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Mechanisms of Impulsive Magnet Reconnection: Global and Local Aspects

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Mechanisms of impulsive magnetic reconnection: Global and local aspects

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The global and local aspects of mechanisms of impulsive magnetic reconnection are discussed focusing on results from a dedicated laboratory experiment, MRX (Magnetic Reconnection Experiment), as well as fusion experiments. Possible application of the present analysis to reconnection phenomena in solar and space plasmas is also discussed. An external force which drives internal current in a fusion plasma causes magnetic flux to accumulate in a core section of the plasma (flux build-up). When the flux build-up generates a magnetic profile that satisfies a condition for a global magnetohydrodynamic instability to develop, reconnection takes place in an induced current layer generated by the instability leading to a global self-organization of the plasma. Generally the flux build-up phase is significantly longer than the reconnection time, $\tau_H \gg \tau_{Rec}$, thus making the waveform of flux evolution or other plasma parameters sawtooth shaped. In the reconnection layer of collisionless plasmas, the two fluid dynamics would lead to the formation of a narrow electron current channel which tends to become unstable against micro-instabilities, leading to an unsteady or impulsive reconnection. A common feature of impulsive reconnection after flux build-up is presented. © *2011 American Institute of Physics*. [doi:10.1063/1.3658034]

I. INTRODUCTION

When an external force is applied to the plasma, the magnetic field lines are reconfigured to find an equilibrium state. When this state becomes unstable, the plasma rapidly reorganizes itself to a new magnetohydrodynamic (MHD) equilibrium state, by way of forming current sheets, driving magnetic reconnection, and changing its magnetic topology.[1,2] The excess magnetic energy is converted to plasma kinetic energy, and the plasma magnetically relaxes or self-organizes to a lower magnetic energy state.[3] This global view of magnetic reconnection is applied to almost all cases of self-organization phenomena in laboratory fusion plasmas, magnetospheric plasmas, solar flare plasmas, and some of the more distant astrophysical plasmas.

It is well recognized that global reconnection phenomena almost always occur unsteadily or impulsively. In laboratory fusion plasmas, the magnetosphere, and solar flares, reconnection is seen to occur suddenly with a very fast speed. Fast local reconnection generally leads to an impulsive global topology change or global magnetic self-organization phenomena. Generally impulsive reconnection occurs after a gradual change of equilibrium builds up sufficient free energy to drive topological changes. Although many theoretical models have been proposed to describe various impulsive behaviors, there is no common theory which universally describes impulsive reconnection phenomena. In this paper, we consider mechanisms that cause impulsive reconnection phenomena in laboratory and astrophysical plasmas.

To the author's knowledge, the effect of external drive was experimentally studied quantitatively for the first time in a plasma merging experiment carried out on the TS-3 device[4,5] through the strong dependence of reconnection rate on the relative velocity of merging plasmas. The flux transfer rate through reconnection was found to be proportional to the mutual merging speed of the two plasmas, which was controlled by external forcing. This result suggests that external forcing would strongly affect the reconnection dynamics as well as its rate. A main objective of the present paper is to consider the role of external boundary conditions on magnetic reconnection together with conditions for impulsive reconnection.

Magnetic reconnection generally occurs because magnetic field lines are driven towards a localized diffusion region to reconnect and to release magnetic energy that is stored on global scales. The movement of magnetic flux caused by external forcing or global boundary conditions can result in the formation of a current layer. In the local reconnection layer, the reconnection rate is determined by the physical mechanisms of the current layer. The local reconnection rate in turn influences the global configuration by determining the amount of magnetic flux transfer through the current layer. The reconnection speed is characterized by the amount of field lines moving from one section of topology to the other. It is shown[3] that if the magnetic energy of a low β global MHD equilibrium state is lowered by a reorganization of plasma topology, reconnection takes place. Reconnection will stop if it no longer lowers the total magnetic energy.

As the reconnection proceeds, the topology of the magnetic field lines changes with the amount of un-reconnected flux decreasing and the amount of reconnected flux increasing. A key question is how fast the flux passes through the reconnection layer, or how much reconnection has happened. If the local reconnection is slow, the global field configuration outside of the layer can change quasi-statically compared to any dynamical rate. If local reconnection occurs very fast compared to the time scale for the inflow of flux, the reconnection rate can become unsteady. If flux inflow is too fast in comparison with the intrinsic reconnection rate at the layer, a flux build up occurs and impulsive reconnection is induced after the build up reaches a threshold value for an instability to take place in the current sheet. From this point of view, instability is regarded as a process for plasma to adjust the local reconnection rate to match the build-up pace of incoming flux.

We will address the following questions regarding actual laboratory reconnection events:

(1) It is often observed that magnetic energy is stored in a system for a long period and then suddenly released, globally driving the plasma to reconnect. What is the relationship between the local reconnection rate and the buildup of global flux?
(2) How do two-fluid effects cause impulsive reconnection?
(3) Is the presence of multiple reconnection-sites important?

With the above questions in mind, both the global and local aspects of impulsive magnetic reconnection are discussed in a mini-review style focusing on results from a dedicated laboratory experiment as well as fusion experiments in which the global conditions are controlled externally and the global and local plasma parameters are quantitatively monitored.

