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LETTER

Recent improvements in confinement and beta in the MST reversed-field pinch

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Abstract
In the general area of confinement improvement and concept advancement, recent results in the Madison Symmetric Torus (MST) reversed-field pinch (RFP) include good confinement of both thermal and large-orbit ions and near doubling of total beta to 26% with deuterium pellet injection. Current profile control enables MST to reduce stochastic transport and achieve tokamak-like confinement. In standard RFP operation, substantial MHD tearing mode activity results in stochastic transport and an energy confinement time of about 1 ms in MST. Application of inductive current profile control reduces MHD activity and accompanying stochasticity, improving confinement by about a factor of ten. Previous work concentrated on electron confinement in improved-confinement RFP operation. Recent work confirms that ions are also well confined, and that high beta and improved confinement can be achieved simultaneously.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

The reversed-field pinch (RFP), and most magnetic-confinement configurations, face four major challenges on the path to fusion: confinement, beta, current sustainment, and resistive wall instabilities. The Madison Symmetric Torus (MST) experiment has recently advanced the RFP concept in the first three of these areas by demonstrating good confinement of both thermal and large-orbit ions, near doubling of total beta (β_{tot}) to 26% with deuterium pellet injection and current drive of 10% of I_p by oscillating field current drive. The fourth area, resistive wall instabilities, has not been a focus of

MST research, but outstanding advances have been made on two other RFP experiments, RFX [1] and EXTRAP T2R [2]. This paper will report recent results from MST in the areas of confinement and beta; work on oscillating field current drive is described in [3].

In standard RFP operation, substantial MHD tearing mode activity results in stochastic transport and a confinement time of about 1 ms in MST. Application of inductive current profile control reduces MHD activity and accompanying stochasticity, improving-confinement by about a factor of ten [4,5]. Previous work concentrated on electron confinement in improved confinement RFP operation [6]. The work reported here confirms that ions are also well-confined, and that high beta and improved confinement can be achieved simultaneously.

The RFP can be broadly defined as 'toroidal plasma confinement with a low magnetic field' [7]. The magnitude of the magnetic field in an RFP is typically ∼10 times smaller than a similar plasma current tokamak; in the core of an RFP $B_\phi \approx B_\theta$ and $\beta_{\rm tot} \geqslant 10\%$. Furthermore, in an RFP the toroidal magnetic field goes to zero and then reverses sign near the edge of the plasma. Self-generated plasma currents that drive magnetic reconnection substantially determine the magnetic field equilibrium of a standard RFP discharge. The low toroidal field at the edge is a substantial advantage for the RFP as a potential fusion reactor, since coil stresses will be relatively low.

MST is a large RFP with major radius $R = 1.5$ m, minor radius $a = 0.5$ m and a thick (5 cm) aluminium conducting shell [8]. Typical plasma parameter ranges in MST are toroidal plasma current $I_{\rm p}$ 0.2–0.6 MA, $|\boldsymbol{B}| \leqslant 0.6$ T, electron density $n_{\rm e}$ (0.5–4) $\times 10^{13}$ cm^{-3} and electron $T_{\rm e}$ and ion $T_{\rm i}$ temperatures 0.1–2 keV. A typical plasma discharge is approximately 70 ms in duration, with a 20–30 ms 'flat-top' in which the plasma current is nearly constant and the plasma is approximately in equilibrium.

The second section describes recent results from MST in the area of thermal and fast (large-orbit) ion confinement. The third section describes the progress that has been made in achieving high density and beta by injection of frozen deuterium pellets. The last section is a brief summary.

2. Thermal and fast ion confinement

2.1. Thermal ion confinement

Standard RFP plasmas exhibit substantial magnetic reconnection activity driven by multiple tearing modes. The safety factor q is $\ll$1 on axis and decreases towards the edge, passing through zero and becoming negative; as a result, $m = 1$ tearing modes are resonant on multiple rational surfaces. Bursts of tearing mode activity occur periodically, typically every few milliseconds, during a standard RFP discharge. These are global reconnection events, and are somewhat similar to a tokamak sawtooth. Both impurity and majority ions are heated ('self-heated') during a global reconnection event. The mechanism of this heating is not yet understood. Charge-exchange spectroscopy measurements [9, 10] of the impurity ion temperature profile show that $T_{\rm i}$ increases significantly in approximately 0.1 ms [11]. During a global reconnection event in which both core $m = 1$ and edge $m = 0$ tearing modes show a burst of activity, the temperature more than doubles and the temperature increase is global, occurring throughout the volume of the plasma (figure 1).

