UDC 533.9

MAGNETIC RECONNECTION AND CURRENT SHEETS IN 2D AND 3D MAGNETIC CONFIGURATIONS

A.G. Frank, S.Yu. Bogdanov, N.P. Kyrie, V.S. Markov
General Physics Institute Russian Academy of Sciences, Moscow, Russia
Annfrank@fpl.gpi.ru; FAX: +7(095) 135-8011; Tel.: +7(095) 132-8240

Experimental results are presented on the study magnetic reconnection phenomena and current sheet formation and evolution in 2D and 3D magnetic configurations with some topological singularities: null-lines, null points, singular lines. Current sheet evolution in 2D fields with null-lines manifests qualitative agreement with principal features of flare-type phenomena. Current sheet formation was revealed to occur in various 3D magnetic configurations, both with and without isolated magnetic null-points, specifically in magnetic configurations with X-lines. Results demonstrate self-organization of current sheets to be a general process for plasma dynamics in non-uniform magnetic fields.

Introduction

Magnetic reconnection in high-conductivity magnetized plasma pertains to the most important fundamental problems of modern plasma physics. At the same time reconnection is a basis for a variety of flare-type phenomena, such as solar and stellar flares, substormes in magnetospheres of the Earth and planets, sawtooth instabilities in tokamaks, rapid changes of the magnetic field structure in reversed field pinches, Z-pinches, theta-pinches, etc. Magnetic reconnection phenomena occur at some discrete regions that separate magnetic fields of different, or opposite directions and where electric currents of high density are concentrated. These regions take ordinarily the form of quasi-one-dimensional sheets, so possibilities and conditions for current sheet (CS) formation are of a crucial importance [1]. We have studied experimentally CS formation and evolution in a variety of 2D and 3D magnetic configurations with some topological singularities: null points, singular lines [2,3]. A basic principle for formation a configuration was a combination of two fields with different symmetry properties. One was 2D magnetic field of translational symmetry with a null-line at the z-axis:

$$\mathbf{B_q} = \{B_x; B_y; B_z\} = \{h\cdot x; -h\cdot y; 0\} \quad (1)$$

h is the field gradient in (x,y) plane, h≅const. The second was an axial symmetric magnetic field with an axis along the null-line; the field could be presented near any point (0,0,Z) at z-axis in a form:

$$\mathbf{B_{as}}=\{B_x; B_y; B_z\} = B_z(Z) + h_r(Z)\cdot\{x;\cdot y; -2(z–Z)\} \quad (2)$$

$h_r(Z)$ is the radial field gradient. We have used several types of axisymmetric fields: the uniform B_z-field with $h_r(Z)=0$, the cusp-field with a null-point, where $B_z(Z)=0$, the non-uniform B_z-field without null-points. A combination of (1) and (2) produced a novel 3D magnetic configuration:

$$\mathbf{B_\Sigma} = \mathbf{B_q} + \mathbf{B_{as}} = B_z(Z) + h\,\{[1+\gamma(Z)]\cdot x; -[1-\gamma(Z)]\cdot y; -\gamma(Z)\cdot(z-Z)\} \quad (3)$$

$\gamma(Z) = h_r(Z) / h$ is the ratio of two gradients. Both (1) and (2) fields could be varied independently, providing formation diversified 3D configurations (3) with gradual transitions between them.

A principle scheme of CS-3D device (Three-Dimensional Current Sheet) is shown in the Fig.1. 2D magnetic field with a null-line at the axis of vacuum chamber was formed by a system of straight external conductors. Four coils with various directions and magnitudes of electric currents produced axial symmetric magnetic fields. Both fields were quasi-steady. Vacuum chamber was filled with He or Ar gas, and initial plasma was produced by pre-ionization. Then perturbations were excited by applying a pulsed voltage between two electrodes, giving rise to plasma flows and electric currents, which might result in appearance of CS. Maximum plasma current I_z≅100 kA, its half-period T/2=5 μs.

