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Collisionless Magnetic Reconnection in a Toroidal Magnetic Cusp

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1. Introduction

Magnetic reconnection, the rearrangement of magnetic field lines in the presence of plasma [1], originates from microscopic processes but affects plasma properties over macroscopic regions. Reconnection plays a fundamental role in solar flares [2], in the interaction between the solar wind and the planets' magnetic field [3], and is associated with fast internal relaxation processes in fusion devices [4]. A number of questions remain open in the physics of magnetic reconnection. For example, although the structure of the magnetic fields around the magnetic null point and of the associated current layer has been observed to follow theory predictions [5], the reason for the large enhancement in the resistivity needed to account for the observed fast time scales in collisionless regimes has not been found so far.

2. Goal of the experiment

A new experimental investigation of the plasma dynamics during reconnection around the magnetic null region in a collision-less MHD regime should have the following properties. A plasma with sufficiently low collisionality to obtain flux conservation everywhere but in a layer around the magnetic null region must be created. The plasma should be confined for a time longer than the reconnection time. The plasma formation stage should be separated from the reconnection stage. The plasma dimensions should be sufficiently large to prevent edge effects from becoming significant and to allow the possible generation of MHD waves. Diagnostic of the magnetic fields and currents in the vicinity of the magnetic null region should be possible with adequate time and space resolution to characterise the driven reconnection. A diagnostic capable of measuring plasma instabilities during the reconnection process should be available. Measurements of particle fluxes and particle distribution functions in the magnetic null region should be available.

The link between the induced change in magnetic topology and the particle dynamics is the primary goal of this investigation. Insight into the basic physics of reconnection will be gained by combining measurements of particle flow velocities and distribution functions with the evolution of the magnetic field line structure and the associated plasma fluctuations.

3. Plasma production and confinement

Most of the above requirements are satisfied by the recently modified Versatile Toroidal Facility, VTF, at the MIT Plasma Science and Fusion Center. The VTF vacuum vessel has a major radius of 92 cm and a rectangular cross-section with horizontal and vertical dimensions of 64 cm and 108 cm. The poloidal cusp field is generated around the torus by four sets of coils installed outside the vacuum vessel and carrying a current up to 200 kA, corresponding to a cusp field magnitude of up to 0.06 T (at 0.2 m from the centre). A toroidal magnetic field up to 0.2 T can also be applied using 18 coils mounted around the VTF vessel. The plasma discharge is created by electron cyclotron resonance heating using a 50 kW klystron micro-wave source at 2.45 GHz. The stainless steel horn antenna used to couple the RF power is visible on Figure 1, which shows a poloidal section of the VTF device.

The confinement of the particles is achieved through the reflection of particles at zones with high magnetic field strength, consequence of the adiabatic invariance of the magnetic moment. In accordance with theoretical calculations, the first measurements suggest that by adding a modest toroidal component to the cusp field the magnetic moment is conserved throughout the poloidal magnetic null region (Figure 2). Guiding centre calculations indicate that curvature and ∇B drifts have no significant effect on the particle confinement. Argon and hydrogen plasmas are routinely created by ECRH with densities and temperatures up to 10^{18} m^{-3} and 30 eV, and Lundquist numbers of the order of 500-1000. These conditions are suitable for the study of magnetic reconnection in a regime where the collisional mean free paths of electrons and ions are much larger than the dimensions of the reconnection layer.

4. Plasma diagnostics

Several diagnostic methods can be used for the field reconstruction and for the particle dynamics. In addition to conventional Langmuir probes, a multiple Mach probe has been installed to map density, electron temperature and flows across the poloidal plane. The probe consists of a ceramic tube to which five smaller tubes are connected, each with four electrodes placed 90^0 apart. A movable 90-channel magnetic probe with three rods, each including 30 coils (10 for each spatial direction), is being installed to reconstruct the evolution magnetic flux during the reconnection process. A microwave interferometer is used to calibrate probe density measurements. Active optical methods such as laser induced fluorescence, LIF, will be applied for the determination of the ion response during the reconnection process. A narrowband, Nd:YAG-pumped pulsed dye laser will be used to pump the ArII 611 nm line and induce LIF over the whole poloidal cross-section.

5. Driven reconnection: experimental method and initial results

VTF is equipped with an ohmic coil system fed by a resonant LC circuit with currents up to 4 kA. Reconnection is driven by the $\mathbf{E}\times\mathbf{B}$ drift resulting from the combination of the poloidal magnetic cusp field and the toroidal electric field induced by the ohmic transformer. For the present coil configuration, the speed at which the plasma drifts into the magnetic null region, forcing reconnection, is of the order of 3 km/s, corresponding to about $0.1v_A$, where v_A is the Alfvén speed calculated 30 cm away from the centre. Figure 3 illustrates the method used on VTF to drive reconnection, along with measurements of ohmic transformer current for a single coil turn and corresponding loop voltages during a typical pulse.

