**Научном већу Института за физику у Београду**

**Предмет: Молба за покретање поступка за избор др Биљане Станков у звање научни сарадник**

У складу са критеријумима прописаним од стране Министарства за просвету, науку и технолошки развој за стицање научног звања научни сарадник, као и са критеријумима прописаним од стране Правилника о поступку и начину вредновања, и квантитативном исказивању научно-истраживачких резултата истраживача, молим Научно веће Института за физику у Београду да покрене поступак за мој избор у звање научни сарадник.

У прилогу достављам:
1. Мишљење руководиоца лабораторије
2. Стручну биографију
3. Преглед научне активности кандидата
4. Елементи за квалитативну оцену научног доприноса са доказима
5. Елементи за квантитативну оцену научног доприноса
6. Списак објављених радова и других публикација, као и њихове копије
7. Податке о цитираности
8. Уверење о стеченом високом образовању трећег степена докторских студија
9. Решење о претходном избору у звање

25. септембар 2020.
Београд,

С поштовањем,
др Биљана Станков

**Научном већу Института за физику у Београду**

Београд, 25. септембар 2020. год

**ПРЕДМЕТ: Мишљење руководиоца лабораторије за спектроскопију плазме и физику ласера др Миливоја Ивковића за избор др Биљане Станков у звање научни сарадник.**

Др Биљана Станков основне студије завршива на смеру физика-метеорологија на Департману за физику, Природно-математичког факултета у Новом Саду 2012. године, са просечном оценом 9.57. Мастер студије завршава на истом факултету одбраном мастер рада „Испитивање услова за снимање спектралних линија хелијума из плазме произведене у електромагнетној Т-цеви“ 2013. године, са просечном оценом 10.00. Уписује докторске студије из области физика-плазме 2013. године на Природно-математичком факултету у Новом Саду. Докторску дисертацију под насловом „Истраживања комплексних облика спектралних линија берилијума у присуству берилијумске прашине“, са др Игором Савићем и др Миливојем Ивковићем као ментором, успешно је одбранила 03.08.2020. године.

Др Биљана Станков, запослена је на Институту за физику од 1.12.2016. У звање истраживач сарадник изабрана је 09.07.2019. године.

Др Биљана Станков до сада има објављена 2 научна рада, из категорије М21 и М22. Област научно истраживачког рада Биљане Станков је емисиона спектроскопија. Примарни интерес истраживања је добијање спектралних линија зида цеви за пражњење направљене од берилијум-оксида у плазми, затим дијагностика параметара плазме и испитивање облика спектралних линија берилијума.

Увидом у њене квалитете и с обзиром да колегиница испуњава све критеријуме прописане Правилником за изборе у научна звања Министарства просвете науке и технолошког развоја сагласан сам ца покретањем поступка у избор др Биљане Станков у звање научни сарадник.

За чланове комисије за избор др Биљане Станков у звање научни сарадник предлажем:

1) Др Миливоје Ивковић, научни саветник, Институт за физику Београд

2) Др Ненад Сакан, научник сарадник, Институт за физику Београд

3) Др Игор Савић, редовни професор, Природно-математички факултет у Новом Саду

С поштовањем,

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Др Миливоје Ивковић

## 1. Биографски подаци о кандидату

Др Биљана Станков рођена је 1989. године у Зрењанину. Завршила је основну школу „Светозар Марковић Тоза“ у Елемиру 2004. године и Зрењанинску гимназију у Зрењанину 2008. године.

Четири године основних студија из физике-метеорологије зарвшава на Департману за физику, Природно-мартематичког факултета, Универзитета у Новом Саду 2012. године. Исте године полаже разлику испита за истраживачки смер на физици и уписује мастер студије из области физике плазме, које завршава следеће године са мастер радом „Испитивање услова за снимање спектралних линија хелијума из плазме произведене у електромагнетној Т-цеви“.

Током завршне године основних и мастер студија, била је стипендиста Доситеје коју додељује Фонд за младе талентге Републике Србије, намењене талентованим и најуспешнијим ушеницима и студентима у Србији и иностранству.

Године 2013. уписује докторске студије из области физике плазме на истом факултету као стипендиста Министарства просвете науке и технолошког развоја. Запошљава се на Институту за физику у Београду 2016. године где стиче звање истраживач приправник. У децембру 2018. године пријавила је тему доктората „Истраживања комплексних облика спектралних линија берилијума у присуству берилијумске прашине“, са др Игором Савићем и др Миливојем Ивковићем као ментором. Одлуком научног већа 09.07.2019. Стекла је истраживањско звање, истраживач сарадник. Др Биљана Станков је одбранила докторску дисертацију 03.08.2020. на Природно-мартематичком факултету, Универзитета у Новом Саду.

Током студирања редовно је учествовала на интернационалној конференцији за студенте физике- ICPS (International Conference of Physics Students), одржаној 2010. у године у Грацу (Аустрија), 2012. године у Будимпешти (Мађарска), 2014. године у Хајлдербегу (Немачка), 2015. године у Загребу (Хрватска), 2016. године у Валети (Малта), 2017. у године у Хелсинкију (Финска). Биљана је учесник летње школе посвећене плазма физици, одржане у Грајсфвалду (Немачка). У фебруару 2019. године добија грант који јој омогућује учешће на конференцији EWCPS (European Winter Conference on Plasma Spectrochemistry), у граду По (Француска) због где је одржала предавање под насловом “Uncovering beryllium line with forbidden component”. Учесник је конференције SPIG (Summer School and International Symposium on the Physics of Ionized Gases) 2016., 2018., і 2020. године.

Др Биљана Станков до сада има објављена 2 научна рада, из категорије М21 и М22.

Област научно истраживачког рада Биљане Станков је емисиона спектроскопија. Примарни интерес истраживања је добијање спектралних линија зида цеви за пражњење направљене од берилијум-оксида у плазми, затим дијагностика параметара плазме и испитивање облика спектралних линија берилијума. Такође, фокус истраживања усмерен је ка развоју спектроскопије ласером индукованог пробоја - ЛИБС (Laser Induced Breakdown Spectroscopy) која се примењује за испитивање узорака који у свом саставу садрже берилијум.

## *2.* Преглед научне активности др Биљане Станков

Прво научно искуство Биљана Станков је стекла током мастер студија, радећи на мастер тези „Испитивање услова за снимање спектралних линија хелијума из плазме произведене у електромагнетној Т-цеви“. Циљ истраживања био је коришћење добијених експерименталних резултата за упоређивање са профилима спектралних линија хелијума добијеним на основу теоријских прорачуна.

Током прве године рада у Институту за физику у Београду др Биљана Станков бавила се конструкцијом и испитивањем спектроскопског извора зрачења - плазма млаза. Намена овог ивора је била да се провери да ли се на овај начин конструисан извор може користити у медицинске сврхе, односно да ли је температура плазма млаза довољно мала, а концентрација електрона у плазма млазу довољно велика.

Научна активност кандидаткиње др Биљане Станков у Институту за физику у Београду усмерена у највећем делу на анализу оптичког емисионог спектра плазме. Највећа пажња посвећена је анализи спектралних линија које се добијају аблацијом зидова цеви за пражњење електричним пражњењем. Примарни фокус истраживања био је омогућавање ексцитације, снимања и проучавања спектралних линија берилијума, због изразитог значаја овог елемента у природи и индустрији. Ова истраживања била су најпре усмерена ка конструкцији новог, безбедног, извора плазме који би служио за ексцитацију линија берилијума. Наиме, берилијум је врло токсичан те је било потребно конструисати извор којим би се могло безбедно руковати у условима који постоје у лабораторији. Након конструкције извора плазме било је потребно открити оптималне услове за рад извора и снимање спектралних линија берилијума, односно услове при којима се спектралне линије берилијума појављују у спектру и интензивније су од линија носећег гаса. Приликом испитивања одређени су оптимални услови за снимање линија берилијума. Даљи рад усмерен је на додатно испитивање линија берилијума снимљених на овај начин, при оптималним условима. Спектралне линије добијене применом оваквог извора зрачења би могле бити коришћене за израчунавање Штаркових параметара.

Резултатима експерименталног рада кандидаткиње је први пут потврђено постојање забрањених компонената код две линије берилијума. Такође, запажено је да под утицајем пражњења долази до формирања прашине берилијума. Како би се избегла појава прашине, наставак истраживања усмерен је ка развоју спектроскопије ласером индукованог пробоја - ЛИБС (Laser Induced Breakdown Spectroscopy) која се примењује за испитивање узорака који у свом саставу садрже берилијум.

Оваква испитивања берилијума су од великог значаја за астрофизику - берилијум је присутан у великом броју звезда чије се зрачење прати. Ови подаци су важни и због фузионих истраживања. Тренутно је у изградњи ИТЕР (*International Thermonuclear Experimental Reactor*). Први слој зидова овог реактора, који је у директном контакту са формираном плазмом, биће направљен од берилијума. Високе температуре плазме могу довести до топљења, испаравања и формирања прашине берилијума. Ово би довело до

оштећења зидова суда, али и до промене састава плазме. Експеримент је спроведен у циљу анализе процеса који доводе до формирања прашине.

Истраживачки рад и научни резултати које је до сада остварила др Биљана Станков, могу се груписати у 4 теме:

- Конструкција и испитивање спектроскопског извора зрачења - плазма млаза
- Конструкција новог извора плазме којим се омогућује ексцитација берилијума аблацијом зида цеви за пражњење
- Испитивање спектралних линија берилијума које се појављују у спектру са забрањеном компонентом
- Развој спектроскопије ласером индукованог пробоја - ЛИБС која се примењује за испитивање узорака који у свом саставу садрже берилијум

**Тема 1**

Кандидаткиња се бавила конструкцијом и испитивањем спектроскопског извора зрачења - плазма млаза, током прве године рада у Институту за физику у Београду. Извор плазма млаза је малих димензија - електроде се налазе на растојању од 1 cm, а отвор на електроди, кроз који пролази плазма млаз, има дијаметар 0,6 mm. Пропагација плазма млаза је праћена коришћењем брзе фотографије чиме је потврђено његово формирање и анализирано простирање. Анализирани су и упоређивани оптички емисиони спектри плазма млаза и цеви у којој се одвијало пражњење. Снимање се обављало *end on* помоћу камере, али и истовремено, уз помоћ три фибера - један за снимање пражњења у цеви, други за снимање плазма млаза и трећи за *end on* снимке. На основу ових снимака и анализом спектара било је могуће утврдити разлике у концентрацији и температури унутар саме цеви и у плазма млазу, као и колики је појединачни допринос ове две плазме у укупном сигналу. Пражњење је успостављано у више гасова, пражњењем кондензатора различитих капацитета. Мењане су димензије, отвор и растојање између електрода, а све у циљу добијања стабилног извора који се може користити за анализу спектралних линија гаса. Утврђено је да овако конструисан извор не може бити употребљаван за третирање биолошких узорака због високе температуре и ниске електронске концентрације. Описани резултати објављени су у раду:

- M. Vinic, **B. Stankov**, M. Ivkovic and N. Konjevic, *Characterization of an Atmospheric Pressure Pulsed Microjet*, 28th Summer School and International Symposium on the Physics of Ionized Gases, Belgrade, Serbia (2016), August 29$^{th}$– September 2$^{nd}$, p. 276

**Тема 2**

Кандидаткиња је учествовала у конструкцији новог извора плазме, који ради у импулсном режиму, који је за основни циљ имао безбедно испитивање спектралних линија берилијума које потичу из плазме произведене у извору пражњења. Појављивање линија берилијума остварено је уметањем керамике, берилијум-оксида, BeO, у цев за пражњење. Испитивана

плазма формирана је унутар цеви за пражњење. Кандидаткиња је вршила испитивања при различитим притисцима гасова: аргона, аргона са хелијумом, хелијума са водоником, криптона. Испитивања су вршена са различитим како електричним конфигурацијама, тако и са различитим поставкама и варијантама самог извора док се није постигао резултат. Спектри су снимани у различитим временима трајања плазме. Помоћу овако конструисаног извора омогућена је детекција присуства берилијума у плазми и проучавање утицаја честица прашине. Овако конструисан извор омогућује испитивање спектара плазме која настаје у цевима израђених од различитих материјала, тако што се у извор уведе цев израђена од материјала који се жели испитати. Кадидаткиња је проучавала и спектре добијене када се унутар цеви за пражњење уметне цев израђена од алумине, $Al_2O_3$, и силицијум-диоксида, $SiO_2$.

Током експерименталног рада примећено је формирање позамашне количине прашине која настаје аблацијом зидова цеви за пражњење. Током испитивања све 3 цеви за пражњење, уочена је појава прашине и појава другог максимума струје. Други максимум струје је највероватније последица формирања негативних јона који су претходници формирању прашине. Ова аномалија је током истраживања коришћена као први показатељ да је дошло да аблације керамике и да се у спектру може очекивати појава линија које потичу од цеви за пражњење.

Кандидаткиња је одредила оптималне услове за рад извора плазме, за све три цеви за пражњење. Описани резултати објављени су у раду:

- **B. D. Stankov**, M. Vinić, M. R. Gavrilović Božović, and M. Ivković, *Novel plasma source for safe beryllium spectral line studies in the presence of beryllium dust*, Review of Scientific Instruments **89**, 053108 (2018), DOI.

**Тема 3**

Кандидаткиња је испитивала емитовано зрачења из новог извора плазме, претходно описаног, када се као цев за пражњење користи берилијум оксид. Приликом испитивања откривена је појава линије једноструко јонизованог берилијума Be II 436,1 nm, прелаза $3p^2$ $P^o$-$4d^2$ D, са забрањеном компонентом прелаз, $3p^2$ $P^o$-$4f^2$ $F^o$. Да би се доказала појава спектралне линије са забрањеном компонентом, кандидаткиња је испитавала је присуство нечистоћа у спектру, и спровела мерење растојања између пикова дозвољене и забрањене компоненте спектралне линије, као и мерење односа интензитета ове две компоненте. Функционална зависност растојања између пикова компонената од таласне дужине, као и функционална зависност односа интензитета максимума компонената од таласне дужине, прати тренд типичан за линије са забрањеним компонентама. Једна од могућих примена линија берилијума са забрањеним компонентама је за одређивање концентрације електрона током in situ испитивања првог зида токамака ЛИБС методом. Описани резултати објављени су у раду:

- **B. D. Stankov**, M. Ivković, M. Vinić and N. Konjević, *Forbidden component of the Be II 436.1 nm line recordered from pulsed gas discharge plasma*, Europhysics Letters **123** 63001 (2018), doi: 10.1209/0295-5075/123/63001
- **B. D. Stankov**, *Beryllium Spectral Line Studies in the Presence of Beryllium Dust*, 29th Summer School and International Symposium on the Physics of Ionized Gases, Belgrade, Serbia (2018), August 28th– September 1st, progress report, p. 145
- **B. D. Stankov**, *Uncovering beryllium line with forbiden component*, European Winter Conference on Plasma Spectrochemistry, PAU Feb. 3 – 8, 2019, student grant lecture, p. 68

**Тема 4**

Кандидаткиња је учествовала у осмишљавању додатног експеримента за анализу спектралних линија берилијума, код којег би били избегнути проблеми накупљања честица те утицаја прашине на спектар, дебљине оптичког пута и додатног електричног поља у импулсном пражњењу. Наставак истраживања кандидаткиње усмерен је ка развоју спектроскопије ласером индукованог пробоја ЛИБС која се примењује за испитивање узорака који у свом саставу садрже берилијум. Кандидаткиња је испитивала могућност снимања линија берилијума са забрањеном компонентом ЛИБС методом. Описани резултати објављени су у раду:

- **B. D. Stankov**, M.R. Gavrilović Božović and M. Ivković, *Appearance of Be II 436.1 nm Line With Forbidden Component in LIBS plasma*, 30$^{th}$ Summer School and International Symposium on the Physics of Ionized Gases, Šabac, Serbia (2020), August 24$^{th}$–28$^{th}$, p. 145

## 3. Елементи за квалитативну оцену научног доприноса

### 3.1. Квалитет научних резултата

#### *3.1.1 Значај научних резултата*

Кандидаткиња се у току досадашњег рада бавила емисионом спектроскопијом, са примарним интересом усмереним ка испитивању појаве спектралних линија зида цеви за пражњење направљене од берилијум-оксида у спектру, затим дијагностиком параметара плазме и испитивањем облика снимљених спектралних линија берилијума.

