# Current sheets in the Earth magnetosphere and laboratory experiments

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Laboratory experiments on current sheets (CSs) were originally aimed at modeling events like solar flares and to substantiate theoretical predictions, see e.g. [1]. In the last few decades, dynamics of CSs and magnetic reconnection phenomena have been studied in a number of laboratory experiments, and extensive data have been obtained for internal structure of CSs, parameters of magnetic fields, plasma, electric fields and currents, plasma flow velocities, etc., see [2,3] and references therein. In the meantime, numerous satellite missions investigated the magnetotail − a stretched current sheet in the Earth's magnetosphere. The most comprehensive results have been obtained recently with the Cluster mission, see [4,5] and references therein. There is a dramatic scale difference of parameters of the magnetosphere and laboratory CSs, and the challenge now is to find out correlations between these CSs [6]. In this paper we compare some experimental results from the CS-3D device [3,7] with the results obtained by the Cluster mission in 2003.

A laboratory current sheet is created by exciting plasma current $J_y$ along a singular $\boldsymbol{X}$ line of the magnetic configuration $\boldsymbol{B} = \{h{\cdot}z;\ B_y^0;\ h{\cdot}x\}$, with a gradient $h \cong (0.4 - 0.6)$ *kG/cm* in the $(x, z)$ plane, and a uniform guide field $B_y^0 \cong (1.5 - 3)$ *kG*. The vacuum chamber, 18 *cm* in diameter and 100 *cm* length, is filled with the *Ar* , *He* or *Kr* gas, and the initial plasma is produced by the Θ-discharge with strong pre-ionization. Then a pulsed voltage is applied exciting plasma current $J_y$ of a sinusoidal form, with amplitude of ≅ (50 – 70) *kA* and a half-period $T/2 \cong 6\ \mu s$. Magnetic fields in the plasma are measured with three-component magnetic probes [8], two-dimensional distributions of the electron density $N_e\,(x,z)$ are recorded by the interference-holographic method [9], the electron and ion temperatures and the velocities of plasma flows are measured by spectroscopic methods [7,10].

The formation of a current sheet results in concentration of the electric current and plasma in a sheet and leads to significant modification of the initial magnetic field by increasing the tangential component $B_x$ and decreasing the normal component $B_z$. (Note that the laboratory CSs are considered here in the magnetospheric coordinate system). The value and direction of the tangential component $B_x(z)$ change sharply at the CS mid-plane ($z$=0) where the current density $j_y(z)$ peaks. The profiles of $B_x(z)$ and $j_y(z)$ qualitatively coincide with the similar profiles observed by Cluster, Fig.1. Near the sheet center the normal magnetic field component $B_z$ is several times smaller than both $B_x$ and $B_y$ components; however, $B_z$ increases with distance from the ***X*** line along the $x$-axis, and so does the $B_z$ component in the magnetotail. Spatial gradients of all parameters along the direction normal to the current sheet ($z$-axis) far exceed gradients along $x$- and $y$-axes, and the spatial scale $2\delta z$ corresponds to the minor transverse size (thickness) of the sheet.

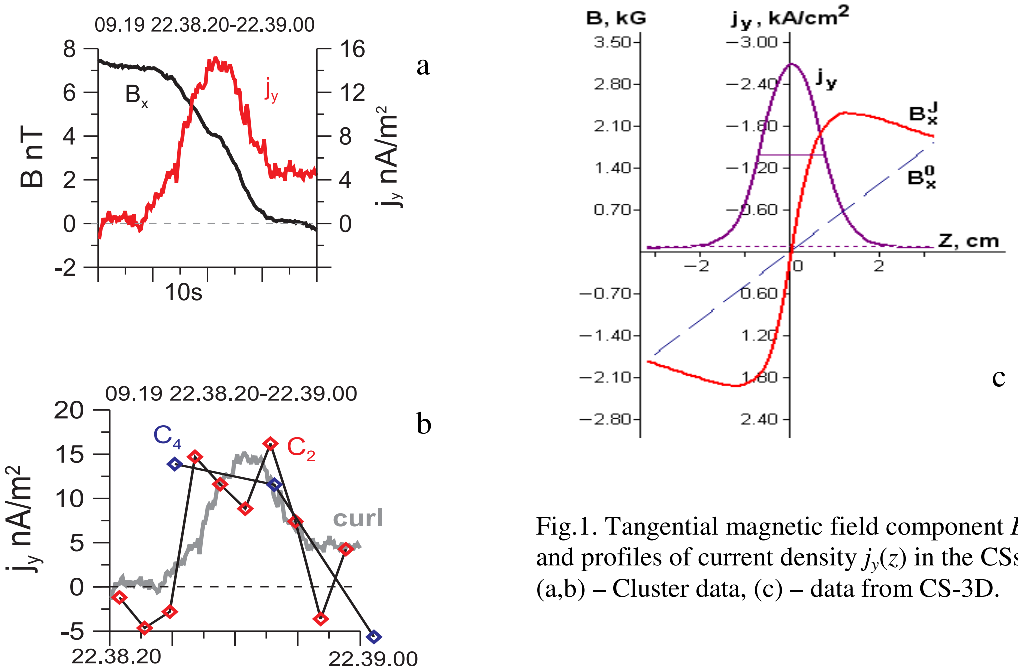


Fig.1. Tangential magnetic field component $B_x(z)$ and profiles of current density $j_y(z)$ in the CSs. (a,b) – Cluster data, (c) – data from CS-3D.

