Confinement of High Energy and High Temperature Ions in the MST Reversed Field Pinch

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Abstract. Confinement of both high energy and high temperature ions has been investigated in the Madison Symmetric Torus (MST) Reversed Field Pinch (RFP), both in standard plasmas with magnetic stochasticity, and improved confinement plasmas in which stochasticity is reduced. We find that (1) energetic ions (produced by neutral beam injection) are very well-confined in the standard RFP plasma despite the presence of significant stochasticity. This is understood from theory and simulation, and has positive implications for feasibility of neutral beam injection and alpha-particle confinement; (2) when magnetic stochasticity is reduced the thermal ion confinement is substantially improved as well. This is evidenced from estimation of ion thermal diffusivity as well as from direct observations of long lasting periods of sustained high ion temperature.

1. Introduction

Magnetic field can be stochastic in numerous laboratory and astrophysical plasma settings. Instabilities or turbulence generate field lines that wander stochastically. The resulting trajectories of charged particles can, therefore, also be stochastic, with large effect on particle transport. One of the main elements of the Madison Symmetric Torus (MST) Reversed Field Pinch (RFP) program is to reduce magnetic fluctuations present in standard RFP plasmas via parallel current profile control. Inductive profile control, pulsed parallel current drive (PPCD) [1, 2], demonstrates significant confinement improvement, including reduction of magnetic field stochasticity, increase of plasma β, and up to a 10-fold increase of the global energy confinement time. Earlier studies focused primarily on the plasma electron component. The present state of ion diagnostics on MST has achieved a level of maturity that permits studies of ion confinement as well. In this paper we analyze the confinement of fast ions, generated via neutral beam injection, as well as the confinement of the bulk plasma ions.

Energetic particle transport in a stochastic magnetic field is influential in fusion energy studies. In RFP in particular, it can affect the feasibility of neutral beam injection as a means to heat the plasma, as well as the confinement of fusion produced alpha-particles. Our results indicate that, even for a level of magnetic fluctuations at which the magnetic field is stochastic, the fast ion energy loss is consistent with the classical slowing down rate, and their confinement time is at least 20 ms. This is much longer than the time (1 ms) from the simple picture of the ions streaming along the stochastic magnetic field. These observations are in agreement with numerical simulation of ion trajectories, as well as with analysis of the overlapping of islands in the ion guiding center trajectories. We find that in PPCD plasma the fast ion confinement increases even further, up to about 30 ms.

We find that the confinement of thermal ions improves several-fold in PPCD regime and becomes comparable to that of the electrons. In addition, we report on a new regime of sustainable high ion temperature.

2. Experimental Setup and Diagnostics

In the MST RFP [3] (with minor radius $a = 0.51$ m, major radius $R = 1.5$ m) fast ion confinement is measured via decay of 2.5 MeV *d-d* fusion neutrons following a short pulse of an atomic deuterium beam injected into the deuterium plasma [4]. This technique was successfully applied for fast ion confinement studies in tokamaks [5, 6], spherical tori [7], helical systems [8], and mirror machines [9]. The RFP introduces the new element of magnetic stochasticity. A short pulse (1.3 ms) of deuterium atoms at an energy of 20 keV (0.5 MW) was injected approximately at the equatorial plane, tangential to the magnetic axis at the crossing point and parallel to the toroidal plasma current. The beam content of particles with the full energy is greater than 90 %. The neutron flux was measured with a plastic scintillator detector. We compare the measurements with result of full orbit simulation of fast ion motion in stochastic magnetic field.

The thermal impurity ions are diagnosed via charge exchange recombination spectroscopy (CHERS) [10, 11] and the majority ion temperature is measured by Rutherford scattering of an energetic helium beam [12]. Both diagnostics use dedicated neutral beam injectors and permit measurements with good spatial and temporal resolution. The temperature profiles provide an input to a simple 1-D transport model in order to determine the global ion confinement.

The measurements were performed both in "standard" and PPCD plasmas. The standard plasma is characterized by the presence of multiple modes of internally resonant tearing magnetic fluctuations, with the particle confinement time about 1 ms [13, 14], the central electron temperature $T_{e0} = 400$ eV, and the central ion temperature $T_{i0} = 350$ eV. The PPCD plasma has a reduced level of magnetic fluctuations resulting in the overall 10-fold confinement improvement of the electron component [1, 2], increased central electron temperature $T_{e0} = 800$ eV, and the central ion temperature $T_{i0} = 400$ eV. The electron plasma density profile was measured with a 11-chord FIR interferometer [15] and the electron temperature profile with a multipoint Thomson scattering system.

