DYNAMICS OF NITROGEN AND XENON PLASMA STREAMS GENERATED BY MPC DEVICE

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Magnetoplasma compressor (MPC) of compact geometry is developed for generation of dense plasma streams of different working gases. Discharge characteristics and parameters of the plasma streams, generated by MPC in different modes of operation are investigated. Dynamics of compression zone formation and energy efficiency of MPC are analyzed.

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INTRODUCTION

Pinching plasmas are remained to be of great interest for solving of many fundamental problems of high-energy density physics and for different technological applications [1]. In particular, dense plasma generated with powerful electrical discharges is considered as candidate-source of extreme ultraviolet (EUV) radiation for the optical lithography. Gas discharge plasma sources may have the potential advantages as far as they can be simpler in design, compact and cost-effective.

The paper presents the investigations of nitrogen and xenon plasma streams generated by magnetoplasma compressor (MPC) of compact geometry with conical-shaped electrodes and pulse gas supply. This device makes possible the investigations of plasma compression dynamics in focus region, peculiarities of generations of EUV and soft X-ray radiation from the focus and features of plasma-surface interaction in high current pinching discharges, operating with heavy noble gases [2, 3]. The main attention in present experiments is paid to investigations of xenon plasma streams parameters and MPC operation regimes.

EXPERIMENTAL DEVICE

MPC consists of two copper coaxial electrodes with disk current collector (separated by figured combined insulator) and pulse gas supply system. The outer electrode has solid cylindrical part of 110 mm in diameter and 147 mm in length and also output rod structure including 12 copper rods with diameter of 10mm and length of 147mm. The rods form the frustum of cone surface with apex angle of 30^0 as it is shown in Fig.1. Design of MPC device is described in detail in [4].

MPC was installed into vacuum chamber with diameter 42 cm and length 130 cm. Working pressure in vacuum chamber 10^{-6} Torr. Nitrogen and xenon were used as working gases. Condenser bank with capacitance of 90 µF and maximal voltage of 25 kV was used for power supply of main discharge in MPC.

High-speed camera, spectrograph DFS-452 and MDR-23 monochromator were applied for plasma density and temperature estimations. AXUV photodiodes were used for EUV radiation intensity measurements. Rogowski coils, compensated high voltage divider, electric and magnetic probes, movable calorimeter and piezodetectors were used for plasma parameters measurements.

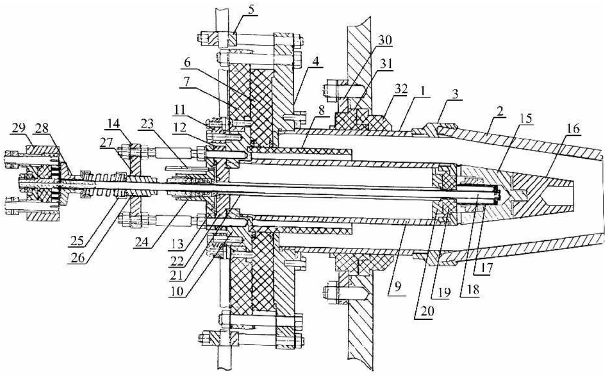

Fig. 1. Block scheme of MPC device

CHARACTERISTICS OF MPC DISCHARGE

Operational regimes of the plasma source have been varied by changing the volume of gas, injected into accelerating channel, and by change of the time delay between start of gas injection and discharge ignition. Integral mass flow rate was changed from 5 to 30 cm^3. Typical wave forms of discharge current and voltage presented in Fig.2.

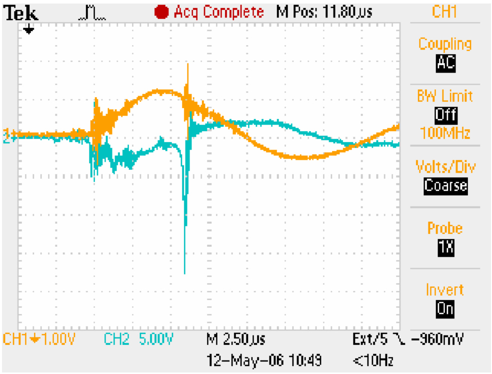

Fig. 2. Discharge current and voltage, Xe, U_c = 20 kV, Δt= 550 µs, ΔV=10 cm^3

Current-voltage characteristics (CVC) were measured in different accelerator modes of operations. The discharge voltage was measured at the time moment corresponding the maximum of discharge current when $L\frac{dI}{dt}=0$. Typical current-voltage characteristics for xenon discharge are shown in Fig. 3. Current-voltage characteristics can be approximated by power function $U_d \propto \eta \cdot I_d^{\beta} / I_{\dot{m}}$, where I_d, U_d – discharge current and voltage correspondently, I_m- effective mass flow rate, η-accelerator efficiency. As it was found in present experiments the power is about $\beta \approx 3$ for nitrogen and about 2 for xenon. In spite of the same value of discharge current the discharge voltage is decreased with increasing mass of working gas.

