Neutral beam injection experiments in the MST reversed field pinch

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Abstract: The new 1 MW (25keV/40A, 95-97% H and 3-5% D) tangential neutral beam injector (NBI) on the MST reversed field pinch (RFP) provides a good test-bed for the study of fast ions in the RFP concept. It is found that fast ions born from co-current NBI are well confined and behave roughly consistent with classical theory in spite of the RFP's stochastic magnetic field. The measured neutron flux decay times following ~5 ms NBI pulse approximately agree with the prediction of classical slowing-down theory. The neutron flux at the beam turn-off time increases with plasma density, also as expected. The estimated fast ion confinement times range from several times to ten times the thermal particle confinement time. The slowing-down of fast protons is directly observed with an advanced neutral particle analyzer. These results corroborate previous experiments with very short and low power neutral beam pulses, and are largely in agreement with TRANSP modelling which also predicts a centrally peaked fast ion density profile with peak value up to 15% of the bulk electron density. The good confinement of fast ions implies a significant population of energetic particles is available to influence the thermal background plasma through momentum injection, altering tearing mode stability, and plasma heating. About 100 eV increase of the electron temperature has been observed by Thomson scattering system in the plasma core during improved confinement periods. Analysis of magnetic modes clearly shows the NBI has induced a substantial reduction of core tearing mode amplitude and a robust increase of mode rotation. Measurements from a toroidal array of fast magnetic loops suggests that the NBI-born fast ions routinely excite a bursting mode in the 60~150 kHz range, which scales with plasma density, not the magnitude field strength.

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). There are a few significant features that can make fast ion confinement in a RFP different from in a typical tokamak. First, the toroidal magnetic field is weak and comparable to the poloidal magnetic field, which can cause the fast ion Larmor radius to be comparable to the gradient length, and thus results in significant prompt loss. Second, the magnetic field in RFPs can be stochastic due to overlapping islands from multiple resonant tearing modes and induce collisionless radial diffusion of charged particles. For example, electrons in the standard RFP operating mode closely follow the magnetic filed lines and they are dominated by this stochastic magnetic transport. However, fast ions born from NBI are much less affected due to their large orbit drift. They can be well confined, with a confinement time that can be ten times or larger than the background electrons [4]. In addition, fast ions are super-Alfvénic and they can excite some Alfvén eigenmodes or energetic particle modes. A new 1 MW (25 kV, 40 A) heating neutral beam injector (NBI) was installed on the Madison Symmetric Torus (MST) RFP [5] in 2009 with a tangential injection geometry, to study momentum injection, plasma heating and current drive. Here we report the recent experimental results of fast ion confinement and effects of NBI on bulk plasmas with this new heating beam.

The MST is a large RFP device (major radius R= 1.5 m and minor radius a 0.51 m) with medium plasma current (I_p=200-600kA). The MST can be operated in two regimes: standard confinement and improved confinement regimes. In standard RFP discharges, multiple m=0 and m=1 modes are resonant. The m=1 modes are near marginal stability but can be driven linearly unstable by gradients in the current density profile induced by the toroidally applied electric field. The m=0 modes are energized through non-linear coupling. The rapid growth of m=1 tearing modes can lead to a large magnetic reconnection event (sawtooth) which redistributes parallel current into a marginally stable profile. In the improved confinement regime, with the help of inductive current profile modification known as Pulsed Poloidal Current Drive (PPCD), the magnetic fluctuation level can be reduced by one order and this substantially increases the particle and energy confinement time [6][7][8][9].

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 for creation of beam-target fusion neutrons and the beam energy is 25 keV with ~86% particle fraction at the full energy component. The neutron flux is measured by a plastic scintillator (Bicron BC-408), coupled to a photomultiplier tube. It is shielded from X-rays by 5-cm thick lead bricks. The electron temperature and density are measured by a multipoint Thomson scattering diagnostic [10] and 11-chord FIR interferometer [11]. Magnetic activity is detected by an array of magnetic coils. A recently installed advanced neutral particle analyzer (ANPA) [12] detects fast ions that charge exchange with background neutrals. It is capable of measuring the energy spectra of hydrogen and deuterium simultaneously with 10 channels per mass species and energy from 1 keV to 30 keV.

