Characterization of dense plasma streams generated by MPC and their interaction with material surfaces

Vadym A. Makhlaj,
Vladimir V. Chebotarev,
Alexander A. Chuvilo,
Igor E. Garkusha,
Maryna S. Ladygina,
Anna K. Marchenko,
Yuriy V. Petrov,
Dmytro G. Solyakov,
Dmytro V. Yelisyeyev

Abstract. Comparative studies of the parameters both pure helium and helium-xenon plasma have been fulfilled in a magneto-plasma compressor (MPC). The current-voltage characteristics of MPC accelerating channel and the maximum plasma velocity of (6–8) × 10^6 cm/s changed negligibly under local xenon injection to compression zone. Nevertheless, the xenon addition causes a growth of maximal plasma pressure up to of 2.3 MPa, an increase of plasma radiation from the compression zone. The plasma density achieved 10^{18} cm.

Key words: magneto-plasma compressor (MPC) • gas-discharge plasma • plasma streams • mixture gas • EUV radiation • surface damage

V. A. Makhlaj✉, V. V. Chebotarev, A. A. Chuvilo, I. E. Garkusha, M. S. Ladygina, A. K. Marchenko, Yu. V. Petrov, D. G. Solyakov, D. V. Yelisyeyev
Institute of Plasma Physics,
National Science Center, "Kharkov Institute of Physics and Technology" (NSC KIPT),
1 Akademicheskaya Str., 61108 Kharkov, Ukraine,
Tel.: +38 057 335 6305, Fax: +38 057 335 2664,
E-mail: makhlay@ipp.kharkov.ua

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Introduction

At present, the dense magnetized plasmas, generated by the different plasma-dynamics systems, are used for numerous applications [2, 3, 5]. Powerful plasmas of light elements (hydrogen and helium) are applied for simulation of transition events in a fusion reactor [2]. In the future tokamak ITER the divertor damage caused by disruptions can be mitigated using preventive massive gas injection into confined plasma during the thermal quench [4]. The injected gas gets ionized in the plasma. Main result of core contamination is the fast loss of energy by radiation. High emissivity properties of plasma heavy gases (e.g. xenon) can be used in lithography application. Power of extreme ultraviolet radiation can be sufficiently increased by using the local injection of xenon into helium plasma streams generated by MPC. This can be explained by the decreasing of absorption extreme ultraviolet (EUV) irradiation in peripheral area with a small content of neutral and low-ionized xenon atoms [6]. Surface processing with pulsed plasma streams of different gases is an effective tool for the modification of surface layers of different materials. In particular, exposure with powerful pulsed plasma streams results in the hardening and alloying of the processed surfaces [5]. Thus, studies of dense plasma streams and their interaction with different surfaces are issues of current importance for plasma technologies, fusion science and engineering, lithography oriented applications and others.

This paper presents the experimental investigations of the plasma streams generated by MPC operating with helium and a mixture of helium and xenon. Features of plasma surface interaction in MPC and the resulting microstructure of the treated tungsten surfaces after the plasma impacts also are discussed.

Experimental device and diagnostics

Discharge gap of MPC [1, 6] is formed by conical-shaped electrodes. Diameters of external electrode (anode) and inner (cathode) at the output of accelerating channel are 8 and 3 cm, accordingly. The MPC is powered by a condenser battery with a stored energy of 28 kJ (at 25 kV). The working regimes were varied by choosing a quantity of gas, supplying the MPC, and altering the time of switching on the discharge between electrodes and the value of the discharge voltage. The amplitude of a discharge current achieves 500 kA, and the discharge half-period is ~ 10 μs. The MPC generates compression plasma streams with plasma density up to 10^{18} cm^{-3}, and plasma energy density varied in the range of 0.05–0.5 MJ/m^2 [6]. The main part of experiments was carried out using pure helium at a residual pressure of 2 torr. In some experiments the additional injection of xenon directly into the compression zone was realized [6].

The radial distributions of the plasma stream energy density have been monitored with movable thermocouple calorimeters. Measurements of plasma pressure were carried out with a piezodetector. Electron density was estimated from the Stark broadening of spectral lines. Plasma stream power and energy densities were calculated on the basis of measured time dependencies of the plasma pressure, plasma stream density and its velocity. Different types of AXUV diodes were used in the analysis of plasma stream radiation in an EUV wavelength range of 5–80 nm.

Experimental results

Two operating modes were used in these experiments a pure helium discharge and a discharge with local injection of xenon in the compression zone [6]. An increase of the voltage at the capacitive storage resulted in a growth of discharge current. The half-period of the discharge current of 9–10 μs is practically independent of the MPC operating modes (Fig. 1). Xenon injection into the compression zone has a negligible effect on the current-voltage characteristics. Discharge characteristics are depend only on the residual gas (helium) pressure. On the basis of current-voltages measurements we estimate the efficiency of energy transfer from the capacitive storage to the MPC accelerating channel. It was found that 35–40% of energy was transferred to the MPC accelerating channel. This value is practically independent of the MPC operating mode.

