Excitation of Electromagnetic Waves in Dense Plasma During the Injection of Supersonic Plasma Flows into Magnetic Arch

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Abstract. A new approach is suggested to study interaction of supersonic (ion Mach number up to 2.7) dense (up to 10^{15} cm^{-3}) plasma flows with an arched magnetic trap field with a strength up to 3.3 T. It opens prospects to model space plasma processes in a laboratory. The process of plasma deceleration during the injection of plasma flow across the magnetic field lines was experimentally demonstrated. Pulsed plasma microwave emission at the electron cyclotron frequency range was observed. It was shown that frequency spectrum of plasma emission is determined by position of deceleration region in the magnetic field of the magnetic arc, and is affected by plasma density. Frequency spectrum shifts to higher frequencies with increasing of arc current (plasma density) because the deceleration region of plasma flow moves into higher magnetic field. The observed emission can be related to the cyclotron mechanism of generation by non-equilibrium energetic electrons in dense plasma.

INTRODUCTION

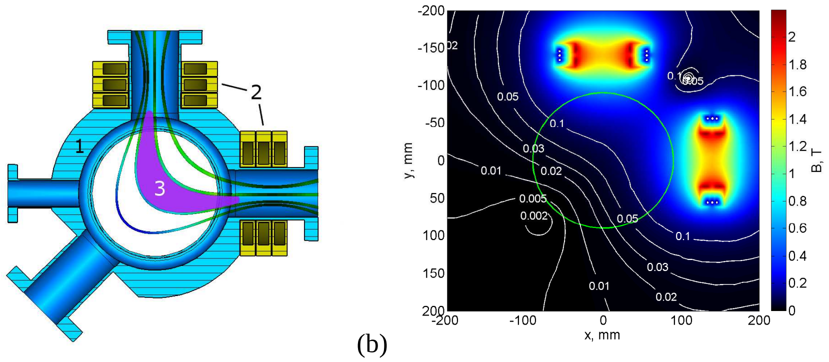
The interaction of the dense supersonic plasma flows and inhomogeneous magnetic field of arched configuration is among the key problems in the physics of near-Earth and space plasma. Indeed, this interaction determines the formation of energetic electron component in the Earths magnetosphere [1], the motion of plasma flows in planetary magnetospheres [2], energy release in magnetic reconnection [3, 4], the generation of electromagnetic radiation and ejection of energetic particles during solar flares [5]. Laboratory investigations of this interaction are of interest for determining physical mechanisms of processes in space plasma and their detailed investigation under reproducible conditions.

Dense plasma flows for laboratory experiments are usually generated by evaporation and ionization of solid target material by high-power laser pulses [6, 7]. Alternatively, these flows can be formed using Z- and θ-pinches [2]. The present paper describes an experimental approach according to which plasma flow is created using vacuum arc discharge, which allows supersonic plasma flows with high degree of ionization and high density to be generated. The obtained plasma flow is directed to an open magnetic trap with an arched magnetic field.

EXPERIMENTAL SETUP

A scheme of the experimental setup is shown in Fig. 1. The base of the setup is a tabletop vacuum chamber with three flanges for mounting plasma generator and magnetic coils, two diagnostic ports and one pumping port. The pumping out of the discharge chamber with turbomolecular pump provides a residual gas pressure at the level of 10^{-7} Torr. Plasma generator is assembled on a standard flange that allows its installation in any of the three operating flange of the vacuum chamber. The setup allows to study the interaction of plasma flows with the magnetic field at the longitudinal and transverse with respect to the magnetic field plasma injection.

The plasma is produced by specially developed generator in which plasma flow of metal cathode material is obtained in the cathode spots of pulsed vacuum arc discharge [8]. Discharge is initiated by the spark breakdown on the surface of the ceramic insert end face. The vacuum arc discharge with pulse duration of about 20 μs between the cathode and the anode (vacuum chamber) is driven by the discharge of high-voltage composite dielectric capacitor.



(a) (b)

FIGURE 1. (a) The scheme of the experimental setup. 1 – discharge chamber, 2 – magnetic coils, 3 – plasma. (b) Distribution of the magnetic field in the central cross-section of the setup for the coil current of 3 kA.

The discharge current amplitude is adjusted by the magnitude of the capacitor charging voltage. At the maximum voltage of 1.5 kV the discharge current increases up to 3.5 kA.

It is possible to regulate plasma density in the cathode discharge region in the range of 10^{13} to 10^{15} cm^{-3} by varying the discharge current amplitude. The arc current duration determines the spatial extent of generated plasma flow. In our case, with duration of the arc discharge of about 20 μs the length of plasma flow is about 40 cm, which is more than twice bigger than the longitudinal dimension of the magnetic trap.

Supersonic plasma flow from the plasma generator made of Al with density up to 10^{15} cm^{-3} and ionization degree more than 80% is injected in magnetic field. Two magnetic coils are placed at the right angle to each other and create a magnetic field configuration in the form of an arched open magnetic trap. Each coil allows to obtain a pulsed magnetic field with the strength up to 3.3 T in the coil center. Distribution of the magnetic field in the central cross-section of the setup is shown in Fig. 1(b). The duration of current pulse in the coils is about 3 ms.

