Time-integrated optical and extreme ultraviolet emission studies of the laser produced neon and nitrogen plasmas

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Outline

- Motivation and aims
- Experimental setup and theoretical simulations
- Results of investigations
- Summary and outlook

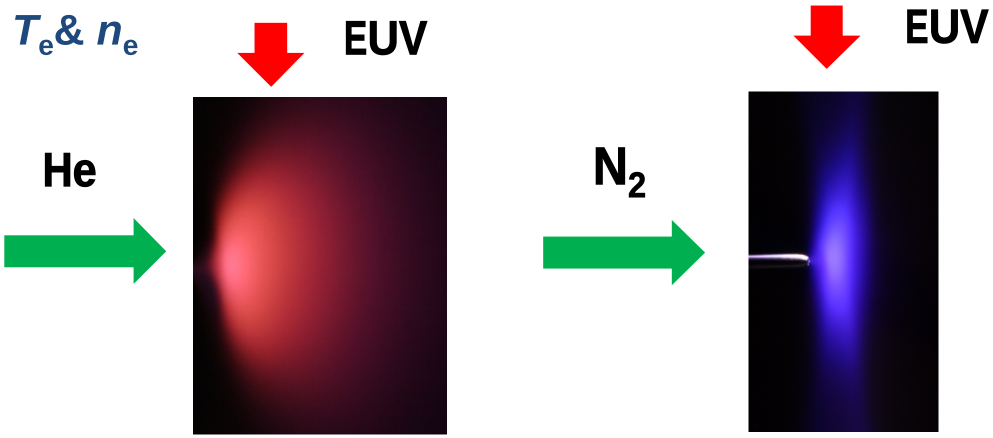
MOTIVATION AND AIMS

Motivation

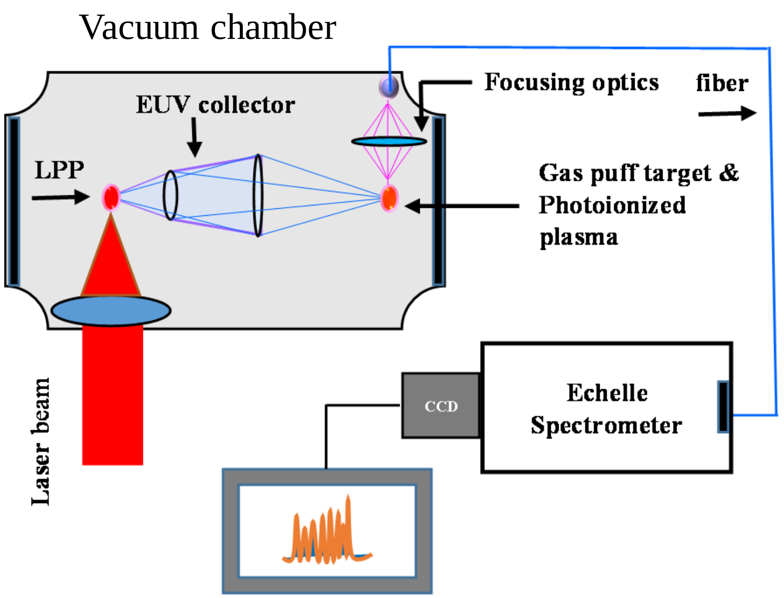
- **Plasmas can be produced by photoionization of atomic and molecular gases with the use of intense EUV nanosecond pulses**
- **Spectral investigations of plasmas provide information about the kinetics and plasma parameters**
- **Research on photoionized plasmas is applicable in astrophysics and technology**

Aims

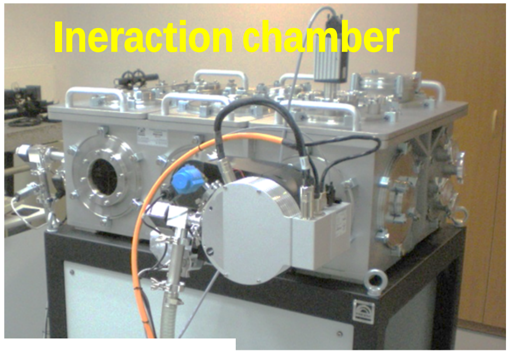
- **To study atomic processes in photoionized plasmas created by LPP EUV/SXR sources.**
- **Estimate basic plasma parameters, T_e& n_e**

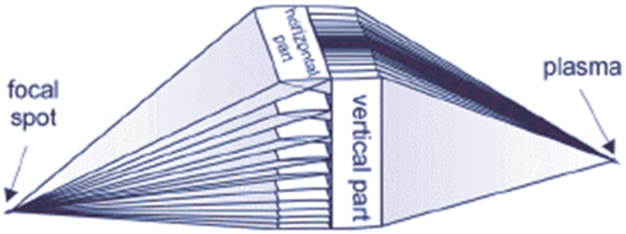


Schematic view and Experimental source
First source



Laser plasma EUV source
driven by a 10 J/10 ns/10 Hz Nd:YAG laser





Scheme of the Multifoil EUV collector

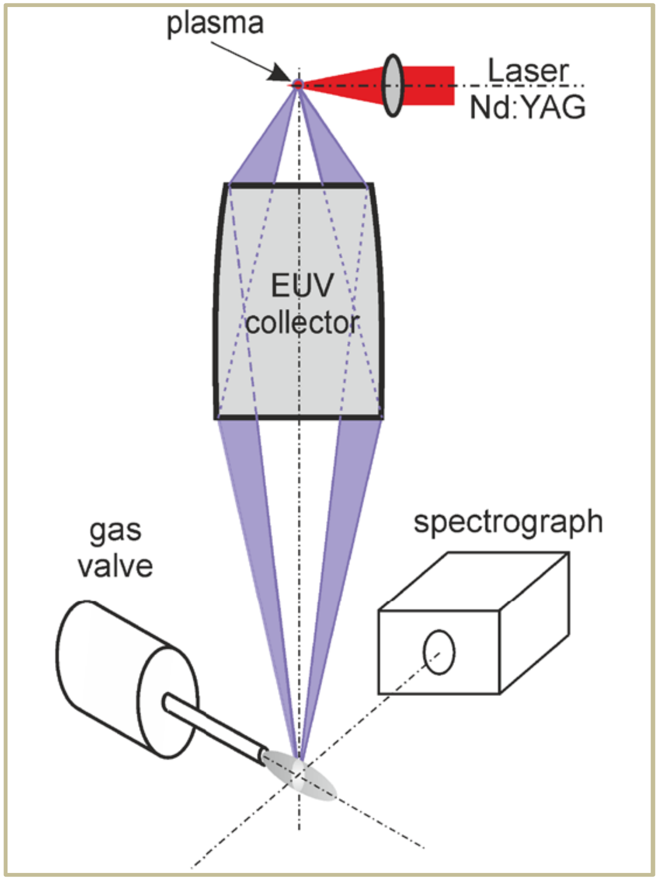
A. Bartnik et al. Phy. Scr. **T161,** 014061 (2014)

