SIMULATION EXPERIMENT ON MAGNETIC FIELD RECONNECTION PROCESSES IN TOKAMAK

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Abstract

Two experimental studies on magnetic field line reconnection processes relevant to tokamak physics are goi..g on in Japan. In Yokohama National Univeristy, reconnect:on of poloidal magnetic field lines is studied by the author when reversing the toroidal current of a small toroidal plasma in a short period (typically less than 4 μsec). Interaction of two current carrying plasma (linear) columns is being studied by Kawashima and his coleagues in Institute of Space and Aeronautical Sciences. Mutual attraction and merging of the plasma columns and resulting plasma heating are reported.

1. Toroidal Current Reversal Experiment

1.1. Introduction

Magnetic field line reconnection is thought to be a fundamental process in the disruptive instability of tokamak plasma. In the internal disruptive instability model, Kadomtsev[1)] invoked the reconnection process in order to drive the redistribution of the poloidal shear magnetic field. In this paper, we report experimental observation of the poloidal magnetic field line reconnections. The observed reconnection process is similar to that of the Kadomtsev model. A difference is in that the experiment was made on the zeroth order poloidal field while the Kadomtsev model is concerned with the higher order shear field which may be difficult to determine experimentally.

1.2. Experimental Method

The experiment is carried out in a small toroidal device. The plasma is produced in a toroidal pyrex tube (major radius 12 cm, minor radius 3.1 cm) closely surrounded by a 1.5 mm thick copper shell. The toroidal magnetic field strength is 3.2 kG on the minor axis. After the stationary poloidal magnetic field distribution is established by ohmic heating current (50 - 100 μsec width, 30 - 100 V one turn loop), the polarity of the toroidal current is reversed in a few μsec. Ignitron switches are used for the primary current wave-form shaping. We use hydrogen, helium and argon as working gas. The chord averaged electron density is typically 2×10^{12} cm^{-3}. The electron temperature determined with the plasma resistivity is about 5 eV (assuming $Z_{eff} = 1$).

Samples of the loop voltage and the plasma current traces are shown in Fig.1. On the application of the reverse electric fiedl pulse (arrows), the time sweep rate on the CRT was changed from 100 μsec/div to 2 μsec/div. In order to make the pulse experiment sufficiently reproducible, we have constructed a comparator-driven trigger circuit so that the reversing electric field pulse is applied at the same level of the toroidal plasma current. Spontaneous poloidal magnetic field fluctuations must be kept at low level also so that the small zeroth order poloidal magentic field structure may not be smeared out. This consideration has lead to the limitation of the toroidal current magnitude to a low value. The low electron temperature, obtained as a result of the low current level, has made it necessary to shorten the transient time of the polarity reversal to a few microsecond which is primary determined by the self-inductance of the plasma ring.

The magnetic field measurement reported here has been made by using a pair of small magnetic probes (1 mm in dia. 20 turns) pointing the major radial direction (R) and the major axial direction (z) and movable in the R-z plane.

1.3. Experimental Results

In Fig.2 are shown the poloidal magnetic field distribution at different times after the initiation of the toroidal current reversal. The arrows stand for the poloidal magnetic field vectors at the measured points (dots). Each vector component of a single arrow is determined by statistically averaging more than 5 shot data. The toroidal current is changed from 830 A to -1260 A in a hydrogen plasma. Although the arrow distributions at t = 1.6 μsec and 1.92 μsec may appear somehwat chaotic microscopically, the general trend of the incoming field reversing zoen can be recognized. At t = 2.24 μsec, the toroidal current is -350 A and the polarity of the field at every point has reversed, though redistribution of the magnetic field is still going on. The toroidal current reaches the negative maximum at t = 3.52 μsec. The arrows at this time are scaled down to halves. Although we have not completed yet the construction of the 2-dimensional magnetic surface mapping, reconnection processes of the poloidal magnetic field lines are evident in Fig.2.

