# Fast ion confinement studies in the MST reversed field pinch

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## I. Introduction

The confinement of fast ions and their impact on the thermal background are crucial issues for fusion plasmas. Experiments have shown that fast ions born from neutral beam injection (NBI) exhibit excellent confinement properties in conventional tokomaks and generally obey classical slowing down theory [1][2][3]. However, this is a barely studied research area for the reversed field pinch (RFP), in which the magnetic field can be stochastic due to the overlapping of multiple tearing modes and the toroidal magnetic is weak and comparable to poloidal magnetic field. A new 1 MW (25 kV, 40 A) neutral beam injector (NBI) has been installed on the Madison Symmetric Torus (MST) RFP [4] with a tangential injection geometry, useful to investigate momentum injection, plasma heating and current drive. Here we report the fast ion confinement measurements for a variety of MST plasmas using the technique of beam “blip” [2] diagnosed with a neutron detector and a neutral particle analyzer. We find that fast ions in the RFP are also well confined in co-injection, roughly consistent with classical slowing-down theory in spite of the stochastic magnetic field. This corroborates with previous experiments with a very short and low power neutral beam pulse [5]. The estimated fast ion confinement times range from several times to ten times the thermal particle confinement time, and charge-exchange with background neutrals seems the dominant fast ion loss mechanism. In contrast, the fast ion confinement in counter-injection is relatively poor because of increased orbit losses and possible turbulent transport.

## II. Experimental setup and diagnostics

In the MST RFP with a major radius of 1.5 m and a minor radius of 0.51 m, the 1 MW neutral beam is injected approximately at the equatorial plan, tangential to the magnetic axis at the crossing point (see Figure 1). The beam is doped with 3%-5% deuterium and the beam energy is 25 keV with ~86% particle fraction at the full energy component. The fast ion confinement time is derived from the decay process of the 2.5 MeV d-d neutron flux following ~5 ms neutral beam injection pulses. The plasma conditions are carefully chosen so that the neutron emission is dominated by the beam-target reactions. Large sawtooth magnetic reconnection events are avoided because they can spontaneously generate a tail population of energetic ions. The neutron flux is measured by a plastic scintillator (Bicron BC-408), coupled to a photomultiplier tube. The electron temperature and density are measured by a multipoint Thomson scattering diagnostic [6] and 11-chord FIR interferometer [7]. An advanced neutral particle analyzer (ANPA) [8] is recently installed on MST to measure fast ions that charge exchange with background neutrals. It is capable of measuring the energy spectra of H and D simultaneously with 10 channels per mass species and energy from 1 keV to 30 keV.

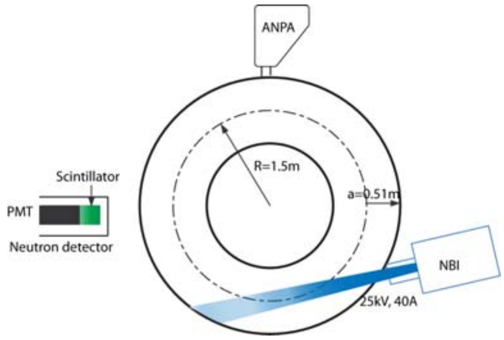

Figure 1. Top view of the MST showing the heating neutral beam, scintillator-based neutron detector and advanced neutral particle analyzer.

### III. Measurements of fast ion confinement

The fast ion confinement time can be deduced by comparing the experimental neutron decay time with the prediction by classical slowing-down theory. For simplicity, assuming that the fusion reactivity decreases exponentially as fast ions slow down classically without loss, the predicted neutron decay time is [9]

$$\tau_{n\_classical} = -\int_{E_n}^{E_{crit}} \frac{dE}{\{dE/dt\}_{classical}} = \frac{\tau_{se}}{3}\ln\left(\frac{E_{inj}^{3/2}+E_{crit}^{3/2}}{E_n^{3/2}+E_{crit}^{3/2}}\right) \quad (1)$$

where $E_{inj}$ and $E_{crit}$ are the beam injection energy and critical energy at which the electron Coulomb friction equals to the bulk ion Coulomb friction, $E_n$ is the energy at which the fusion reactivity has fallen by 1/e, and $\tau_{se}$ is the slowing down time on. If we lump fast ion losses, the experimental neutron decay time $\tau_{n\_\exp}$ can be modelled as $1/\tau_{n\_\exp} = 1/\tau_{fi} + 1/\tau_{n\_classical}$. (2)

