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REVIEW OF RECENT EXPERIMENTS ON MAGNETIC RECONNECTION IN LABORATORY PLASMAS

BY

M. YAMADA

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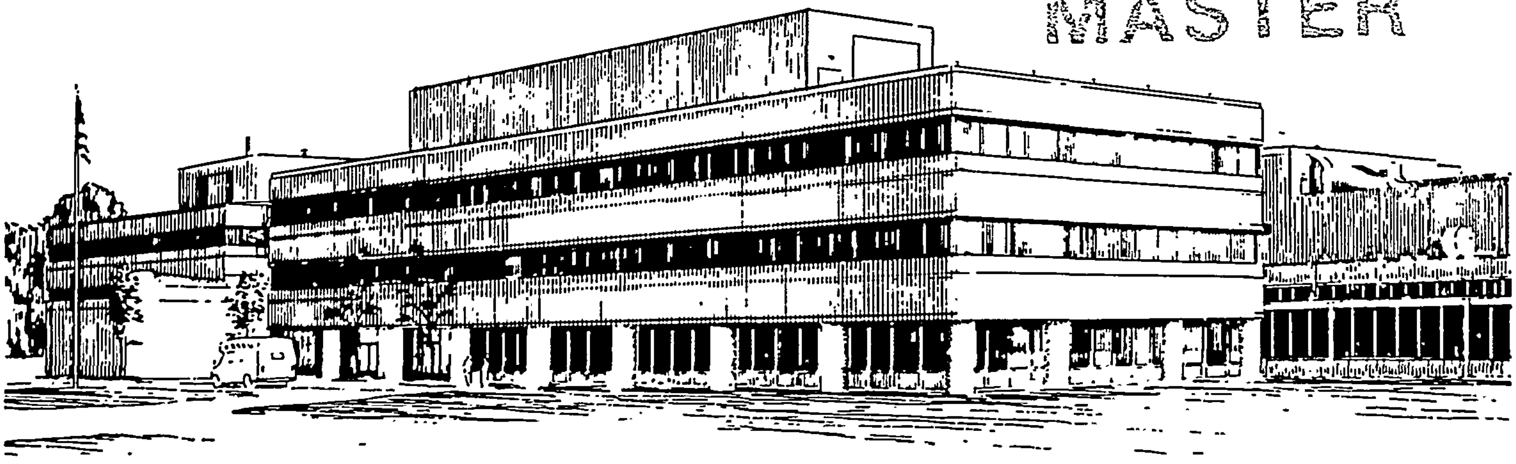

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Review of Recent Experiments on Magnetic Reconnection in Laboratory Plasmas

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Abstract

The present paper reviews recent laboratory experiments on magnetic reconnection. Examples will be drawn from electron current sheet experiments, merging spheromaks, and from high temperature tokamak plasmas with the Lundquist numbers exceeding 10^7. These recent laboratory experiments create an environment which satisfies the criteria for MHD plasma and in which the global boundary conditions can be controlled externally. Experiments with fully three dimensional reconnection are now possible. In the most recent TFTR tokamak discharges, Motional Stark effect (MSE) data have verified the existence of a partial reconnection. In the experiment of spheromak merging, a new plasma acceleration parallel to the neutral line has been indicated. Together with the relationship of these observations to the analysis of magnetic reconnection in space and in solar flares, important physics issues such as global boundary conditions, local plasma parameters, merging angle of the field lines, and the 3-D aspects of the reconnection are discussed.

1. INTRODUCTION

Magnetic reconnection, a topological rearrangement of magnetic field lines, is an important manifestation of interplay between plasma and magnetic field [*Parker,* 1979; *Vasyliunas*, 1975; *Shi et al.*, 1988; *Taylor*, 1986; *Priest*, 1973]. It is considered to be a key process in the evolution of solar flares and in the dynamics of the Earth's magnetosphere. Magnetic reconnection also occurs as one of the relaxation processes in fusion research plasmas; it often plays a dominant role in determining the confinement characteristics of the high temperature plasmas.

The study of the evolution and the interaction of the solar flares has been intensified because of the soft X-ray pictures of the sun recently taken by the Yohkoh satellite [*Tsuneta et al.*, 1991]. Many large solar flares were observed to be interacting actively and changing their topology rapidly, on a short time scale of a few minutes, much faster than the values predicted by classical theory. Magnetic reconnection may be attributed to these observed activities [*Parker*, 1979].

Dayside magnetic reconnection in the terrestrial magnetosphere is often depicted as a series of "flux transfer events". The configuration of the reconnection patch and its turbulence can be directly related to observed magnetospheric phenomena [*Russell and Elphic*, 1988].

In highly-conductive plasmas for fusion research, magnetic reconnection plays an essential role in the dynamic changes of magnetic field configuration. The major and minor disruptions of tokamak plasmas for magnetic fusion research are caused by the reconnection of magnetic field lines, resulting in degradation of confinement properties [*Kadomtsev*, 1975; *Wesson*, 1985]. Magnetic reconnection always occurs during plasma formation and/or configuration change, and is regarded as the most important self-organization phenomenon in plasmas.

The motion of magnetic field lines in a plasma can be described by combining Maxwell equations and Ohm's law;

$$\frac{\partial B}{\partial t} = \nabla \times (V \times B) + \frac{\eta}{\mu_o} \nabla^2 B \ . \qquad (1)$$

The first term of the right hand side represents a motion of plasma moving with field lines with plasma being frozen to them[*Parker*, 1979]. The second term describes a diffusion of magnetic fields with the diffusion coefficient proportional to the plasma resistivity. The representative time scale for the second term, $\tau_D = \mu_o a^2/\eta$, is called a diffusion time, where a is the scale of the plasma, and η and μ_o are the plasma resistivity and the vacuum permeability. If the Lundquist numbe is defined by $S \equiv \tau_D/\tau_A$, where $\tau_A \equiv a/V_A$ (V_A is the Alfvén velocity), it has to be significantly larger than unity in order for plasmas to be treated as MHD fluids. For typical MHD plasmas such as solar flares, $S > 10^{10}$, for tokamaks, $S > 10^7$, and for the MRX/TS-3 experiments [*Yamada et al.*, 1990,1991], $S \sim 10^2$- 10^3.

A few recent laboratory experiments have created an environment in which the global boundary condition can be externally controlled. Three typical examples of such experiment will be mentioned.

Stenzel and Gekelman [*Stenzel* and *Gekelman,* 1981; *Gekelman et al.*, 1982,1988] investigated the magnetic reconnection, using parallel conductor plate currents in a linear plasma. In their elaborate series of experiments, many important local features of magnetic reconnection were investigated.

Sawtooth relaxation of a tokamak plasma provides a good example of magnetic reconnection [*Kadomtsev*, 1975; *Wesson*, 1986]. During the sawtooth relaxation, the average pitch of field lines changes suddenly, as the field lines rearrange themselves by breaking their initial topological linkage and by recombining.

