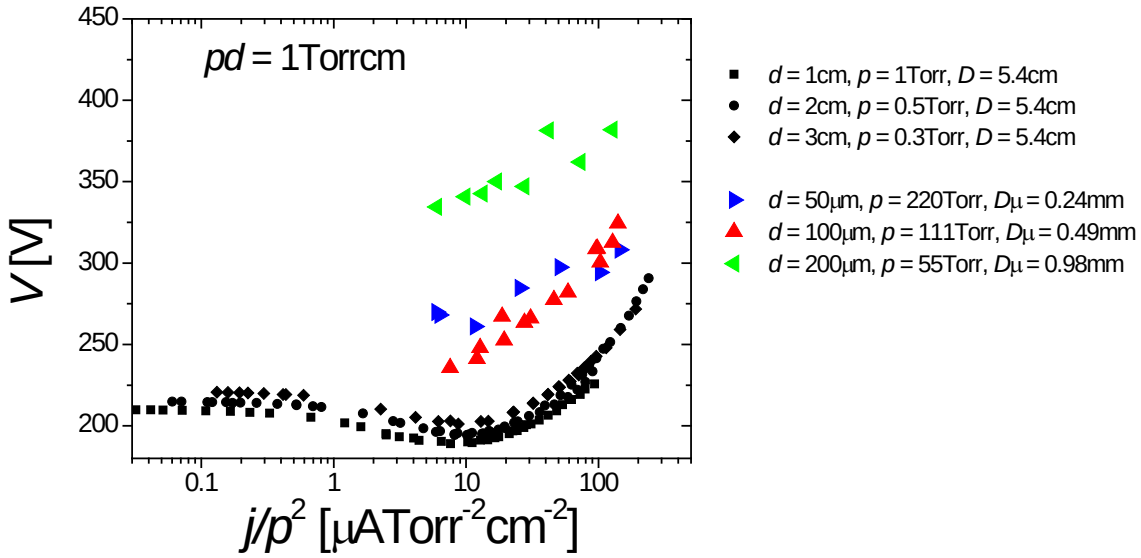

Figure 5. *V-I* characteristics for standard size and micro discharges obtained by using the jd^2 scaling and *pD* scaling for the size of the constricted regions. One should not pay attention to the actual vertical scale, normally it is taken care of by subtracting the breakdown voltages in each case, but in the case of micro discharges we could not make accurate measurements as it was not possible to achieve stable operation in the Townsend regime. The vertical scale variations are due to different conditions on the electrodes surface [17].

6. Discharges with inhomogeneous cathodes

The usual assumption in the low current limit is that the discharge is uniform over the entire surface and the radial profile is the solution to the diffusion equation. Only in the higher current (glow) regime a constriction develops and only when the field ceases to be constant along the axis. This has been questioned recently for micro discharges when it was found that the scaling laws are maintained only when an assumption of localized modes is made, the modes that have a dimension proportional to the diffusion length for the given pressure [17]. The problem is hindered further by the high pressure that reduces the diffusion length and by the fact that the ratio of gap to radius becomes very small in practical experiments [17].

We have, however, observed localized discharges in Townsend regime for standard size discharges (1 cm) and moderately low pressures [24]. In figure 6 we show one such example in nitrogen where the discharge is limited in the radial direction by the region of deposited material due to numerous pulses in the high current mode. It is clear that the deposited region has a lower secondary electron yield γ and thus the discharge cannot be self-sustained over that area for the given voltage. In order to overcome this region of reduced γ, the volt-ampere characteristics have to be quite different as compared to the one with pristine cathode. Even a positive differential resistance is observed [24].

The characteristics of such a discharge may be a prototype for the breakdown in pulsed DC discharges where numerous discharges change the properties of the cathode considerably. In addition, one may construct cathodes of different materials and design desired characteristics. For example, cathodes coated by a semiconductor [25, 26] have been often used for achieving some properties that are not easily accessible by conducting electrodes. The high resistance of the semiconductor which is in the innermost circuit assures a broader range of stable operation [14]. Combining conducting and semiconductor materials may help reduce the breakdown potential while achieving a *V-I* characteristic that is less prone to oscillations.

7. RF breakdown

When rate of change of the field is such that ions cannot complete their trajectories, then it is possible to operate in conditions when electrons may be the only particles sustaining the discharge. The feedback is provided by returning electrons in the second half of the period and thus a full circle is achieved. It has been assumed in old textbooks and papers [27] and in more recent papers [28, 29] that an optimum breakdown condition is achieved when the average electron can cross the gap in one half period. In fact, the breakdown condition has been used to obtain experimental values of the drift velocities for RF fields and convert them to DC values by assuming that in RF fields the drift velocity is a sinus function peaking with the DC drift velocity and having no delay [29]. We modelled the RF breakdown using a detailed Monte Carlo

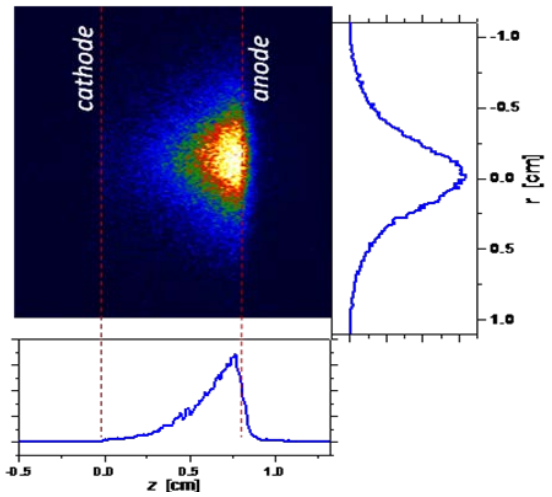

Figure 6. Townsend regime discharge in N_2 with Cu cathode and for d = 0.8 cm, D = 2 cm, p = 2 Torr and V_b = 310 V. The axial profile shows exponential growth peaking at the anode while the radial profile is very narrow covering only a small part of the diameter (D).

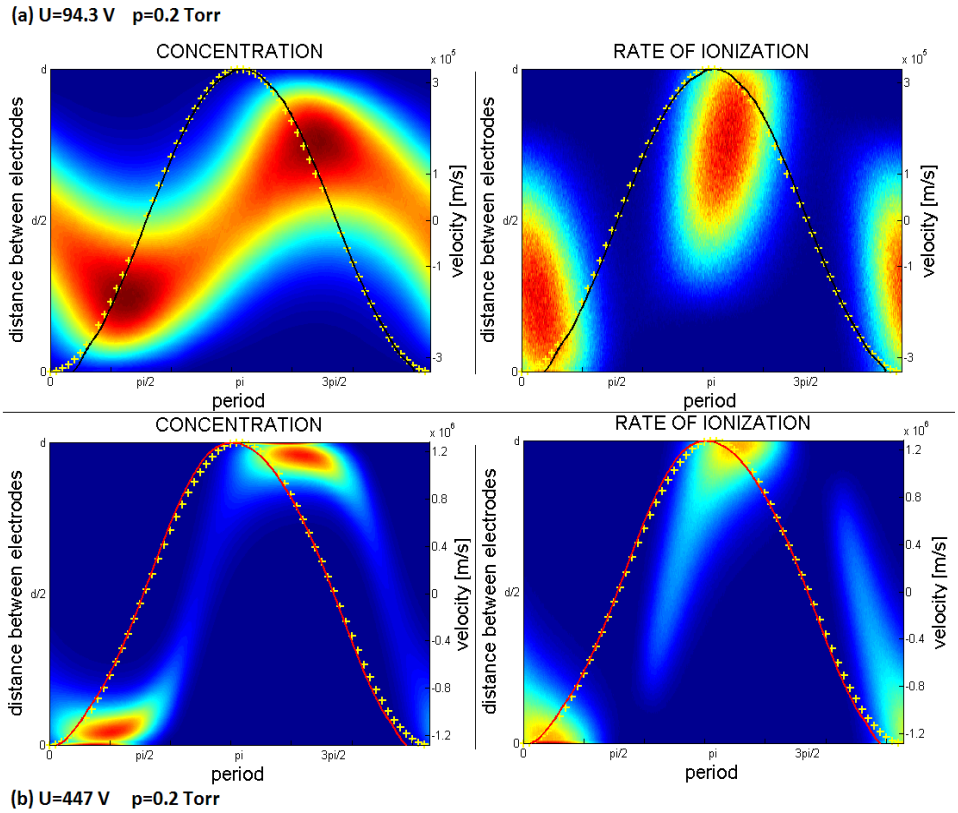

Figure 7. Development of density and ionization rate for the breakdown of RF swarms. Solid curves represent mean velocity (different colours are for better contrast), while the dotted sinusoidal lines represent inversed AC field. Both curves are for 0.2 Torr; the top curves are for the minimum breakdown voltage (93 V) while the bottom curves are for the maximum breakdown voltage (447 V) [30].

representation of all the collisions and field dependence on time. Figure 7 shows the temporal development of the concentration of electrons and of the ionization rate [30]. As the quasi-Paschen curve for the RF breakdown has double values for breakdown voltage at the same *pd* (for a range of *pd*) we show results at the lower and at the higher breakdown point. Outside these borders the discharge cannot be ignited. At the lower point, the breakdown condition is achieved by merely matching the production without much of the electrodes overlapping with the swarm. At the higher end, however, the swarm overlaps considerably with the electrodes thus representing significant losses to the electrodes. At the same time, the peaking ionization must compensate for all the losses.

We found that, while the standard explanation of the RF breakdown is very good, still some fine tuning needs to be done by a full kinetic representation (such as a Monte Carlo simulation) to be able to describe all the intricacies. In addition, one needs to extend our model by the contribution of ions and fast neutrals as well as photons. These will modify the Paschen like curve and hopefully make it more realistic but for a wide range of conditions one may find that electrons dominate in sustaining the plasma. We also have to include the secondary electrons formed by the electron impact on electrodes. This effect will lead to the so-called multipacting modes.

One should also note that numerous attempts to use analytical and semi analytical models based on simplified expressions for the basic properties have migrated from DC discharges to the RF breakdown. These results provide insight into pertinent processes [31-34] but require some form of fitting to provide quantitative agreements.

8. Conclusions

The oldest chapter in the book on plasma physics, the breakdown and low current discharges, has been changed tremendously in the past twenty years. The main agent facilitating the feedback needed to achieve DC breakdown, the ions colliding with surfaces, have been changed to include photons, fast neutrals, metastables as well as ions. By including all these processes, as well as back-diffusion [3,35] one was able to predict effective yields and Paschen curves based on the binary collision data [3].

The field of low pressure DC discharges proved to be a fertile ground for both fundamental studies and for obtaining and testing the applicability of the fundamental data that would eventually be used for modelling of more complex systems. Extensions to micro discharges and RF breakdown have been made, together with first attempts to model RF plasmas with secondary electron yields [36] as obtained in a more detailed and recent analysis.

