J. Plasma Fusion Res. SERIES, Vol. 2 (1999) 62–66

Magnetic Reconnection and Self-organized Plasma Systems

YAMADA Masaaki and JI Hantao
Princeton Plasma Physics Laboratory
P.O. Box 451, Princeton, New Jersey 08654, USA

(Received: 14 April 1999 / Accepted: 9 June 1999)

Abstract

In this paper the recent results from the Magnetic Reconnection Experiment (MRX) at PPPL are discussed along with their relationship to observations from solar flares, the magnetosphere, and current carrying pinch discharges such as tokamaks, reversed field pinches, spheromaks and field reversed configurations. It is found that the reconnection speed decreases as the angle of merging field lines decreases, consistent with the well established observation in the dayside magnetosphere. This observation can also provide a qualitative interpretation of a generally observed trend in pinch plasmas, namely that magnetic field diffuses (or reconnects) faster when magnetic shear is larger. A recently conceived research project, SPIRIT (Self-organized Plasma with Induction, Reconnection, and Injection Techniques), will also be discussed.

Keywords:

magnetic reconnection, compact toroids, self-organization

1. Introduction

Magnetic field generated by current in a plasma can effectively confine high temperature plasmas by generating a stable toroidal pinch configuration. But this configuration is often susceptible to relaxation phenomena which always invoke changes in the magnetic field topology and magnetic reconnection. Also in the solar physics community there has been growing interest in magnetic reconnection – a topological change of magnetic fields in solar flares [1].

In this paper, experimental findings on magnetic reconnection are briefly reviewed to elucidate the fundamental physics mechanisms of magnetic reconnection. Then the basic features of self-organization of toroidal pinch plasmas caused by magnetic reconnection are presented. Based on the findings of recent merging experiments, this paper also discusses a recently conceived research project, SPIRIT (Self-organized Plasma with Induction, Reconnection, and Injection Techniques), in the context of studying confinement physics of low aspect ratio current carrying toroidal plasmas.

2. Magnetic Reconnection Experiments

The MRX device is the most recent device dedicated to investigating the fundamental physics of magnetic reconnection. The primary objective of MRX is the fundamental study of reconnection utilizing a very flexible merging toroidal plasma configuration. The MRX device creates an environment to satisfy the criteria for MHD plasmas (the Lundquist number $S \sim 10^3 \gg 1$, and the ion gyro-radius is much smaller than the plasma size $\rho_i \ll L$), and the boundary condition can be controlled externally. The initial MRX experiments have been carried out in the double annular plasma set-up in which two toroidal plasmas with annular cross section are formed independently around two flux cores [2] and reconnection is driven in the quadrupole field; Fig. 1(a). By pulsing currents in the TF coils after a quadrupole poloidal magnetic field has been established, plasmas are inductively created around each flux core due to poloidal electric fields. Then the PF coil current can be decreased to drive magnetic reconnection around the x-point. Magnetic reconnection has been intensively studied with and without the third vector component (toroidal or azimuthal direction) of the magnetic field. To document the internal magnetic structure of the reconnection on a single shot, a two-dimensional magnetic probe array with 90 channels is placed on an R-Z plane or toroidal cut-off plane, as shown in Fig. 1(a). Plasma parameters are: $B \sim 0.5 - 1.0$kG, $T_e \sim 10 - 30$eV, and $n_e \sim (0.1 - 1.0) \times 10^{14}$cm^{-3}.