Кандидаткиња је имала значајну и некада кључну улогу у припремању експерименталне поставке, планирању и изведби експеримената. Кандидаткиња је самостално радила на 2 експеримента у Лабораторији за физику плазме и ласере, Института за физику у Београду; од којих је у првом осмишљен и конструисан нов извор плазме за

испитивање спектралних линија које потичу из материјала зида цеви за пражњење. Извор је описан у раду чији је кандидаткиња први аутор. Новоконструисани извор омогућује испитивање спектралних линија берилијума. Оваква испитивања берилијума су веома ретка због познате токсичности берилијума и берилијумске прашине. При раду кандидаткиње на експерименту снимљене су линије берилијума које претходно нису испитиване експерименталним путем, према доступној литератури. Кандидаткиња се највише бавила анализом спектара добијених применом новог извора плазме.

У раду чији је кандиткиња први аутор, по први пут је, према доступној литератури, описана спектрална линија берилијума са забрањеном компонентом.

Друга експериментална поставка на којој кандидаткиња самостално ради је усмерена ка развоју ЛИБС технике за испитивање узорака који у свом саставу садрже берилијум. Радом на овом експерименту, кандидаткиња је показала да се у спектрима добијеним фокусом наносекундноог импулсног ласерског снопа на мету берилијум оксида у комори под ниским притиском, појављује спектрална линија берилијума са забрањеном компонентом. Захваљујући овом експерименту, биће омогућено испитивање линија берилијума без присуства додатног поља или прашине, што је значајно јер је тиме омогућена употреба експерименталних резултата за поређење са спектралним линијама берилијума добијеним теоријским моделима.

### *3.1.2 Параметри квалитета часописа*

Кандидаткиња др Биљана Станков је објавила укупно 2 рада у међународним часопосим, чији је први аутор, и то:

•1 рад у врхунском међународном часопису *Europhysics Letters / EPL* (ИФ=1.958, СНИП=0,746)

•1 рад у истакнутом међународном часопису *Review of Scientific Instruments/Rev Sci Instrum* (ИФ=1.587, СНИП=0,899)

Укупан импакт фактор објављених радова је 3,545.

### *3.1.3 Позитивна цитираност научних радова кандидата*

Према бази Web of Science, радови др Биљане Станков су цитирани укупно 2 пута, од чега 1 пут изузимајући аутоцитате. Док је Хиршов индекс према истој бази 1.

### *3.1.4 Додатни библиометријски показатељи*

| | ИФ | М | СНИП |
|---|---|---|---|
| Укупно | 3,545 | 13 | 1,645 |
| Усредњено по чланку | 1,7725 | 6,5 | 0,8225 |
| Усредњено по аутору | 0,709 | 2,6 | 0,329 |

### *3.1.5 Међународна сарадња*

Међународне активности др Биљане Станков обухватају учешће на летњој школи физике плазме за студенте у Грајсфалду, Немачка, 2017. године. Такође, кандидаткиња је освојила грант који јој је омогућио да одржи усмено предавање на конференцији EWCP (European Winter Conference on Plasma Spectrochemistry“) у граду По, Француска, 2019. године. Ову награду је освојило 12 студената из целог света, који су на тај начин добили прилику да представе свој рад.

## 3.2. Нормирање броја коауторских радова, патената и техничних решења

Оба рада на којима је кандидаткиња први аутор су експериментална. Број аутора на оба рада је мањи од 7. У складу са Правилником Министарства о поступку, начину вредновања и квантитативном исказивању научно истраживачких резултата, када су у питању експериментални радови у природно-математичким наукама, са пуном тежином признају се радови до 7 коаутора, те нема потребе за нормирањем М бодова.

## 3.3. Учешће у пројектима, потпројектима и пројектним задацима

Кандидат је од уписа докторских студија на пројекту ОИ17104 под називом „Спектроскопска дијагностика нискотемпературне плазме и гасних пражњења: облици спектралних линија и интеракција са површинама“, чији је руководилац био др Никола Коњевић и касније др Соња Јовићевић.

## 3.4. Утицај научних резултата

Утицај научних резултата кандидаткиње наведен је у одељку 3.1 овог извештаја. Пун списак радова и подаци о цитираности дати су у прилогу.

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

Кандидаткиња је своје истраживачке активности реализовала у Институту за физику у Београду. Кандидаткиња је дала кључни допринос објављњним радовима, гдеје први аутор.

## 4. Елементи за квантитативну оцену научног доприноса

**Остварени М бодови по категоријама публикација**

| Категорија | М бодови по раду | Број радова | Укупно М бодова | Нормирани број М бодова |
|---|---|---|---|---|
| М21 | 8 | 1 | 8 | 8 |
| М22 | 5 | 1 | 5 | 5 |
| М33 | 1 | 5 | 5 | 5 |
| М70 | 6 | 5 | 6 | 6 |

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

| | **Потребно** | **Остварено** |
|---|---|---|
| **УКУПНО:** | **16** | **24** |
| **М10+М20+М31+М32+М33+М41+М42** | **10** | **18** |
| **М11+М12+М21+М22+М23** | **6** | **13** |

## 5. Списак радова и осталих публикација др Биљане Станков

**Радови у врхунским међународним часописима (М21):**

**B. D. Stankov**, M. Ivković, M. Vinić and N. Konjević, *Forbidden component of the Be II 436.1 nm line recordered from pulsed gas discharge plasma*, Europhysics Letters **123** 63001 (2018), doi: 10.1209/0295-5075/123/63001

**Радови у истакнутим међународним часописима (М22):**

**B. D. Stankov**, M. Vinić, M. R. Gavrilović Božović, and M. Ivković,
*Novel plasma source for safe beryllium spectral line studies in the presence of beryllium dust*, Review of Scientific Instruments **89**, 053108 (2018), DOI.

**Саопштења са међународних скупова штампана у целини (М33):**

**B. D. Stankov**, *Beryllium Spectral Line Studies in the Presence of Beryllium Dust*, 29th Summer School and International Symposium on the Physics of Ionized Gases, Belgrade, Serbia (2018), August 28th– September 1st, progress report, p. 145

M. Vinić, M.R. Gavrilović Božović, **B. Stankov**, M. Vlainić and M. Ivković, Nanoparticles on a sample surface as laser induced breakdown spectroscopy enhancers, 29th Summer School and

International Symposium on the Physics of Ionized Gases, Belgrade, Serbia, August 28th-September 1st, p. 190-193

**B. D. Stankov**, *Uncovering beryllium line with forbiden component*, European Winter Conference on Plasma Spectrochemistry, PAU Feb. 3 – 8, 2019, student grant lecture, p. 68

**B. D. Stankov**, M.R. Gavrilović Božović and M. Ivković, *Appearance of Be II 436.1 nm Line With Forbidden Component in LIBS plasma*, 30th Summer School and International Symposium on the Physics of Ionized Gases, Šabac, Serbia (2020), August 24th–28th, p. 145-148

M. Vinic, **B. Stankov**, M. Ivkovic and N. Konjevic, *Characterization of an Atmospheric Pressure Pulsed Microjet*, 28th Summer School and International Symposium on the Physics of Ionized Gases, Belgrade, Serbia (2016), August 29th– September 2nd, p. 27-30

# Biljana D. Stankov

https://publons.com/researcher/3913645/biljana-d-stankov/

## Current affiliation:

- Institute of Physics - University of Belgrade from 2016 until present

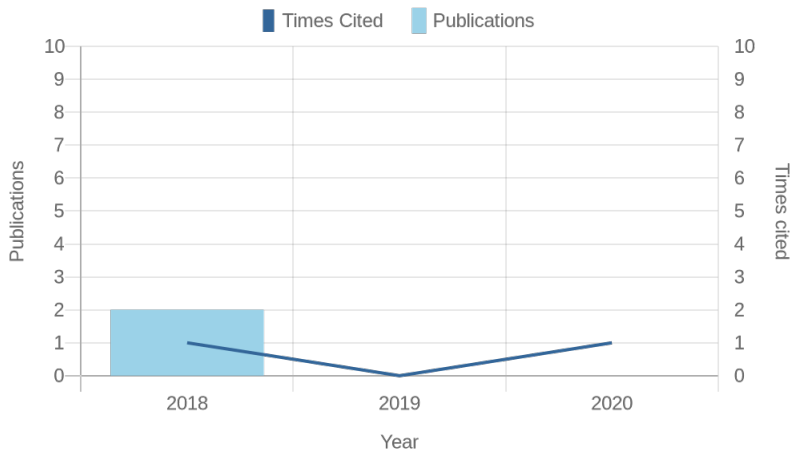
## Publications

### PUBLICATION METRICS

For all time

| CITATIONS | H-INDEX | PUBLICATIONS | *WEB OF SCIENCE* PUBLICATIONS |
|---|---|---|---|
| 2 | 1 | 2 | 2 |

### PUBLICATION IMPACT OVER TIME




### PUBLISHING SUMMARY

(1) Review of Scientific Instruments WOS

(1) EPL (Europhysics Letters) WOS

**MANUSCRIPTS PUBLISHED (2)**

**TIMES CITED (ALL TIME)**

Forbidden component of the Be II 436.1 nm line recorded from pulsed gas discharge plasma

Published: Sep 2018 in EPL (Europhysics Letters)
DOI: 10.1209/0295-5075/123/63001

0

Novel plasma source for safe beryllium spectral line studies in the presence of beryllium dust

Published: May 2018 in Review of Scientific Instruments
DOI: 10.1063/1.5025890

2

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Broj dosijea: 69d/13

Na osnovu člana 29. st. 1 Zakona o opštem upravnom postupku "Sl. glasnik RS" br. 18/2016, u skladu sa članom 112. Zakona o visokom obrazovanju "Sl. glasnik RS" br. 88/2017, uvida u matične knjige studenata doktorskih studija Prirodno-matematičkog fakulteta Univerziteta u Novom Sadu i zahteva Stankov Slavica Biljane, iz Elemira izdaje se

# U V E R E NJ E

O STEČENOM VISOKOM OBRAZOVANJU TREĆEG STEPENA
DOKTORSKIH STUDIJA

Stankov (Slavica) Biljana

rođena 16.02.1989. godine u Zrenjaninu, opština Zrenjanin, država Republika Srbija, završila je visoko obrazovanje trećeg stepena-doktorskih studija, na studijskom programu Doktorske studije - Fizika, Departmana za fiziku Prirodno-matematičkog fakulteta Univerziteta u Novom Sadu, dana 03.08.2020. godine, sa prosečnom ocenom 9.50 (devet i 50/100), u toku studija i postignutim ukupnim brojem ESPB bodova 180.00 (slovima: sto osamdeset i 00/100) i stekla naučni naziv Doktor nauka-fizičke nauke. Naslov doktorske disertacije je: "Istraživanja kompleksnih oblika spektralnih linija berilijuma u prisustvu berilijumske prašine"

Uverenje se izdaje radi lične upotrebe i zamenjuje diplomu do izdavanja iste.

Na osnovu člana 19. stav 1. tačka 7. Zakona o republičkim administrativnim taksama ("Sl. glasnik RS" broj 43/2003, 51/2003 - ispr., 61/2005, 101/2005 - dr. zakon, 5/2009 i 54/2009) ovo uverenje je oslobođeno takse.

Prodekan za nastavu
Prirodno-matematičkog fakulteta

*dr Tatjana Pivac, redovni profesor*

Novi Sad, 02.09.2020.

EWCPS-2019

# CERTIFICATE OF ATTENDANCE

**Biljana STANKOV**

attended

the European Winter Conference on

Plasma Spectrochemistry

in Pau, France, 3-8 February 2019

**Ryszard Lobinski**

**Conference Chair**

Pau, February 8th, 2019

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Датум 09. 07. 2019

На основу члана 82. Закона о научноистраживачкој делатности ("Службени гласник Републике Србије", број 110/2005, 50/2006 - испр., 18/2010 и 112/2015), члана 32. Статута Института за физику и захтева који је поднела

БИЉАНА СТАНКОВ

на седници Научног већа Института за физику одржаној 09.07.2019. године, донета је

# ОДЛУКА
# О СТИЦАЊУ ИСТРАЖИВАЧКОГ ЗВАЊА

**БИЉАНА СТАНКОВ**

стиче истраживачко звање

***Истраживач сарадник***

*ОБРАЗЛОЖЕЊЕ*

Биљана Станков је 29.01.2019. године поднела захтев за избор у истраживачко звање истраживач сарадник. Научно веће Института за физику је на седници одржаној 16.04.2019. године образовало Комисију за спровођење поступка у саставу др Миливоје Ивковић, научни саветник, Институт за физику у Београду, др Ненад Сакан, научни сарадник, Институт за физику у Београду и проф. др Игор Савић, ванредни професор Природно-математичког факултета у Новом Саду. Научно веће је на седници од 09.07.2019. године утврдило да именована испуњава услове из члана 70. став 2. Закона о научноистраживачкој делатности за избор у звање **истраживач сарадник,** па је одлучило као у изреци ове одлуке.

Одлуку доставити подносиоцу, архиви Института за физику, кадровској служби Института за физику и рачуноводственој служби Института за физику.

**Председник Научног већа**
**др Жељка Никитовић**

**Директор Института за физику**
**др Александар Богојевић**

ИНСТИТУТ ОД НАЦИОНАЛНОГ ЗНАЧАЈА ЗА РЕПУБЛИКУ СРБИЈУ
УНИВЕРЗИТЕТ У БЕОГРАДУ · ИНСТИТУТ ЗА ФИЗИКУ · БЕОГРАД

# Novel plasma source for safe beryllium spectral line studies in the presence of beryllium dust

B. D. Stankov, M. Vinić, M. R. Gavrilović Božović, and M. Ivković

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View Table of Contents: http://aip.scitation.org/toc/rsi/89/5
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# Novel plasma source for safe beryllium spectral line studies in the presence of beryllium dust

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Plasma source for beryllium spectral line studies in the presence of beryllium dust particles was realised. The guideline during construction was to prevent exposure to formed dust, considering the toxicity of beryllium. Plasma source characterization through determination of optimal working conditions is described. The necessary conditions for Be spectral line appearance and optimal conditions for line shape measurements are found. It is proven experimentally that under these conditions dust appears coincidently with the second current maximum. The electron density measured after discharge current maximum is determined from the peak separation of the hydrogen Balmer beta spectral line, and the electron temperature is determined from the ratios of the relative intensities of Be spectral lines emitted from successive ionized stages of atoms. Maximum values of electron density and temperature are measured to be $9.3 \times 10^{22}$ m$^{-3}$ and 16 800 K, respectively. Construction details and testing of the BeO discharge tube in comparison with $SiO_2$ and $Al_2O_3$ discharge tubes are also presented in this paper. *Published by AIP Publishing.*
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## I. INTRODUCTION

The interest for Be spectral lines studies stems from the prevalence of Be, which occurs in nature and is used in many devices. Beryllium is an element which has six times the specific stiffness of steel and at the same time it is one-third lighter than aluminum. This unusual combination of properties makes it suitable for a wide range of applications: aerospace, military, information technologies, energy exploration, medical, and other advanced applications. The three most used forms of beryllium are beryllium-containing alloys, pure beryllium metal, and beryllium ceramics, also known as beryllium oxide ceramic.