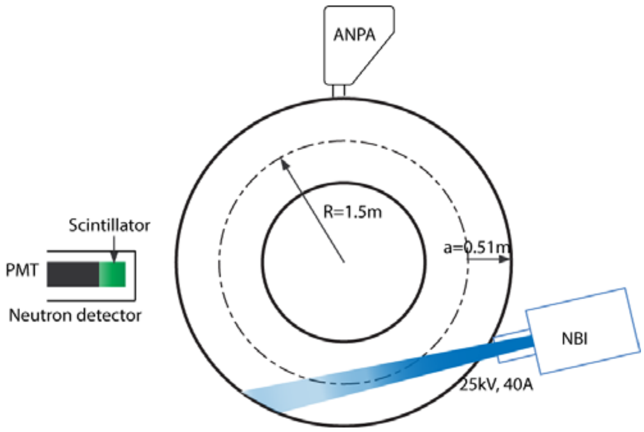

Figure 1. Top view of the MST showing the heating neutral beam, scintillator-based neutron detector and advanced neutral particle analyzer.

II. Fast ion confinement experiments and TRANSP modelling of NBI on MST

II.1 Fast ion confinement experiments

The confinement of neutral beam born fast ions is studied with the technique of beam "blips" [2]. On MST, the fast ion confinement time is deduced from the decay of the 2.5 MeV d-d neutron emission following ~5 ms neutral beam injection pulses. In these experiments, plasma conditions are carefully chosen so that the neutron emission is dominated by the beam-target reactions. Large sawtooth magnetic reconnection events are avoided since they can either spontaneously generate a tail population of energetic ions or degrade the fast ion confinement. The neutron flux decay after beam turn-off is essentially the combination process of fast ions slowing down and fast ion loss. For simplicity, assuming that the fusion reactivity decreases exponentially as fast ions slow down classically without loss, the predicted neutron flux decay time is [13]

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

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 τ_{se} is the slowing down time on electrons. If we lump fast ion losses, the experimental neutron flux decay time $\tau_{n\_\exp}$ can be modelled as

$$1/\tau_{n\_\exp} = 1/\tau_{fi} + 1/\tau_{n\_classical} \qquad (2)$$

The fast ion confinement time can be deduced by comparing the experimentally measured neutron flux decay time with the prediction of Eq. (1) by classical slowing-down theory.

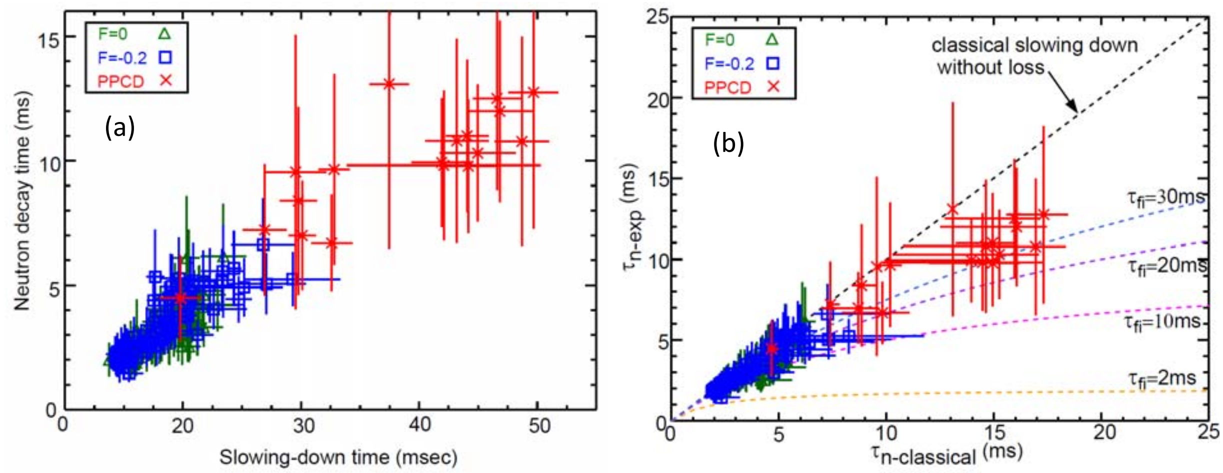

Figure 2 (a) Comparison of measured neutron flux decay time and calculated fast ion slowing time using core electron density and temperature; (b) Comparison of experimental neutron flux decay time with the predictions of classical slowing-down theory. The dashed lines in (b) are estimated τ_n with Eq. (2) with assumed τ_{fi} of 2, 10, 20, 30ms. 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 green and blue symbols represent the shots in standard F=0 and F=-0.2 plasmas with plasma current between 250 and 525 kA, density between 0.7×10^{13}cm-3 and 1.3×10^{13}cm^{-3}. The red symbols represent the data in 200-300 kA PPCD plasmas.