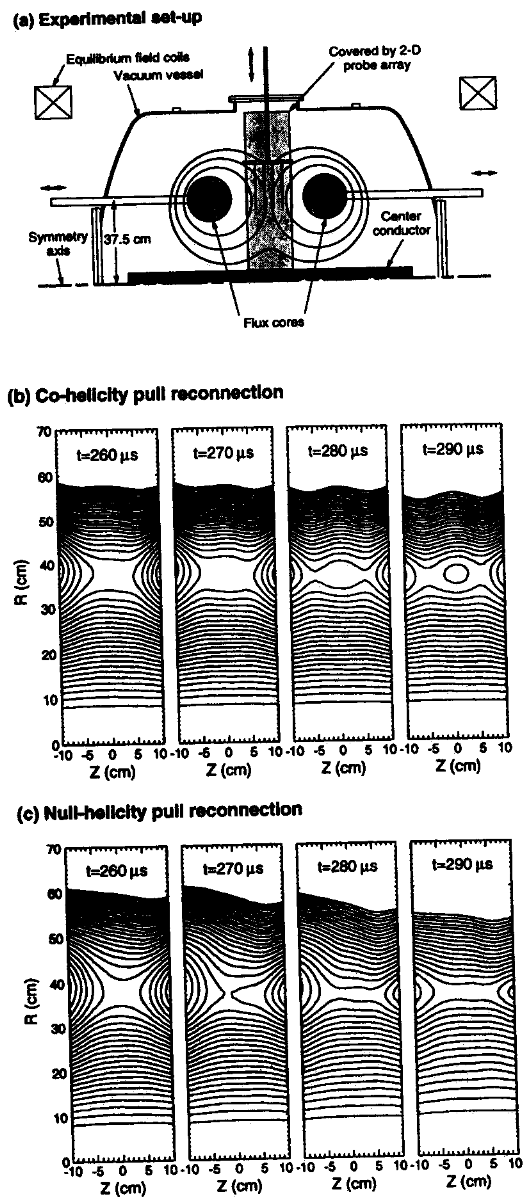

Fig. 1 (a) Experimental setup including 2-D magnetic probe array. Poloidal flux contour evolution for (b) co-helicity and (c) null-helicity reconnection.

Two distinctively different shapes of neutral sheet current layer are identified, depending on third vector components of reconnecting magnetic fields. Fig. 1(b) and Fig. 1(c) show the time evolution of the poloidal flux contours during reconnection processes of null-helicity and co-helicity plasmas. The contours are derived assuming axisymmetry (assured by a center conductor placed at the major axis) in a *R-Z* plane. Other operational conditions are held constant for each discharge. As poloidal flux is driven toward the diffusion region, a neutral sheet is formed. Without the third component (null-helicity reconnection), a thin double-Y shaped diffusion region is clearly identified; Fig. 1(c). With a sizable third component (co-helicity reconnection), an O-shaped sheet current appears; Fig. 1(b). This O-point current channel grows into a spheromak configuration.

Quantitatively, it has been found that the measured reconnection rates agree well with a generalized Sweet-Parker model, which incorporates compressibility, downstream pressure, and the effective resistivity [3].

A quantitative study of the merging angle dependence of reconnection speed V_R and current sheet thickness δ is being carried out. By controlling the magnitude of the axial field component, B_T, the angle between merging field lines can be varied. As shown in Fig. 2, V_R increases as δ decreases by a factor of 2.5 as the angle is increased from 55 degree to 180 degree. While this data is preliminary, data points between 0 and 55 degree will be added in the future. We can draw a comparison between our preliminary study and observations at the dayside magnetopause. Variations in the interplanetary magnetic field (IMF) cause the impinging field to alternate between having a northward and southward component. It is observed that "flux transfer events", likely signatures of magnetic reconnection, are clearly correlated with southward antiparallel wind in agreement with the present results.

3. Magnetic Reconnection and Self-organization of Toroidal Pinch Plasmas

Magnetic reconnection occurs whenever electric current is induced in a plasma with finite dissipations. Typical examples of such plasmas are laboratory toroidal pinches, where a toroidal current is induced to heat and compress the plasma through the well known pinch effects. Tokamak, reversed field (toroidal) pinch

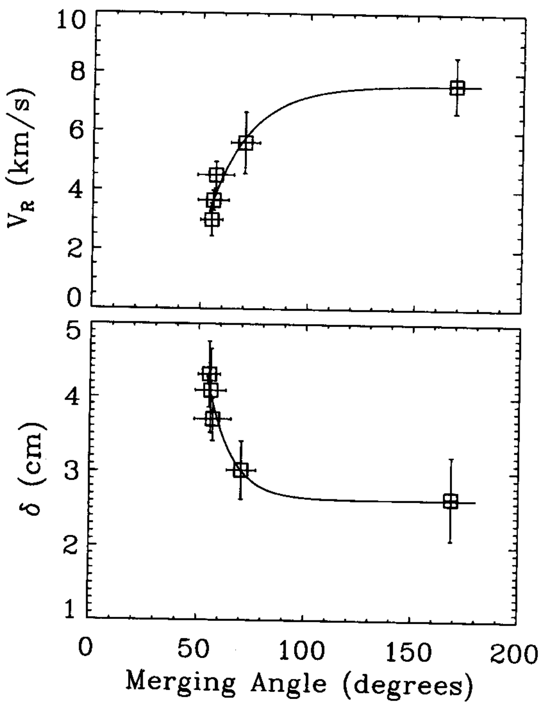

Fig. 2 Dependence of (top) reconnection speed V_R and (bottom) current sheet thickness δ on the merging angle between magnetic field lines.

