COMPRESSION ZONE FORMATION IN MAGNETOPLASMA COMPRESSOR OPERATING WITH HEAVY GASES

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Present work is devoted to experimental investigations of the plasma compression zone dynamics and its influence on radiation characteristics. The construction of magneto-plasma compressor (MPC) of compact geometry with conical copper electrodes is described. Comprehensive information about dynamics of compression zone formation, it position, plasma parameters and geometric dimensions was obtained using spectral diagnostics. Plasma stream density ~ 10^{18}cm^{-3} was measured by Stark broadening of Xe spectral lines. Electron temperature 5...7 eV was estimated using the ratio of Xe lines intensities. EUV radiation intensity was detected by registration system consisting on absolutely calibrated AXUV diodes with integrated thin-films filter for different wavelength ranges and multi-layered MoSi mirrors. Spatial distributions of electrical currents has been performed also.

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1. INTRODUCTION

Investigations of dense magnetized plasmas of different gases are of importance for various scientific and technological applications such as generators of hot plasma and efficient fuelling techniques (plasmoids), testing of fusion reactor materials with high energy loads etc. Dense plasma is especially attractive object of investigations aimed at development of efficient source of multicharged ions and intense radiation in a wide wavelength range (from XR and EUV to infrared radiation) [1, 2]. In particular, dense xenon plasma cloud can provide effective shielding of divertor plates and mitigation of disruptions due to high emissivity of xenon and resulting re-radiation of impacting energy [3].

2. EXPERIMENTAL SETUP AND DIAGNOSTICS

MPC electrode system consists of solid cylindrical part and output rod structure including 12 copper rods with diameter of 10mm and of 147 mm in length as presented on Fig.1. Electro-technical characteristics of MPC are as follows: discharge current – 500 kA, capacity of condenser bank – 90 μF, charging voltage 15…25 kV, pulse duration – (15…20 μs), working gases – N, Xe, He and their mixtures. Current experiments were carried out using He as a residual gas and Xe as a working gas. Variation of operation regimes is varied by means of electrodynamic valve which provides residual pressure in a range of 2…10 Torr or pulsed gas filling into the inter-electrodes area.

All the routine diagnostic techniques, i.e. voltage- and current-probes, movable calorimeters, piezo-detectors, photomultipliers, were applied simultaneously. To perform spectroscopic measurements the use was made of a visible spectrometer coupled with an electron-optical converter. EUV radiation intensity was detected by registration system consisting on absolutely calibrated AXUV diodes with integrated thin-films filter for different wavelength ranges (5…13, 12.2…15.8 and 17…80 nm) and multi-layered MoSi mirrors.

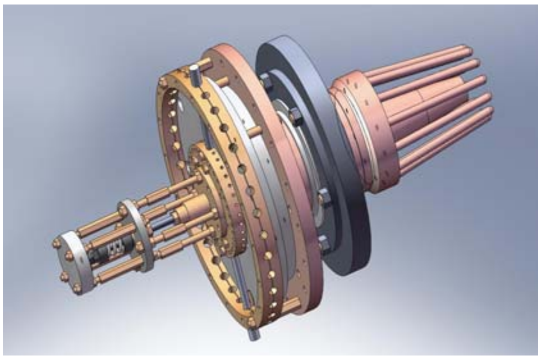

Fig.1. MPC electrode system

3. TEMPORAL AND SPATIAL DISTRIBUTIONS OF PLASMA ELECTRON DENSITY

Xenon spectral lines of different species Xe (II–V) are recorded with short enough exposition t_{exp} = 2 μs (in a comparison with the discharge duration) and with different delays τ_d in the relation to the discharge beginning. Example of typical Xe spectrum is presented in Fig. 2. It is important to note that radiation of high-ionized Xe spectral lines is attributed to the plasma focus formation and it corresponds to hot and high-energy part of plasma stream with duration of generation ~ 1.5…2 μs.