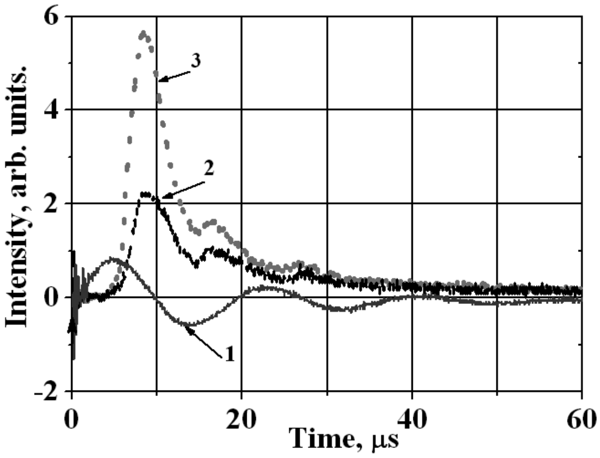

Fig. 1. Waveforms of the discharge current (I_{max} = 450 kA) (1), intensities of plasma visible radiation in helium plasma streams (2), and for a local xenon injection (3), ΔV(Xe) = 7 cm^3, and τ = 500 μs.

The maximum velocity of (6–8) × 10^6 cm/s is reached at the front of the plasma stream. It weakly depends on xenon injection into the compression zone. For the pure helium plasma stream, the maximal pressure of 1.5 MPa is achieved also at the front of the plasma flow (Fig. 2). The local xenon injection causes a 1.5 times growth of plasma pressure at the first peak up to 2.3 MPa. For the later moments of time, the plasma pressure is almost not different for both the cases. Life time of plasma stream with pressure more than 0.5 MPa achieved 30 μs. Maximal plasma density is 10^{18} cm^{-3} [6].

The measured radial distributions of the energy density in the plasma flow at a distance of 7 cm from the MPC edge in different MPC operating modes is shown in Fig. 3. It can be seen that a compression zone with a typical diameter of 2–4 cm is formed in both MPC operating modes. The maximum energy density of 0.45–0.47 MJ/m^2 achieved in the near axial region of pure helium plasma. Local injection of xenon into the compression zone generally had little effect on the radial distribution of the energy density in the flow. Exception is only the axial region with a diameter of 1–1.5 cm. The energy density decreased down to 0.35–0.4 MJ/m^2 for this part of plasma stream. The total energy content of

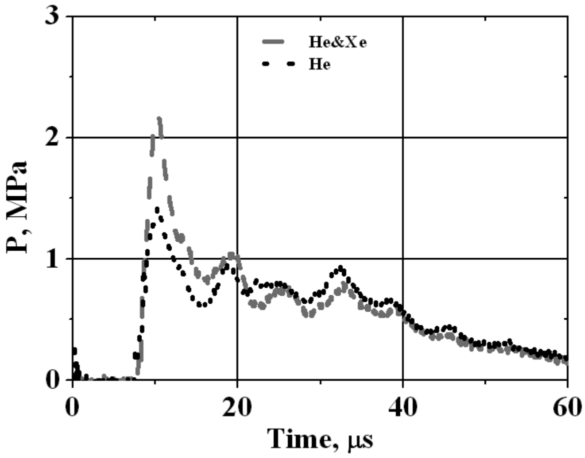

Fig. 2. Waveforms of the pressure in the compression zone: helium (He) plasma streams and for a local xenon injection in helium plasma (He and Xe), ΔV(Xe) = 7 cm^3, and τ = 500 μs.

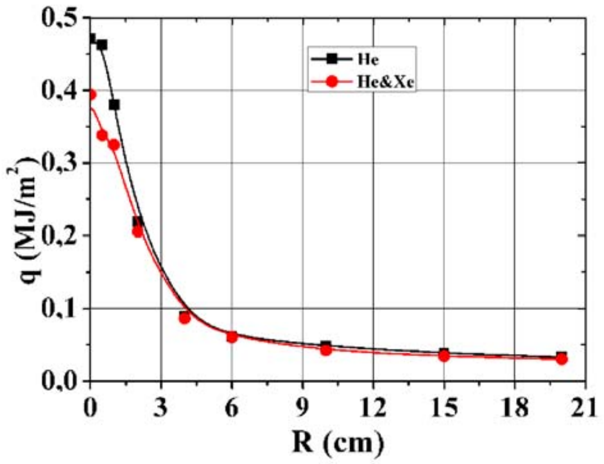

Fig. 3. Radial distributions of energy density in helium (He) and helium-xenon (He and Xe) plasma streams.

the flow decreased from 6 kJ in the helium plasma to 5.5 kJ after the addition of xenon injection. Decreasing of total energy measured by a colorimeter is caused by losses to ionization of heavy impurities (Xe).