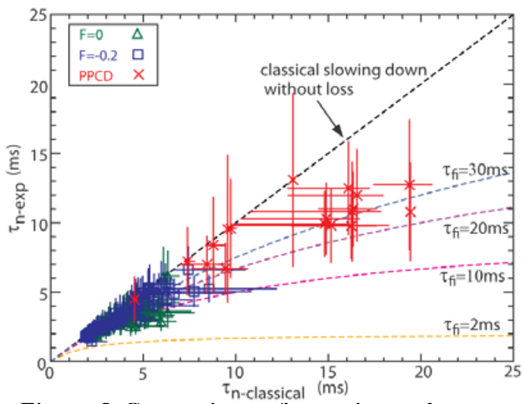

Figure 2 Comparison of experimental neutron decay time with the predictions of classical slowing-down theory. The vertical and horizontal error bars are due to the uncertainty in the neutron signal and the change of density and temperature in decay period respectively. The dashed lines are estimated $\tau_n$ with Eq. (2) with assumed $\tau_{fi}$ of 2, 10, 20, 30ms.

Figure 2 compares the experimentally measured neutron decay time with the prediction of classical slowing down theory with measured plasma parameters in the core (r/a<0.2) in a variety of MST plasmas. In most plasmas, $\tau_{n\_\exp} \sim \tau_{n\_classical}$. The estimated fast ion confinement time is ~10 ms in F=0 and F=-0.2 standard plasmas and ~25 ms in an improved confinement regime (PPCD), much higher than the thermal particle times ($\tau_p \approx 1$~2 ms in F=0 and F=-0.2 standard plasmas and $\tau_p \approx 10$ ms in PPCD plasmas). This confirms the previous experiments using 1.3 ms NBI pulse with much smaller fast ion population [5]. The relative immunity of fast ions to magnetic field stochasticity has been attributed to the grad B and curvature drifts of the fast ion guiding center [5].

The small difference between $\tau_{n\_\exp}$ and $\tau_{n\_classical}$ implies that there are some fast ion losses. Possible candidates are charge exchange loss, orbit loss and turbulent transport. The lower boundary of fast ion confinement time $\tau_{fi\_\min}$ can be calculated by expression (2) with $\tau_{n\_\exp}$ to be the best fit to the bottom envelope of neutron signal. This is routinely lower than the best estimation of fast ion confinement from Figure 2. As shown in Figure 3(a), $\tau_{fi\_\min}$ slightly increases with plasma current (i.e. magnetic field strength) due to the decrease of orbit loss. Figure 3(b) suggests that $\tau_{fi\_\min}$ is inversely proportional to the background neutral density, which is calculated by matching measured H_alpha line emission with the models created by NENE code [10]. TRANSP modelling suggests that charge exchange loss with background neutrals is the dominant fast ion loss mechanism, as discussed below.

The ANPA raw data show some direct evidence that fast ions may behave classically. Although the channel to channel flux magnitude calibration has not been done, Figure 4(e) shows that hydrogen fast ions with energy near $E_{inj}$= 23.5 keV slow down after beam turn-off and stay confined inside the plasma for another few ms until a sawtooth burst occurs. The fast ions with

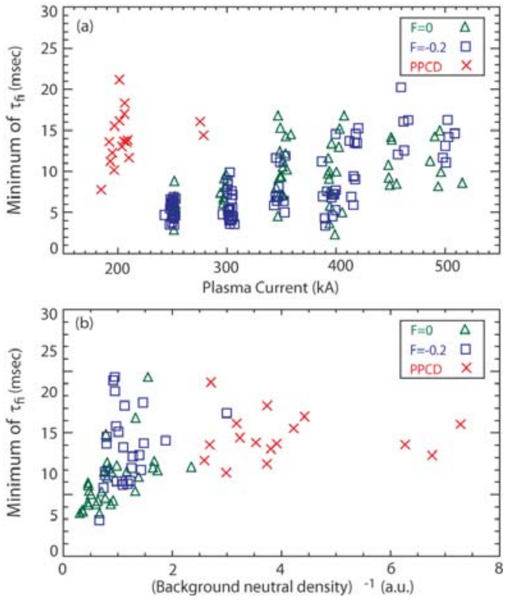


Figure 3 Correlation of lower boundary of fast ion confinement time with (a) plasma current and (b) background neutral density