With the new drive for benchmarking plasma modelling systems [37], we believe that the best strategy would be to start from the swarm benchmarks and then use the negative differential resistance of a DC Townsend discharge as a benchmark for space charge effects and also use some additional breakdown properties. This would provide clear and simple experimental observables that may be modelled exactly and independently and provide the next step for more complex plasma benchmarks.

Acknowledgement

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Conference scope

While many plasma technologies have matured in the past decade, so they might not attract much scientific interest any more, as many if not more so have sprung out. The plasma scientists' community has expanded enormously and is currently facing attractive challenges in solving global problems by touching yet undiscovered possible solutions for environmental, food and health issues. The scope of ICAPT conferences has always been discussing recent innovations and suggesting future challenges. Round tables are organized on a couple of hot topics of plasma technologies – medicine and agriculture. The first five ICAPT conferences were organized in Europe, the sixth one was organized in Siem Reap, Cambodia, while this year the organizers have decided to move to Vietnam – probably the region of highest demand for advanced plasma solutions in the next future. For example, the Hue University of Medicine and Pharmacy has launched ambitious research on plasma medicine recently. ICAPT conference provides a forum for extensive and in-depth discussions related to specific problems and create more opportunities for collaborations between leaders and experts in this scientific field.

Research topics

- Basic aspects of plasma technologies
- Characterization and modelling
- Plasma-surface interactions
- Plasma technologies in traditional industries
- Plasma technologies in biology and medicine
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- Powerful discharges for rapid surface modifications
- Environmental aspects of plasma technologies

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Measurements and simulations of RF breakdown in gases

Zoran Lj. Petrović (1, 2), Antonije Đorđević (1, 3), Marija Puač (2, 3), Jana Petrović (2), Jelena Sivoš (2), Gordana Malović (2), Dragana Marić (2)

(1) Serbian Academy of Sciences and Arts, Knez Mihajlova 35, 11000 Belgrade, Serbia
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Unlike DC breakdown, RF breakdown may be achieved purely by the effect of electron multiplication leading to the plasma in the so-called alpha regime. In that sense, RF breakdown is easier to achieve i.e. it can be achieved at lower voltage. On the other hand, measurements of the event of breakdown itself are much more difficult in RF due to the very large displacement current. Most plasma experiments and models do not focus on the breakdown phase and skip to the well-established plasma, seeking to model its properties. The difficulty of achieving breakdown at atmospheric pressure opens numerous questions on the mechanisms that may be used to reduce the breakdown potential, as well as to reduce the possibilities of the development of higher current thermal modes of discharge. In this review, we shall present a survey of a broad range of results obtained first by Monte Carlo simulations and then promote a novel experimental technique to minimize the effects of the displacement current and to allow detection of the discharge currents in the ten micro-ampere range.

As for results of simulations, we shall discuss the basic breakdown mechanism for different pd values, for different gas number density normalized frequencies and also, we shall explain double valued breakdown curves at low pd. Scaling will be tested by observing spatial profiles of electron density, ionization and excitation rates, and mean energy. In addition, electron energy distribution functions resolved in time and in space will be studied to give support to spatial profiles. Effects of electron reflection and multipacting will be reviewed, as well as the secondary electron production by ions. We shall compare the RF breakdown in rare gases and in gases with large attachment to try to provide some background for the strategies in generating atmospheric-pressure non-equilibrium plasmas.

Finally, we shall show our system that uses a capacitive bridge to discern the discharge current from the much larger displacement current. First results of measurements in argon will be shown and compared to simulations and other experiments.

ESCAMPIG 2018 July 17-21, 2018

24th Europhysics Conference on Atomic and Molecular Physics of Ionized Gases

General Information

ESCAMPIG is a biennial international conference of the European Physical Society, focusing on basic and applied plasma physics research. This year the conference will be hosted by the University of Glasgow, on behalf of a consortium of UK plasma research institutes. The conference will consist of a mixture of invited talks covering general and topical themes, interactive workshops and posters. A small number of contributed papers may be selected as hot topic oral presentations

Conference topics:

1. Atomic and molecular processes in plasmas	2. Transport phenomena; kinetic distributions
3. Physical basis of plasma chemistry	4. Plasma surface interactions
5. Plasma diagnostics	6. Plasma discharges: theory and simulation
7. Self-organisation in plasmas, dusty plasmas	8. Upper atmospheric plasmas and space plasmas
9. Low pressure plasma sources	10. High pressure plasma sources
11. Plasmas and gas flows	12. Laser-produced plasmas

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General Invited Lecture	Topical Invited Lecture
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Crookes Prize winner	James Walsh (United Kingdom)

Abstract submission deadline:	March 15 2018
Abstract acceptance notification	April 14, 2018
Early bird registration:	May 31, 2018
Late registration deadline:	June 30, 2018


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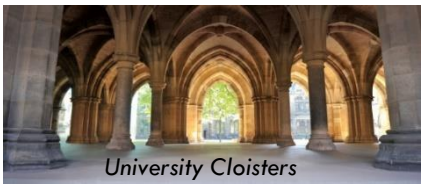
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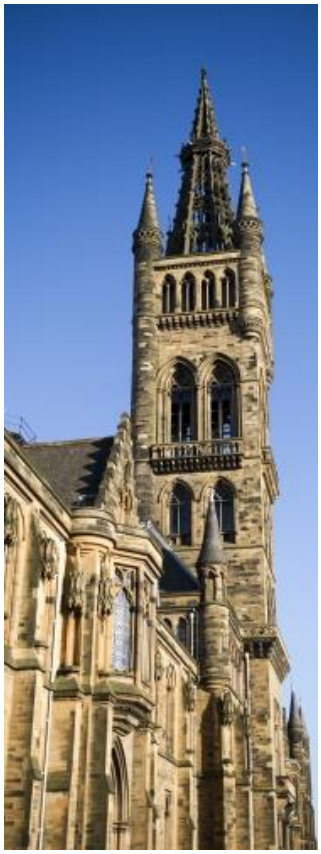

Venue:

The conference will be hosted on the wonderful campus of the University of Glasgow, in the city's dynamic west end. There is a wide choice of accommodation of all types available via the conference web pages, and offered by the accommodation booking service of the City of Glasgow Conference Bureau. The welcome reception will be held in the magnificent City Chambers, and the conference dinner in the spectacular Glasgow Science Centre on the River Clyde, with planetarium shows for all delegates.


Glasgow City Chambers


Glasgow Science Centre

The city of Glasgow is a beautiful, vibrant cultural venue, with a wide variety of museums, concert halls, theatres and restaurants, and a lively night time culture. There will be a choice of two excursions: one to Loch Lomond, and one to Stirling Castle.

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Full student fee, no excursion	£290
Full student fee plus excursion	£315
Full fee (ie non student), no excursion	£350
Full fee plus excursion	£375
Late full fee, no excursion*	£425
Accompanying other	£100

Schematic of conference format

	Tues 17/7	Wed 18/7	Thu 19/7	Fri 20/7	Sat 21/7
AM		Oral session	Oral session	Oral session	Oral session
		Coffee	coffee	Coffee	coffee
		Oral session	Poster	Oral session	Oral session
		Lunch	Lunch	Lunch	Lunch & Close
PM	Registration	poster	Excursion	poster	
		Coffee		Coffee	
		Workshop		workshop	
evening	Reception			Conf Dinner	

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Poster format is A0 Portrait Mode. Please ensure your poster is in place by 2pm on the relevant day. Posters 1-111 (inclusive) are in Poster Session 1 (Wed 18th), the remainder are in Poster Session 2 (Friday 20th). Velcro fasteners will be provided – please don't use tacks or tape!

Please note that there is not sufficient space to record all the poster authors here, but the conference abstract booklet has a comprehensive author list

Poster	Submitting Author	Poster Session 1: Title of poster	Topic
1.	Jung, Young-Dae	Renormalization shielding effect on the electron-impact ionization in dense plasmas	1. Atomic and molecular processes in plasmas
2.	Rice, John	X-ray Observations of K_β Emission from Medium Z He-like Ions in C-Mod Tokamak Plasmas	1. Atomic and molecular processes in plasmas
3.	Blin Simiand, Nicole	Butanoic acid and butanoic acid/ethanol mixture removal by electro-ceramic barrier discharge	1. Atomic and molecular processes in plasmas
4.	Blin Simiand, Nicole	Acetone decomposition in homogeneous and filamentary plasmas of atmospheric gases	1. Atomic and molecular processes in plasmas
5.	Suzuki, Susumu	Determination of Arrhenius equations for collisional quenching rate coefficients of Ar(3P2) by Ar(1S0) and H2O	1. Atomic and molecular processes in plasmas
6.	Aleksandrov, Nickolay	Recombination of electrons with water cluster ions in afterglow of high-voltage nanosecond discharge	1. Atomic and molecular processes in plasmas
7.	Aleksandrov, Nickolay	Collisional quenching of $N_2(C^3\,\Pi_u)$ and $N_2+(B^2\,\Sigma^+_u)$ by hydrocarbon molecules in nanosecond discharge afterglow	1. Atomic and molecular processes in plasmas
8.	Fursa, Dmitry	Vibrationally resolved electron-impact excitation of molecular hydrogen	1. Atomic and molecular processes in plasmas
9.	Van de Steen, Cyril	Mobility of Kr_2^+ ions in Kr for cold plasma modelling	1. Atomic and molecular processes in plasmas
10.	Khassenov, Mendykhan	Emission and level population in noble gases and their binary mixtures ionized by ion beam	1. Atomic and molecular processes in plasmas
11.	Khassenov, Mendykhan	Luminescence spectra of noble gases and their binary mixtures excited by products of $^6Li(n,\alpha)^3H$ nuclear reaction	1. Atomic and molecular processes in plasmas
12.	Wünderlich, Dirk	Yacora on the Web: providing collisional radiative models for plasma spectroscopists	1. Atomic and molecular processes in plasmas
13.	Plasil, Radek	Elementary processes in low temperature plasma down to 30 K – experimental setup	1. Atomic and molecular processes in plasmas
14.	Gibson, Andrew	Calculated electron impact excitation and dissociation cross sections for H2O2 and implications for plasma modelling	1. Atomic and molecular processes in plasmas
15.	Koepke, Mark	Experimental development of iso-electronic line ratio temperature diagnostic for soft x-ray absorption spectra	1. Atomic and molecular processes in plasmas

Poster format is A0 Portrait Mode. Please ensure your poster is in place by 2pm on the relevant day. Posters 1-111 (inclusive) are in Poster Session 1 (Wed 18th), the remainder are in Poster Session 2 (Friday 20th). Velcro fasteners will be provided – please don't use tacks or tape!