In the most recent series of colliding spheromak experiments, an investigation of three-dimensional MHD effects in magnetic reconnection dynamics has been carried out [*Yamada et al.*, 1990, 1991; *Ono et al.*, 1993]. A careful analysis of magnetic field line evolution indicated a new plasma acceleration mechanism parallel to the neutral sheet.

The present paper summarizes these three recent laboratory experiments.

2. TWO DIMENSIONAL RECONNECTION MODEL AND EXPERIMENTAL OBSERVATIONS

Fig.1 presents the most commonly used 2-D description of magnetic reconnection [*Sweet*, 1958; *Parker*, 1957,1979; *Petschek,* 1964], in which two sets of field lines are oppositely directed above and below the separatrix. As magnetized plasmas move from both sides toward the separatrix, a strong sheet current develops perpendicular to the page sheet plane associated with a strong curl **B** effect. This sheet current diffuses due to plasma resistivity and reconnection of field lines occurs. This region is often called the "diffusion region". After the reconnection of field lines, acceleration of plasma particles (up to the Alfvén velocity) occurs parallel to the plane. The Sweet-Parker model and the Petschek model are based on this 2-D picture, although the evaluated reconnection rates are quite different.

A series of well diagnosed experiments were carried out by Stenzel and Gekelman using a linear plasma device [*Stenzel* and *Gekelman* , 1981; *Gekelman et al.*, 1982,1988]. In their experiments, a reconnection regime was created by driving currents in the parallel sheet conductors shown in Fig. 2a , and a detailed local study of magnetic reconnection was made. Although the ion gyro-radius was too large($\rho_i/a > 1$) for the experiment to be in full MHD domain, precise local measurements were made to identify microscopic physics issues associated with reconnection (Figs. 2b-d). Profiles of electron pressure n_eT_e, magnetic force density $\boldsymbol{J} \times \boldsymbol{B}$ and ion velocity v were measured.

In particular, the typical 2-D feature of particle acceleration discussed in Fig.1 was verified [*Gekelman et al.* 1982]. Figures 2c and 2d depict typical 2-D ion flows perpendicular to the neutral line from the diffusion region to the outside. The local force on the plasma, $[\boldsymbol{J} \times \boldsymbol{B} - \nabla p_e]$ was compared with the measured particle acceleration. It was found that the ion acceleration was strongly modified by scattering of wave turbulence. After several Alfven times, the plasma was observed to develop the classic flow pattern, jetting from the neutral sheet with velocities close to the Alfven speed. This experiment was later extended to a 3D study [*Gekelman* and *Pfister,* 1988], in which tearing of the current sheet was observed.

3. TOKAMAK SAWTOOTH OSCILLATION AND MAGNETIC RECONNECTION

A sawtooth crash in a tokamak is a typical example of magnetic reconnection in a high temperature plasma. A sawtooth oscillation [*Kadomtsev*, 1975; *Wesson,* 1986,1987] is characterized by a periodic repetition of peaking and sudden flattening of electron temperature (T_e) profile as shown in Fig.3. The crash or flattening phase is a manifestation of magnetic reconnection, since breaking of field lines and topological re-arrangement occurs during this period. A highly peaked T_e profile often can lead to a peaked current profile with central $q < 1$, where q denotes the inverse of the rotational transform, indicating the pitch of field lines. It is often called the safety factor. Due to this current profile, a helical MHD instability develops near the $q=1$ flux surface and this instability can induce magnetic reconnection, Fig. 3b. Kadomtsev proposed that this reconnection event (crash) should make the central q rise to unity; a similar evolution would be repeated cyclically.

3.1. *Electron temperature evolution*

It is regarded that a tokamak consists of nested flux surfaces on which T_e is constant. The electron cyclotron emission (ECE) radiation spectrum which gives the T_e profile can thus provide information about flux surfaces or magnetic field contours. The electron temperature profile in the poloidal plane of the plasma was measured with ECE by Nagayama *et al.* [1991]. The sawtooth crash phase which takes 150 - 800 μsec has been studied extensively by use of tomographic techniques as shown in Fig. 4 [*Nagayama et al.* 1991; *Yamada et al.,* 1992]. By depicting transfer of heat by color coding, fast electron heat transfer was documented. Just before the crash, a shrinking circular hot peak shows up and a crescent-shaped flat island grows inside the q=1 region. Fast heat transfer was observed from inside to outside of the q=1 surface. A partial magnetic reconnection was attributed to this fast heat flow [*Yamada et al.,* 1994]. The T_e profile inside the inversion radius becomes completely flat after the crash, which is consistent with Kadomtsev's prediction, Figs. 3b and 3c.

3.2. *Magnetic reconnection verified by measured evolution of q profile*

We employ the motional Stark effect (MSE) diagnostic to obtain the profile of magnetic pitch angle, and hence the q profile [q(R) = local safety factor], using polarimetry measurements of the Doppler shifted D_α emission from a neutral deuterium--beam injection (NBI) heating line [*Levinton et al.,* 1993]. An important advantage of this technique is that this non-invasive and nonperturbative measurement of the field-line pitch is localized to the geometric intersection of the field of view with the neutral beamlines, which leads to good spatial resolution of $\delta r = 3 \sim 5$ cm. If the plasma is considered to have good flux surfaces, the measured field line pitch can be translated into a radial profile of rotational transform, or q(R) profile, based on tokamak equilibrium calculations [*Yamada et al.,* 1994]. The measured q profiles indicate that q values at the magnetic axis (q_0) increase by 5-10% typically from 0.7 to 0.75, during the sawtooth crash phase but do not relax to unity, even while the pressure gradient diminishes inside the q=1 region. In this example, as well as most tokamak sawtoothing discharges, q_0 is below one, and remains below unity throughout the sawtooth cycle. Because only field-line breaking and re-arrangement can make a q(R) change on such a short time scale, this verifies a magnetic field-line reconnection, although it is small.

3.3. *Heuristic model for sawtooth crash*

The observations raise an important question as to why the magnetic field lines inside the q=1 region do not form a flat q~1 inner region after the crash as suggested by Kadomtsev[1975], while the temperature gradient diminishes to zero as predicted by him for full reconnection. A simultaneous analysis of $T_e(r,\theta)$ and q(R) profile evolutions was made in the TFTR tokamak[*Yamada et al.,* 1994]. Based on the experimental results, a heuristic model has been proposed for the sawtooth crash.

