EUV induced photoionized plasma, a medium for spectral investigation

A Bartnik, P Wachulak, H Fiedorowicz, W Skrzeczynowski, T Fok, R Jarocki, L Węgrzyński
Institute of Optoelectronics, Military University of Technology, Warsaw, Poland

Email: andrzej.bartnik@wat.edu.pl

Abstract. In this work a method of low temperature photoionized plasma creation is presented. Photoionized plasmas are produced by irradiation of gases with extreme ultraviolet (EUV) radiation pulses of high intensity. The gases are injected into a vacuum chamber synchronously with the EUV pulses. Such configuration allows for spectral investigation in the EUV range. Examples of emission and absorption spectra are shown.

1. Introduction
Photoionized plasmas produced by irradiation of gases with intense soft X-ray (SXR) or extreme ultraviolet (EUV) pulses are interesting objects for spectral investigations. This kind of plasmas are produced for experimental simulation of similar plasmas formed in Space, especially close to X-ray radiating compact stars. These experiments are called laboratory astrophysics and are conducted using high energy density facilities delivering X-ray pulses of extremely high energy [1,2]. Photoionized plasmas can be also produced using small scale laboratory SXR/EUV sources. In this case interaction of the ionizing radiation with a small portion of gas results in creation of a low temperature plasma. In contrast to low temperature plasmas produced using standard generators employed in technological processes, electron density of photoionized plasmas can be a few orders of magnitude higher, reaching $10^{18}$ cm$^{-3}$ [3]. Apart from that such plasmas are produced locally in a vacuum chamber, hence, can be investigated using different methods requiring at least low vacuum environment, including EUV/SXR spectroscopy. Parameters of low temperature photoionized plasmas created in laboratory can be easy controlled and adjusted for specific conditions that can be encountered in Space. It concerns for example hydrogen plasmas with parameters similar to photospheres of white dwarfs. The corresponding experiments allowing for investigation of hydrogen Balmer emission and absorption line profiles were performed at the Z Pulsed Power Facility at Sandia National Laboratories [4]. Plasmas of similar parameters can be also produced using the above mentioned low energy EUV/SXR sources.

In this paper some results concerning experimental investigations of low temperature, photoionized plasmas are presented. Photoionized plasmas were created by EUV irradiation of small portions of gases injected into the interaction region synchronously with the radiation pulse. A laser plasma EUV source based on a 10 J/10 ns Nd:YAG laser system and equipped with a multifoil [5] or ellipsoidal [6] EUV collector was employed for the gas irradiation. Measurements of emission and absorption spectra for photoionized plasmas created this way were performed. Examples of emission spectra acquired in UV/VIS and EUV ranges are presented. Absorption spectra measured in the EUV range for photoionized plasma created in neon are also shown.
2. Emission spectra

The EUV emission and absorption spectra were recorded using a grazing incidence, flat-field spectrometer (McPherson, Model 251), equipped with a 450 lines/mm toroidal grating. The spectral range of the spectrometer was \(\lambda = 10 - 95 \text{ nm}\) and the resolution \(\lambda/\Delta \lambda \approx 500\). Optical axis of the spectrometer was perpendicular to the optical axis of the EUV collector thus the emission spectra are well separated from the spectra of laser-plasma radiation. It is very important because the laser-plasma emission is approximately \(10^6\) times higher comparing to the photoionized plasma emission. The spectra, integrated over 50 pulses, were recorded using a CCD detector, cooled down to a temperature of \(-65^\circ\text{C}\).

The second instrument was an Echelle Spectra Analyzer ESA 4000, equipped with the ICCD Kodak KAF 1001 camera. The spectrometer system allowed for simultaneous measurements of complex spectra within the wide ultraviolet and visible (UV/VIS) spectral range, \(\lambda = 200 \div 780 \text{ nm}\). Spectral resolution of the spectrograph was \(\lambda/\Delta \lambda \approx 20000\). Similarly to the EUV spectrograph, optical axis of the UV/VIS spectrograph was perpendicular to the optical axis of the EUV collector.

In Fig.1 examples of emission spectra obtained for photoionized plasmas created in molecular gases are presented. In case of the EUV measurements, the spectral lines originate exclusively from atomic ions. In case of the UV/VIS range most molecular spectra were recorded.

![Emission spectra](image)

Figure 1. Emission spectra obtained from photoionized plasmas created in molecular gases: a) O II and O III EUV spectrum; b,c) \(\text{N}_2^+\) spectra; d,e) \(\text{N}_2^+\) spectra simulated using the LIFBASE [7] code.