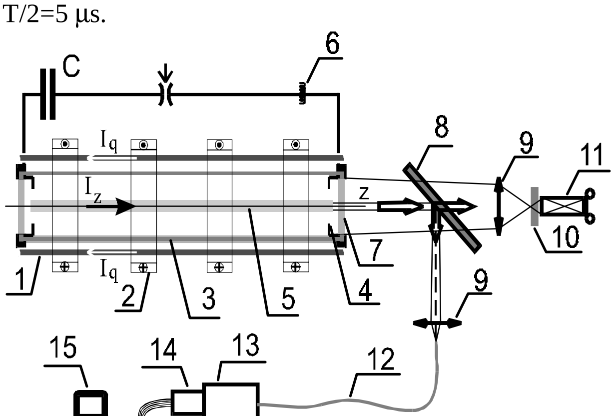

Fig.1. Experimental device CS-3D: 1-straight conductors to produce 2D field (1); 2-four coils to produce axial-symmetrical magnetic fields; 3-vacuum chamber ∅=18 cm, l=100 cm. 4-grid electrodes; 5-CS; 6-Rogowskii coil. 7-quartz windows; 8-50% mirror; 9-lenses; 10-interference filter; 11-frame-camera; 12-quartz optical fiber; 13-monochromator; 14- multi-channel optical registration system MORS-3; 15-PC

Current sheets in 2D magnetic fields with null-lines

The best-known example of a singular line is the null-line of 2D magnetic field. Plasma dynamics in magnetic fields with null-lines has been actively investigated for many years, both theoretically and experimentally [1,2]. It has been established that a planar CS, which accumulates an excess magnetic energy, can be formed in a vicinity of the null-line. The tangential magnetic field component increased in ≅10

Problems of Atomic Science and Technology. 2000. № 6. Series: Plasma Physics (6). p. 94-96

times near the sheet surface, the electric current density ≅10 kA/cm^2 peaked at the CS middle plane, the CS thickness ≅ 0.8 cm was about 10 times smaller than its width [4]. Plasma was rapidly compressed into the planar sheet: the electron density $N_e^{sh} = (1\div2)\cdot10^{16}$ cm^{-3} exceeded both the initial and surrounding plasma densities in 10-15 times [5]. It was revealed [4-5] that CS was rather stable relatively the tearing-mode instability [6]. Internal magnetic structure of CS was dictated by initial conditions of its formation allowing produce CS either as an open magnetic configuration with the X-type null-line, or as a closed configuration containing null-lines of both O- and X-types, or as a neutral CS [7]. Plasma was accelerated in open configurations along CS surface, from the middle to the edges, so that super-thermal plasma flows appeared near CS edges. An increase in thermal plasma energy dominated in CS with closed magnetic field lines [8]. Comparing with solar flares, one should treat the metastable CS as pre-flare situation [1].

The flare itself appeared as fast impulsive phase of magnetic reconnection terminating long-lived metastable stage and resulting in CS disruption [2,4,7]. We observed the change in the magnetic field topology, electric current density redistribution, excitation of a nonlinear wave, propagating along the CS surface with a super-Alfvenian velocity $v_x≅10^7$cm/s, while $v_a≅1.5\cdot10^6$ cm/s. The planar plasma sheet was also destroyed rapidly [5]. Generation inductive electric fields resulted in bursts of accelerated electrons ($E_e \geq 10$ keV) [9]. Thus, impulsive phase of magnetic reconnection displayed obviously the qualitative agreement with principal features of solar flares [1,2].

An analysis of experimental data made us conclude that an interruption the metastable stage and the start of flare-type events were triggered by magnetic island formation inside CS followed by super-fast increase in the thermal plasma energy. As a result the balance of CS transverse equilibrium was disturbed [7,8]. Plasma turbulence registered by spectroscopic methods was seemingly of a secondary nature [8,10].

Current sheet formation in 3D magnetic configurations

Considerable recent attention has been focussed on 3D magnetic configurations, which are more general and much more typical for both astrophysical objects and laboratory plasma confinement devices. Theoretically CS formation has been predominantly associated with the presence of isolated magnetic null-points, and these configurations have been examined analytically and by computer simulation [11-13]. Experimentally 3D configurations containing null points were produced by a combination of 2D-field (1) and a cusp field, so that a new configuration was built up [14]:

$$\mathbf{B}_\Sigma = h\ \{(1+\gamma)\cdot x;\ -(1-\gamma)\cdot y;\ -2\gamma\cdot z\} \qquad (3')$$

Characteristics of the configurations (3′), namely magnetic field derivatives in different directions, separatrix plane position depend essentially on γ parameter [3, 15].

Magnetic measurements [16], and registration of plasma images in HeII spectral line [17] were employed as well as spectroscopic techniques [18], Fig.1.

It has been established experimentally for the first time [15] that generation plasma electric current resulted in CS formation near the null-point, with plasma compressed into the sheet. CS assumed an intermediate angular position in a cross-section perpendicular to plasma electric current, between 2D case (α=0) and a separatrix plane of initial 3D magnetic configuration with the null-point (α=45°). CS formation was revealed over wide range of configurations with null-points, while CS angular orientation was determined by the parameter γ, Fig.2 (points 1,2) [3,15].