UV/VIS spectrometer

- An Echelle Spectra Analyzer (ESA 4000)
- Spectral range: **200-780 nm**
- Spectral resolution: **$\lambda/\Delta\lambda \approx 20000$**

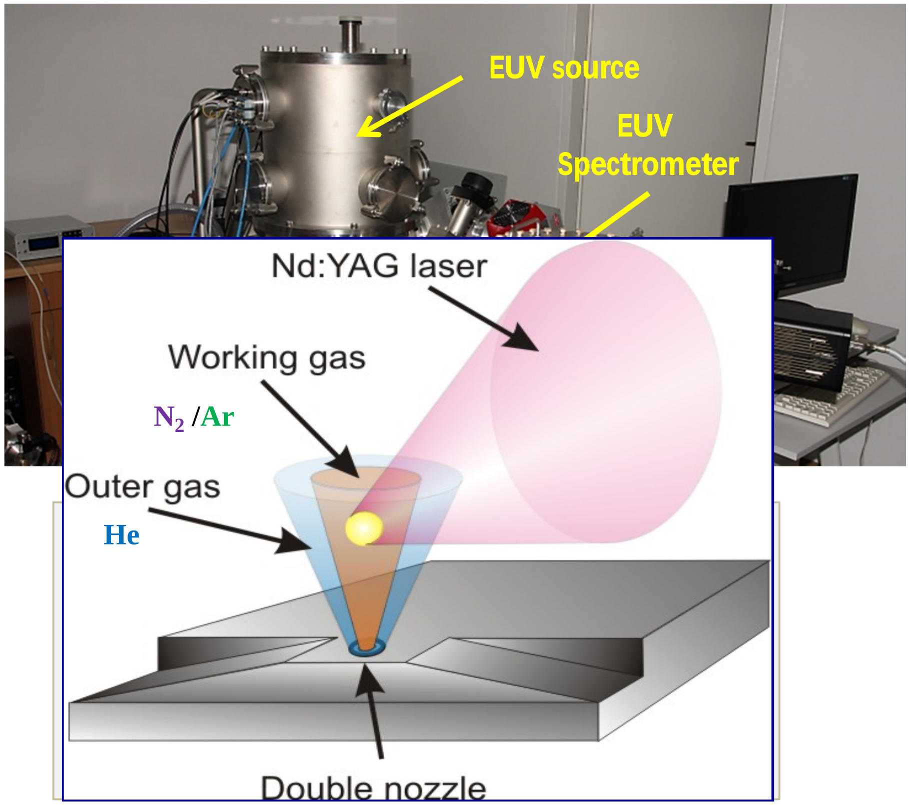
http://www.lla-instruments.com

Schematic view and Experimental source
Second source

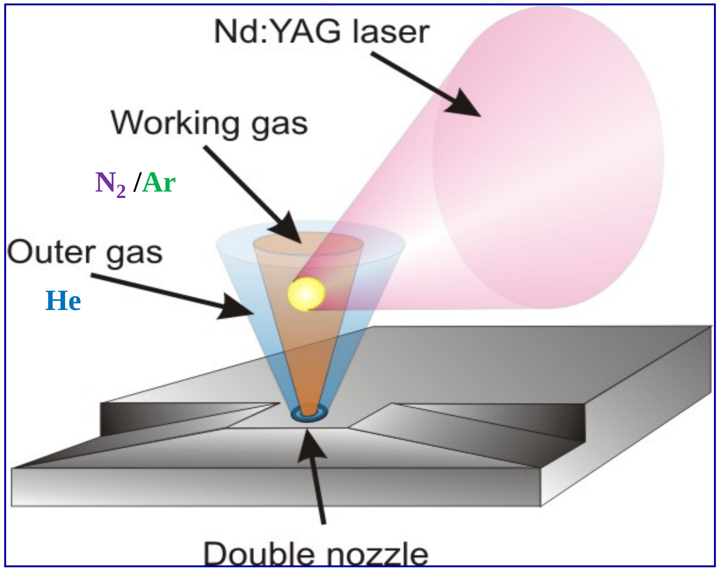


EUV intensity
10^7 - 10^8 W/cm^2

Laser plasma EUV source
driven by a 0.8 J/4 ns/10 Hz Nd:YAG laser

