35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, O-3.026 (2008)

Experimental observations of the out-of-plane quadrupole magnetic fields resulting from generation of the Hall currents in current sheets

Anna Frank[1], Sergey Bugrov[1], Vladimir Markov[1]

[1]*Institute of General Physics, Russian Academy of Sciences, Moscow, Russia*

Abstract: We present experimental results on the structure and time evolution of the Hall currents in current sheets produced in the 2D magnetic fields with the null line, in plasmas with heavy ions. Three-component magnetic fields were measured, with a particular emphasis on the “out-of-plane” component, which is a signature of the Hall currents and has a quadrupole structure. We revealed that the current sheet includes the Hall currents of the opposite directions, which practically compensate for each other at every time moment and form four closed current circuits that produce the out-of-plane quadrupole magnetic field.

1. The formation of a current sheet (CS), which separates differently directed magnetic field lines, is prerequisite to magnetic reconnection - the process underlying flare-type phenomena in astrophysics and laboratory plasmas. Two-fluid plasma properties and generation of Hall currents can modify the structure and dynamics of CS and thereby affect the magnetic reconnection processes. In our previous experiments an appearance of the Hall currents was deduced by the indirect route, from an asymmetry of plasma sheets produced in the 3D magnetic configurations with a guide field [1-3]. The sheets arising in the 2D magnetic fields with a null line are planar and symmetrical showing no evidence of the Hall currents. At the same time, an analysis of plasma parameters indicated that the Hall currents might be also generated in CS formed in the 2D fields, in plasmas with heavy ions, where two-fluid plasma properties increase in importance [2-4].

2. The experiments have been carried out in the CS-3D device, Fig. 1. Straight current-carrying conductors produce a quasi-steady 2D magnetic field $\boldsymbol{B}_{\perp} = h\ \{y; x; 0\}$ with the null line aligned with the chamber axis (z-axis) and the field gradient $h = 0.5 \div 0.65$ *kG/cm*. The initial plasma is produced in the *Ar* or *Kr* gas ($p \cong 20$ *mTorr*) by a Θ-discharge; both the magnetic field $\boldsymbol{B}_{\perp}$ and initial plasma are uniform in z-direction. A pulsed voltage applied between two electrodes placed at the ends of vacuum chamber (Φ=18 *cm*, L=100 *cm*) gives rise to plasma current $J_Z(t) \cong J_Z^{max} \sin(2\pi t / T)$; $J_Z^{max} \cong 70 \div 80$ *kA*, $T/2 \cong 6\ \mu s$. The J_Z current forms CS, its cross-section is shown in Fig. 1. Magnetic fields produced by plasma currents were measured by 3-component magnetic probes moving in the middle of the chamber along the dotted lines AA′, BB′, etc. ($y = \pm\ 0.8$ *cm*; $x = -\ 0.8$ *cm*; $x = -\ 5$ *cm*), Fig. 1.

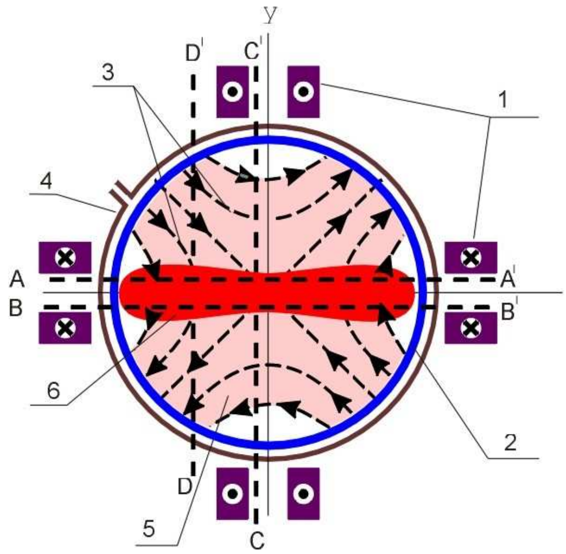

Fig. 1. *Device CS-3D (cross section): 1 - conductors to form 2D magnetic field with a null line; 2 – vacuum chamber; 3 – magnetic field lines of the initial 2D magnetic field; 4 – Θ-discharge to produce plasma; 5 – the initial plasma shape; 6 – current sheet; the dotted lines - directions for moving magnetic probes .*

