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Momentum Transport during Spontaneous Reconnection Events in the MST Reversed Field Pinch

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1. Introduction

Plasma rotation plays a central role in the toroidal magnetic fusion configurations providing stabilization of resistive wall modes, formation of the internal transport barriers, and assisting in transition to the high-confinement H-mode. Therefore, the underlying physics of flow generation and transport is currently a subject of intensive research.

Madison Symmetric Torus (MST) [1] is a reversed field pinch (RFP) [major radius R=1.5m, minor radius a=0.52m], toroidal plasma configuration similar to a tokamak. However, because of a relatively weak toroidal magnetic field, the magnetic field in RFP is strongly sheared and multiple resonant surfaces, where the safety factor $q(r)=rB_t/RB_p$ is a rational number m/n, exist across the minor radius. Standard MST discharges exhibit quasi-periodic sawtooth-like magnetic reconnection (relaxation) events with a duration of ~0.2 ms, when amplitudes of the tearing modes ($f \leq 50$ kHz) increase several-fold. These events are characterized in part by generation of toroidal magnetic flux from the increased dynamo activity. Previous experiments have observed rapid radial transport of the momentum parallel to the magnetic field at the reconnection events [2] and established that coupling of the multiple tearing modes plays an essential role [3]. Momentum profile relaxation has been also predicted by the two-fluid magnetohydrodynamic (MHD) theory [4] and observed in the nonlinear MHD computations [5].

In this article we report detailed measurements of the parallel momentum profile relaxation during magnetic reconnection in the MST RFP. We also discuss parallel momentum balance in the core and in the edge and present measurements of the torques (stresses) arising from tearing instability. In the core, only the Maxwell stress is measured and it is an order of magnitude larger than the ion inertia term. In the edge, both Maxwell and Reynolds stresses are also individually large, however they are oppositely directed with the difference approximately equal to the rate of change of plasma momentum.

2. Measurements of the momentum transport during spontaneous reconnection events

New diagnostics have been employed to characterize the plasma flow dynamics during reconnection events with improved spatial resolution. The parallel velocity in the core is reconstructed from the poloidal velocity of the bulk plasma, measured with the Rutherford scattering diagnostic [6], and the toroidal phase velocity of the core resonant resistive tearing modes, measured with an edge array of 32 magnetic pick-up coils. The edge flow is measured by the Mach probe. The experiments have been performed in standard MST discharges with a relatively low plasma current I_p=200-250 kA, which allowed routine operation of the probes in the plasma edge. The other operating parameters were: the line averaged plasma density $n=1\times10^{13}$ cm^{-3}, the reversal parameter F=-0.2, the pinch parameter Θ=1.7.

Fig. 1(a) presents the evolution of the radial profile of the parallel momentum normalized by the magnetic field amplitude, and Fig. 1(b) shows the parallel velocity at three radial locations through the reconnection event. Quiescent MST plasma exhibits spontaneous rotation, which peaks at the plasma center. At the global reconnection event the parallel velocity abruptly decreases in the core and speeds up in the edge which results in the flattening of the parallel momentum profile. The transport of parallel momentum occurs much faster than can be explained by the classical collisional diffusion.

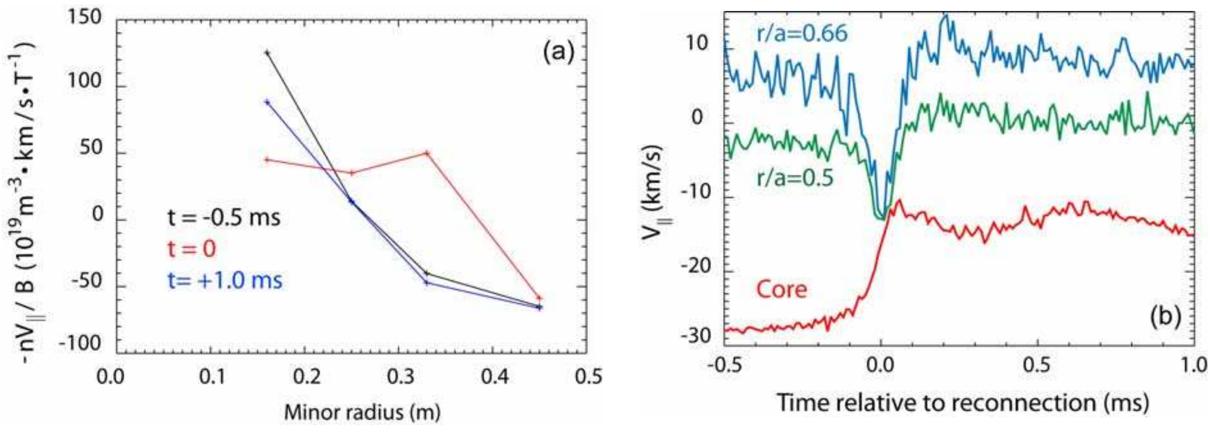

Fig.1. (a) Radial profile of the parallel momentum evolution (normalized by the magnetic field). (b) Parallel velocity at three radial locations through the reconnection event in MST.

3. Momentum balance in the core and in the edge and measurements of the stresses

To investigate the cause of momentum transport let us examine the parallel mean-field momentum balance equation, which in the framework of MHD can be written as

$$\rho\frac{\partial\langle V_\parallel\rangle}{\partial t}=\langle\tilde{\mathrm{j}}\times\tilde{\mathrm{B}}\rangle_\parallel-\rho\langle\tilde{\mathrm{V}}\nabla\tilde{\mathrm{V}}\rangle_\parallel, \tag{1}$$

where j, B, V, ρ are the current density, magnetic field, plasma velocity and the mass density, respectively. The first term on the right hand side represents the Maxwell stress. The second term is the Reynolds stress. The other terms, e.g. classical diffusion, has been neglected. To derive Eq. (1), we (a) represented each plasma quantity as a sum of its mean-field value and a non-axisymmetric fluctuating component (denoted by a tilde), (b) performed averaging over magnetic flux-surface (denoted by <…>), and (c) took the component parallel to the unperturbed equilibrium magnetic field.

