Study of the microwave interaction with supersonic plasma sheets and jet generated by Magneto-Plasma Compressor

V G Brovkin¹, P V Vedenin¹, I Ch Mashek², N M Ryazanskiy¹

¹ Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
² Saint-Petersburg State University, Universitetskaya Naberezhnaya 7/9, Saint-Petersburg, 199034, Russia

E-mail: brovkin47@mail.ru

Abstract. In this paper, we present investigation of a method for converting a supersonic plasma axisymmetric jet, created by a Magneto-Plasma Compressor, into flat plasma layers with various thicknesses and electron concentration. This kind of plasma layer has comparatively homogeneous structure and may use for experimental modelling of interaction of X-band radiation with high-speed plasma flow. The results of experimental studies of the microwave radiation transition through these layers are presented. The analysis of the received results within the one-dimensional (1D) approximation is carried out and the plasma concentrations are calculated.

1. 1. Introduction

When a hypersonic vehicle moves through the atmosphere, a high-density plasma layer forms around it. The density of this plasma layer reaches values sufficient to lock the radio signal [1]. For experimental investigation of such effects in supersonic flows the using of plasma jets, generated by Magneto-Plasma Compressors (MPC) was proposed [2]. The modelling of interaction of microwave (MW) radiation with plasma layers usually bases on approximation of thin homogeneous plasma sheet with transvers dimensions essentially more than using wavelength and area of plasma-MW interactions [3, 7]. The verification of these models needs in experimental version of thin plasma sheets with comparatively high temperature and electron density. Usually, of a large-volume plasma (or a flat plasma layer) source bases on discharges with gridded anode or multianode systems [4, 5]. Another variant for such plate plasma creation – space distributed dielectrically barrier discharge (DBD) [6]. All these ways leads to arising regular and periodic nonuniformities in plasma density distribution and cannot be used with MW radiation with wavelength less, ore compare with it characteristics dimensions. Experiments presented in this paper, have shown that the magnetic plasma compressor with addition plate outlet nozzle can be used for creation of the flat plasma layers with comparatively high transverse dimensions, under the high pressure and space irregularities essentially less than X-band wavelength. The applications of created plasma sheets also provides an opportunity to study the interaction of radiation with layers of different configurations, inclined layers and assess the effect of the magnetic field.
2. The object and the methods of research

The magneto-plasma compressor of compact geometry is the result of further development of large-scale MPC [8, 9]. The MPC jet formed near the focal region of the converging microwave beam propagated along the electric field of the beam (Fig.1). A pulsed magnetron used to generate MW radiation with the following parameters: pulse power does not exceed the value of 700 kW; \( \lambda \approx 2.3 \) cm; \( \tau \approx 4 \) \( \mu \)s. Microwave radiation through the horn and lens was introduced into the vacuum chamber with a size 1m in length and 0.7 m in diameter. Using a dielectric lens, a slightly diverging linearly polarized electromagnetic beam was formed in the chamber and falls on a focusing mirror with a radius of about 0.3 m. Outside the zone of interaction was installed the microwave probe.

The PSO sensicam camera recorded through the mirror (Fig.2) the plasma jet of the MPC with a minimum exposure time of 1 \( \mu \)s and the ability to shift the registration time relative to the start of the process. The range of speeds of the plasma streams generated by such MPC shall be 2-10 Km/s, the jet lifetime should not be less than 50 \( \mu \)s, in the range of the surrounding gas (air) static pressures 10-500 Torr. The electron density reaches values of \((10^{16} - 10^{17}) \) cm\(^{-3}\), at a temperature of about 3 eV [2].

![Figure 1](image1.png)

**Figure 1** Scheme of the experiment (the top view). 1 - Focusing mirror; 2 – plates with a gap where the plasma jet moves; 3 – microwave probe; 4 – MW beam; 5 – horn with lens for entering microwave radiation into the chamber. The plasma flat layer was formed along the electric field vector of the wave and perpendicular to the direction of the MW beam propagation. This layer completely overlapped the focused beam.

