# CHARACTERISTICS OF PLASMA STREAMS AND OPTIMIZATION OF OPERATIONAL REGIMES FOR MAGNETOPLASMA COMPRESSOR

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The main objective of these studies is characterization of dense xenon plasma streams generated by magnetoplasma compressor (MPC) in different operational regimes. Optimization of plasma compression in MPC allows increase of the plasma stream pressure up to 22…25 bar, average temperature of electrons of 10…20 eV and plasma stream velocity varied in the range of (2…9)×$10^6$ cm/s depending on operation regime. Spectroscopy measurements demonstrate that in these conditions most of Xe spectral lines are reabsorbed. In the case of known optical thickness, the real value of electron density can be calculated with accounting self-absorption. Estimations of optical thickness were performed and resulting electron density in focus region was evaluated as $10^{18}$ $cm^{-3}$.

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## INTRODUCTION

Experimental investigations of high-energy plasma streams present considerable interest for different practical applications, such as surface modification by pulsed plasma processing, deposition of different coatings, development of powerful radiation sources in various wavelength ranges. The plasma compression zone that is formed in different pinching discharges is a source of intensive electron and ion beams, neutrons, hard X-ray and EUV radiation.

In this paper experimental studies of magnetoplasma compressor (MPC) operating with Xe and He gases are presented and characteristics of dense plasma are discussed. Measurements of plasma parameters, e.g. spatial and temporal distributions of plasma stream density, plasma pressure distributions, temperature and velocity provide detailed information about dynamics of plasma streams and features of plasma compression. These characteristics are important from the point of view optimization of MPC operation regimes in lithography oriented applications, i.e. for achievement of maximal intensity of EUV radiation in the characteristic wavelength of 13.5 nm, corresponding to tenfold ionized Xe.

## EXPERIMENTAL SETUP

Magnetoplasma compressor MPC is described in details in [1]. The outer electrode has solid cylindrical part and also output rod structure including 12 copper rods with diameter of 10 mm and length of 147 mm. The central electrode consists of the cylindrical part 60 mm in diameter and 208 mm in length. Pulsed injection of working gas is realized with fast electro-dynamical valve through number of holes in the inner electrode. The power supply of MPC discharge and gas valve comes from capacitor banks. The capacity of discharge power supply system is 90 μF and the operation voltage is up to 30 kV. The power supply battery of gas valve has capacity of 700 μF and the working voltage up to 5 kV.

Mainly, xenon was used as working gas. Measurements were carried out at discharge voltage of 20 kV for two different operation regimes with time delays between the gas injection start and discharge ignition $\tau$=500 μs and $\tau$=550 μs respectively.

## ANALYSIS OF SPECTRAL LINES SELF-ABSORPTION

One of the key effects, which may influence on the accuracy of plasma density measurements by broadening spectral lines, is effect of spectral lines self-absorption. Calculations of electron density taking into account self-absorption effect can be made if the plasma thickness is known.

The consideration of optical spectra emitted from MPC compression zone showed that the most of xenon spectral lines are self-absorbed (except some lines with low intensity). This phenomenon may introduce significant errors at Ne determination, namely the density value is usually increased. Therefore, in this case plasma parameters measurements were carried out using contours and intensities of spectral lines both with taking into account self-absorption and without it applying following comparison of obtained results. Electron density in plasma can be estimated using self-absorbed line contour for known value of optical thickness as self-absorption parameter [2].

Two methods have been used for determination of optical thickness. First method has been applied when optical thickness value was not very large and it was possible to use the spectral lines belonging to one multiplet, i.e. when all characteristic values for the lines (excitation energy, transition energy, terms and etc.) are the same. With variation of the absorptive atoms concentration or plasma column length the lines intensities within one multiplet must be changed on the same value. This value is product of g×f (g – statistical weight, f – oscillator force) what is proportional to line intensity [3]. So the ratio of g×f (theoretical) and the ratio of observed lines intensities (experimental) are equal for spectral lines without self-absorption, otherwise investigated lines are reabsorbed. Using the equation (1) one possible to find dependencies of g×f product from optical thickness ratio:

$$d(\tau,\alpha,\lambda)=\frac{1-e^{-\tau}}{1-e^{\frac{-\tau}{\alpha}}}, \tag{1}$$

where $\alpha=(gf)_1/(gf)_2$. Obtained results for majority of spectral lines are indicated in the Table below.

*Optical thickness for XeII and XeIII spectral lines in regimes with time delays of $\tau$ =500 and 550 μs*

| λ, nm | τ (500 μs) | τ (550 μs) |
|---|---|---|
| Xe II 529.2 | 10 | 18 |
| 533.9 | 3 | 4.5 |
| 460.3 | 3.2 | 5 |
| 433.0 | <1 | <1 |
| XeIII 392.2 | 3.2 | 3.6 |
| 395.0 | 3.16 | 3.5 |

Second method consists in determination of optical thickness using experimentally measured lines intensities. Lorenz (Stark) half-width of the line was found from the experimental shape of spectral lines, using the Foigt functions.