(RFP), spheromak, and field reversed configuration (FRC) belong to this category. However, toroidal fields are supplied differently in these systems; the tokamak's toroidal field is very strong and is primarily created by external coils, while the toroidal field of the RFP is created by the combined effects of internal current and small external field and is much weaker than that of a tokamak. The toroidal field of a spheromak is generated entirely by the internal current. To another extreme, the FRC plasmas does not have a significant toroidal field at all throughout the plasma. There is a sharp contrast in the direction of magnetic fields in these pinch plasmas: in high-q tokamaks, the angle of field lines vary little throughout the plasma (or equivalently the magnetic shear is low), and they are primarily in the toroidal direction. In the RFP and spheromak plasmas, the angle of field lines vary over a wide range (or the magnetic shear is large), and they change from primarily toroidal at the magnetic axis to primarily poloidal at the plasma edge. In the FRC plasmas, the angle of magnetic field changes 180 degrees across the magnetic axis or the magnetic null.

All these pinch plasmas are mostly produced and sustained by an external transformer, which continuously supplies the poloidal flux (or equivalently drives the toroidal current). The process of poloidal flux resistive diffusion at the magnetic axis can be regarded as field line annihilation or "magnetic reconnection" in a general sense. Supply of new flux from the outside resembles the external drive of magnetic reconnection. Then the merging process of field lines at the magnetic axis belongs to the category of "co-helicity" reconnection for tokamaks, RFP's and spheromaks, since the merging angle is less than 180 degrees, but their angles vary for the case of a tokamak to an RFP and/or a spheromak plasma. On the other hand, the "null-helicity" reconnection happens in the FRC plasmas. The rate of magnetic reconnection or diffusion can be measured by the toroidal electric field, or the quantity usually referred to as the one-turn loop voltage needed to sustain the plasma. The larger the loop voltage is, the faster the diffusion happens. Experimentally, it is a general observation that an ohmically driven tokamak can be sustained by a much lower loop voltage than an RFP for the same given toroidal plasma current. Although the usual interpretation is that the quality of energy confinement is much poorer in low-q pinch plasmas, another interpretation can be given that the rate of reconnection or diffusion is much faster with larger merging angles, qualitatively consistent with MRX results.

Anomalous diffusion or poor energy confinement is generally regarded as a consequence of large fluctuations associated with self-organization activities, which is a remarkable common feature for all of these low-q pinch plasmas. After an initial highly turbulent state, the plasma settles into a relatively quiescent stable final state, which is insensitive to initial conditions.

4. Current Carrying Plasma Systems for Compact Fusion Reactor

In addition to confinement quality, the achievable beta is critical to the cost-effectiveness of a fusion reactor. However, in general, the highest betas are not necessarily achieved with the best confinement characteristics. Often, the opposite trend is seen among the pinch plasmas discussed in the previous section. Figure 3 schematically presents the achieved beta regime of representative toroidal configurations generated by external and internal magnetic field with respect to an internal field factor. The horizontal axis can be considered to be a self-organization factor, since the internal field is created by self-organization of plasmas. Among these compact toroidal configurations,

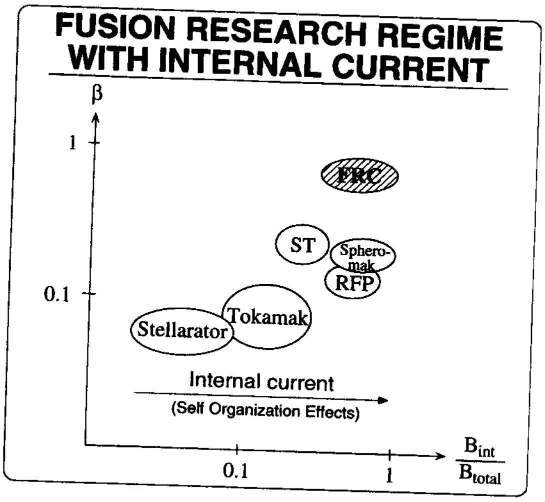

Fig. 3 Diagram for magnetic confinement systems in plasma beta and ratio of internal to external current.

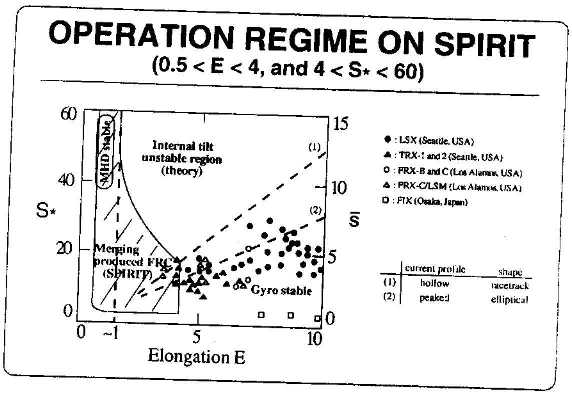

Fig. 4 Operation regimes of SPIRIT are shown with regards to s^* (gyro-radius factor) and E (elongation). Tilt stability conditions are emphasized in this figure.

the FRC which does not have toroidal field and is dominated by perpendicular currents, is uniquely attractive for a compact fusion reactor core. It has the highest beta (near unity) conceptually attainable in equilibrium. However, the nature of its self-organization process is qualitatively different from that happening in RFP's and spheromaks, where parallel currents dominate. The high-beta equilibrium of an FRC has been successfully attained in relatively small devices, although its lifetime is limited to the order of the energy confinement time (< 1ms). Properly formed FRC plasmas appear experimentally to be quite stable to global modes. If questions regarding formation, stability, sustainment, and confinement are successfully resolved, then FRC's may offer a high-power-density and easily maintainable alternative approach to fusion power production.