In this model, the plasma is viewed as concentric toroidal regions separated by the q=1 surface. A kink mode develops and displaces the pressure contours on an ideal MHD time scale to a helical (m=1, n=1 poloidal and toroidal mode numbers) structure, thus inducing a forced reconnection at the most stressed region(X-point) in the q=1 flux surface. It is suggested that the X-point region appears at a certain toroidal position with a ballooning structure on the weak field side of a poloidal plane . A rapid efflux of thermal energy occurs through this X-point region along newly connected field lines [*Lichtenberg* , 1992]. The precipitous drop of the pressure gradient, which occurs within a short period of 100-200 μsec $<< t_{\text{Sweet-Parker}}$ [*Sweet,* 1958; *Parker,* 1957,1979], removes the free energy to drive the kink instability, inhibiting full reconnection.

The central q values have been measured in the sawtoothing plasmas by several groups [*Soltwisch* 1988; *Levinton et al.* 1993; *Yamada et al.* 1994 and references therein] for the past ten years. Although there is a difference among them concerning the final values of the central q after the crash, all reported $\Delta q < 0.1$ during sawtooth and the results can be explained by the proposed model by Yamada *et al.* [1994]. Another important finding to date is that the magnetic reconnection in a tokamak plasma is driven by an internal MHD mode (driven reconnection) and is thus determined by the growth rate of the MHD instability. The plasma's stability depends on the plasma parameters [$n_e(R)$, $T_e(R)$ and $T_i(R)$], current profile (q profile), and three-dimensional boundary conditions.

4. THREE-DIMENSIONAL STUDY OF MAGNETIC RECONNECTION IN COLLIDING SPHEROMAKS

Three-dimensional effects of magnetic reconnection have been recently investigated by axially merging two spheromaks [*Yamada et al.*, 1990; *Ono et al.*, 1993] in the TS-3 device at the University of Tokyo. MRX device which is under construction at Princeton University will be devoted to extensive study of these phenomena. In these experiments, two toroidal plasma rings, with equal or opposite helicity, are formed and brought together. It has been found that plasmas of opposite helicity reconnect appreciably faster than those of same helicity, and that the direction of the toroidal field plays an important role in the reconnection process.

4.1. *Experimental profiles*

Now we consider an experiment in which two plasma toroids of spheromak type merge together, contacting along a toroidally symmetric line. The spheromaks with a "flux hole" (currentless region) in the center are easy to translate. They can be generated with different helicities. Two spheromaks which carry identical toroidal current with the same or the opposite toroidal field (let us call them co-helicity merging or counter-helicity merging, respectively) are made to merge to induce reconnection by controlling external coil currents.

In both cases, identical amounts of toroidal current flow parallel to each other. Thus, the 2-D pictures of these two cases are exactly the same. However, they are quite different in the three-dimensional picture as seen in Figs. 5a and 5b. In the co-helicity case, the field lines merge with large shear angles at the reconnection region, while in the counter-helicity case, they merge with exactly anti-parallel fields.

There is another important difference in the reconnection pattern. For co-helicity merging, the transition of the configuration should be globally smooth. But in counter-helicity merging, the pitch of the field lines changes abruptly at the reconnection point as seen in Fig. 5b. We expect a violent plasma acceleration in the toroidal direction as the field lines contract after the merging of two toroidal plasmas of opposite helicity. The acceleration mechanism and the direction of acceleration are importantly different from that conjectured in the typical 2-D models . In the 2-D picture a plasma acceleration occurs perpendicular to the x-line as shown in Fig.1. But in the 3-D picture shown in Fig. 5, plasma acceleration can occur along the x-line.

4.2. *Experimental results*

To identify critical physics issues for magnetic reconnection, experiments have been carried out at the University of Tokyo in collaboration with Princeton University. Figure 6a shows the set up of the TS-3 experiment in which 2 spheromaks of toroidal shape are created and allowed to merge together. The toroidal flux of each spheromak is generated by the Z-discharges between electrodes. To document the internal magnetic structure of the reconnection in a single shot, a two-dimensional magnetic probe array is placed in an r - z plane as shown in this figure. Plasma parameters are as follows; B~ 0.5-1 kG, $T_e \sim 10$ eV, and $n_e \sim 2\text{-}5 \times 10^{14}$ cm^{-3}. Figure 6b shows the time evolution of the poloidal flux contours derived experimentally from internal probe signals for merging of co-helicities and counter-helicities. Other plasma parameters were held identical for each discharge.

Merging of spheromaks of opposite helicity occurs faster than merging of the same helicity. In the initial phase, reconnection progresses with the same speed for both. But in the case of co-helicity merging, the reconnection rate is seen to slow down significantly midway through the merging, while for counter-helicity merging, reconnection continues until the merging is completed.

Let us consider a possible cause of the observed faster reconnection for counter-helicity merging. When two plasmas of parallel toroidal fields are brought together, a new equilibrium is formed among the toroidal field pressure (outward), poloidal-field pressure (attractive force: inward), and the plasma pressure (outward). For the merging of plasmas of two anti-parallel toroidal fields, the central toroidal field is quickly reduced to zero and the attractive force becomes so dominant that reconnection is accelerated.

Based on the magnetic field evolution, toroidal current density contours were deduced for the same sequence of shots [*Ono et al.*, 1993], which verified an important 2-D feature of magnetic reconnection. It was measured that the plasma resistivity based on the observed current decay was enhanced by more than factor of 10 over classical value.

Another important observation was a strong dependence of the reconnection speed on global forcing, i.e., in this case, the colliding velocity of the two plasmas. Figure 7 presents the reconnection rate γ [defined by the flux transfer rate, $(1/\Psi)\delta\Psi/\delta t$) versus initial colliding velocity of two plasmas for co- and counter-helicity merging cases. It is observed that γ increases almost proportionally to v_i. This result is not consistent with the leading 2-D theories of Sweet and Parker and/or Petschek, which suggest no dependence on external forcing. The experiment clearly suggests the importance of an external driving force in determining the reconnection rate, and supports an important aspect of the driven-reconnection model [*Sato*, 1985].

It was noted earlier that we expect a violent plasma acceleration in the toroidal direction as the field lines contract after the merging of two toroidal plasmas of the opposite helicitiy. Evidence of such a mechanism was observed in the recent experiment [*Ono et al.*, 1993]. Figure 8a depicts the time evolution of profile of toroidal field, B_t, versus z (axial) direction for counter-helicity merging. This result was obtained by a B_t probe array inserted at r=14 cm, which runs through the magnetic axis. Initially, the merging plasmas formed the B_t profile shown in the figure, positive on the left and negative on the right side. As reconnection progressed, the value of B_t decreased as expected but then the B_t profile flipped (changed its polarity) between t=20 and 30 μsec. This overshoot is regarded as evidence of the *toroidal sling shot effect* [*Yamada et al.*, 1991] discussed earlier in Fig.5. Figure 8b describes schematically the dynamic (3-D) evolution of magnetic field lines during and after the reconnection. The recent numerical MHD simulations, also shwed similar 3-D effects in solar flare processes [*Matsumoto et al.* 1993] and in magnetosphere physics [*Hawkins et al.* 1994]. Energy transfer from magnetic to plasma thermal energy is expected in this dynamic toroidal field annihilation process. Indeed, strong ion heating has been recently documented during counter-helicity Merging [*Ono et al.* 1993].

