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PLASMA HEATING AND GENERATION OF PLASMA JETS IN CURRENT SHEETS FORMED IN 3D MAGNETIC CONFIGURATIONS

N.P. Kyrie, A.G. Frank, V.S. Markov, G.S. Voronov

A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow, Russia

1. Introduction

Current sheets are spatially localized regions of magnetized plasma where magnetic reconnection, once initiated, is accompanied by effective conversion of magnetic energy into energy of plasma, accelerated particles, and radiation [1, 2]. Magnetic reconnection is the basis for flare phenomena both in space and laboratory, such as solar and stellar flares, substorms in the Earth and planetary magnetospheres, disruption instabilities in tokamaks, transient phenomena in pulsed discharges.

In laboratory experiments in the CS-3D device under certain conditions, we observed an extremely rapid growth in the plasma thermal energy, which disturbed the transverse equilibrium of the current sheet and triggered the impulsive phase of magnetic reconnection and the subsequent catastrophic disruption of the sheet [3]. We emphasize that the role played by thermal processes in disruption of the current sheet is similar to "thermal trigger of solar flares" [4].

In the present paper, attention is focused on the temporal evolution of the electron temperature in the current sheet plasma, the effective ion charge, and measurements of thermal and directed ion velocities in current sheets formed in 2D and 3D magnetic configurations with an *X* line.

2. Experimental device and measurement procedure

Current sheets were formed in magnetic fields with a singular *X* line in the CS-3D device shown schematically in Fig. 1. Initial plasma was produced by electric breakdown in a working gas (argon) in a magnetic field. The transverse field gradient was h = 0.4-0.6 kG/cm; the longitudinal component of magnetic field directed along the *X* line was varied in the range B_Z = 0 - 6 kG. The maximal value of plasma current producing a current sheet was varied in the range J_z = 50 - 70 kA.

Time evolution of spectral line intensities of argon ions (*Ar II* and *Ar III*) and impurity (*C III*) was measured using the optical scheme also shown in Fig. 1. Based on these data, we calculated the electron temperature for different experimental conditions by using the mathematical code [5] developed on a basis of the collisional-radiative model of plasma, taking into account the processes of ionization, excitation, and MHD plasma flows that are initiated at the sheet formation stage and cause compression of the plasma into a sheet.

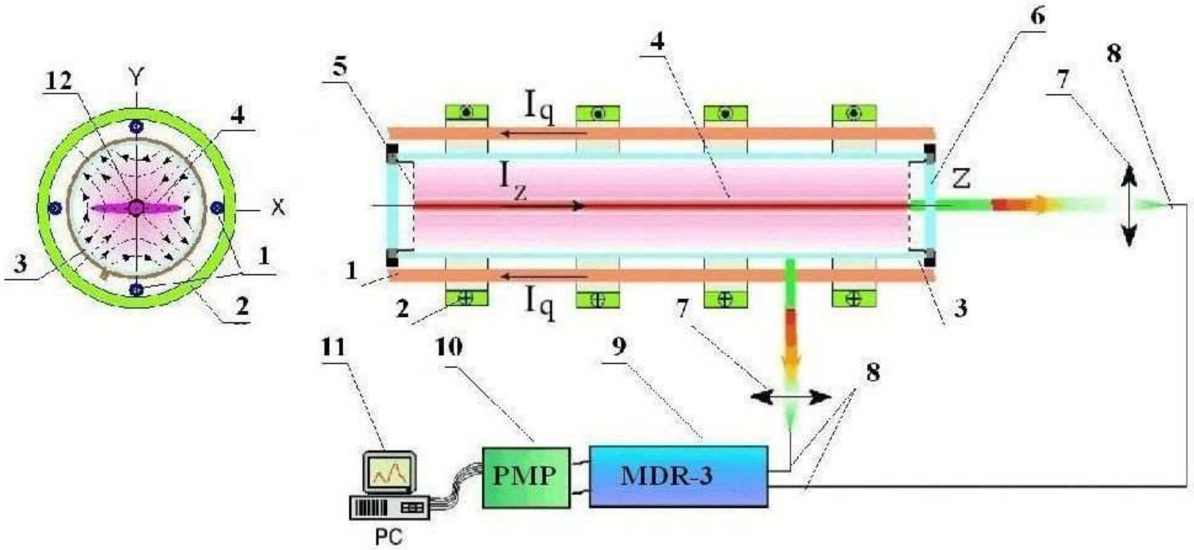

Fig.1. *CS-3D device and diagnostics: (1) straight current conductors producing a 2D field, (2) coils producing a field B_Z, (3) quartz vacuum chamber 18 cm in diameter and 100 cm long, (4) current sheet, (5) grid electrodes, (6) windows, (7) lenses, (8) quartz fibers, (9) monochromator, (10) photomultipliers, (12) plasma region under study.*