II. GLOBAL PHYSICS OF IMPULSIVE RECONNECTION

Regarding global reconnection physics, important progress was made by studying the features of relaxation phenomena in laboratory fusion plasmas. A large MHD instability driven by global boundary conditions often produces a current layer in a specific magnetic flux surface inducing magnetic reconnection. Reconnection occurs because magnetic field lines are driven towards a current sheet localized in a 3-D geometry. Usually magnetic energy is stored for a long period of time in a plasma system and then suddenly released, globally driving the plasma to a relaxed state. By observing how it happens, the relationship between the local reconnection rate and the buildup of global stored energy is found to be key.

A. Impulsive reconnection in the crash phase of sawtooth oscillation

A sawtooth oscillation[6–9] in a tokamak plasma is observed as a periodic repetition of peaking and sudden flattening of the electron temperature (T_e) profile in the minor cross section. The time evolution of the observed signals from *bremsstrahlung* X-ray emission or electron cyclotron emission (ECE) from the plasma core depicts the shape of sawtooth as shown in Fig. 1(a).

The sawtooth oscillation period is divided into two phases, a flux build-up phase and a reconnection (crash)

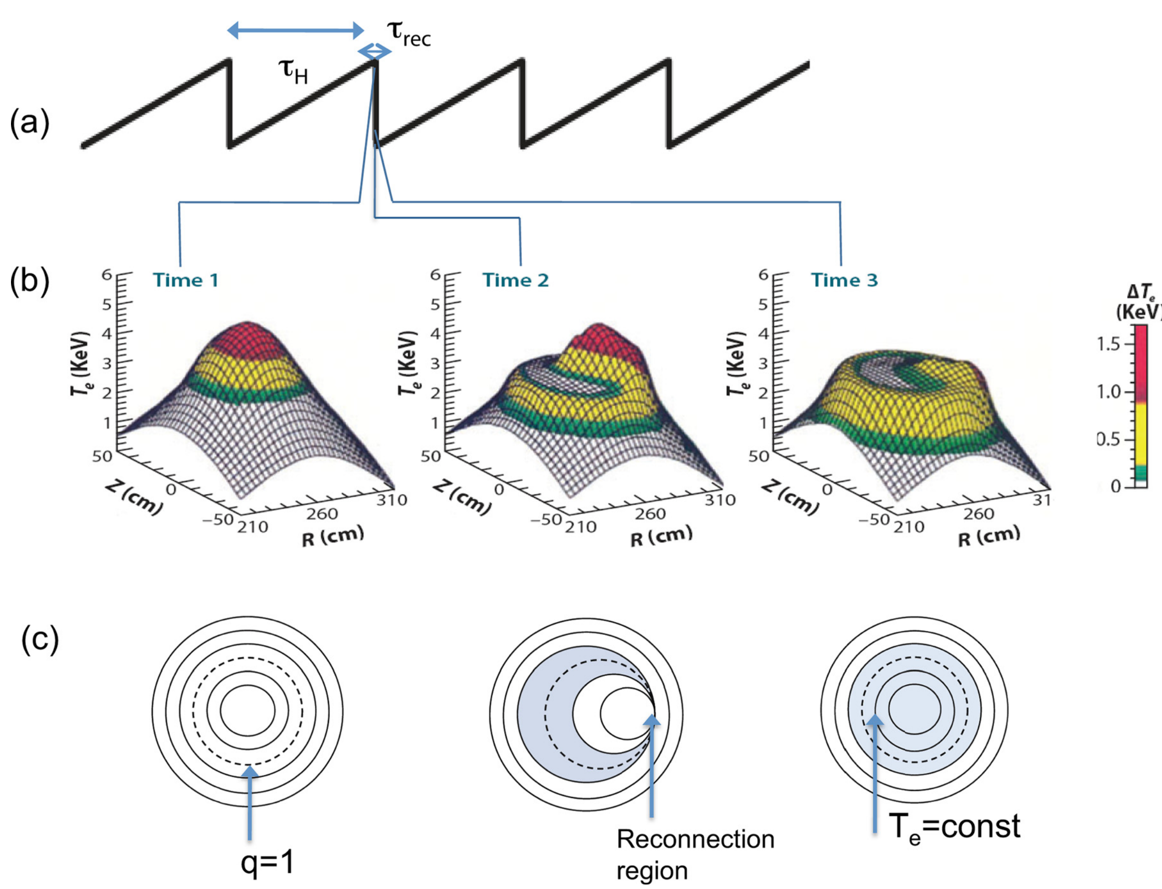

FIG. 1. (Color online) Evolution of measured central electron temperature (T_e) profile on a poloidal plane during a short crash phase, and expected flux surfaces during the same period based on MSE diagnostics. (a) Flux build up time (τ_H) is typically 100 ms and crash (reconnection) time (τ_{rec}) is 100–150 μs. (b) Crash phase evolution of $T_e(R, Z)$ during 150 μs. (c) Shaded (gray) area shows constant T_e region indicating field lines that are reconnected through the reconnection region. Broken lines show the original radius of q = 1 flux surface.[8]