In the experiment plasma flow velocity was about $v_0 = 2 \times 10^6$ cm/s, the average ion charge $Z = 2.5$, the electron temperature $T_e = 6$ eV, and the kinetic energy of directional ion motion $E_i = 60$ eV [9]. For such plasma flow, the ionic (ion sound) Mach number is $M_S = v_0/c_s = 2.7$, where $c_s = \sqrt{ZT_e/m_i}$ is the ion sound velocity and m_i is the ion mass. In the plasma flow with ion density of $n_i \sim 10^{15}$ cm^{-3} the ratio between gas pressure and magnetic pressure $\beta = 8\pi NT/B^2$ may be changed in the range from 6 to 0.01 while changing the magnetic field strength from 0.02 T to 0.5 T. Such a dispersion of the parameter β indicates that in the discharge chamber conditions for magnetic reconnection may be implemented for a specified plasma flow.

We used photographing of optical plasma emission through a longitudinal quartz window of the discharge chamber as a main visual diagnostic tool. From the integral photographs of plasma glow one can judge on how magnetic tubes are filled with plasma and define the formation of high plasma density areas.

In the experiments we studied the dynamic spectrum and the intensity of stimulated electromagnetic radiation from the plasma with the use of different antennas: a broadband horn antenna (bandwidth 2-20 GHz), dipole-like antennas. All signals were recorded by broadband oscilloscope Tektronix DPO 71254C (analog bandwidth 12.5 GHz, time resolution 10 ps). The dynamic spectra were calculated from the recorded data by short-time Fourier transform windowed with a Hamming window.

EXPERIMENTAL RESULTS

First experiments were made with plasma injection along magnetic field lines [10], where the plasma generator was mounted in the same operating flange of the vacuum chamber as one of the magnetic coils. Substantial redistribution of current densities at the probes located in various places of the discharge chamber was observed. More than 90% of the plasma flow from the plasma generator was effectively trapped by the magnetic field.

In the present work processes during plasma injection across the magnetic field lines are described. Plasma generator was located at the flange which was free from magnetic coils. The behavior of plasma flow in inhomogeneous magnetic field was studied by making photos of optical plasma emission. Figure 2 shows changes in the shape of discharge glow when plasma flow penetrates the magnetic field of different strength. The formation of the region with large plasma density gradient is observed where the plasma flow stops as it moves in the direction of a strong magnetic field across the lines of the trap.

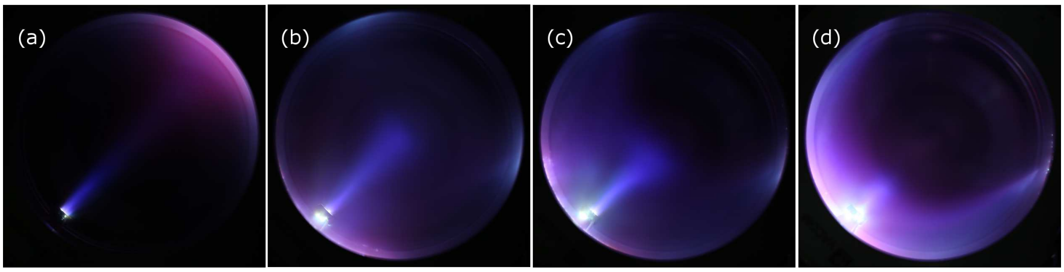


FIGURE 2. Optical glow of plasma flow generated by arc discharge with current of 2.3 kA (a) without ambient magnetic field and penetrating the magnetic arc, created by coils with current of (b) 2.55 kA, (c) 3.35 kA, (d) 6.63 kA.

Photos of the discharge were used to estimate the position of the plasma flow stopping point at different magnetic fields. The dependence of the plasma luminosity at the line of plasma flight on the distance from the plasma generator cathode was investigated. At the same arc discharge current a spatial shift of plasma flow stopping point position is observed with an increase of the magnetic coils current. The dependency of plasma stop point on magnetic coil current is shown in Fig. 3 together with magnetic field at that point calculated numerically. In Fig. 3(b) it is seen that regardless of the coil current the stop point is observed at almost the same magnetic field $B_{stop} = 0.064 \pm 0.007\,\mathrm{T}$. The width of plasma flow deceleration region in terms of magnetic field strength is $\Delta B = 0.038 \pm 0.007\,\mathrm{T}$.

With the increase of magnetic coils current plasma flow stop point is shifted closer to the cathode of plasma source, i.e. to the region with $\beta \sim 1$. The increase of coil current changes the distribution of magnetic field in the trap. Thus on the plasma flow propagation path always there is a region with the corresponding value of the magnetic field strength, however, this area is located in different places for different values of coil current. For the fixed magnetic coil current, the deceleration region is broadened and moved to the area of stronger magnetic field with the increase of arc discharge current.