Since Be is also a naturally occurring element in metal-poor stars,[1] the study of the spectral lines emission of beryllium is important for astrophysics. For example, spectral lines coming from Be II deexcitation at 313.0 nm and 313.1 nm are used for the analysis of some stars' origin.[2] Hence, basic knowledge about beryllium spectral emission is available but still, according to critical reviews,[3–9] spectroscopic investigations and Stark parameters' studies are almost exclusively limited to Be II resonance lines at 313 nm.[10–13] In several of these studies,[10–12] the plasma source was an electromagnetically driven "T" tube. Beryllium was deposited in the form of thin layers of $BeCl_2$ on the electrode[10,11,13] and by dusting the quartz tube with $BeCl_2$.[12]

Because of its low atomic number and very low absorption for X-rays, the oldest and still one of the most important applications of beryllium is in radiation windows for X-ray tubes.[14,15]

Also, the beryllium has been chosen as the element to cover the first wall of ITER (International Thermonuclear Experimental Reactor). The first wall of ITER is a part of the blanket that is constructed with 440 panels that completely cover inner wall of the vacuum vessel. Those panels will be covered with 8-10 mm of beryllium armor, leading to approximately 12 tons of beryllium in total, distributed over a surface area of about 700 m$^2$ (Ref. 16, Sec. 13.3.1.2). In addition, beryllium oxide is also used as insulation in some ITER components (Ref. 16, Table 13.3-1). Beryllium is the material of choice in ITER due to its light weight, low tritium absorption, and efficient trapping of oxygen impurities at its surface forming BeO. The drawback of Be is its low melting temperature what makes it vulnerable to edge-localized modes (ELMs) and disruptions.[17] ELMs and disruptions may provoke large thermal transient loads on beryllium components of the first wall leading to rapid heating of the beryllium surface. Rapid heating can result in plasma-surface interaction processes and can lead to material loss, melting, evaporation, and formation of beryllium dust. Erosion of beryllium under transient plasma loads will determine a lifetime of ITER first wall.[18] The presence of dust particles in fusion reactors has several consequences. There is a safety issue because Be is toxic in the case of inhalation, so constant air monitoring must be provided.[19] Other problems regard the pollution of the plasma by particles, causing the reduced performance, or its deposition on diagnostic equipment. Still, the knowledge of dust creation processes and behavior in a plasma environment is very limited,[20] partially due to the previously mentioned safety issues when handling plasma sources with toxic materials, as beryllium.

Research on dusty plasma is gaining in popularity due to its unique properties and importance for novel technologies.[21] Furthermore, the dust in plasma shows interesting

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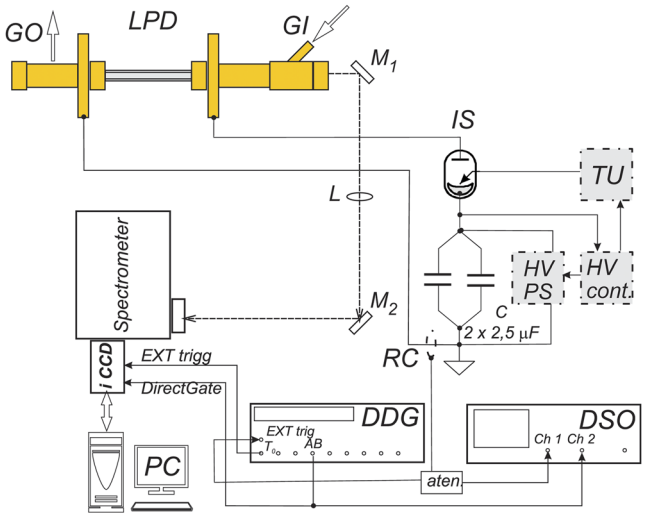



FIG. 1. Experimental setup, LPD—linear pulsed discharge, GO—gas outlet, GI—gas inlet, $M_1$—mirror, L—lens, $M_2$—mirror, IS—ignitron switch, TU—trigger unit, HV PS—high voltage power supply, RC—Rogowski coil, DSO—digital storage oscilloscope, DDG—digital delay generator, ICCD—Intensified Charge Coupled Device camera, PC—personal computer.

fundamental phenomena like plasma crystals and dust acoustic waves.[22–24] In many applications, besides already mentioned ITER, the dust in plasma is the unwanted effect, e.g., for plasma etching and thin film deposition in semiconductor industry. This increases the relevance of dust particle formation studies and sets the need to relate it to some other physical phenomenon, like spectral emission from the tokamak plasma.[25,26]

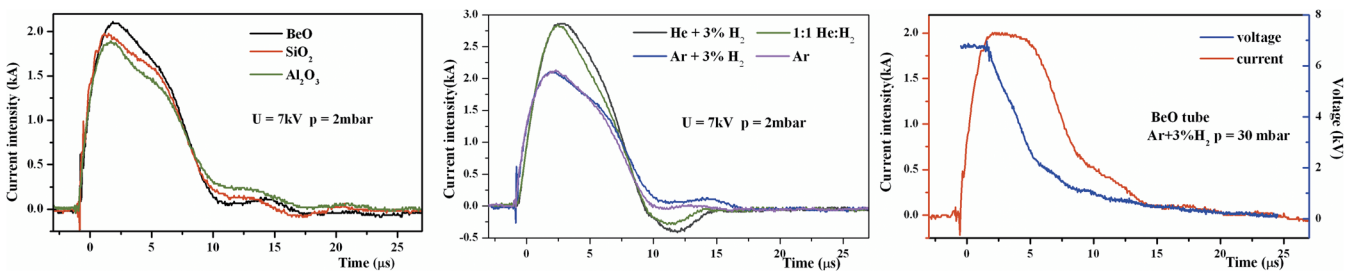
In addition, *in situ* examination of plasma facing materials in tokamak (beryllium and others) by laser induced breakdown spectroscopy (LIBS)[27,28] requires the knowledge of their atomic data (transition probabilities, Stark broadening parameters, etc.). The lack of Stark parameters for Be spectral lines was one of the main inspirations for this plasma source construction.

The main goal of this work was not only to obtain a stable plasma source for the beryllium spectral lines' study but also to enable the examination of dust particles' influence on emission spectra when optimal conditions for Be spectral emission are achieved. The idea was to obtain beryllium spectral lines from erosion of the beryllium oxide, BeO discharge tube, and preferentially, the lines belonging to transitions other than resonant, which are the only ones studied in detail up to now. To draw an analogy with previous studies[10–13] in the experiemental setup we used, beryllium was introduced through the ablation of a ceramic tube settled inside the discharge tube, which allowed more consistent ablation, longer and more reliable work, and appearance of various Be spectral lines. In order to closer investigate the influence of specific discharge tube material on dust particle production and emission spectra, two additional discharge tubes were made. Construction details and testing of the BeO discharge tube in comparison with $SiO_2$ and $Al_2O_3$ discharge tubes are also presented in this paper.

## II. EXPERIMENT

The experimental setup is presented in Fig. 1. Capacitor C is charged between 4 and 8 kV, using a high voltage power supply, HV PS, operated through the laboratory made high voltage control. When voltage reaches a selected value, the pulse is generated by high voltage control and shaped by the trigger unit in order to initiate ignitron switch, which starts the current flow through the linear pulsed discharge tube. The current shape is monitored by the Rogowski coil and recorded with a digital storage oscilloscope, DSO (Tektronix TDS 360); see typical current shapes for different discharge tubes in Fig. 2(a). The same but attenuated signal from the Rogowski coil is used for the triggering of intensified charge coupled device (ICCD) camera (Andor DH720); see Fig. 1. The acquisition gate width, $t_G$, and delay, $t_D$, are determined with a Digital Delay Generator (DDG) (Stanford Research Systems SRS, Model DG535). The spectra are recorded using a gate width of 50 ns at different delays in order to determine the temporal evolution of plasma parameters.

The 1:1 image of the radiation emitted end-on along the axis of the discharge tube is projected on the entrance slit (20 $\mu$m wide) of the Shamrock 303 (Andor) imaging spectrometer using folding mirrors $M_1$ and $M_2$ and a quartz achromatic lens (focal length f = 33 cm). The change of the diffraction grating (300, 1200, or 2400 groves/mm), slit width, and wavelength position is performed using the commercial Andor Solis software. The instrumental width with 2400 g/mm grating and 20 $\mu$m slit width determined using Oriel penlight calibration lamps is 0.09 nm.




(a) (b) (c)

FIG. 2. Current shapes for (a) different discharge tubes for the same gas type Ar + 3% $H_2$, pressure p = 2 mbar, and discharge voltage U = 7 kV, (b) BeO tube with different gasses at the same pressure 2 mbar and the same voltage 7 kV, (c) temporal evolution of voltage and current for the BeO tube and Ar + 3% $H_2$.

## III. EXPERIMENTAL DETAILS AND PROCEDURE

The discharge tube was made and studied under different experimental conditions. Electrode material and dimension, electrodes separation, discharge voltage, initial discharge pressure, and direction of various gas flows through the tube, see Fig. 3, were alternated. The general layout and construction details of discharge tubes with special attention on safety measures are given first in Sec. III A, followed by the electrical characterization and optimization of the discharge in Sec. III B. Influence of discharge parameters on emission spectra is fully described and discussed in Sec. III C, while appearance and some properties of the dust particles formed during the discharge operation are described in the Sec. III D.

### A. Construction details of the discharge tubes

According to Material Safety Data Sheets, MSDS,[29] beryllium, BeO, and especially their dust are highly toxic and must be handled with great precautions. Therefore, the BeO discharge tube with an inner diameter of 2.6 mm, an outer diameter of 10 mm, and an overall length of 130 mm was settled inside the Pyrex glass tube with an inner diameter of 11.5 mm, an outer diameter of 14 mm, and an overall length of 140 mm; see Fig. 3(a). In such a way, exposure of the beryllium tube to atmosphere was prevented. The position of the inner (ceramic) tube inside the outer (glass) tube was adjusted using Teflon rings or Teflon tape; see Fig. 3(a). This extra space prevented cracking or destruction of the tube due to the significant mismatch in the thermal expansion coefficient between the Pyrex glass and BeO tube and/or destruction caused by shock waves generated by pulsed discharge.

Several additional safety measures were undertaken to prevent exposure to beryllium oxide components and especially to the BeO dust. When handling the BeO tube, the surgical gloves, surgical mask, laboratory coat, and goggles were used. Assembling and manipulation of the discharge tube were performed in the fume hood of the chemical part of the laboratory.

The discharge tube connectors had a gas inlet or outlet port and an electrode holder in the middle, ending with Wilson connectors for vacuum tight connection on one side and quartz windows for spectroscopic observations on the other side; see Fig. 3(b). The position of the high voltage connections and electrically isolated support is also presented in Fig. 3(b). Discharge tubes worked under low pressure continuous gas flow. The gas was supplied from the gas cylinder using the regulation and needle valve, with continuous monitoring of gas pressure on the inlet side of the tube. Two positions of the tube inlet were tested, 90° angle and 45° angle relative to the discharge tube axis. The liquid nitrogen cooled trap and HEPA (high efficiency particulate air) filter were inserted in the front of and at the exit of the rotary vane vacuum pump. Gas exhaust from the vacuum pump lead to the pump settled outside the laboratory and equipped with an additional filter.

Two additional tubes were used for the comparative study of the discharge tube material influence on the dust generation. The first one, made of alumina ceramics, $Al_2O_3$, with an inner diameter of 2.6 mm, an outer diameter of 10 mm, and an overall length of 125 mm was settled inside the glass tube with the same dimensions as the one used for the BeO tube. The second one, made of quartz, $SiO_2$, with an inner diameter of 3 mm, an outer diameter of 6 mm, and an overall length of 140 mm was attached with an additional adapter to the same construction; see Fig. 3(c). In Fig. 3(a), the inner diameter of the hollow electrodes, ***d***, is presented. Throughout the experimental course of the study, the value of ***d*** was changing between 0.6 mm and 2 mm.

### B. Electrical characterization and optimization

In this study, different gasses (Ar, Ar with 3% of $H_2$, He + 3% of $H_2$ and 1:1 He/$H_2$ mixture) at different pressures (1, 2, 3, 4, 5, 10, 20, and 90 mbar) were used. As the first step, Pashen curves were determined, and then current shapes were recorded for each gas/pressure/voltage combination. Typical examples of voltage and current shapes are presented in Fig. 2. Current shapes for different tube materials at the same conditions are presented in Fig. 2(a). Comparison of current shapes for the BeO tube with different gasses is illustrated in Fig. 2(b). Temporal evolution of voltage and current for the BeO tube are is presented in Fig. 2(c). As can be seen from the current curves in Fig. 2, the duration of the current pulse was around 10 $\mu$s, while the current maximum was detected around 3 $\mu$s. Besides the basic condition that the discharge voltage must be larger than breakdown voltage, its value should be chosen in a way that parasitic discharge in the space between the ceramic and glass tube, see Fig. 3(a), is avoided. Such discharge may not only introduce spectral lines of impurities in the recorded

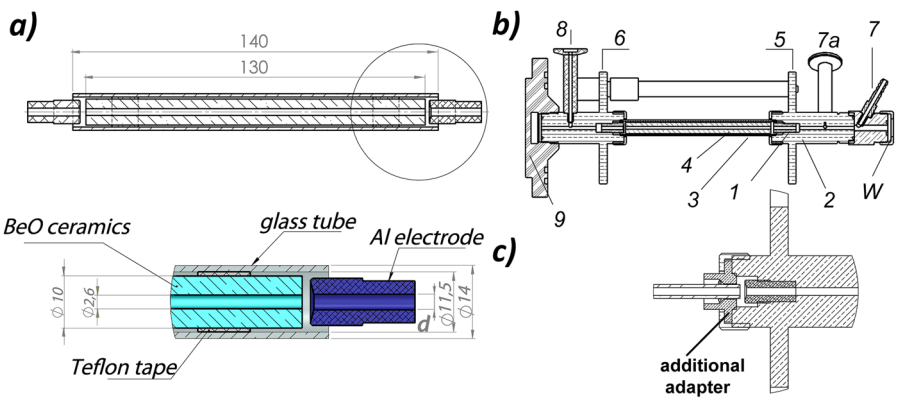



FIG. 3. (a) Construction of the BeO tube and its position inside the glass tube; (b) discharge tube: (1) electrode, (2) holding body, (3) Pyrex glass tube, (4) tube made of BeO or $Al_2O_3$, (5) anode connection, (6) cathode connection, (7) gas inlet at 45° angle, (7a) gas inlet at 90° angle, (8) gas outlet, (9) dielectric support; (c) additional adapter used for the $SiO_2$ tube.

spectrum but also burn the Teflon tape and cause total destruction of the discharge light source. In order to prevent this phenomenon, the discharge tube was first constructed in such a way that electrodes come in the ceramic tube; see Fig. 3. Therefore, the part of the electrode that goes inside the ceramic tube must have outer diameter smaller than 2.6 mm, limiting the maximum inner diameter of the electrode to 1.5 mm. Such electrodes also centre the ceramic tube inside the glass tube. However, the parasitic discharge still appears, Sec. III A. In addition, the optical signal from discharge tubes with such electrodes had very low intensity and poor reproducibility. Therefore, further measurements were performed with construction having a small separation between the ceramic tube and electrodes, and with the Teflon rings being placed toward the middle of the discharge tube. In this configuration, parasitic discharge has never appeared.

Three types of electrodes were tested. First, the electrode made of tungsten with an opening of $\boldsymbol{d}$ = 0.6 mm described earlier[30] was used. The idea was to obtain plasma with higher electron densities and additional plasma emission from the plasma jet at the outer side of the electrode, see Ref. 31, in order to use the spectral line emitted from the plasma jet as a reference line for wavelength shift measurements. Unfortunately, spectral lines of beryllium from the jet were not detected, while the radiation intensity was very low, in addition with a poor reproducibility. The spectra recorded using aluminum alloy electrodes with inner diameters 2 and 3 mm showed similar behavior irrespective of the diameter, while the signal to noise ratio was higher with larger electrode openings. Therefore, all further measurements were performed using aluminum alloy electrodes with 3 mm inner diameter. It should be stressed that under used experimental conditions spectral lines of the electrode material (tungsten and aluminum alloy $AlMgCu_5$) were not observed in the case of the BeO and $Al_2O_3$ tube.

For the optimal conditions for the BeO tube, see Sec. III C 2, the maximum current value goes up to 2.1 kA. The current minimum (observed in the case of $He/H_2$ mixtures) is caused by the change of plasma impedance resulting in periodic current pulse behavior. Namely, the resistor in the discharge circuit was chosen to obtain the aperiodic current pulse with Ar, which is not optimal for discharge with He. The origin of the second maximum detected only when working with Ar and Ar with 3% $H_2$, see Fig. 2, is somewhat more complex and it will be addressed later in Sec. III D.