The ion temperature and the velocities of directed motion of argon ions were deduced from Doppler broadening of the *Ar II* 460.6 nm line observed simultaneously in mutually perpendicular directions: along the x and z axes (Fig. 1). The profiles of the *Ar II* 460.6 nm line were recorded point by point across the spectrum.

3. Results of experiment and simulation

Figure 2c shows the calculated time evolution of the electron temperature, which gives the best fit to the experimental values of electron density [3] and intensities of *Ar II*, *Ar III*, and *C III* spectral lines (Fig. 2a, 2b). It can be seen from Fig. 2c that the electron temperature in the time interval t ≈ 0.3 - 3 μs (after the beginning of the current) increases from 5 to 11 eV, the estimated error being 10 - 15%.

To study the influence of the guiding field B_Z on the plasma parameters, we carried out a series of experiments in which the field B_Z was varied in the range from 0 to 6 kG with a step ΔB_Z = 1.5 kG. The experiments showed that, as B_Z increased from 0 to 6 kG, the electron density in the sheet decreased by a factor of ~ 4, whereas the electron temperature increased by a factor of ~ 1.6, from $T_e \approx 8$ eV to $T_e \approx 13$ eV.

The change in the electron temperature with increasing B_Z involved a change in the spatial distributions of intensities of *Ar II* and *Ar III* lines. Figure 3 shows the calculated distributions of intensities of *Ar II* and *Ar III* lines and plasma parameters along the *y* axis.

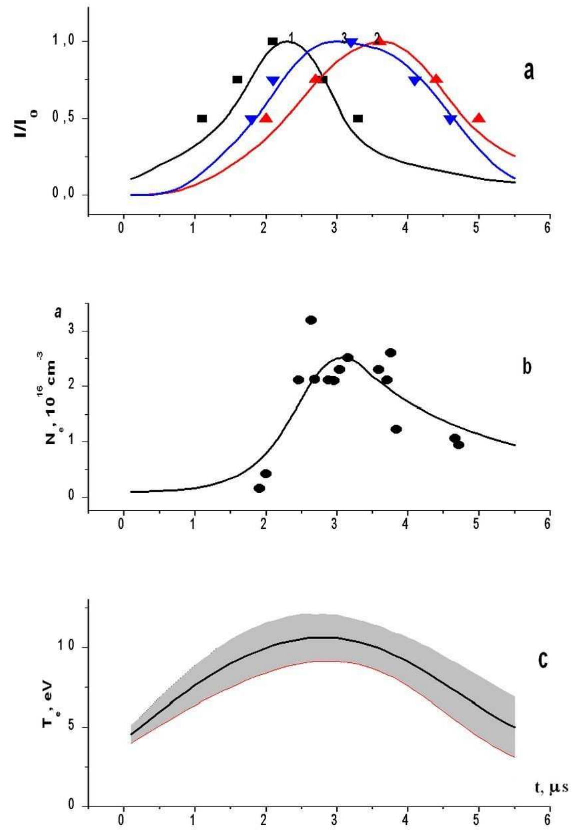

Fig.2*. Measured (points) and calculated (curves) evolution of (a) spectral lines (1) Ar II 480.6 nm, (2) Ar III 379.5 nm, (3) C III 464.7 nm; (b) electron density* N_e*; and (c) electron temperature* T_e*.*

The *Ar II* ions are completely depleted (and the *Ar III* ions are partially depleted) when the temperature T_e and density N_e attain their maximal values at the middle plane of the sheet ($y = 0$). As the guiding field B_Z increased, the regions of maximum emission intensity of these ions shifted away from the midplane of the sheet to its periphery along the *y* axis.

