Studies on Dynamic Pressure of Compression Plasma Flow

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The temporal evolution of dynamic pressure of a compression plasma flow, generated by a magneto-plasma compressor, was investigated in a range of initial voltages from 2 to 4.5 kV by an interferometric method. The main advantages of the method are that it is insusceptible to electromagnetic noises and mechanical vibrations, requires no calibration procedures and ensures local readings from small areas. Depending on the initial voltage, the pressure values varied from 0.7 to 16 atm.

Keywords: compression plasma flow, pressure, magneto-plasma compressor

1 INTRODUCTION

Quasi-stationary gas-discharge magneto-plasma compressors (MPCs) capable of producing compression plasma flows (CPFs) are widely used for modification of various surfaces and in other applications [1-4]. High plasma parameters of compression flows, along with large discharge durations (~100 μs), make MPC a good facility for material surface modification [3, 4]. One of the important issues in studying MPC or any other pulsed-plasma systems (e.g. plasma focus, low-inductance vacuum spark, exploding wires, or Z-pinch with pulsed gas injection) is a time-resolved measurement of plasma characteristics. Pressure is among fundamental parameters determining thermal and hydrodynamic properties of the plasma. Knowing it is also of interest in the development of thrusters for space vehicles, in studies of high-power pulsed laser/solid interaction, etc. So over the past decades, a variety of pressure sensing devices such as piezoelectric detectors, polyvinylidene fluo-ride gauges, optical pressure probes and so on have been designed and used [5]. Polarimetric and interferometric schemes including those based on Fabry–Perot resonators are basically intended to detect low pressures.

2 DESCRIPTION OF THE METHOD

In this study, temporally resolved measurements of the CPF dynamic pressure were conducted using an interferometric pressure sensor (Fig. 1). The sensor includes an acoustic element made of copper rod, a He-Ne laser, and a photomultiplier. The highly polished rear face of the rod reflects the light beam back into the laser cavity. The intensity of the beam outgoing from the laser rear mirror and falling on the photomultiplier depends on the relationship between phases of the reflected beam and that in the cavity.

The CPF hitting the front face of the rod excites a compression wave that propagates along the rod at a velocity of sound in copper. The reflection of the wave from the polished face causes it to shift from the initial position. As a consequence, the relation between the phases begins to vary, and the intensity of the beam falling on the photomultiplier will modulate with a frequency proportional to the velocity of the rear face shift. An expression below [6] states the relationship between instantaneous values of the flow pressure, $P(t)$, and the velocity of shift, $v(t)$:

$$P(t)= c_{\mathrm{o}} \rho \, v(t) \qquad (1)$$

where c_o and ρ are the velocity of sound in the rod and density of the rod material, respectively. One period of the signal modulation corresponds to the shift equal to a half wavelength of the laser radiation. In other words:

$$v(t)=(0.5\, \lambda_{laser}) / \Delta t \qquad (2)$$

where Δt is the period of modulation at the moment t.

The accuracy of measurements is limited by changes in the velocity of sound in the rod (because of density variations in the rod

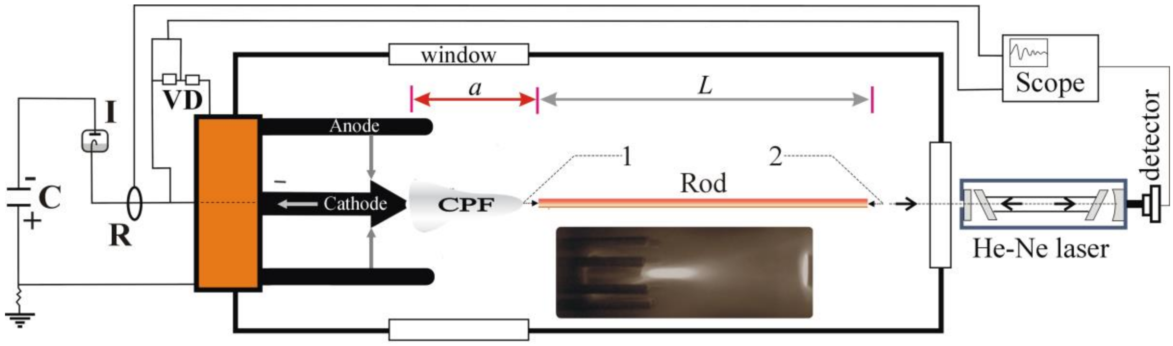

Fig.1: Experimental setup: C—capacitor, I—ignitron, R—Rogowski coil, VD—voltage divider