161.	Yin, Helen	Pseudospark plasma-sourced sheet electron beam for application in high power millimetre wave radiation generation	9. Low pressure plasma sources
162.	Ronald, Kevin	Development of an apparatus to study nonlinear microwave coupling in magnetised plasma	9. Low pressure plasma sources
163.	Doyle, Scott	Electron and ion dynamics in capacitively coupled radio-frequency plasmas with structured electrodes driven by tailored voltage waveforms	9. Low pressure plasma sources
164.	Rauner, David	RF power transfer and heating mechanism of low pressure H2/D2 ICPs	9. Low pressure plasma sources
165.	Vicente Gabás, Ignacio Gabriel	Optimization of the discharge compartment geometry of a toroidal electron beam source	9. Low pressure plasma sources
166.	Bowden, Mark	Plasma Breakdown between Wire Grid Electrodes	9. Low pressure plasma sources
167.	Bowden, Mark	Characterisation of Transparent Cathode Discharges	9. Low pressure plasma sources
168.	Irwin, Rachael	Characterisation of Atmospheric Pressure Plasmas	9. Low pressure plasma sources
169.	Ahr, Philipp	Novel efficient stochastic heating mechanism in periodically structured vortex fields for large-area discharges	9. Low pressure plasma sources
170.	Marić, Dragana	Detection of RF breakdown by balanced capacitive bridge	9. Low pressure plasma sources
171.	Malović, Gordana	Low-pressure DC discharges in vapours of alcohols	9. Low pressure plasma sources
172.	van Veldhoven, Jacqueline	Optimizing a low-energy plasma system towards low contamination for use in nanolithography material studies	9. Low pressure plasma sources
173.	Lamba, R. P.	Technological Advancement in High Power Plasma Switches Development at CSIR-CEERI, Pilani, India	9. Low pressure plasma sources
174.	Ashizuka, Naokazu	Dependence of plasma temperature and breakdown voltage on ambient medium temperature in high pressure CO2 including supercritical phase	10. High pressure plasma sources
175.	Kossyi, Igor	Excited by microwave beam discharge with advanced stages of ionization-overheating instability as a basis of plasmachemicalurban atmosphere cleaning reactor	10. High pressure plasma sources
176.	Invernizzi, Laurent	Characterization of He plasma jet in interaction with a liquid target by laser absorption spectrometry and optical emission spectroscopy	10. High pressure plasma sources
177.	Hamdan, Ahmad	Characterization of a microwave plasma jet in water	10. High pressure plasma sources
178.	Borzosekov, Valentin	Subthreshold discharge excited by a microwave beam as a basis of a plasma-chemical reactor for urban atmosphere cleaning from mercaptans	10. High pressure plasma sources
179.	Yagi, Hidetsugu	Analysis of carbon films by microwave-plasma assisted chemical vapour deposition in open-air system	10. High pressure plasma sources

Low-pressure DC discharges in vapours of alcohols

J. Sivoš(*)[1], D. Marić[1], N. Škoro[1], G. Malović[1] and Z. Lj. Petrović[1,2]

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Here we present measurements of breakdown properties at low pressure, for different electrode gaps, in several organic vapours i.e. primary and secondary alcohols. Paschen curves are recorded for *pd* range from 0.06 Torr cm to 2 Torr cm. Based on emission spectra we identify species existing in these discharges. Most likely H atoms and some heavier dissociation fragments (OH and/or CxHy species) take dominant part in heavy particle processes of ionization and excitation. Measurements of Volt-Ampere (*V-A*) characteristics of discharges for the conditions close to the minimum of Paschen curve at *pd* of 0.4 Torr cm and *d* = 1.1 cm are also presented.

In past years the field of nonequilibrium discharges in organic liquids and their vapours became an important area for developing of applications. Discharges involving alcohols, whether in liquid or in vapour, are suitable for hydrogen production [1], the growth of graphene layers and nanotubes [2] and for development of different types of high energy particle detectors and sensors [3]. Simple design of devices based on these discharges is certainly an advantage, but for further development of novel applications, it is necessary to understand and know elementary processes and their balance in discharge. Studies of breakdown and electrical characteristics of discharges can provide knowledge on fundamental processes that are an integral part of discharges in alcohol vapours.

Our experimental measurements were conducted in a simple plane-parallel geometry, with the copper cathode and quartz anode coated with conductive, transparent platinum film. The separation (*d*) between electrodes was adjustable. The vapours were evaporated from 95% ethanol and 99% samples of methanol, isopropanol and n - butanol. More experimental details can be found elsewhere [4].

We recorded Paschen curves (breakdown voltages V_b versus product of pressure *p* and electrode distance *d*) in low-pressure dc discharges in alcohol vapours at different interelectrode separations (fig. 1). Curves are recorded for *pd* range from 0.06 Torr cm to 2 Torr cm. For each point in the Paschen curves, spatial profiles of the discharges operating at low-current limit were recorded.

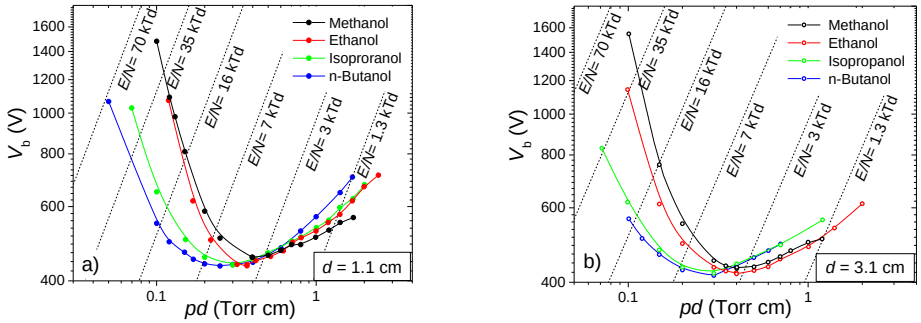

Fig. 1. Paschen curves of discharge in alcohol vapours at two electrode gaps: a) 1.1 cm and b) 3.1 cm

In addition, we have made measurements of emission spectra for methanol, ethanol (fig. 2a)), isopropanol and n-butanol vapours (fig.2b)), that enabled identification of species existing in these discharges. In all cases, emission coming from OH, CH and Hα (Balmer series lines for H atom) are visible in the spectral range from 300 nm to 900 nm. In ethanol, isopropanol and n-butanol, emission that originates from CO can be noticed. According to measured spectra, we can assume that heavy particles that participate in processes of collisional excitation and ionization are H atoms and perhaps some heavier dissociation fragments (OH and/or CxHy species) [5].

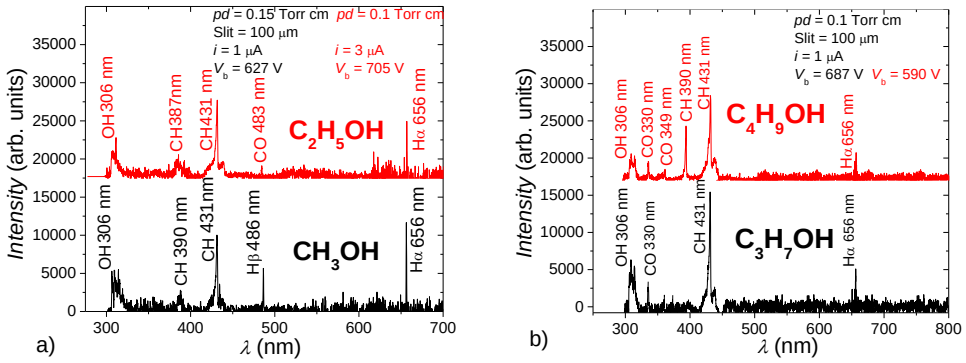

Fig. 2. Emission spectra of alcohol vapours discharges: a) methanol (black) and ethanol (red) and b) isopropanol (black) and n-butanol (red)

Along with breakdown measurements, it is important to comprehend electrical characteristics of discharges, since majority of applications work in glow discharge regime. Here we show Volt-Ampere (*V-A*) characteristics for methanol and ethanol recorded at working conditions close to the Paschen minimum (fig. 3). Operating regimes typical for low-pressure dc discharges can be clearly distinguished. After the breakdown, discharge runs in Townsend mode. Positive space charge effectively increases the field in front of the cathode, which leads to higher ionization coefficient and secondary electron yield, allowing the discharge to run at lower voltage. With the current increase, in region of transition towards the normal glow, regime of free running oscillations occurs – interval of discontinuity in *V-A* characteristics which starts at currents of 6 μA for methanol and around 10 μA for ethanol. At even higher currents, the discharge runs in normal glow regime. In ethanol vapour this regime extends to almost 8 mA while in methanol discharge normal glow ends at around 600 μA. After normal glow, further increase of the discharge current is followed by voltage increase i.e. the discharge operates in abnormal glow regime. Electrical measurements are supported with recordings of axial discharge structure by an ICCD camera.

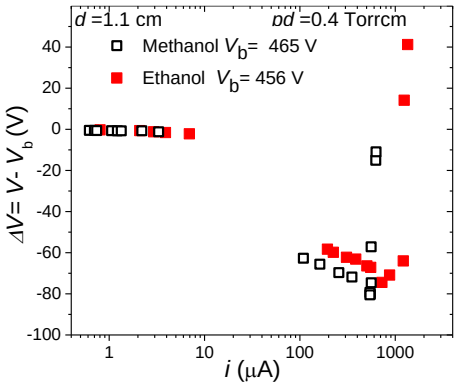

Fig. 3. Volt-Ampere characteristics for discharges in methanol (black squares) and ethanol (red squares) at *pd* = 0.4 Torr cm and *d* = 1.1 cm.

The data obtained for several organic vapours is complete set of reliable breakdown data necessary for modelling. Based on recorded spectra we were able to identify the most significant excited species in these alcohol vapours discharges. Also, the *V-A* characteristics have shape anticipated for this type of non-equilibrium discharges. In abnormal regime we have observed anomalies in discharge behaviour in methanol (around the Paschen minimum) and ethanol (in left branch of Paschen). Further studies will include recording of *V-A* characteristics for isopropanol and n-butanol.

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Monday, October 5, 2020 8:00 AM - 8:30 AM

Session BM1 : Welcome Remarks - Kallol Bera, Applied Materials Inc - Tag(s): Live

8:00AM BM1.00001: Welcome Remarks — Welcome Remarks 8:00am - 8:30am

Monday, October 5, 2020 8:30 AM - 12:00 PM

Session BM2 : Tutorial I: Plasma Physics Fundamentals I - Greg Severn, University of San Diego - Tag(s): Live

8:30AM BM2.00001: Plasma Two Ways: Foundations of Kinetic and Fluid Models of Plasma, a Tutorial [Invited] GREGORY SEVERN, Dept. of Physics \& Biophysics, Univ. of San Diego, STEVE SHANNON, Dept. Nuclear Engineering, North Carolina State Universty-Raleigh, SCOTT BAALRUD, Dept. of Physics \& Astronomy, Univ. Iowa, VENKATTRAMAN AYYASWAMY, Mechanical Engineering, Univ. California-Merced, BEN YEE, Sandia National Laboraties — This tutorial will present a pedagogical introduction to plasma kinetic and fluid equations, emphasizing theoretical foundations for the two common plasma models, as well as their numerical solution; particularly particle-in-cell and two-fluid. The intended audience is graduate students, as well as colleagues who work on more applied topics or who are changing areas of research and who seek an introduction to the foundations of plasma model equations, the physical processes included and excluded from different approximations, and numerical methods used to solve these equations. In order to focus on a definitive example, each of the theoretical models and numerical solution techniques will be applied to an experimentally-motivated problem of streaming instabilities in the plasma-boundary transition region. The theory will be broadly applicable, but the example chosen to illustrate distinguishing features of kinetic and fluid models.