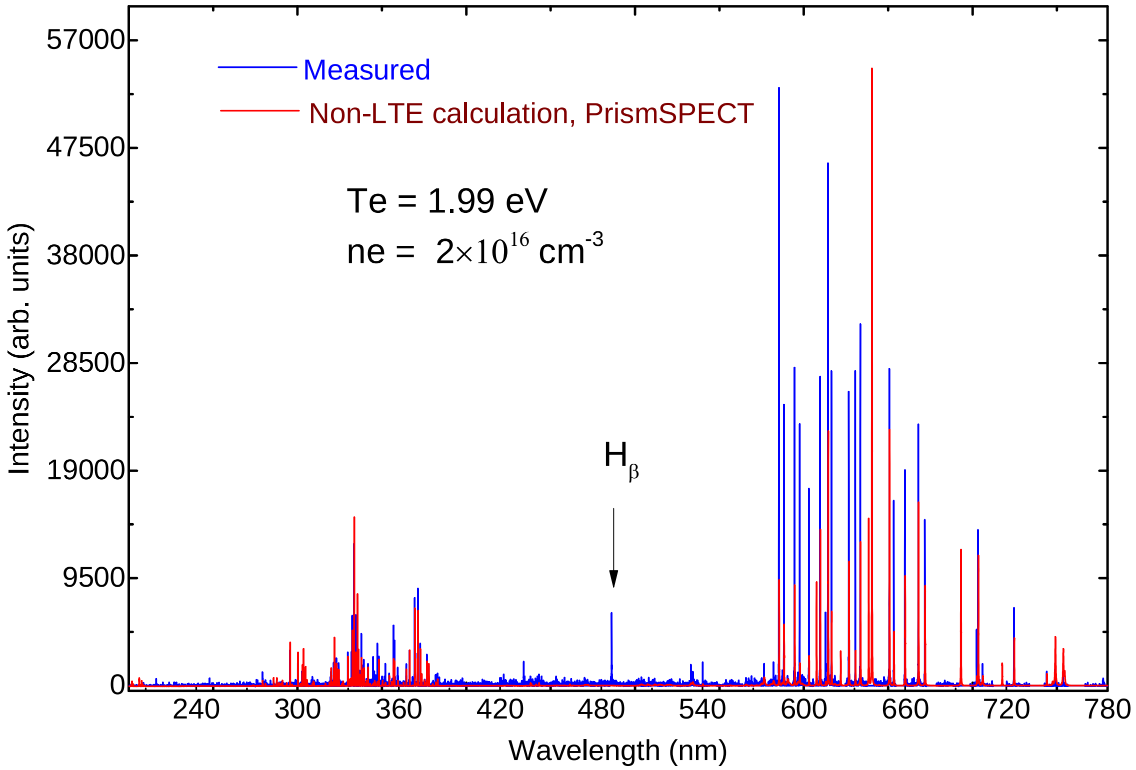


Gas Puff-target



Selected Results

Measured and simulated emission spectra of Ne photoionized plasma

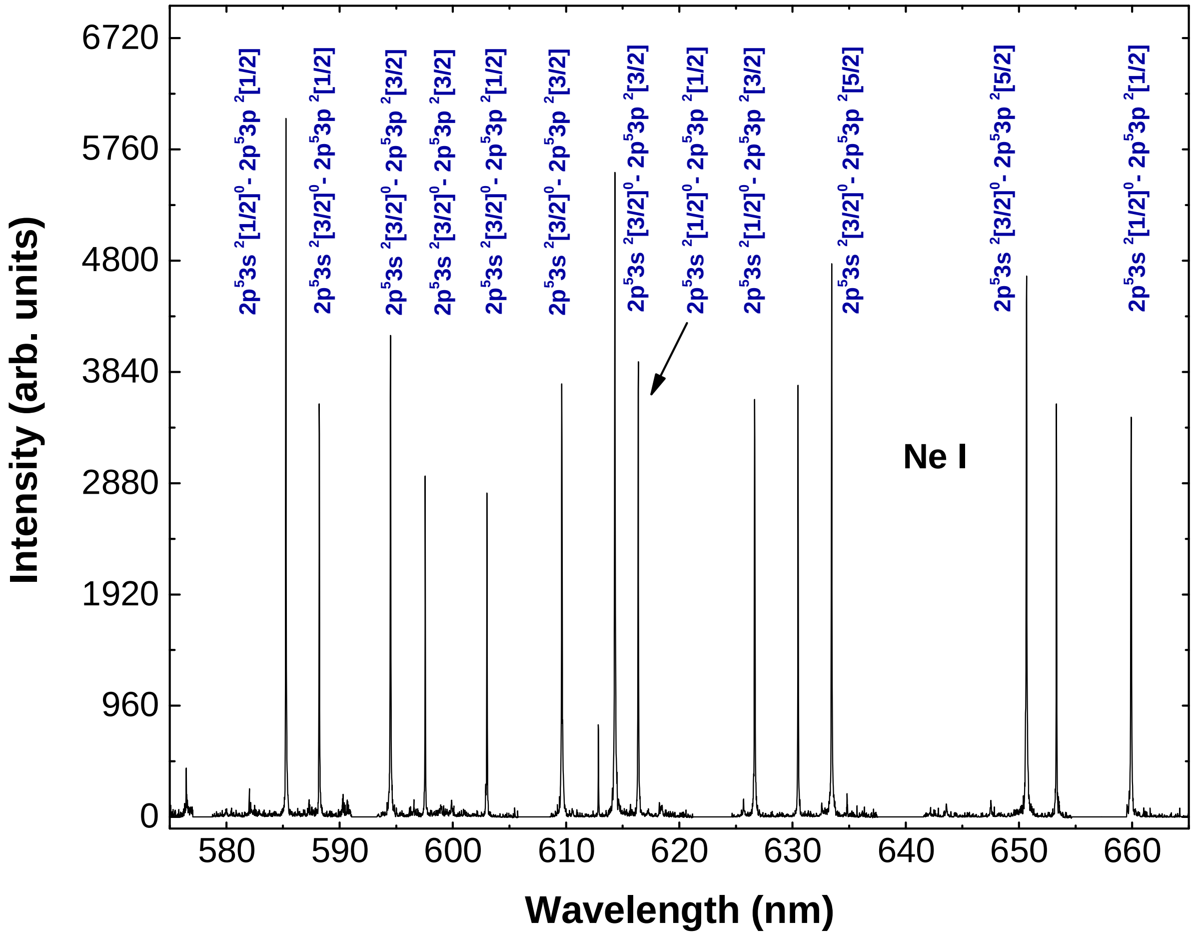


Accumulated 10 pulses
Integrated over 3ns, 5.6 J

- ✓ **The intense spectral lines were from Ne I and Ne II ions**
- ✓ **Emission lines of Ne I-IV were detected with relatively low intensity comparing to neutral and single charged ions**

