Formation of current sheets in 3D magnetic fields with a null point

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It has been established experimentally, for the first time, that current sheets can form in 3D magnetic configurations containing a null point. A smooth change in the angular orientation of the current sheet has been observed in the transition from a 2D configuration with a null line to various 3D magnetic configurations. It is shown that current sheets can form under conditions such that the electric current is flowing perpendicular to the separatrix plane.

1. Of fundamental importance to research on the problem of magnetic reconnection is the possible formation of current sheets, which are quasi-1D magnetic-field–plasma configurations with a high electric current density. These sheets separate regions in which the magnetic fields are in opposite directions, and they collect excess magnetic energy. The relationship between the localization of current sheets and structural features of the original current-free magnetic configurations is important. In the case of 2D fields, there is both theoretical and experimental proof that current sheets form near null lines of a magnetic field.[1,2] In the case of 3D configurations, the problem has so far been taken up only theoretically. It has been shown, through self-similar solutions of the MHD equations and through numerical simulation, that current sheets can form near null points and separatrix surfaces of 3D magnetic fields.[3–5]

In this letter we are reporting the first experimental study of the spatial distributions of the current and the plasma in 3D magnetic fields which contain a null point. We have observed the formation of current sheets in a wide variety of magnetic configurations with a null point. We have determined the changes in the characteristics of the sheet in the transition from a 2D configuration with a null line to various 3D configurations.

2. The 3D configurations were set up experimentally through the superposition of magnetic fields of two types, as proposed in Ref. 6. The first type of field is a 2D planar field with a null line which coincides with the z axis:

$$B_q=\{B_x;\ B_y;\ B_z\}=\{hx;-hy;\ 0\}, \tag{1}$$

where h is the field gradient, and the null line is the intersection of two separatrix planes (SP): $x=0$ and $y=0$. The second field is an axisymmetric cusp field with the z axis as symmetry axis and with a null point which lies in the $z=0$ SP. This point is at the origin of coordinates, O:

$$B_c=\{h_r x;\ h_r y;\ 2h_r z\}, \tag{2}$$

TABLE I. Magnetic configurations created through the superposition of magnetic fields (1) and (2): $B_{\text{tot}}=B_q+B_c$, $h>0$, $h_r>0$.

$\gamma=\frac{h_r}{h}$	$h_x=\frac{B_x}{x}$	$h_y=\frac{B_y}{y}$	$h_z=\frac{B_z}{z}$	SP	Configuration
0	$1.0h$	$-1.0h$	0	$x=0$ $y=0$	2D magnetic field with a null line (z): $B_z=0$; $h_x=-h_y$
0.1	$1.1h$	$-0.9h$	$-0.2h$	$x=0$	Onset of a B_z component of the magnetic field, destruction of the SP ($y=0$), $\|h_y\|>\|h_z\|$
0.33	$1.33h$	$-0.67h$	$-0.67h$	$x=0$	Cusp system with x axis, $h_z=2\|h_y\|=2\|h_z\|$
0.67	$1.67h$	$-0.33h$	$-1.34h$	$x=0$	$\|h_y\|<\|h_z\|$
0.9	$1.9h$	$-0.1h$	$-1.8h$	$x=0$	$\|h_y\|\ll\|h_z\|$
1.0	$2.0h$	0	$-2.0h$	$x=0$ $z=0$	2D magnetic field with a null line (y): $B_y=0$; $h_x=-h_z$
1.1	$2.1h$	$0.1h$	$-2.2h$	$z=0$	Change in the sign of the B_y component of the magnetic field and in the orientation of the SP; $h_x\gg h_y$
∞ ($h=0$)	$1.0h_r$	$1.0h_r$	$-2.0h_r$	$z=0$	Cusp system with z axis, $\|h_z\|=2h_x=2h_y$

where h_r is the radial field gradient. The superposition of (1) and (2) is

$$B_{\text{tot}}=B_q+B_c=\{(h+h_r)x;\ -(h-h_r)y;\ -2h_rz\}, \tag{3}$$

a 3D configuration with a null point. The particular type of configuration depends on the ratio of h and h_r (Table I). Changing the sign of one of the pair h, h_r changes the orientation of the SP. In other words, over the interval $0<\gamma<1$, the $x=0$ SP is replaced by the $y=0$ SP.