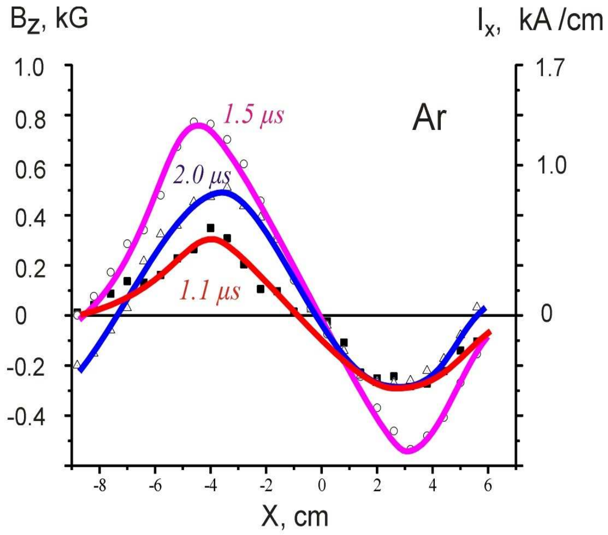

Fig. 2. *Distributions of the out-of-plane magnetic field $B_Z (x, y = +0.8\ cm)$ in the current sheet, for different time moments ($B_Z^0 = 0$; $h = 0.64$ kG/cm; Ar, 20 mTorr; $J_z^{max} = 65$ kA).*

3. Considering the initial 2D magnetic field and the magnetic field produced by the J_Z current, one may assume that only two in-plane components (B_X, B_Y) exist in CS, whereas the third component B_Z should be absent. At the same time, we detected the out-of-plane magnetic field B_Z in CS formed in plasmas with heavy ions, Fig. 2. The maximum of B_Z attains far away from the null line, at $|x| \cong (4 \div 5)$ *cm*, at every instant. B_Z is small enough near the null line ($x \cong 0$) and is opposite in sign on each side of the null line. It follows that along with the basic current J_Z, the additional currents are generated in the (x, y) plane. B_Z component disappears rapidly, Fig. 2, and the time when B_Z exists increases with the ion mass. The currents in the (x, y) plane might be identified as the Hall currents

Measurements carried out on the other side of CS, at $y = -0.8$ *cm*, show that B_Z is opposite in direction to B_Z measured at $y = +0.8$ *cm*, whereas at the equal x – coordinate the other spatial and temporal characteristics of B_Z are identical. It follows that the out-of-plane component B_Z changes its direction as either the x-axis or y-axis is intersected, and hence B_Z exhibits a typical **quadrupole structure** [5,6]. It is also evident that there are currents in the x-direction, along the CS surface, as it was supposed in [1,2].

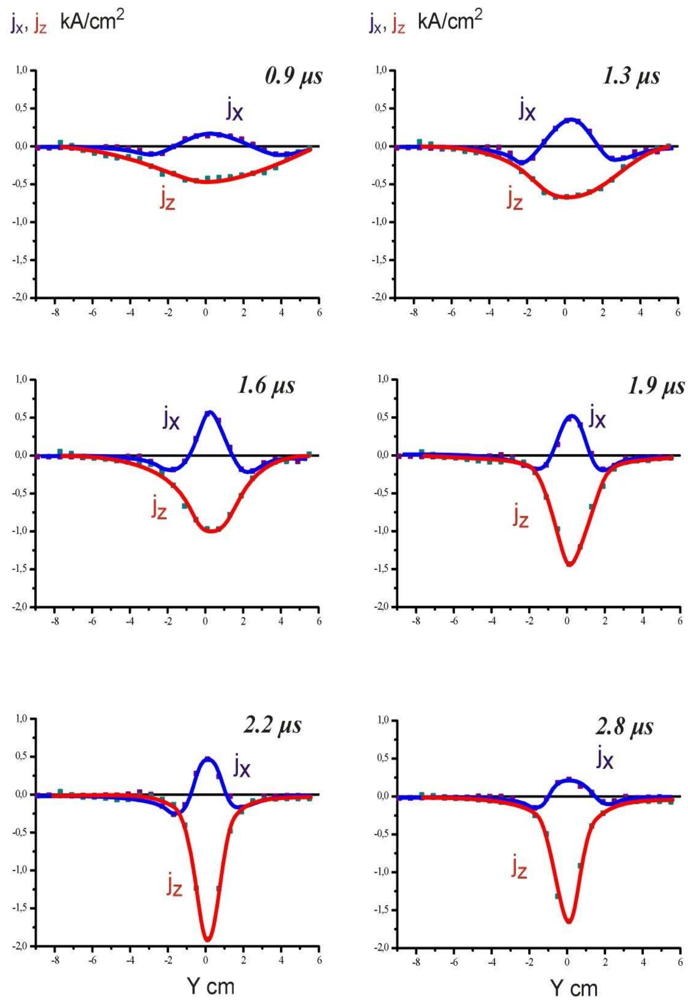

Fig. 3. *Distributions of the Hall current j_X and the basic current j_Z in the y-direction, at x = -5 cm, at successive times. ($B_Z^0 = 0$; h = 0.64 kG/cm; Ar, 20 mTorr; J_z^{max} = 65 kA).*

4. On the base of $B_Z(x)$ distributions we estimated the currents j_Y that flow along the normal to the CS surface. In the CS central part j_Y are directed outward, forming an outflow region, while j_Y are of the opposite sign at $(|x| > (4 \div 5)\ cm)$, forming two peripheral inflow regions at both side edges of CS.