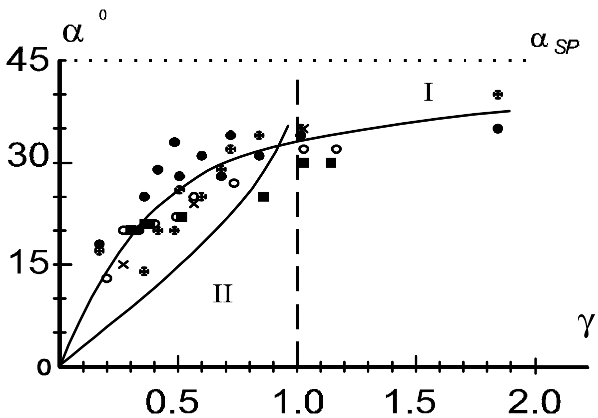

Fig.2. CS angular positions in 3D magnetic configurations vs local |γ|-value, curve I: points 1,2,3–configurations with null-points; points 4,5 configurations without null-points. Data obtained from plasma images (1,5) and from magnetic measurements (2,3,4): (2) - section z_1=0 (Fig.13); (3; 4) - section (z_1 = – 1). Curve II – angular position of the normal to the field lines of the vacuum magnetic field with a null-point at the section z_1=0

A vicinity of an isolated null-point forms only a small part of 3D magnetic configuration, so there was a question how far from a null-point CS formation could take place? It was shown on the base of magnetic measurements that electric current acquired a sheet shape in every cross-section, while CS angular orientations differed from one cross-section to another both in direction and in magnitude following the local value of the parameter γ(Z), Fig.2 (points 3) [19]. So CS formation occurred also far away from a null-point, and constituted a twisted surface throughout the whole 3D configuration. Moreover, we registered CS in non-uniform magnetic fields containing no null-points, Fig.2 (points 4,5) [19]. Thus CS formation was observed in a presence of relatively strong longitudinal magnetic field component B_z.

The effect of B_z-field was studied in 3D configurations containing singular X-lines with a uniform longitudinal B_z-component [20]. 2D images, Fig.3, demonstrated peculiarities of plasma structures arising after plasma electric current generation along the X-line. Various combinations of transverse gradient h and B_z-component were used. Images 1,2 correspond to formation planar CS, which were practically similar to

2D case (1), though B_z exceeded the transverse field $|\boldsymbol{B}_{\perp}|$ = h×|**r**| in the most part of plasma volume. Plasma density inside CS decreased with enhancement of B_z, displaying a transition to a behavior of uncompressible plasma. Images 3,4 correspond to sheet-like double-piece structures separated by a slopping split. These structures appeared under condition B_z /h>15 cm that was presumably related to geometrical factors. It is apparent now that CS formation, magnetic reconnection and related processes can take place within rather wide but limited range of initial conditions, while the gradient of transverse magnetic field is the most important among other parameters.

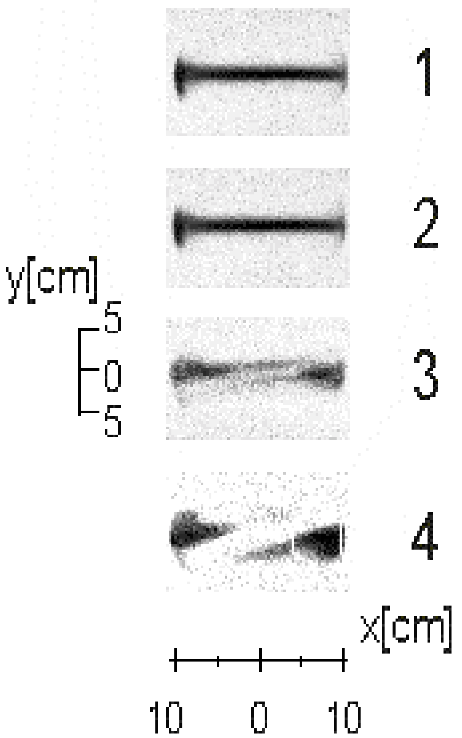

Fig.3. Plasma images in HeII 468.6 nm spectral line under different gradients h of 2D field (1): h = (1) 570, (2) 420, (3) 280 and (4) 200 G/cm. B_z = 4.3 kG, $I_z^{max} \cong 100$ kA, t ≅ 2.5 μs

Acknowledgements

Supported by the Russian Foundation for Basic Research, project 99-02-18351.

