Supersonic plasma flow injection across the magnetic arch in a table-top laboratory setup

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Abstract. The dynamics of the plasma deceleration process during the injection into the tridimensional magnetic arch formed by magnetic coils is studied. The effect of the magnetic field lines deformation in the apex is experimentally observed when the plasma flow stops in the region where its ram pressure equals the magnetic pressure. The propagation direction of the plasma flow is changed as a result of plasma flow interaction with the magnetic arch. The plasma flow velocity along magnetic field lines is experimentally measured and is in a good agreement with numerical estimates of Alfvén velocity. The transition layer is formed with a transverse size of the order of ionic inertial length as a result of the interaction of the plasma flow with the magnetic field. Non-thermal microwave emission of plasma is experimentally detected in the electron cyclotron frequency range during plasma deceleration process. The electromagnetic spectrum at frequencies of 1–2 GHz has been studied in detail.

1. Introduction
Laboratory study of the interaction of supersonic flows of strongly ionized plasma with magnetic fields of the arched configuration is relevant for understanding the physical mechanisms of a number of space plasma phenomena observed in the inner regions of the coronal loops on the Sun [1, 2, 3], in the transition regions of planetary magnetospheres [4, 5], such as, boundary layers of the Earth’s magnetosphere and the planets of the solar system. In this paper, we present results of an experimental study of plasma flow deceleration during transverse injection into a magnetic arch using a table-top laboratory setup [6, 7].

2. Experimental setup and diagnostics
The plasma deceleration process is studied in a table-top vacuum chamber with an ambient pressure below $10^{-6}$ Torr. The scheme of the setup is shown in figure 1 and is fully described in [6, 8]. A flow of fully ionized plasma is created by a plasma generator that evaporates the material of the Al cathode as a result of a vacuum arc discharge. The plasma parameters: plasma flow velocity $v_0 \simeq 1.5 \times 10^6$ cm/s, electron temperature $T_e \simeq 3$ eV, the kinetic energy of ion flow $E_{\text{kin}} \simeq 33$ eV, and the average ion charge $Z \simeq 1.7$ [9]. The flow velocity is constant at distances much farther than 1 mm from the cathode surface, and is only defined by the cathode material and does not depend on the arc discharge current [10]. For such plasma flow parameters, the ion sound Mach number is $M_S = v_0/c_S = 3.5$, where $c_S = \sqrt{Z T_e/m_i}$ is the ion sound velocity, and $m_i$ is the ion mass.
By varying the discharge current amplitude, the plasma density in the cathode discharge region can be controlled in the range of $10^{13} - 10^{15}$ cm$^{-3}$. With the arc current duration of 20 µs, the length of the generated plasma bunch is about 40 cm, which is more than the doubled diameter of the vacuum chamber in the interaction cross-section.

The plasma flow is injected across the magnetic field created by two magnetic coils located at right angles to each other. The current pulse duration in the coils is about 3 ms, the maximum magnetic field at the center of each coil reaches 3.3 T. To understand experimental results, we will use the value of the vacuum magnetic field strength $B_0$ in the center of the discharge chamber in the central cross-section. This value linearly depends on the coil current and equals 23 mT for the 1 kA current.

Under experimental conditions, the thermal pressure in the plasma flow is much less than the ram pressure $\rho v_0^2 = n_i m_i v_0^2$. Thus, the ratio between plasma flow pressure and magnetic pressure can be defined as $\beta = 8\pi n_i m_i v_0^2 / B^2$. The $\beta$-ratio is changing in a wide range of $10^{-2} - 10^3$ with respect to different positions in the vacuum chamber. The plasma generator was located in a region where the influence of the external magnetic field can be neglected and $\beta \gg 1$.