Here, one should notice that for different inner diameters of BeO, $Al_2O_3$, and $SiO_2$ tubes, current densities through the discharge tubes are different as well: 98 A/mm$^2$ for BeO, 87 A/mm$^2$ for $Al_2O_3$, and j = 69 A/mm$^2$ for $SiO_2$. Taking into account different tube lengths, the energy densities are 0.058 J/mm$^2$, 0.06 J/mm$^2$, and 0.046 J/mm$^2$ for BeO, $Al_2O_3$, and $SiO_2$ tubes, respectively.

## C. Spectra recordings

Since the main objective of this work was the construction of a safe and stable plasma source for beryllium spectral lines' recording, the next step was to examine the change of the spectra under different discharge conditions. Construction details ($\boldsymbol{d}$, gas flow direction), gas type and gas pressure, discharge voltages, etc. were varied and their influence on recorded spectra was monitored. All spectroscopic studies were performed in three steps. The position of the projected plasma image on the ICCD sensor was checked through the recordings with the fully open slit of the imaging spectrometer and with the grating in the zero diffraction order. Afterwards, overall spectra were recorded with the shortest possible delay from the beginning of the current pulse (800 ns in this experiment, determined by reliable triggering of the ICCD camera) using a gate width of 50 ns. Finally, the temporal evolution of the spectra under various conditions was obtained and the influence of the particular discharge condition was studied. The influence of the different construction geometries on discharge operation has already been addressed in Secs. III A and III B, while here the impact of the gas type, pressure, flow, and different applied voltages on the quality of spectral emission is inspected more closely.

### 1. Discharge gas

To study the influence of the gas type on spectra recording, i.e., on the appearance of the tube material's spectral lines, three carrier gasses were used, He with 3% $H_2$, Ar, and Ar with 3% $H_2$. The 1:1 $He/H_2$ mixture was excluded from further measurements since beryllium lines were difficult to detect. Helium was chosen as one of the possible solutions for carrier gas because it has a small amount of spectral lines, while hydrogen is added for diagnostic purposes, since it enabled diagnostics of electron density using separation of the hydrogen Balmer beta line-peaks method.[32] At 1 mbar of gas pressure, capacitor C = 5 $\mu$F charged to 7 kV, and delay of 12 $\mu$s, spectral lines of Be were narrower and had much lower intensity for He + 3% $H_2$ in comparison to Ar and Ar with 3% $H_2$; see Fig. 4. With He + 3% $H_2$ as a carrier gas, only prominent lines of Be appeared in current decay and lasted only few $\mu$s. By contrast, with Ar and Ar with 3% $H_2$, lines of Be lasted 8 $\mu$s longer. The highest intensity of Be lines was obtained using the $Ar/H_2$ mixture. Therefore, all proceeding measurements were conducted using Ar with 3% $H_2$.

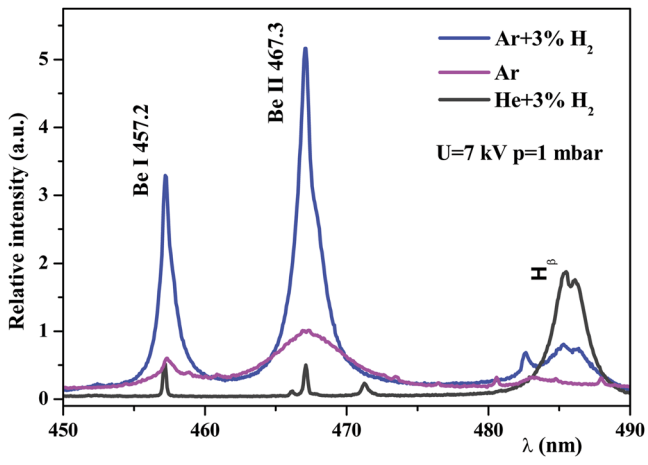



FIG. 4. Influence of different gasses, Ar with 3% $H_2$, Ar and He with 3% $H_2$, on spectral line shapes of beryllium lines and the hydrogen Balmer beta, at discharge voltage 7 kV and pressure 1 mbar, delay 12 $\mu$s.

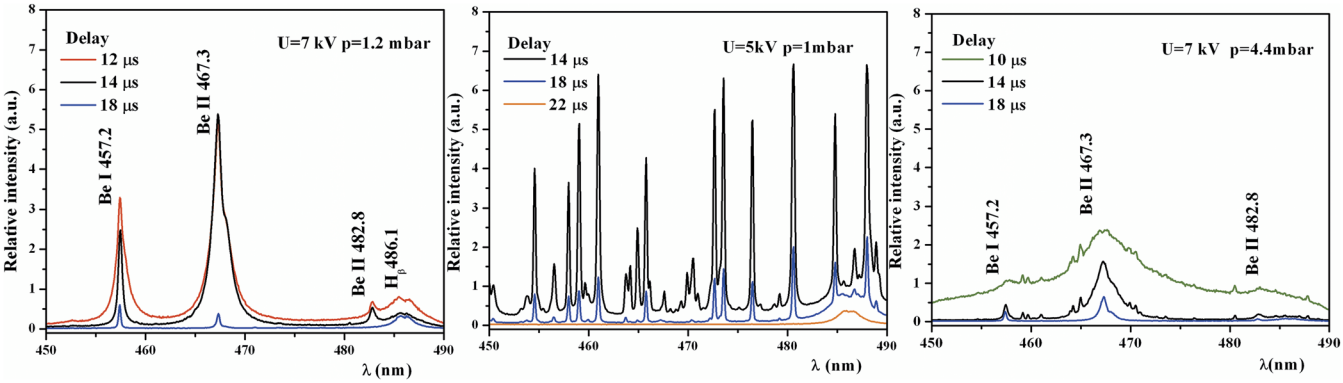



FIG. 5. Influence of different discharge voltage and pressure on spectral line shapes of beryllium in argon with 3% of hydrogen.

Under certain conditions, discussed later in Sec. III D, the dust of the discharge tube material was produced and often accumulated in small electrode openings (if smaller than 2 mm). These particles prevented evacuation of the discharge tube. In addition, with electrodes with 3 mm opening, the dust particles were reaching the observation window, causing degradation of transmittance and lowering of the optical signal. Since the increase of the gas flow rate did not eliminate deposition of dust particles on the observation window, the gas flow direction was reversed; see Fig. 3(b). Also, the additional adapter inlet enabling gas flow under the 45° angle was introduced, see Fig. 3(b), which also helped in preventing dust particle deposition on the window. It was confirmed that the change of the gas flow direction did not affect the spectra recordings, so for the rest of the measurements gas was flowing from the output window toward the discharge tube support.

### 2. Discharge voltage and gas pressure

Spectra recorded for the same gas, pressure, and gate width but different discharge voltages vary significantly. Namely, the differences between spectra were reflected in line intensity, line width, and in appearance of non-beryllium lines. As can be seen in Fig. 5(a), at 7 kV voltage, the beryllium lines are clearly distinguishable, while Ar lines are not observed at delays greater than 10 $\mu$s, i.e., after the current pulse. On the contrary, at a discharge voltage of 5 kV, spectra are rich in spectral lines of discharge gas. Spectral lines of the gas appeared during and lasted after the current pulse, while spectral lines of the tube material were not observed, Fig. 5(b). That is probably due to low abrasion, i.e., low quantity of beryllium in the plasma, or due to overlapping of Be spectral lines with stronger lines of Ar. The same is to be expected when using voltages less than 5 kV. Even though dust particles are produced at voltages of 7 kV, only at higher voltage of 8 kV they were deposited on the glass windows, lowering optical transparency in spite of all undertaken measures described in Sec. III C 1. Therefore, all forthcoming measurements were performed at a discharge voltage of 7 kV.

Gas pressure influences greatly the Be spectral line intensity. A slight increase of pressure leads to more effective excitation of argon and appearance of argon lines in spectra. At a pressure of 4.4 mbar shown in Fig. 5(c), the spectral lines of Be are broader and the continuum is more pronounced, compared to Fig. 5(a). This is most probably due to the increase of electron density. On the other hand, the intensity of Be lines is lower and argon lines are observed. Here, one should have in mind that the spectral line at 467.3 nm presented in Fig. 5 is the most intense beryllium line recorded in this study, i.e., other spectral lines have very low intensity, if observed at all at a pressure of 4.4 mbar and higher. Therefore, all proceeding measurements were conducted at a pressure of 1.2 mbar in order to record spectral lines of beryllium.

The temporal evolution of spectra recorded between 330 nm and 660 nm with the beryllium tube is presented in Fig. 6. The spectra were recorded for the conditions described earlier, i.e., Ar with 3% $H_2$ and gas pressure 1.2 mbar (gas discharge voltage 7 kV), which were found to be optimal. At early delays (around 10 $\mu$s), see Fig. 6, spectral lines of argon and pronounced continuum were evident. After current pulse, the intensity of spectral lines of the discharge tube material was increasing, reaching the maximum value approximately at the time of the second maximum of the current pulse; see Fig. 2. The maximum intensity of the tube material's spectral lines was detected around 12 $\mu$s. At that time, lines of Be were prominent and Ar spectral lines were not detected. The beryllium lines were detected in spectra up to 25 $\mu$s.

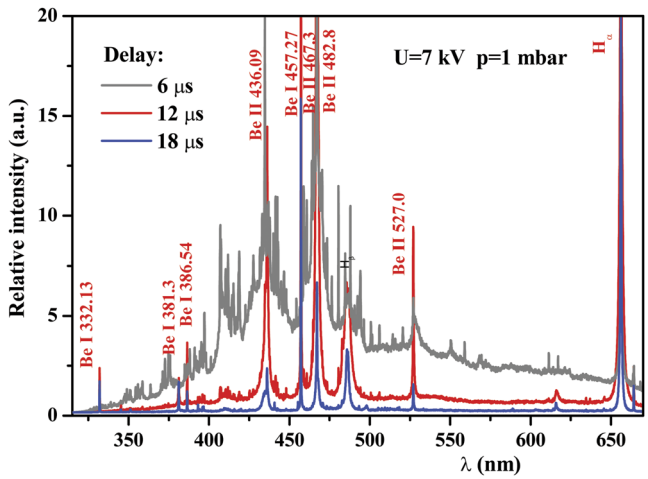



FIG. 6. Temporal evolution of the spectra between 320 nm and 660 nm in low pressure pulsed discharge with the beryllium tube.

### 3. Comparison of plasma spectrum recorded from different tube materials

As mentioned previously, three different tube materials were used. Emphasis is placed on the BeO tube, while spectra obtained using tubes made from $SiO_2$ and $Al_2O_3$ were used for comparison. In Fig. 7, spectra recordings with the tubes made of different materials are presented. The optimal conditions for measuring line shapes of Be were concluded to be at C = 5 $\mu$F, U = 7 kV, gas Ar + 3% $H_2$, and p = 1.2 mbar. At those same conditions, spectral lines of Al emitted from the $Al_2O_3$ tube were self-reversed, in consequence of self-absorption, while spectra when using the $SiO_2$ tube could not be recorded because of occasional glass tube breaking and saturation of the optical signal, even with the shortest gate. The best line/continuum ratio for recordings with the glass $SiO_2$ tube was achieved at C = 5 $\mu$F, U = 4 kV, gas Ar + 3% $H_2$, and p = 3 mbar, while for the $Al_2O_3$ tube those conditions were at C = 5 $\mu$F, U = 6 kV, gas Ar + 3% $H_2$, and p = 1.5 mbar.

Temporal evolutions of spectral lines emitted from the tube material differ for all the three cases. In early times (during the current pulse), there were no spectral lines of Be or they were not resolved due to overlapping with numerous much stronger Ar lines and intense continuum; see Sec. III C 2. Spectra of lines emitted from the $SiO_2$ and $Al_2O_3$ tubes were impossible to record at early delays due to the more intense continuum, which caused saturation of the optical detector even at shortest gate time. As mentioned in Sec. III C 2, the lines of beryllium were detected in spectra up to 25 $\mu$s delay. The lines emitted when using $SiO_2$ and $Al_2O_3$ tubes were more persistent and they were observed in spectra up to 40 $\mu$s delay. In spectra obtained with the $SiO_2$ tube, two very narrow aluminum lines coming most probably from aluminum alloy ($AlMgCu_5$) electrodes were detected. Spectral lines from the electrode's material did not appear in BeO tube's spectra. The dust particles were formed in all three cases.

From the results of the spectroscopic studies with tubes made of different materials and at various plasma conditions, one can conclude that, if the space between the discharge tube and electrodes exists, a cooler discharge region is formed which enables the study of self-absorbed line shapes.

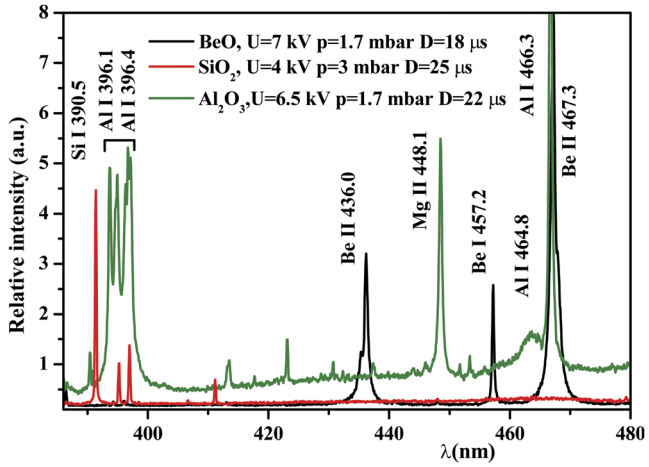



FIG. 7. Comparison of spectra from low pressure pulsed discharge observed for three different tubes under optimized conditions.

### 4. Plasma diagnostics

In order to characterize the plasma source, the electron density, $N_e$, and temperature, $T_e$, were determined by using the iterative method.

The electron number density during plasma afterglow was estimated using peak separation $\Delta\lambda_{ps}$ of the hydrogen Balmer beta line by using formula (6) from Ref. 32,

$$\log N_e\,(\mathrm{m}^{-3}) = A + B\,\log\,\Delta\lambda_{ps}(\mathrm{nm}) = 22.65 + 1.53\,\log\,\Delta\lambda_{ps}(\mathrm{nm}). \quad (1)$$

In order to use that formula, the value of $T_e$ was presupposed to be 13 000 ± 3000 K, and based on $T_e$, the corresponding value of parameters A and B was taken from Ref. 32. Using this range of $T_e$, the uncertainty of $N_e$ was 30%. For, in such a way, determined electron number densities, the temperature was estimated from the ratio of Be II 467.3 nm/Be I 457.3 using the following formula:

$$\frac{I_1}{I_2} = \frac{h^3}{2(2\pi mk)^{3/2}}\frac{(gA)_1\lambda_1 N_e}{(gA)_2\lambda_2 T_e^{3/2}}\exp\left(\frac{E_2 - E_1 + E_1^{ion} - \Delta E}{kT_e}\right), \quad (2)$$

where $E_1{}^{ion}$ is the ionization potential and $\Delta E$ is the ionization potential lowering.

After few iteration, $N_e$ and $T_e$ were determined. Transition probabilities were taken from the NIST database.[33]

Succeeding the determination of the excitation temperature and electron density, it is necessary to check if the conditions for LTE (Local Thermodynamic Equilibrium) have been met. The expression (12) from Ref. 34 in the case of beryllium sets the boundary value of the electron concentration to be $2.85 \times 10^{22}$ $\mathrm{m}^{-3}$ for the temperature of 14 200 K. This means that the conditions for the complete LTE in the plasma used in this experiment have been met. Given that only three neutral and three ionic spectral lines were recorded, and considering that those transitions have very similar upper level energies, the use of the Boltzmann plot could not provide more precise values of $N_e$ and $T_e$.

The temporal evolution of $T_e$ and $N_e$ during plasma afterglow is presented in Fig. 8.

