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Studies of interaction of plasma jets generated in a plasma focus facility with an ambient plasma in external magnetic field

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Abstract The aim of the present experiments was to reproduce and to study in laboratory quasi-perpendicular supercritical collisionless shocks similar to the Earth-Solar Wind shock, by using a plasma focus facility as the plasma source. The experiments were performed on the PF-3 facility (Filippov-type plasma focus) at a level of energy supply of about 1 MJ. Directed plasma jets are produced with axial velocities $\sim 10^7$ cm/s after compression of a plasma-current sheath in the initial stage of plasma focus formation. These jets then travel through an ambient plasma resulting in early gas ionization by X-ray radiation from the plasma focus, and at an angle of 90° to the 2500 G external magnetic field applied by a system based on rear-earth magnets. Our experimental conditions allowed us to reach a range MA $\sim$ 5÷10.

Key words collisionless shocks • plasma focus • plasma jets

Introduction

A specific feature of the Plasma Focus-type (PF) systems is a non-cylindrical configuration of the plasma-current sheath (PCS) at the stage of its compression. As it is known, at optimum – matched parameters of the power supply source, gas pressure and the discharge system geometry, the PCS – compression rate at the instant of collapse at the system axis attains a few units times 10^7 cm/s. This results in the plasma expulsion from the compression zone under which the radial PCS-compression rate is transformed into the longitudinal plasma jet velocity. An analysis of the results of studies on plasma jet parameters has shown [2] that the plasma jet velocity in optimal discharges attains approximately – the same magnitude ($\sim 10^7$ cm/s) in spite of considerable differences in the power supply and in the masses of the used gases (Ar, Ne, D_2). These circumstances show that the hydrodynamical mechanism of the jet generation is related to the current sheath compression rate towards the axis and not to the thermal plasma expansion of the compressed pinch.

On the other hand, Plasma Focus is an intensive source of soft X-ray radiation (SXR) [3]. This radiation takes place during the phase of maximal PCS compression at the axis ($\sim 10^{-7}$ s) and results in an ionization of the ambient gas in the discharge chamber. Due to that the directed velocity of the plasma jet may considerably exceed a thermal velocity of its extension, the compact bunches can move through the background plasma at a significant distance. These PF properties are rather attractive to the simulation of colli-

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sionless shock waves at passing of supervelocity plasma jets through magnetized plasma [1].

As it is known, when the solar wind plasma interacts with the terrestrial magnetic field, a shock wave appears that is characterized by the Alfven Mach number. Depending on the angle between the velocity direction of the solar wind and the earth magnetic field, the shock wave is characterized by various physical processes [4]. A lot of physical and numerical studies have been made to understand all these processes but there are still some unresolved problems, which have to be simulated in laboratory experiments for better understanding. The aim of this study is to reproduce a superalfvenic collisionless shock wave by using the plasma focus facility as plasma source.

Experimental setup

The experiments were performed on the PF-3 facility. This installation represents the plasma focus, Filippov-type, with a flat geometry of electrodes. The diameter of the anode and that of the chamber were equal to 1 m and 2.5 m, respectively. The height of an insulator was 26 cm. The distance between the anode and the upper cover of the discharge chamber (cathode) was 22 cm. Maximum energy stored at the power supply (C_{max} = 9.2 mF, V_{max} = 25 kV) was 2.8 MJ. The experiments were done at a level of supplied energy up to 1 MJ and at a discharge current up to 3 MA with neon or argon, as a working gas, under pressure of 0.5÷1.0 Torr.

A porcelain cylinder, 40 cm in diameter, 40 cm in height was installed upon the upper cover of the PF-3 discharge chamber for studying the plasma jet interaction with magnetic field. Different magnetic systems for creating magnetic field in the interaction volume were developed: the system based on electromagnet (B = 0÷ ±500 G); on combination of electromagnet and permanent magnets (B = 0÷1000 G) and on rare earth magnets (B = 2500 G). In all cases the direction of the magnetic field is transversal to the discharge chamber axis. The distance between the poles was 110÷120 mm. The scheme of experiments is shown in Fig. 1.