5. SUMMARY

A number of recent laboratory experiments on magnetic reconnection have been reviewed with special focus on the merging experiments of two toroidal plasmas and the observation of sawtoothing tokamak plasmas with the Lundquist numbers exceeding 10^7.

These recent laboratory experiments created an environment which satisfied the criteria for the MHD regeme ($V_A/c << 1$, $S >> 1$, $\rho_i/a << 1$) and in which the global MHD boundary conditions could be controlled externally. Experiments with fully three dimensional reconnection are now possible. These experiments found that magnetic reconnection was influenced by the merging angle of the field lines, by 3-D aspects, by global boundary condition, as well as by local plasma parameters.

During a sawtooth crash, magnetic reconnection has been verified as partial mixing of field lines, and the resulting small changes of the q profile documented. It has been shown that the q values stay substantially below 1, despite the fact that the T_e contour evolution from ECE diagnostics shows apparently the Kadomtsev-like full reconnection patterns. A simultaneous analysis of poloidal $T_e(r,\theta)$ and $q(R)$ profile evolutions has led us to propose a model in which a non-axisymmetric 3-D MHD mode plays an essential role in driving field line reconnection. Fast parallel transport along the newly connected field lines can cause a rapid efflux of internal energy through the X-point region, thus creating a fast crash of the central plasma pressure. This precipitous drop of the pressure gradients is attributed to a cessation of the Kadomtsev-type full reconnection process.

In colliding spheromak experiments, local and global MHD issues important for magnetic reconnection have been extensively investigated in a 3-D geometry. The three-dimensional features of magnetic reconnection were found to be quite different from the two-dimensional features, depending on whether the two plasma toroids have co-helicity or counter-helicity configurations. Evidence of driven reconnection has been observed and a quantitative dependence of reconnection rate, γ, on external forcing flow, v_i, was documented ($\gamma\ \alpha\ v_i$). A new plasma acceleration mechanism accompanied by significant ion heating has been indicated during the 3-D reconnection process. The results proved that the double spheromak geometry is a well suited configuration for basic study of magnetic reconnection. More comprehensive studies of local and global characteristics will give a full picture of magnetic reconnection in three dimensions and will address issues such as: (1) What are the most critical factors, both globally and locally in determining the rate of magnetic reconnection? (2) How is the magnetic energy converted to particle energy or thermal energy? (3) Do deviations from axisymmetry spontaneously arise and, if so, how do they occur ? (4) How is the patchy reconnection which occurs in the magnetopause related to impulsive driven reconnection in laboratory plasmas?

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Figure Captions

Fig. 1. Typical 2-D depiction of magnetic reconnection.

Fig. 2. Results from Stenzel and Gekelman's experiment.
(a) Cross-sectional view of the device, showing the magnetic field geometry without plasma.
(b) Transverse field line contours at t=50 μs, (c) & (d). Measured ion velocity vectors at t = 60 & 80 μs at axial position of z= 87 cm.

Fig. 3. Sawtooth oscillation of a tokamak plasma.
(a) Change of $T_e(r)$ and q(r) profiles with respect to minor radius r; center is the plasma's magnetic axis. (b) Kadomtsev model; m=1/n=1 MHD instability develops near q=1 flux surface and induce magnetic reconnection. After the crash, central q rises to unity to form a flat q=1 region.
(c).Time evolution of T_e contours measured by ECE .

Fig. 4. $T_e(r,\theta)$ profiles in the poloidal plane(R, z) during the crash period of sawtooth. Heat transfer ΔT_e is superposed with coded color contours. Time step between each figure is ~120 μsec:; *Yamada et al.*,1992, 1994.

Fig. 5. Three dimensional description of magnetic reconnection. (a) and (a'), For two toroidal plasmas with equal helicity, before and after reconnection; (b) and (b'); For two plasmas with opposite helicity.

Fig. 6a. Experimental set-up in TS-3 device (Fig. 6a). The central column provides stability effects for spheromaks with a flux-hole (currentless region) at the major axis.

Fig.6b. Evolution of poloidal flux contours for co- and counter-helicity merging. The other plasma parameters are kept identical for the cases shown. Each step for flux contours ($\Delta\psi$) corresponds to 2×10^{-4} Weber (2×10^{4} G.cm^2).

Fig. 7. Evidence of driven reconnection.; Reconnection rate, γ, versus colliding velocity, v_i , for co- and counter-helicity merging.

Fig. 8 Observation of toroidal sling-shot effect.(a) Time evolution of axial profile of toroidal magnetic field B_t. (b) Schematic description of overshoot phenomenon of the toroidal field.