Results Continue…

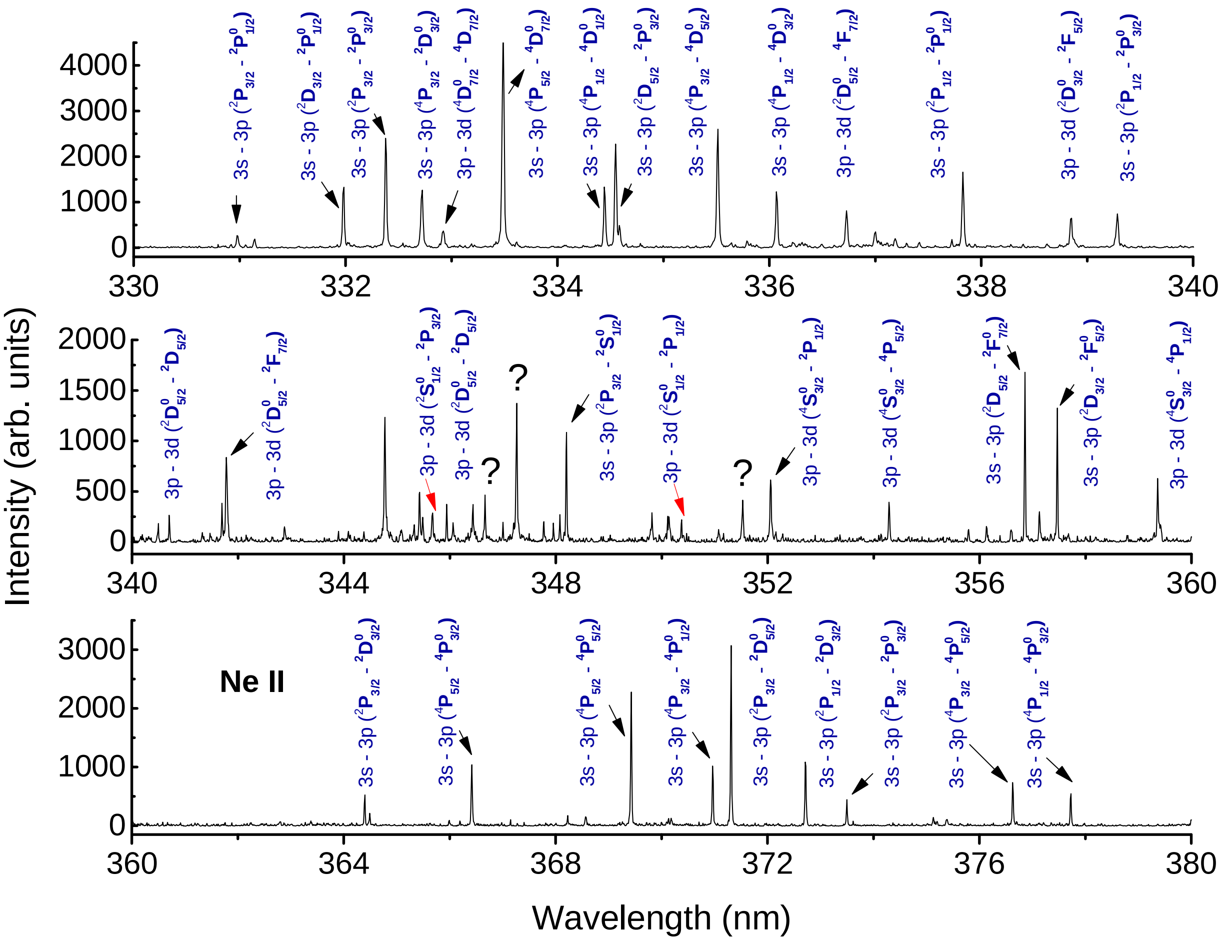
Emission spectra emitted from Ne I in the visible range



✓ **All emission lines corresponding to the spectral lines of atomic neon**

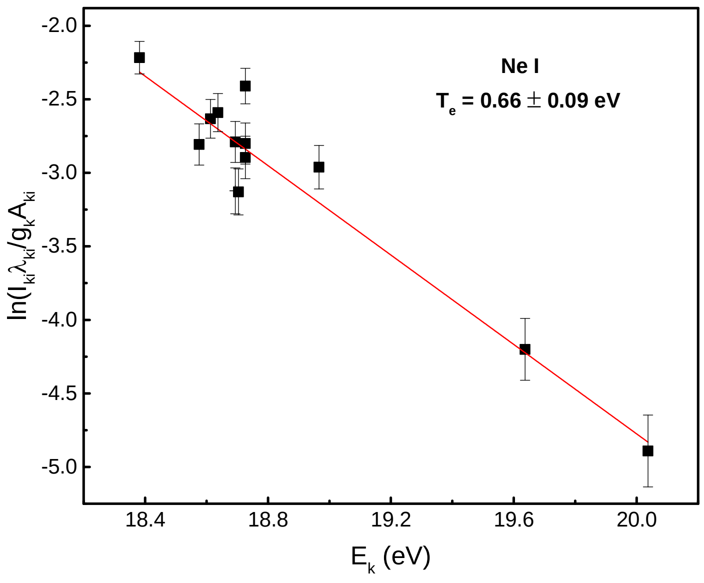
Results Continue…

Part of emission spectra observed in the ultraviolet region of Ne II

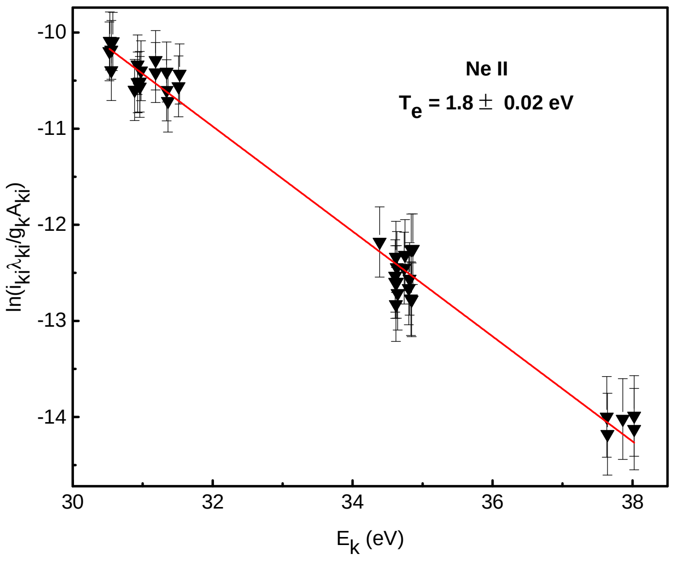


Results Continue…

The slope of the best fit straight line indicated temperature of 1.8 eV in Ne II and almost 0.7 eV in Ne I