8:45AM BM2.00002: Using the plasma fluid equations to understand two stream instability and vice versa [Invited] STEVEN SHANNON, North Carolina State University — The plasma fluid equations, derived by taking velocity moments of the Boltzmann equation, are one of the most heavily employed sets of equations used in studying basic plasma phenomena. When combined with Maxwell's equations, a large fraction of the plasma universe can be studied analytically and computationally. The two stream problem presents a simple framework from which the utility of the fluid equations in capturing plasma behavior can be demonstrated and compared against plasma models that employ Boltzmann or Vlasov equations directly instead of using their velocity moments to obtain a fluid representation. In this tutorial, the two stream instability will be used to introduce the fluid equations, the derivation of the plasma dispersion relation, and the determination of stability for a plasma system.

10:15AM BM2.00003: Break (10:15am - 10:30am) —

10:30AM BM2.00004: Foundations of Plasma Kinetic and Dielectric Response Theory [Invited] SCOTT BAALRUD, Univ of Iowa — This talk will review the foundations of plasma kinetic and linear dielectric response theory, as well as its application to predicting the stability properties of low temperature plasmas. Plasma kinetic theory for the reduced phase-space distribution will be derived by coarse graining the exact N-body Klimontovich description. In the limit that interactions between charged particles are weak, this is approximated by the Vlasov equation. The Vlasov equation can be used to compute the linear dielectric response function for a plasma, which describes the dispersion and growth or damping of fluctuations, including Landau damping. A general stability condition called the Penrose criterion can be obtained by applying Nyquist's method to the plasma dielectric response function. The Landau damping, and growth, of waves predicted by the kinetic theory has no analog in fluid theory. To demonstrate this, stability conditions in the presence of counter-streaming populations, as are common near boundaries of low-temperature plasmas, will be investigated. Connections with the fluid limit and nonlinear solutions from PIC simulations will also be discussed.

Monday, October 5, 2020 8:30 AM - 11:30 AM

Session BM3 : Workshop I: Artificial Intelligence & Machine Learning in Plasma Science and Beyond - Satoshi Hamaguchi, Osaka University, Japan - Tag(s): Live

8:30AM BM3.00001: Artificial Intelligence {\&} Machine Learning in Plasma Science and Beyond; Introduction* [Invited] SATOSHI HAMAGUCHI, Osaka Univ — Artificial intelligence (AI) and machine learning (ML) can play important roles in plasma science and its application to a wide range of technologies in various ways. For example, they can be used to extract useful information from a large amount of data produced in experiments and numerical simulations. As the technologies for plasma diagnostics, supercomputing, and data management continue to advance and their costs continue to decrease, data produced in this field is expected to grow exponentially and must be analyzed nearly automatically. For physical phenomena that are too complex to be understood by deduction from the first principles, AI and ML may help one to find correlation or even causation among seemingly unrelated physical quantities or physical events, inferring possible underlying physical mechanisms or even phenomenological predictive models. In this Workshop, speakers specializing in different branches of plasma science and technologies will present their latest research work on the utilization of data in their own specialties. The Workshop is intended to provide an exemplary insight into this exciting development of "new means" of analyses in plasma science and technologies.

*JSPS Grant-in-Aid for Challenging Exploratory Research (18K18753)

LT2.00001: Spatial and time evolution of N_2(C), N_2(B) and N in atmospheric nitrogen plasma created by nanosecond repetitively pulsed discharges ARNAUD GALLANT, CentraleSupélec — Atomic nitrogen sources are essential for nitridation processes and for other applications such as nanomaterial synthesis or biomedical engineering. Nitrogen plasmas produced by nanosecond repetitively pulsed (NRP) discharges at pressures above atmospheric are considered as a potential source of atomic nitrogen owing to their high energy efficiency and atomic yield. In the present work, we are operating in pure molecular nitrogen at atmospheric pressure. We have measured during the first nanoseconds of the discharge down to 100 us in the postdischarge, the density of N2(C), N2(B) using absolutely calibrated 2D optical emission spectroscopy. The density of ground state N is deduced from the density of N2(B) whose certain vibrationnal states (here v=11) are in partial kinetic equilibrium with the ground state of N.

LT2.00002: Spatial distribution of emission in low pressure DC discharges in water and alcohol vapours* JELENA MARJANOVIC, DRAGANA MARIC, GORDANA MALOVIC, Institute of Physics, University of Belgrade, Serbia, ZORAN LJ. PETROVIC, Serbian Academy of Sciences and Arts, Belgrade, Serbia; School of Engineering, University of Ulster, UK — Here we show the spatial distributions of emission in the DC breakdown in water vapour and alcohol vapours, for electrode gaps 1.1 and 3.1 cm. We recorded the 2D side-on distributions of emission using an ICCD camera. For the same \textit{pd}, at different electrode gaps d, the anatomy of the discharge changes. The radial discharge width is smaller at larger electrode gaps, as shown for the case of a gap of 3.1 cm, as compared to the gap of 1.1 cm. This difference is most noticeable at low pressures (large E/N).At given electrode diameter to gap ratio the increased diffusional losses at lower pressures will violate \textit{pd} scaling, however, it is interesting that processes induced by heavy particles are more sensitive to changes in geometry of the discharge than electron induced processes. Under the investigated conditions, most of the emission comes from the cathode region due to the heavy-particle excitation. As the electrode gap increases the radial distribution of emission near the cathode becomes significantly narrower than that near the anode. We propose that the smaller radial discharge widths at larger gaps may be due to the change of electric field distribution in the vicinity of the cathode edges, in addition to the diffusion losses of charged particles near the discharge chamber walls. Consequently, processes of excitation and ionization in this region would be less prominent.

*Supported by the Serbian MESTD, Projects No. 171037 and 410011

LT2.00003: Rarefaction Flow in Bounded Plasma with Adiabatic Electrons* ALEXANDER KHRABROV, Belle Mead, NJ 08502 USA, IGOR KAGANOVICH, JIAN CHEN, Princeton Plasma Physics Laboratory, HENG GUO, Department of Engineering Physics, Tsinghua University, Beijing, China 100084 — We study, by numerical and analytical means, the evolution of a collisionless plasma initiated between absorbing walls. The ensuing flow is described by rarefaction waves that travel inward from the boundaries, interact, and eventually vanish after crossing through, leading up to the asymptotic stage of the decay. Particle simulations indicate that the kinetic evolution strongly resembles one found in isentropic gas dynamics. Namely, a very gradual density profile forms in the expanding central region where the rarefaction waves interact, with an accompanying linear velocity profile. Asymptotically, the density falls off as $1/t$. The density and the flux at the boundary show little variation over the period when rarefaction waves still exist. Plasma potential, on the other hand, drops quite rapidly (on the underlying ion-acoustic time scale) to less than T_e when over 70\% of the particles still remain in the system. This is due to electron kinetics being governed by conservation of adiabatic invariant in a slowly varying potential well. Analytical model of the velocity distribution is presented to explain the simulations. The results have implications for afterglow plasmas used in material processing and also for ion-extraction devices.

*The work of J. Chen was supported in part by the China Scholarship Council.

LT2.00004: DOLI-II upgrades at UW-Madison* PEIXUAN LI, NOAH HERSHKOWITZ, Dept. of Engineering-Physics, University of Wisconsin-Madison, GREG SEVERN, Dept. of Physics \& Biophysics, University of San Diego — The upgrade of the triple plasma device at the University of Wisconsin-Madison is close to being finished. The device consists of two outer plasma source chambers and a central chamber with biased grids placed in between. Plasma is produced in each outer chamber by thermionic electrons which are emitted from negatively biased filaments. Permanent magnet line cusps were placed around each chamber to trap the ionizing electrons. The device can be used to study double layer structures and nonlinear wave propagation. Diagnostic tools such as Langmuir probes and emissive probes are used to take measurements of plasma parameters. New upgrades include laser-induced fluorescence and Mach probe diagnostics to directly measure ion speed. The initial design and construction of this device was discussed by Justin Kim et al. at the 56th APS-DPP conference. The latest device status will be presented at this meeting.

*Work supported by NSF grant nos. PHY-1804654, 1804240

LT2.00005: Does the discrepancy between Langmuir Probe and emissive probe measurements of plasma potential depend on ion flow and sheath formation?* MICHAEL SHAHIN, Dept. of Physics \& Biophysics, University of San Diego, PEIXUAN LI, NOAH HERSHKOWITZ, Dept. of Engineering-Physics, University of Wisconsin-Madison, GREG SEVERN, Dept. of Physics \& Biophysics, University of San Diego — It has recently been shown that emissive probes (EPs) measure plasma potential profiles correctly in plasma presheaths, and that Langmuir probes (LPs) do not, in low temperature, low pressure plasma. It has been argued that these differences are thought to be caused by inherent, diffuse, ion flow in the presheath region toward the negatively biased electrode, characteristic of sheath formation. One of the roles of experiment is that of suggesting models and to spur theory formation. In pursuit of this goal, we test the hypothesis that ion flow to the boundary plays an essential role by examining the difference between plasma potential measurements made by Langmuir probes and emissive probes in single ion species plasmas of differing mass number. The Bohm speeds for Xe, Kr, Ar, Ne, and He plasmas are known to vary. Experiments are performed in unmagnetized discharges in the parameter regimes, $0.1 \leq P_n \leq 1 mTorr$, with $1 \leq T_e \leq 5eV$, and $1 \times 10^9 \leq n_e \leq 1 \times 10^{10} cm^{-3}$. Results are discussed.