3. Confinement of Fast Ions

The flux of neutrons (Fig. 1) increases during beam injection, attributed to the build-up of the fast ions. Thereafter it slowly decays in several ms. If we assume a slowing down of ions by classical Coulomb collisions, then we can determine the fast ion confinement time. The total neutron flux can be calculated from:

$$\Gamma_n(t) = \int n_e(\mathbf{r}) n_{fi}(\mathbf{r},t) \sigma_T(E_{fi}(t)) v_{fi}(t)\, dV , \tag{1}$$

where $\sigma_T(E_{fi})$ is the cross section of the $D + D \rightarrow He^3 + n(2.45\text{ MeV})$ reaction [16] and n_{fi} is the fast ion density. We model the fast ion energy losses by the classical collisional rate [17]:

$$\frac{1}{E_{fi}}\frac{dE_{fi}}{dt}=-\frac{Z_{fi}^2e^4n_em_{fi}^{1/2}\ln\Lambda}{4\sqrt{2}\pi\varepsilon_0^2m_eE_{fi}^{3/2}}\left(\frac{4}{3\pi^{1/2}}\left(\frac{m_e}{m_{fi}}\frac{E_{fi}}{T_e}\right)^{3/2}+\sum_i\frac{m_e}{m_i}\frac{n_iZ_i^2}{n_e}\right) \quad (2)$$

where E_{fi} and m_{fi} are the fast ion energy and mass, and the remaining notation are standard. The first term in the brackets describes slowing down by plasma electrons and the second term by plasma bulk and impurity ions. At the initial fast ion energy of 20 keV the main contribution arises from the plasma electrons (82%), followed by the bulk ions (15%). The plasma mean ion charge was assumed $Z_{eff}=2$ with C^{+6} being the main impurity. We further assume that the fast ion particle losses can be described by a single time constant τ_{fi}^{loss} according to

$$\frac{dn_{fi}}{dt}=S_{fi}-\frac{n_{fi}}{\tau_{fi}^{loss}} \quad (3)$$

where S_{fi} is the fast ion source, proportional to the injection current. Equations (1 - 3) are solved simultaneously to infer τ_{fi}^{loss}. More details on the modeling can be found in [4]. The calculated neutron flux time history for different values of τ_{fi}^{loss} is shown in Fig. 1 (solid lines). The curve with the fast ion confinement time $\tau_{fi}^{loss}=20$ ms lies just below the experimental points and the curve corresponding to the stochastic confinement time $\tau_{fi}^{loss}=1$ ms decays much faster than the experimental data. Therefore, confinement is much longer than predicted by the simple stochastic estimate and is bounded from below by 20 ms.

To compare with experiment we compute ion trajectories in the magnetic field using the code RIO which resolves full ion orbits in a magnetic field (equilibrium and perturbed). Helical magnetic perturbations with poloidal mode numbers $m=0,1$ and toroidal mode numbers from $n=1$ - 32 that are dominant in MST are included. The radial profiles of each tearing mode were computed by a nonlinear resistive MHD code DEBS [18], and the amplitudes were normalized to the corresponding values measured at the MST wall. The energy losses in

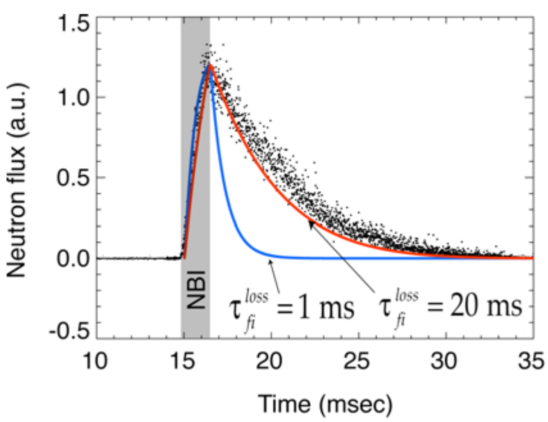

FIG. 1. Comparison of measured neutron signal (dots) and modeling (solid lines). The shaded area represents the NBI duration. The solid $\tau_{fi}^{loss}=20$ ms and $\tau_{fi}^{loss}=1$ ms lines show the fits for the corresponding fast ion confinement times.

