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Features of plasma focus formation in different operation modes of gas-discharge magnetoplasma compressor

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Abstract. The paper presents investigations of dense plasma streams generated by the magneto-plasma compressor (MPC) of compact geometry. Distributions of electrical currents in plasma stream are carefully measured for different operation regimes by sets of magnetic probes. Output currents achieve $(25 \div 35)$ % of I_d. Development of electric current vortexes in plasma resulting in formation of compact plasma toroid is discussed. Maximum plasma stream density was about $10^{18}\,\mathrm{cm}^{-3}$, average electron temperature along a line of view $\sim 5 \div 7$ eV and plasma stream velocity at the MPC output 10^7 cm/s. EUV (extreme ultraviolet) radiation measurements from the compression region show that radiation power of Xe plasma in $12.2 \div 15.8$ nm wavelength band achieves 18 kW. The obtained results are in importance for lithography-oriented applications of MPCs, for development of hot plasma generators and efficient fuelling techniques (plasmoids) as well as Xe plasma injectors for disruption mitigation and other fusion applications.

Key Words. Magnetoplasma compressor, gas-discharge plasma, spectroscopy diagnostic, EUV radiation, outlet currents, plasma electron density.

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Introduction

Extreme ultraviolet (EUV) sources at $\lambda = 13.5\,\text{nm}$ basing on gas discharge Xe plasma are considered to be most promising candidates for next generation lithography [1], [2]. One of the perspective systems for generation of powerful EUV radiation by dense magnetized plasma is magneto-plasma compressor (MPC). Studies of high-energy plasma dynamics are in importance also for other fundamental problems: development of new technologies of materials modification, fusion researches, plasma propulsion and thrusters and powerful radiation sources of broad spectrum.

For these tasks, development of diagnostics for dense magnetized plasma of different ions, including heavy noble gases is necessary to estimate efficiency of plasma systems. Spectral analysis of high-ionized plasma composition and studies of plasma dynamics important for understanding of acceleration and compression processes. In particular, plasma compression zone is also interesting object for investigations of different nonlinear effects occurred in dense magnetized plasmas, for example, hot spots [3].

This paper presents investigations of dense plasma streams generated by the magneto-plasma compressor (MPC) of compact geometry [4], which is able to operate with different gases and their mixtures and, thus, to provide variation of operation regimes in wide range for different applications. Different modes of MPC operation were investigated and compared: helium discharge, pure xenon discharges with pulsed gas supply and discharges in helium under various residual pressures with additional pulsed injection of xenon directly into the compression zone [5].

Experimental setup and diagnostic equipment

Figure 1 shows general view of MPC experimental device and plasma source itself. The both electrodes of magnetopalsma compressor was made from copper. Outer electrode (anode) consists of solid cylindrical part ($\varnothing_{\text{cyl}} = 130\,\text{mm}$) and output rod structure including 12 copper rods with diameter of 10 mm and of 147 mm in length ($\varnothing_{\text{out}} = 92\,\text{mm}$). Inner electrode (catode) has diameter of 60 mm in cylindrical part and out diameter is 30 mm in conical part. MPC is equipped with electrodynamic valve to provide the required amount of gas supply either for operation under the varied residual pressure or for pulsed gas supply to the inter-electrodes area. The discharge is powered from the condenser bank ($C_{\text{v}} = 90\,\mu\text{F}$) charged up to 25 kV, discharge current can achieved 500 kA, duration is equal to $8 \div 10\,\mu\text{s}$ and corresponds to half-period of discharge current.

Spectral diagnostics included EUV and X-ray spectrometer, visible spectrometer, electron-optical converter, which was synchronized with discharge ignition, monochromators, PEMs (photomultiplier), high-speed imaging using CMOS camera PCO AG and fast photo recorder with 1 μs temporal resolution. EUV radiation intensity was analyzed by registration system consisting of absolutely calibrated AXUV diodes with thin-films filters for different wavelength ranges ($5 \div 13$ nm, $12.2 \div 15.8$ nm and $17 \div 80$ nm) and multi-layered MoSi mirrors. Moveable callorimeters, electric and magnetic probes, Rogovski coils, high-voltage dividers etc. were applied also.