Performed analysis has shown that we are dealing with mixed line-contour with predominant Lorentz effect. Corresponding dependencies for both Lorentz and Doppler contours were obtained (Fig. 1) using following equations for optical thickness:

$$\Delta\lambda_L = \frac{\Delta\lambda_{mL}}{\Delta\lambda_o}(\tau) = \sqrt{\frac{\tau}{\ln\left(\frac{2}{1+e^{-\tau}}\right)} - 1}, \qquad (2)$$

$$\Delta\lambda_D = \frac{\Delta\lambda_{mD}}{\Delta\lambda_o} = \frac{1}{\sqrt{\ln 2}} \cdot \sqrt{\ln\left(\frac{\tau}{\ln\left(\frac{2}{1+e^{-\tau}}\right)}\right)}, \qquad (3)$$

where $\Delta\lambda_{mL}$ and $\Delta\lambda_{mD}$ – measured Lorentz and Doppler widths correspondingly (Å); $\Delta\lambda_o$ – line width for optically thin layer, i.e. calculated with theoretical data (Å); $\tau$ – optical thickness. Using these equations value of optical thickness was found for Stark contour. Electron density was estimated using $\Delta\lambda_o$. This method is suitable for large values of optical thickness then distortion of spectral lines shape is large.

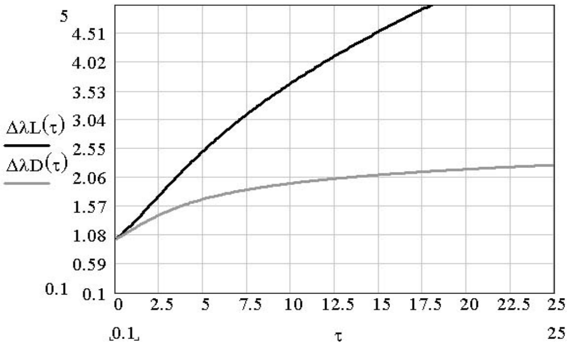

*Fig.1. Optical thickness determination using Stark or Doppler contours*

## PLASMA DENSITY MEASUREMENTS

Electron density was calculated using Stark broadening of Xe II and Xe III spectral lines. Stark widths for Xe II lines are available in [4] and for Xe III – in [5]. Electron density average value for both time delays are practically the same and equal to $1\times10^{17}$ cm$^{-3}$. The plasma parameters in compression zone were calculated from self-absorbed spectral lines and they are in a good agreement with corresponding characteristics obtained for line-contours without re-absorption. It is found that maximal xenon plasma concentration in compression zone can achieve $10^{18}$ cm$^{-3}$. It is estimated also that due to the re-absorption phenomenon the real $N_e$ magnitude can be increased on 20…30%.

## PLASMA PRESSURE MEASUREMENTS

Several movable small-size piezoelectric detectors were designed and manufactured for plasma pressure measurements. All detectors were calibrated for absolute measurements [6]. The radial distribution of plasma stream pressure was measured at two different distances – 10 and 20 cm from the MPC output. The results of these measurements are shown in Figs. 2, 3. Plasma stream has good symmetry and the pressure at distance 10 cm from MPC output is achieved 22 and 17 bars for operation modes with time delays 500 and 550 μs correspondingly (see Fig. 2). Average plasma stream diameter, calculated as half width of plasma pressure radial distribution, is equal to 20…25 mm. At the same time it is seen that in near axis region with typical diameter of about 1 cm, the plasma pressure is not changed and this region with maximal pressure can be considered as effective plasma stream diameter at the output of compression zone.

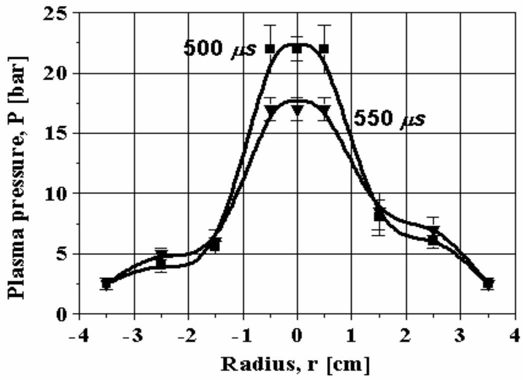

*Fig. 2. Radial distributions of plasma pressure at the distance of 10 cm from MPC output*

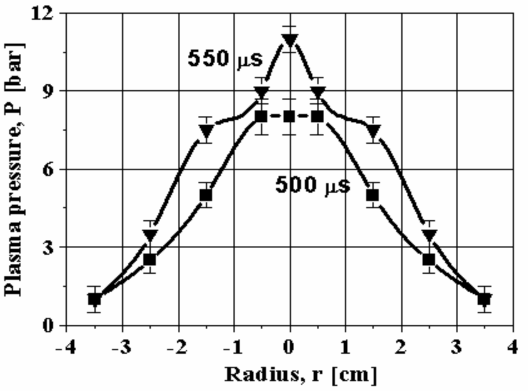

*Fig. 3. Radial distributions of plasma stream pressure at the distance of 20 cm from MPC output*

At the distance of 20 cm from the MPC output the plasma stream pressure decreases to 8 bars for time delay of 500 μs and to 11 bars for time delay of 550 μs (see Fig. 3). It is interesting that pressure peak is observed in near axis region for regime with time delay of 550 μs. At the same time pressure plateau in near axis region is observed for MPC mode of operation with time delay of

500 μs. It can be indication of changing position of compression zone in different operation regimes.