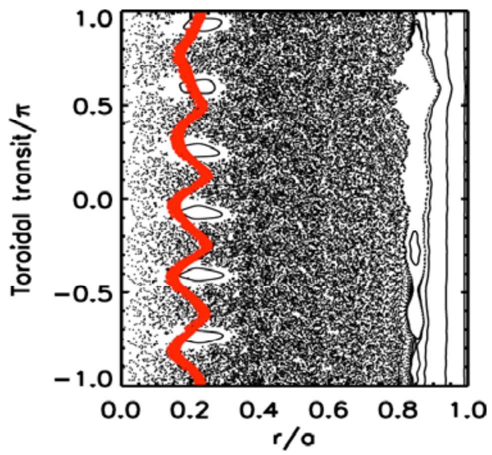

FIG. 2. Puncture plots of magnetic field line and ion guiding center (red) with the same starting point r/a = 0.20. The field line randomly wanders through the plasma volume while the fast ion stays attached to a flux surface.

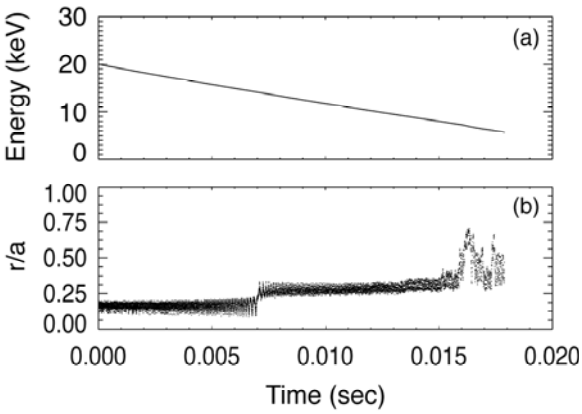

FIG. 3. Calculated time dependence of ion energy (a) and the position of the ion guiding center (b).

the background plasma are represented by the friction force $-m_{fi}(v_s^e + v_s^i)\mathbf{v}_{fi}$, which includes the fast ion slowing down on plasma electrons and ions. The velocity pitch angle scattering and diffusion are small relative to slowing down and were neglected.

Fig. 2 illustrates the difference between the ion guiding center orbits and the field lines which are shown for the same starting point, $r/a = 0.20$. The ion orbits stay attached to the starting flux surface, but the field lines quickly diffuse in the radial direction and exhibit stochastic behavior. The difference stems from the fact that the orbit drifts modify the resonance coupling to the magnetic field perturbations. The ion orbits have a rotational transform different from that of the field lines which changes the resonant interaction with the magnetic fluctuations.

The dynamical evolution as the fast ions slow down is shown in Fig. 3. The ion energy decays according to the collisional slowing down rate while the position of the ion guiding center remains attached to a flux surface, until the energy reaches a threshold value ($\approx$ 7 keV for a D ion) at t = 16 msec at which point the ion guiding center trajectory becomes stochastic. This agrees with an expectation that at a sufficiently low energy the ion trajectory will approach the field line and will replicate its stochastic properties. The threshold energy corresponds to a relative value of the ion Larmor radius $\rho_L / a \approx 0.05$.

The fast ion confinement results in PPCD are similar to that in standard RFP plasma and the value for the fast ion confinement time was measured $\tau_{fi}^{loss} = 30\,\mathrm{ms}$. A modest improvement of fast ion confinement is understood on the premise that the stochasticity weakly affects the fast ions, and other loss mechanisms (e.g. charge exchange) may be dominant.

4. Transport and Confinement of Thermal Ions

Anomalously hot ions in RFP plasmas have been observed for a long time - see for example [19] and references therein. It is believed that the heating is caused by the strong magnetic activity in RFP plasmas. The magnetic fluctuations are dominated by global tearing resistive modes resonant inside the plasma. In addition, discrete events are often observed during which the mode amplitudes quickly increase on the time scale of about 100 μs. During these events a significant part of equilibrium magnetic flux is reconnected and a large fraction of the equilibrium magnetic field energy is released, thereby providing a free energy source for the ion heating. Indeed, the ion temperature is observed to increase strongly during the reconnection events, often exceeding the electron temperature [20]. We show that even between the events the ions are heated by an anomalous process. The nature of the heating mechanism is still under investigation.