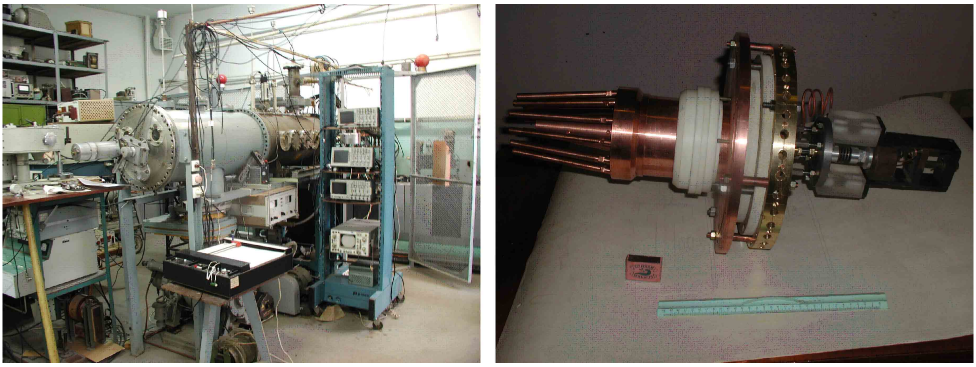

Fig. 1. Experimental device

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. Lines of equal electrical current value in plasma stream for different modes of MPC operation are presented in Fig. 2.

Performed measurements show that total value of electric current flowing outside accelerating channel is about $25 \div 30$ % of discharge current $I_{\rm d}$. Electrical current propagated to distance up to $25 \div 30$ cm from MPC output during first half period of discharge current for both modes of operation with buffering gas and pulsed gas supply. It is found correlation between configuration of output current and dynamics of compression plasma focus region. The current vortexes appearance is attributed to the inclined shock wave formation in compression zone that affects on plasma dynamics outside the source. Shock wave is observed by high-speed imaging (Fig. 3), shock wave existence can also be recognized from electric current peculiarities as shown in (Fig. 2b). High-speed imaging can also provide about plasma pinch evolution with temporal resolution 1 μs, from these images it was possible to estimate the plasma stream

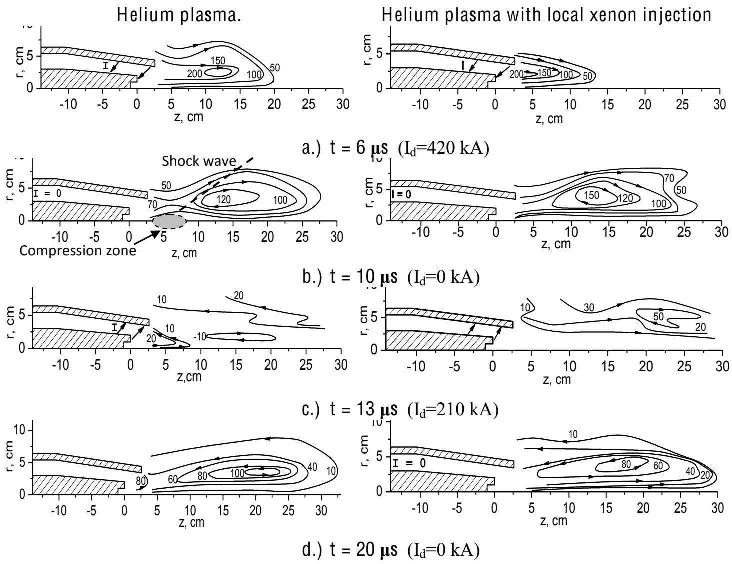

Fig. 2. Time evolution of outlet currents in helium and helium-xenon plasma stream; values of outlet currents are in kA, direction is marked by arrow

average velocity which is equal to $(2 \div 4) \times 10^6$ cm/s. In some regimes the current displacement from the compression region was observed. In conditions when currents are pulsed out and compression region became current free, the magnetic and gas dynamical pressure balance at the boundary of compression zone is achieved at the B-field energy of $10 \div 15\,\mathrm{J/cm^3}$. For measured by Stark broadening electron density in compression region $N_\mathrm{e} = (5 \div 7) \times 10^{17}\,\mathrm{cm^{-3}}$ the plasma temperature can be estimated as $(T_\mathrm{e} + T_\mathrm{i}) \sim 50 \div 100\,\mathrm{eV}$.