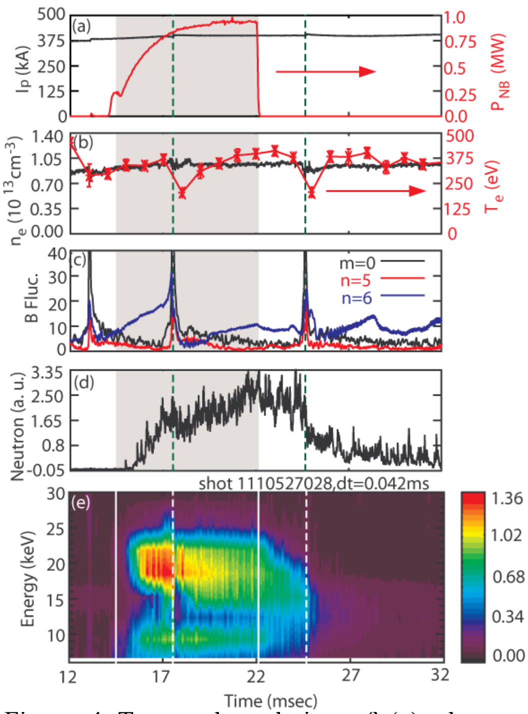


Figure 4 Temporal evolution of (a) plasma current and neutral beam power; (b) electron density and electron temperature; (c) magnetic fluctuation of m=0, and m=1, n=5,6 modes; (d) neutron flux; (e)raw signals of ANPA in the 10 hydrogen channels. The two dashed lines mark the two time-slices with strong sawteeth.

energy lower than 10 keV are lost quickly. Note that the neutron flux persists after the sawtooth burst (t=24.5 ms), but the ANPA signals disappear rapidly. This could be because the two signals originate from fast ions in different phase space: the neutron signal is primarily from core localized passing fast (and bulk) ions, while the ANPA mainly measures trapped fast ions near the edge (where large background neutral density exists) due to the NBI and ANPA setup geometry (see Figure 1)

**IV. Modelling of neutral beam injection on MST**

The NUBEAM module [11] , a Monte-Carlo package in the Tokamak transport TRANSP code [12], is used to study the neutral beam injection physics on MST. Currently only F= $B_\varphi(a)/<B_\varphi>=0$ plasmas have been simulated since TRANSP requires monotonic toroidal flux, which is violated for normal RFP equilibria with F<0. Figure 5 shows the TRANSP modelling of a typical F=0 plasma with plasma current $I_p$=400 kA, electron density $n_e(0)=1.0x10^{13}$ $cm^{-3}$, electron temperature $T_e(0)$=400 eV, particle confinement time $\tau_p$=1 ms and 1 MW NBI injection between 20 and 40 ms. It is shown in Figure 5(a) that the local fast ion density could be as high as 15% of plasma density in the core. The fast ions are confined in the core region with r/a<0.2 (see Figure 5(b)) and they are mainly passing particles with $v_{||}/v$~0.9 (see Figure 5(c)). Figure 5(d) shows the charge exchange loss is the dominant fast ion loss mechanism, and 20% of NB power is shine-through loss, similar to the experimental observation.

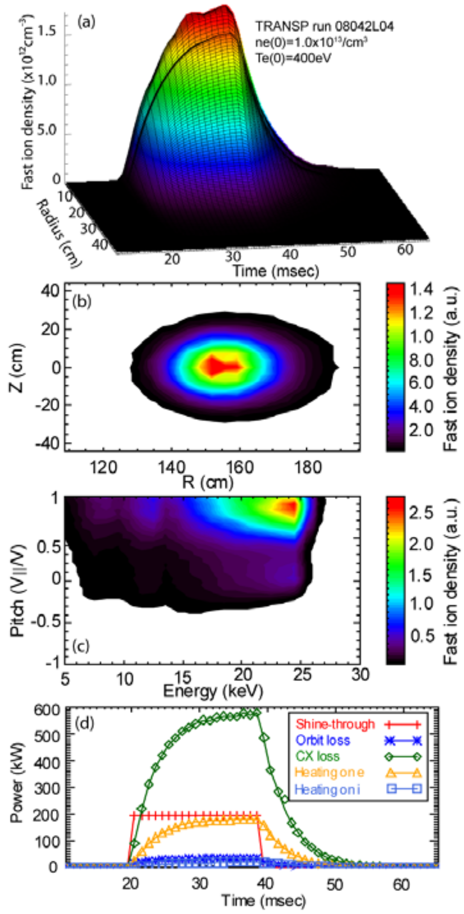


Figure 5 (a) temporal evolution of fast ion density on the midplane, (b) fast ion density profile in real space at t=28 ms, (c) volume averaged fast ion density profile in phase space at t=28msec, (d) temporal evolution of beam power deposition on electrons and ions, charge exchange loss, orbit loss and shine-through.

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