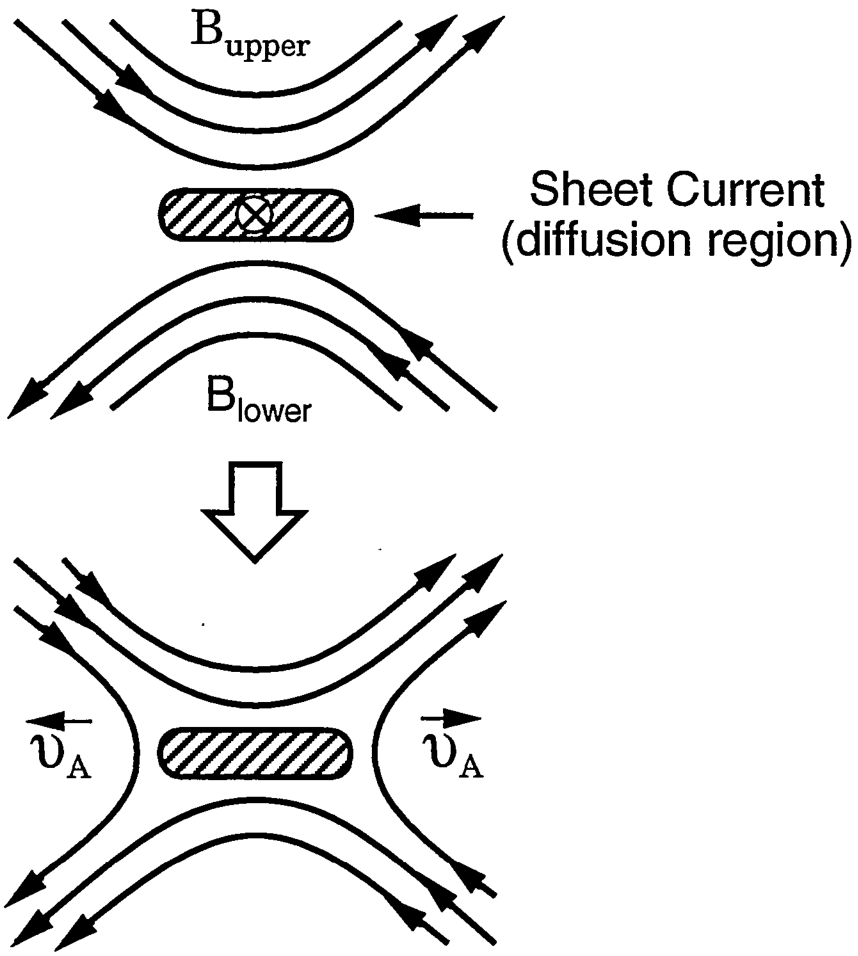
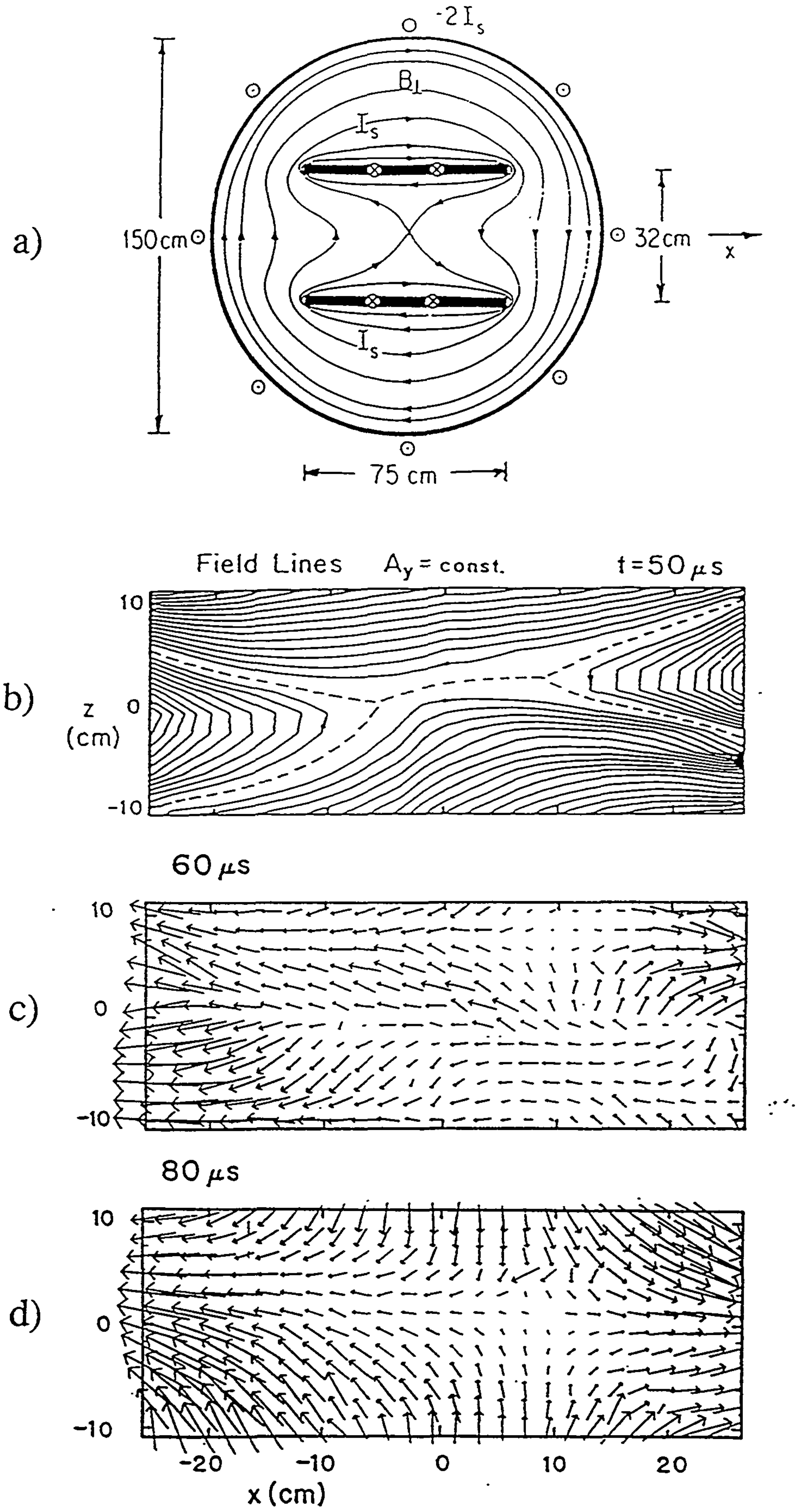