EUV radiation measurements.

EUV radiation in $5 \div 80$ nm wave range was detected by registration system consisting on absolutely calibrated AXUV diodes with thin-films filters for different wavelength ranges and multi-layered MoSi mirrors. Measurement scheme is presented in Fig. 4. Set of different AXUV diodes was placed into duralumin corps. Connection tube with diaphragms determined spatial resolution which was typically below 1 cm. Permanent magnets was installed to produce magnetic field of 0.5 T inside the tube to avoid plasma contact with registration elements. Multilayer Mo/Si mirror was used for selection of different parts of EUV radiation spectrum. Thus, visible radiation and particles made no influence on EUV radiation measurements. Typical waveforms of discharge

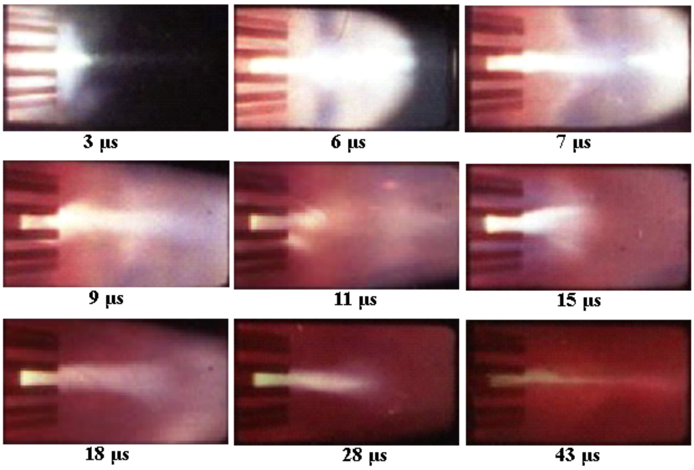

Fig. 3. High-speed imaging of plasma compression with frame exposition 1 μs

current and signal from AXUV 20 Mo/Si in $12.2 \div 15.8$ nm wave range are presented in Fig. 5 for discharge current $I_{\mathrm{d}} = 400$ kA and helium filling pressure of 5 Torr. Experiments show that radiation energy increases with increasing discharge current and it strongly depends on MPC operation regime. For pure Xe discharges EUV radiation from compression zone is strongly absorbed in surrounding peripheral area by neutral and low ionized xenon atoms. Xe injection applied directly into the compression zone and optimization of operation regimes allowed essential increase of EUV energy in $12.2 \div 15.8$ nm wavelength range achieving 10^{-1} J ($P_{\max} = 18$ kW). In this regime, Xe V spectral lines were registered by spectroscopy in plasma focus area and its appearance correlate with significant increase of EUV radiation detected.

Spectroscopy measurements

In spectral observations of temporal behavior of Xe spectral lines emission, EOC (electro–optical converter) operation was synchronized with plasma discharges with varied time of exposition start. Xenon spectral lines are recorded with short enough exposition (in a comparison with the discharge duration) and with different delays in the relation to the discharge beginning. In visible wavelength spectroscopy studies, particular attention was paid to the temporal and spatial behavior of Xe spectral lines and impurities. Xe II–V species