Boltzmann plot utilizing neutral lines



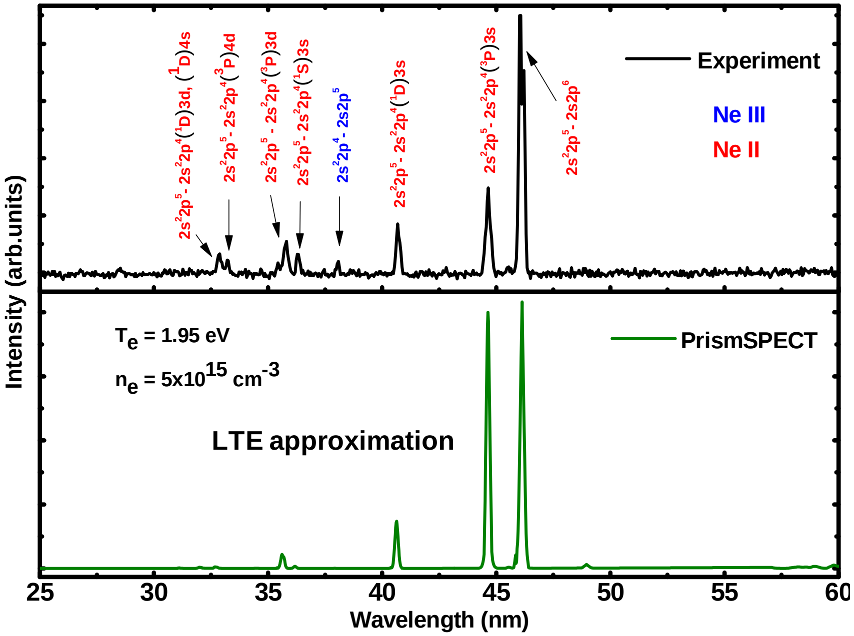
Boltzmann plot utilizing Ne II ionic lines

Results Continue…

Spectra of gases ionized with EUV radiation pulses from a laser-plasma source: Neon

Ne, EUV 100 pulses
P=5bar, PW=300 μs

- ✓ The most intense emission lines were assigned to singly charged ions.
- ✓ The other emission lines belong to doubly ionized ions or neutral atoms

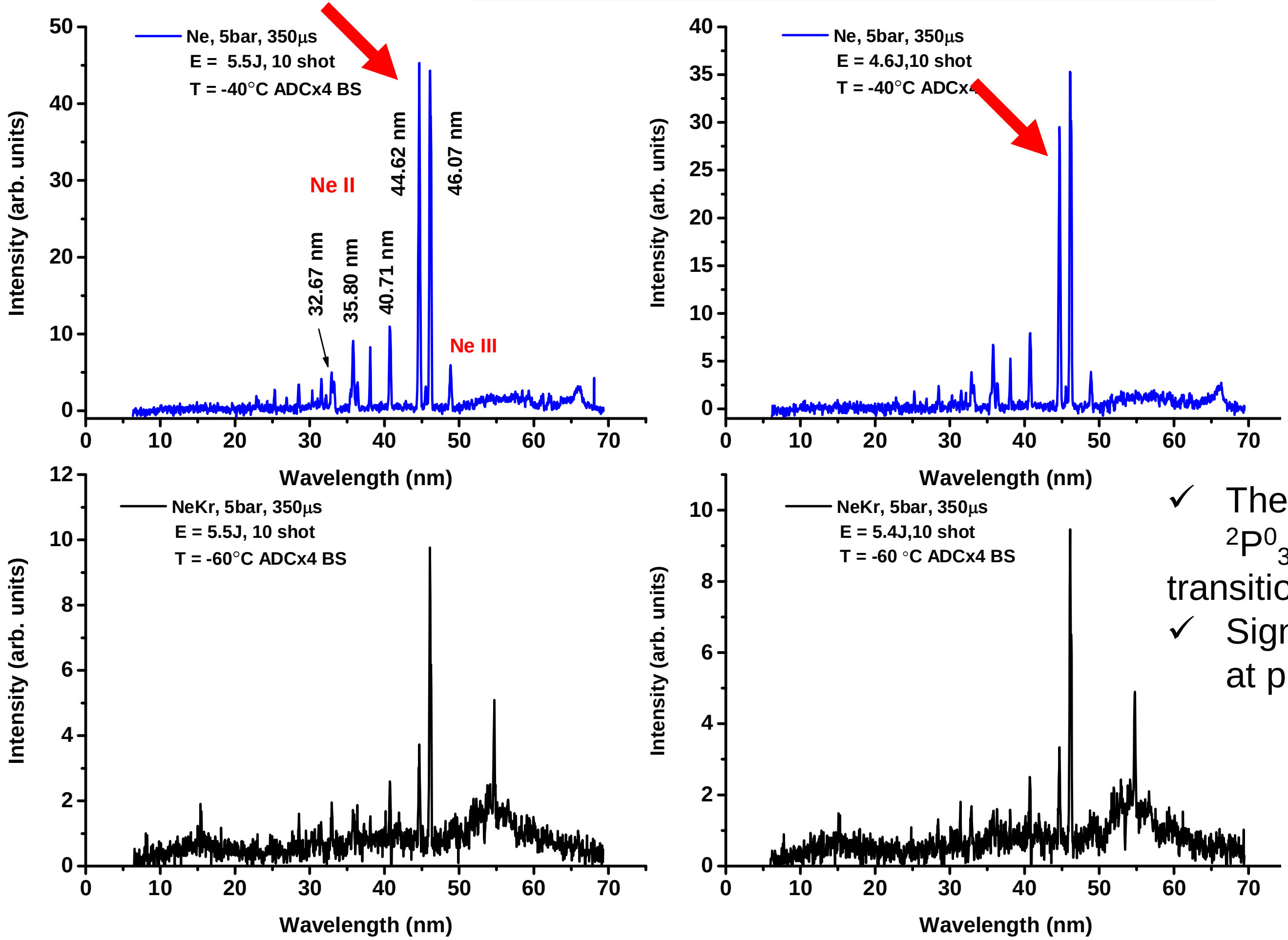


- ✓ Mostly, the spectral lines corresponding to $2s^22p^wnl - 2s^22p^{w-1}nl$ transitions

Submitted to Proceeding of The 15th International Conf. on X-Ray Lasers, Japan

Results Continue…

EUV spectrum of Ne ions



- ✓ The spectra dominated by $2s^22p^5$ $^2P^0_{3/2}$ - $2s^22p^43s,^2P_{3/2}$ transitions
- ✓ Significant decreased in intensity at presents of Kr gas

Results Continue…

Examination of excitation and radiative rates in plasma: To clarify the LTE condition

The excitation rate coefficient $\langle\sigma_{ik}v_e\rangle$ can be calculated as*

$$\langle\sigma_{ik}v_e\rangle = 1.6\times10^{-5}\left(\frac{f_{ik}\langle\bar{g}\rangle}{\Delta E(kT_e)^{1/2}}\right)\exp\left(-\frac{\Delta E}{k_BT_e}\right)$$