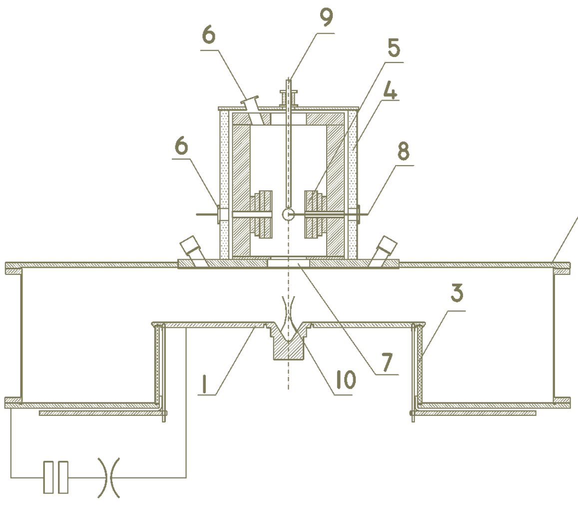

Fig. 1. Scheme of experiments: 1 – anode; 2 – cathode; 3 – insulator; 4 – chamber of interaction; 5 – magnet poles; 6 – diagnostic ports; 7 – preventive mesh; 8 – magnetic probe; 9 – Faraday cup; 10 – dense plasma focus.

Diagnostics technique

A list of the main parameters registered under this study includes: ambient plasma and plasma jet densities and temperatures; plasma jet profile and its velocities (average one along the path length and an instantaneous velocity in the interaction zone); magnetic field compression at the shock wave front; ion energy distribution at the plasma jet boundary. All the diagnostics were adjusted with a laser respective to the magnetic system centre located at the chamber axis at a distance of 38 cm from the anode plane.

A few mutually – supplementing techniques were used for measuring the plasma jet velocity. Registration of the instant of plasma jet emergence at the known distance from the anode with the collimated light probes was the main technique for measuring the average jet velocity. The light probes include a collimator, a light guide and a photoelectron multiplier. The collimation allows one to register the light radiation from a relatively-small plasma volume (diameter of a region entering the collimator field of vision does not exceed 5 mm at the interaction chamber centre). The area at the anode centre, located on the anode surface plane, is conditionally assumed to be the place of generation. The implementation of two collimated light probes (double light probe) oriented at various neighbouring areas has allowed one to measure an instantaneous jet velocity in this area.

The image scanning with a streak-camera having a vertical slit was the main technique for determining an instantaneous plasma jet velocity and the dynamics of its change under interaction with the magnetic field. The instantaneous velocity was also determined with two sequential frames of electron-optical converters (EOC) produced at the known time delays.

Photographing of the jet with EOC and with the streak-camera, having the slit orientation parallel to the anode plane were used for plasma jet profile studies.

The measurements of n_e and T_e in the chamber centre with time resolution continuously beginning from an instant of the X-ray pulse emergence and finishing by the shock wave passage were done by the optical spectroscopy techniques with a multi-channel registering system. Determination of the electron density, n_e, was based on the Stark broadening measurement of the spectral hydrogen lines. The measurement of the spectral line intensity ratios for the atoms and the ions of hydrogen and helium were used for determining the plasma electron temperature, T_e. For that purpose hydrogen and helium (small amounts 5–7%) were added to the working gas, neon, for diagnostics.

The magnetic field changes were registered with a magneto-optical probe of special design. The light guide and the coil are placed within the same quart pipe. A bright luminosity with a steep leading edge usually emerges at the jet shock upon the probe pipe that gives a clear time reference of the jet arrival instant. This circumstance allows one to synchronize the magnetic field changes with the plasma jet dynamics. The treatment of the magnetic probe signal was done by the combination of an RC-circuit with a time integrating constant, 2 μs, and the numerical integration of a signal after its recording with a computer.

The Faraday cup was introduced through the upper cover of the chamber of interaction along its axis. Its frame was galvanically-connected to the upper cover. The detector face was located 5 mm above the conditional centre of the magnetic system. A bias voltage, -27 V, was applied to the central electrode of the detector.

The control over the discharge quality was realized by registration of the discharge current derivative and by registration of the total X-ray radiation yield with a pin-diode (in arbitrary units). The current-plasma sheath compression at the discharge chamber axis and the plasma focus production were studied with the streak-camera with the slit parallel to the discharge axis ("vertical slit"). The slit has allowed one to observe the processes in the zone up to 22 cm over the anode surface.

Experimental results

The first experiments on plasma jet generation have shown two important phenomena:

- At PCS compression, the generation of plasma jets with velocity $\geq 10^7$ cm/s takes place;
- The plasma jets move with its own captured magnetic field, whose magnitude can reach several kG.

The last circumstance is extremely unfavorable. At first, the magnitude of the captured field appears commensurable with the effect of compression of the exterior magnetic field in the front of the shock wave that essentially hampers the analysis of the results. Secondly, the driving of the plasma jet with the captured field through the background plasma may be accompanied by its braking. For preventing of the penetration of the own magnetic field captured by the plasma jet, the entrance to the chamber of interaction, 120 mm in diameter, was closed by the mesh with square cells, 20×20 mm^2, made of the copper strip. It has reduced the captured field by more than one order. At the same time, it was shown that the use of the mesh does not render noticeable influence on the average jet velocity and on its shape.