phase. In the flux build-up phase, the current density in the central region increases, magnetic flux is injected into the region through a slow reconnection process, and the pressure of the central region increases since the energy injection rate is larger than the energy dissipation rate ($1/\tau_E$), and T_e increases. A tokamak plasma in a stable equilibrium is considered to consist of toroidally concentric nested flux surfaces on each of which T_e is constant, and the plasma is well confined on each flux surface.[7] Because of good thermal conductivity of electrons, the T_e(r,z) profiles represent the profiles of magnetic surfaces, where the (r,z) plane is a poloidal plane. A peaked T_e(r,z) profile generally leads to a more highly peaked current profile, in which a large amount of free energy is stored in the plasma. When the profile of magnetic field or plasma pressure in the core region reaches a certain state, an unstable MHD kink mode develops inside the $m = 1/n = 1$ resonant flux surface as shown in Figs. 1(b) and 1(c); where m, n stand for mode numbers in the poloidal and toroidal directions. As a result, the helically deformed plasma drives a fast magnetic reconnection (crash) at a point where a highly localized current sheet is formed in the $q = 1$ surface; q is the safety factor.[7] Reconnection occurs in this current sheet generating a topological rearrangement of the magnetic field lines, connecting the field lines of the outside and the inside of the $q = 1$ surface through a reconnection region. The peaked electron temperature becomes flat due to the fast electron heat conduction along the newly connected field lines while simultaneously making the toroidal current profile broader (Fig. 1(b)).[8,9] This makes the current and q profile more flat and reorganizes the plasma into a lower energy state; Fig. 1(c). The flow of flux is reversed from that of the flux build-up phase. When the field lines are reconfigured, the magnetic and plasma pressure gradient that drives the MHD instability is suddenly reduced and reconnection is terminated. This is a good example of impulsive reconnection which occurs in a short time ($\tau_{rec} \approx 200\,\mu$s.) after a long flux build-up time ($\tau_H \approx 200$ ms).

Generally the flux build-up phase is significantly longer than the reconnection time, $\tau_H \gg \tau_{Rec}$, thus making the waveform sawtooth shaped. Sometimes, heat loss from the central region occurs so quickly during the reconnection phase, due to the high heat conduction, that the magnetic reconnection can terminate before the relaxation process is complete.[8,9] Thus in a tokamak sawtooth crash, the Kadomtsev-type full reconnection is truncated because the high pressure gradient that drives a kink mode is reduced.[8] We note that this is a good example of the case in which evolution of the global plasma configuration is determined by the fast energy transport between the local reconnection layer and the global plasma during reconnection. Thus the current profile (or q profile) does not change much during this partial reconnection process.

In low-q pinch discharges in other laboratory fusion devices such as the spheromak and the RFP (reversed-field-pinch), we observe similar sawtooth events which also consist of a slow flux build-up phase through a slow reconnection and a fast reconnection/relaxation phase.[2] In the former phase, the current density in the center core gradually increases while in the latter an impulsive current profile flattening occurs with reconnection. Generally, reconnection occurs in the resonant flux surfaces in the plasma core and, under some conditions, at the edge. In some cases two unstable tearing modes in the core region are observed to couple to each other to nonlinearly drive reconnection at a third location in the outer plasma edge region.[10,11]

It is conjectured that similar phenomena occur in active solar arcade flares where spontaneous reconnection at one location can drive reconnection at other locations, leading to eruptions.[12] In solar flares, reconnection sites are identified with hard X-ray emissions near the top of solar flare arcades during CME (coronal mass ejection) and coronal eruptions.[13] Reconnection speed was measured to be much faster than the Sweet-Parker rate. We could hypothesize that global magnetic self-organization phenomena in both tokamak sawtooth crashes and solar flares share a common process. Klassen reported sawtooth phenomena in solar flares.[14] When reconnection occurs in a certain region of the globally connected plasma, a topology change results. A sudden change of magnetic flux over a short time is induced in a newly connected part of the global plasma. This leads to a large electric field along the magnetic field lines and acceleration of electrons to super thermal energy. Indeed in reconnection events in both solar flares and tokamak sawteeth, we observe a significant amount of high energy (runaway) electrons. A careful comparative study of tokamak sawteeth and RFP relaxation events should illuminate this important energy flow channel.

III. LOCAL ASPECTS OF IMPULSIVE RECONNECTION

A. The two-fluid dynamics in the collisionless reconnection layer

The plasma dynamics of the diffusion regions are very important in determining the reconnection rate and the flux transfer in the vicinity of the reconnection layer. During the past 12 years, important progress in understanding the physics of local reconnection in collisionless plasma has been made through numerical simulations, observations from satellites, and dedicated laboratory plasma experiments.[2,15] It is now recognized that two-fluid effects,[16–18] resulting from the different behavior of ions and electrons in the reconnection layer, are important within the critical layer where reconnection takes place. An important physical picture for the field structure and the dynamics of ion and electron flows in a typical neutral sheet (without guide field) was generated from the numerical calculations and the results from the Magnetic Reconnection Experiment (MRX).[22] Discussion of electron motions was presented by Ren *et al.*[23,24] and Yamada *et al.*[2] The laminar flows of electrons are analytically described in a calculation that includes Hall effects by Uzdensky and Kulsrud.[25] After these studies of the two-fluid physics of the local reconnection layer, Hall effects are now considered to facilitate the fast reconnection observed in the collisionless neutral sheets in the magnetosphere[19] and in laboratory plasmas.[18,20,21]

