Investigation of plasma jet sources with high kinetic energy

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Abstract. Results of coaxial and rail electromagnetic accelerators investigation with pulsed gas puffing and different shapes and lengths of electrodes are presented. The influence of an additional magnetic field on accelerator parameters was studied. The method for plasma jet parameters controlling was developed with the use of a piezo-sensor and infrared camera. The plasma jet pressure dependences on the accelerator length and polarity of the electrode voltage, as well as on the distance from accelerator were derived in experiments on the plasma gun test bench. Coaxial plasma gun with the electrode length 220 mm, negative polarity of the central electrode voltage and focusing insert placed into the initial part of the accelerator proved to be most effective. At the output of the accelerator deuterium plasma jet was obtained with flow velocity up to 160 km/s and pressure up to 2 MPa.

1. Introduction
Plasma sources are of considerable interest in research on the problem of controlled thermonuclear fusion. With the use of dense plasma sources, studies are successfully carried out on fueling devices with magnetic plasma confinement, irradiating structural materials of the first wall of a future thermonuclear reactor, and also heating the plasma in a collision of oppositely directed flows [1,2]. The efficient and effective fueling the thermonuclear reactor will make it possible to control the processes of discharge ignition, burning and quenching. The need to develop an efficient fueling to the tokamak reactor is due to the strong dependence of thermonuclear power on the plasma density $P_{\text{Fus}} \sim n^2$. To feed thermonuclear reactor, a plasma source is required, which must generate density of more than $10^{22} \text{ m}^{-3}$ and velocity of more than 100 km/s. The pulsed supersonic gas puffing in the tokamak is not effective. Low-energy particles of neutral gas are mainly decelerated at the periphery and do not penetrate into the central region of the plasma volume. Centrifuges, pneumatic and railguns accelerate solid particles to velocity not exceeding 7 km/s [3,4]. The highest velocities of motion of substance (more than 100 km/s) were achieved by pulsed plasma accelerators, such as Marshall gun [5], Bostick erosion source, compact torus [6]. The highest plasma density ($\sim 10^{26} \text{ m}^{-3}$) was obtained with discharges in capillary channels and plasma focus. Such plasma contains a large amount of impurities and cannot be used to fill thermonuclear devices. The use of neutral injection method as a method of fueling the reactor is problematic due to the high cost of the ion source of 1 MeV range [7]. None of the known sources cannot generate simultaneously dense, moving at high velocity, free from impurities jet of matter.

This study is a continuation of previous work on the development and application of source of dense and pure plasma with high kinetic energy, suitable for efficient fueling the central region of magnetic plasma confinement systems.
2. Experimental test bench

The study of accelerators has been carried out on the plasma gun test bench, that consists of a 2.5 m³ vacuum chamber, plasma accelerator and diagnostics for measuring the parameters of the plasma jet (figure 1). The plasma jet could flow freely into a large volume of chamber without interacting with its walls. The pressure of the plasma jet at different distances from the source was recorded using a piezoelectric sensor with a diameter of 20 mm. This method is described in detail in [8].

New method of measuring the transverse dimension and energy profile of the jet using the infrared (IR) camera FLIR SS7300M series was developed. For this purpose 0.1 mm thick screen was placed in the vacuum chamber in the cross section of the jet. On the blackened shadow side of the screen the temperature field created by the plasma flow with help of IR camera was recorded.

![Figure 1. Plasma gun experimental test bench with diagnostics.](image)

The characteristic dimension of the thermogram spot with high accuracy characterized the transverse diameter of the plasma jet at the place of its interaction with the screen. Moving the screen along the axis of the jet made it possible to measure the dependence of the jet diameter on the distance to the source. The temperature profile on the screen remained unchanged for ~ 1 s. The frame rate of the IR-camera was 5 ms. Velocity measurement of ionization front of the plasma jet was carried out using an electro optical video camera K008 manufactured by BIFO Ltd in linear sweep mode. These methods are described in detail in [8].
Figure 2. Railgun with a pulsed gas feeding a ceramic vacuum chamber, and tested electrodes 180 mm long; 1 – vacuum chamber, 2 – pulse valve, 3 – ceramic chamber of the railgun, 4 – external conductors.

Figure 2 shows a laboratory model of railgun in a ceramic vacuum chamber, as well as tested electrodes. Pulsed puffing of deuterium ($10^{20}$ particles) into the accelerator was performed using an electrodynamic valve for ~ 300 mks before the start of the discharge. The railgun accelerator was powered using a 160 mkF capacitor with voltage up to 5 kV, discharge current of up to 120 kA and pulse duration of ~ 15 mks. The choice of the maximum operating voltage and discharge current was due to the restriction of impurities from the accelerator electrodes. In order to increase the accelerating magnetic field the railgun was equipped with two additional conductors located outside the ceramic chamber parallel to accelerator electrodes. For the first time such railgun has already been successfully applied to accelerate solids [9]. The distance between electrodes in the gas puffing area and at the accelerator outlet was 10 and 20 mm respectively. Deuterium, hydrogen and argon were used as working gas. The current in the external conductors allowed increasing the magnetic field in the gap between the electrodes of the railgun. It was created before the start of the discharge with help of 200 mkF capacitor with voltage of 5 kV. The discharge in the accelerator ignited at the moment when the external magnetic field was maximum.