The effects of the reconnection drive in the case of a relatively strong toroidal field are shown in Figure 4. On the left we represent the density contours at different times during the cycle of reconnection drive, for the indicated values of the toroidal electric field. The effect of the inward/outward plasma flow is clearly seen. The density appears to be nearly constant along field lines and to be a function of the flux variable. The observations of radial and vertical components of the flow induced by the reconnection drive are reported on Figure 4 (right) for two different values of the toroidal electric field. The direction of the flows are as expected, although their magnitudes seem to exceed the calculated v_{ExB}.

Despite relatively large values of the imposed loop voltage, no evidence of a significant toroidal plasma current has been found in such configuration. This, together with the observation that the plasma flows across the separatrix, suggests that fast magnetic reconnection is achieved in VTF. During the reconnection drive, broad band fluctuations have been observed using magnetic and electrostatic probes for frequencies up to 20 MHz. The magnitude of the fluctuations appears to be maximum where and when the driven flows are the strongest. Although experimental investigations in different regimes still need to be undertaken, together with a full reconstruction of the magnetic flux evolution, these fluctuations do not appear to be strong enough to generate significant anomalous resistivity.

An alternative mechanism for fast reconnection, i.e. for a large effective resistivity in the absence of collisions, can be found in the particle inertia effect [6], related to the finite particle transit time through the region of acceleration by the electric field. Consistently with the idea of particle inertial resistivity, significant toroidal currents, up to 1 kA, are measured only for large values of the ratio between the toroidal and the cusp magnetic field intensity.

6. Conclusions

A new experimental approach to the study of magnetic reconnection physics has been undertaken on the MIT-PSFC VTF device, based on a toroidal cusp configuration with separate plasma production (by ECRH) and reconnection drive (by **E**×**B** drift). The achieved temperatures, densities and drift velocities are suitable for investigating various aspects of reconnection physics in a collision-less regime, including the combined effect of plasma flows, particle orbits, and the development of instabilities on the possible enhancement of the plasma resistivity, and the associated transfer of energy from magnetic fields to particles.

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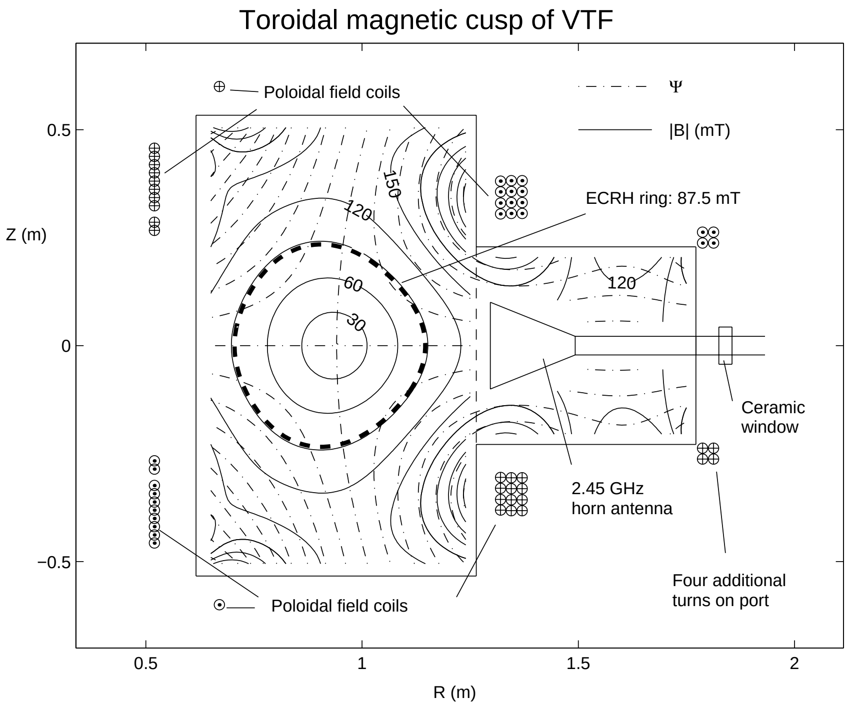

Fig.1 *VTF cross section. The solid contours represent the poloidal magnetic field strength. The dashed contours correspond to constant levels of poloidal magnetic flux.*