Time dependencies of discharge current and voltage were used for estimation of energy fraction passed from capacitor bank into accelerator. This energy was calculated as $Q = \int_0^T I_d(t) \cdot U_d(t)dt$, where T – time moment when discharge voltage changes sign.

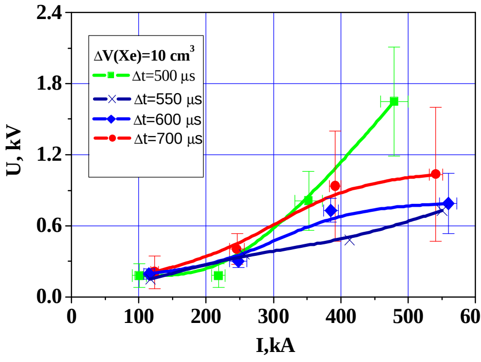

Fig. 3. Current-voltage characteristics for xenon discharges in MPC

The energy delivered to the discharge channel is increased with increasing capacitor voltage and this dependence can be described by power function with power ~ 2. This is consequence of increasing active part of total impedance of the electrical circuit with increase of capacitor voltage due to higher plasma stream density and velocity. The total energy containment in plasma stream, measured by local calorimeter, is about (5-7) % of the energy stored in capacitor bank.

PLASMA STREAM PARAMETERS

Plasma stream velocity

The plasma stream velocity was estimated by time – of-flight method between two photo diodes installed along the vacuum chamber. Average velocity of nitrogen plasma stream is achieved 2.7×10^7 cm/s at discharge current of 320 kA. Average xenon plasma stream velocity is smaller and the measured value is $(3\text{-}4)\times10^6$ cm/s at discharge current 500 kA.

Time dependence of xenon plasma stream velocity obtained from the shift of radiation peaks on photodiodes signals is shown in Fig. 4. As follows from these measurements the maximum value xenon plasma stream velocity is $(6\text{-}8)\times10^6$ cm/s and it achieved after 10-12 μs from the discharge start (t = 0). For later time moments t=35-40 μs the velocity drops to $(2\text{-}3)\times10^6$cm/s. The duration of plasma stream generation estimated as period of time when stream velocity decreased in two times is ~ 5-10 μs.

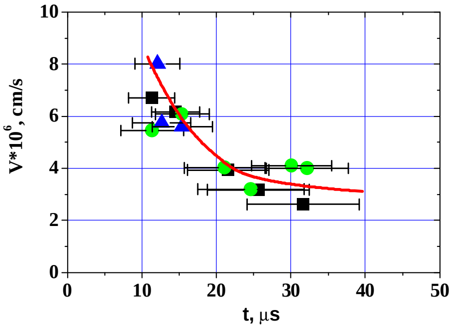

Fig. 4. Time dependence of xenon plasma stream velocity; I_d=400 kA; ΔV=10 cm³; Δt=500 μs

Plasma stream density distribution

The electron density distributions were measured from the broadening of XeII and XeIII spectral lines in visible wavelength range. Results of electron density measurements at the different distances from MPC output are presented in Fig 5. Density value calculated from single and double ionized xenon atoms differs not significantly. Electron temperature estimated from the ratio of XeIII/XeII intensities is about 2.5-3 eV in all operation regimes. This value corresponds to the peripheral region of plasma stream. For temperature measurements in the core of compression region, EUV spectroscopy should be applied.

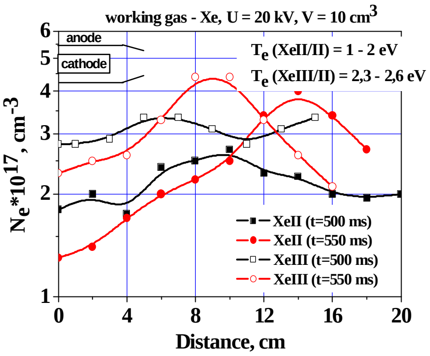

Fig. 5. Spatial distributions of electron density in Xe plasma; I_d=400 kA; ΔV=10 cm³

High speed imaging

High-speed imaging of the plasma discharge, which illustrates the compression dynamics, is carried out in frame-by-frame regime. Time resolution is 1 μs. Evolution of MPC discharge and formation of compression region are presented in Fig.6. As it is seen, focus is formed at the distance of 8-10 cm from MPC output after 6-10 µs from the discharge start. The average focus diameter is ~ 1-2 cm and the length is 2-4 cm.