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Because the symmetry of the magnetic field distribution with respect to the z = 0 plane has been well documented, it may be instructive to determine the flux function[2)]

$$\psi(R,\ t) = \int dRRB_z(R,\ z = 0,\ t) \qquad (1)$$

on the euqatorial plane z = 0. As an example we examine the $B_z(r,\ z = 0,\ t)$ distribution after the reversal of the toroidal current in an hydrogen plasma as shown in Fig.3(a). The toroidal current was changed from 1390 A to -1520 A in 3.5 μsec. The experimentally determined flux function at each time is plotted in Fig.3(b). For convenience of display, the flux function $\psi(R = 12\ cm,\ t)$ on the minor axis is taken to be zero. By definition of the flux function, if ideal MHD theory holds, points with the same value of ψ are on the same magnetic surface. In Fig.3(b) it is recognized that the outermost magnetic surface conforms the inner wall surface of the pyrex tube. The most remarkable feature in Fig.3(b) is that there are two points at R < 12 cm which have the same value of ψ as the local maximum of ψ at R > 12 cm. The three points are on the same magnetic surface. This particular magnetic surface forms a separatrix of crescent shape as depicted schematically in Fig.4. The dotted circles indicates the neutral shell where the poloidal magnetic field is zero. The polarity of the poloidal magnetic field changes across the neutral shell. The crosses in each figure indicate the location of the null points where $B_z = 0$ on the equatorial plane.

The inward propagation of the separatrix surface is undoubtedly associated with a magnetic field reconnection process, though the dynamics of the separatrix and the null points are not fully understood in terms of Kadomtsev's reconnection model. Magnetic forces may not play the decisive role in the present experiment. The inward propagation velocities of the outer (R > 12 cm) and inner (R < 12 cm) null points were determined experimentally as shown in Table 1. The propagation velocity ranges from 1×10^6 cm/sec to 3×10^6 cm/sec. A notable point is that the propagation velocity is smaller for larger toroidal current namely for stronger magnetic forces. Dissipative effects may be more decisive in the reconnection process of the present experiment because the larger toroidal current leads to higher electron temperature and higher electrical conductivity and eventually to lower diffusion velocity.

2. Experiment at ISAS on plasma column merging

Mixing or merging of separate tokamak plasma rings are of considerable interest recently in terms of plasma heating[3)] and quasi steady operation of a tokamak.[4)] Interactions between current carrying two plasma columns have been studied by Kawashima and his coleagues in Institute of Space and Aeronautical Sciences.[5)]

2.1. Experimental Method and Results

Two current carrying plasma colums are produced by capacitor discharge (10 μF 20 kV) between mesh electrodes at both ends of a 250 mm copper column whose cross-section is shown in Fig.5. The ionization starts at the inner surface of the column then as the current increases two separate plasma colums form on the axes of the two cylinders. The two columns spontaneously attract each other as shwon in Fig.6. The merging speed increases as the plasma current along each column is increased as shown in Fig.7. The motion of the two colums is well described by considering JxB interaction between two current carrying rods with finite mass. On merging of the columns ions are accelerated in the direction antiparallel to the column current. This fact suggests that a strong electric field is generated in the merging region in the opposite direction to the column current. The motions of the two columns can be controlled as shown in Fig.8 by adjusting the current flowing along the six control rods shown in Fig.5. In Fig.8(A) the left plasma colum was pushed into the right plasma column by energizing the left control rods. Figure 8(B) shows the two plasma columns hept separated by energizing the central control rods.

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REFERENCES

[1] Kadomtsev, B.B, Sov. J. Plasma Phys. 1 (1975) 389.
[2] Bateman, G., MHD Instabilities, MIT Press, Cambridge, Massachusetts and London (1978).
[3] Shafranov, V.D., Nuclear Fusion, 19 (1979) 187.
[4] Ohyabu, N., Hsieh, C.L. and Jensen, T.H., G. A. Report A14283 June (1977).
[5] Recent results are reported in Sakae Besshou "Experiments on Merging of Two Current-Carrying Plasma Columns" Doctoral dissertation submitted to University of Tokyo (1980).

working gas	Toroidal Current (in A)		Velocity of neutral shell (in 10^6 cm/sec)	
	initial	final	inner	outer
Ar	780	-1190	1.8	2.8
	960	-980	—	1.4
	1110	-1190	1.3	2.0
	1520	-1520	1.1	1.5
H_2	720	-910	2.8	2.9
	1220	-1040	2.5	1.1
	1390	-1520	1.4	2.2
	830	-1260	2.1	2.1
H_e	760	-1080	—	1.4