In the core, near the q=1/6 resonant surface, the parallel component of the fluctuation-induced Maxwell stress has been measured using the high-speed laser Faraday rotation diagnostic [7]. The large increase in the Maxwell stress torque is observed during the reconnection event. The torque is an order of magnitude larger than the change in the plasma rotation and also oppositely directed (Fig. 2(a)). This suggests that other terms in the momentum balance equation must play an important role and the Reynolds stress looks like the most plausible candidate to balance the Maxwell stress in the core. A toroidal CHERS system is presently under construction to evaluate the Reynolds stress there.

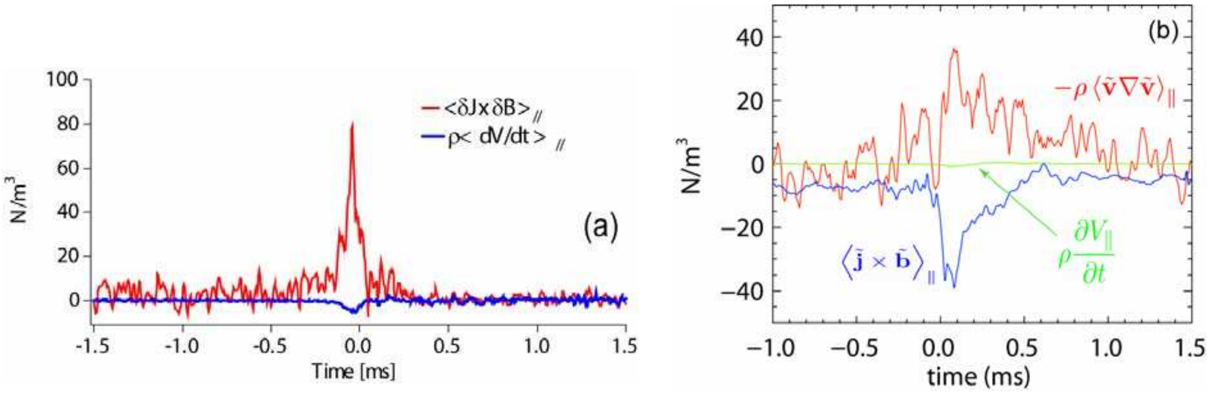

Fig.2. (a) Comparison of the Maxwell stress and inertial terms in the parallel momentum balance equation in the core, near q=1/6 resonant surface. (b) Momentum balance in the edge, near the reversal surface, through the reconnection event. Rapid oscillations in the data curves indicate experimental uncertainty.

In the edge, we have employed insertable probes to measure both the fluctuation-induced Maxwell and Reynolds stresses [8]. It can be shown that the expression for the parallel (poloidal) component of the Maxwell stress in the cylindrical approximation can be represented as $\langle \tilde{\mathrm{j}} \times \tilde{\mathrm{B}} \rangle_{\parallel} = \frac{1}{\mu_0}\left(\frac{\partial}{\partial r} + \frac{2}{r}\right)\langle \tilde{B}_r \tilde{B}_\theta \rangle$, and the Reynolds stress as $\langle \tilde{\mathrm{v}} \nabla \tilde{\mathrm{v}} \rangle_{\parallel} = \left(\frac{\partial}{\partial r} + \frac{2}{r}\right)\langle \tilde{\mathrm{v}}_r \tilde{\mathrm{v}}_\theta \rangle$ (assuming that plasma is incompressible, i.e. $\nabla \cdot \mathrm{V} = 0$). Thus, measurement of the fluctuation-induced stresses requires evaluation of the magnetic field (or velocity) correlator at one spatial location in a given discharge and then calculation of the radial derivative relying on good shot-to-shot reproducibility. For the Maxwell stress measurements we have utilized a magnetic probe, which is composed of six magnetic coil triplets separated spatially by ~1.5 cm. The Reynolds stress is measured using a combination of an optical and a Mach probe placed inside the plasma at a distance much smaller than the characteristic wavelength of the fluctuations of interest. The optical probe measures the radial ion velocity fluctuations locally using the Doppler spectroscopy [9]. The Mach probe consists of four current collectors biased with respect to the reference tip and allows for measurements of the poloidal and toroidal components of the bulk plasma flow. The results presented in Fig. 2(b) demonstrate that the Maxwell and Reynolds stresses approximately balance each other in the edge, near the reversal surface, with the difference on the order of the ion inertia term.

The momentum transport problem appears to be closely coupled to the current density transport, since the Maxwell stress term also enters the Ohm's law, where it balances the parallel electric field near the corresponding resonant surfaces in the core [10] and in the edge [11]. This phenomenon is also known as the Hall dynamo effect. Therefore, the need for the large Maxwell stress to balance the electric field in the Ohm's law may automatically require a large Reynolds stress to preserve the momentum balance.

To study further the relationship between the momentum transport and tearing fluctuations, we have also carried out experiments, where external torque was transiently applied to the plasma edge with biased electrodes. The slowing down time of the core plasma rotation after removing the torque is five times larger in the improved confinement discharges (with reduced tearing activity due to inductive current profile control) than in standard discharges in agreement with previously observed reduction of particle and energy transport. These results will be a subject of future publications.

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