As shown in Figure 2 (a), the measured neutron flux decay is roughly linearly correlated with calculated fast ion slowing down time with measured plasma parameters in the core (r/a<0.2) in a variety of MST plasmas. It implies that the neutron flux decay after beam turn-off is dominated by the slowing down process, not the fast ion loss term. Figure 2 (b) compares the experimentally measured neutron flux decay time with the prediction of classical slowing down theory with Eq. (1). In most cases, $\tau_{n\_\exp} \sim \tau_{n\_classical}$. The estimated fast ion confinement time is ~10 ms in F=B_φ(a)/<B_φ>=0 and F=B_φ(a)/<B_φ>=-0.2 standard plasmas and ~25 ms in improved confinement regime (PPCD), much higher than the thermal particle confinement times ($\tau_p \approx 1 \sim 2$ ms in F=0 and F=-0.2 standard plasmas and $\tau_p \approx 10$ ms in PPCD plasmas). 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. TRANSP modelling suggests that charge exchange loss with background neutrals is likely the dominant fast ion loss mechanism, as discussed in Section II.2. Figure 3 shows that neutron flux Γ_{n_off} at beam turn-off tune time increases with plasma density and injected neutral beam power, as expected. The empirical fit shows it also has a weak dependence on plasma temperature and plasma current or toroidal magnetic field, i.e. $\Gamma_{n\_off} \propto n_e(0) T_e^{0.25} I_p^{0.125}$. This can be understood since high T_e increases fast ion slowing down time and high I_p (or magnetic field) reduces fast ion Larmor radius and prompt loss. These results confirm the

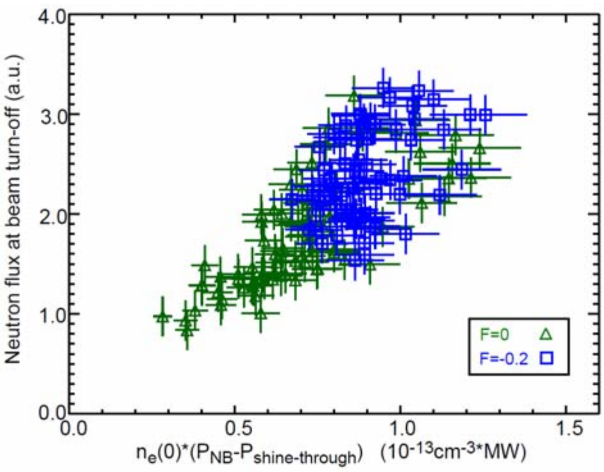

Figure 3 The neutron emission at the end of ~5ms neutral beam pulses increase with core electron density and neutral beam power in .F=0 and F=-0.2 standard RFP plasmas.

previous experiments using a 1.3 ms NBI pulse with much smaller fast ion population [4]. 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 [4].

Fast ions are also well confined in PPCD plasmas, but their behaviour is more complicated. During PPCD periods, magnetic fluctuations are significantly reduced, and plasma particle and energy confinement time could be more than ten times larger than in standard RFP plasmas. In the experiments with NBI into 200-300 kA PPCD plasmas, beam-target fusion neutron emission shows nice decay after beam turn-off, as in standard RFP plasmas. However, at high current 500 kA PPCD plasmas, neutron emission continues to increase (rather than decay) after beam turn-off, possibly due to rapidly evolving plasma density and temperature profiles. In some 550 kA PPCD plasmas with high temperature (T_e~2 keV, T_i~1keV) and hollow impurity profile, the beam-target fusion neutron emission becomes much less than background fusion neutron emission. The difference of neutron emission between the shots with and without NBI becomes negligible. It could be argued that the hollow high Z_{eff} profile induces large pitch angle scattering and fast ions are deposited in the outer region, instead of plasma core. More experiments to investigate NBI into high current PPCD plasmas are under way.