Particular attention was paid to the temporal and spatial behavior of Xe spectral lines. Basing on the known theory of the Stark effect [4], one could estimate that the maximal plasma electron concentration corresponding to the compression stage was 10^{18} cm^{-3}.

As a result of MPC optimization [5] it has been shown that only operation mode with 2 Torr of He residual pressure and local Xe injection into compression region is characterized by swift plasma stream compression with significant increasing of main plasma parameters.

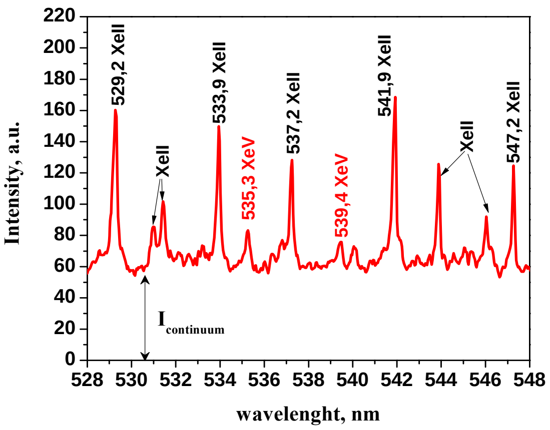

Fig.2. Xe optical spectrum recorded with
t_{exp} = 2 μs and τ_d= 6 μs

Particularly Fig. 3 clearly illustrates the plasma stream dynamics. We observed the electron density rise in 5 times after 6 μs of the discharge beginning. Space-time distribution of N_e provides us information about plasma compression zone dimensions. Experimental results reveal that plasma compression zone of 1…1.5 cm in diameter and 2…3 cm in length is formed at the distance of 6 cm from MPC central electrode. Plasma electron temperature T_e averaged along the line of view was estimated using intensity relations between different Xe spectral lines. For example, using intensity relations between Xe II/II lines it was obtained T_e = 3.5…5 eV. However, T_e = 7 eV corresponding to the intensity relation of Xe III/II lines seems to be more realistic due to the rather high accuracy of used method [6].

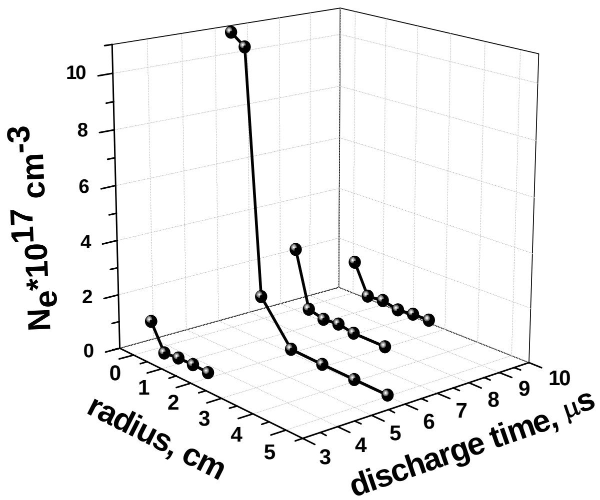

Fig. 3. Space-time plasma electron density distribution at distance of 6 cm from central electrode obtained with t_{exp} = 0.9 μs

4. DYNAMICS OF OUTLET PLASMA CURRENTS

Spatial distributions measurements of magnetic field in MPC plasma stream were carried out with local movable magnetic probes. Reconstruction of electrical current distributions has been performed from measurements of azimuthal magnetic field using Maxwell equations. Current magnitude in plasma layer is difference of corresponding values of current lines (Fig. 4). Performed measurements show that total value of electric current flowing outside accelerating channel is about 25…30% of discharge current. Electrical current propagated to the distance up to 30 cm from MPC output during first half period of discharge current. In most cases the current vortexes appearance is attributed to the inclined shock wave formation in compression zone that affects on plasma dynamics outside the source. In some regimes the current displacement from the compression region was observed.