5. Proposed Device SPIRIT

We have proposed a concept exploration device called SPIRIT to investigate comprehensively the MHD stability and the confinement features of FRCs in comparison with other CT plasmas, by maintaining such plasmas much longer than their energy confinement times. Primary features of the proposed research are: (1) Form FRC's with large flux (50mWb) by merging two spheromaks made by the flux core induction scheme with opposite helicities, and (2) Assess the stability and confinement characteristics of the new regimes of FRC configuration by varying the important stability parameter s^* and the elongation factor E and by using passive stabilizers. (3) Sustain the FRC for a significantly longer time (1-10 msec) than the energy confinement time using a center stack ohmic-heating (OH) transformer and/or NBI current drive to provide a firm base for assessing confinement characteristics of FRC plasmas. (4) Investigate comparatively the global characteristics of all compact, current-carrying toroidal configurations.

In the proposed SPIRIT device, FRC plasmas and other compact toroidal plasmas can be generated by utilizing inductive formation schemes followed by merging of co- and counter helicity spheromaks, based on the previous experiments in the TS-3 [4,5,6] and MRX [7]. The FRC plasmas were formed by merging counter-helicity spheromaks whose opposing toroidal flux is annihilated during the merging to accelerate ions from 10 to 200eV thus allowing $\beta \sim 1$. This novel inductive formation scheme, which invokes neither conventional fast shock heating nor electrode discharges, has significant advantages for the development of a compact reactor core.

SPIRIT will be dedicated to the exploration of new regimes of compact toroid configurations, in particular, FRCs with variable ratio of the ion gyro-radius to the plasma size. It is expected that counter-helicity merging of two spheromaks will lead to the formation of FRC plasmas with a toroidal current of up to 300kA and with a separatrix radius R_s of up to 50cm. The gyro-radii of ions can be significantly smaller than R_s, and their ratio s will be varied over a wide range (2–40). Here $s \sim 4\,\bar{s}$. Important questions are for what s values are these CT plasmas susceptible to a tilt mode, and under what conditions can they be made stable with conductive shells? In Fig. 4, operation regimes for SPIRIT are shown versus s and E (elongation) and compared with the previous regime [8].

A center stack which contains an OH transformer will be inserted to extend the lifetime of FRC plasmas to more than one millisecond and/or further increase the plasma current, so that a confinement study can be carried out in a quasi steady-state regime. The MHD characteristics and global confinement features of the four different compact toroid plasmas with additional ohmic current drive by the center stack will be comparatively investigated in the Phase I research stage.

Furthermore, this project will be designed to accommodate an upgrade consisting of neutral-beam injection (NBI) of a few megawatts to extend the lifetime of the plasma for much longer than one millisecond. This will significantly broaden the scope of the experiment by enabling active control of plasma stability with toroidal rotation and also by providing an additional means of current drive and beam heating. If a high-fueling (~ 100Amps) neutral-beam of 30–60kV energy range is injected into the FRC plasma, it is possible to sustain this configuration for a long period of time (> 10ms). This NBI would induce spinning of the plasma with high velocity up to the Alfven speed, which would in turn help stabilize the global MHD modes. NBI would also decrease the value of s. Additionally, SPIRIT can create a low aspect ratio RFP (R/a = 1.05 – 1.5), which has never been studied before [9].

References

[1] S. Tsuneta, Astrophys. J. **456**, 840 (1996).
[2] M. Yamada *et al.*, Phys. Rev. Lett. **78**, 3117 (1997).
[3] H. Ji *et al.*, Phys. Rev. Lett. **80**, 3256 (1998).
[4] M. Yamada *et al.*, Phys. Rev. Lett. **65**, 721 (1990).
[5] Y. Ono *et al.*, Phys. Fluids B **5**, 3691 (1993).
[6] Y. Ono *et al.*, *Proc. of 1992 IAEA Meeting* **2**, 619 (1993).
[7] M. Yamada *et al.*, *Proc. of 1996 IAEA Meeting* **2**, 253 (1997).
[8] H. Ji *et al.*, Phys. Plasmas **5**, 3685 (1998).
[9] H. Ji and M. Yamada, this proceeding.