It can be seen from Fig. 8 that $N_e$ has increased after the end of the current pulse. The second maximum of $N_e$

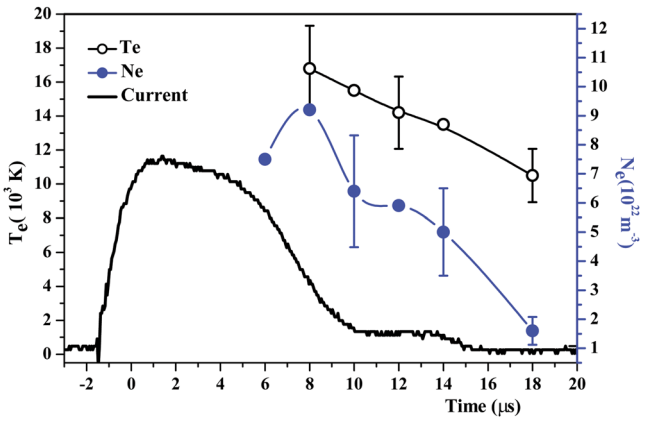



FIG. 8. Evolution of $T_e$ and $N_e$. $N_e$ is determined from peak separation of the hydrogen Balmer beta line,[32] and $T_e$ is estimated using the ratio of intensities of beryllium lines, Be II 467.3 nm and Be I 457.3.

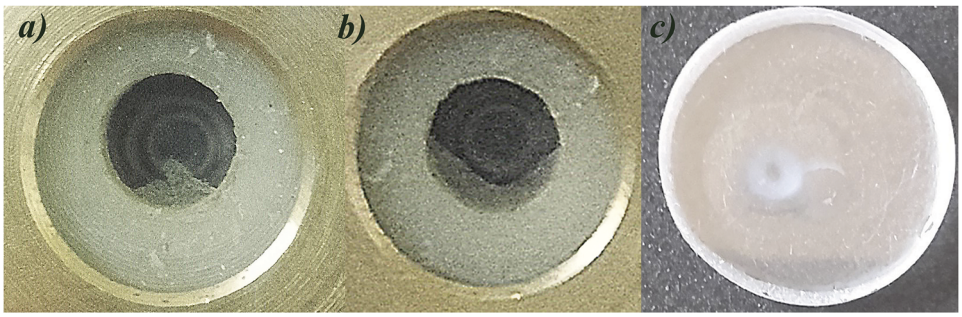



FIG. 9. Two forms of dust deposits: (a) cone, (b) half-moon, (c) degradation of the observation window caused by dust particles' deposition.

coincides with the second maximum of the current pulse, i.e., with the time position characterized by the most intense Be spectral lines around 12 $\mu$s. As a conclusion, it can be said that optimal conditions for Be spectral line shape measurements are achieved with C = 5 $\mu$F, U = 7 kV, gas Ar + 3% $H_2$, and p = 1.2 mbar and that Be lines reach their maximum intensity at t = 12 $\mu$s.

### D. Generation of dust particles

Throughout the course of the source construction and optimization of Be line shape measurements, significant quantity of the dust was produced. The appearance of the dust particles may be related to the existence of the second current maximum which is most likely to be a consequence of the formation of negative ions that are the precursors of particle formation;[35] see Fig. 2. Namely, the electron density, as shown in Fig. 8, follows the current shape and this increase of the electron density after the main current pulse could be related to the charging and de-charging (ionization and recombination) of particles inside the plasma volume, as observed earlier in the pulsed complex plasma.[36,37] Anomalous behavior of the current pulse was used as a first sign that beryllium was ablated from the tube wall and that the Be spectral line should appear in the observed spectrum. Visible dust particles in the discharge were observed in the form of deposits on the observation window. These particles were noticed with gas flowing from the discharge tube support toward the output window. With the increase of discharge voltage, the generation of dust particles became more pronounced and appearance of the dust particles' deposit on the observation window became clearly visible. After a few operational hours, the deposit covered window completely decreasing optical signal to that extent that further spectroscopic measurements were impossible. The interesting fact is that with subsequent current pulses two forms of the dust deposits were observed: cone shaped after odd current pulse and "half ring" shaped after even current pulse; see Figs. 9(a) and 9(b), respectively, and the supplementary material in the form of movie. All measurements had to be taken in 1 h, and after this time the accumulated dust had to be removed and window had to be cleaned. To enable longer measurements, the gas flow direction was reversed, meaning gas was flowing from the output window toward the discharge tube support; see Sec. III C 1. In this configuration, dust deposits were not observed, but the degradation of window still occurred; see Fig. 9(c). This degradation of the window stopped occurring when the special inlet at an angle of 45° with respect to the discharge tube axis was installed; see Fig. 3(c). This inlet did not prevent the degradation of the window when working with pressures less than 1 mbar and voltages higher than 7 kV.

Deposits on the observation window were easily cleaned and since the BeO is highly toxic, the dust particles were collected by exfoliation using adhesive tape, with all safety precautions; see Sec. III A. After that, tape was folded in order to insure dust particle isolation. When larger quantities of dust was collected from the discharge tube or from the liquid nitrogen trap, a special handling and disposal procedure was performed. The dust particles were mixed with the PMMA component in the glass bowel, after that the second component, resin, was added and the polymer with BeO dust was produced. In such a way, safe handling and disposal of toxic dust was enabled. For further precaution, the glass bowel is closed with the lid, thus preventing the possibility of evaporation if heated.

In order to study conditions for producing dust particles in the discharge, two additional tubes made from alumina and quartz were constructed; see the description in Sec. III A. For both tubes, dust particles were formed. Indication for dust formation was the appearance of the second current maximum; see Fig. 2(b). Although the occurrence and duration of the second current maximum, hence dust production, were slightly different for all three tubes, there were some common features: the dust was always formed when Ar was used as discharge gas; smaller retention of particles was observed for higher pressures; the deposition of particles on the observation window was more pronounced when working with low pressures and high voltages. However, two forms of dust deposits (cone shaped and "half ring"), which can be seen when working with the BeO tube, were not noticed. Also, with the $SiO_2$ tube, dust was accumulated on the window even with reverse gas flow and with a 45° angle inlet installed.

The study about the influence of dust movements on spectral line shapes is in progress. Due to the high toxicity of dust, the shapes and dimensions of the obtained particles were not studied in this work.

## IV. CONCLUSIONS

In this work, the construction details and optimization of the low pressure pulsed discharge for safe beryllium spectra studies in the presence and in the absence of dust particles were presented. Beryllium lines were obtained from erosion of the discharge tube made of beryllium oxide ceramic, BeO.

Electrical and spectroscopic studies were used for determination of the capacitance C, discharge voltage, gas type, and pressure, as well as electrodes distance, diameter of electrode openings, and other construction details. As a result, optimal conditions for beryllium lines observation are determined: low inductance 5 $\mu$F capacitor charged to 7 kV, 1.2 mbar of Ar + 3% $H_2$, 3 mm diameter of the electrode opening and the smallest possible distance between electrodes and ceramic tube, see Fig. 3 and Sec. III C 2. At discharge voltages greater than 7 kV, the productions of dust particles became excessive, thus preventing the study of the discharge tube material's particles on spectral line shapes. Using discharge tube modifications, i.e., with the gas inlet at 45° angle and reversed gas flow, longer measurements were enabled.

Under the optimized conditions, studies of Be lines in the presence of the Be dust were enabled for the first time. From the point of signal to noise ratio, optimal emission spectra of Be were obtained from 10 to 20 $\mu$s (measured from the beginning of the discharge), Fig. 2, coincident with the time of the second current maximum appearance. This shape of the current pulse was used as a first sign that beryllium was ablated from the tube wall and that the Be spectral line should appear in the observed spectrum. Stable operation of this novel beryllium plasma source creates the possibility of deepening the knowledge about the atomic data of Be, very much needed for the *in situ* examination of plasma facing materials in the tokamak by LIBS.

Hypothesis of relation between the second current maximum and optimal spectral emission from the tube material was proved using two additional tubes made of $SiO_2$ and $Al_2O_3$, even though discharge conditions differ. The dust particles were formed from all the three tubes. In this way, it is shown that this kind of low pressure pulsed discharge can be used for dust production and introduction of various materials into the plasma.

## SUPPLEMENTARY MATERIAL

See supplementary material for the illustrations of two forms of dust deposits inside the discharge tube.

## ACKNOWLEDGMENTS

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LETTER

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# Forbidden component of the Be II 436.1 nm line recorded from pulsed gas discharge plasma

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PACS 52.70.Kz – Optical (ultraviolet, visible, infrared) measurements

**Abstract** – We report results of the experimental study of the singly charged beryllium spectral line 436.1 nm, transition $3p^2P^o$-$4d^2D$, and forbidden component, transition $3p^2P$-$4f^2F^o$, which is for the first time identified in this work. Beryllium lines are recorded from gas discharge, after ablation of a beryllium oxide discharge tube, running in pulsed regime with the following gases: helium with traces of hydrogen, argon with traces of hydrogen and pure krypton. The ratio of line intensities and wavelength separation of the Be II 436.1 nm line and neighbouring line located at the blue wing are followed in the electron density range $(1.16–6.4) \times 10^{22}\,\mathrm{m}^{-3}$ determined from the hydrogen Balmer beta line ($H_\beta$) in the electron temperature interval between 10500 K and 15500 K. The functional dependence of the wavelength separation range and peak intensity ratio of these lines upon electron number density suggests the complex profile of the forbidden and allowed line, which can be used for diagnostics of low-temperature beryllium containing plasmas.

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**Introduction.** – The subject of this experimental study is an investigation of the shape of the Be II 436.1 nm line which appeared with a strong component, located at the blue wing, in our gas discharge [1]. The assumption was that this may be the forbidden component of the allowed line 436.1 nm, and this work is an attempt to prove this hypothesis. If proven, this result will partially fill the gap between the investigations of this type of transitions along a lithium isoelectronic sequence, with already published data for Li I [2–4], C IV [5–7] and N V [7].

The spectral lines with forbidden components attracted attention some time ago, see, *e.g.*, [8], because of numerous applications in the field of Stark broadening theory testing, for electron number density, $N_e$, laboratory plasma diagnostics and in astrophysics for the analysis and modelling of the star atmosphere, see, *e.g.*, [9]. In addition, in the case of beryllium lines there are two more specific applications. One is related to the study of the inner plasma-wall interaction in ITER (International Thermonuclear Experimental Reactor) since this wall is considered to be covered with beryllium [10]. The other important field of application is in astrophysics, considering that beryllium is a naturally occurring element in metal-poor stars [11].

Here, it should be emphasized that under a forbidden component (transitions with $\Delta l \neq \pm 1$, where $l$ is the angular momentum quantum number) we consider lines which occur as a result of the breakdown of the parity selection rules induced by ambient plasma electric microfield. This effect has nothing to do with the forbiddeness associated to magnetic dipole, electric quadrupole or higher multipole transitions. A forbidden line starts to appear close to the allowed one when wave functions become mixed. It happens when plasma broadening of the allowed line becomes comparable with the energy levels separation between the allowed transition and the nearest dipole allowed perturbing level or levels. With an increase of the electric field (*i.e.*, an increase of the charged particles density), the mixing of the wave functions becomes stronger, and the wavelength difference between the allowed and forbidden components peaks becomes more pronounced. A further increment of the electric field brings an overall profile of the line shape close to the one of a hydrogen-like emitter with linear Stark effect. The conclusion here is that the overall shape of these lines is sensitive to the charged particle

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density. Therefore, it can be used for the $N_e$ plasma diagnostics. It should be stressed that plasma conditions when a forbidden component becomes significant differ from element to element and even from line to line. The overall shape of lines with forbidden components to a smaller extent depends also on the electron temperature, reduced mass and ratio between electron and gas temperature [12], which opens possibilities for other plasma parameters diagnostics. The most frequently studied spectral lines of this type belong to the visible spectrum of He I, see, *e.g.*, [8,13,14]. The application of parameters of these lines for electron density diagnostics is demonstrated in several publications and references therein [12,15–21]. In addition, parameters of these lines are applied also for DC electric-field measurements, see, *e.g.*, [22,23].

To achieve the aim of this work, we recorded the overall shape of the Be II 436.1 nm line, together with nearby lines, in a discharge tube with different carrier gases. Simultaneously, $N_e$ and the electron temperature, $T_e$ and the dependence of the line profile parameters upon $N_e$ were determined.

**Experiment.** – In this section the experimental setup, the measurement procedure as well as the method and results of plasma diagnostics will be described. The experimental apparatus was set up as for the standard end-on linear discharge plasma observation, see, *e.g.*, [1]. For data acquisition two spectra recording systems were used. In both cases the 1:1 axial image of the plasma source was projected onto the entrance slit of a monochromator, by the use of a focusing mirror and achromatic lens, see fig. 6 in [24]. Almost all spectral line shape recordings were performed using an imaging spectrometer (Shamrock 303 Andor), having instrumental half-width of 0.09 nm equipped with ICCD camera DH734 (Andor). These line shape recordings were performed with full vertical binning and gate width of 50 ns at various delay times. Delay times from the beginning of the current pulse, monitored by the Rogowski coil were determined with a digital delay generator (Stanford Research Systems, DG535). In order to check the influence of the instrumental broadening to the line shape, the cross-check with a second high-spectral-resolution recording system was performed. The spectra were obtained using a 1 m monochromator (McPherson Model 2051), having the instrumental half-width of 0.02 nm. This monochromator was supplied with a stepping motor and photomultiplier radiation detector, PMT (EMI 9658 R). The signal from the PMT was observed by the digital oscilloscope Tektronix TDS360 (bandwidth 200 MHz), triggered by the signal supplied from the Rogowski coil. The step motor rotates the diffraction grating of the monochromator so that, at different wavelengths, the radiation intensity can be recorded. The computer simultaneously collects data from the oscilloscope and controls the step motor. The end signal represents the mean value of 4 consecutive signals. This shot-to-shot technique was justified considering that the pulse-to-pulse current reproducibility was better than 2%. More details about data acquisition and data manipulation can be found in [24].

Plasmas are created in a BeO ceramic discharge tube with inner diameter of 2.6 mm, outer diameter of 10 mm and length of 130 mm. Beryllium spectral lines are detected in the discharge after evaporation of Be off the inner tube wall by ablation induced by the discharge itself. Here, it should be emphasized that due to the toxicity of beryllium, a special procedure in handling the discharge tube and ablation products was always adapted [1]. The most important result of the previous study [1] is that the optimum conditions for excitation of Be spectral lines in our discharge are achieved when the capacitor $C = 5\,\mu$F is charged up to 7 kV in argon with 3% of hydrogen at $p = 1.2$ mbar. At lower discharge voltages only lines of the carrier gas appear in spectra [1]. In addition, only at low gas pressure, $p < 5$ mbar, the percentage of the beryllium atoms in the discharge becomes significant and Be becomes the main plasma constituent and most of the Be spectral lines appear in the recorded spectra.

In order to characterize the plasma source, diagnostics of $N_e$ and $T_e$ were performed. The electron number density, $N_e$, was determined from the peak separation $\Delta\lambda_{ps}$ of the $H_\beta$ line using formula (6) from [25]:

$$\log N_e[\mathrm{m}^{-3}] = A + B\log\Delta\lambda_{ps}[\mathrm{nm}] = 22.65 + 1.53\log\Delta\lambda_{ps}[\mathrm{nm}]. \quad (1)$$

The values of parameters $A$ and $B$ are taken from [25] for a presupposed electron temperature of $13000 \pm 3000$ K. For electron number densities determined in such a way, the electron temperature, $T_e$ was estimated from the ratio of Be II 467.3 nm/Be I 457.3 line intensities using the formula

$$\frac{I_1}{I_2} = \frac{h^3}{2(2\pi mk)^{3/2}}\frac{(gA)_1\lambda_1 N_e}{(gA)_2\lambda_2 T_e^{3/2}} \times \exp\left(\frac{E_2 - E_1 + E_1^{ion} - \Delta E}{kT_e}\right). \quad (2)$$

After several iterations $N_e$ and $T_e$ were determined. The required transition probabilities were taken from the NIST database [26].