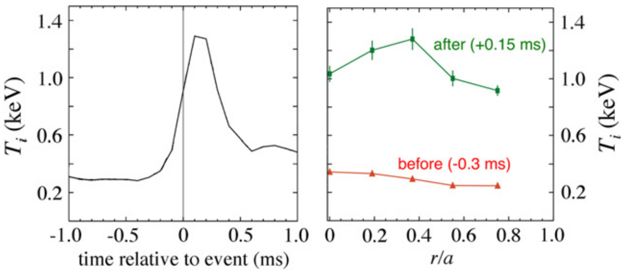

Figure 1. Left: the impurity (C^{+6}) ion temperature at $r/a = 0.37$ through a global reconnection event. Right: radial profiles of the impurity ion temperature before and after a global reconnection event.

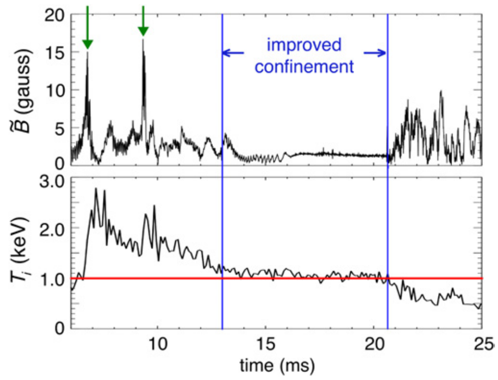

Figure 2. (Top) Magnetic fluctuation amplitude is reduced during the improved-confinement period. (Bottom) C^{+6} impurity ion temperature is sustained at approximately 1 keV. The two vertical arrows mark reconnection events during which ions are strongly heated.

In standard RFP operation, ion temperature normally drops rapidly following a reconnection event (figure 1). But by initiating an improved-confinement period (by application of inductive current profile control) following a reconnection event, ion energy can be retained in the plasma for the duration of the improved-confinement period (figure 2). Ion temperature is sustained at a high level, typically $\geqslant$1 keV, during the improved-confinement period [12]. Charge-exchange recombination spectroscopy and Rutherford scattering measurements confirm that both impurity and majority ions are heated and sustained at a high temperature.

Electron temperature is also greater than 1 keV in these improved-confinement discharges (figure 3). This confirms that the improved confinement resulting from current profile control applies to both electrons and ions. Both electron and ion temperatures have now been measured to be simultaneously $\geqslant$1 keV during improved-confinement periods. These temperatures are achieved with only a few megawatts of ohmic input power to the plasma. A detailed transport analysis is underway using the equilibrium reconstruction code MSTFit.

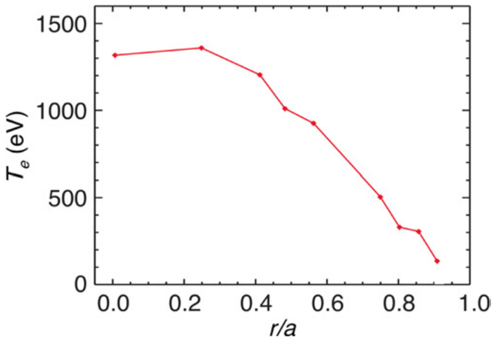

Figure 3. Electron temperature as measured by Thomson scattering is also greater than 1 keV during improved-confinement discharges.

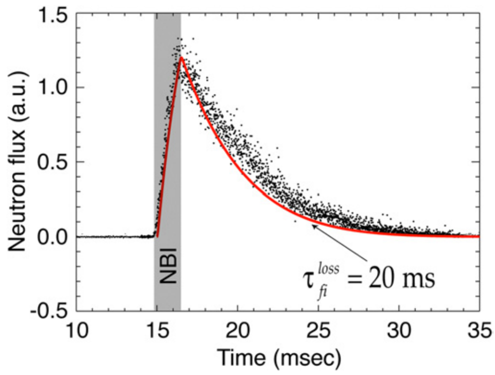

Figure 4. Comparison of measured neutron signal (dots) and modelling (solid line). The shaded area represents the neutral beam injection duration. The solid $\tau_{\mathrm{fi}}^{\mathrm{loss}} = 20$ ms line is a result of modelling with classical fast-ion slowing down and 20 ms fast-ion confinement time.

2.2. *Fast-ion confinement*

One of the consequences of the fluctuation activity in standard RFP discharges is magnetic stochasticity, yet measured confinement (>20 ms) of injected fast ions is much better than that expected (∼1 ms) if the ions simply stream along the stochastic field lines [13]. This experimental investigation was carried out with a short-pulse (1.3 ms) of fast (20 keV) deuterium neutrals injected into a deuterium plasma in MST. Fusion D–D neutrons from fast-ion/plasma-ion collisions were recorded by a scintillator detector. The decay of this neutron signal indicates that the fast-ion confinement is >20 ms (figure 4); the fast ion slowing down is as expected from classical coulomb collisions with plasma electrons and ions. Full orbit numerical calculation of particle trajectories in the stochastic field of the RFP indicates that these large gyro-orbit ions do not follow the magnetic field lines (figure 5) until they have deposited most of their energy into the plasma; only then are they stochastically transported out of the plasma. This has positive implications for the feasibility of neutral beam injection and alpha-particle confinement.