Average plasma stream diameter, estimated as half width of plasma pressure radial distribution, is increased to 3 cm for operation mode with time delay of 500 μs and to 4…4.5 cm for time delay of 550 μs.

## TEMPERATURE MEASUREMENTS

Calculations were performed for xenon ions (with different ionization state) in the framework of Saha-Boltzman combined equations at local thermodynamic equilibrium (LTE) approximation. The analysis of its applicability is carried out using well known Griem criterion. Such analysis is especially desirable taking into account important temperature measurements. Time and chord averaged electron temperature determined using the ratio of XeII/XeIII lines intensities is 4…4.3 eV. From theoretical Saha-Boltzman calculations it was estimated that XeIV and XeV species, which observed in the spectra, must be registered at electron temperature ~ 10…20 eV (Ne~$10^{18}$ $cm^{-3}$). It was obtained that at $\Delta t$ = 550 μs these spectral lines were more intensive than in other working regime.

## PLASMA STREAM VELOCITY

Plasma stream velocity was calculated using plasma pressure and electron density. Minimum velocity was in central area of plasma flow and it was equal to $(9\times10^5)\ldots(1.5\times10^6)$ cm/s in regime with 500 μs time delay. The velocity of plasma bunch is spreading grew with shift from the axis of plasma stream and it had value about $(2\ldots3)\times10^6$ cm/s. For time delay of 550 μs, the distributions of plasma stream velocity showed opposite tendency. Maximum value of velocity up to $(6\ldots9)\times10^6$ cm/s was measured in near axis region of plasma stream. This value is in 2–3 times higher than velocity of peripheral parts of plasma stream $((2\ldots4)\times10^6$ cm/s).

## CONCLUSIONS

Characterization of dense xenon plasma streams generated by magnetoplasma compressor in different operational regimes has been performed. Optimization of plasma compression in MPC allows increase of the plasma stream pressure up to 22…25 bar. Measured plasma core diameter is about 1 cm. Depending on operation regime the plasma stream velocity is varied in the range of $(2\ldots9)\times10^6$ cm/s.

Maximal plasma stream density measured from xenon spectral lines with taking into account self absorption is about $(1\ldots2)\times10^{18}$ $cm^{-3}$. Presence of Xe IV and XeV spectral lines in spectra allows us to expect that electron temperature in compression zone riches 10…20 eV.

Analysis of the obtained results has shown that at time delay between gas puff and discharge ignition $\tau$ = 550 μs it is observed more pronounced accelerating character of plasma flow, while at $\tau$ = 500 μs stronger compression effects are observed.

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## ХАРАКТЕРИСТИКИ ПЛАЗМЕННЫХ ПОТОКОВ И ОПТИМИЗАЦИЯ РАБОЧИХ РЕЖИМОВ МАГНИТОПЛАЗМЕННОГО КОМПРЕССОРА

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Проведены эксперименты по оптимизации режимов работы МПК, измерены параметры плазменных потоков при работе на ксеноне. Проанализированы распределения давления в плазменном потоке, скорость и температура плазмы. Спектроскопические измерения показали, что большинство спектральных линий ксенона самопоглощены. В случае известной оптической толщины реальная электронная плотность может быть вычислена с учетом эффекта самопоглощения. Проведены оценки оптической толщины, в результате чего рассчитано значение концентрации электронов в области компрессии – $10^{18}$ $см^{-3}$.

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## ХАРАКТЕРИСТИКИ ПЛАЗМОВИХ ПОТОКІВ ТА ОПТИМІЗАЦІЯ РОБОЧИХ РЕЖИМІВ МАГНІТОПЛАЗМОВОГО КОМПРЕСОРА

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Проведено експерименти з оптимізації режимів роботи МПК та виміряно параметри плазмових потоків при роботі на ксеноні. Проаналізовано розподіли тиску в плазмовому потоці, швидкість та температура плазми. Спектроскопічні вимірювання показали, що більшість спектральних ліній ксенону самопоглинені. У випадку відомої оптичної товщини, реальна електронна густина може бути обчислена з урахуванням ефекту самопоглинання. Були проведені оцінки оптичної товщини, в результаті чого розрахована величина концентрації електронів в області компресії – $10^{18}$ $см^{-3}$.