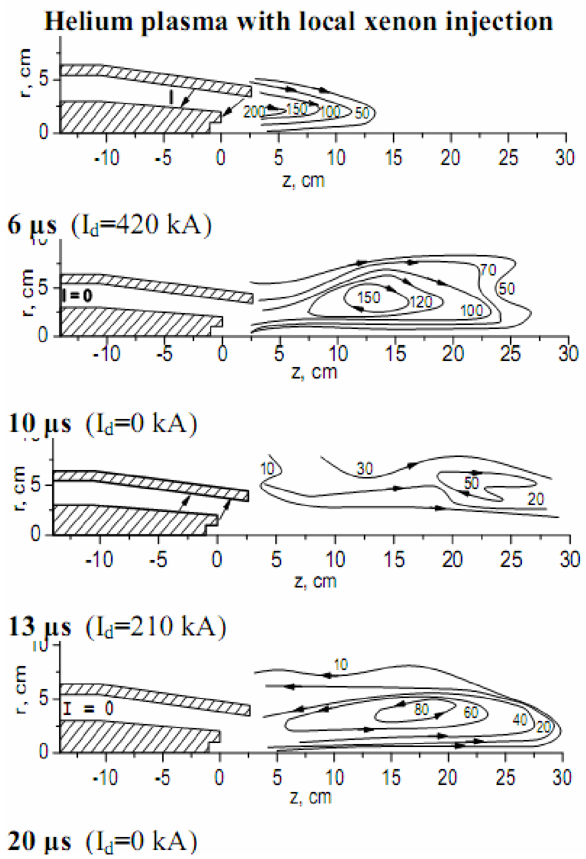

Fig. 4. Time evolution of outlet currents in He-Xe plasma stream. Values of outlet currents are in kA, direction is marked by arrow

5. EUV RADIATION ENERGY MEASUREMENTS

Xenon plasma compression zone also can be an intense source of radiation in a wide wavelength range, particularly, in the range of 13.5 nm. In order to measure EUV radiation energy there were applied AXUV diodes for 12.2…15.8 nm range. Experiments show that radiation energy increases with increasing discharge current and it strongly depends on MPC operation regime namely on the residual He pressure and time delay (Fig. 5). Performed measurements confirm that operation mode with 2 Torr of He is the most optimal for achievement of maximal EUV radiation energy and additional Xe injection applied directly into the compression zone allowed essentially increase EUV radiation energy from 33 up to 58 mJ. There are observed some oscillations of the energy behavior depends on time delays τ.

Such nonmonotonic dependence was confirmed by numerous experiments, but the nature of these fluctuations still not clear for us.

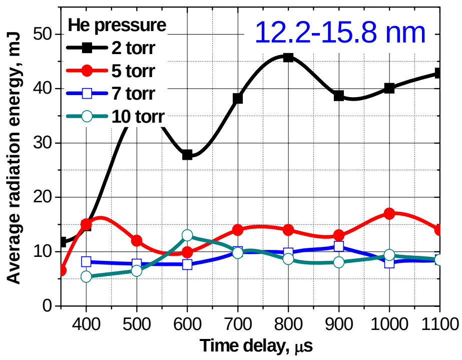

Fig. 5. Dependencies of average radiation energy in EUV wavelength range (12.2…15.8 nm) on time delays for different MPC operation modes

6. CONCLUSIONS

Features of plasma compression zone formation within MPC facility have been investigated by means of spectral and probe diagnostics. As a result of spectroscopic measurements different species (II–V) of xenon lines were identified in a visible wavelength range. Electron density measured with high temporal and spatial resolution using Stark broadening is achieved 10^{18} cm^{-3}.

Spatial distributions of electrical currents in plasma stream have been studied. Output currents achieve 30% of I_d. In some cases current vortexes appearance is attributed to the inclined shock wave formation in compression zone which affects on plasma dynamics outside the source. In some regimes the current displacement from the compression region was observed.