Xenon injection causes an increase of plasma visible radiation (Fig. 1). Time dependences of plasma radiation are qualitatively similar to plasma pressure distributions (Figs. 1 and 2). Peaks on time dependences of pressure and radiation correspond to the first, second, third and others half-periods of discharge current. The measurements of radiation energy have shown that the maximum value of energy achieved (50–60) × mJ in the range of (12.2–15.8) nm. Maximal power of EUV radiation per pulse makes up 18 kW [6].

The heat loads to tungsten targets surface exposed to MPC plasma streams were also measured. The target has been set perpendicularly to plasma stream. Maximal heat load to target surface exposed to helium plasma achieved 0.39 MJ/m^2. The heat load to the surface exposed to helium-xenon plasma is decreased to 0.33 MJ/m^2. Microscopic observations have shown that the applied heat load results in pronounced melting of tungsten surfaces (Fig. 4). Network of major cracks is formed on tungsten surfaces. Size of the major crack mesh achieved 0.7 mm for both helium and helium-xenon exposure. After 10 plasma pulses, the major cracks width is within 5–15 μm for both cases. There are two networks of the microcracks with a size of a few microns inside the major crack mesh. Typical cell sizes of such microcracks are 20–40 μm and 15–25 μm. More fine cracks with a typical cell size of 2–7 μm appear in the background of microcrack meshes.

The X-ray diffraction (XRD) measurements have shown that the tungsten lattice spacing in the stress-free section initially grows, but then it decreases with increasing number of plasma pulses resulting in melting. Probably, this is caused by the appearance of a melt layer on the surface. In the molten layer the increasing solubility promotes penetration of light impurities, first of all helium into the surface layer.

Summary and conclusions

The main parameters of the plasma streams generated by MPC on pure helium and with an additional injection of xenon into the compression zone have been investigated.

Xenon injection into compression zone has a small effect on the current-voltage characteristics, which depends only on the residual gas (helium) pressure.

The maximum velocity of (6–8) × 10^6 cm/s is weakly depended on the xenon injection into the compression zone. Maximal plasma density is 10^{18} cm^{-3}. The local xenon injection causes a growth of plasma pressure up to 2.3 MPa. Time generation of plasma streams with a pressure more than 0.5 MPa achieved 30 μs.

Local xenon injection causes an increase of plasma optical radiation and a decrease of energy density in the near axis region due to its additional losses to ionization of heavy impurities.

Irradiation of tungsten surface with MPC plasma with a heat load of 0.4 MJ/m^2 resulted in pronounced melting of tungsten surfaces. The major and fine networks of cracks are created in the result of plasma pulses.

The results of MPC plasma exposures will be compared with long-pulse (τ ~ 0.25 ms) plasma-surface interaction ITER ELMs (edge localized modes) simulation experiments performed with a quasi-stationary plasma accelerator – QSPA Kh-50. The contribution of the heavy gas impurities to the surface damage and the behavior of tungsten impurities in the near-surface plasma need further investigations.

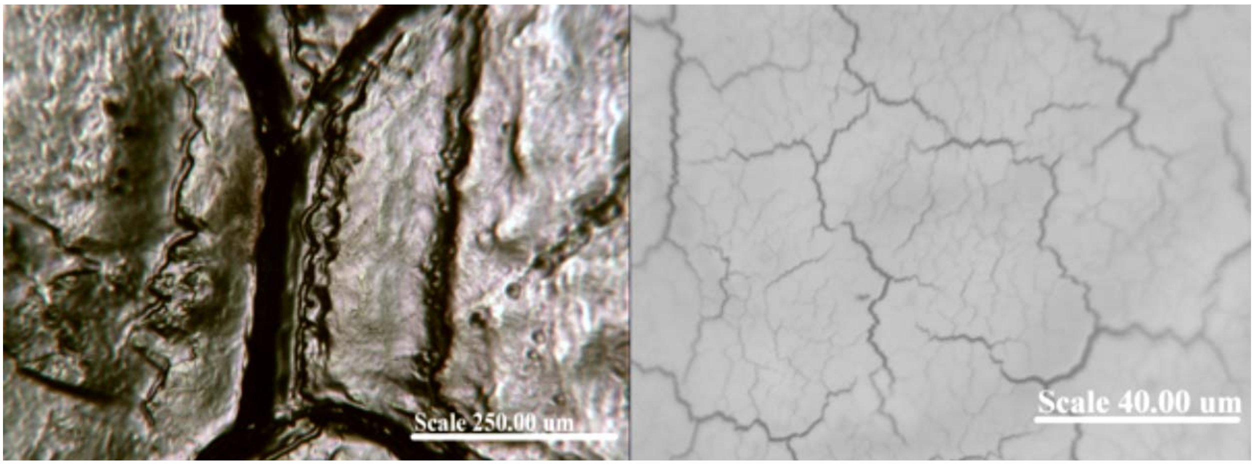

Fig. 4. Images of major cracks (left) and network (right) of fine cracks on tungsten surface exposed to helium plasma streams.

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