References

1. S.I. Syrovatskii. Pinch sheets and reconnection in astrophysics // *Annu. Rev. Astron. Astrophys*. 1981, **19,** P.163-229.
2. A.G. Frank Formation, evolution, and explosive disruption of current sheets in plasma // in: *Plasma Physics and Plasma Electronics.* Nova Science Publishers, Commack N.-Y.1989, P.131-169.
3. A.G. Frank. Magnetic reconnection and current sheet formation in 3D magnetic configurations. // *Plasma Physics & Control. Fusion* 1999, **41**, Suppl. 3A, P. A687-A697.
4. N.P. Kirii, V.S Markov, A.G. Frank, A.Z. Khodzhaev. Rapid change in the structure of the magnetic field of a current sheet // *Sov. J. Plasma Phys.* 1977, **3** (3), P. 303-306.
5. S.Yu. Bogdanov, G.V. Dreiden, A.G. Frank et al. Plasma dynamics inside the current sheet // *Physica Scripta* 1984, **30**, 282-283.
6. H.P. Furth, M. Killen, M.N. Rosenbluth. Finite-resistivity instabilities of a sheet pinch // *Phys. Fluids* 1963, **6**, 459-484.
7. S.Yu. Bogdanov, G.V. Dreiden, N.P. Kirii et al. Plasma dynamics in current sheets: linear and non-linear regimes // *Sov. J. Plasma Phys*. 1992, **18**(10), 654-668.
8. N.P. Kirii, V.S. Markov, A.G. Frank. Flash of emission from multiply charged ions in a current sheet // *Sov. JETP Letts.* 1988, **48**(8), P. 459-463. Local pulsed plasma heating and destruction of a current sheet. *JETP Letts.* 1992, **56**(2), P. 82-87.
9. S.Yu. Bogdanov, V.S. Markov, A.G. Frank. Observation of accelerated-particle fluxes emerging from a current sheet across a strong magnetic field // *JETP Letts*. 1990, **51**(11), P. 638-641.
10. A.G. Frank A.G., V.P. Gavrilenko, Ya.O. Ispolatov et al. Anomalous electric fields inside a dense plasma of a current sheet // *Contrib. Plasma Phys*. 1996, **36**(6), P. 667-678.
11. P. Rosenau. Three-dimensional flow with neutral-points // *Phys. Fluids* 1979 **22**(5)**,** P. 849-858.
12. S.V. Bulanov, M.A. Ol'shanetskii. On the magnetic collapse near the zero points of the magnetic field // *Physics Letters* 1984, **100A,** P. 35-38.
13. J.M. Green. Reconnection of vorticity lines and magnetic lines // *Phys. Fluids* B, 1993, **5**(7)**,** P. 2355-62.
14. S.V. Bulanov, A.G. Frank. About one approach to the experimental study of magnetic reconnection in three-dimensional magnetic configurations // *Russ. J. Plasma Phys.* 1992, **18**(12)**,** P. 795-799.
15. S.Yu. Bogdanov, V.B. Burilina, V.S. Markov, A.G. Frank. Formation of current sheets in 3D magnetic fields with a null point. // *JETP Lett.* 1994, **59**(8), P. 537-541.
16. V.B. Burilina, V.S. Markov, A.G. Frank. Determination of current-layer parameters in three-dimensional magnetic-field configurations based on magnetic measurements // *Plasma Phys. Reports*. 1995, **21**(1), P. 33-37.
17. S.Yu. Bogdanov, Yu.F. Bondar, V.B. Burilina et al. Spatiotemporal evolution of emission in different spectral lines from a current-sheet plasma. // *Tech. Phys.* 1994, **39**(9), P. 877-881.
18. St. Buesher., N.P. Kyrie, H.-J, Kunze, A.G. Frank. Spectroscopic measurements of the electron density in a current sheet produced under high-pressure helium filling // *Plasma Phys. Reports.* 1999, **25**(2), P. 164-169.
19. A.G. Frank A.G., S.Yu. Bogdanov, V.B. Burilina. Quasi-one-dimensional current sheets in three-dimensional magnetic configurations // *Bull. Russ. Acad. of Sciences (Physics).* 1995, **59**(8), P. 1331-1341.
20. S.Yu. Bogdanov, N.P. Kyrie, V.S. Markov, A.G. Frank. Current sheets in magnetic configurations with singular X-lines. // *JETP Lett.* 2000, **71**(2), P. 53-58.