Using three components of the magnetic field vectors measured by a 2-D probe array, detailed measurements of two-fluid effects were carried out in MRX. In Fig. 2, the reconnecting field lines derived from three measured components of magnetic fields are shown in 3D. This figure is

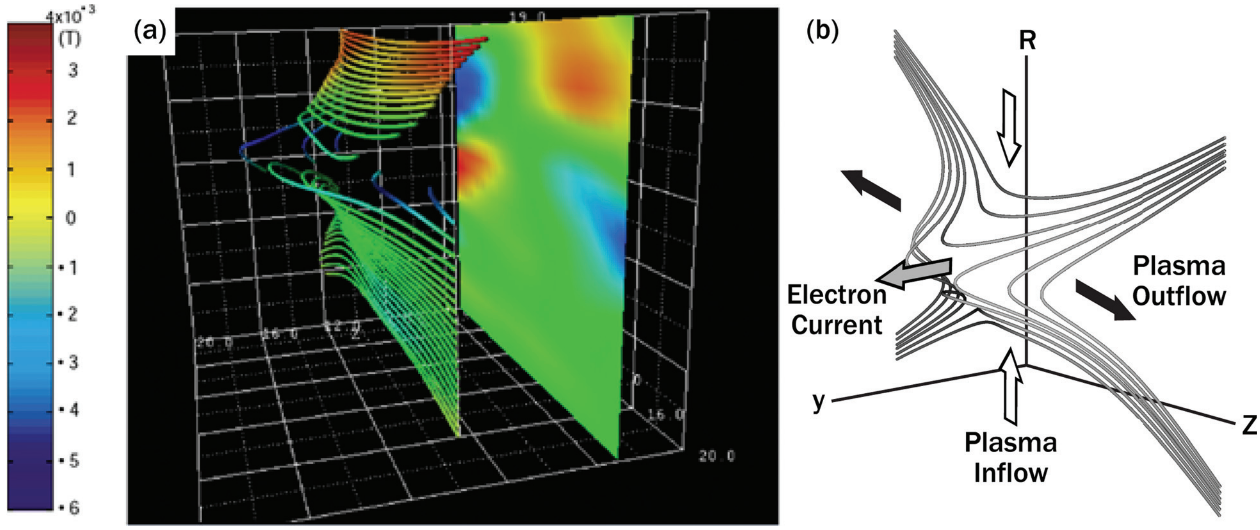

FIG. 2. (Color) (a) 3D profiles of reconnecting magnetic field lines measured in MRX, together with a schematic display (b) in the (R, Z, y) coordinates. The spatial resolution is 4 cm ($\sim c/\omega_{pi}$) in the Z direction (outflow) and 1 cm in the R direction (inflow) by scanning the probe radially and averaging several shots at each position. The field lines are stretched by the electron current flow in y direction (out of the reconnection plane).

generated by tracing field lines through magnetic field vectors, **B**, measured in the reconnection (R, Z) plane. It is seen that the field lines entering the reconnection region are stretched in the direction of electron current sheet.

B. Electron dynamics in the reconnection layer

Let us look into the flow dynamics of the electron fluids in the reconnection layer in the (R, Z) plane. The electrons which are initially bound to the reconnecting field lines enter the ion diffusion region flowing inward towards the X-point; Figs. 3(a) and 3(b) show electron flow vectors in a half reconnection plane. We describe this as the electrons' $E_y \times B_z$ motion making them migrate towards the X point, where the magnetic field weakens. This electron drift becomes larger near the X point. Without reconnection, a pileup of electron density would occur and a strong negative potential well would be formed. When reconnection happens, the electrons are ejected out from the X-region in both the y and z directions: Fig. 2(b). The electron flow pattern generates net circular currents in the reconnection (R, Z) plane and creates an out-of-plane magnetic field $B_y(R, Z)$ with a quadrupole profile shown in Fig. 2(a); a signature of the Hall effect. It is important to note that electrons are mostly not following magnetic field lines near the X-point region.

The in-plane current flows, $\mathbf{V}_d = \mathbf{V}_i - \mathbf{V}_e$, were derived in MRX from the measured out-of-plane Hall field $B_y(R, Z)$ profile from the relation $\mathbf{j}_{in} = -ne\mathbf{V}_e = \text{Curl } \mathbf{B}/\mu_0$ where it is safely assumed $\mathbf{V}_e \gg \mathbf{V}_i$ (measured as $\leq 0.1\ \mathbf{V}_A$). Fig. 3(a) shows electron flows in a half R-Z plane derived in the reconnection plane from the MRX measurements and compared with simulation results shown in Fig. 3(b). In Fig. 3(a), the outflow velocity is measured to be very large, verifying that the electron flows represent currents (except right at the separatrix regions where the electron and ion flow velocity can be comparable and cancel out). Fig. 3(b) shows, with a remarkable resemblance, the result from a two-fluid simulation in the same physical dimension by adjusting the size with respect to c/ω_{pi}. It shows a very similar pattern of electrons flows, namely, when electrons enter the diffusion region, they flow along the separatrices toward to X point. When they pass the separatrices, they make a sharp turn and are accelerated to a value much larger than the (ion) Alfvén velocity and flow to the exit directions.