Table 1. Velocity of Neutral Shell

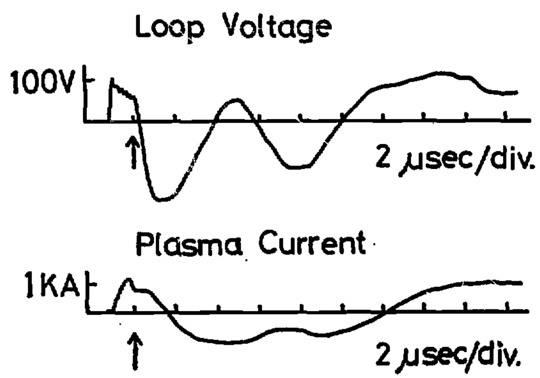


FIG.1. Sample traces of one-turn loop voltage and plasma current.

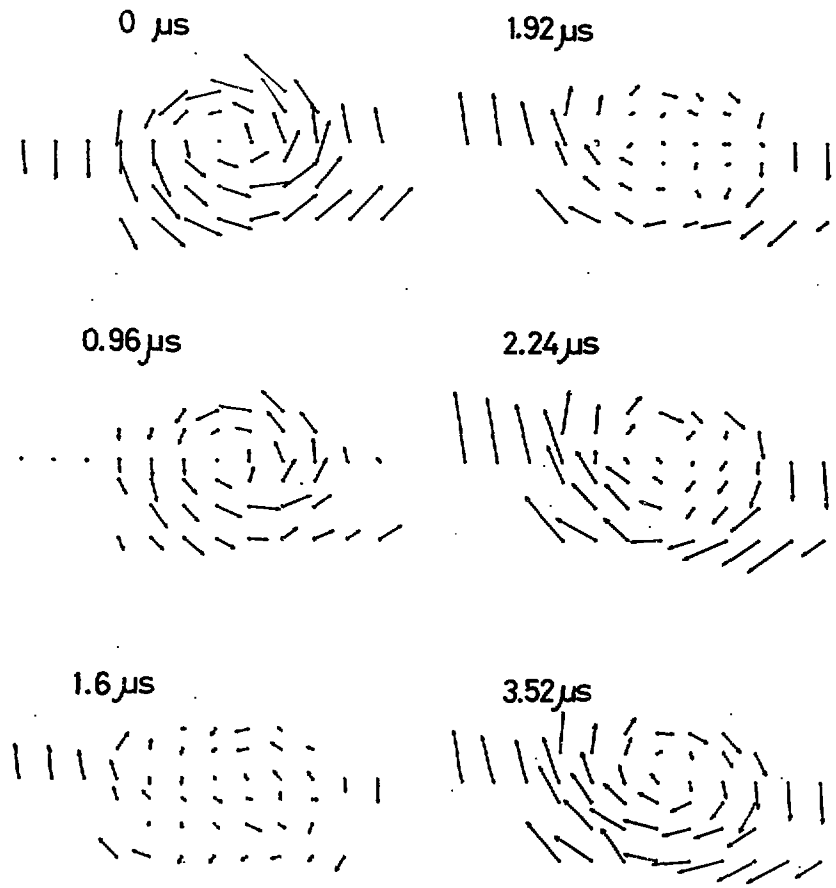


FIG.2. Poloidal magnetic field distribution on (R, z) plane at different times after applying reversing electric field pulse. Hydrogen plasma. Toroidal current changes from 830 A to -1260 A.