3. High density and beta from pellet injection

Injection of frozen deuterium pellets [14] triples density in improved-confinement plasmas, while maintaining fluctuations at a reduced level [15]. Figure 6 is a representative

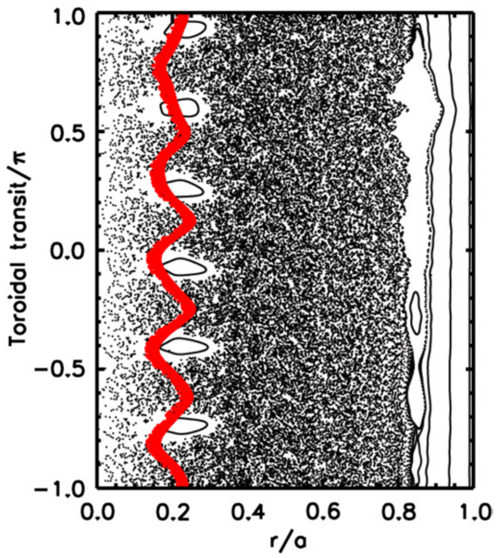

Figure 5. A puncture plot of magnetic field lines (dots) and a fast-ion orbit guiding centre (solid line) from a simulation of a standard RFP discharge. Full orbit simulation shows that fast-ion drift orbits do not follow the magnetic field lines, resulting in different rotational transforms for fast ions and magnetic field lines.

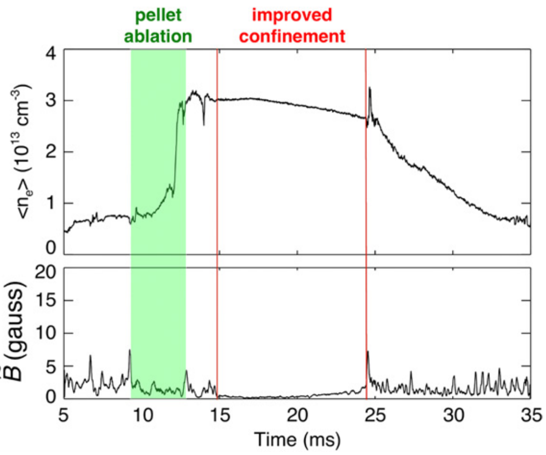

Figure 6. Injection of a frozen deuterium pellet at the start of an improved-confinement period triples the line-average electron density while magnetic fluctuations are maintained at a reduced level. Pellet ablation occurs during the shaded time, and the improved-confinement period is delimited by vertical lines.

example of a single discharge into which a pellet was injected. Pellet injection has been done at both low plasma currents (<200 kA) and high currents (∼500 kA) with approximately similar tripling of the density. Fuelling the plasma to high density by gas puffing does not maintain fluctuations at a low level. Total beta β_{tot} (including both electron and ion contributions) nearly doubles to 26% with pellet injection into low current plasmas; at high current β_{tot} is approximately 17%. Total beta is defined as $\beta_{\mathrm{tot}} = 2\,\mu_0\langle p\rangle_{\mathrm{V}}/(B_\phi^2 + B_\theta^2)_{r=a}$, where the pressure is volume-averaged and the magnetic field measured at the plasma surface. Toroidal beta, $\beta_{\mathrm{toroidal}} = 2\mu_0\langle p\rangle_{\mathrm{V}}/(B_\phi^2)_{\mathrm{vac}}$, where the magnetic field is the vacuum toroidal magnetic field, is approximately 80% during pellet injection. Equilibrium reconstruction of these pellet injection discharges is underway, particularly to aid in the study of beta limits. Even in these high beta ohmically heated discharges, there is no obvious indication that a beta limit has been reached. Application of auxiliary heating such as neutral beam injection may be required to probe the beta limit.

4. Summary

Recent results from MST have demonstrated good ion confinement with ion temperature sustained $\geqslant 1$ keV and fast-ion confinement time >20 ms. Steady high beta is achieved with injection of frozen deuterium pellets, with total beta of 26%. In context with previous results, the RFP has now demonstrated good confinement of thermal and fast electrons, good confinement of thermal and fast ions, simultaneously with high beta operation. Next steps to further explore RFP confinement include a heating neutral beam at the MW level and rf injection (electron Bernstein wave and lower hybrid) for current profile control and heating.

Acknowledgments

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