*Work supported by NSF grant nos. PHY-1804654, 1804240

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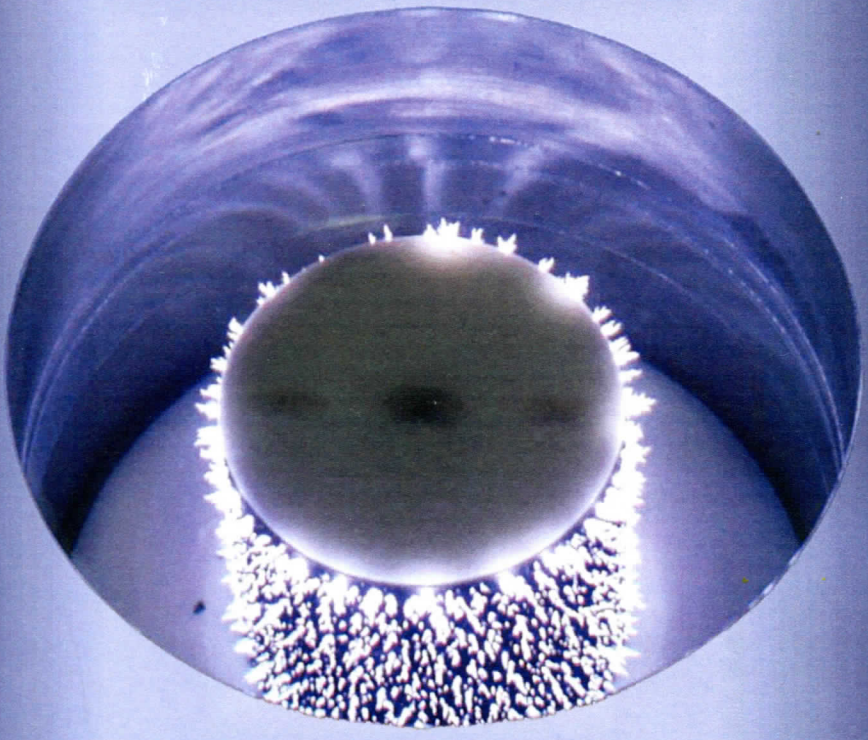

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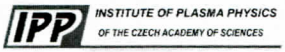

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Transit time of ions in low-current low pressure water vapour discharge

Dragana Marić[1], Jelena Sivoš[1], Nikola Škoro[1], Gordana Malović[1] and Zoran Lj Petrović[1,2]

[1]Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia
[2]Serbian Academy of Sciences and Arts, Knez Mihailova 35, 11000 Belgrade, Serbia

Following the most pressing needs in data on elementary processes in plasma-liquid interaction [1], we have studied DC breakdown and non-equilibrium discharges in pure water vapour, in very simple geometry. Results presented in our recent paper [2] show that heavy particles, i.e. positive ions and fast neutrals have significant contribution to the processes of excitation at moderate and high reduced electric fields (*E/N*). Hydrogen ions and fast atoms are the most probable candidates in the case of water vapour, as the lightest products in water vapour discharge.

In order to identify dominant ions in the discharge, we calculated ion transit time according to the analytical model of oscillations in Townsend regime, developed by Phelps and co-workers [3]. Ion transit time (T) is related to frequency of oscillations and parameters of electrical circuit:

$$\omega^2 = \frac{I_{ss}}{R_s C T}\left[(R_s + R_m)\frac{\partial g}{\partial V} - \frac{k_I}{\gamma_{ss}}\right]\left[1 + \frac{I_{ss}(k_I - R_m k_V)}{\gamma_{ss}(1+\gamma_{ss})}\right]^{-1} - k^2$$

where ω is angular frequency and k is damping coefficient of oscillations, C is effective capacitance of electrical circuit, R_s and Rm are resistances in the electrical circuit, $\partial g/\partial V$ is differential of the coefficient of electron multiplication g by discharge voltage V, γ_{ss} – effective yield of electrons per ion arriving at the cathode, at the stationary discharge voltage. The k_V term approximates contribution of "kinetic" ejection of electrons from the cathode surface and the k_I term represents the first-order effects of space charge on the electric field.

Calculations were done for the discharge initiated at electrode gaps from 1 to 3 cm and pressure (p) x gap (d) of 0.6 Torrcm which corresponds to the conditions of the minimum of Paschen curve, and 0.3 Torrcm, in the left hand branch of Paschen curve.

Transit times of ions in water vapour were compared with transit times of hydrogen ions (H^+, H_2^+, H_3^+) in hydrogen discharge [4]. Initial analysis indicates that H_2^+ is dominant ion in the range of moderate *E/N*s. Accelerated H_2^+ lead to production of fast H atoms in subsequent reactions. Our further investigation will be to extend the analysis to wider range of operating conditions.

Acknowledgements

This work is supported by the MESTD projects ON 171037 and III 41011 and COST TD1208.

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29th Summer School and International Symposium on the Physics of Ionized Gases

Aug. 28 - Sep. 1, 2018, Belgrade, Serbia

CONTRIBUTED PAPERS

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SPIG 2018

VOLT-AMPERE CHARACTERISTICS AND ABNORMAL GLOW DISCHARGES IN METHANOL AND ETHANOL VAPOURS

J. Sivoš[1], D. Marić[1], N. Škoro[1], G. Malović[1] and Z. Lj. Petrović[1, 2]

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[2] *Serbian Academy of Sciences and Arts, Knez Mihailova 35, 11001, Belgrade, Serbia*

Abstract. Here we present measurements of Volt-Ampere characteristics for low-pressure discharges in methanol and ethanol vapours for electrode gap of 1.1 cm, at *pd*-s (pressure x gap) close to the Paschen minimum. We focus on changes in operating mode of discharges that are observed in abnormal glow regime. The transition occurs after certain time and it is smooth, without any instability in *V-A* waveforms.

1. INTRODUCTION

The field of non-equilibrium plasmas in liquid alcohols and their vapours have become very attractive subject of research in past years. These discharges have drawn attention due to the wide area of application from environmental remediation, biomedicine to nanotechnology. The first nanographene layers were synthesized in discharges of liquid alcohol solutions [1], the fuel industry recognizes them as suitable sources of hydrogen [2] and they are integral part of high energy particle detectors and sensors [3]. Since majority of applications work in glow discharge regime, it is important to comprehend electrical characteristics of discharges. Here we present Volt-Ampere (*V-A*) characteristics for methanol and ethanol vapour discharges measured at working conditions close to the minimum of the Paschen curve, with detailed analysis of unusual behaviour observed in abnormal glow regime of the discharge.

2. EXPERIMENTAL SET-UP

The electrode-system is placed inside tightly fitting cylindrical quartz chamber, due to prevent long-path breakdown. Plan-parallel electrode-system consists of copper cathode and quartz anode coated with transparent conductive thin film of platinum. The electrodes are 5.4 cm in diameter ($2r$) and 1.1 cm

apart. Vapours are obtained from 99 % methanol and 95 % ethanol. Volt-Ampere characteristics are measured by applying a pulse of voltage in addition to running discharge at small DC current (~ 1 μA). During the pulse, axial emission profiles are recorded by fast sensitive ICCD camera (Andor IStar DH720-18U-03). More information on the measurement technique can be found elsewhere [4].

3. RESULTS AND DISCUSSION

Volt-Ampere characteristics were recorded in a range of discharge currents from ~1 μA to several mA. In Fig. 1 we show plots of voltage and current dependence in methanol (squares) at $pd = 0.4$ Torr cm and ethanol (circles) at $pd = 0.2$ Torr cm. Operating regimes typical for low-pressure DC discharges can be clearly distinguished [5]. Evidently in both cases, abnormal regime is characterized with a very steep positive slope for currents above 800 μA.

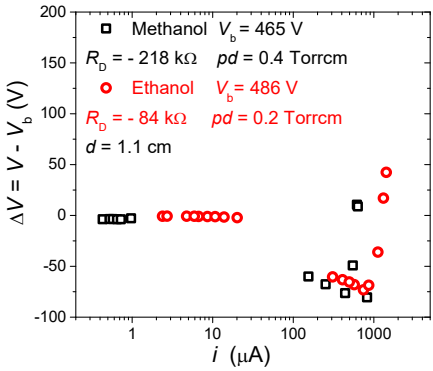

Figure 1. Volt-Ampere characteristics for discharges in methanol and ethanol vapours at $d = 1.1$ cm.

Measurements in abnormal regime of these discharges reveal changes in steady-state current and voltage values within single voltage pulse. In Fig. 2 we show examples of voltage and current waveforms for methanol and ethanol, with pronounced step-like shape, due to the mode change.

In methanol vapour discharge (Fig. 2a) initial current is 830 μA and transition in operation mode occurs after approximately 2 ms. At the beginning of the pulse, the discharge operates at lower voltage and higher current, and then it switches to ~80 V higher voltage and ~190 μA lower current. For ethanol vapour discharge (Fig. 2b) transition in operation mode occurs 30 μs after stable operation. Like in the case of methanol vapour, ethanol vapour discharge at beginning operates at higher current and lower voltage, and then switches at ~70 V higher voltage and ~320 μA smaller current. For both alcohols, transition in discharge operation is smooth, without any instabilities or oscillations in *V-A* waveforms. Furthermore, there are no significant changes in spatial structures of the discharges that could explain the mode change.

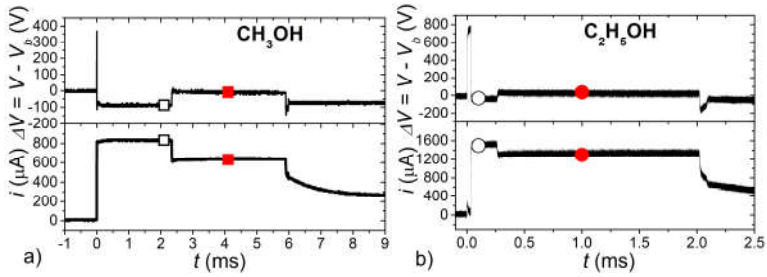

Figure 2. Waveforms of voltage and current for a) methanol abnormal discharge at pd = 0.4 Torr cm and b) ethanol abnormal discharge at pd = 0.2 Torr cm.

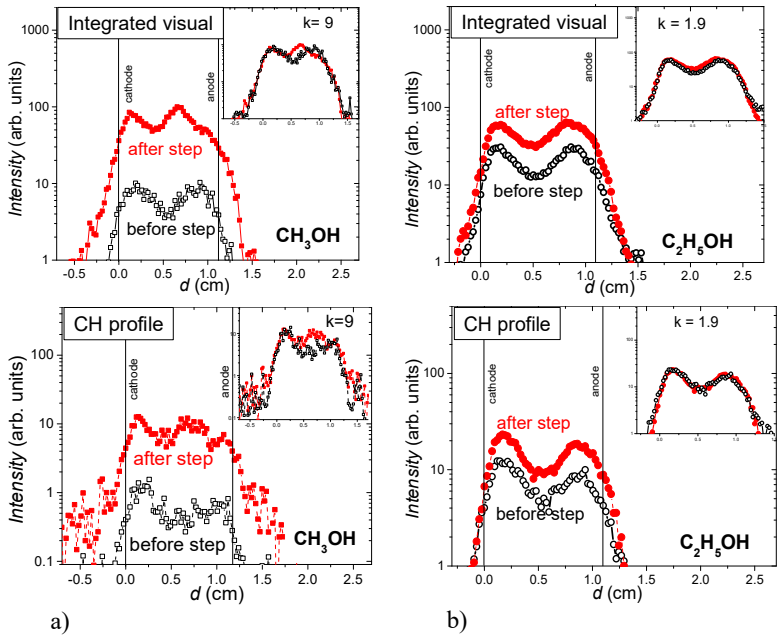

Figure 3. Axial profiles of emission from: a) methanol vapour discharge at d = 1.1 cm and pd = 0.4 Torr cm, and b) ethanol vapour discharge at d = 1.1 cm and pd = 0.2 Torr cm in abnormal regime taken in the visible range and with optical filter for CH band (431 nm). Open symbols correspond to points before the 'step' and full symbols – after the 'step'. Insets show axial profiles of emission normalized by a suitable coefficient k, for easier comparisons.

