Experimental study of plasma jets generated in current sheets

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According to present notion, magnetic reconnection in current sheets (CSs) is the basis for dramatic astrophysical phenomena, such as coronal mass ejections (CMEs), solar and stellar flares, substorms in the Earth and other planetary magnetospheres, as well as for disruption instabilities in tokamak plasmas. Magnetic reconnection leads to effective transformation of magnetic energy into thermal and kinetic plasma energy, into energy of accelerated particles and radiation, but most of the energy goes into the generation of plasma jets. CMEs and flares have been investigated for many decades in numerous astrophysical observations. At the same time, the laboratory experiments carried out in well controlled and reproducible conditions, by using modern methods of plasma diagnostics, may contribute to better understanding of the physical nature and interplay of these events. We report on recent observations of generated superthermal plasma jets in the CSs produced under laboratory conditions. Analysis of magnetic fields, plasma currents and the Ampere forces $[\boldsymbol{j}\times\boldsymbol{B}]$ gives an insight into plasma acceleration processes, which involve outflow plasma motions directed from the center of the sheet toward its both side edges.

The experiments are performed with the device CS-3D, in magnetic configurations with a singular line of the $\boldsymbol{X}$ type, $\boldsymbol{B} = \{h{\cdot}y;\ h{\cdot}x;\ B_z^0\}$ [1,2]. The magnetic fields are produced by currents in external conductors and coils, which surround cylindrical vacuum chamber, 18 cm in diameter and 100 cm length, Fig.1. An $\boldsymbol{X}$ line aligned with the z-axis is coincident with the axis of the vacuum chamber, the magnetic field gradient in the (x, y) plane is $h \cong (0.5 - 0.7)$ kG/cm, the uniform guide field is $B_z^0 \cong (0 - 3)$ kG. The vacuum chamber is preliminarily filled with the *He* or *Ar* gas; the initial plasma in the magnetic field is produced by the Θ-discharge with strong pre-ionization, and then the plasma current J_z is excited, giving rise to a current sheet. The form of $J_z(t)$ is approximately sinusoidal, with amplitude of $\cong (50 - 100)$ kA and a half-period $T/2 \cong 6$ μs. The magnetic fields produced by plasma currents are measured by magnetic probes [3-5], the electron density, the electron and ion temperatures and velocities of plasma flows are studied using spectroscopic methods [5,6].

Measurements of magnetic fields and plasma currents make it possible to calculate the forces, which can accelerate plasma and generate the outflow plasma jets. Plasma motion is

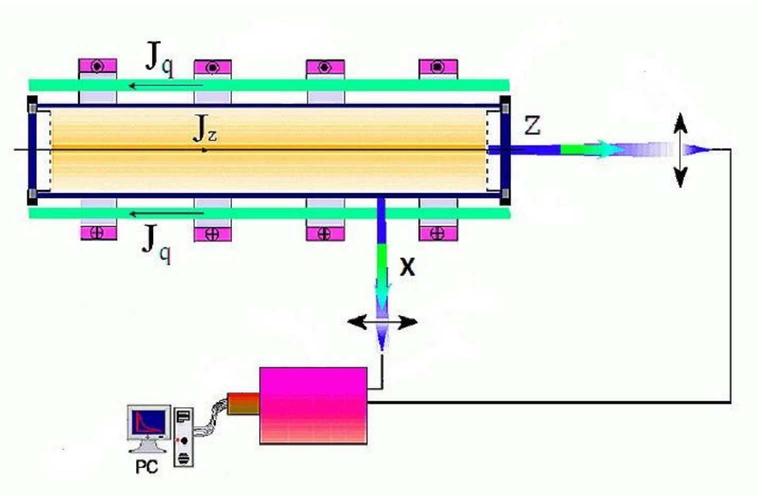

Fig. 1. Schematic diagram of the CS-3D device and two-channel optical system for recording plasma emission in different spectral lines observed in the *z*- and *x*-directions.

governed by both the pressure gradient and the Ampere force:

$$(M_i \cdot N_i)\cdot d\boldsymbol{v}/dt = -\nabla p + 1/c\cdot[\boldsymbol{j}\times\boldsymbol{B}]. \qquad (3)$$

The Ampere forces acting along the normal to the CS surface (*y*-axis) result in the current and plasma compression, the pressure gradient impedes compression, and after CS formation equilibrium is established. The pressure gradient is negligible along the CS surface (*x*-axis), whereas the Ampere forces are of crucial importance in both excitation of the Hall currents [3] and generation of plasma jets [7,8]. The Ampere force $[\boldsymbol{j}\times\boldsymbol{B}]_x$ along the CS width is determined by current j_z and normal component B_y which is usually nonzero in the metastable CS, so that on each side of the ***X*** line the forces F_x are oppositely directed, Fig.2.