The electron impact excitation rate is given by**

$$S = n_e\langle\sigma_{ik}v_e\rangle$$

- $\langle\sigma_{ik}v_e\rangle$ represents coefficient rate of excitation
- f_{ik} is represents the absorption oscillator strength
- $\langle\bar{g}\rangle$ is effective grant factor averaged over all Maxwellian velocity distribution function.
- ΔE (in eV) is the energy difference between the states and
- k_{B} and T_{e} are respecprively the Boltzmann constant and plasma electron temperature

* H.J. Kunze, Space Sci. Rev. **13**, 565 (1972)

** J. D. Hey, J. Quant. Spectrosc. Radiat. Transf. **16**, 69 (1976)

Results Continue…

Rates of excitation and radiative decay

Single charged ions

Ne II 333.484 nm, $2s^22p^43s\ 4P_{5/2} - 2s^22p^43p\ \ 4D^0_{7/2}$

Ne II 356.585 nm, $2s^22p^43p\ 4S^0_{3/2} - 2s^22p^43d\ \ 4P_{3/2}$

Ne II 371.313 nm, $2s^22p^43s\ 2P_{3/2} - 2s^22p^43p\ \ 2D^0_{5/2}$

Neutral atoms

Ne I 584.258 nm, $2s^22p^53s\ 2[1/2]^0_1 - 2s^22p^53p\ \ 2[1/2]_0$

Ne I 588.189 nm, $2s^22p^43s\ 2[3/2]^0_2 - 2s^22p^43p\ \ 2[1/2]_1$

Ne I 594.483 nm, $2s^22p^43s\ 2[3/2]^0_2 - 2s^22p^43p\ \ 2[3/2]_1$

Results Continue…

Results of investigation for excitation and radiative decay rates

Excitation rate coefficient

Excitation rate

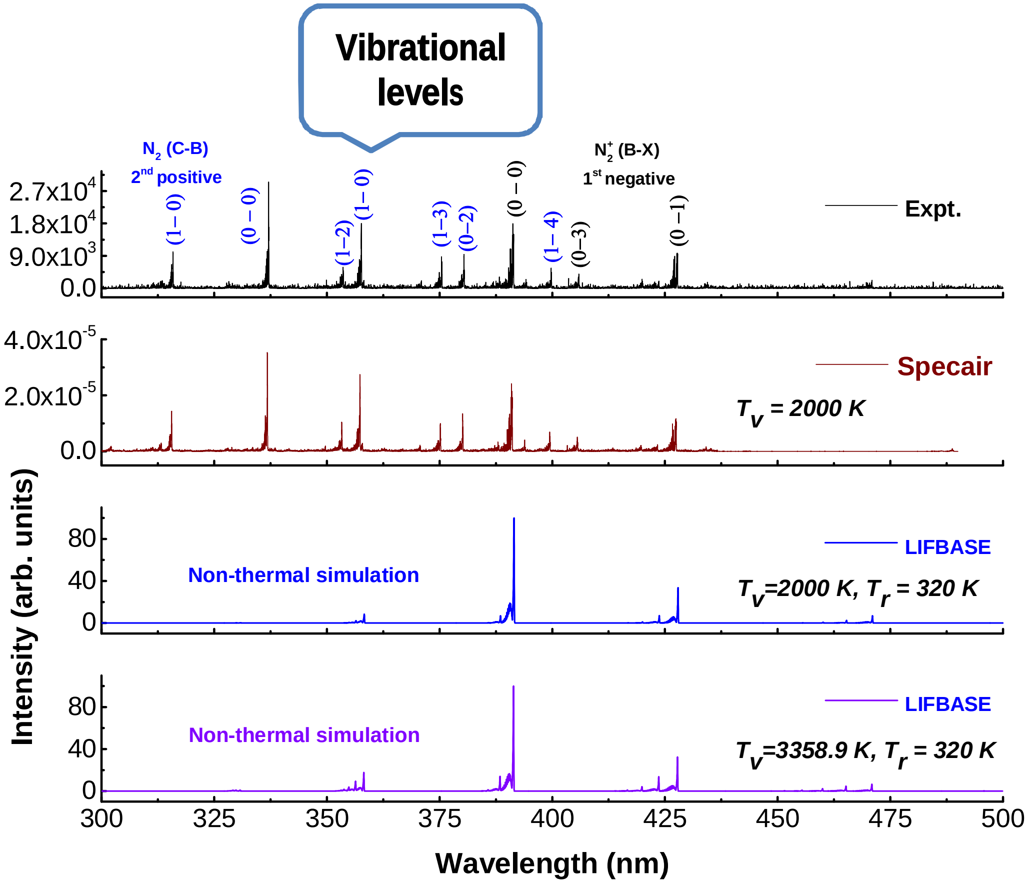
10 times Radiative decay

ion	line	Excita. Rate	n_e	n_e*Excita.	A_{ki}	10*A_{ki}
Ne II	333.484	2.726E-07	1.301E+15	3.5E+08	1.80E+08	1.80E+09
Ne II	356.585	2.972E-07	1.434E+15	4.3E+08	6.20E+07	6.20E+08
Ne II	371.313	3.688E-07	3.713E+15	1.4E+09	1.30E+08	1.30E+09
Ne I	585.258	2.650E-08	2.856E+16	7.6E+08	6.82E+07	6.82E+08
Ne I	588.189	8.273E-09	5.412E+16	4.5E+08	1.15E+07	1.15E+08
Ne I	594.483	1.440E-08	6.495E+16	9.4E+08	1.13E+07	1.13E+08

- ✓ The plasma electron density n_e each of these lines has been evaluated from a Voigt's FWHM fit of the experimental profile
- ✓ Partial local thermodynamics equilibrium found to be realized

Results Continue…

Measured and simulated UV/VIS emission spectra of N_2 photoionized plasma



The measured spectra dominated by vibrational transition in second positive and first negative systems of the nitrogen molecule