An important result from the recent comparative study of the reconnection layer between experiments and 2D numerical

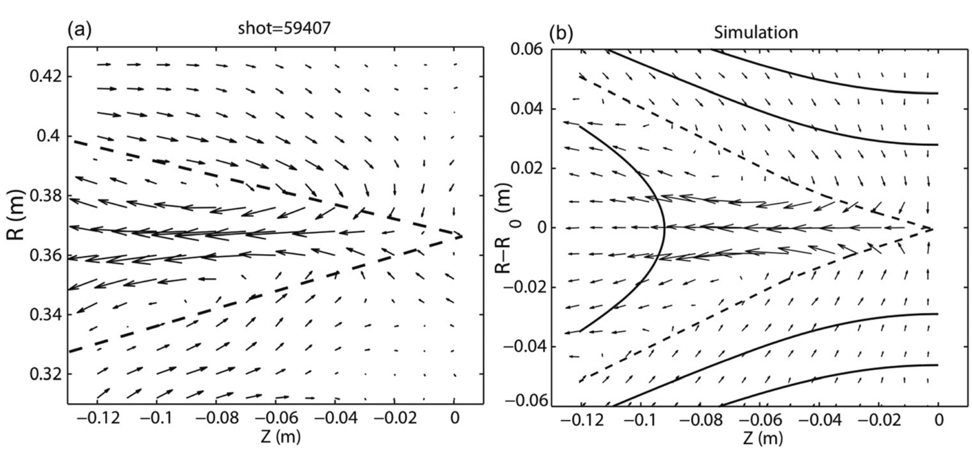

FIG. 3. (a) The electron drift velocity (arrows) in a half reconnection plane, $\mathbf{V}_d = \mathbf{V}_e - \mathbf{V}_i$, deduced from the out-of-plane field measurement and separatrices inferred (black broken lines) in a hydrogen plasma, fill pressure = 2 mTorr; (b) simulation: in-plane electron flows shown in arrows, flux lines in solid lines, and separatrices in broken lines from the numerical simulation by Breslau and Jardin (2003).

simulations is the demonstration of a two-scale diffusion layer, in which an electron diffusion layer resides inside the ion diffusion layer whose width is the ion skin depth (Pritchett,[35] Ren *et al.*[24]). It was found that demagnetized electrons are accelerated to a value that significantly exceeds V_A in the outflow direction in the reconnection plane. The width of the electron diffusion region, which is measured by the profile of the electron outflow with fine resolution ($\delta \sim 1$ mm) probe arrays [Ren *et al.*[24]], scales with the electron skin depth as 5–7 c/ω_{pe}. The electron outflow velocity scales with the local electron Alfvén velocity ($\sim V_{eA}$).

As magnetized electrons are mostly moving along the field lines except near the X-point, they also are simultaneously accelerated by the reconnecting field E_y, pulling the field lines in the y direction. This pulling deforms the reconnecting field lines to generate the out-of-reconnection-plane quadrupole field pattern shown in Fig. 2. This is another way of describing the observed Hall effect. The electron flow in the y direction should generate a radial potential drop towards the X point regions (or potential well), since the electrons convey the potential of the upstream points with their large electric conductivity. The strong negative potential in the (R, Z) plane which would be expected without reconnection is reduced. Recent measurements by the CLUSTER spacecraft[26] measured a very thin potential well, with a half width in the range of 60–100 km [(3–5) c/ω_{pe}], around the center of reconnection. This observation supports the above description of electron dynamics very well. If reconnection occurs slowly, a sharp negative potential build-up should occur due to the pile up of electrons.

C. Impulsive reconnection caused by unsteady electron diffusion layer dynamics

It is observed that these electron flows often fluctuate on a variety of time scales causing impulsive and turbulent reconnection. The electron current channel becomes unstable due to a sharp radial gradient of current density, making the local flux transfer rate fluctuate and generating impulsive reconnection. The reconnection rate measured by flux transfer rate at the diffusion layer was compared with the global rate of flux inflow rate by Ren[23] and an experimental campaign is being carried out on this topic in more detail on MRX.[27]

Let us examine how fluctuations correlate with reconnection rate based on the observation made by Ren on MRX.[23] The same coordinate system as Figs. 2(a) and 2(b) and Figs. 3(a) and 3(b) was employed. Multiple high-resolution magnetic pick-up probes were used to measure magnetic fluctuations at several locations in the (R, Z) plane near the electron diffusion region as shown in Fig. 4.