To gain an insight into a structure of the Hall currents in CS, magnetic measurements were done at x = - 5 *cm* (DD′ line), and distributions of the Hall currents $j_X(y)$ and the basic current $j_Z(y)$ were obtained for different times, Fig. 3. The both Hall currents and basic current are concentrated with time about the CS middle plane ($y = 0$), so that the maximum current densities increase, and the CS thickness decreases. The Hall currents of the opposite directions exist in CS, while the basic current has only one direction over the whole range of the *y*-coordinates. Near the CS middle plane the Hall current is positive, flowing from the peripheral region toward the null line. By contrast, at larger distances, in both sides from the middle plane, the Hall currents become reversed. The Hall currents of both directions exist only at the regions, where the basic current flows: $jz \neq 0$.

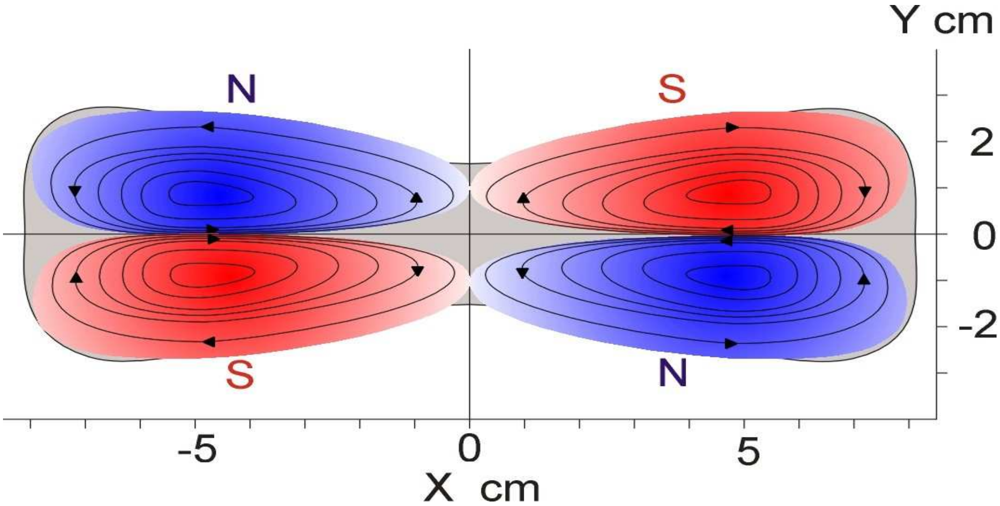

Fig. 4. *Structure of the Hall currents (shown with black lines), which produce the out-of-plane magnetic field of the quadrupole type (shown with blue and red) in the current sheet (grey background).*

We demonstrate that the total positive Hall current $I_X^{(+)}$ and the sum of the negative Hall currents $I_X^{(-)}$ have nearly the same absolute values at every time moment, and hence the oppositely directed Hall currents compensate for each other [5,6]. It might be concluded that the Hall currents form four closed current circuits in the (x, y) plane perpendicular to the CS basic current J_Z, thereby producing quadrupole magnetic fields directed along the initial null line, Fig. 4.

Supported by the Russian Foundation for Basic Research (grant no. 06-02-17011).

[1]. A.G. Frank, et al. // Proc. 30-th EPS, St-Petersburg, Russia, **27A**, P-1.35 (2003).

[2]. A.G. Frank, S.Yu. Bogdanov, G.V. Dreiden et al. // Phys. Lett. A, **348**, P.318 (2006).

[3]. S.Yu. Bogdanov, et al. // Plasma Phys. Reports, **33,** P.930 (2007).

[4]. A.G. Frank, et al. // Proc. ICPP2006, Kiev, Ukraine, A008o (2006).

[5]. A.G. Frank, et al. // Proc. XXVIII (ICPIG_28), Prague, Czech Rep., P.362 (2007).

[6]. A.G. Frank, S.G. Bugrov, V.S. Markov // Phys. Plasma, submitted (2008).