Diameters of the outer and inner electrodes of the coaxial accelerator were 46 and 10 mm respectively. The length of the electrodes varied from 80 to 350 mm. The accelerator was powered using a capacitor of 160 mkF with voltage up to 5 kV, a discharge current up to 120 kA and pulse duration 15 mks. Gas puffing was carried through the side surface of the outer electrode in the initial part of the accelerator using an electrodynamic valve. The outer electrode was equipped with a cylindrical and later a conical insert located on the initial part of the accelerator. The reason for the use of the insert was the results of previous studies of the movement of the current bridge in a coaxial accelerator [10]. For electrodes with the length of 0.5 m and less the measurements have shown that the ionization front can outlet the accelerator in a time of 1-3 mks. In the present work, in order to continuously move the current bridge, the distance between the electrodes in the initial part of the accelerator was reduced by means of an insert connected to the outer electrode.

3. Results
Parameters of the plasma jet created by deuterium puffing to the ceramic vacuum chamber of the railgun were measured.
Figure 3 shows the dependence of pressure at the jet axis on the distance to the railgun for various electrodes. It is seen that the accelerator with all the tested electrodes generated a jet with the pressure not exceeding 0.3 MPa. Increasing in the distance between the accelerator and the sensor from 50 to 400 mm decreased the pressure significantly from 0.3 to 0.01 MPa.

Picture of time-integrated plasma jet irradiating the screen located in the vacuum chamber is shown in figure 4a. One can see the torch of the jet and the intense radiance near the center of the screen. The thermogram created by the plasma jet flow on the screen after 5 ms irradiation is shown in figure 4b. The thermogram characterized the profile of the kinetic energy and pressure of the plasma jet at the place of its interaction with the screen. The maximum radiance at the center of the screen corresponded to the maximum temperature. It is also seen that the spot was axially symmetrical.

Figure 4. a) Plasma jet irradiating the screen located in vacuum chamber; b) thermogram produced by the plasma jet on the screen after 5 ms irradiation; c) the dependence of screen temperature on distance along the selected direction indicated on the thermogram; 1 – without external magnetic field; 2 – with external magnetic field. Distance between screen and accelerator was 970 mm.

The horizontal line showed the direction along which the screen temperature was measured for cases when the current in the external conductors was 0 and 100 kA respectively (figure 4c). It is seen that growing the magnetic field in the gap from 3 to 5 T the temperature in the center of the screen increased from 16 to 25 °C. Its average temperature also increased from 8 to 12 °C. Estimates showed that with increasing the field the energy released in the screen increased from 134 to 200 J, i.e. from 7 to 10 % of the total energy of the capacitor. The spot diameter at the level of $T_{0.5\text{max}}$ was ~ 120 mm and did not depend on magnetic field.
Figure 5. Dependencies of pressure at the jet axis on distance to the coaxial accelerator for different polarities and lengths of electrodes.

Figure 5 shows the dependences of jet pressure and diameter on distance to the coaxial accelerator for different polarities and lengths of electrodes. With negative voltage at the central electrode the pressure of jet increased by 2 times compared with pressure created by accelerator with positive polarity (the polarity of plasma focus). For different lengths of electrodes the dependences of the jet pressure on the distance to the plasma source were investigated. Lower graph in figure 5 shows that the greatest pressure was created by accelerators with an electrode length of less than 220 mm. The pressure significantly decreased from 1.6 to 0.1 MPa with increasing the distance from 50 to 400 mm. In later experiments the length of the electrodes was 220 mm.

Figure 6. Plasma jet irradiating the screen: a) accelerator with cylindrical insert; b) accelerator with conical insert. The distance between the screen and the accelerator is 970 mm, the voltage on the capacitor was 5 kV.

Picture of the time-integrated plasma jets produced by coaxial accelerator with cylindrical and conical inserts are shown in figure 6. One can see that the conical insert ensured the focusing of the plasma jet.

The thermogram of the target after interaction with the plasma flow of coaxial accelerator and the temperature dependence along the selected direction are shown in figure 7. One can see that the transverse spot dimension was axially symmetrical and its diameter at the level of $T_{0.5\text{max}}$ was $\sim 75$ mm with the screen distance from the source of 860 mm. The maximum radiance near the center in the screen corresponded to the maximum temperature. The horizontal line showed the direction along which the temperature of the screen was displayed on the graph.
The calculations showed that the accelerator with conical insert increased energy in the target by 2 times more compared with the energy in the target created by accelerator with cylindrical insert.

4. Conclusion
Studies of railgun plasma source with pulsed gas puffing, various shapes and lengths of electrodes, as well as with an additional magnetic field created by external conductors with current were conducted. Increasing the magnetic field in the gap between the electrodes using external conductors with current made it possible increasing of kinetic energy of the plasma jet without growing the discharge current. Method of measuring the transverse dimension and energy profile of the jet using IR camera was developed and adjusted. The dependences of pressure and jet diameter on the distance to the accelerator were obtained. Plasma with pressure of \(~0.3\) MPa was achieved at the output of the railgun. Coaxial accelerator with different geometry and polarity of voltage on the electrodes has been studied. At the output of the coaxial accelerator deuterium plasma with a pressure near the jet axis of \(~2\) MPa was obtained. Coaxial plasma accelerator with length of not more than 220 mm, negative polarity of the voltage on the central electrode and focusing insert placed in the initial part of the external electrode proved to be most effective.

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