Figure 3a) and 3b) show axial profiles of emission recorded at moments marked in Figure 2a) and 2b) respectively. Axial profiles of emission in methanol (Fig. 3a) and ethanol (Fig. 3b) vapour discharges are integrated in visual range and resolved spectrally using optical filter for CH band at 431 nm.

Profiles of both alcohols reveal significant influence of heavy particles in excitation and ionization (unveiled through the peak of emission near the cathode). Furthermore, spectrally resolved profiles follow the integrated emission profiles in shape, with noticeable peak in front of the cathode indicating that heavy particles (positive ions and fast neutrals) have significant contribution to excitation of CH radical emitting at this wavelength. The profiles recorded after the transition have higher overall intensities and the emission peaks near the anode (negative glow) are slightly shifted toward the cathode in comparison with the profiles obtained before the transition, due to a change in electric field distribution. Also, the ratios of maximum intensities of profiles, recorded with and without optical filter, are the same.

Evidently, discharge after some time of stable operation slides into more preferable operating mode, with lower current and higher voltage. This behaviour is probably consequence of changes in balance of charged or excited species: ions or electronically and vibrationally excited dissociation products and adsorbed species created in discharges. This effect is, at the same time, interesting from the point of view of basic discharge properties and for applications that work in pulsed or high frequency glow regime. Further experimental investigations will provide information on processes behind the change in discharge regime.

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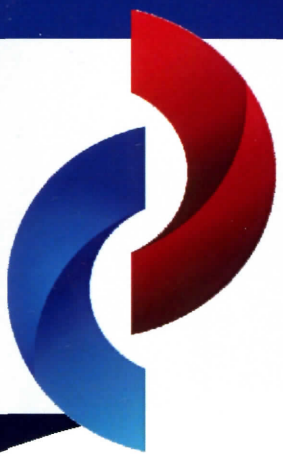

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V Workshop on Non-Equilibrium Processes

POSMOL 2019

BOOK OF ABSTRACTS

Editors

David Cassidy, Michael J. Brunger,
Zoran Lj. Petrović, Saša Dujko, Bratislav P. Marinković,
Dragana Marić and Sanja Tošić

Serbian Academy
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Ionization Coefficients in Low-Pressure DC Discharge in Vapours of Alcohols

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Non-equilibrium discharges in alcohols gain more attention of researchers due to a very broad field of application, from nanoscience, biomedicine, food and cosmetic industry to environmental remediation. However, despite the rapid development of various applications, there is still a lack of data on elementary processes in these discharges. Therefore, it is very important to conduct systematic measurements in well controlled conditions that can provide correct data and accurate phenomenology. The basic processes are, in quantitative terms, best studied in simple geometry and for this reason, our measurements were performed in a non-equilibrium plate-parallel DC discharge in the vapours of several selected alcohols: methanol, ethanol, isopropanol and n-butanol.

In our experiment, the breakdown voltages and ionization coefficients are measured between 3.1 cm separated copper cathode and quartz anode deposited with the transparent, conductive platinum film [1]. The ionization coefficients for alcohol vapours are obtained from steady-state Townsend discharge by using axial emission profiles and Paschen curves [2]. This is justified by the fact that swarm-like conditions can apply for breakdown itself and for the discharges operating in the low current limit (zero space charge effect) [3, 4], where the emission profiles reflect the multiplication of electrons between electrodes. Accordingly, the slope corresponds to the ionization coefficient once equilibrium with the local field is reached [2, 5]. However, spatial emission profiles of discharges in alcohol vapours at moderate (close to Paschen minimum) and high (left-hand branch of Paschen) reduced electric fields (E/N) have the dominant part of emission due to excitation by heavy-particles – by ions and fast neutrals. These processes can mask the emission from electron induced excitation, so the determination of effective ionization coefficient (α/N) from discharge emission profiles is limited to the range of conditions where dominant emission is induced by electrons from 1 kTd to 9 kTd. Our results (copper cathode) are compared with the results by Hasegawa and Date [6], gained with a quartz plate and a gold thin-film plating embedded in the middle of the cathode. The results show a good agreement in the part where the ranges of the reduced electric field overlap ($E/N > 1$ kTd). Additionally, we used experimentally attained ionization coefficients for the calculation of the secondary electron yields for alcohol vapours discharges.

Acknowledgement: This work is supported by MESTD of the Republic of Serbia projects OI 171037 and III 41011.

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Comparison of RF Breakdown in Argon and Oxygen – Monte Carlo Simulation

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Since 1940s and von Engel's simple theory [1], physical background of radio-frequency (RF) breakdown hasn't been updated to a greater extent. There have been some explanations by experimental scientist Valeriy Lisovskiy [2], but he was basically expanding on the von Engel's theory. In general, breakdown can be described as a movement of charged particles in externally applied electric field, with electrodes representing the boundaries. In case of RF electric field, breakdown can be achieved only with electrons, where alternating field direction pulls electrons back and forth between the two electrodes. That is a feedback mechanism for maintaining the discharge. The best approach to modelling the breakdown is to follow a charged particle swarm by applying a Monte Carlo technique. In our previous work [3] we have examined RF breakdown in argon. As an extension of that work, we will examine how breakdown conditions change for an electronegative gas such as oxygen. In figure 1 are shown breakdown voltage curves for argon and oxygen as background gases. At this point, only electrons are included and there are no effects on electrode surfaces.

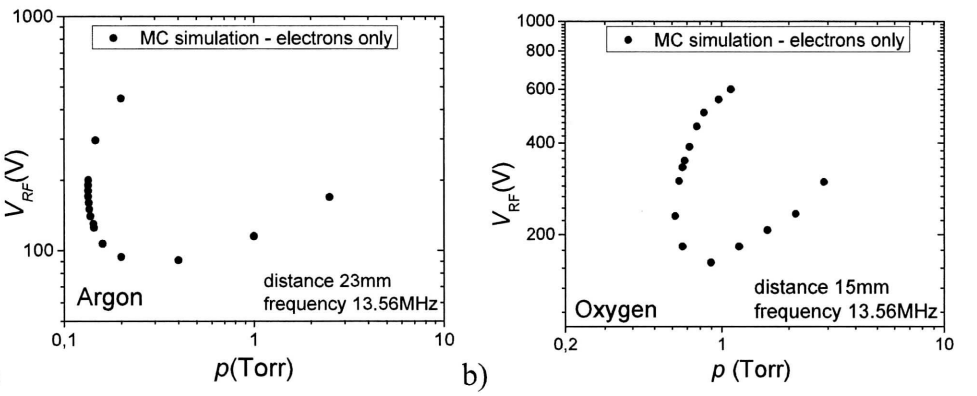

Figure 1: a) Voltage breakdown curve for argon as a background gas, distance between electrodes is 23 mm and frequency is 13.56 MHz; b) voltage breakdown curve for oxygen as a background gas, distance between electrodes is 15 mm and frequency is 13.56 MHz.

The main difference between argon and oxygen is in electron attachment in oxygen. At low pressures the slope of the oxygen curve is not that different from the argon curve. At these conditions the main loss mechanism is absorption by electrodes. On the other hand, at high pressures, slope of the oxygen curve is significantly steeper compared to the argon curve. This increase of the breakdown voltage is a direct consequence of increased losses in gas volume due to the electron attachment. This process also affects strongly the spatial profile of the electron swarm as compared with that for argon.

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Non-Equilibrium in Ionized Gases Determined by Charged Particle Collisions with Molecules

Zoran Lj. Petrović,
with: Saša Dujko, Dragana Marić, Gordana Malović, Nevena Puač, Danko Bošnjaković, Olivera Šašić, Marija Puač, Jelena Sivoš, Milovan Šuvakov and Nikola Škoro
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In their recent, excellent, review Taccogna and DiLecce [1] have tried to systematize the types and to some degree the origins of non-equilibrium in low temperature plasmas. Above all, that paper made a point (perhaps not intentionally) that the intellectual underpinning of the non-equilibrium physics is in explaining how all these different manifestations come about and how those may be explained. We have been trying to make a similar point for many years in a number of review lectures and even some of the papers albeit indirectly in attempts to show how swarm physics brings non-equilibrium into the plasma models [2-5]. The basic idea was that, while thermal equilibrium (TE) is able to provide us with laws that are universally applicable the model of thermal equilibrium is hardly ever applicable in its true and full meaning. At the same time non-equilibrium plasmas with their diversity cannot be explained in terms of formulae but their fundamental description is based on three pillars:
1) elementary data (for a variety of existing particles including the data for their reactions);
2) procedures to model (equations, transport equations, continuity etc…) and
3) inclusion of the boundaries.
In that respect the common, universal rules are provided in the realm of experience rather than the universal, prescribed thruths (formulae). Please note that Local Thermodynamic equilibrioum (LTE) is just the simplest model of non-equilibrium. The main systematics should include splitting phenomena observed in the ionized gases (which also includes positrons in gas filled traps and in the local atmosphere) into two groups:
a) Local field equilibrium (when properties may be stable in space and/or time but processes are not balanced as expected for TE).
b) Non-local, non-hydrodynamic phenomena.
Under the latter group one may label different situation when balances of one or more of the main conserved quantities are not met (number due to non-conservative collisions or local losses, energy and momentum). The relaxation time for these processes may be determined from the elementary processes and the available data and were used as the basis for correcting for non-local phenomena in fluid models. Different combinations of non-equilibrium in different situations produce a large number of the so called 'kinetic phenomena' that may not be easily explained based on the elementary data and where one needs kinetic modelling to reproduce the phenomenon.
This work is supported by MESTD of the Republic of Serbia projects OI 171037 and III 41011 and SASA 155.