The EUV spectrum, measured for photoionized plasmas created in oxygen, contains mainly O II lines, however a single O III line was also recorded. Similar spectra were obtained for different gases, either atomic or molecular [5,6,8]. In most cases mainly singly charged ions were detected. Numerical simulations of EUV spectra performed for Ne, He and F plasmas allowed for estimation of electron temperatures [6,9,10] to the value of the order of 1 eV. Similar values were obtained employing Boltzmann plots constructed for S or Kr plasmas [10,11].

The UV/VIS spectrum measured for photoionized plasmas created in nitrogen, contains exclusively line series corresponding to excited \(\text{N}_2\) molecules or \(\text{N}_2^+\) molecular ions. Numerical simulation of the \(\text{N}_2^+\) spectrum performed using the LIFBASE [7] code, for vibrational temperature of 1500 K and rotational temperature 130 K, gave spectral distribution similar to the measured one (Fig.1 b-e).

3. Absorption spectra

The absorption spectra were measured employing a continuous part of Xe laser plasma radiation for backlighting of photoionized plasmas. The most interesting spectra were obtained for He [6] and Ne (Fig.2) plasmas. In both cases the pronounced absorption lines were recorded for neutral atoms present in the photoionized plasmas. In case of not ionized gases absorption lines were hardly visible.
4. Summary

A possibility of creation and spectral measurements of low temperature photoionized plasmas was presented. Photoionized plasmas were created by irradiation of gases, injected into the vacuum chamber, using a laser plasma EUV source. Examples of emission spectra acquired in EUV and UV/VIS ranges for plasmas created in molecular gases are shown. Numerical simulation of $N_2^+$ spectrum allowed for estimation of vibrational and rotational temperatures. Significant differences between absorption spectra obtained for Ne gas and low temperature Ne plasma are presented.

Acknowledgments

This work was supported by Grant No. UMO-2013/09/430 B/ST2/01625 of the National Science Centre, Poland

References

[1] S. Fujioka, H. Takabe, N. Yamamoto, D. Salzmann, F. Wang, H. Nishimura, Y. Li, Q. Dong, S. Wang, Y. Zhang, Y. Rhee, Y. Lee, J. Han, M. Tanabe, T. Fujiwara, Y. Nakabayashi, G. Zhao, J. Zhang, and K. Mima, Nature Phys. 5, 821–825 (2009)
[2] D. H. Cohen, J. J. MacFarlane, J. E. Bailey, and D. A. Liedahl, Rev. Sci. Instrum. 74, 1962 (2003)
[3] A. Bartnik, P. Wachulak, T. Fok, Ł. Wegrzynski, H. Fiedorowicz, T. Pisarczyk, T. Chodukowski, Z. Kalinowska, R. Dudzak, J. Dostal, E. Krousky, J. Skala, J. Ullschmied, J. Hrebicek, T. Medrik, Physics of Plasmas 22, 4, 043302 (2015)
[4] R.E. Falcon, G.A. Rochau, J.E. Bailey, J.L. Ellis, A.L. Carlson, T.A. Gomez, M.H. Montgomery, D.E. Winget, E.Y. Chen, M.R. Gomez, T.J. Nash. High Energy Density Physics 9, 82-90 (2013)
[5] A. Bartnik, P. Wachulak, H. Fiedorowicz, T. Fok, R. Jarocki, M. Szczurek, „Extreme ultraviolet-induced photoionized plasmas”, Physica Scripta T161, 014061 (2014)
[6] A. Bartnik, P. Wachulak, H. Fiedorowicz, T. Fok, R. Jarocki, M. Szczurek, Physics of Plasmas 20, 11, 113302 (2013)
[7] J. Luque and D.R. Crosley, ”LIFBASE: Database and spectral simulation (version 1.5)”, SRI International Report MP 99-009 (1999)
[8] A. Bartnik, H. Fiedorowicz and P. Wachulak, Physics of Plasmas 21, 073302 (2013)
[9] A. Bartnik, R. Fedosejevs, P. Wachulak, H. Fiedorowicz, C. Serbanescu, E.G. Saiz, D. Riley, S. Toleikis, D. Neely, Laser and Particle Beams 31, 2, 195-201 (2013)
[10] A. Bartnik, P. Wachulak, H. Fiedorowicz, W. Skrzeczansowski, R. Jarocki, T. Fok, Ł. Wegrzynski, Journal of Instrumentation 11, Issue 3, C03009 (2016)
[11] A. Bartnik, P. Wachulak, H. Fiedorowicz, W. Skrzeczansowski, Physics of Plasmas 23, 043512 (2016)