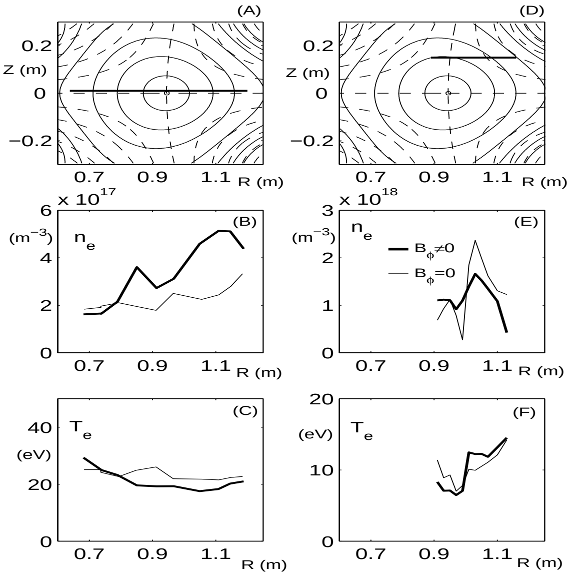

Fig.2 *Plasma profile measurements with Langmuir probes. A, D: probe location. B, C, E, F: density and temperature measurements, with and without a toroidal field.*

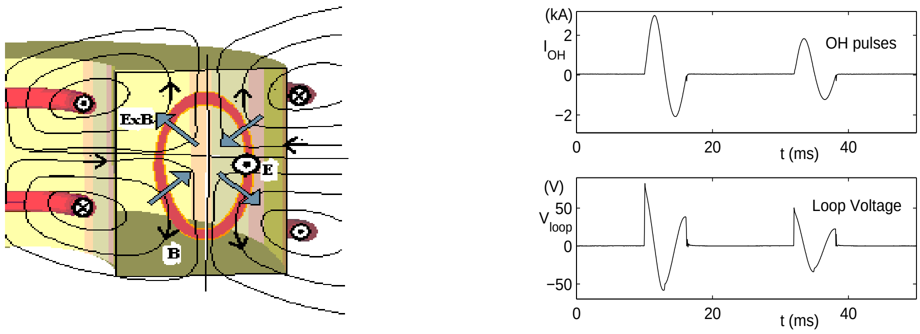

Fig.3 *Left: sketch of VTF reconnection drive. Right: measured coil currents and loop voltage*

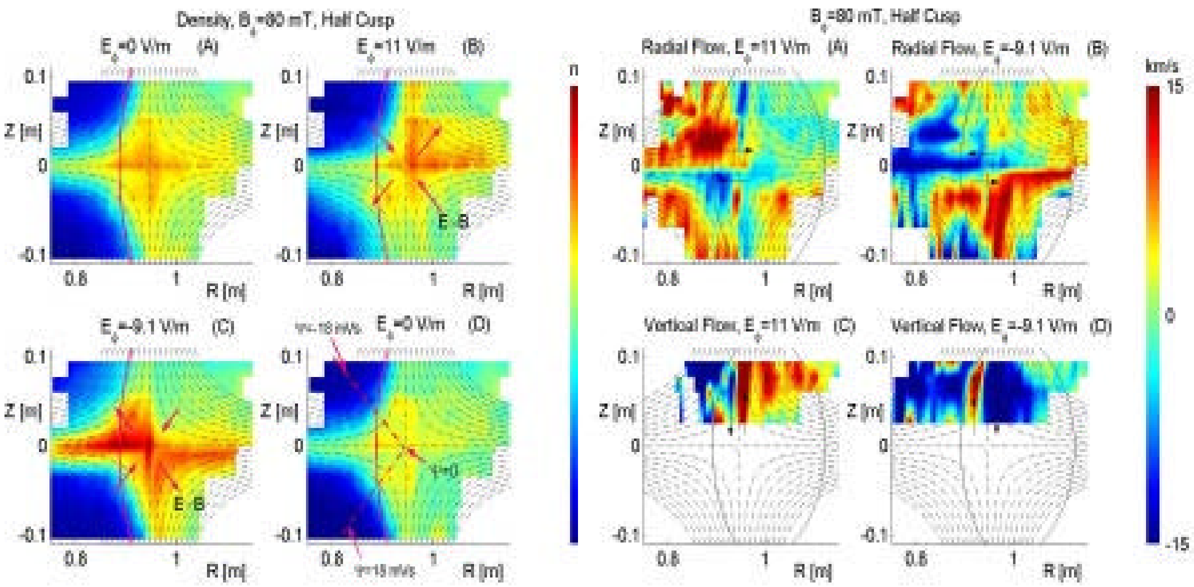

Fig.4 *Effect of reconnection drive on VTF. Left: density contours. Right: flow measurements*