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iPlasmaNano-X

September 15-20, 2019

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Keynote: 40 min including questions

IT: 30 min including questions (25+5 min)

Short talks: 15 min including questions (12+3 min)

Poster Session:

The posters will be presented throughout the whole conference in the conference hall.
The format of the posters is A0 Portrait

Sunday 15-Sept		
14:00	Reception-registration	
17:00 – 17:15	**CONFERENCE OPENING CEREMONY& OPENING SESSIONS** **Welcome: E. Kovacevic, J. Berndt, U. Cvelbar** **Chair: Eva Kovacevic**	
17:15 – 17:55	S-1	**K. Koga** *Faculty of Information Sicence and ElectricalEngineering, KyushuUniversity, Japan* *Center for Novel Science Initiatives, National Institutes of Natural Sciences, Japan* Time of Flight Size Control of Nanoparticles in Reactive Plasmas
17:55 – 18:25	S-2	**J. G. Eden** *Department of Electrical and Computer Engineering, University of Illinois, Urbana, IL 61801, USA* Electromagnetic (MM-wave) and nanofabrication applications of microcavity plasmas
18:25 – 18:55	S-3	**Z. Lj. Petrović** *Institute of Physics, University of Belgrade POB 68 11080 Zemun Serbia, Serbian Academy of Sciences and Arts, Knez Mihailova 35, 11001 Belgrade, Serbia* Global Model and Diagnostics of an Atmospheric Pressure Plasma Jet in Mixtures of Helium and Water Vapour
19:15	**WELCOME DRINK &DINNER**	

Monday 16-Sept		
Chair: Johannes Berndt		
9:00 – 9:30		**R. van de Sanden** *DIFFER, P.O. Box 6336, 5600 HH Eindhoven, The Netherlands* *Department of Applied Physics, Eindhoven University of Technology, Eindhoven, The Netherlands* Recent trends in renewable energy driven chemistry for energy conversion and storage: plasma chemistry as the special case
Session M1 **NANOPARTICLES**		
9:30 – 10:00	M1-1	**H. Biederman** *Department of Macromolecular Physics, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic* Low Pressure Plasma-based Formation of Heterogeneous Nanoparticles
10:00 – 10:30	M1-2	**T. Strunskus** *Chair for Multicomponent Materials, Kiel University, Germany* Application of UV light and X-rays to the analysis of nanoparticles created in a plasma
10:30 – 11:00	**coffee break & poster session**	
11:00 – 11:30	M1-3	**T. Belmonte** *Institut Jean Lamour CNRS&Université de Lorraine, Nancy, France* Metastability: the ultimate virtue of nanoparticles?
11:30 – 11:45	M1-4	**N. Krstulović** *Institute of Physics, Zagreb, Croatia* Synthesis, analysis and applications of nanoparticles prepared by laser ablation in liquids
11:45 – 12:00	M1-5	**J. Zavašnik** *Jožef Stefan Institute, Jamova 39, 1000 Ljubljana, Slovenia* In-situ TEM synthesis of NPs with ionic liquids
12:00 – 14:30	**LUNCH AND BREAK**	
Chair: Thomas Strunskus		
14:30 – 15:00	M1-6	**M. Santos** *The University of Sydney, NSW 2006, Australia* Controlled Synthesis of Nanoparticles in Dusty Plasmas for Applications in Nanomedicine
15:00 – 15:30	M1-7	**A. Choukourov** *Department of Macromolecular Physics, Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic* Functionalized Plasma Polymer Nanoparticles
Session M2 **PLASMAS&LIQUIDS**		
15:30 - 16:00	M2-1	**T. Ohta** *Department of Electrical and ElectronicEngineering, MeijoUniversity, Japan* Synthesis of nano-materials using gas-liquid interfacial plasma
16:00 – 16:30	**coffee break& poster session**	
Chair: Thierry Belmonte		
16:30 – 17:00	M2-2	**E. Robert** *GREMI, UMR7344 CNRS-Universitéd'Orléans, BP 6744 45067 OrléansCedex 2, France* Plasma generation using Plasma Gun above or inside liquid solutions

17:00 – 17:30	M2-3	**M. Sunkara** *Conn Center for Renewable Energy Research and Chemical Engineering, University of Louisville, Louisville, KY 40292* Plasma-molten metal and/or liquid interactions for materials processing
17:30 – 18:00	M2-4	**F. Endres** *Clausthal University of Technology Institute of Electrochemistry, ClausthalZellerfeld* Plasma Electrochemistry with Ionic Liquids
Session M3 **PLASMA CATALYSIS &MATERIAL TREATMENT** **Chair: Alexei Nefedov**		
18:00 – 18:30	M3-1	**A. Bogaerts** *Research group PLASMANT, Department of Chemistry, University of Antwerp, Universiteitsplein 1, BE-2610 Wilrijk-Antwerp, Belgium* Computer modeling for answering burning questions in plasma catalysis
18:30 – 19:00	M3-2	**S. Spirk** *Graz University of Technology, Institute of Paper-, Pulp- and FibreTechnology (IPZ), Inffeldgasse 23, 8010 Graz, Austria* Plasma treatment for cellulosic materials
19:30	**DINNER**	
Tuesday 17-Sept		
Session T **PEGASUS DAY:GRAPHENE&CARBONS** **Chair : Elena Tatarova**		
9:00 – 9:05		**E. Tatarova** Welcome to Pegasus Day
9:05 – 9:45	T-1	**M. Hori** *Center for Low-temperature Plasma Sciences, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Japan* Challenge of Plasma Nanoprocesses for Industry and Life Innovations
9:45 – 10:15	T-2	**A. Nefedov** *Institute of Functional Interfaces, KarlsruheInstitute of Technology, 76344 Eggenstein-LeopoldshafenGermany* Vertically oriented carbon nanostructures
10:15 – 10:45	T-3	**W. Bodnar** *Leibniz Institutefor Plasma Science and Technology, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany* Graphene-related carbon nanoparticles synthesized from a liquid isopropanol precursor in an one-step atmospheric plasma process
10:45 – 11:15	**coffee break& poster session**	
11:15 – 11:45	T-4	**C. Corbella** *Dept. Mechanical & Aerospace Engineering, George Washington University, DC, United States of America* Synthesis of Nanomaterials by Pulsed Anodic Arc Discharge
11:45 – 12:15	T-5	**L. Zajíčková** *CEITEC and Faculty of Science, Masaryk University, Brno, Czech Republic* Carbon Nanotubes Functional Devices Prepared by Plasma and Other Dry Gas-Phase Methods
12:15 – 14:30	**LUNCH AND BREAK**	
Chair:Uroš Cvelbar		
14:30 – 15:10	T-6	**E. Tatarova** *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*

		Microwave Plasmas Applied for Graphene Based Hybrid Nanostructures Synthesis
15:10 – 15:30	T-7	**A. Dias** *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal* Microwave plasma synthesis of graphene-metal oxides nanocomposites
15:30 – 16:00	T-8	**A. Almeida** *Centre of Physics and Engineering of Advanced Materials, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal* Structural characterization of N-graphene/Mn oxide nanocomposites synthesized by microwave plasmas
16:00 – 16:30	**coffee break& poster session**	
Chair: Nikša Krstulović		
16:30 – 17:00	T-9	**E. Valcheva** *Faculty of Physics, Sofia University, 1164, Sofia, Bulgaria* Electrical Transportin Microwave Plasma Fabricated Free-standing N-Graphene Sheets at Low Temperatures
17:00 – 17:15	T-10	**D. Tsyganov** *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049 – 001 Lisboa, Portugal* N-graphene formation applying atmospheric microwave plasma: theoretical analysis
17:15 – 17:30	T-11	**N. Bundaleska** *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049 – 001 Lisboa, Portugal* N-graphene synthesis – direct microwave plasma method
17 :30 – 18 :00	T-12	**D. Marić** *Institute of Physics, University of Belgrade, Belgrade, Serbia* Breakdown and Discharges in Low-Pressure Alcohol Vapors
18:00 – 18:30	T-13	**E. Felizardo** *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Portugal* Vacuum Ultraviolet and Extreme Ultraviolet Spectroscopy of Surface Wave Discharges
18:30 – 19:00	T-14	**J. Henriques** *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisboa,Portugal* Vacuum Ultraviolet Radiation Emitted by Microwave Argon Plasmas
19:00	**DINNER**	
Wednesday 18-Sept		
Session W **ENERGY, DIAGNOSTIC, THRUSTERS** **Chair: J. Gary Eden**		
8:30 – 9:00	W-1	**R. Boswell** *Space Plasma Power and Propulsion Laboratory Centre for Plasmas and Fluids, RSPE Australian National University, Canberra, ACT, Australia* Quo Vadis Plasma
9:00 – 9:30	W-2	**D. Ruzic** *Center for Plasma Material Interactions, Department of Nuclear, Plasma and Radiological Engineering, University of Illinois at Urbana-Champaign, Urbana IL, 61801 USA* Femtosecond Laser Texturing at Multiple Wavelengths
9:30 – 10:00	W-3	**H. Kersten**

		Institute for Experimental and Applied Physics, Kiel University, Kiel, Germany Surface modification and nanostructuring of highly porous 3D networks by plasma treatment
10:00 – 10:30	W-4	**C. Charles** *Laboratory, ResearchSchool of Physics, TheAustralianNationalUniversity, Canberra, ACT 2601, Australia* Pocket Rocketelectrothermal plasma thruster status
10:30 – 11:00	**coffee break& poster session**	
11:00 – 11:30	W-5	**M. J. Gordon** *Dept. of Chemical Engineering, Solid State Lighting and Energy Electronics Center (SSLEEC), University of California, Santa Barbara, USA* OES imaging and Langmuir probe studies of DC and RF flow-through microplasma jet sources
11:30 – 12:00	W-6	**J. L. Walsh** *Centre for Plasma Microbiology, Department of Electrical Engineering and Electronics, University of Liverpool, L69 3GJ, United Kingdom* Turbulence and entrainment in plasma jets
12:00 -12:30	W-7	**M. Momčilović** *Institute of Nuclear Sciences Vinca, University of Belgrade,Belgrade, Serbia* Laser Induced Breakdown Spectroscopy (LIBS): An alternative approach
12:30 – 14:30	**LUNCH**	
15:00 – 23:00	**EXCURSION : Magic Istria and the truffle road** **& GALA DINNER in Rovinj**	
Thursday 19-Sept		
Session Th1 **PLASMA SURFACE INTERACTION: FROM ETCHING TO COATINGS** **Chair:Masaru Hori**		
9:00 – 9:30	Th1 – 1	**M. Vuković** *TEL Technology Center America, LLC, USA* Moore's law and the evolution of plasma etch equipment and process
9:30 – 10:00	Th1 – 2	**K. P. Giapis** *Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena, CA, USA* Dynamic Chemistry in Plasma-Surface Interactions
10:00 – 10:30	Th1 – 3	**J. Beckers** *Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600MB Eindhoven, The Netherlands* EUV-induced plasma in nanolithography
10:30 – 11:00	**coffee break& poster session**	
11:00 – 11:30	Th1 – 4	**A. Barranco** *Consejo Superior de Investigaciones Científicas, Instituto de Ciencia de Materiales de Sevilla (CSIC-US) c/Américo Vespucio 49, Sevilla, E-41092, Spain* Encapsulation of perovskite solar cells and supported nanostructures by ultrathin plasma polymers
11:30 – 12:10	Th1 – 5	**J. G. Han** *School of Advanced Materials Science and Engineering, Center for Advanced Plasma Surface Technology (CAPST), NU-SKKU Joint Institute for Plasma Nano Materials (IPNM), Sungkyunkwan University, Suwon 440-746, South Korea* Novel design and control of thin film nucleation and growth by 3D magnetic field control in magnetron sputtering
12:10 – 14:30	**LUNCH**	