Energetic super thermal plasma jets have been detected in the CSs using spectroscopic methods [7,8]. The profiles of spectral lines (SL) of the argon or helium ions: *Ar II* 4806 Å, *He II* 4686 Å, *He II* 3203 Å were recorded, and plasma parameters were extracted from these

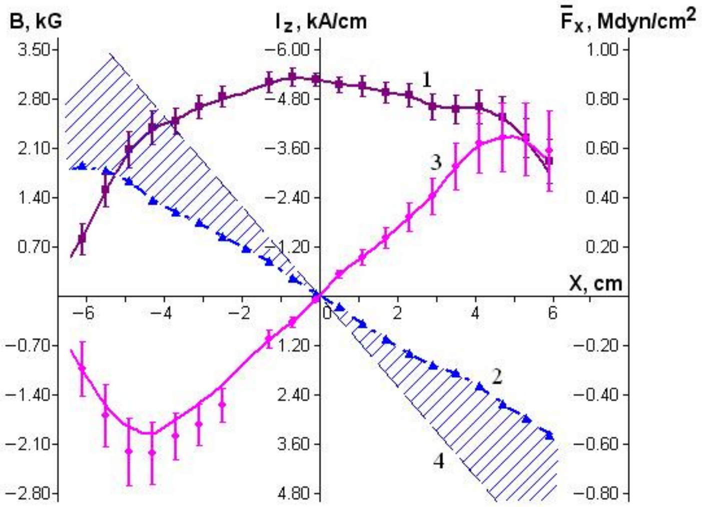

Fig. 2. Distributions of the current $I_z(x)$ inside the region $|y| \le \Delta y = 1.2$ cm (1), normal magnetic field component $B_y^J(x)$ measured by a magnetic probe (2), Ampere force $F_x(x)$ averaged over the region $2\Delta y$ (3), and the function $\{-B_y^0(x)\} = -h\cdot x$ (4). The height of the shaded area between (4) and (2) corresponds to the component normal to the CS: $\{-B_y(x)\} = -(B_y^0 + B_y^J)$.
Ar, $p = 28$ mTorr, $h = 0.63$ kG/cm, $J_z^{max} = 96$ kA; $t = 1.9$ µs.

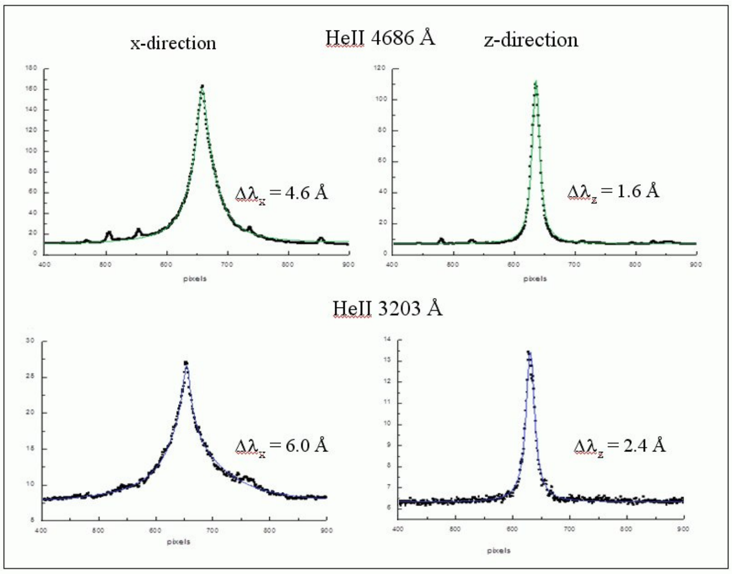

Fig. 3. Profiles of the He II 4686 Å and He II 3203 Å SLs emitted by the CS plasma in the x and z directions and detected by the Nanogate 1UF camera. The abscissa axis shows the radiation wavelength (100 pixels = 12.5 Å), the ordinate axis shows the intensity in arbitrary units.

He, $p = 320$ mTorr, $B_z^0 = 0$; $h = 0.5$ kG/cm; $J_z^{max} = 70$ kA; $t = 4.3 \pm 0.4$ μs.

data. The broadening of the *Ar II* 4806 Å SL is defined only by the Doppler effect. The SLs *He II* 4686 Å and *He II* 3203 Å (Fig.3) broaden due to both the Doppler effect and Stark effect in electric micro-fields of plasma. By measuring profiles of two *He II* SLs we determined the energies of thermal and directed ion motions and the electron densities, Fig.4.

It was found that averaged energies of plasma jets are time increasing. In the CS formed in the *Ar* plasma the jet energies attained $W_x^d \cong 100$ eV, whereas the ion temperature was lower, $T_i \leq 45$ eV [7]. The work of the Ampere forces over the half width of the CS is sufficiently large for acceleration of the *Ar* ions up to the energy $W_x^d \cong 100$ eV [4].