Since the Be lines have noticeable intensity in a very short time interval, the plasma diagnostics was performed only for times between 8 $\mu$s and 18 $\mu$s from the beginning of the current pulse. It should be stressed that $N_e$ was determined only with a gas mixture of Ar with 3% $H_2$, since the intensity of the $H_\beta$ line under other experimental conditions was negligible. Namely, in the stated delay times interval, lines of other elements have very low intensity with the exception of O II lines (originating from the ablation products of BeO ceramics) and $H_\beta$. The recorded O II lines have a width equal to the instrumental width and they are located on the broad wings of the studied Be II line shape, see fig. 2, and, therefore, they are not convenient for $N_e$ diagnostics. The intensity of $H_\beta$ line

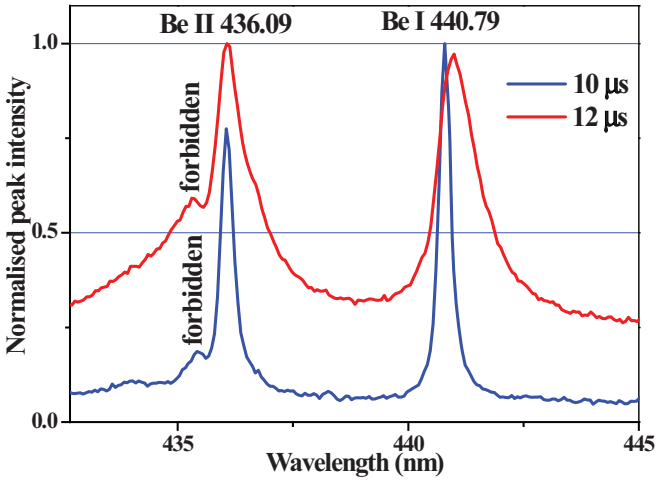


Fig. 1: (Colour online) Beryllium spectrum between 429 nm and 445 nm with normalised peak line intensities recorded in 1.2 mbar of He + 3% $H_2$ gas mixture at discharge voltage of 7 kV at different delays after beginning of the discharge current pulse.

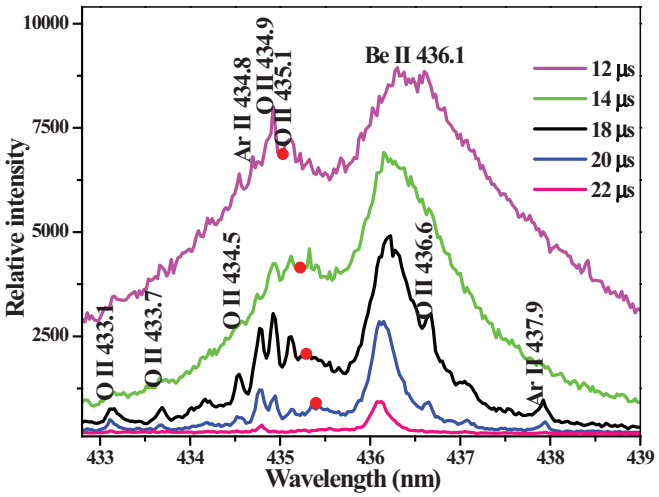


Fig. 2: (Colour online) Temporal evolution of the Be spectrum between 433 nm and 439 nm, recorded at discharge voltage of 7 kV at 1.2 mbar of Ar with 3% of $H_2$. The wavelength positions of the peaks are taken from [25]. Peak intensity and wavelength position of the forbidden component are denoted with circles and presented in table 1.

at the time of interest in helium with 3% of hydrogen gas mixture was very weak and not usable for diagnostics as well. Small contribution of hydrogen traces in krypton plasma prevented detection of $H_\beta$ line, also. The use of strong Be lines for $N_e$ diagnostic has a significant drawback since their Stark widths may introduce inaccuracy due to pronounced self-absorption and even self-reversal in the case of resonant lines 313.0 nm and 313.1 nm.

**Results and discussion.** – The main result of this experimental study is the identification of the forbidden component $3p^2P$-$4f^2F^o$ allong with allowed component $3p^2P^o$-$4d^2D$ of the Be II line at 436.1 nm in various gases. Although it has been previously stated [1] that the best conditions for excitation of beryllium lines were achieved when the carrier gas was argon, we first present the results in He with 3% $H_2$ plasma, see fig. 1. The reason for this being that in spectra recorded when the carrier gas was He with 3% $H_2$, only beryllium lines appeared, *e.g.*, there are no other lines that could entail confusion in the determination of a forbidden line shape and peak wavelength position.

However, in such discharge, beryllium lines appeared in a shorter period of time (10–$n$12 $\mu$s). In order to confirm that the recorded line belongs to singly ionized beryllium and to analyse the possible influence of the Ar II and O II lines on the wavelength position and intensity of the forbidden component, spectra recordings were performed for Ar and Kr using the same discharge conditions that were employed for He with 3% $H_2$.

In fig. 2 recordings made from Ar plasma are presented. It can be seen that on the blue side of Be II 436.1 nm the appearance of other spectral lines can call into question the presence of the forbidden Be II line in the spectra presented in fig. 2. Lines which may interfere with the Be II 436.1 nm overall line profile belong to hydrogen Balmer gamma ($H_\gamma$) 434.0 nm, Ar II at 434.81 nm and O II at 434.91 nm and 435.1 nm.

Having in mind the Stark shift and intensity of the $H_\gamma$, this line influence on the Be II 436.1 nm profile, at our experimental conditions, is small. Namely, for the estimated $T_e$ of 10500 K–15500 K the $H_\gamma$ line has at least twice lower peak intensity than the $H_\beta$ line, recorded at the same experimental conditions, see fig. 5 in [1], and even smaller intensity at the position of the forbidden component due to the $\Delta\lambda^{-5/2}$ line wing dependence.

In order to resolve the influence of other non-hydrogenic plasma constituents, spectra recordings presented in fig. 2 were performed with smaller instrumental broadening, *i.e.*, the apparatus with better resolution, see section "Experiment". From the results in fig. 2 one can conclude that the Ar II and O II lines may interfere in the determination of the peak wavelength position of the forbidden component. Fortunately, the difference in line widths (the forbidden line is much broader) confirms the existence of the forbidden component.

In the case of Kr plasma, fig. 3, the forbidden line is clearly visible, but its peak intensity and wavelength position are different in comparison with Ar plasma, under the same excitation conditions. Also, the appearance of the forbidden component in the Kr plasma is prolonged.

Differences between spectra recorded in various gases are illustrated by the change of ratio between the intensity of the allowed Be II line 436.1 nm and Be I line 440.79 nm, see figs. 1 and 3, thus indicating that the plasma parameters are incomparable.

In order to use the Be II line 436.1 nm with forbidden component $3p^2P$-$4f^2F^o$ for plasma diagnostics, the functional dependence of the wavelength separation between

Table 1: Temporal variation of $N_e$, $T_e$, $s$ and $F/A$ in argon with 3% of hydrogen for $p = 1.2$ mbar and $U = 7$ kV.

| $t$ ($\mu$s) | $N_e$ ($10^{22}$ m$^{-3}$) | $T_e$ (K) | $s$ (nm) | $F/A$ |
|---|---|---|---|---|
| 10 | 6.40 | 15500 | 1.5 | 0.97 |
| 12 | 5.90 | 14200 | 1.3 | 0.78 |
| 14 | 5.00 | 13500 | 1.01 | 0.68 |
| 16 | 3.01 | 11980 | 0.93 | 0.55 |
| 18 | 1.16 | 10500 | 0.88 | 0.38 |
| 20 | | | 0.74 | 0.26 |

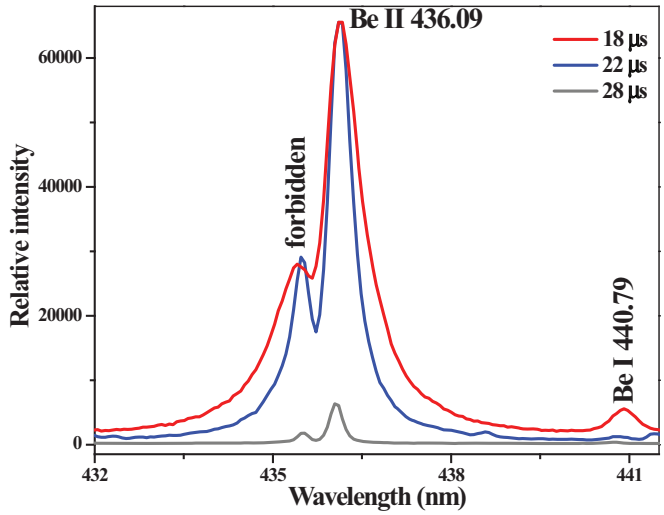


Fig. 3: (Colour online) Temporal evolution of the Be spectrum between 429 and 445 nm, recorded at discharge voltage of 7 kV at 1.2 mbar of Kr.

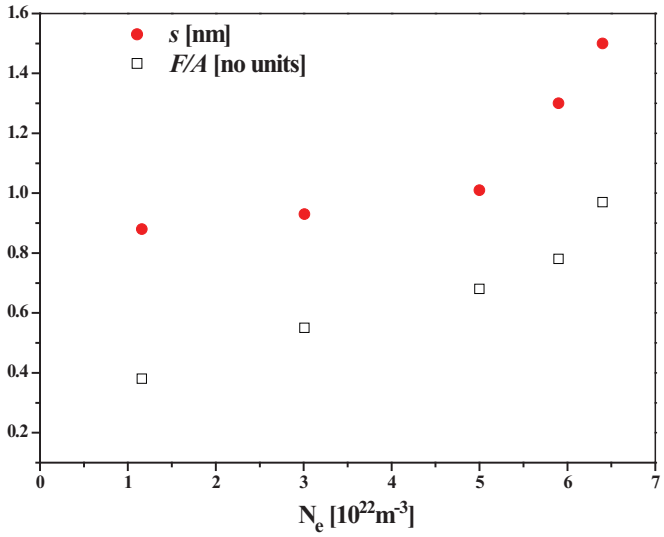


Fig. 4: (Colour online) The dependence of wavelength peaks separation $s$ and peaks intensity ratio $F/A$ dependence upon $N_e$ for Be II allowed $3p^2P^o$-$4d^2D$ component and forbidden $3p^2P$-$4f^2F^o$ component at $p = 1.2$ mbar of Ar + 3% $H_2$ at $U = 7$ kV.

their peaks $s$, and/or the ratio between the maximum intensities of the forbidden component and allowed component, $F/A$, upon $N_e$ should be determined. Unfortunately for our experimental conditions the Be II lines appear in a short time interval in which diagnostics of $N_e$ is very difficult. Nevertheless, in spite of all the difficulties to determines the $s(N_e)$ and $F/A(N_e)$ dependences, we made an attempt to demonstrate the potential of this line with the forbidden component for the plasma diagnostics application, see fig. 4 and table 1.

The range of $s$ and $F/A$ and the corresponding $N_e$ determined in the case of Ar with 3% $H_2$ suggests the possibility of using the Be II 436.1 nm line with forbidden component for plasma diagnostics purposes. Namely, it is shown that under our experimental conditions ($p = 1.2$ mbar, $U = 7$ kV and $C = 5\,\mu$F) during plasma generation and decay $s$ changes between 0.74 nm and 1.5 nm, while $F/A$ changes between 0.26 and 0.97 in the range of electron densities $(1.16–6.4) \times 10^{22}$ m$^{-3}$ and electron temperatures 10500 K–15500 K. The aforesaid functional dependence of wavelength separation and intensity ratios of two lines upon electron density are typical for lines with forbidden components. Unfortunately, a small $N_e$ range does not allow the determination of the best-fit formulas $N_e = f(s)$ or $N_e = f(F/A)$ for reliable plasma diagnostics.

**Conclusions.** – On the bases of our experimental study we conclude that the spectral line located at the blue wing of the Be II 436.1 nm line, transition $3p^2P^o$-$4d^2D$, has all the characteristics of the forbidden transition. In order to prove that this line originates from the forbidden $3p^2P$-$4f^2F^o$ transition we carried out several studies like wavelength analysis of plasma impurities, measurement of the wavelength separation and ratios of two line intensities *vs.* electron number density. All results are indicating that the forbidden line $3p^2P$-$4f^2F^o$ is present in spectra of our discharge, which is well illustrated in figs. 1–3. The functional dependence of the wavelength separation and intensity ratios of two lines upon electron density are typical for lines with forbidden components, see, *e.g.*, He I lines [12,18–21]. Thus, on the basis of all the presented results one may conclude that the line at the blue wing of Be II 436.1 nm line, is a forbidden line belonging to the $3p^2P$-$4f^2F^o$ transition. Finally the wavelength separations and the ratios of peak line intensities in table 1 cannot be used for the testing of the overall line shape modelling of this beryllium allowed line with forbidden component since the influence of the allowed line optical thickness and additional electric field has not been examined in this work. For the same reason the data in table 1 may be applied for low-temperature plasma diagnostics with great precautions. One interesting application can be for the $N_e$ determination during *in situ* examination of plasma facing materials in tokamak (containing beryllium) by laser-induced breakdown spectroscopy (LIBS) [27], in which electron density and temperature ranges are close to the values studied in this work.

On the basis of the analysis of energy levels along a lithium isoelectronic sequence for Li I [2–4], C IV [5–7], NV [7] and our results for Be II, we propose the study of the B III line 195.38 nm from the same transition $3p^2P^o$-$4d^2D$ in order to check whether the forbidden components, $3p^2P$-$4f^2F^o$ and $3p^2P$-$4f^2P^o$ will appear. In the present study of the Be II lines the forbidden component $3p^2P$-$4f^2P^o$ was not detected.

* * *

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## ABSTRACTS of INVITED LECTURES, TOPICAL INVITED LECTURES and PROGRESS REPORTS

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# APPEARANCE OF Be II 436.1 nm LINE WITH FORBIDDEN COMPONENT IN LIBS PLASMA

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**Abstract.** In this work study of LIBS on BeO target in low pressure gas mixture of Ar (97 %) and $H_2$ (3%) using a nanosecond pulsed laser with 266 nm wavelength is presented. The appearance of forbidden component of Be II 436.1 nm was observed and presented in comparison with the previously acquired results for pulsed gas discharge plasma.

## 1. INTRODUCTION

The results of the experimental study of the singly charged beryllium spectral line 436.1 nm, transition $3p^2\ P^o$- $4d^2\ D$, and its forbidden component, transition $3p^2\ P$-$4f^2\ F^o$, were previously reported, e.g.: see Stankov et al. 2018.a In this paper beryllium lines were recorded from gas discharge running in pulsed regime, after ablation of beryllium oxide (BeO) discharge tube. The plasma source was described in detail, e.g.: see Stankov et al. 2018.b.

The reason for the necessity of devising another experiment, to examine Be II with forbidden line, is twofold: a) there were dust particles in the pulsed discharge plasma observed, e.g.: see Stankov et al. 2018.b.; b) published experimental results can not be used for testing of the overall line shape modeling because the influence of the allowed line optical thickness and additional electric field has not been accounted for, e.g.: see Stankov et al. 2018.a.

LIBS stands for Laser Induced Breakdown Spectroscopy technique that uses a short laser pulse to create plasma on the sample surface. Analysis of this plasma enables determination of material's elemental composition, without sample preparation and with simple experimental setup. Difficulties that arise during analysis are mainly associated with the fast evolving plasma which demands well temporally and spatially resolved measurements.

This paper explores the possibility of recording Be II line with forbidden component in LIBS plasma. As a comparative study, LIBS method was chosen because it is assumed there will be no dust particles production. Besides, experimental setup used for LIBS plasma creation gives the possibility for spatially resolved measurements and experimental testing of self-absorption, which could not be performed in gas discharge experiment. Aim of this study is to check the possibility of spatially and temporally resolved measurements of Be line with forbidden component in dust free environment.

## 2. EXPERIMENT

Experimental apparatus for pulsed gas discharge plasma recordings, e.g.: see Stankov et al. 2018.b, was set up as for the standard end-on linear discharge plasma observation. Axial image of the plasma source was projected onto the entrance slit of a spectrometer (Andor Technology, Shamrock 303), by the use of a focusing mirror and achromatic lens. For line shape recordings the imaging spectrometer was equipped with iCCD camera (Andor Technology, model DH734). Line shape recordings were performed with full vertical binning and gate width of 50 ns at various delay times.

For the LIBS method, the fourth harmonic of Nd:YAG Q-switched laser (Quantel, Q-smart 450) at 266 nm, with repetition rate of 10 Hz, was used. The pulse energy at 266 nm was 70 mJ, on the average. The laser beam was focused perpendicular to the BeO target by the means of biconvex achromatic lens L1 ( f1 = 100 mm), see Figure 1.

