# Coalescence of magnetic islands in a current sheet

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A parameter which controls the change in the magnetic structure of a current sheet has been found experimentally. When the value of this parameter is below a threshold, the magnetic islands that arise during the onset of the tearing-mode instability move away from each other. In the opposite case, the islands coalesce, with the result that an extended current sheet is converted into a current filament.

A current sheet separating plasma regions with antiparallel magnetic fields is a "reservoir" of free energy of the magnetic field. An effective mechanism for the release of this energy, through a global change in the magnetic field structure, is the coalescence of the magnetic islands that form as a result of the tearing-mode instability in the sheet. That this mechanism can operate in a real current sheet is indicated by the results of Ref. 1, where the coalescence of magnetic islands was observed. In other experiments, however, the magnetic islands were instead observed to move apart and escape from the sheet.[2] In the experiments which we are reporting here, we studied the conditions under which magnetic islands coalesce in a current sheet.

The experiments were carried out at the UN Phoenix device, which is a $\theta$-pinch device. The initial plasma (hydrogen, $n_0 = 7\times10^{11}$–$2.5\times10^{12}$ cm$^{-3}$, $T_{e0} \simeq T_{i0} = 1$–$5$ eV) is produced in a quasisteady magnetic field $B_0 = 310$–$440$ G, directed along the axis of the working volume of the device. The plasma is compressed by a cylindrical magnetic piston produced by a shock turn 18 cm in diameter with a width $L = 30$ cm. The field of this shock turn varies sinusoidally over time with a peak value $B^{\sim} = 1300$ G and a half-period of 1.3 $\mu$s. This field is directed antiparallel to the initial field $B_0$. A cylindrical current sheet forms at the boundary of the plasma column and converges on the axis of the device. The measurements show that the electron temperature in the sheet rises to 500–800 eV in a time interval $\lesssim 80$ ns after the sheet begins to form, as a result of the dissipation of the current in the anomalous resistance.[3]

The magnetic structure of the sheet is studied with a movable system of six magnetic probes separated along the radius. These probes measure the field component $B_z$, parallel to the axis of the device. The spatial resolution along the $z$ axis is determined by the spacing of the probes and is $\simeq 1$ cm; the radial resolution is $\sim 0.5$ cm. These measurements show that the magnetic field is axisymmetric within $\sim 5\%$. In this case the contour curves of the magnetic flux, $\Phi(r,z) = \int_0^r B_z(\rho,z)\rho d\rho$, constructed from the probe signals coincide within the same error with the magnetic lines of force. The value of the field at each point is averaged over three "shots." The time resolution of the procedure ($\sim 10$ ns) is determined by the accuracy at which the time scales of the probe signals are matched.

The evolution of the current sheet can be followed on patterns of the magnetic lines of force constructed in the volume below the shock turn at various times. After

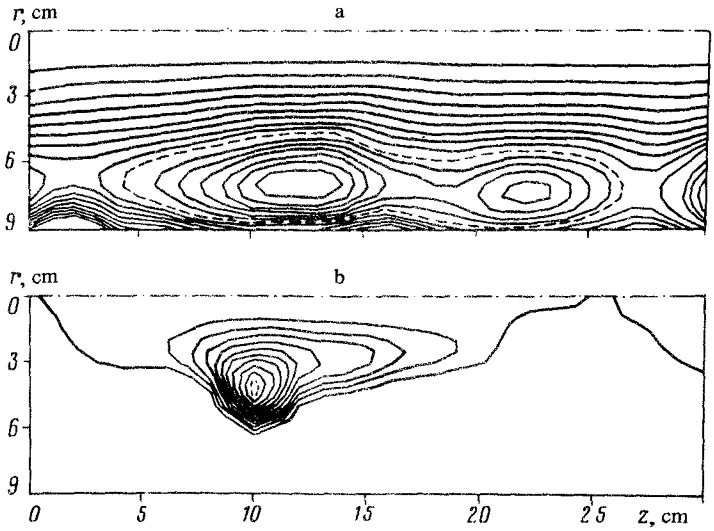

FIG. 1. a—Contour map of the magnetic flux at the time 80 ns; b—the same, at 540 ns. The contour lines are drawn at intervals of 500 G · cm$^2$ and are bounded by the separatrix $\Phi = 0$. The dashed line is the contour with $\Phi = 5 \times 10^3$ G · cm$^2$; $z = 0.30$ cm is the boundary of the shock turn. ($B_0 = 440$ G, $n_0 = 2.6 \times 10^{12}$ cm$^{-3}$.)

the appearance at $t = 0$ of a magnetic null line ($B_z = 0$), an extended current sheet of thickness $\Delta \simeq 2$–3 cm and width $L \simeq 30$ cm $> 10\Delta$ forms at the boundary of the plasma column. After $\tau \simeq 100$–150 ns, spontaneous reconnection leads to the formation in the layer of a regular structure of closed magnetic configurations: islands differing in spatial dimensions and in the level of the magnetic flux closed in them (Fig. 1a). The scale time $\tau$ and the scale length $\lambda$ ($\lambda$ is the distance between adjacent $X$-type singularities of the magnetic field) for the development of the islands can be explained in terms of the excitation of a collisionless tearing-mode instability with a growth rate $\gamma$ ($\tau \gtrsim 5\gamma^{-1}, \gamma^{-1} \simeq 20$ ns for the typical parameters of the plasma in the sheet) and with a wave number $k = 2\pi/\lambda$ satisfying the condition[4] $k\Delta/2 > 1$.