In the CS formed in the *He* plasma, in the absence of the guide field ($B_z^0 = 0$) the jets gained much higher energies: $W_x^d \cong (400 - 1000)$ eV, and the electron density sharply increased near the CS side edges $N_e^x \cong (8 - 18) \times 10^{16}$ cm^{-3}, whereas in the CS central region $T_i \leq 100$ eV and $N_e^0 \leq 10^{16}$ cm^{-3}, Fig.4. At the same time, in the presence of the guide field ($B_z^0 = 2.9$ kG) neither plasma motion in the *x*-direction, nor an increase of the electron density N_e^x near the CS edges was observed, Fig.4. Analyzing these results we suggest that plasma acceleration is not spatially uniform over the thickness of CSs formed in the *He* plasma, and the most effective acceleration should take place in the regions with lower plasma density, which are located at some distance from the CS midplane [5,8].

Generation of plasma jets is also confirmed by observation of reverse currents, which flow at the CS side edges in a direction opposite to the main current through the system [4]. The reverse currents can be excited by high-speed plasma jets, which are moving along the *x*-axis toward the CS edges, where the normal component B_y is strong enough [5]. The CSs containing reverse currents were predicted by Syrovatskii [9].

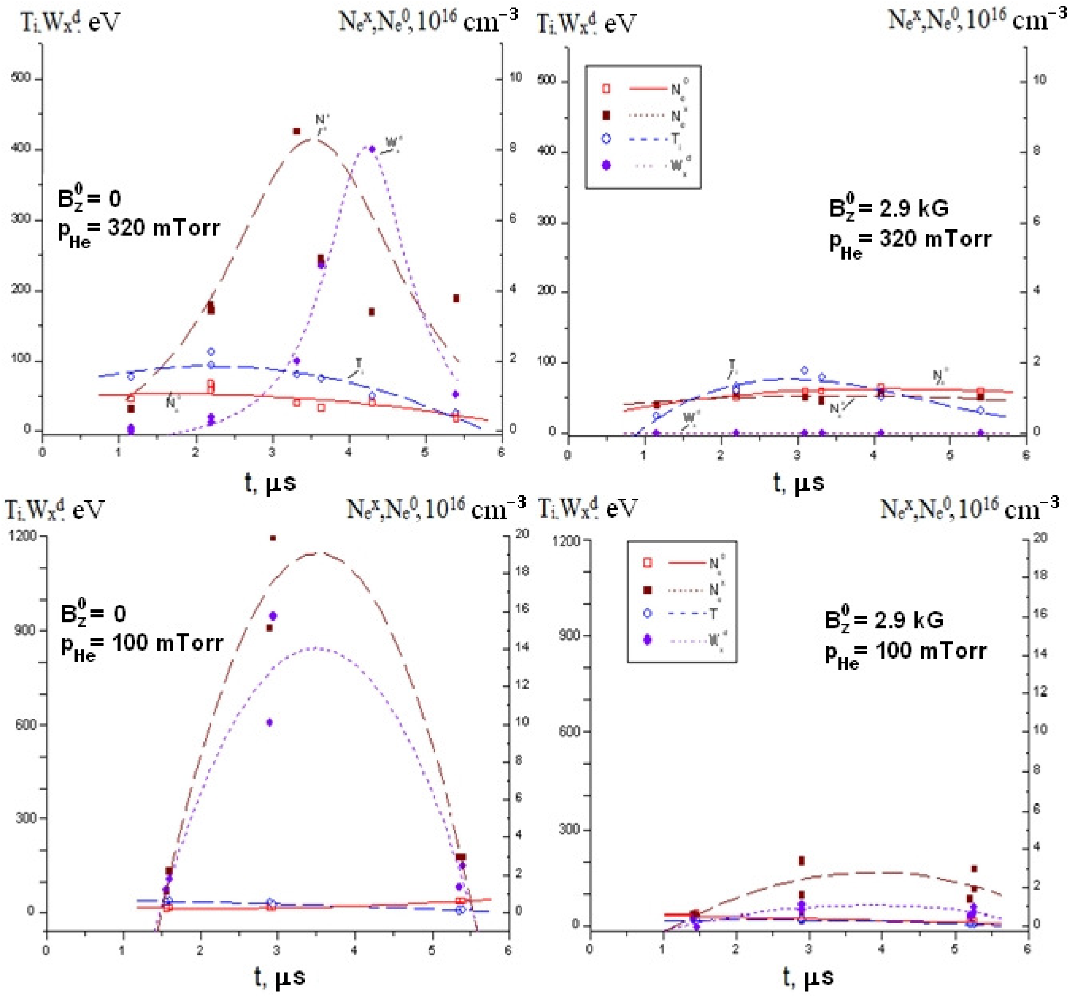

Fig. 4. Time dependences of electron densities N_e^0 and N_e^x, correspondingly, in the central part of the CS and at its periphery; the ion temperature T_i, and the averaged energy W_x^d of plasma flows along the CS surface. He, $h = 0.5$ kG/cm; $J_z^{max} = 70$ kA; $B_z = 0$; 2.9 kG; $p = 320$; 100 mTorr.

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