Photographs of the optical plasma emission are made by the EOS DSLR camera through a longitudinal window of the vacuum chamber. Figure 1(b) shows time-integrated photograph of optical plasma glow during injection transversal to the magnetic field lines. Photographs are made with daylight white balance set up and an exposure time of 1 s, which is much longer than the time of the plasma flow evolution in the experiment. The spatial distribution of the plasma glow intensity characterizes the spatial distribution of the plasma density, i.e. more intense light emission corresponds to the greater density of electrons.

The dynamics of the plasma flow interaction with the magnetic arch is studied using a high-speed camera VideoMig (VideoScan LLC, Moscow) based on a CMOS sensor of the size 128 × 64 pixels, which is capable of making 8 consecutive frames with an exposure time from 34 ns to 20 µs. The exposure time of each frame is equal to the half of the interframe interval. The photographs of plasma glow were compared with the vacuum magnetic field distribution in the
discharge chamber calculated without taking into account the plasma.

Moreover, we study the dynamic spectrum and the intensity of microwave emission from the plasma with the use of a broadband horn antenna (bandwidth 1-20 GHz). All signals are recorded by the broadband oscilloscope Tektronix DPO 71254C (analog bandwidth 12.5 GHz, sampling rate 100 GSa/s). The dynamic spectra are calculated from the recorded data via short-time Fourier transform windowed with a Hamming window.

3. Plasma deceleration during injection across the magnetic arch

From the integral photographs in figure 1(b) of plasma flow deceleration across the magnetic arch we can understand the distribution of plasma density on the propagation path, which is shown in figure 2. One may see that there is a drop in the glow intensity profile. This drop is related to the plasma flow expansion and consequent decrease of the plasma density in the inverse proportion to the distance from the cathode surface squared. The further increase in the glow intensity is due to the plasma flow deceleration process.

From the analysis of photographs, it follows that plasma flow with initial $\beta \gg 1$ propagates to a region where the ram pressure becomes equal to the magnetic pressure, compresses the magnetic field and then begins to gradually propagate along the magnetic field lines, forming a bright peripheral glow [7]. The schematic view of this process is shown in figure 3. In this case, the energy initially stored in the ion kinetic energy is transferred to the electrons due to the formation of an ambipolar electric field in the so-called stop-layer [11]. The electric field is formed due to the significant difference in the positions of the stopping points of the electron and ionic components of the flow. This process can also be responsible for the formation of a nonequilibrium fraction of electrons, which could generate electromagnetic emission from the stopping region [6].

The characteristic feature of plasma deceleration process shown in figure 1(b) is the formation of a bright region in the vicinity of the plasma flow stop point. With the increase of the magnetic field strength, this region shifts closer to the plasma source [6]. It can be seen that when braking in a magnetic field, the plasma flow changes the shape of the magnetic field lines. The apex of the magnetic field lines which is on the line of plasma flight is displaced away from the plasma source. This contributes to the fact that the plasma deceleration region, determined by its

**Figure 2.** The optical plasma glow intensity profile on the plasma propagation path from the photograph in figure 1(b), which is shown in the insert in the gray scale. Adopted from [7].

**Figure 3.** The schematic view of the plasma deceleration process. Adopted from [7].
luminescence, becomes strongly localized in space. The width of the transitional region is about
ion inertial length $c/\omega_{pi}$, where $\omega_{pi}$ is an ion plasma frequency and $c$ is a speed of light in a
vacuum. From figure 2 one may obtain that the stop-layer width is about 2 cm while numerical
estimates give the value of about 2.9 cm for the magnetic field $B_0 = 75$ mT in the chamber center
which corresponds to coil current of 3.3 kA. Under these conditions, the ion gyroradius is about
2.3 cm.

Figure 4. High-speed photographs of plasma injection across a magnetic. Current in magnetic
coils at the time of plasma injection is 4.5 kA ($B_0 = 104$ mT). The plasma generator is located
in the bottom left corner. Peak arc discharge current is 8.1 kA.