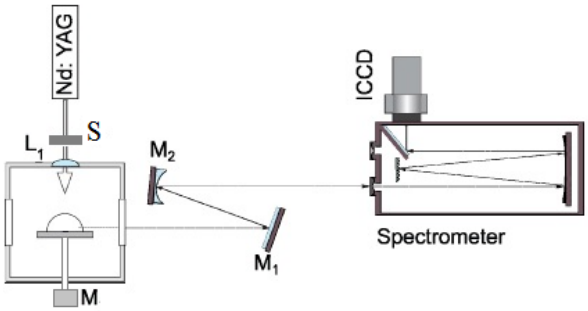


Figure 1: LIBS setup

Target made from BeO ceramics was glued to the carrier, which was rotated by the motor (M), in the low pressure chamber. 1 : 1 image of the plasma plume was projected by optical mirrors M1 and M2 on the entrance slit (20 μm wide) of a 0.5 m Ebert-type spectrometer (f/8.6 equipped with a grating of 1180 grooves per mm). The spectrometer was mounted with an iCCD camera (Andor Technology, model DH734I-18U-03, with 1024 x 1024 pixels, 13 x 13 μm size, 18 mm intensifier diameter). The iCCD camera was operated in the image mode and controlled using a pulse generator (DDG 535, Stanford Research Systems) triggered optically by the occurrence of plasma on the BeO target. Fast photodiode placed towards the target was used to convert the light signal. The shatter (S), placed between the laser and the lens L1, was changing open/close position for every 16 laser shots. Images of the plasma were accumulated over 16 laser shots and the final signal was the product of 10 such accumulations. Accumulation of the signal was performed to exclude the influence of the eventual shot-to-shot changes in the signal. The acquisition gate width was 100 ns.

## 3. RESULTS AND DISCUSION

Diagnostics of plasma parameters, the electron number density, *Ne,* and electron temperature, *Te,* was used for characterization of two experimental methods.

For optimal conditions in the pulsed discharge plasma electron number density, *Ne,* was determined from the peak separation $\Delta\lambda ps$ of the $H_\beta$ line using formula (6) from e.g.: see Ivković et al. 2015. *Te* was estimated from the ratio of Be II 467.3 nm/Be I 457.3 line intensities, using formula (1):

$$\frac{I_1}{I_2} = \frac{h^3}{2(2\pi mk)^{3/2}} \frac{(gA)_1 \lambda_1 N_e}{(gA)_2 \lambda_2 T_e^{3/2}} exp\left(\frac{E_2 - E_1 + E_1^{ion} - \Delta E}{kT_e}\right), \quad (1)$$

where $E_1{}^{ion}$ is ionization potential and $\Delta E$ is ionization potential lowering.

After several iterations *Ne* and *Te* were determined, and presented in Table 1, e.g.: see Stankov et al. 2018.a. Maximum values of *Ne* and *Te* are measured to be $9.3 \cdot 10^{22}$ m$^{-3}$ and 16800 K.

For LIBS method, the chamber was filled with 10 mbar of Ar (97%) and $H_2$ (3%) mixture. The previously mentioned experimental conditions were chosen in order to achieve maximum Be and H line intensity.

Experimental profile of the Hα line fitted with Voigt function was used for determination of *Ne* in LIBS plasma. Stark halfwidth, $w_S$, is determined by assuming $w_S = w_L$ and introducing this result in Eq. (12), e.g.: see Konjević et al. 2012. Instrumental line profile was measured at several wavelengths using Oriel penlight calibration lamp. *Te* was estimated from the ratio of Be II 467.3 nm/Be I 457.3 line intensities, equation (1). The electron density and plasma temperature are displayed in Figure 2a as functions of time. Temporal evolution of Be II nm with forbidden component is presented in Figure 2b. Forbidden component, transition $3p^2$ P- $4f^2$ F$^o$, is easily seen on the blue wing of Be II, transition, $3p^2$ P$^o$-$4d^2$ D.

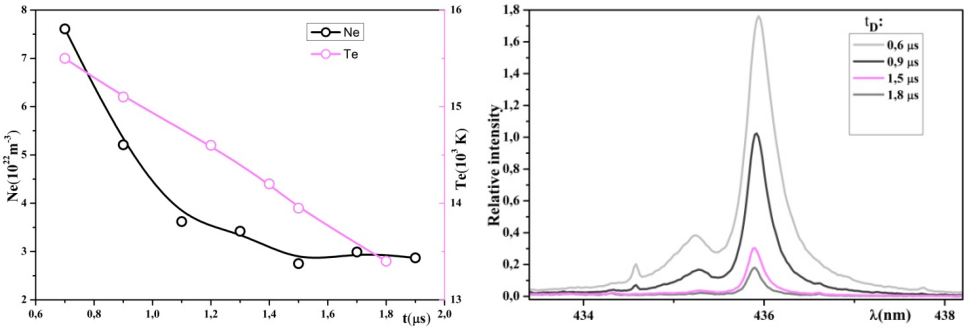


Figure 2: a-Temporal evolution of Ne and Te for LIBS on BeO target, b-Temporal evolution of Be II with forbidden component for LIBS on BeO target

The dependence of wavelength peaks separation *s* and peaks intensity ratio *F/A* upon *Ne* for Be II allowed and forbidden component is shown in Figure 3.

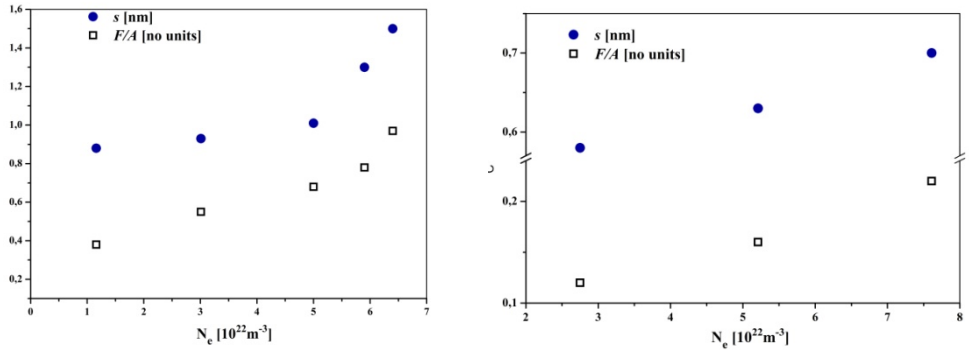


Figure 3: wavelength peaks separation *s* and peaks intensity ratio *F/A* dependence upon *Ne* for Be II Line with forbidden component for: a) pulsed discharge plasma b) LIBS plasma

Slight discrepancy between s[nm] values for two experimental setups exists. More notable discrepancy is observed for F/A values. Reason for this may be presence of self-absorption and spatial inhomogenity in both experimental setups. The example of spatially resolved Be II 436.1 nm line is presented in Figure 4.

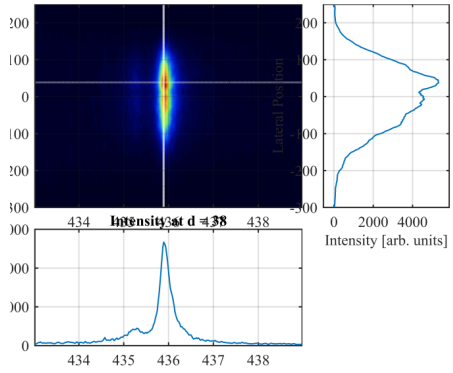


Figure 4: Spatially resolved Be II 436.1 nm line in LIBS plasma

In the next step of investigation, *Ne* and *Te* will be determined using spatially resolved measurements of Be and H lines. Since there were no dust particle observed, as assumed, results obtained from LIBS experiment may be used to evaluate the effect of dust particles on Be line parameters obtained from gas discharge.

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|---|---|
| **Chair: Volker Hoffmann** | |
| 10:45-11:10 | KM-4: Z. Weiss - *Excitation and ionization of iron in argon and neon glow discharges: non-LTE considerations* |
| 11:10-11:25 | OM-02: J. Fandiño - *Concentric-electrodes atmospheric pressure glow discharge for the analysis of volatile organic compounds* |
| 11:25-11:40 | OM-04: B. Stankov - *Uncovering beryllium line with forbidden component* |
| 11:40-11:55 | OM-06: A. Ganeev - *New possibilities of time-of-flight mass spectrometry with pulsed glow discharge in combined hollow cathode* |
| 11:55-12:10 | OM-08: L. Lobo - *Quantification strategies for the analysis of major and minor components by means of pulsed Glow Discharge Time-of-Flight Mass Spectrometry* |
| 12:10-12:25 | OM-10: V. Brückel - *Mass spectral imaging of iodinated contrast agents in biological tissue samples by means of LA-FAPA-MS* |
| 12:25-14:00 | *Lunch* (*Exhibition Hall*)<br>Shimadzu lunch seminar (*room Alphand*)<br>Anton Paar lunch seminar (*room Monpezat*) |
| 14:00-15:10 | **Poster sessions** *(salle des Ambassadeurs)*<br>**Fundamentals** (posters MP-1 – MP-44)<br>**Glow Discharge Spectrochemistry** (posters MP-45 – MP-52)<br>**Sample Introduction and Transport Phenomena** (MP-53 – MP-65) |

| **PARALLEL SESSION: SINGLE PARTICLE ANALYSIS (1)** (Auditorium Alfred de Vigny) | |
|---|---|
| **Chair: Jan Preisler** | |
| 15:10-15:35 | KM-5: H. Goenaga Infante - *The power of micro-second detection ICP-MS for the accurate determination of nanoparticle number concentration: Underpinning metrology for biomedical applications* |
| 15:35-15:50 | OM-11: F. Laborda - *About detectability and detection limits in single particle ICP-MS* |
| 15:50-16:05 | OM-13: K. Inagaki - *Multi-spray CGrid nebulizer for perfect matrix-matching in single-particle ICP-MS* |
| 16:05-16:20 | OM-15: D. Mozhayeva - *A novel data processing strategy for quantification of nanoparticles and dissolved metals in mixtures with SP-ICP-MS and microsecond time resolution* |
| 16:20-16:35 | OM-17: K. Chun - *Double-Viewing-Position SP-ICP-AES* |

# OM-04 Uncovering beryllium line with forbiden component

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Beryllium is uniquely strong and light element, it has six times the specific stiffness of steel and at the same time it is one-third lighter than aluminum which makes it suitable for a wide range of applications: aerospace, information technologies, energy exploration, medical and other. Beryllium is naturally occurring element in metal-poor stars **[1]**. Also, beryllium has been chosen as the element to cover the first wall of international thermonuclear experimental reactor (ITER) **[2]**. But still, spectroscopic investigations and Stark parameters studies are almost exclusively limited to Be(II) resonance lines at 313 nm. The reason for the lack of experimental data may be found in the toxicity of beryllium.

During this research novel plasma source was constructed in order to safely record the beryllium lines in laboratory condition **[3]**. Beryllium lines appeared as a result of the ablation of the discharge tube made of ceramic, BeO. The presence of dust particles was also observed. It is found that the optimal conditions for Be spectral line shapes measurements are achieved with C = 5 F, U = 7 kV, gas Ar +3% H2, p = 1.2 mbar. The electron density, Ne, and temperature, Te, were determined by using the iterative method. The electron number density during plasma afterglow was estimated using the peak separation Δps of the hydrogen Balmer beta line and the electron temperature is determined from the ratios of the relative intensities of Be spectral lines emitted from successive ionized stages of atoms.

From this pulsed discharge plasma, several beryllium lines were observed and amongst them the Be(II) 436.09 nm line with a forbidden component detected for the first time, to the authors knowledge. This result partially fills the gap between the investigations of this type of transitions along lithium isoelectronic sequence, with already published data for Li(I), C(IV), and N(V).

**Keywords:** beryllium lines, forbidden lines, optical emission spectroscopy, spectral line shapes, plasma sources, dusty plasma

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β - Corresponding author: biljanas@ipb.ac.rs


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## ABSTRACTS OF INVITED LECTURES, TOPICAL INVITED LECTURES, PROGRESS REPORTS AND WORKSHOP LECTURES

Editors:
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Duško Borka and Milan Rajković

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# NANOPARTICLES ON A SAMPLE SURFACE AS LASER INDUCED BREAKDOWN SPECTROSCOPY ENHANCERS

M. Vinić[1,2], M. R. Gavrilović Božović[1], B. Stankov[1], M. Vlainić[1] and M. Ivković[1]

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**Abstract.** Signal enhancement of Laser Induced Breakdown Spectroscopy in the presence of gold nanoparticles was studied. Nanoparticles were synthesised using pulsed laser ablation of the rotating Au target immersed in liquid mediums. Stability of nanocolloids was estimated. Nanosuspensions were applied to sample surface what enabled studies of Nanoparticle Enhanced Laser Induced Breakdown Spectroscopy. The effect of spectral line enhancement was observed under the optimised conditions both for neutral and ionic lines of the studied sample material.

## 1. INTRODUCTION

Laser Induced Breakdown Spectroscopy (LIBS) is emission spectroscopy technique that uses a short laser pulse to create plasma on the sample surface, and analyses formed plasma to gather information about the sample studied. Despite of all its advantages (fast response, no or minimal sample treatment, simple setup, requires only optical access to the sample), lower detection limit is the largest drawback of this technique. One way of signal enhancement is deposition of metallic nanoparticles on sample surface before laser irradiation. In this way, the order of magnitude enhancement of optical signal can be obtained [1,2].

In this work, nanoparticles (NPs) were synthesised using laser ablation of the bulk gold in liquid medium, and then applied on the surface of the sample. Surface prepared in such a way was than irradiated with the laser beam, Nanoparticle Enhanced LIBS (NELIBS) plasma was formed and spectra were recorded. It was shown that application of Au NPs on the target surface prior to laser induced breakdown leads to signal enhancement of sample's element optical emission.

## 2. EXPERIMENT

Experiment was conducted in several steps. Firstly, it was necessary to synthesize Au NPs, uniform by size and shape. Next, the size of the NPs needed

to be evaluated, based on the position of a Surface Plasmon Resonance (SPR) band maximum. In order to do that, absorption spectra of all produced colloids were recorded with spectrophotometer [3-5]. After that, synthesised colloids of NPs ought to be applied to analysed metal target ($AlMgCu_5$), where proper volume of the colloid drop and surface coverage had to be determined experimentally. As a final step, conditions for NELIBS spectra recordings had to be optimised.

Method of choice for NPs synthesis was laser ablation in different solutions. Experimental setup consisted of laser (Nd:YAG, 2nd harmonic 532 nm), mirror for guiding the laser beam (45° angle), focusing lens of 2.5 cm focal length and rotating table on top of which cuvette with a solution and immersed Au target were positioned., see Figure 1a. In order to find the optimal conditions for NPs generation, laser energy and wavelength were changed. Also, different distances between the target and lens were set, so different energy densities on the target surface were obtained, leading to the NPs of various sizes. Duration of ablation was varied in order to obtain different colloid concentrations. NPs were synthesized in water (distilled and deionized) and in different organic solvents (DMSO, Acetonitrile and Chloroform) [6]. Characterisation of formed nanocolloids was performed with measurements of SPR band using spectrophotometer Beckman Coulter DU720. Stability of formed solutions was also estimated.

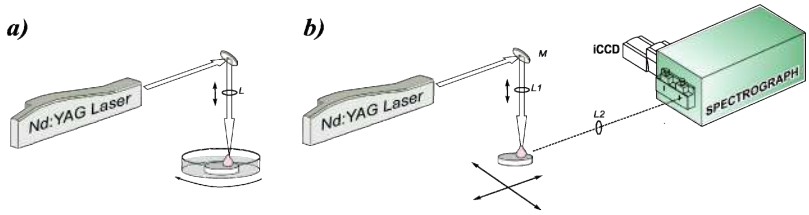


**Figure 1.** Experimental setup: a) for synthesis of Au nanocolloid; b) for NELIBS.

Experimental setup used for measurements of NELIBS spectra of prepared samples consisted of: laser (Nd:YAG, 2nd harmonic 532 nm), mirror (45° angle), focusing lens of 2.5 cm focal length ($L_1$) and lens for focusing NELIBS plasma ($L_2$, f=20cm) onto the entrance slit of detection system (imaging spectrometer equipped with ICCD camera), see Figure 1b. Position of the projection lens $L_2$ with respect to the spectrometer was varied, i.e. different portions of the plasma volume were collected by optical system, which had prove to have direct consequence on the spectral line emission enhancement.