The thermal ion energy transport was analyzed with a simple 1-D transport model

$$\frac{\partial}{\partial t}\left(\frac{3}{2}n_iT_i\right)+\nabla\bullet\left(\frac{5}{2}\Gamma_iT_i\right)-\frac{\Gamma_i}{n_i}\nabla(n_iT_i)+\nabla\mathbf{q}_{cond}=p_{ei}-p_{CX}+p_{anom} \quad (4)$$

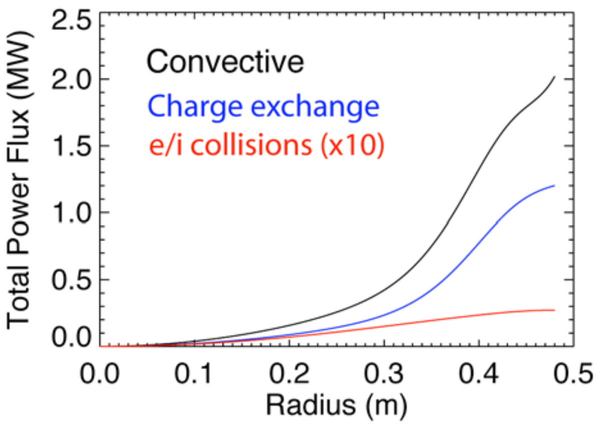

FIG 4. Radial profile of volume integrated ion convective heat flux, charge exchange losses, and e/i collisional heating.

where $\mathbf{q}_{cond}=-\chi_in_i\nabla T_i$ is the conductive heat flux, p_{ei} is the classical rate of e/i collisional heating, p_{CX} is the charge exchange loss and p_{anom} is a depository of any extra heating beyond the collisions (also includes a classical viscous heating). The ion particle flow density Γ_i is equal (via ambipolarity) to that of the electrons and can be obtained through the particle continuity equation

$$\partial_t n_e+\nabla\bullet\Gamma_i=n_en_0\langle\sigma_e v_e\rangle \quad (5)$$

where the ionization source in the RHS includes the neutral density n_0. The neutral density is also critical for the CX losses through $p_{CX}\propto n_in_0\langle\sigma_{CX}v_i\rangle T_i$. For the modeling a set of standard 400 kA RFP plasma discharges was used with measured profiles of plasma density, ion and electron temperatures, neutral density, and charge exchange losses.

Neglecting the time derivative (between the reconnection events) and integrating Eq. (4) over the plasma volume an equation describing the energy flow through a radius r is obtained.

$$P_{conv}(r)-\chi_in_i\nabla T_iA_{plasma}+P_{CX}(r)=P_{ei}(r)+P_{anom}(r) \quad (6)$$

The total anomalous power generated in the plasma volume can be estimated from Eq. (6) by comparing the values at the plasma boundary $r=a$ and neglecting the conductive flow at $r=a$:

$$P_{anom}=P_{conv}(a)+P_{CX}(a)-P_{ei}(a), \quad (7)$$

The radial profile of the convective energy flow $P_{conv}(r)=\frac{5}{2}\Gamma_iTA_{plasma}-\int\frac{\Gamma_i}{n_i}\nabla(n_iT_i)dV$, charge exchange energy flow $P_{CX}(r)=\int p_{CX}dV$ and e/i collisional heating $P_{ei}(r)=\int p_{ei}dV$ is shown in Fig. 4. The magnitude of $P_{anom}=3.2$ MW is about 50% of the total Ohmic power. We can also estimate the particle confinement time $\tau^p=\int n_edV/\Gamma_i(a)A_{plasma}$, the global ion energy confinement time $\tau_i^\varepsilon=\int 1.5n_iT_idV/\left(P_{conv}(a)+P_{CX}(a)\right)$, and the average ion thermal

TABLE 1: COMPARISON OF ION TRANSPORT IN STANDARD AND PPCD PLASMAS

	Standard plasma $I_p = 400$ kA $\bar{n}_e = 10^{19}$ m^{-3} $T_{e0} =$ 400 eV $T_{i0} =$ 350 eV	PPCD $I_p = 400$ kA $\bar{n}_e = 10^{19}$ m^{-3} $T_{e0} =$ 800 eV $T_{i0} =$ 400 eV
P_{conv} (MW)	1.9	0.23
P_{CX} (MW)	1.1	0.14
P_{ei} (MW)	0.09	0.03
P_{anom} (MW)	3.2	0.30
τ^p (ms)	0.9	7.1
τ_i^ε (ms)	1.3	10
χ_i (m^2/s)	46	5.7

conductivity $\chi_i = a^2 / 4\tau_i^\varepsilon$. These and other pertinent results are assembled in Table 1. The table also contains results from modeling of PPCD plasma.