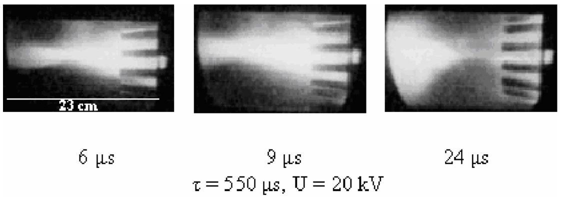

Fig. 6. Xenon plasma stream. I_d*=400 kA; 10* cm^3*; Δt=500 µs*

EUV radiation

AXUV 20Mo/Si photodiodes (wave range of 12.2-15.8 nm) were used for analysis of plasma stream radiation. AXUV were installed into the tube and adjusted to vacuum chamber through special system, which gives possibility for changing direction of measurements. The radiation intensity is increased more than in three times with increasing capacitor voltage by 30% from 15 to 20 kV. At the same time the intensity of radiation in visible wave range, measured by conventional photodiodes, increased less than in two times.

DISCUSSION AND CONCLUSIONS

MPC of compact geometry is developed for generation of dense plasma streams of different working gases. The main electro-technical characteristics are investigated. Volt-ampere characteristics can be described by power function with power ~ 3 for nitrogen and ~ 2 for xenon working gas. The average plasma stream velocity can be described by function [5] $v \propto I_d^{\alpha} \big/ \sqrt{M_i}$, where v – plasma stream velocity, I_d – discharge current and M_i – mass of working gas. Discharge voltage can be described by $U_d \propto \int v(r) \cdot H_{\varphi}(r) dr$, where $v(r)$ – radial distribution of plasma velocity and $H_{\varphi}(r)$ – azimuthal component of magnetic field in discharge channel. Thus, for the same value of discharge current the discharge voltage is decreased with increasing mass of working gas.

Maximal energy in xenon plasma stream measured by movable calorimeter is about (5-7) % of the energy in capacitor banks. The energy containment in plasma stream strongly depends on MPC operation mode. For example, it drops from 1.8 kJ to 0.4-0.45 kJ with increasing time delay of the discharge from 500 to 550 µs.

The average plasma stream velocity at the MPC output achieves 2.7×10^7 cm/s and 3×10^6 cm/s for operation with nitrogen and xenon accordingly. Maximum velocity corresponds to the front of xenon plasma stream and achieves $(6\text{-}8) \times 10^6$ cm/s. Then it drops in two times during 5-10 µs.

Compression zone with diameter of 1-2 cm and the length of 2-4 cm is formed at the distance of 8-10 cm from the central electrode. The maximum value of electron density in focus zone is $Ne \approx 2 \times 10^{18}$ cm^{-3} for nitrogen and $(4\text{-}5) \times 10^{17}$ cm^{-3} for xenon plasma. Time averaged electron temperature (during all discharge) at the MPC output is 7-8 eV for nitrogen and 2-3 eV for xenon plasma respectively. The measured values correspond to the peripheral region of the plasma stream.

First results of plasma radiation measurements in EUV wave range of 12.2-15.8 nm, obtained with AXUV photodiodes are presented.

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ДИНАМИКА АЗОТНЫХ И КСЕНОНОВЫХ ПЛАЗМЕННЫХ ПОТОКОВ, ГЕНЕРИРУЕМЫХ МПК

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Создан магнито-плазменный компрессор (МПК) компактной геометрии для генерации плотных плазменных потоков различных газов. Исследованы характеристики разрядов и параметры плазменных потоков, генерируемых МПК в различных режимах работы. Проанализированы динамика формирования зоны компрессии и энергетическая эффективность МПК.

ДИНАМІКА АЗОТНИХ І КСЕНОНОВИХ ПЛАЗМОВИХ ПОТОКІВ, ЩО ГЕНЕРУЮТЬСЯ МПК

В.В. Чеботарьов, І.Є. Гаркуша, М.С. Ладигіна, Г.К. Марченко, Ю.В. Петров, Д.Г. Соляков, О.В. Царенко, В.І. Терешин, С.А. Трубчанінов, Д.В. Єлісєєв, А. Хассанейн

Створено магніто-плазмовий компресор (МПК) компактної геометрії для генерації густих плазмових потоків різних газів. Досліджено характеристики розрядів і параметри плазмових потоків, що генеруються МПК у різних режимах роботи. Проаналізовано динаміку формування зони компресії й енергетичну ефективність МПК.