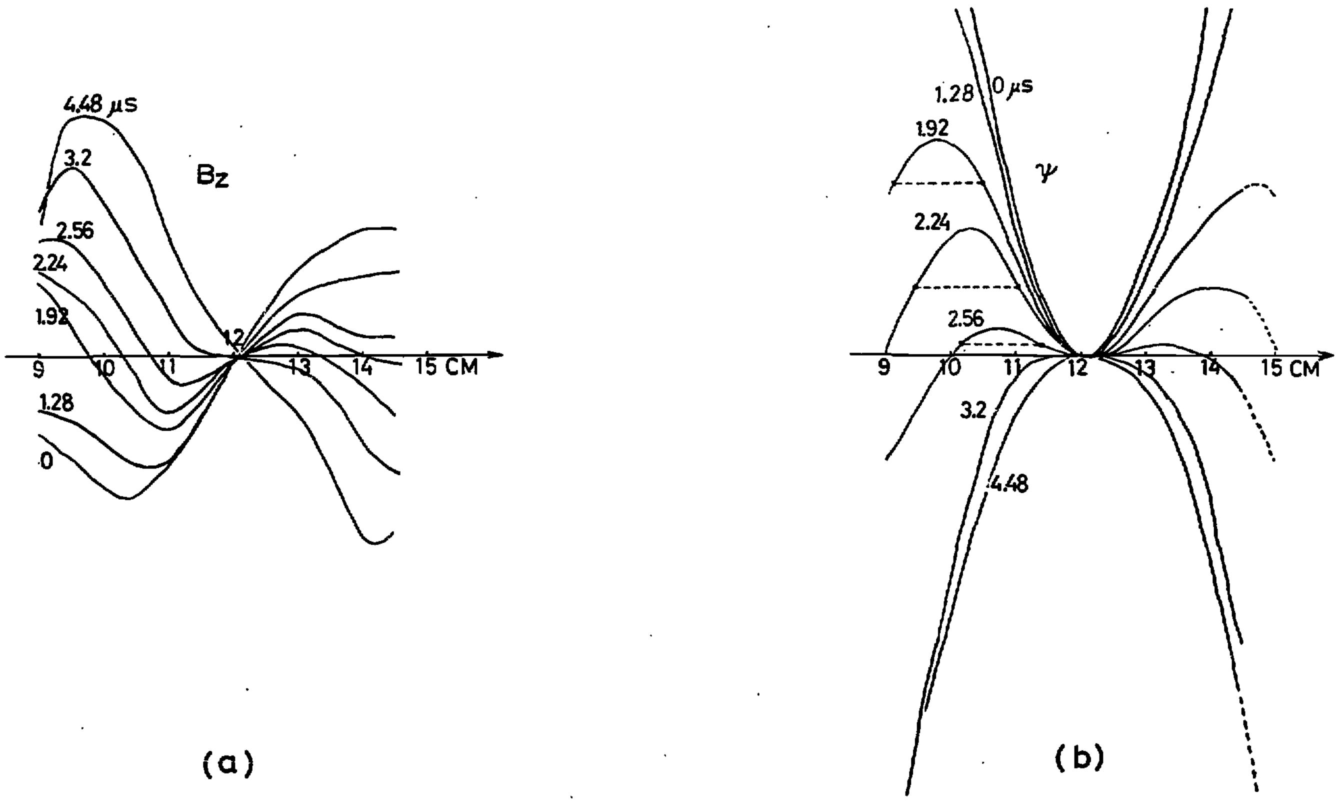


FIG.3.(a) B_z distribution on the equatorial plane (hydrogen plasma).
(b) Flux function determined from B_z.

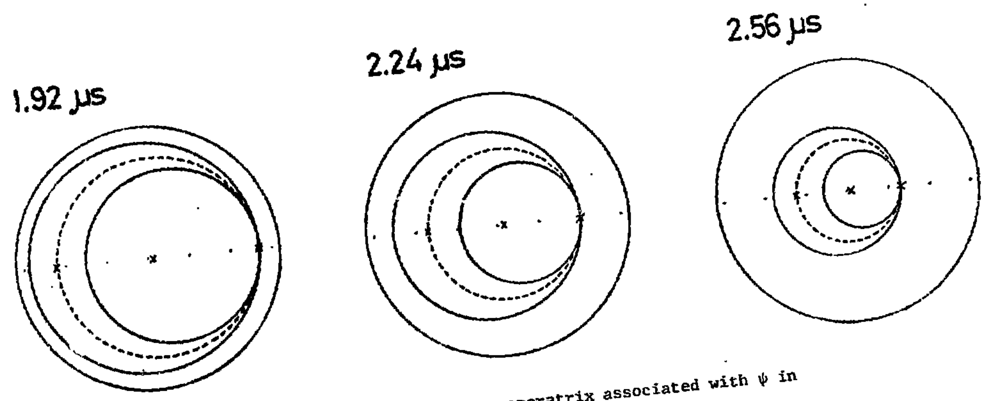


FIG.4. Schematic view of the separatrix associated with ψ in FIG.3(b).