The strength of the initial guide field $B_y^0$ is a parameter affecting the maximum current density $j_y^{max}$, plasma density $N_e^{max}$ in the sheet mid-plane ($z$=0), and the CS thickness $2\delta z$ [3,9]: as $B_y^0$ increases, $2\delta z$ increases while both $j_y^{max}$ and $N_e^{max}$ decrease, Table 1.

An enhancement of the guide field $B_y$ over its initial value $B_y^0$ has been revealed in the laboratory-produced CSs [8]. The profiles of the guide field variations $\delta B_y(z) = \{B_y(z) - B_y^0\}$ perfectly coincide with the current density profiles $j_y(z)$, and the direction of $\delta B_y$ is always the same as the direction of $B_y^0$ [8]. These peculiarities are in good qualitative agreement with the spacecraft observations, Fig.2. Note that the guide field amplification $\delta B_y$ is provided by plasma currents $j_x$, which are of the same magnitude as the CS basic current $j_y$.

The electron temperature peaks at the mid-plane of the laboratory CSs where $B_x \approx 0$, $T_e^{max} \leq 10$ eV, Fig.3a, whereas the ion temperature is higher, $T_i \approx 40 \div 60$ eV [7,10]. Identical effects were observed by the Cluster mission: $T_i / T_e \approx 5 \div 10$, Fig.3b,c. The ions in the laboratory CSs are not magnetized in contrast to the electrons, which are magnetized and transfer most of the plasma current, just they do in the magnetotail CS.

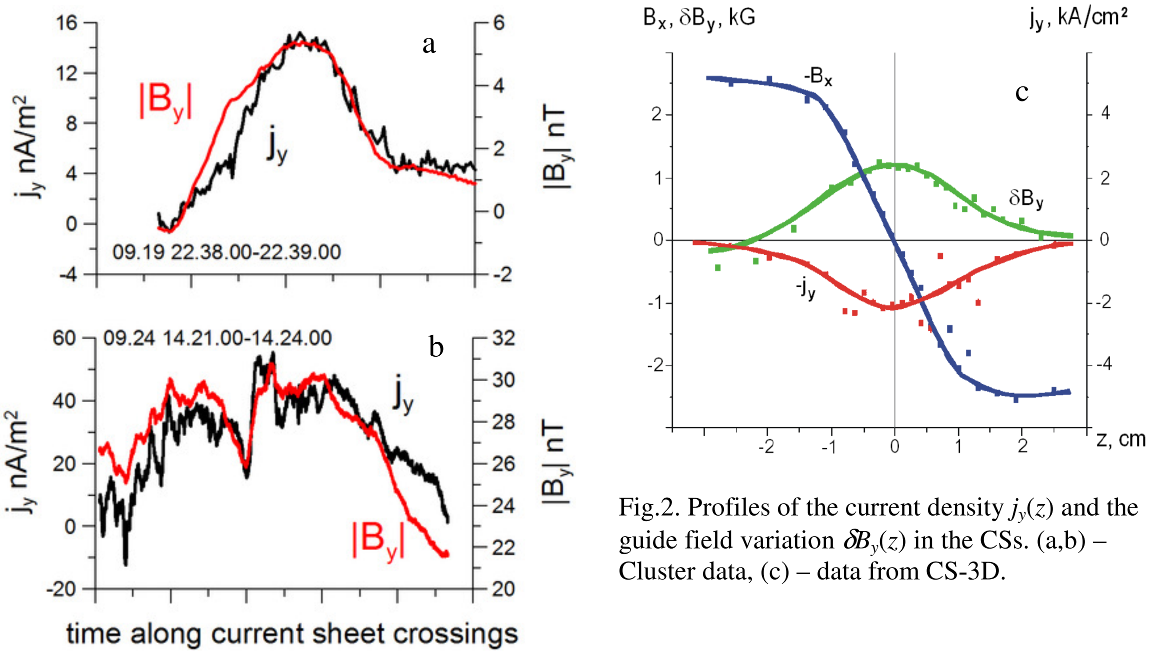


Fig.2. Profiles of the current density $j_y(z)$ and the guide field variation $\delta B_y(z)$ in the CSs. (a,b) – Cluster data, (c) – data from CS-3D.

The half-thickness $\delta z$ of the laboratory CSs formed under various conditions agrees closely with the ion skin depth c / $\Omega_{0i}$, where $\Omega_{0i}$ is the ion plasma frequency calculated for the corresponding ion density, Table 1.