## 3. RESULTS AND DISCUSION

When a metal particle is exposed to light, the oscillating electromagnetic field induces a collective coherent oscillation of conduction band electrons. The amplitude of the oscillation reaches maximum at a specific frequency, called surface plasmon resonance. The SPR induces a strong absorption of the incident light and thus can be measured using a UV–Vis

absorption spectrometer [5]. Based on the measured position of SPR band maximum, sizes of Au NPs were estimated, see Figure 2a. After few days, recordings were repeated in order to verify stability of solutions, Figure 2b. The variations in position of the SPR maximum were almost negligible after two days, leading to the conclusion that produced colloids are rather stable. Significant change in the SPR maximum position was only detected four days after the colloid synthesis.

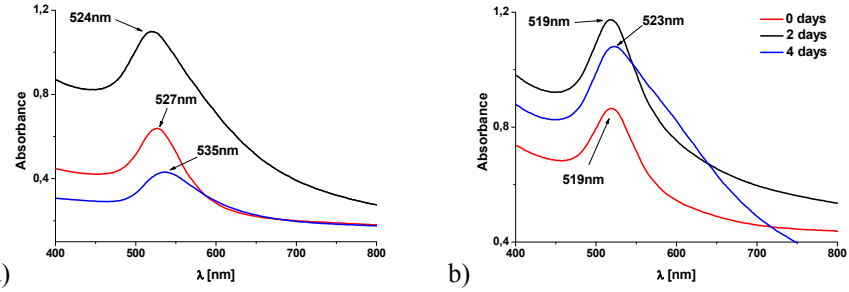


**Figure 2.** SPR band of formed solutions: a) size estimation; b) stability check.

Estimated sizes of Au NPs (30±5 nm) [3] were in the range of sizes that have already been reported to produce NELIBS effect [1], even two days after synthesis. Besides NPs size, important parameter for line intensity enhancement is the NP surface concentration. It was found that after certain limit, further increase of concentration does not contribute to signal enhancement [2]. In order to test that, nanocolloid was first applied on the sample surface in a form of large droplets (~10µl). In this case, the deposition of colloid was inhomogeneous such that the concentrations at the edges were higher than at the center, i.e. “"coffee-ring" effect [7], resulting in noticeable enhancement only when particular place on a drop was irradiated. This indicates that, with the large droplets, surface concentration of NPs was above critical, leading to decreased NELIBS performance [7]. Since enhancement is strongly dependent on the total amount of colloid, smaller droplets should be used. Having this in mind, further on microdroplets (0.5 µl) were applied with micropipette on the previously irradiated surface of the target.

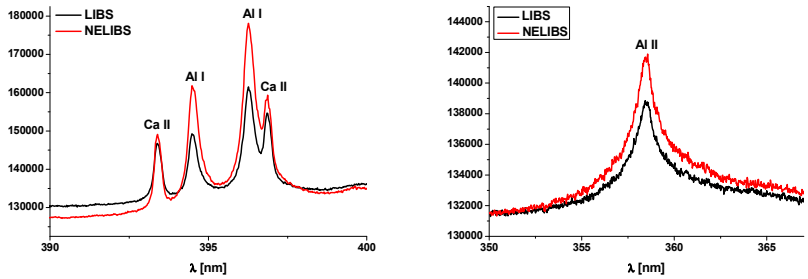


**Figure 3.** Comparison of LIBS and NELIBS spectra for neutral and ionic lines of main target constituent.

Spectra obtained with microdroplets are shown in Fig. 3. All presented spectra were recorded with single shot. Further enhancement of optical signal could be obtained if signal accumulation was performed. Increase of signal intensity was present in both neutral and ionic lines. Enhancement of spectral line intensity was more pronounced in case of neutral lines, possible due to larger emission volume of NELIBS plasma. Since LIBS and NELIBS plasma have similar plasma parameters [1], larger emission volume of NELIBS plasma means more contributions from "colder" layers which are emitters of mostly neutral lines. It is important to emphasize this was the reason why lens $L_2$ was positioned in such a way that complete plasma volume was focused to the spectrometer. This configuration corresponds to the maximum signal enhancement.

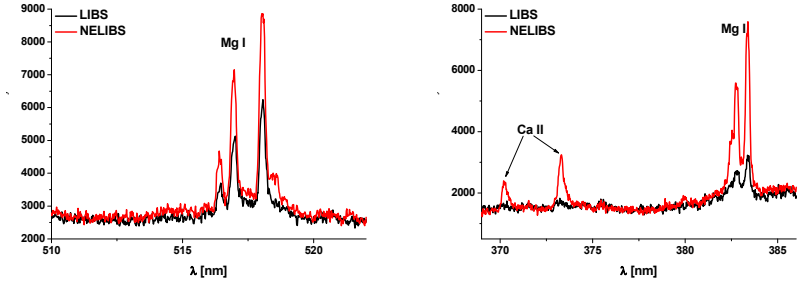


**Figure 4.** Comparison of LIBS and NELIBS spectra of minor elements in sample.

Fig. 4 illustrates intensity increase of spectral lines of magnesium which is minor sample constituent. Also, lines of Ca appeared in NELIBS spectra. Calcium can be present in $AlMgCu_5$ in small amounts, but also can come from water used as a medium during the NPs synthesis. Because of this uncertainty, it can be concluded that this method is not reliable for investigations of calcium containing samples.

## Acknowledgements

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

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# CONTRIBUTED PAPERS

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## ABSTRACTS OF INVITED LECTURES, TOPICAL INVITED LECTURES, PROGRESS REPORTS AND WORKSHOP LECTURES

Editors:
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# BERYLLIUM SPECTRAL LINE STUDIES IN THE PRESENCE OF BERYLLIUM DUST

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Beryllium is the element which has six times the specific stiffness of steel and at the same time it's one-third lighter than aluminum which makes it suitable for a wide range of applications: aerospace, information technologies, energy exploration, medical and other. Since Be is also naturally occurring element in metal-poor stars [1] study of the spectral lines emission of beryllium is important for astrophysics. Also, the beryllium has been chosen as the element to cover the first wall of ITER (International Thermonuclear Experimental Reactor) [2]. Hence, basic knowledge about beryllium spectral emission is available but still spectroscopic investigations and Stark parameters studies are almost exclusively limited to Be II resonance lines at 313 nm. In this research special plasma source was made in order to broaden the studies of spectral line shapes of beryllium [3]. Guideline during the construction of the source was to prevent exposure to formed dust, considering the toxicity of beryllium. Plasma source characterization through determination of optimal working conditions is described. It is found that the optimal conditions for Be spectral line shapes measurements are achieved with C = 5 μF, U = 7 kV, gas Ar +3% $H_2$, p = 1.2 mbar. Beryllium lines appeared as a result of the ablation of the discharges tube made of ceramic, BeO. The presence of dust particles is also observed. The electron density, Ne, and temperature, Te, were determined by using the iterative method. The electron number density during plasma afterglow was estimated using the peak separation $\Delta\lambda_{ps}$ of the hydrogen Balmer beta line, and the electron temperature is determined from the ratios of the relative intensities of Be spectral lines emitted from successive ionized stages of atoms.

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## ABSTRACTS OF INVITED LECTURES, TOPICAL INVITED LECTURES, PROGRESS REPORTS AND WORKSHOP LECTURES

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# CHARACTERIZATION OF AN ATMOSPHERIC PRESSURE PULSED MICROJET

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**Abstract.** The results of an experimental study of atmospheric pressure pulsed microjets in helium and gas mixture are presented. The images of plasma jet propagation were recorded and emission spectra from glass discharge tube and plasma jet were analyzed and compared. From helium spectral lines electron density was calculated for several different configurations of discharge source. Temporal dependence of electron density was determined. The influence of various capacitors and discharge voltages on plasma jet emission and propagation were studied also.

## 1. INTRODUCTION

Atmospheric pressure He microdischarges have many different configuration and many applications. Most of them are constructed in order to obtain cold plasmas for medical and plasma chemical applications. It can be used for cleaning, decontamination, etching, or coating surfaces at atmospheric pressure and low temperature. [1] One reason for why plasma jets are advantageous is because even though the electrons are hot, the overall gas is at room temperature. Another important advantage of using atmospheric plasmas is the possibility to process materials which are not resistant to vacuum. [2,3] The main disadvantage of such microdischarges is high consumption of He.

Here, we present attempt to construct and characterize low flow atmospheric pressure He single pulse plasma microjet.

## 2. EXPERIMENT

Schematic sketch of pulsed atmospheric pressure plasma jet is shown in Figure 1a. The experimental setup consists of microjet, focusing optic, radiation intensity detection system (imaging spectrometer equipped with ICCD camera), computer and electronics system for synchronization, detector gating and spectrum storage, Figure 1b:

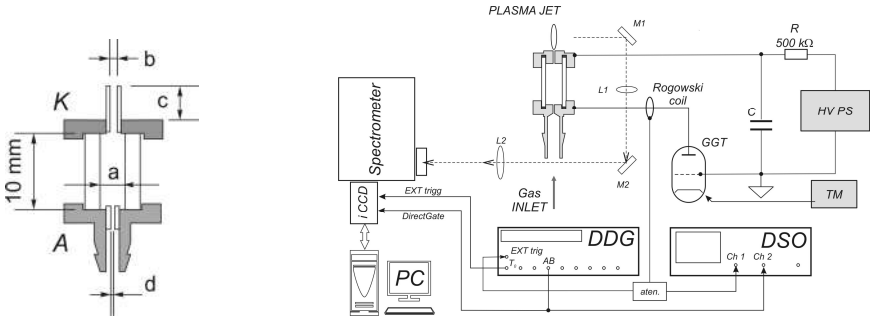


**Figure 1.** a) Microjet; b) Experimental setup.

Light emitted from microjet was focused by the use of lens $L_1$ having focal length of 32 cm. For the recordings of plasma jet images an additional lens $L_2$ was used having focal length of 17 cm.

Plasma image was projected on the 20 μm wide entrance slit of the 0.3 m imaging spectrometer Andor Shamrock 303, equipped with ICCD camera. The camera gating was performed with digital delay generator (DDG) by processing signal from Rogowsky coil which was used for current pulse measurements. The spectra were recorded at different delay times in respect to beginning of current pulse monitored by digital storage oscilloscope (DSO). The fast pulse discharge is driven by a different capacitors - C, charged with high voltage power supply - HV PS.

In microjet gas is fed through a hole in center of lower electrode (d), with passage trough glass tube and output through hole in an upper electrode (b) see Fig. 1a. Glass tubes with various inner diameters were used (a). In some cases, stainless steel tubes (SST) of different lengths were placed in upper hole (c), Table 1.

**Table 1.** List of different configurations of microjet.

| label | MJ1 | MJ2 | MJ3 | MJ4 | MJ5 | MJ6 | MJ7 | MJ8 | MJ9 | MJ10 | MJ11 | MJ12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| a [mm] | 4 | 4 | 4 | 4 | 4 | 4 | 2 | 2 | 1 | 1 | 1 | 2 |
| b [mm] | 0.50 | 0.70 | 0.70 | 0.70 | 0.70 | 0.45 | 0.70 | 0.45 | 0.70 | 0.70 | 0.45 | 0.5 |
| c [mm] | 0 | 6 | 15 | 0 | 6 | 6 | 6 | 6 | 0 | 6 | 6 | 0 |
| d [mm] | 0.50 | 0.10 | 0.10 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 |

First step of our experiment was to record plasma images. After analyzing images, next step was to record spectrum of main discharge and plasma jet area. Helium and gas mixture (He with 1.5% $CO_2$ and 1.5% $N_2$) were used as carrier gasses. For the electron density determination we used the separation between allow and forbidden component of He I 447.1 nm line [4].

## 3. RESULTS AND DISCUSION

Due to an insufficient space in this publication we show only several results out of large number of images and spectra recordings.

Images of jet propagation were recorded, see example in Figure 2. First image depicts emission from discharge tube and plasma jet. In order to record images of jet, emission from discharge tube was blocked. It was discovered that jet appears 1 µs after beginning of discharge current, reaches maximum intensity at 2.5 µs and lasts until 14 µs. Based on these observations time and spatial position of subsequent measurements were selected. Another result from images appeared - in this type of discharge there is no plasma propagation, i.e. plasma stays in contact with upper electrode.

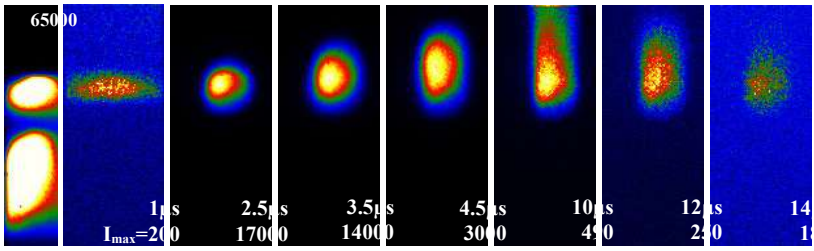


**Figure 2.** Images of jet evolvement. Each image is normalized to max light intensity.

In order to obtain aperiodic waveform of discharge current the resistor (0.4 Ω) connected in series with discharge was used. Figure 3 illustrates different current waveforms depending on used capacitor and applied voltage:

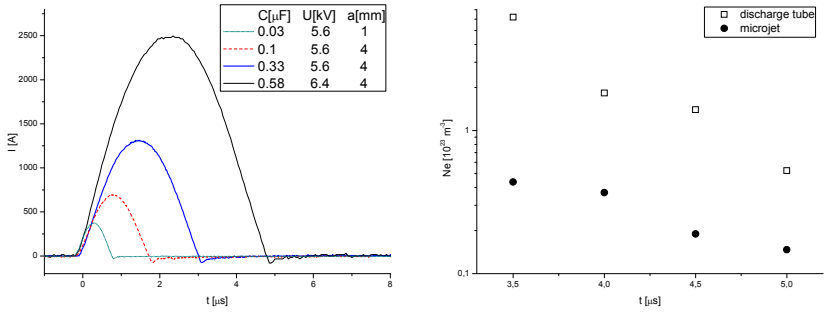


**Figure 3.** a) Current waveform depending of C and U; b) Temporal dependence of electron density for discharge tube and microjet (MJ12), C=0.33 µF, U=3.6 kV.

Temporal dependence of Ne for microjet without SST is shown in Figure 3b. Strong continuum obstructed estimation of Ne at the beginning of discharge so first evaluated Ne value is at 3.5 µs. At that moment, electron density in discharge tube is $6.2 \cdot 10^{23}$ $m^{-3}$, while Ne in jet is $4.4 \cdot 10^{22}$ $m^{-3}$.

The distinction between spectra from discharge tube and jet is shown in Figure 4a.

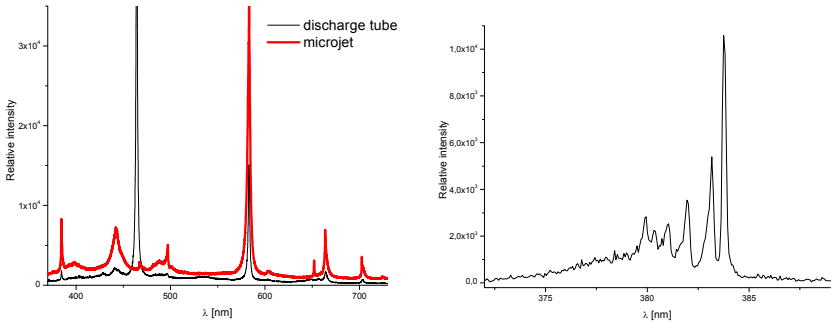


**Figure 4.** a) Comparison of spectra from discharge tube and microjet (MJ1), C=0.33 μF, U=5.6 kV; b) $N_2^+$ FNS (MJ8), C=0.33 μF, U= 5.6 kV.

Molecular bands of $N_2$ were detected in spectra when gas mixture was used as carrier gas, see Figure 4b. This is an indication that plasma jet temperature is low.

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