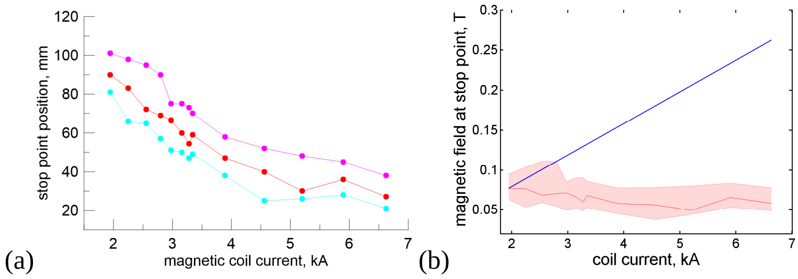


FIGURE 3. (a) The dependency of plasma stop point on magnetic coil current. Here upper and lower curves define the width of deceleration region, middle curve defines the stop point position. (b) Magnetic field at stop point calculated numerically. Blue line on (b) panel shows magnetic field strength in a fixed point at distance 90 mm from the plasma generator. The arc discharge current equals to 3.2 kA.

Plasma microwave emission was observed during plasma flow injection across magnetic field lines, see Fig. 4. One can define two types of emissions: (1) broadband pulses observed during the increase of discharge current and (2) emission at the stage when discharge current is decreasing. The broadband emission of the first type at frequencies from 1 to 20 GHz is also observed without ambient magnetic field applied. This type of emission is more likely related to the excitation of waves by the flows of energetic electrons at the very beginning stage of arc discharge. Such flows of energetic electrons at this discharge stage were also reported in [10].

The emission of the second type was observed at frequencies from 0.5 to 4 GHz for different plasma flow parameters. The spectral width of this emission is about 1 GHz and the mean frequency of the emission is slowly increasing in time with a speed about 20 MHz/μs. Also the second harmonic of this emission is sometimes observed.

Frequency of narrowband microwave emission in the range 1.5-2 GHz corresponds to the electron cyclotron

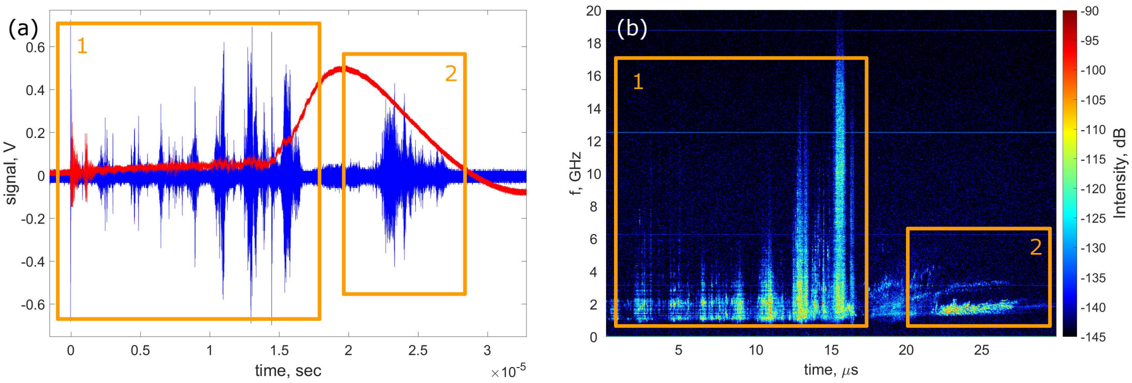


FIGURE 4. Microwave emissions during plasma flow injection across magnetic field lines. (a) Waveforms of electric field oscillations in the wave (blue) and arc discharge current (red). (b) Dynamic spectrum of registered microwave emission.

frequency at fundamental harmonic in magnetic field strength of 0.05-0.07 T in the plasma flow stop point. It was shown experimentally that the emission frequency doesn't depend on coil current. But frequency spectrum shifts to higher frequencies with the increase of arc discharge current in proportion with the increase of magnetic field in stop point. Therefore the source of this microwave emission is located in plasma flow stop point, i.e. in the area of $\beta \sim 1$. Apparently, the observed radiation has cyclotron nature, associated with the excitation of waves by energetic electrons during plasma flow intense deceleration in the magnetic arch. In such conditions this emission can be explained by excitation of whistler waves or electron Bernstein waves. Due to the lack of experimental data it is not yet possible to define which mode is excited, as well as determine frequency dependence on plasma density in a source region. This will be done in a future work.

SUMMARY

The process of plasma deceleration during the injection of plasma flow across the magnetic field lines was experimentally demonstrated. Pulsed plasma microwave emission at the electron cyclotron frequency range was observed. It was shown that frequency spectrum of plasma emission is determined by position of deceleration region in the magnetic field of the magnetic arc, and is affected by plasma density. Frequency spectrum shifts to higher frequencies with the increase of arc current (plasma density) because the deceleration region of plasma flow moves into higher magnetic field. The observed emission can be related to the cyclotron mechanism of generation by non-equilibrium energetic electrons in dense plasma.

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