In PPCD plasma the global confinement is improved, the neutral content is reduced, and the electron temperature increased. Correspondingly, both ion charge exchange and convective losses decrease, resulting in an improved ion confinement. Surprisingly, the ion temperature does not change much. The modeling shows that both the heating and the energy losses are reduced approximately by the same factor, which attributes to the small change of the ion temperature. The similar reduction might indicate that they largely remain to be of a fluctuation origin, therefore, both are reduced by the same amount according to the reduction of the fluctuation activity. A better understanding of the fluctuation induced ion heating will provide a useful insight on the radial profile of the anomalous source. That, given the global constrains, will allow us to obtain the local χ_i.

A new regime with a high sustainable ion temperature is achieved in MST. The high ion temperature is obtained in high $I_p > 500$ kA discharges via the anomalous ion heating from a series of reconnection heating during the current ramp phase. PPCD is applied at the end of the ramp up, which results in an extended duration of high T_i - Fig. 5. The high T_i decay

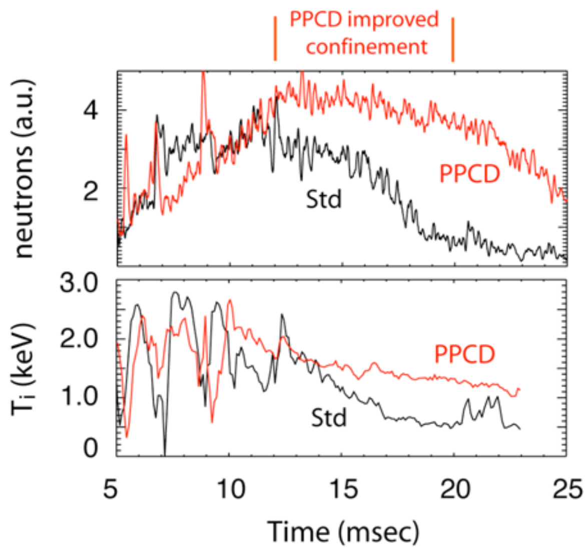

FIG. 5. Comparison of central ion (C^{+6}) temperature and neutron flux in high Ip PPCD (red) and standard (black) plasma. PPCD is turned on at t = 10 ms and a quiescent period lasts from t = 12 ms to t = 20 ms. The ion are anomalously heated prior to PPCD as result of magnetic reconnections (appear as discrete spikes on the signals).

during PPCD is much slower than in standard plasmas.

5. Summary

Confinement of energetic and thermal ions has been investigated in the MST RFP. Energetic ions obtained via beam injection are shown to be well confined even in presence of a stochastic magnetic field. The fast ion confinement time (> 20 ms) is much longer than the estimate for particles that closely follow field lines (~ 1 ms), and also longer than the bulk plasma confinement time (~ 1 ms). This relative immunity of fast ions to field stochasticity agrees with computation of particle orbits in the RFP stochastic field, and is understood from inspection of ion guiding center islands, which can differ significantly from magnetic islands. These results illustrate the limits of the simple transport estimates based on an assumption that particles follow field lines. They also show that fast ions are well-confined in the RFP, a favorable result for the use of neutral beam injection as a control tool, and for confinement of fusion-generation alpha particles. For the latter, the observed threshold transition to poor confinement at a low energy can possibly be exploited as a means for "ash" removal.

Confinement of the thermal ions is observed greatly improved during a transition to a plasma with reduced magnetic fluctuations. The result of the modeling indicate that the global thermal ion energy confinement time $\tau_i^{\varepsilon} \approx 10$ ms and the average thermal diffusivity $\chi_i \approx 6$ m^2/s, which is comparable to that of the electrons. The modeling also shows that anomalous ion heating still persists, although at a much reduced value. The mechanism of the ion heating is under investigation. In addition, a new regime of sustained high ion temperature is observed in high-current PPCD plasmas. The high temperature itself originates from reconnection events prior to PPCD as a result of the large fraction of the released magnetic energy deposited into the ions. The mechanism is not yet understood. Followed the heating events the elevated ion temperature is sustained within the duration of PPCD.

Acknowledgement

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