The first experiments were carried out with a magnetic system based on electromagnets. It has allowed to change the magnetic field direction (±500 G) and to carry out check experiments without this magnetic field. During these experiments, formation of the shock wave and compression of the magnetic field on its front was unequivocally shown. The experiments without the magnetic field have also confirmed a collisionless character of the plasma bunch driving: A noticeable plasma jet braking in the interaction chamber at B=0 was not observed. Some diminution of the magnitude of the instantaneous velocity on the comparison with its average value can be connected with braking of the jet on the stage of its driving to the entrance in the interaction chamber because of the captured field presence at this stage.

Further experiments were carried out with the magnetic field 2500 G, created by rare-earth magnets.

It was shown that the average velocity of the plasma jet on the path of flight (~38 cm) in optimal discharges attains $(0.5\div1.5)\times10^7$ cm/c in spite of a considerable difference in the power supply and in the masses of the used gases (Ar, Ne, D_2). The instantaneous velocity at the entrance into the magnetic volume is closed to that value.

The important parameters of the interaction processes are the electron density, ne, and the temperature, T_e, in the background plasma, as well as in the very plasma jet. Result of H_α profile measurements for one of discharges is given in Fig. 2. Dependencies of n and T on time for this discharge are given in Fig. 3. Typical parameters of the ambient plasma are the following: $n_e = (0.5\div1.0)\times10^{16}$ cm^{-3}, $T_e = 0.8\div1.8$ eV. The ones for the plasma jet are $n_e = (5\div6)\times 10^{16}$ cm^{-3}, $T_e \cong 5$ eV.

The last results show that the directed jet velocity can exceed by more than an order over the thermal velocity of jet transversal extension. An analysis of the plasma blob configuration confirms the proposed assumption: transversal jet dimensions are 5–10 cm at the distance of about 40 cm from the anode. This circumstance is very important for collisionless shock wave modelling, because allows us to determine very precisely an angle of interaction, taking into account the plasma jet configuration. Examples of the plasma jet configuration are given in Fig. 4. Taking into account the fact that the photographing (Fig. 4) is done from two opposite sides, one of the frames is given in a mirror reflec-

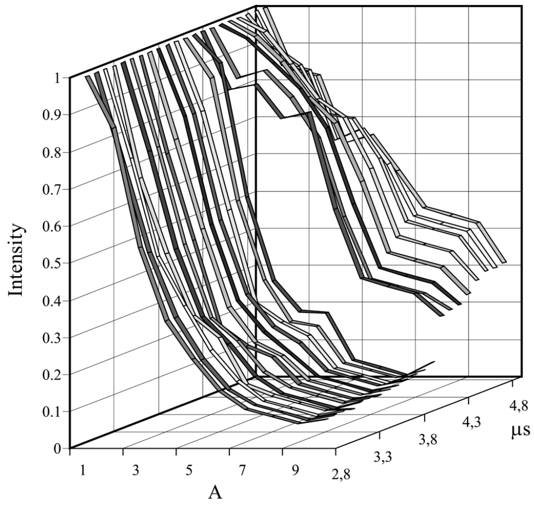

Fig. 2. Typical H_α profiles at different instant of time after dense plasma focus formation (t = 0) in the centre of the magnetic system.

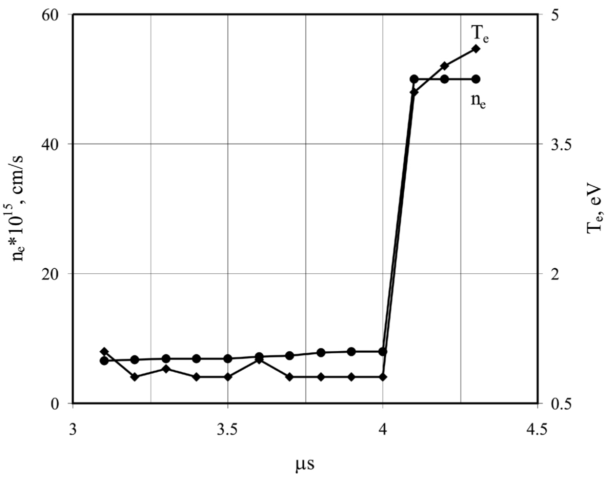

Fig. 3. Plasma density and temperature *vs.* time in the centre of the magnetic system.