Table 1. *Parameters of CSs formed under various $B_y^0$ fields in the CS-3D device*

| | $B_y^0$, kG | $j_y^{max}$, kA/cm$^2$ | δz, cm | $N_e^{max}$, cm$^{-3}$ | c / $\Omega_{0i}$, cm | $\delta z \cdot \Omega_{0i}/c$ |
|---|---|---|---|---|---|---|
| a | 1.35 | 4 | 1.4 | $10^{16}$ | 1.4 | ≈1 |
| b | 4.3 | 2.1 | 2.2 | 0.5 $10^{16}$ | 2.0 | ≈1 |

The important characteristics of the magnetosphere and laboratory CSs are outlined in the Table 2. Though plasma density $N_e$ in the magnetotail is less than one particle per cm$^3$, and the Debye length is as large as $r_d \approx 0.6$ km, we have to do with the magnetospheric plasma sheet, since the CS dimension $\delta z$ is two orders of magnitude larger than $r_d$.

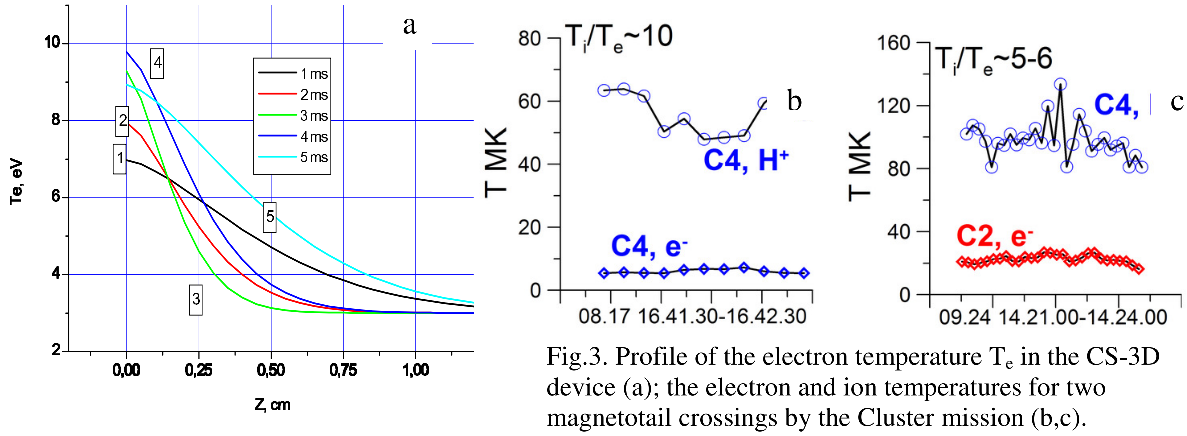


Fig.3. Profile of the electron temperature $T_e$ in the CS-3D device (a); the electron and ion temperatures for two magnetotail crossings by the Cluster mission (b,c).

The fact of a fundamental importance is that the CS spatial scale $\delta z$ is very close to the ion skin depth $c / \Omega_{0i}$, their ratio is estimated as ≈ 1 for both magnetotail and laboratory CSs, see Table 2. Note that for the magnetotail CS the ion skin depth is comparable with the ion Larmor radius [4-6]. One can also see that the current drift velocity $u_{dr}$ is somewhat higher than the Alfven velocity $v_A$, their ratio is ≥ 1.

The close examination of results obtained in the course of the Cluster mission in 2003 year and in experiments with the CS-3D device makes it evident that CSs exist both in the Earth magnetosphere and in laboratory conditions. The natural and laboratory CSs having different sizes, magnetic field strengths, current densities, plasma concentration and temperatures, do exibit a number of common features. This suggests that laboratory experiments can give us a deeper insight into the physics of the magnetosphere in the framework of "Laboratory astrophysics".

Table 2. *Parameters of the CSs in the magnetosphere and in the CS-3D device.*

| | **Magnetosphere** | **CS-3D** |
|---|---|---|
| B, G | $10^{-4}$ | $3 \cdot 10^3$ |
| $N_e$, $cm^{-3}$ | < 1 | $10^{16}$ |
| $\delta z$, cm | $2 \cdot 10^7$ (200 km) | 1.5 |
| $r_d$, cm | $6 \cdot 10^4$ (0.6 km) | $3.3 \cdot 10^{-5}$ |
| $\boldsymbol{\delta z / r_d}$ | $\boldsymbol{3.3 \cdot 10^2 >> 1}$ | $\boldsymbol{4.5 \cdot 10^4 >> 1}$ |
| $c/\Omega_{0i}$, cm | $2.3 \cdot 10^7$ (230 km) | 1.4 |
| $\boldsymbol{\delta z \cdot \Omega_{0i} / c}$ | **≈ 1** | **≈ 1** |
| j, $A/cm^2$ | $3 \cdot 10^{-12}$ | $2.7 \cdot 10^3$ |
| $u_{dr}$, cm/s | $4 \cdot 10^7$ | $1.7 \cdot 10^6$ |
| $v_A$, cm/s | $3 \cdot 10^7$ | $10^6$ |
| $\boldsymbol{u_{dr} / v_A}$ | **≥ 1** | **≥ 1** |

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