At $T > 150$ ns, when the transverse component of the magnetic field $B$ reaches $(0.3$–$0.6)B_b$ ($B_b$ is the magnetic field at the boundary of the current sheet), the increase in the magnetic flux in the islands comes to a halt (Fig. 2). For each pair the evolution of the islands that have formed is determined by the value of the parameter $A(t) = \Delta\Phi_1(t)\Delta\Phi_2(t)/\lambda_{12}$, where $\lambda_{12}$ is the distance between corresponding $O$ points, and $\Delta\Phi_{1,2}$ are the magnetic fluxes closed in the islands, given by $\Delta\Phi_{1,2} = \Phi^0_{1,2} - \Phi^x$, where $\Phi^0_{1,2}$ are the fluxes at the $O$ points, and $\Phi^x$ is the flux at an $X$ point outside the pair of islands under consideration. If $A$ is lower than the threshold value $A_0 \simeq 5 \times 10^5$ erg (Fig. 3), the islands move away from each other, while in the case $A > A_0$ we observe their interaction. Adjacent islands move closer together; then the flux closed in the island with the smaller value of $\Delta\Phi$ rapidly disappears, while the flux in the larger island remains essentially unchanged (curves 2 and 3 in Fig. 2). Two islands thus coalesce into a single island; at the time of the coalescence, we observe a sharp

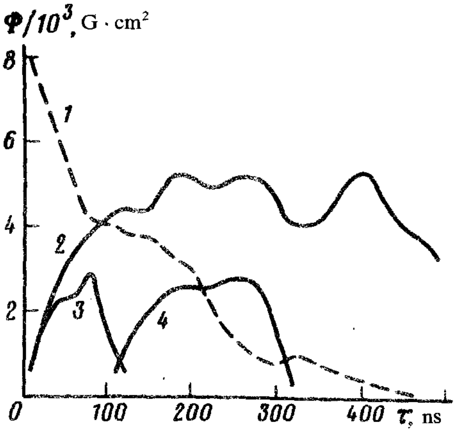

FIG. 2. 1—Unreconnected part of the magnetic flux, $\Phi^x(t)$; 2–4—the part of the flux trapped in the islands, $\Delta\Phi$.

spike in the electric field at the $X$ point between the coalescing islands. The sign of this spike is opposite that of the field which arises here as a result of reconnection.

As a result of the coalescence of the islands, the magnetic structure of the sheet simplifies, but the reconnection process that continues in the presence of unreconnected flux gives rise to a new magnetic island, and the coalescence process repeats itself (curve 4 in Fig. 2). The entire magnetic flux is ultimately closed in a single island, where it slowly dissipates (Fig. 1b).

The following scenario for the evolution of an extended current sheet can be suggested on the basis of these experimental results. The spontaneous reconnection that results from the onset of the tearing-mode instability gives rise to magnetic islands in the originally uniform sheet and to an increase in the magnetic fluxes closed in these islands. As long as the level of these fluxes remains below the values that determine the threshold value $A_0$, the islands are moved away from each other by the magnetic pressure $B_b^2/8\pi$. The scale time for this process is $\sim L/v_a$. If, however, the magnetic flux trapped in the islands increases rapidly enough that the condition $\tau \ll L/v_a$ holds, the attraction of neighboring islands to each other becomes dominant, and these islands coalesce. We wish to emphasize that the disappearance of the flux of the smaller island here, measured from the $X$ point *external* with respect to the interacting islands, means that the coalescence process is accompanied by a rapid *dissipation*. The joint effects of the tearing-mode instability and the coalescence of the islands result in a complete reconnection of the lines of force, accompanied by the formation of one

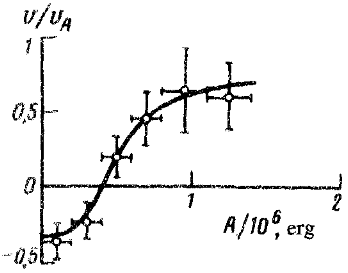

FIG. 3. Velocity at which the islands move closer together ($v>0$) and further apart ($v<0$) versus the parameter $A$ ($v_a = B_0/(4\pi n_0 m_i)^{1/2}$.

island. This process corresponds to a conversion of an extended current sheet into a current filament (in the cylindrical geometry of these particular experiments, it is a conversion into a "compact-torus" plasma configuration). When this change in the sheet structure occurs, the magnetic field energy decreases substantially. A similar mechanism, operating in the current sheet in the active region of the sun, may lead to the flare-associated release of energy over a time on the order of $L/v_a$.

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[2] N. Ohyabu and N. Kawashima, J. Phys. Soc. Jpn. **33**, 496 (1972).

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Translated by Dave Parsons