The reconnecting electric fields at three locations were monitored in Fig. 5; at the current sheet center (R = 37.5 cm) at two Z positions (Z = 0 cm and −9 cm) and upstream at R = 29 cm and Z = 0 cm. The reconnecting electric fields (reconnection speed) at the current sheet center show oscillating behavior (Fig. 5(c)) and their peaks in time evolution are followed by the large high frequency fluctuations measured (Figs. 5(b) and 5(a)). The reconnecting electric field at

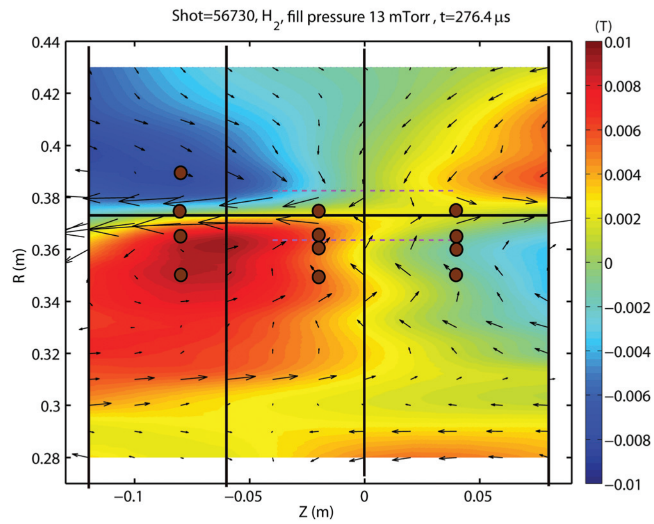

FIG. 4. (Color) The probe configuration of the experiment on MRX.[23] The fine magnetic probe arrays (vertical solid black lines) at Z = −12 cm, −6 cm, 0 cm, and 8 cm; the 4-channel magnetic fluctuation probe arrays (the brown filled circles showing the positions of individual coils) at Z = −8 cm, −3 cm, and 4 cm. The arrows represent the in-plane Hall current associate with the quadrupole out-of-plane field (color surface plot). The horizontal solid line denotes the position of the current sheet center (R = 37. 5 cm) and the horizontal magenta dashed lines show the current sheet edges. The electron current sheet resides in the range of R = 37.5 cm ± 1 cm, −10 cm < Z < 10 cm.

the upstream location shows much less oscillating behavior and is smaller than the reconnecting electric field at the current sheet center [Fig. 5(c)]. Since in a steady-state reconnection, the flux supplying rate ($\partial\psi/\partial t = E$) should be equal to the reconnecting flux rate, the data indicates that the reconnection occurring here is not steady-state and it can be described as impulsive or intermittent. The difference between the reconnection electric fields ($\partial\psi/\partial t = E$) at the reconnection layer and the upstream should lead to $dE_y/dR = \text{Curl } E = \partial B/\partial t \neq 0$, i.e., non-steady reconnection. This is an important example in which an external flux injection rate to drive reconnection does not match the fast impulsive reconnection rate caused by a local instability of the electron diffusion layer. On a long time scale, however, the local reconnection rate should adjust to balance an external rate of flux injection. The measured current sheet width changes with respect to time, and the broadening of the width coincides with the peaking of the reconnection rate Fig. 5(d). The reconnecting electric field at the off-center location (R = 37.5, Z = −9 cm) also shows oscillating behavior. Its peaks are delayed by about 2 μs compared to those of the reconnecting electric field at Z = 0 cm; Fig. 5(c). If the pulse of electric field is propagating from Z = 0 cm to Z = −9 cm, the corresponding velocity is about a half of the Alfvén velocity $\sim 4.5 \times 10^6$ cm/s in the system.

Also impulsive high frequency (> 6 MHz) magnetic fluctuations[28] were observed concomitantly with a sudden increase of reconnection rate. The correlation among the magnetic fluctuations, the electron flows, and reconnection rate at the current sheet center suggests the following picture: As the neutral sheet current narrows, the electron current sheet becomes unstable and suddenly disrupts generating broader current profiles in both the R and Z directions, the magnetic