due to elastic deformations) which do not exceed 10 % [5].

The main feature of the proposed system is an arrangement of all its components on a single optical axis. This ensures ease of adjustment, reasonable vibration resistance, and recording of signals after the optical and electrical noises appreciably weaken or cease (depending on the acoustic element length). The acoustic element can be manufactured from a suitable elastic material. When possible, it is preferable to make the rod from a target material: in this way, the problems of mounting the target on the acoustic element and calibrating the sensor will be avoided. The length of the rod (*L*) may be chosen based on an expected duration (*T*) of a process under study:

$$L = T \cdot c_0 / 2 \qquad (3)$$

By this moment (*T*), the compression wave upon reflection from the front face will return back to the rear one, causing its additional shift and thus distorting a longer-lasting signal.

3 EXPERIMENTAL SETUP

The experimental setup used in this study is schematically presented in Fig. 1. The MPC electrode system is connected through an ignitron (I) to 1200 μF capacitor banks (C). The initial voltage (U_0) varied in the range between 2 and 4.5 kV. The discharge current and the voltage between the MPC electrodes were measured using a Rogowski coil (R) and a voltage RC-divider (VD), respectively. The signals were simultaneously recorded by a digital storage oscilloscope.

The MPC operated in a "residual gas" mode: the pre-evacuated compressor chamber was filled with a plasma-forming gas (nitrogen) up to 400 Pa pressure. The copper rod (*L*=84 cm, 8 mm in diameter) was located at distance *a* = 12 cm from the cathode tip. Due to such length of the rod, the sensor could record undistorted signals of ~500 μs duration.

The 10 mW He-Ne laser (λ=633 nm) was used as a light source.

The plasma flow parameters were as follows: pulse duration ~100 μs, the maximum plasma flow velocity (5–6)×10^6 cm/s, electron concentration (4–7)×10^{17} cm^{-3}, and plasma temperature 2–3 eV.

4 RESULTS AND DISCUSSION

The measurements were carried out at the initial voltages U_0 in the range of 2-4.5 kV, which corresponded to peak values of discharge current from 53 to 126 kA. The developed CPF passes the distance *a* = 12 cm from the electrode tip to the rod front face in t_i ~12–17 μs after start of current rise. The impact of the flow on the front face of the sensor rod results in the development of a shock-compressed plasma layer visible at its surface in the shape of a bright segment (inset in Fig. 1). The sensor responds to the pressure exerted by this layer.

In Fig. 2, signals from the sensor obtained at different initial voltages are presented. The instantaneous values of pressure, *P(t)*, were calculated using Eqs (1) and (2). The temporal evolution of plasma flow pressure and discharge current for U_0 = 4.5 kV is shown in Fig. 3. The pressure signal appears in ~12 μs after the start of current rise (the time required or the initial shock wave to arrive at the front face of the sensor rod).