Chair: Andrey Choukourov		
14:30 – 15:00	Th1 – 6	**F. Faupel** *Chair for Multicomponent Materials, Faculty of Engineering, Kiel University, Kaiserstr. 2, 24143 Kiel, Germany* Recent advances in tailoring functional particulate and layered nanocomposites
15:00 – 15:30	Th1 – 7	**S. Radovanov** *AppliedMaterials /Varian BU, Gloucester, Massachusetts, UnitedStates of America* RF and DC sources capabilities for precision material modification and ion implantation
15:30 – 16:10	Th1 – 8	**A. Borras** *Nanotechnology on Surfaces Lab, Materials Science Institute of Seville / Consejo Superior de Investigaciones Cientificas (CSIC), Spain* One-reactor fabrication of supported 3D nanomaterials: first steps towards the all-in-one solution for the fabrication of self-powering systems and multisource energy scavengers
16:10 – 16:30	**coffee break& poster session**	
16:30 – 17:00	Th1 – 9	**J. P. Borra** *LPGP CNRS, Paris-Sud University&Paris-Saclay Univ (UMR 8578), @Centrale-Supélec, F91405 France* Plasma-based aerosol processes for composite core-shell nanoparticles and thin films: post-discharge condensation for nanoscale polymer and inorganic coatings
17:00 – 17:30	Th1-10	**A. Anselmo** *Helmholtz-Zentrum Berlin fürMaterialien und Energie GmbH, Albert-Einstein-Str. 15 12489 Berlin, Germany* CALIPSOplus – a gateway for research at light sources
Session Th2 **PLASBIOSENS SESSION: BIOLOGY&BIOSENSING** **Chair: Eva Kovacevic**		
17:30 – 18:00	Th2-1	**K. Makasheva** *LAPLACE, Université de Toulouse, CNRS, UPS, INPT, Toulouse, France* Plasma-based synthesis of multifunctional thin dielectrics: probing the interaction of silver nanoparticles with DsRed proteins
18:00 – 18:30	Th2-2	**V. Shvalya** *Jožef Stefan Institute, Ljubljana SI-1000,Slovenia, EU* Exploring Performance of Highly Robust Au/Pd Plasmonic Substrates for Biosensing with SERS
18:30 – 19:00	Th2-3	**K. Takahashi** *Faculty of Electrical Engineering and Electronics, KyotoInstitute of Technology, Japan* Bio-applications of water mist in plasmas as a form of dusty plasmas
19:00 – 19:30	Special Talk	**K. Ken Ostrikov** *Convenor – iPlasmaNano conference series* *Queensland University of Technology (QUT) and CSIRO-QUT Joint Sustainable Processes and Devices Laboratory Brisbane, QLD 4000, Australia* Clean future: what can plasma do for you?
19:30	**DINNER**	
Friday 20-Sept		
Session F **Chair: Zoran Lj. Petrović**		
9:00 – 9:30	F-1	**D. Pai**

		Institut Pprime (CNRS UPR 3346 – Université de Poitiers – ISAE-ENSMA), 11 boulevard Marie et Pierre Curie, F-86962 Futuroscope Chasseneuil, France In-situ OES and Raman spectroscopy related to nanostructuration by atmospheric-pressure plasmas
9:30 – 9:45	F-2	**M. Košiček** *Jožef Stefan Institute, Jožef Stefan International Postgraduate School, Ljubljana, Slovenia* Phase transformations in copper oxide nanowires
9:45 – 10:00	F-3	**M. Rakić** *Institute of physics, Zagreb, Croatia; University of Illinois at Urbana-Champaign, USA* Laser resonators with nanoparticles gain medium for new laser profiles and optical logic gates
10:00 – 10:30	**coffee break**	
10:30 – 11:00	F-4	**S. Dujko** *Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, Serbia* Electron transport in C_2H_x gases (x = 2, 4 and 6) in DC and RF fields
11:00-11:30	F-5	**M. Mičetić** Ruđer Bošković Institute, Zagreb, Croatia Preparation and basic properties of Ge quantum dot lattices in amorphous Al_2O_3, Si_3N_4 and SiC matrices
11:30	**CLOSING CEREMONY**	

K. Makasheva[1], A. Scarangella[1,2], M. Soumbo[1,3], C. Villeneuve-Faure[1],
C. Bonafos[2], A. Mlayah[2], M.-C. Monje[3], and C. Roques[3]

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Current strategies for development of new biomaterials take into consideration the fundamental "protein adsorption problem" and the associated protein structure/function relationship because of the exposure of proteins to non-biological solid surfaces. Plasma-based processes successfully apply to the synthesis of biomaterials. However, their rational engineering requires knowledge on the plasma behavior in order to design the structural, optical, electrical and bio-related properties of the deposits.

In this work we exploit the multifunctionality of silver nanoparticles (AgNPs) as plasmonic antenna when embedded in thin SiO_2 layers (called plasmonic substrates) and as biocide agents because of their strong toxicity towards micro-organisms [1]. We propose an appropriate strategy to study the 'protein-adsorption problem' and to probe the interaction of AgNPs with proteins through coupling of AgNPs and *Discosoma* red fluorescent proteins (DsRed) that display exceptional photo-stability [2-4].

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Breakdown and Discharges in Low-Pressure Alcohol Vapors

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Discharges involving alcohols, weather in a liquid phase, gaseous phase or at their interface, are found to be advantageous in nanotechnologies, for the fast growth of graphene layers and nanotubes [1]; in the fuel industry, in hydrogen production and in fuel reforming [2]; and many other fields. Our work is motivated by the key challenges in transport, chemistry, reaction rates and cross sections relevant for such discharges. We present measurements of electrical and emission properties of discharges in vapours of methanol, ethanol, isopropanol and n-butanol in the range of *pd* (pressure x electrode gap) from 0.06 Torr cm to 2 Torr cm, covering the region of Paschen minimum [3]. Space, time and spectrally resolved emission profiles of the discharges reveal kinetics of electrons, ions, and fast

neutrals. Furthermore, recorded emission profiles enable determination of effective ionization coefficients and secondary electron yields [3] for the *E/N* (electric field/gas number density) range 1 kTd–5 kTd. The measured data provide information on elementary processes and identification of relevant species, which represents a basis for modelling of plasmas in alcohol vapours.

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Laser Induced Breakdown Spectroscopy (LIBS): An alternative approach

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We will present laboratory LIBS setup developed in our research group. The proposed LIBS setup differs from the commonly practiced LIBS systems in two respects, applied the infrared TEA CO_2 laser as the excitation source and time integrated spatially resolved (TISR) signal detection. This original LIBS system is of lower complexity and cost compared to standard LIBS systems. In ours previous works, we already reported that plasma produced by irradiation of a TEA CO_2 laser related to Nd:YAG laser has comparable capabilities for spectrochemical analysis of different types of samples.

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RF Breakdown as a Swarm Experiment

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DC breakdown may be modeled by swarm models as it develops under conditions of diminishingly small space charge, while the effects of the ongoing discharge are unlikely to affect the active particles in secondary collisions. As a result, breakdown experiments have been used to reveal a wide range of transport data as their model is exact and thus data may be easily extracted. For example, secondary electron yields, Townsend's ionization coefficients and other critical parameters may be measured under breakdown or in Townsend regime discharges and be directly applied to collisional plasmas [1]. While DC breakdown has a relatively simple explanation and may be directly related to the observable parameters situation, the case of RF breakdown is somewhat different [2].

The RF breakdown may be achieved by electrons ONLY, although other agents present in the DC breakdown may also affect the exact value of the voltage for a given frequency, pressure and gap. The breakdown has a phenomenological foundation in the condition that the electrons under the breakdown conditions have to travel the gap between two electrodes during one half-period. While seemingly realistic, one cannot really understand why the presence of electrons at the opposing electrode is required before the next half period commences. No secondary electron production due to electron bombardment is called upon to justify the breakdown and compensate the losses of charged particles. It is only requested that electrons commence their return to the original position as the direction of the field changes. One could then ask whether under some conditions electrons could maintain the breakdown by oscillating between some arbitrary points well within the gap. On the other hand, the basic frequency and the corresponding transit times have been used even to obtain high accuracy drift velocity data that agreed very well with the predictions based on a two term DC field Boltzmann equation and at lower *E/N* those data seemed to agree very well with the drift velocities obtained in high accuracy experiments.

Measurements of the RF breakdown are made difficult by the displacement current that may be several orders of magnitude larger than the low current required to maintain the discharge under conditions free from the space charge effects. Detecting the plasma current that is at 90^o to the displacement current and is at least two or three orders of magnitude smaller proved impossible so far. Thus, other approaches were sought in the literature such as detection of light emission [3] or detection of sudden changes in the applied voltage [4,5]. In both cases, however, one needed to go to relatively large currents with possible transitions into higher-current regimes before required effects could be observed.

Another obstacle in both experimental studies and Monte Carlo simulations is the fact that electron multiplication varies very much during a period and while the voltage is low, the

number of electrons may drop down to the level that is too low to maintain the discharge. In any case, one needs to follow the growth of ionization over many periods to make sure that the initial decrease of the electron density does not lead to the cessation of the discharge. In addition, the shape of the breakdown curve in the voltage versus *pd* (pressure times the gap) plot is U shaped. While it seems similar to the Paschen law, it is not, as the basic physics is different and the U shape is slanted, allowing double values for a given *pd*. Thus, one has to perform measurements or simulations for a large number of voltages at a fixed *pd* or to vary pressure along the constant voltage as shown in Fig.1.

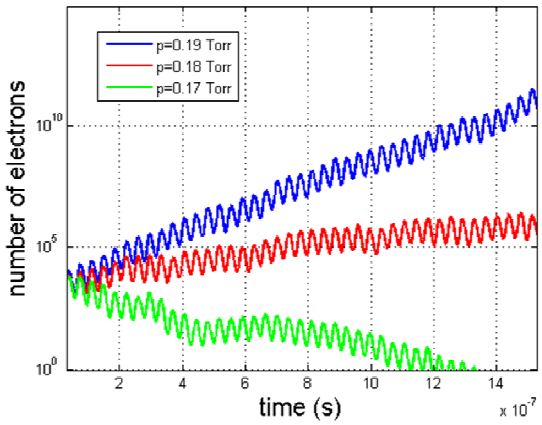

Fig. 1: The growth of electron density in argon for V = 447 V.

In addition to the exact Monte Carlo model of RF breakdown, we have developed a new technique to measure the breakdown voltage based on a capacitive bridge. Such bridges, when properly balanced, are extremely sensitive and in addition to the breakdown voltage may also provide the time development of the current and voltage. First results obtained by this technique will be presented and compared to simulations and other available data

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