The plasma flow injection process was studies with the use of a fast frame camera, see
figure 4 [7]. The labels on each photo show the moment of the beginning of the exposure which
is 780 ns, the inter-frame interval is equal to 1.56 $\mu$s. The total duration of the process on a
series of photographs is about 12.5 $\mu$s, which is slightly longer than the time of flight of plasma
from the source to the opposite metal wall of the vacuum chamber in the absence of an external
magnetic field. From the analysis of plasma movement across the magnetic field lines, we can
retrieve the plasma flow velocity which equals about $1.3 \times 10^6$ cm/s. The velocity of plasma
movement along magnetic field lines can be estimated as about $1.25 \times 10^6$ cm/s. These values
agree well with both previous numerical estimates and initial plasma flow parameters.

4. Plasma microwave emission due to deceleration process
Non-thermal microwave emission of plasma is experimentally detected in the electron cyclotron
frequency range during plasma deceleration process [6]. The emission is observed at frequencies
1-5 GHz for different plasma flow parameters at the developed discharge stage. An example
of the microwave spectrum is shown in figure 5. The spectral width of this emission is about
1 GHz and the mean frequency of the emission is slowly increasing in time with a rate of about
20 MHz/$\mu$s.

It is experimentally shown that the emission frequency doesn’t depend on the magnetic field
distribution when parameters of the plasma flow are fixed. This result is consistent with the
photographic measurements of the deceleration region position [6]. Despite the fact that the
increase of the plasma flow density (arc discharge current) leads to a displacement of the stopping
point towards a stronger magnetic field, the microwave emission spectrum remains almost the
same. According to the described concept of plasma flow deceleration, shown in figure 3, the
actual magnetic field distribution is affected by the plasma flow such that the magnetic field
strength inside the plasma flow becomes smaller than the corresponding vacuum field. Thus, to
understand this phenomenon in more details we need to measure the change in the magnetic
field distribution by magnetic probes.
Figure 5. The dynamic spectrum of microwave emissions during plasma flow injection across the magnetic field. The arc discharge current is about 1 kA, the coil current is 5.12 kA, $B_0 = 118$ mT. Time base is connected with the moment of maximum arc current.

The frequency of the microwave emission in the range 1.2-2 GHz corresponds to the electron cyclotron frequency $\omega_{ce}/2\pi$ at the fundamental harmonic in the plasma deceleration region (magnetic field strength of 40-70 mT). It is shown that the observed emission is stimulated and has cyclotron nature. In the source region electron plasma frequency $\omega_{pe}$ is much higher than $\omega_{ce}$ and the frequency of the observed emission $\omega \sim \omega_{ce}$. Therefore, this emission can be explained as excitation of whistler waves or electron Bernstein waves in dense plasma \[6\] by energetic electrons formed during deceleration process, as it was noted earlier.

5. Summary
The dynamics of the plasma deceleration process during the injection in the tridimensional magnetic arch formed by magnetic coils is studied. The experimental results confirm the concept of the stop-layer formation. The effect of the magnetic field lines deformation in the apex is experimentally observed when the plasma flow stops in the region where its ram pressure equals the magnetic pressure. The propagation direction of plasma flow changed as a result of plasma flow interaction with the magnetic arch. The plasma flow velocity along magnetic field lines is experimentally measured and is in a good agreement with numerical estimates of Alfvén velocity.

Based on the obtained experimental data, it is shown that the nonthermal electromagnetic radiation observed in the interaction of plasma flows with a magnetic arch is the result of the development of kinetic instabilities of a nonequilibrium fraction of electrons. The formation of a nonequilibrium electronic component occurs either at the point of stopping the plasma flow due to the ambipolar electric field in the transition layer due to a significant difference in the positions of the stopping points of the electron and ion components of the flow, or during magnetic reconnection as a result of a rupture of the magnetic arch by a dense plasma flow. Under the conditions of experiments, as well as from the analysis of such processes in space plasma, the most likely mechanism for generating radiation is the generation of electron Bernstein waves with their subsequent transformation into electromagnetic modes (for example, as a result of scattering by thermal ions).

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