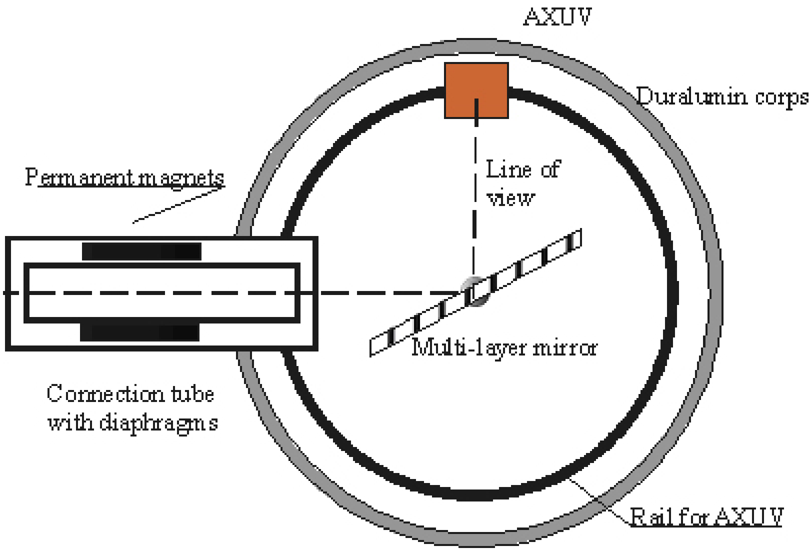

Fig. 4. Scheme of EUV radiation measurements

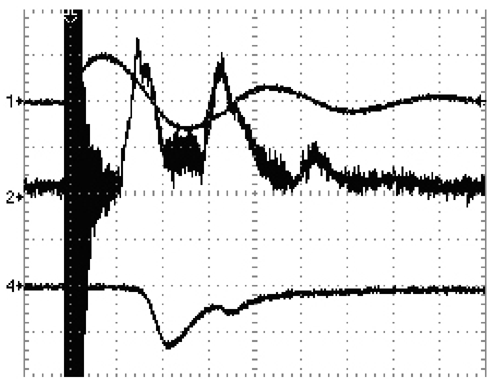

Fig. 5. Wave forms of discharge current (1), AXUV signal in wave range of $12.2 \div 15.8$ nm (2) and signal from photodiode in visible range (4) for local xenon injection into compression zone; maximum discharge current is 400 kA, buffering He gas pressure 5 Torr

were identified, however high-ionized Xe ions are recorded only for MPC operation with local injection of Xe into compression region and achievement of maximal plasma parameters in compression zone. Thus, radiation of Xe V spectral lines is attributed to the plasma focus formation and it decreases with Xe II species appearance. Temporal dependence of Stark widths for Xe V

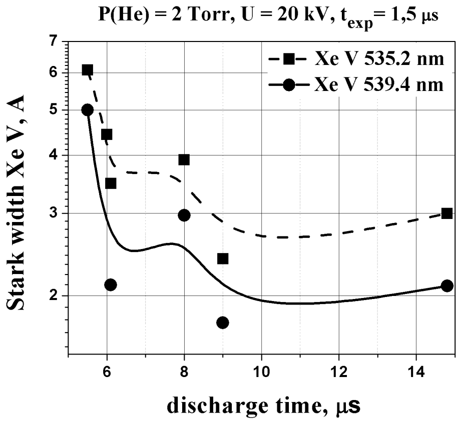

Fig. 6. Temporal distributions of XeV Stark widths

spectral lines (Fig. 6) illustrates the dynamics of plasma compression and it corresponds to hot and high-energy part of plasma stream with duration of generation $\sim 1.5 \div 2\,\mu\mathrm{s}$.

Electron density was measured using Stark broadening of Xe II and Xe III lines. Temporal dependence of N_e obtained for buffering gas pressure 2 and 10 Torr with local Xe injection into compression zone is presented in Fig. 7 with different temporal resolution. Electron density distribution for operation mode when buffering gas filled whole accelerating channel (10 Torr) has only one peak with maximum value $N_\mathrm{e} = 7 \times 10^{17}\,\mathrm{cm}^{-3}$. Operation with smaller pressures (2 Torr) is characterized by two peaks on N_e dependence, which correspond to the first and second half-periods of discharge current respectively. Radiation intensity of Xe II, III lines in the second half-period of discharge current for high residual pressure (10 Torr) is considerably smaller. Therefore plasma density estimations were not performed in this case. Impurities (Cu, C) are appeared in plasma column after 10 μs from the discharge ignition, but even in late stage the impurity spectral lines are not dominant in whole spectrum and they do not influence on plasma focus formation.