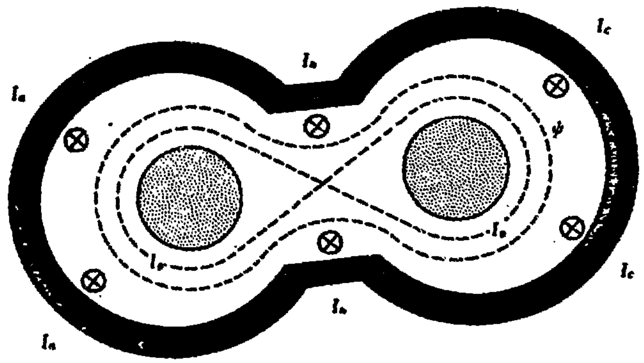
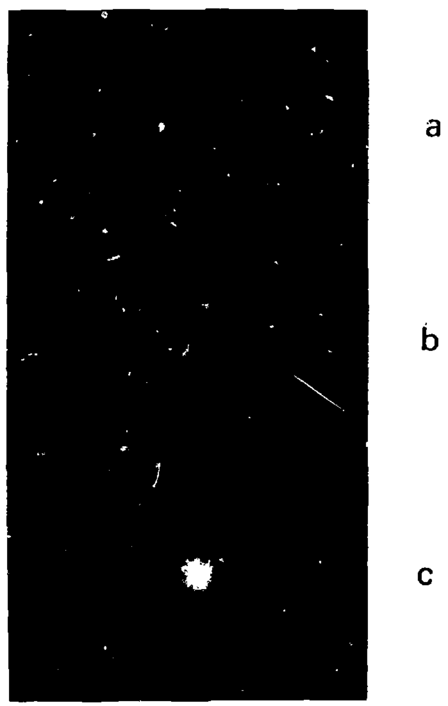
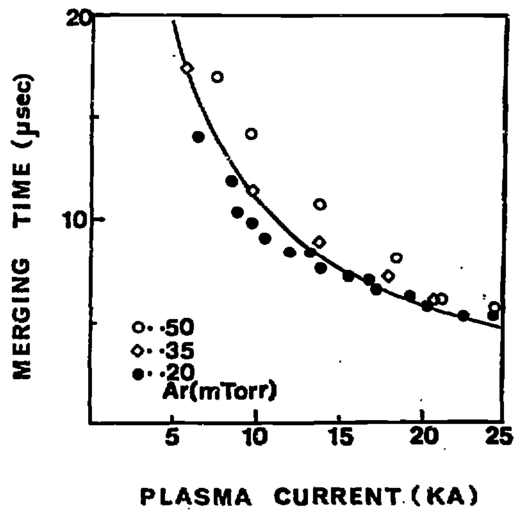


FIG.5. Cross-sectional view of the copper column. Two copper pipes (73 mm in diam., 250 mm long, 3 mm thick) are connected. Six conducting rods are placed inside for positional control of plasma columns.





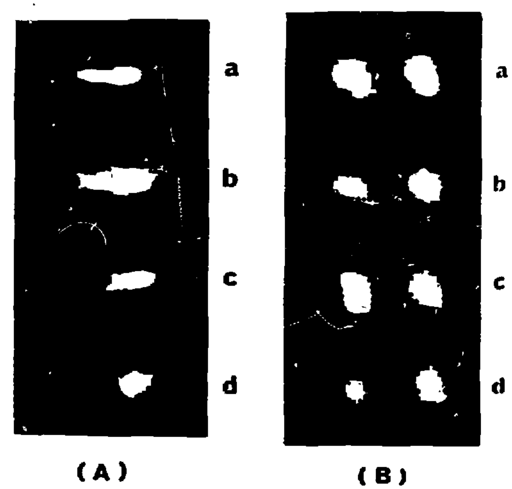


FIG.6.

Time resolved photographs of plasma columns (a) 4 μsec (b) 6 μsec (c) 8 μsec after discharge. I_p = 12 kA in argon plasma with p = 20 m Torr.

FIG.7.

Merging time as a function of plasma current. Solid line shows $\propto I_p^{-1}$ dependence.

FIG.8.

Time resolved photographs of positionally controlled plasma columns. (a) 4 μsec (b) 5 μsec (c) 6 μsec (d) 10 μsec after discharge.

(A) Acceleration of merging. Left plasma column is pushed into a right plasma column. Control current (23 kA/rod) I_a is applied at 5 μsec.

(B) Blockade of merging. Two plasma columns are kept separated by a stationary control current I_b (6 kA/rod).