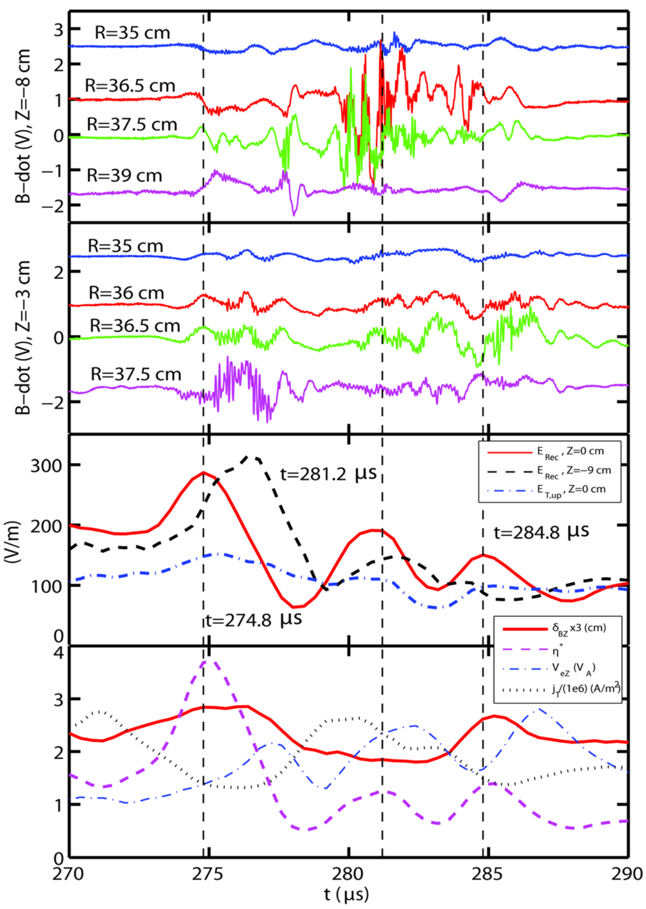

FIG. 5. (Color online) (a) and (b) B-dot ($=\partial B/\partial t$) signal from magnetic fluctuation probe arrays at $Z=-8$ cm and $Z=-3$ cm, respectively (with coil positions shown on top of each waveform); (c) reconnecting electric field ($\partial\psi/\partial t=E$) measured at current sheet at $Z=0$ cm (red solid line), at $Z=-9$ cm (black dashed line), and at $Z=0$ cm in the upstream ($R=29$ cm) (blue dashed-dotted line); (d) the current sheet width (in cm) measured at $Z=0$ cm (red solid line), the normalized resistivity ($\eta^*=\eta/\eta_{Spitzer}$) (magenta dashed line), the electron outflow velocity (V_{eZ}) at $Z=-6$ cm (blue dashed-dotted line) normalized by local Alfven velocity and the reconnecting current density (j_T: MA/m^2) (black dotted line). The vertical dashed lines show the times when the reconnecting E field at $Z=0$ cm peaks: Ren.[23]

fluctuations also propagate together with the reconnected magnetic field lines moving outward in both the R and Z directions. In other words, the outgoing electrons carry magnetic field lines with them accelerating the reconnection rate, and generating an impulsive reconnection event. In this instant, the local reconnection rate can significantly exceed the flux injection rate by external forcing. After the magnetic flux is ejected out of the reconnection region to exit region with a higher speed than the incoming flux rate, reconnection slows down and a slow flux build-up up resumes. The flux build-up phenomena are currently studied in MRX during driven experiments.[27] The sequence of flux build-up and sudden disruption of the magnetic profile is remarkably similar to the sawtooth reconnection phenomena observed in fusion plasmas mentioned in the earlier sections. The impulsiveness of reconnection can be related to a drift kink instability expected to occur in the local current sheet, while the cause of the sudden crash of the current profile is considered to be caused by an MHD instability in the tokamak plasma.

IV. MULTIPLE LAYER RECONNECTION AND IMPULSIVE RECONNECTION

Most of the work on reconnection in the past, both numerical and experimental, has investigated relatively small systems – 10–100 ion skin depths. In recent numerical simulations, it is found that multiple current sheets or reconnection layers develop in the reconnection region that can affect the reconnection rate in both collisional and collisionless regimes. Astrophysical systems are much larger than the characteristic scale of reconnection such as the ion skin depth and ion gyro-radius in collisionless plasmas, or the Sweet-Parker width in the collisional MHD plasmas. For example, in simple 2-D resistive MHD simulations for a significant Lundquist number ($S > 10^4$), a laminar Sweet-Parker layer is transformed into a chain of secondary magnetic islands and the reconnection process becomes inherently non-steady.[29,30] There should be mechanisms to generate multiple small scale current sheets in which field line reconnection takes place. In collisionless plasmas, the current sheet structures can be small enough to decouple the motion of electrons from that of ions. These smaller scale sheets can fluctuate leading to faster reconnection,[31] and a large number of these layers should lead to a large energy release such as seen, for example, in the magnetosphere and RFPs. In RFP plasmas, reconnection in multiple layers are observed to generate a significant magnetic self-organization of the global plasma and a strong ion heating,[10,11] which is currently under investigation. Intensive effort is underway to solve this problem.

Recently a kinetic 2-D numerical study of the reconnection layer found that a formation of plasmoids leads to impulsive reconnection.[31] This observation can be related to the recent results in MRX described in Sec. II. As an imbalance of incoming flux and out going flux at the electron diffusion region generates plasmoids or flux ropes, the reconnection rate becomes unsteady and fluctuates with large amplitude (50%). This process can invoke turbulence in the layer and the study has been extended to 3D to find out the structure of break-up. The appearance of multiple layers may become dominant particularly in 3-D system. Daughton *et al.* have recently found that a collisionless reconnection layer beaks up into many islands or flux ropes generating a highly turbulent reconnection region in their 3D simulation[32] as shown in Fig. 6. The majority of the flux ropes are formed by secondary instabilities within electron layers. These flux ropes appear spontaneously leading to a turbulent reconnection layer. We expect quite impulsive reconnection rates in this situation.

Their result suggests that turbulence can significantly broaden the electron diffusion regime as well as the ion diffusion region and the generalized Sweet-Parker model with an enhanced resistivity and viscosity can then describe the fast reconnection.