3. The TS-3D experimental apparatus is described in Ref. 6. The axis of the cylindrical quartz vacuum chamber, 18 cm in diameter, coincides with the null line of 2D field (1). A cusp field (2) with a null point is produced at one end of the device. The magnetic fields are in a quasisteady state with respect to the processes which unfold in the plasma. The chamber is filled with helium to a pressure of 300 mtorr. The initial plasma is produced by preionization. When a voltage pulse is applied across two electrodes inserted 60 cm into the chamber from its ends, an electric current I_z is excited in the plasma. The maximum value of this current is 40–50 kA; its half-period is $T/2=5$ μs.

4. Two diagnostic methods were used: magnetic measurements and recording of images of the plasma in the light of the He II 4686-Å emission line. The component

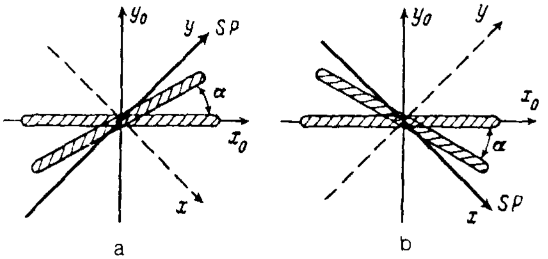

FIG. 1. Images of the plasma in the (x,y) plane (integrated along the z direction) obtained with an image-converter camera during excitation of an electric current I_z in 3D fields with null points, produced through a superposition of a 2D field with $h=200$ G/cm and the field of a cusp system. a—$h_r=130$ G/cm, $\gamma>0$, $x=0$ SP, $\alpha=30°$ (>0); b—$h_r=-130$ G/cm, $\gamma<0$, $y=0$ SP, $\alpha=-30°$ (<0).

B_φ of the magnetic field generated by the plasma current was measured by magnetic probes outside the vacuum chamber in the $z=0$ plane. These probes were at four azimuthal positions within one quadrant ($\varphi=0$, 25°, 65°, 90°). The probes were at a distance $R=9.3$ cm from the axis.[7] The experimental $B_\varphi(\varphi)$ curves were approximated by theoretical curves derived with the help of *a priori* assumptions regarding the symmetry of the current region and the distribution of the current. In most cases, the best fit was achieved under the assumption that the current was distributed in a sheet. On this basis we determined the width of the sheet, $2b$, and its angular orientation in the $z=0$ plane.

The intensity distribution of the plasma emission in the x, y plane, integrated along the z direction, was detected by an image-converter camera with an exposure time of 80 ns. The light was first passed through a narrow-band interference filter corresponding to the spectral line He II 4686 Å (Ref. 8). Images of the plasma were formed from light coming from three regions: from the region of the 3D magnetic field with a null point ($-10\leqslant z\leqslant 10$ cm), from the region with an essentially 2D field with a null line (the z axis) ($-45\leqslant z\leqslant -25$ cm), and from an intermediate region. The results found by this method clearly show that the emitting plasma in the 3D magnetic fields also assumes the shape of a sheet.

5. The excitation of a current along the null line of 2D magnetic field (1) leads to the formation of a plane current sheet.[1,2] Let us assume that the sheet lies in the $y=0$ plane. The emitting plasma is then also concentrated in a planar sheet, and its 2D image is a thin stripe along the x_0 axis.[8] The image changes in a 3D magnetic field: The horizontal stripe is joined by an additional thin stripe, which intersects the x_0 axis at an angle α (Fig. 1). This result is evidence that the plasma also acquires the shape of a thin sheet near the null point. The angular orientation of the projection of the sheet onto the x, y plane is different from that in the 2D case. A change in the sign of h_r causes a change in the direction in which the sheet rotates away from its position in the 2D case. In other words, it causes a change in the sign of the angle α. The plane of the sheet rotates toward the SP and assumes an intermediate angular position between that in the 2D case ($\alpha=0$) and the orientation of the SP ($\alpha=45°$) (Fig. 1). Analysis