Measurements of EUV radiation from MPC compression zone revealed that maximum radiation energy corresponds to 12.2…15.8 nm wavelength range. It is shown that radiation energy strongly depends on xenon mass flow rate and time delay between gas injection and discharge ignition. Xe injection applied directly into the compression zone and optimization of operation regimes allowed to increase EUV radiation energy in 12.2…15.8 nm wavelength range on 50%.

REFERENCES

1. H. Tanuma, et al. EUV emission spectra from exited multiply charged xenon ions produced in charge-transfer collisions // *Nucl. Instr. And Meth. In Phys. Res.* 2005, B235, p. 331-336.
2. H. Merabet, et al. EUV emission from xenon in the 10-80 nm wavelength range using a compact ERC ion source // *Nucl. Instr. and Meth. in Phys. Res.* 2005, B241, p. 23-29.
3. I.E. Garkusha, et al. // *Ukr. Conference on Plasma Physics and Controlled Fusion.* Kyiv, October 2009, p. 11 (in Ukrainian).
4. L.C. Popovich and M.S. Dimitrijevic. Stark broadening of Xe II lines //*Astron. Astrophys. Suppl. Ser.* 1996, v. 116, p. 359-365.
5. I.E. Garkusha, et al. Characterization of Dense Xe and He-Xe Plasma Streams Generated by Magnetoplasma Compressor // *Proc. of 23rd Symp. on Plas. Phys. and Techn.* Czech Republic, Prague, June 16-19, 2008, p. 44.
6. G. Grim. *Spectroscopy of plasma*. Moscow: "Atomizdat", 1969 (Russian translation).

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ФОРМИРОВАНИЕ ЗОНЫ КОМПРЕССИИ В МАГНИТО-ПЛАЗМЕННОМ КОМПРЕССОРЕ, РАБОТАЮЩЕМ НА ТЯЖЕЛЫХ ГАЗАХ

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В центре внимания экспериментальные исследования динамики формирования плазменного пинча и его влияния на излучательные характеристики плазмы. Обсуждается конструкция магнито-плазменного компрессора (МПК) компактной геометрии с коническими медными электродами. Исчерпывающая информация о динамике формирования зоны сжатия, ее локализации, плазменных параметрах и геометрических размерах получена с помощью спектральной диагностики. Электронная плотность плазмы (~10^{18} см$^{-3}$) измерена по штарковскому уширению спектральных линий Xe. Электронная температура (5...7 эВ) оценивалась по отношению интенсивностей спектральных линий Xe. Регистрирующая система, состоящая из абсолютно калиброванных AXUV диодов с покрытием для различных диапазонов длин волн и многослойного MoSi-зеркала, использовалась для регистрации ВУФ-излучения плазмы. Также представлены пространственные распределения электрических токов выноса.

ФОРМУВАННЯ КОМПРЕСІЙНОЇ ЗОНИ В МАГНІТО-ПЛАЗМОВОМУ КОМПРЕСОРІ, ЯКИЙ ПРАЦЮЄ НА ТЯЖКИХ ГАЗАХ

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В центрі уваги експериментальні дослідження динаміки формування плазмового пінча і його впливу на випромінювальні характеристики плазми. Обговорюється конструкція магніто-плазмового компресора (МПК) компактної геометрії з конічними мідними електродами. Вичерпна інформація про динаміку формування компресійної зони, її локалізацію, плазмові параметри та геометричні розміри отримана за допомогою спектральної діагностики. Електронна густина плазми (~10^{18} см$^{-3}$) виміряна із штарківського розширення спектральних ліній Xe. Електронна температура (5...7 еВ) визначалась по відношенню інтенсивностей спектральних ліній Xe. Реєструюча система, яка складається із абсолютно каліброваних AXUV діодів з покриттям для різних діапазонів довжин хвиль та багатошарового MoSi-дзеркала, використовувалась для реєстрації ВУФ-випромінювання плазми. Також представлено просторові розподіли електричних струмів.