V. SUMMARY AND DISCUSSION

The local and global aspects of impulsive magnetic reconnection have been discussed focusing on results from a dedicated laboratory experiment as well as fusion experiments

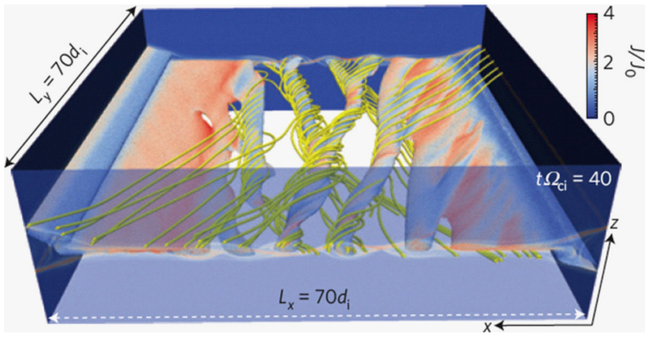

FIG. 6. (Color online) Formation of primary flux ropes. At early time $t = 40$ ($1/\omega_{ci}$), the tearing instability forms flux ropes as illustrated by an iso-surface of the particle density coloured by the magnitude of the current density (normalized) along with sample magnetic-field lines (yellow) (Ref. 32). Note that their coordinate system (Z, x, y) should correspond to our (R, Z, y) system employed in the rest of figures of the present paper.

in which the global conditions are controlled externally and the global and local plasma parameters are quantitatively monitored. The results were compared with the cases of magnetic reconnection in solar flares and in the magnetosphere to bring out a common picture.

In formation of fusion plasma equilibrium with internal current, flux build-up occurs in a core section of the plasma. When the magnetic profile reaches a condition for a global MHD instability to develop, a deformation of the plasma profile takes place inducing a current layer in which reconnection occurs. During the reconnection phase, it is found that if the total energy of the global MHD equilibrium state is lowered by a re-organization of plasma topology, reconnection proceeds. Reconnection would stop if it would no longer lower the total free energy. Generally, the flux build-up phase is significantly longer than the reconnection time, $\tau_H \gg \tau_{Rec}$, thus making the waveform of flux evolution sawtooth shaped. We have also addressed the energy transport between the local reconnection layer and the global plasma. Magnetic self-organization of plasma is found to be often affected by the energy or particle transport between the local region and the global plasma. Examples are found in tokamak "sawtooth" and RFP relaxation phenomena.

In the laboratory experiments, we have addressed how global systems generate local reconnection structures through formation of one or multiple current sheets, either spontaneously or forced by boundary conditions. Investigating the interrelated occurrence of multiple reconnection layers should provide a key to resolving fast magnetic self-organization. In toroidal fusion devices reconnection occurs in the resonant flux surfaces in the plasma core and, under some conditions, at the edge. In the RFP, two unstable tearing modes in the core region are observed to couple to each other to nonlinearly drive reconnection at a third location in the outer plasma edge region.[10,11] Recently multiple reconnection layers have been documented by 2-D ECE (electron cyclotron emission) diagnostics during the sawtooth crash in a tokamak device and it is found that their 3 dimensional features affect the reconnection rate.[33,34]

In the local analysis of collisionless reconnection, the two-fluid dynamics lead to the formation of a narrow electron current channel. If external flux injection is applied to a plasma slowly enough to match the local reconnection rate at the reconnection layer, reconnection occurs quasi-steadily. On the other hand, if flux inflow is faster than the intrinsic reconnection rate at the layer, a flux build-up occurs and an impulsive reconnection is induced after the build-up reaches a threshold value for an instability to take place. The reconnection can be triggered and driven by a micro-instability that is excited in the reconnection layer (as seen in the MRX reconnection layer) or that is driven by global evolution of plasma profiles (as seen in tokamak and RFP devices). There is a clear commonality in the sequence of impulsive reconnection in these cases; it is accelerated by a spontaneous instability after a slow build-up of injected fluxes: $\tau_{\text{flux-build}} \gg \tau_{\text{Rec}}$. When local reconnection occurs very fast at the layer compared to the time scale for the inflow of flux, the reconnection rate slows down after fast flux transfer and reconnection rate becomes unsteady and impulsive. In this situation the overall reconnection rate (time-averaged) is determined by external flux inject rate, namely external forcing.

In a large plasma system such as seen in astrophysical environments, the reconnection layer can easily form multiple islands or flux ropes through secondary instabilities within electron layers. These flux ropes appear spontaneously leading to a turbulent reconnection layer. We expect quite unsteady reconnection in this situation. This type of multilayer reconnection can occur in space or solar flares resulting in impulsive particle acceleration.[14] If a local reconnection occurs steadily, the magnetic flux outside of the layer moves slowly, the system transforms with a quasi-static manner, and a steady reconnection can be realized as conjectured by Parker.[1] However the externally given flux injection rate does not generally match the intrinsic rate of flux transfer in the local reconnection layer(s). Thus reconnection often tends to be unsteady or impulsive.

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