Fig. 1


a)
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I_s
I_s
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x
75 cm
b)
Field Lines A_y = const.
t = 50 μs
z (cm)
10
0
-10
c)
60 μs
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0
-10
d)
80 μs
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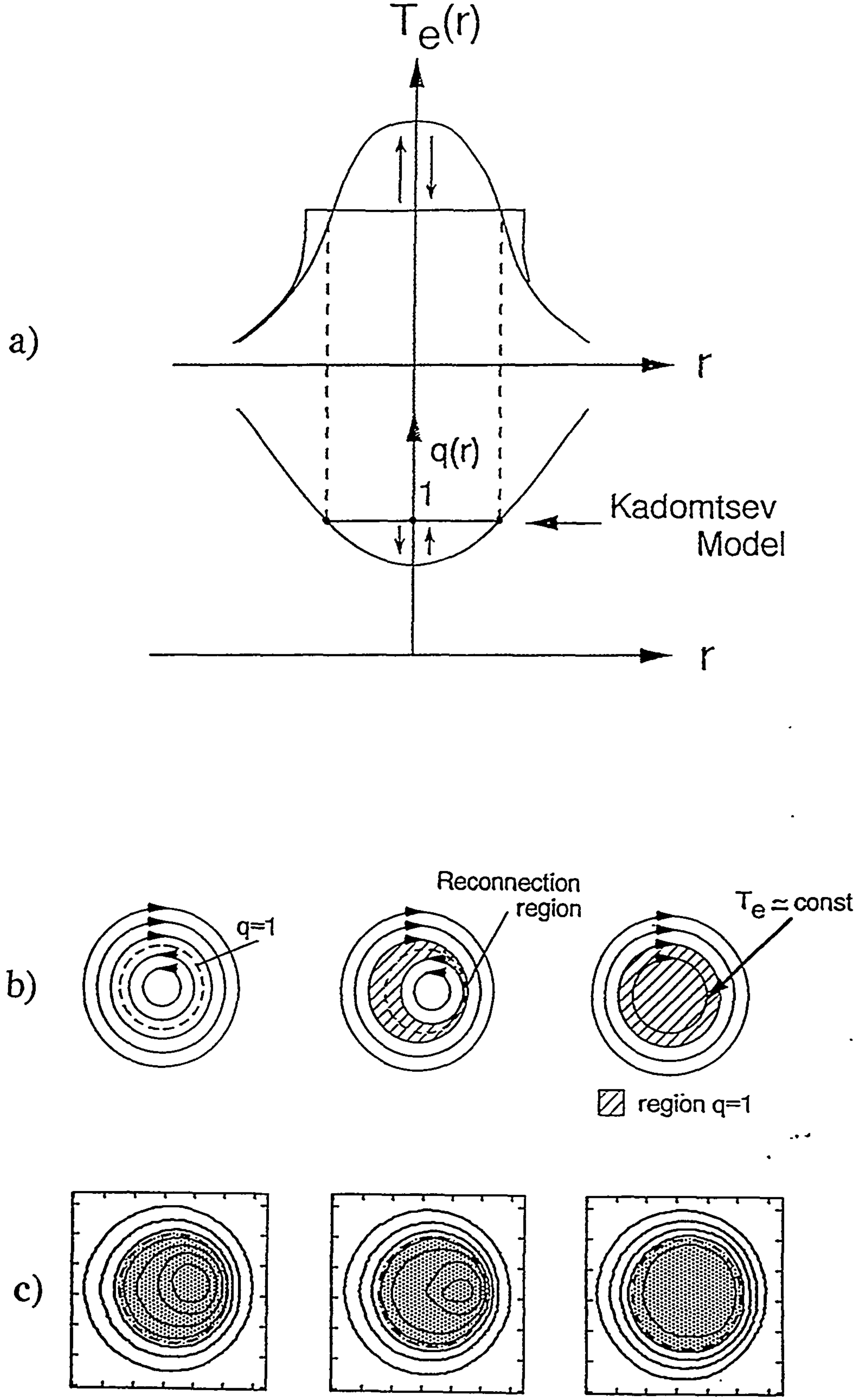
-10
-20
-10
0
10
20
x (cm)

Fig. 2


a)
Te(r)
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Kadomtsev
Model
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b)
q=1
Reconnection
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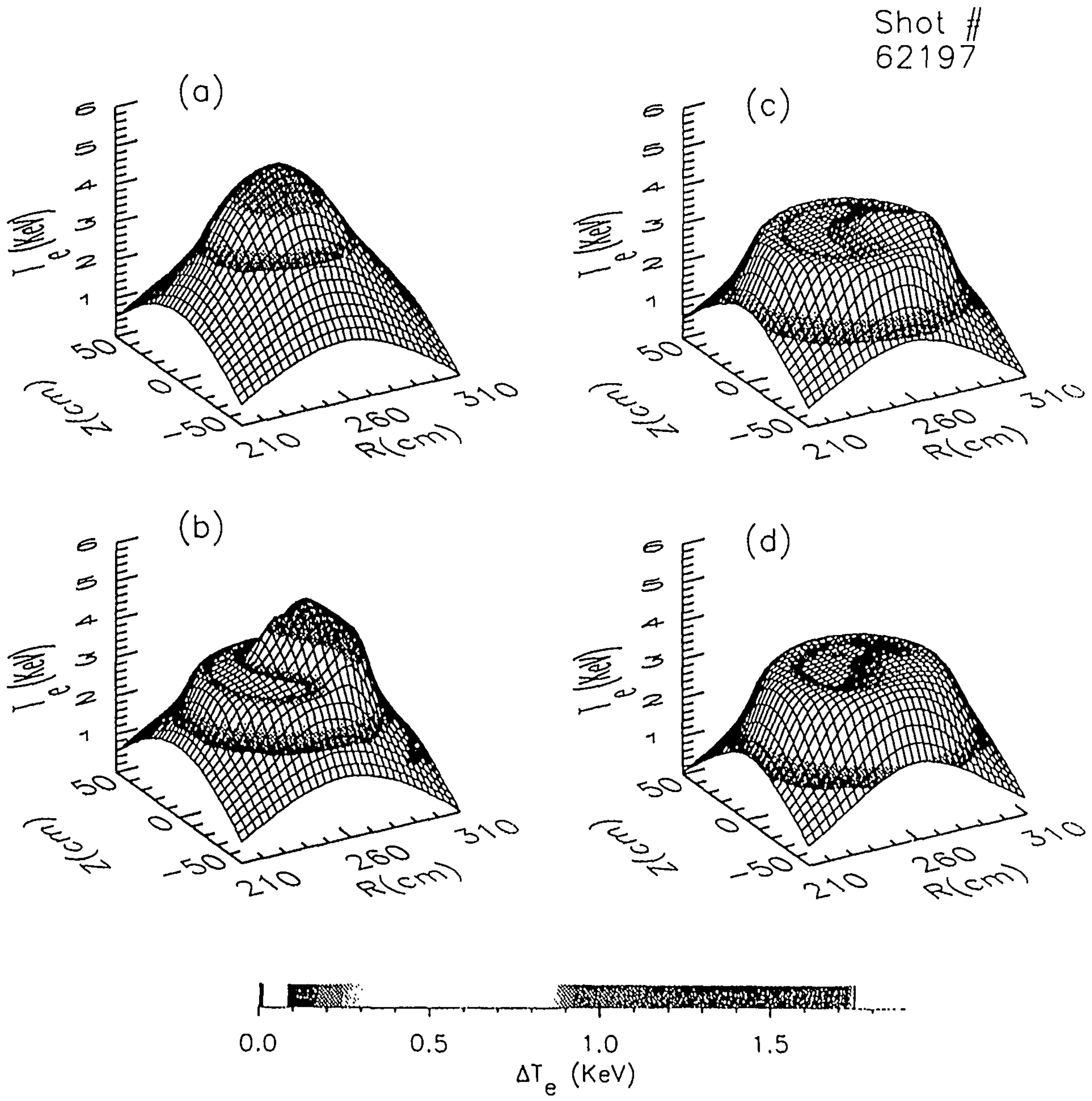
c)

Fig. 3


Shot #
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T_e (KeV)
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210
260
310
R(cm)
0.0
0.5
1.0
1.5
ΔT_e (KeV)