Emission lines originated from the following band systems

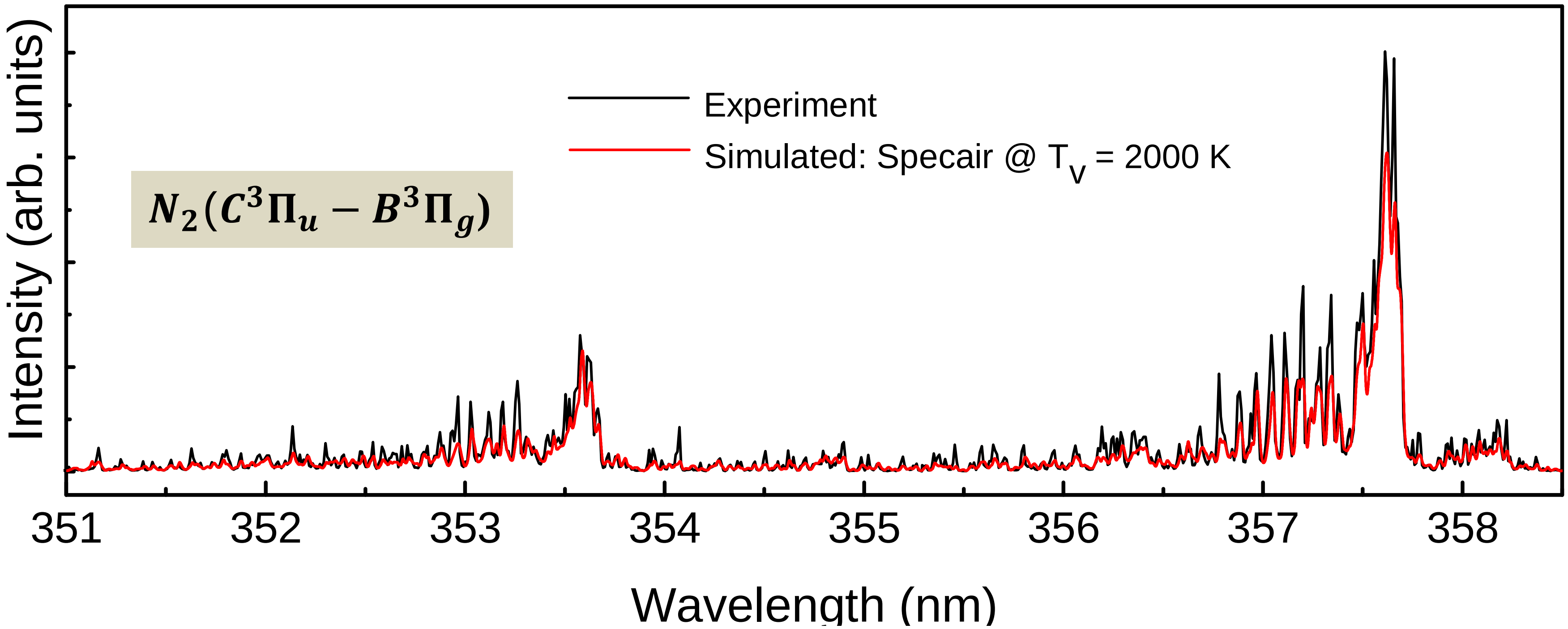
$N_2^+ : B^2\Sigma_u^+ - X\,^2\Sigma_g^+$ First negative

$N_2 : C^3\Pi_u - B^3\Pi_g$ Second positive

$N_2 : B^3\Pi_g - A^3\Sigma_u^+$ First positive

LIFBASE: *J. Luque and D.R. Crosley. Lifbase: Database and spectral simulation program (version 2.1.1). SRI International Report MP 99-009, 1999.
Specair: E. Pawelec, Eur. Phys. J. Special Topics 144, 227-231 (2007)

Results Continue…



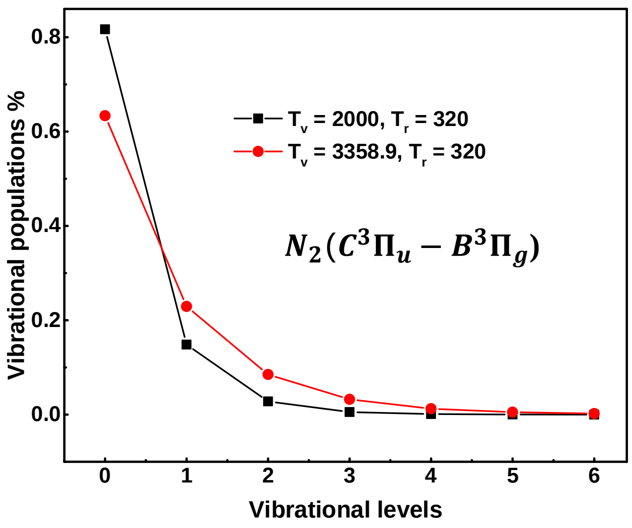
- ✓ Direct fitting of vibration bands give accurate data on the electron vibrational temperature
- ✓ And also result in a good agreement with the measured vibrational levels

Results Continue…

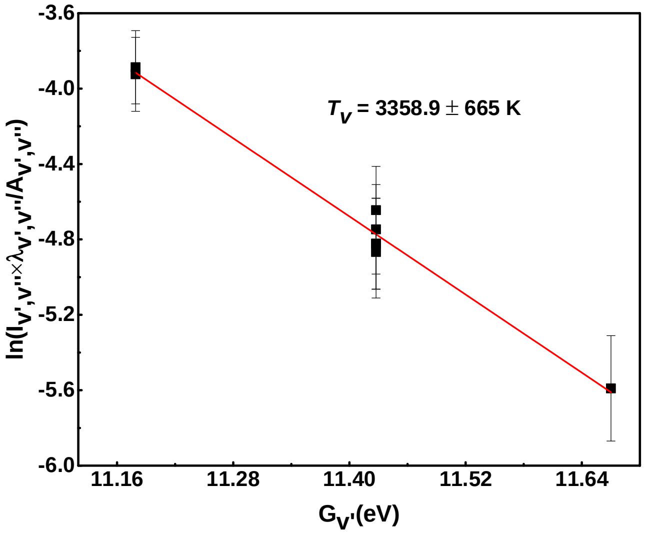
Determination of vibrational T_v temperature of a plasma created in a molecular nitrogen

$$\ln\left(\frac{I(v',v'')\times\lambda(v',v'')}{A(v',v'')h\nu}\right) = -\frac{h\nu G(v')}{K_B T_v} + Const.$$ [*]

$I(v',v'')$ intensity of vibrational band
$G(v')$ vibrational energy of the upper level
$A(v',v'')$ the transition probability and
$\lambda(v',v'')$ is wavelength of the band head.



Vibrational populations of non-thermal mode vibrational levels of N_2^+, obtained at the end of the simulations for two different temperatures (T_v,T_r).



Vibrational temperature determination from the Boltzmann plot of the Δv= 0, ±1,-2, and -3 sequences in second positive band transitions $N_2(C^3\Pi_u - B^3\Pi_g)$.