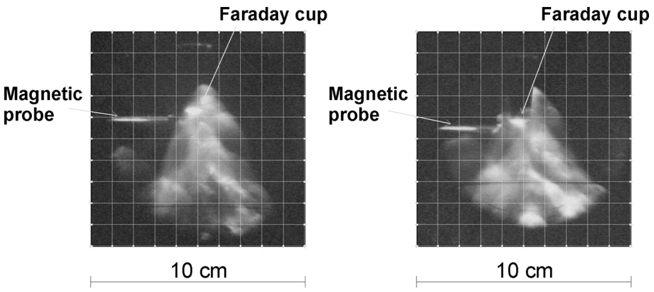

Fig. 4. Images of plasma jet obtained by electron-optical converter, time shift between frames is 320 ns; time exposure is 12 ns; B = 2500 G.

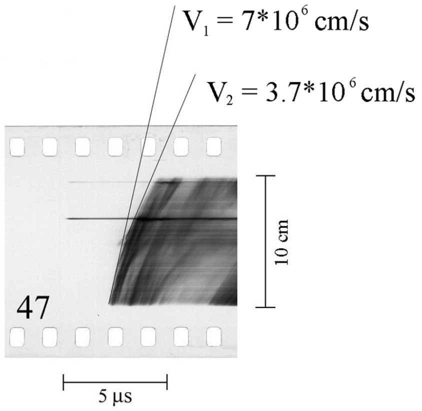

Fig. 6. Streak pictures of plasma jet; slit orientation is parallel to the chamber axis; bright longitudinal line is stipulated by a luminescence of the end face of the Faraday cup.

tion. From the photographs the magnetic probe and the Faraday cup, luminous in the reflected light, are clearly seen. Two successive frames allow one to obtain the instantaneous plasma front velocity, which is in agreement with the velocity obtained by the photographing with the streak-camera slit scanning and the double light probe measurements.

In Figs. 5 and 6 the results of measurements obtained in one from the discharges at a neon pressure of 0.7 Torr are given. The compression of the magnetic field in the front of the shock wave with a consequent formation of the diamagnetic cavity is visible. On the scanning of the jet image, produced by the streak-camera with the vertical slit jet, braking is observed.

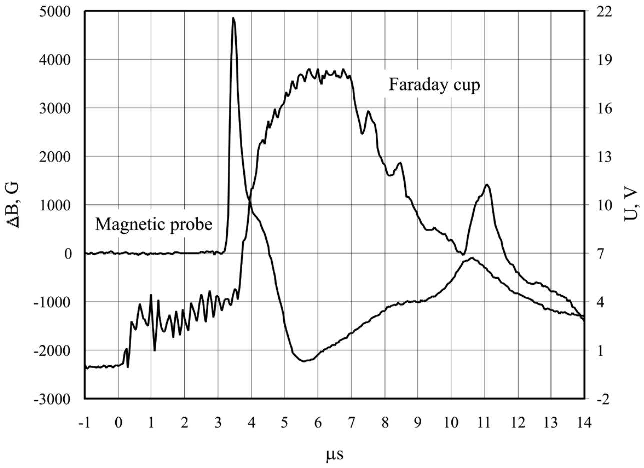

Fig. 5. Waveforms of magnetic probe (upper beam) and Faraday cap (lower beam).

The dissipation of the plasma jet energy should be accompanied by the modification of the ion distribution function at the wave front and emerging of the group of accelerated particles. The investigations with the Faraday cup were an important part of this study. But the ion registration in the given energy range is a rather complicated experimental task. The plasma jet interaction with the magnetic field occurs in the experimental chamber filled with the background plasma, at the density 10^{15}–10^{16} cm^{-3}. These experimental conditions noticeably differ from the traditional experimental conditions which take place within the expanding plasma in vacuum, emerging under an effect of laser – high power-radiation on the substance [5], in the experiments with classical Z- and θ-pinches or in the discharges with the pulsed gas puffing. Nevertheless, it seems to be expedient to perform indirect measurements by analyzing the signal configuration under various conditions (with the magnetic field and without it). Now this work is in progress.

Summary

As it was shown, the systems of plasma focus type may be successfully used for the experimental simulation of the Solar wind interaction with the Earth magnetic field. For these purpose the magnetic system for strong transversal magnetic field (up to 2.5 kG) production and a wide set of diagnostics were developed. Our experimental conditions allowed us to provide collisionless driving of superalfvenic plasma jets with the velocity ~10^{7} cm/s through the ambient plasma with the density 10^{15}–10^{16} cm^{-3}. Brightly expressed directed driving of the jet (the directed velocity on an order of magnitude exceeds the velocity of the transversal extension) allows to simulate formation of the quasi-perpendicular supercritical collisionless shocks with the Alfven Mach number up to 10. The compression of the magnetic field in the shock wave front and the dissipation of the plasma jet energy were shown.

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