Fig. 4

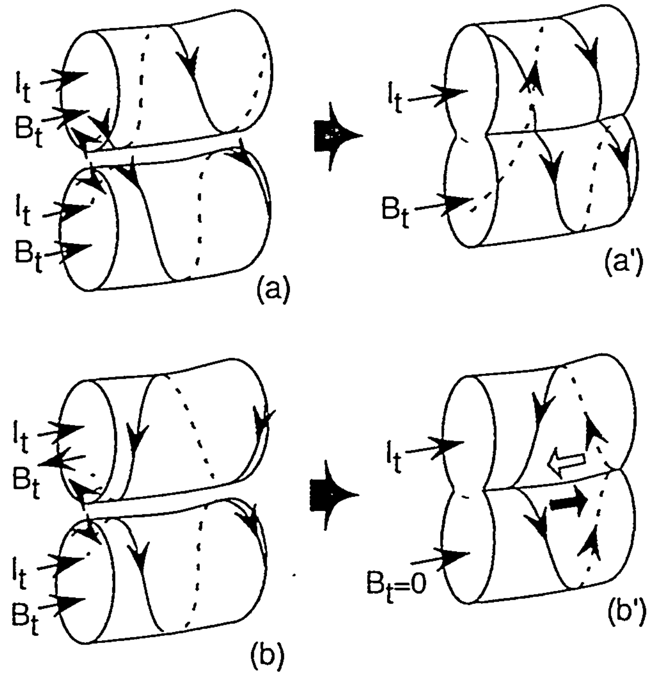


Fig. 5

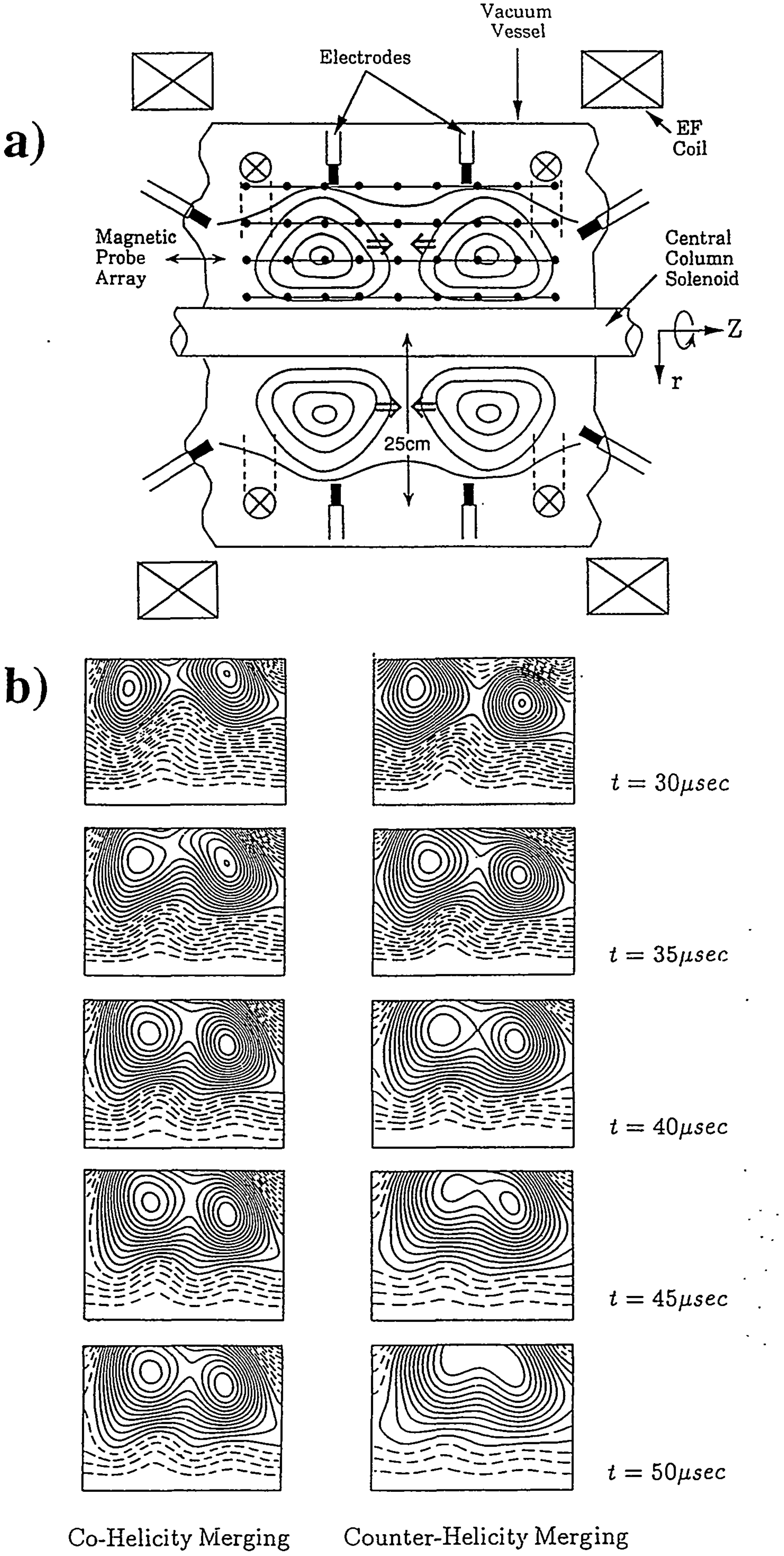

a)
Vacuum Vessel
Electrodes
EF Coil
Magnetic Probe Array
Central Column Solenoid
Z
r
25cm
b)
t = 30μsec
t = 35μsec
t = 40μsec
t = 45μsec
t = 50μsec
Co-Helicity Merging
Counter-Helicity Merging