[*] C.O. Laux, Radiation and Nonequilibrium Collisional-Radiative Models, von Karman Institute Lecture Series, July 2002.

Summary and Outlook

- ✓ **LLP EUV sources were used to study time-integrated emission lines from photoionized plasmas in atomic and molecular gases.**
- ✓ **The observed and identified spectral lines were mostly originated from radiative transitions in single and double charged ions.**
- ✓ **Initial calculations of electron impact excitation and radiative decay rates were presented from neutral and singly charged ions.**
- ✓ **We measured the band spectra (first negative and second positive systems) of the nitrogen molecule and we examined the vibrational temperature of the $N_2(C^3\Pi_u - B^3\Pi_g)$ band transitions.**
- ➢ **Collision frequencies between the plasma particles and other plasma parameters will be evaluated for hydrodynamics calculations of the LPP EUV source in the near future.**

Publications & Conf. Proceedings

[1] **I.Saber**, A. Bartnik, P. Wachulak, W. Skrzeczanowski, R. Jarocki and H. Fiedorowicz: **Temporal variations of electron density and temperature in Kr/Ne/H_2 photoionized plasma induced by nanosecond pulses from extreme ultraviolet (EUV) source,** *Physics of Plasmas* ***24***, 063501 (2017); doi: http://dx.doi.org/10.1063/1.4984254

[2] A. Bartnik, W. Skrzeczanowski, P. Wachulak, **I. Saber**, H. Fiedorowicz, T, Fok and Ł. Wegrzynski: **Low-temperature photoionized plasmas induced in Xe gas using an EUV source driven by nanosecond laser pulses.**
Laser and Particle Beams **35**(1), 42-47 (2017). DOI: https://doi.org/10.1017/S0263034616000781

[3] **I. Saber**, A. Bartnik, P. Wachulak, W. Skrzeczanowski, R. Jarocki, and H. Fiedorowicz: **Spectroscopic studies on time-integrated emission spectra in low- temperature neon photoionized plasma,** ready to submit

[4] **I. Saber**, A. Bartnik, W. Skrzeczanowski, P. Wachulak, R. Jarocki and H. Fiedorowicz: **Emission spectra of photoionized plasmas induced by intense EUV pulses: Experimental and theoretical investigations:**
AIP Conf. Proc. **1811**, 140001 (2017). http://aip.scitation.org/doi/abs/10.1063/1.4975738

[5] **I. Saber**, A. Bartnik, P. Wachulak, W. Skrzeczanowski, R. Jarocki and H. Fiedorowicz: **Spectral lines and characteristic of temporal variations in photoionized plasmas induced with laser-produced plasma extreme ultraviolet source.**
Proc. Nucl. Inst.methods research B (NIMB). https://doi.org/10.1016/j.nimb.2017.06.017

[6] **I. Saber**, A. Bartnik, P. Wachulak,W. Skrzeczanowski, R. Jarocki, H. Fiedorowicz: **Photoionization of atomic neon induced using nanosecond pulses of extreme ultraviolet source.**
Proc. of the 15th International Conference on X-ray Lasers (ICXRL 2016) in Japan.

[7] A.Bartnik, W.Skrzeczanowski,P.Wachulak, I.Saber, H.Fiedorowicz, T.Fok, Ł.Węgrzyński: **Reflective optics for effective collection of x-ray and EUV radiation: use for creation of photoionized plasmas and detection of weak signals.** Vol.102350D (2017); http://doi: 10.1117/12.2269438

[8] **I. Saber**, A. Bartnik, P. Wachulak, W. Skrzeczanowski, R. Jarocki, H. Fiedorowicz and J. Limpouch: **Experimental and theoretical emission spectra in nitrogen photoionized plasma induced with intense EUV pulses,**
***Proc.* of** European Physical Journal (EPJ). *To be submitted*.

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Prof. H. Fiedorowicz	**MUT**
Dr. P. Wachulak	**MUT**

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Thank you for your attention

Approximate estimation of n_e

Main free path of photoelectrons

$$\sigma = \sigma_i + \sigma_{ex}$$

$$l_e = \frac{1}{n\sigma}$$

10^{-17} cm^2

Assume that thermalization is possible in case l <<d
Where *d* is plasma size and assumed to be 1 mm

$n \sim 2.25 \times 10^{17}$ cm^{-3}

The lower limit for electron density for which plasma, somehow to satisfy LTE*

$$n_e\left(cm^{-3}\right) > 1.61018\times10^{12}\cdot T_e^{1/2}\left(\Delta E\right)^3$$

ΔE is the higher energy different in eV of the levels whose populations are given by LTE conditions

***R. W. P. McWhirter, Spectral Intensities, in Plasma Diagnostic Techniques, ed. R. H. Huddlestone and S. L. Leonard, Academic Press, New York, 1965, ch. 5, p. 206.**

Electron density has been determined from the line profiles of the isolated Krypton neutral lines neglecting the contribution of the ion impact broadening and Doppler broadening

$\Delta\lambda$ = 0.00884 nm, Lorentzian FWHM

ω =0.0886 nm, Stark broadening parameter

N_r (reference electron density).

Neutral atoms: $N_r = 10^{16}$ cm^{-3}

Singly ionized atoms: $N_r = 10^{17}$cm^{-3}

$$N_e = \frac{0.00884 \times 10^{16}}{2 \times 0.0886} \approx 5 \times 10^{14} cm^{-3}$$

N. Konjevic *et al*, J. of Phys. Chem. Ref. Data 31, 819 (2002).

[*]J. Luque and D.R. Crosley. Lifbase: Database and spectral simulation program (version 2.1.1). SRI International Report MP 99-009, 1999.

Abstract

Emission lines in different electromagnetic radiations from low temperature photoionized plasmas of atomic and molecular gases were investigated. The photoionized plasmas were induced using nanosecond radiation pulses of laser-produced plasma extreme ultraviolet (EUV) source. The source was based on a double stream gas puff target irradiated with a commercial Nd:YAG laser of 10 ns 10 Hz repetition rate with low and high pulse energy system. The EUV radiations were focused onto a gas stream, injected into a vacuum chamber synchronously with the EUV pulses. The radiation was collected and focused using different EUV collectors. A range of non-local equilibrium (NLTE) models and the radiative collisional codes have been used to reproduced theoretical spectra for further interpretation.