The temperature of argon ions in the time interval t ≈ 2 - 5 μs increased from 25 to 45 eV, whereas the average energy of directed motion increased from 30 to 85 eV. Hence, the inequality $W_x > T_i > T_e$ holds and the temperatures of the ion and electron components are in the ratio $T_i/T_e \approx 3$. The experiments show that, in contrast to the electron temperature, the ion temperature does not depend on whether a sheet forms in the 2D or 3D magnetic configuration.

According to our estimates the ion heat conductivity along the magnetic field B_X in 2D current sheets is very low and plays no part in heat transport. It is not surprising, then, that the field B_Z in 3D magnetic configurations, which is perpendicular to the *x* axis, has no effect on the temperature of argon ions. The electron heat conductivity along magnetic lines (the *x* axis) is also low, but still sufficient to cause some loss of the energy of the electron component. The magnetic field B_Z does

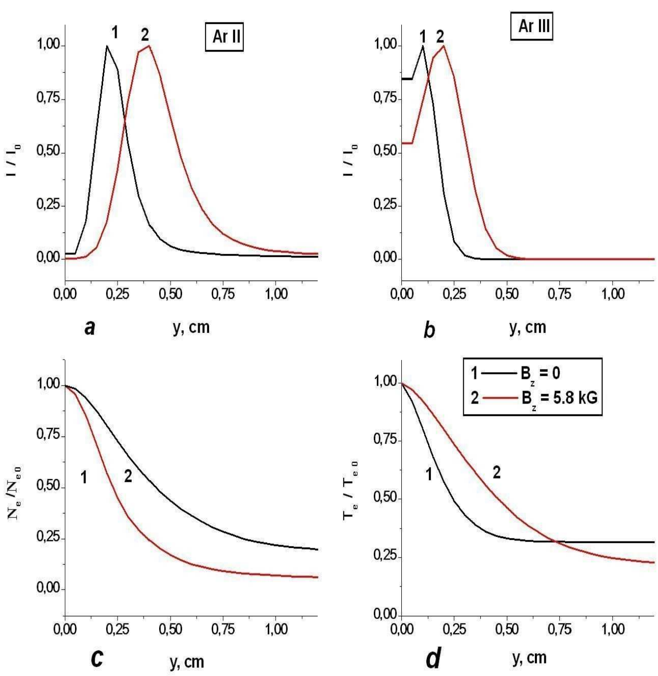

Fig.3*. Effect of field* B_z *on distributions of plasma parameters over the sheet thickness (the y axis): (a) Ar II, and (b) Ar III line intensities, (c) electron density* N_e*, and (d) electron temperature* T_e*.*

limit the longitudinal heat conductivity so that the electron temperature should increase somewhat (it increases by a factor of ~ 1.6, from $T_e \approx 8$ eV to $T_e \approx 13$ eV, at $\Delta B_Z = 0 \div 6$ kG).

4. Conclusion

We have investigated time evolution of basic plasma parameters in current sheets formed in 3D magnetic fields. We used spectroscopic methods combined with numerical simulation. Our findings are the following:

(1) The maximum electron temperature was $T_e \approx 11$ eV at $B_Z = 0$ (in the 2D current sheet). In the 3D magnetic configurations, as B_Z increased from 1.5 to 6 kG, the electron temperature increased by a factor of ~ 1.4, from $T_e \approx 9$ eV to $T_e \approx 13$ eV, while the the electron density in the sheet decreased by a factor of ~ 4. The maximum ion temperature was $T_i \approx 45$ eV in both 2D and 3D configurations.

(2) Superthermal plasma flows directed along the x axis were observed in the sheet. The maximum energy of directed motion of argon ions is $W_X \approx 85$ eV, so that $W_X > T_i > T_e$.

(3) The effective plasma charge was estimated as $Z_{eff} \approx 2.2$ - 4.7, depending on experimental conditions (h, J_Z, B_Z).

(4) From the measured values of T_i , T_e and Z_{eff} we could estimate an increase in the field component B_Z inside the sheet [3].Thus for the current sheet formed in Ar at $h = 0.5$ kG and $B_Z = 2.9$ kG, it was found that $\delta B_Z \approx 0.95$ kG/cm. This result correlates with magnetic measurements $\delta B_Z = 0.8$ kG [6].

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