Fig. 6

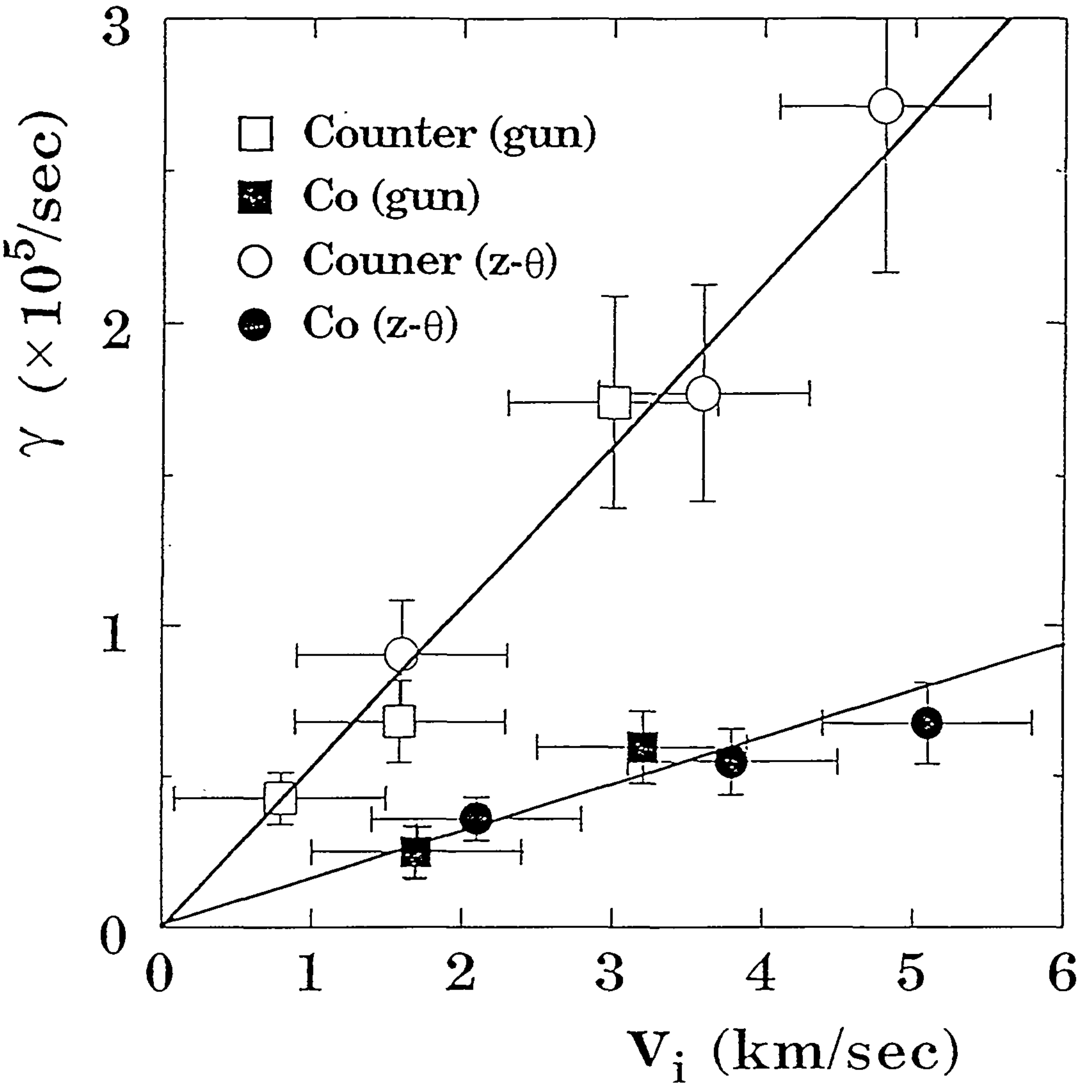
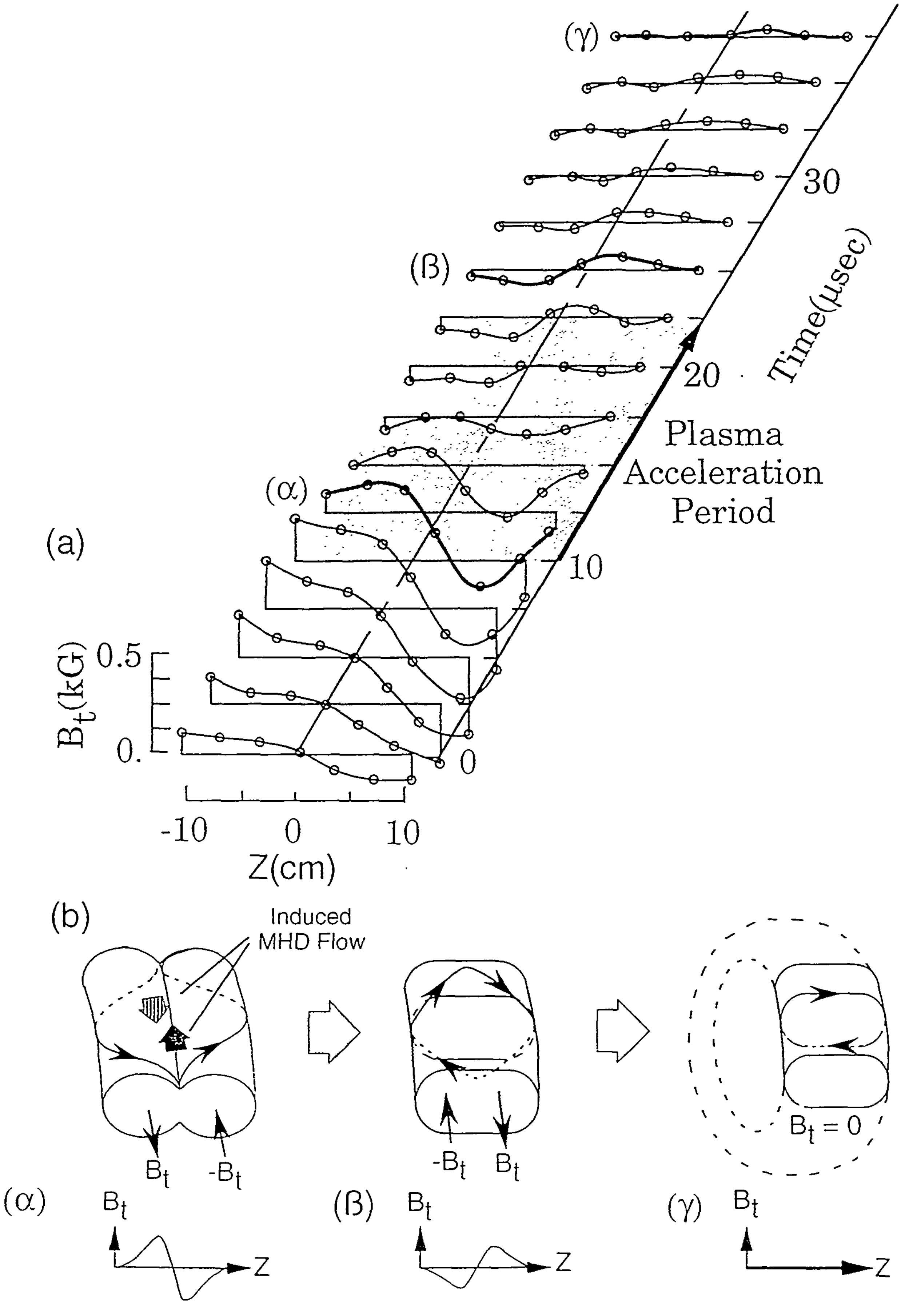

3
2
1
0
0
1
2
3
4
5
6
γ (×10^5/sec)
V_i (km/sec)
Counter (gun)
Co (gun)
Couner (z-θ)
Co (z-θ)

Fig. 7



(a)
(γ)
(β)
(α)
30
20
10
0
Time(μsec)
Plasma
Acceleration
Period
B_t(kG)
0.5
0.
-10
0
10
Z(cm)
(b)
Induced
MHD Flow
B_t
$-B_t$
$-B_t$
B_t
$B_t = 0$
(α)
B_t
Z
(β)
B_t
Z
(γ)
B_t
Z

Fig. 8

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