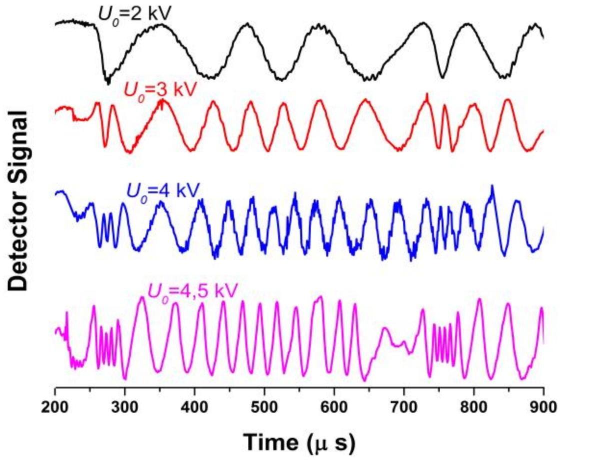

Fig.2: Detector signal vs. time for voltages U_0=2, 3, 4, and 4.5 kV

The pressure of the plasma flow reaches its maximum (~ 16 atm) in ~ 30 μs after starting of its rise, then reduces to about 2 atm and remains almost constant even after the current crosses the zero-axis.

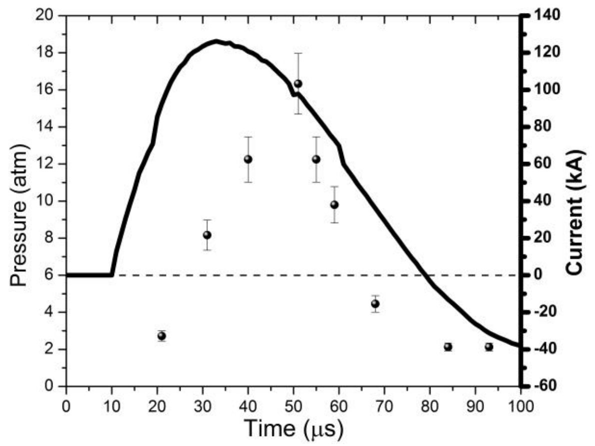

Fig.3: Plasma pressure (dots, left scale) and discharge current (solid line) vs. time for U_0=4.5 kV

Noteworthy is that there is some time shift between discharge current peak and plasma pressure peak. This is because the plasma flow needs some time to reach the sensor rod. The results of pressure calculations for $U_0 = 3.0$ kV and $U_0 = 4.0\,kV$ are shown in Fig. 4. Maximum pressure values for $U_0 = 3, 4$, and 4.5 kV amount to 6, 10, and 16 atm, respectively.

It should be noted that registered plasma pressure may depend on the diameter of the sensor rod, because the size of the target may influence the parameters of the shock-compressed layer. But the results of numerical

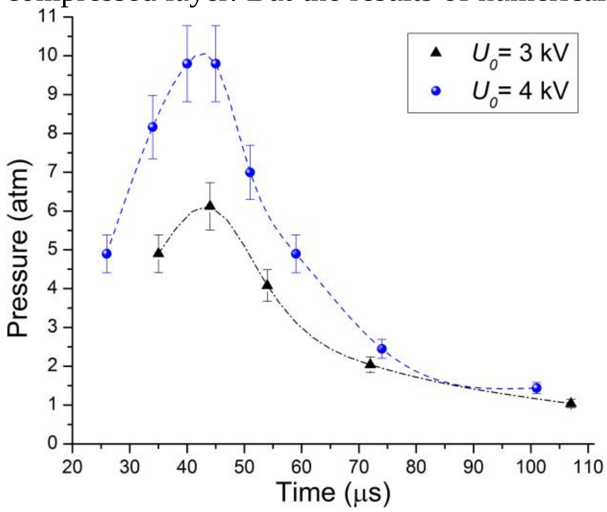

Fig.4: Plasma pressure for U_0=3.0 and 4.0 kV

simulation with the model, described in [7], have shown, that for target diameters below ~1 cm, this dependence is weak.

5 CONCLUSION

To evaluate dynamic pressure exerted by the CPF, an optical sensor was used which is based on a three-mirror interferometric scheme. The maximum registered pressure amounts to ~ 16 atm. The advantages of such sensors in comparison with piezoelectric ones are the ease of maintenance and insensitivity to electrical interferences. The registered time evolution of plasma pressure for various voltages shows the feasibility of the proposed approach for a variety of application in this area.

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