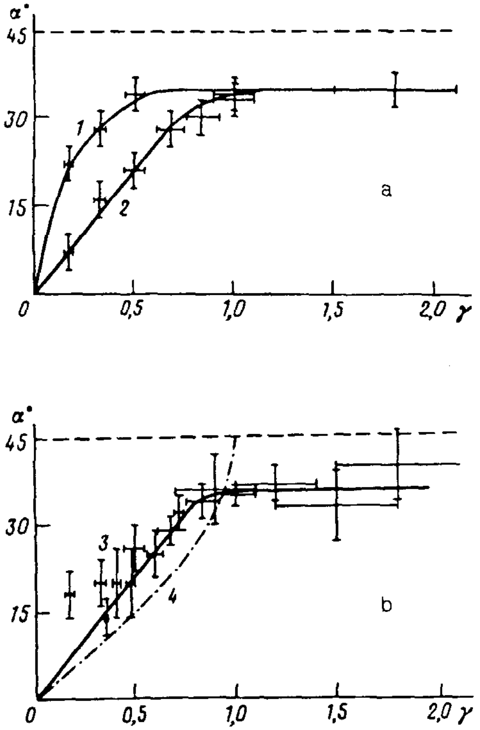

FIG. 2. Angle through which the sheet rotates, α, near the null point of the magnetic field versus the quantity $\gamma = h_r/h$, where h_r is the radial gradient of the cusp field, and h is the gradient of the 2D field. 1, 2—Curves constructed from the magnetic measurements [1) $t = 1.3\ \mu s$; 2) $t = 2.5\ \mu s$]; 3—curves constructed from measurements of the plasma emission, $t < 1.6\ \mu s$; 4—change in the angular position of the normal drawn to the field lines of the vacuum magnetic field from the origin of coordinates in comparison with the 2D case, with $\alpha_n = \delta - \delta_0$.

of the results of the magnetic measurements leads to similar conclusions.

It has thus been established experimentally, for the first time, that a current sheet can form in a 3D magnetic field with a null point. In this case, in contrast with the 2D case, the sheet is not planar. It is a more complex, twisted surface, which changes in angular orientation with distance along the z axis. Near the null point the rotation of the plane of the sheet is toward the SP of the vacuum magnetic field.

6. Analysis of distributions of the current and of the emitting plasma in various gradients h and h_r revealed that a sheet is formed over a wide range of configurations with a null point and that the angular position of the sheet in the $z=0$ plane is determined by the parameter

$$\gamma = h_r/h. \tag{4}$$

The curves of $\alpha(\gamma)$ found from the magnetic measurements and from the plasma emission (Fig. 2) reveal the same tendency: an essentially linear increase in the sheet rotation angle from 0 to $\simeq (35 \pm 5)^\circ$ over the interval $0 < \gamma < 0.8$, followed by a region $(0.8 < \gamma < 2)$ in which the orientation of the sheet remians constant (within the experimental errors), at $\alpha = (37 \pm 6)^\circ$.

The results differ from the results of self-similar solutions,[3-5] in which the plane of the current sheet near the null point coincides with the SP. Experimentally, there is a smooth change in the angular orientation of the sheet as the magnetic configuration changes; this smooth change seems more plausible from the physical standpoint. Our reasoning is that the sheet is formed by electrodynamic forces $\mathbf{f}=\frac{1}{c}[\mathbf{j}\times\mathbf{B}]$. Since the current is directed along the z axis, we would expect the angular orientation of the sheet in the $z=0$ plane, where we have $B_z=0$, to be approximately normal to the magnetic field lines. At $\gamma<1$, the normal drawn to the field lines of the vacuum field, (3), from the origin of coordinates makes an angle δ with the x axis, where

$$\tan\delta=\sqrt{\frac{(1+\gamma)}{(1-\gamma)}}. \tag{5}$$

In the 2D case ($\gamma=0$) this angle is $\delta=\delta_0=45°$. The overall nature of the changes in the difference $\alpha=\delta-\delta_0$ as a function of γ in the interval $0<\gamma<0.8$ agrees qualitatively with the experimental curves (Fig. 2).

7. A completely unexpected result emerged in the interval $1\leqslant\gamma\leqslant 2$: Under these conditions the current sheet forms fairly rapidly, over a time $t<1.6\ \mu$s, and the angular orientation of the sheet is essentially independent of γ (Fig. 2). At $\gamma>1$, SP is the plane ($z=0$) perpendicular to the plasma current I_z, as can be seen from Table I. Under these conditions, the self-similar solutions predict that either a current sheet will not form[3,4] or it will form only over an extremely long time.[5] The experimental results, in contrast, imply that a sheet does indeed form and that the time required for it to form is not significantly longer than in cases with $\gamma<1$. We cannot rule out the possibility that regions comparatively far off along the z axis, in which the relation $|h_r|<h$ holds, have some effect on the processes occurring near the null point.

8. In summary, it has been established experimentally, for the first time, that current sheets can form in a plasma in a wide range of 3D magnetic configurations with null points. This result implies that the process is universal. We have observed the evolution of the properties of the current sheet in the transition from a 2D magnetic field with a null line to 3D magnetic fields with a null point.

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