![Figure 2](image2.png)

**Figure 2** Scheme of the jet registration (the top view). 1 - plates with a gap where the plasma jet moves; 2 – mirrors; 3 - PSO sensicam camera; 4-quartz window; 5 - MW beam.

In this series of experiments, the dynamics of the jet was recorded at different times in order to determine its optimal size to overlap the microwave beam. A similar procedure was performed when the jet expanded between the plates.

3. The research results

The results of the experiments and corresponding calculations are presented below. On the Fig.3a shows the vertical plasma jet on 40\( \mu \)s of its development. Its diameter size is close to the microwave length and reached \( \sim 25 \) mm, at a height of \( \sim 70 \) mm. The front of the plasma flow moves up at a speed of \( \sim 2 \)
km/s to the radiation focus area, gradually blocking the microwave beam. The amplitude of the signal characterizing the transmitted radiation decreases. Later an open slot device was created in the form of two parallel radio-transparent plates (65 × 75 mm), the size of the gap has changed from 3 to 10 mm. Plates set near the electrodes of the MPC (Fig.1 - position 2). Such device transformed a cylindrical type jet into a flat layer and this makes it possible to conduct experiments on the interaction of MW radiation with plasma layers of different thicknesses. It should be noted, that there was a good repeatability of the processes. As shown by preliminary experiments, the rate of expansion of the plasma flow in the slit space was about \( V \approx 1.5 \text{ km/s} \) and fairly homogeneous a flat layer up to 75 mm in size was formed (Fig.3b,c).

![Figure 3](image-url)

**Figure 3** Plasma jet (a) at 40 µs converted into a flat layers of 10 mm (b) and 5 mm (b) thickness, \( t_{\text{exp}} = 3 \mu s, P = 25 \text{ Torr} \).

The transverse size of the flat plasma flow was three to four times more than the MW length, and it completely covered the incident microwave beam. In experiments plasma layers with a thickness of 3, 5 and 10 mm at air pressure of 25-30 Torr were used. It was started the study of the processes of the microwave passage (in conditions of \( E/P < 40 \text{ V/cm•Torr} \)) through the plasma during the formation and decay of the layer. Note that the quasi-stationary phase of the flow as well as in a conventional jet is observed in the period from 30 µs to \( \sim 80 \mu s \). In this interval, the signals of the microwave radiation transmitted through the layer were recorded.

Based on these data, it have been executed the estimation of plasma concentration in the layers. The analysis of the experiments results is carried out within the one-dimensional (1D) approximation. Monochromatic linearly polarized wave propagating along the \( z \) axis

\[
\mathcal{E}_{Wx}(t, z) = \text{Re}\{E_{Wx} \exp(i(\omega t - k z))\},
\]

where \( k \) is the wave vector, \( k = \omega / c \), \( c \) is the speed of light, normally falls to infinite in the \( x, y \) directions plasma layer. Under the influence of the electric field of the wave, a high-frequency current is excited inside the plasma.

In the absence of information on the plasma distribution, we will use the approximation of the effective plasma layer with an uniform plasma density distribution

\[
N_p(z) = \begin{cases} N_p, & 0 \leq z \leq \Delta, \\ 0, & z < 0, \, z > \Delta. \end{cases}
\]

In the microwave range, it can be assumed that the ions are motionless at the oscillation period. In addition, we neglect the thermal and directional movement of electrons. Under these assumptions, the current excited in the plasma with the density, \( j_e \), is coupled with the electric field by the expression

\[
j_e = \sigma \mathcal{E}.
\]

where \( \sigma = e^2 N_p / m(\nu - i\omega) \) is the high-frequency complex electrical conductivity, \( m \) is the electron mass, \(-e\) is the electron charge, \( \nu \) is the effective collision frequency of electrons with molecules.
The degree of the microwave transition through the layer is characterized by the parameter

\[ D = 10 \log \left( \frac{|E_W|}{|E_T|} \right) \tag{4} \]

which is measured in decibels. Here \(|E_T|\) is the amplitude of the transmitted wave. The expression for this amplitude is as follows:

\[ |E_T| = 4|E_W| \left( \sqrt{\frac{\varepsilon}{\varepsilon + 1}} \right)^2 \exp\left( -2\pi \chi \Delta, \lambda \right), \tag{5} \]

where \( \chi = \sqrt{0.5\left( (1 - N_e)^2 + (N_e, \nu_e)^2 - 1 + N_e \right) \varepsilon} = 1 + i \frac{\sigma}{\omega \varepsilon_0} \) is the complex permittivity of the plasma, \( \varepsilon_0 \) is the permittivity of free space. \( N_e = \frac{e^2 \nu}{m_\nu (\omega^2 + \nu_e^2)} \), \( \nu_e = \frac{\nu}{\omega} \), \( \Delta \lambda = \frac{\Delta}{\lambda} \), \( \lambda \) is a wavelength. Thus,

\[ D = 20\pi \chi \Delta, \log e + 10 \log \left( \frac{\left( (\sqrt{\varepsilon + 1})^2 - (\sqrt{\varepsilon - 1})^2 \exp\left( -4\pi \Delta, \lambda \right) \right)}{4\sqrt{\varepsilon}} \right). \tag{6} \]

From the equation (6) one can find the value of the plasma density corresponding to a given degree of the microwave transition through the plasma layer. For the layer thickness \( \Delta = 3, 5, 10 \) mm, the following values of the degree of radio transparency \( D \approx 1.5, 2, 2.6 \) dB were experimentally obtained. These values correspond to the levels of the plasma density \( N_p \approx 4.6, 3.6, 2 \times 10^{15} \) cm\(^{-3}\).

4. Conclusions

The paper shows the possibilities of using plasma flow, produced by a magneto plasma compressor, in a plasma experiment. Plasma stream of MPC can be successfully applied both for the study of flow around models and for creating plasma layers. In the latter case, it is shown that the use of slit spaces allows the formation of flat plasma layers with specified properties. The first experiments were performed with (3, 5, 10)mm layers through which the microwave propagated. The analysis of the received results within the one-dimensional (1D) approximation is carried out. The corresponding plasma densities are obtained: \( N_p \approx 4.6, 3.6, 2 \times 10^{15} \) cm\(^{-3}\).

This work was partially supported by grant RFBR 18-08-00707

References

[1] A. E. Bezmenov, V. A. Aleksashenko. Radiophysics and gas-dynamic problems passing atmosphere. Moscow, Mechanical engineering, 1982.

[2] B. A. Balakirev3, V. A. Bityurin1 at all. Supersonic plasma jets in experiments for radiophysical testing of bodies flow, Journal of Physics: Conf. Series 946 (2018).

[3] B. A. Balakirev3, V. A. Bityurin1 at all. Propagation of microwave radiation through an inhomogeneous plasma layer in a magnetic field, Conf. Series: Journal of Physics: Conf. Series 946 (2018).

[4] Yuan C., Tian R., Eliseev S.I., Bekasov V.S., Bogdanov, E.A., Kudryavtsev, A.A., Zhou Z. On self-sustainment of DC discharges with gridded anode. Journal of Applied Physics, Volume 122, Issue 14, October 2017.

[5] Yuan C., Yao J., Eliseev S.I., Bogdanov, E.A., Kudryavtsev, A.A., Zhou Z. Numerical simulation and analysis of electromagnetic-wave absorption of a plasma slab created by a direct-current discharge with gridded anode. Journal of Applied Physics, Volume 123, Issue 11, March 2018.

[6] P. B. Repin, A. G. Rep’ev Self-Organization of the Channel Structure of a Nanosecond Diffuse Discharge in a Wire–Plane Electrode System. Technical Physics, Vol. 46, No. 5, 2001, pp. 632–634.

[7] Bityurin V A, Brovkin V G and Vedenin P V 2017 J. Phys. D: Appl. Phys. 50 275201 629–633

[8] Morozov A I 1990 Physics of Plasma 16 131–146

[9] Astashinsky B, Bakanovich G and Minko L 1980 Journal of Applied Spectroscopy 33 629–633