Measurements of temporal behavior of N_e were supplemented with spatial ones. Abel inversion procedure was applied for determination of radial distributions of plasma density in near axis region. Example of space-time distributions of electron density at distance 6 cm from central electrode is presented in Fig. 8. For MPC operation at buffering gas pressure of 2 Torr and Xe local injection maximum plasma stream density achieves $10^{18}\,\mathrm{cm}^{-3}$, average electron temperature along the line of view $\sim 5 \div 7\,\mathrm{eV}$ and plasma stream velocity at the MPC output $\sim 10^{7}\,\mathrm{cm/s}$.

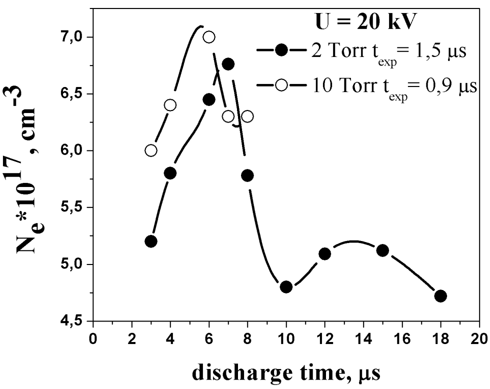

Fig. 7. Temporal plasma electron density for different MPC operating modes

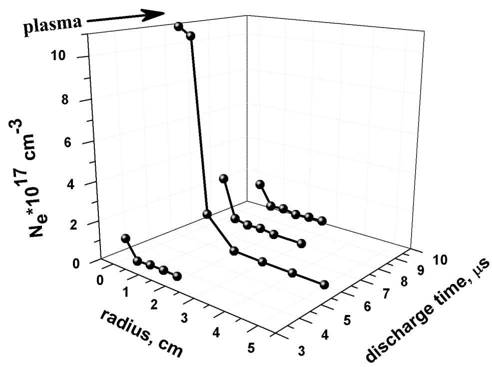

Fig. 8. Space-time electron density distribution at distance of 6 cm from central electrode obtained for MPC operation at buffering He pressure of 2 Torr and local Xe injection

Conclusions

Features of plasma compression zone formation in different modes of MPC operation have been investigated. Spectroscopic analysis of Xe II–Xe V lines identified in visible wavelength range was performed. Electron density was measured with high resolution ($\sim 0.5\,\mu s$) using Stark broadening of Xe II and Xe III lines. Corresponding values of electron density achieved $10^{18}\,cm^{-3}$ in operation mode with buffering He gas and local Xe injection into compression region.

Spatial distributions electrical currents in plasma stream have been studied. Output currents achieve $25 \div 30\,\%$ of I_d. Development of electric current vortexes in plasma was found. Current loops promote the formation of compact plasma toroid. The 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. Pressure balance at the boundary achieved at the B-field energy of $10 \div 15\,J/cm^3$. For $N_e = (5 \div 10) \times 10^{17}\,cm^{-3}$ the $(T_e + T_i) \sim 50 \div 100\,eV$.

Observation of compression zone dynamics with high speed imaging well correlate with temporal dependencies of N_e and spatial distributions of output current for different time moments.

Analysis of EUV radiation from compression region shows that radiation energy increases with increasing discharge current and it strongly depends on MPC operation regime. For pure Xe discharges EUV radiation from compression zone is strongly absorbed in surrounding peripheral area by neutral and low ionized xenon atoms. Xe injection applied directly into the compression zone and optimization of operation regimes allowed essential increase of EUV energy in $12.2 \div 15.8$ nm wavelength range achieving 10^{-1} J ($P_{max} = 18\,kW$). In this regime, Xe V spectral lines were registered by spectroscopy in plasma focus area and its appearance correlate with significant increase of EUV radiation detected.

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