The ANPA raw data show some direct evidence that fast ions behave classically. Although the channel to channel flux magnitude calibration has not been completed, 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 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)

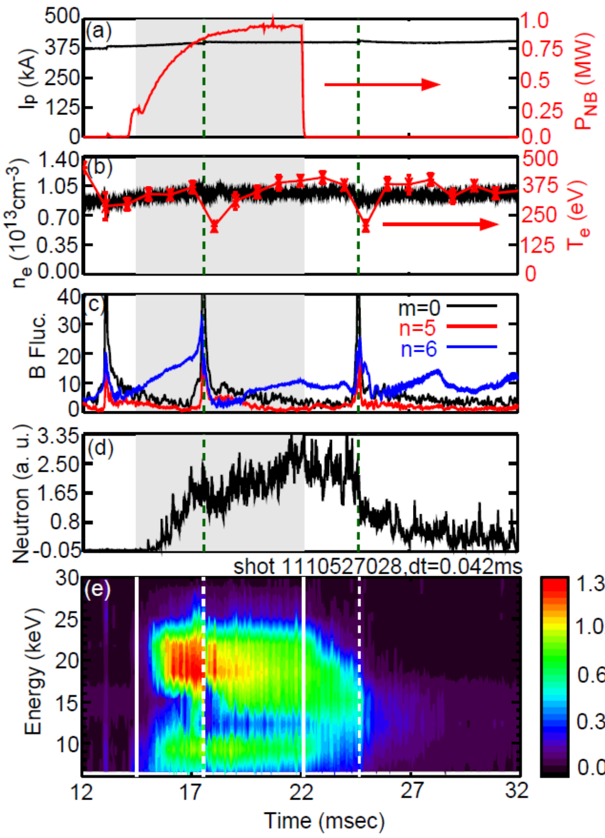

Figure 4 Temporal evolution of (a) plasma current and neutral beam power; (b) electron density and electron temperature; (c) magnetic fluctuation of m=0, and m=1, n=5,6 tearing modes; (d) neutron flux; (e)raw signals of ANPA in the 10 hydrogen channels. The two dashed lines mark the two time-slices with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

II.2 TRANSP modelling of NBI into F=0 plasmas

The NUBEAM module [15], a Monte-Carlo package in the Tokamak transport TRANSP code [16], is used to study the neutral beam injection physics on MST. Currently only F= $B_\varphi(a)/\langle B_\varphi\rangle$=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 τ_p=1 ms and 1 MW NBI injection between 20 and 40 ms. It is shown in Figure 5(a) that the central fast ion density increases on a roughly 10 ms time scale to ~15% of the background electron density. It also shows the fast ion density decaying on about 10 ms time scale after beam turnoff. 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) suggests 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.

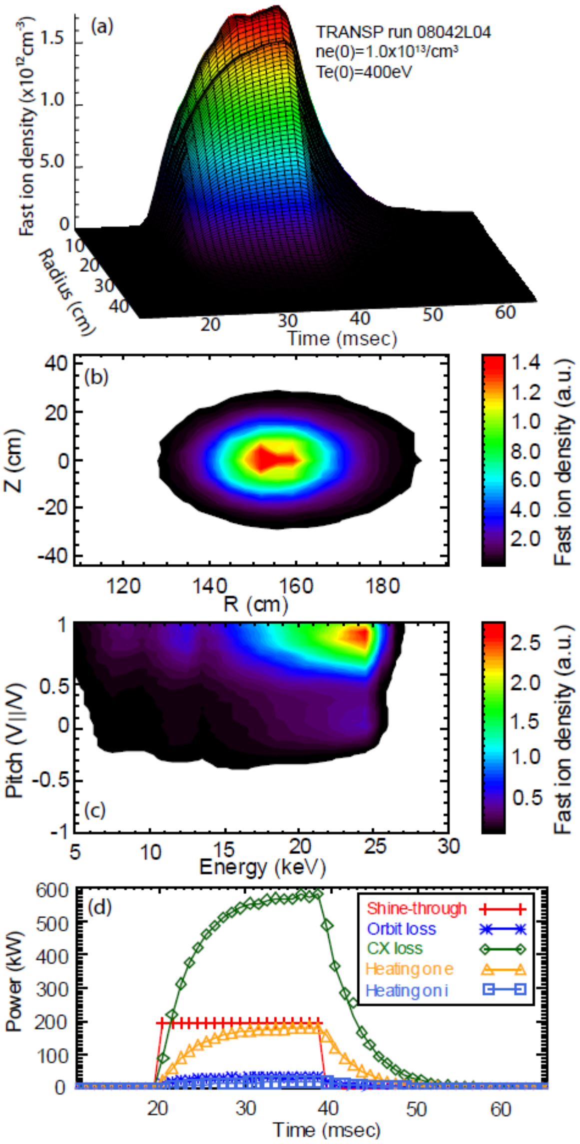

Figure 5 (a) temporal evolution of fast ion density on the midplane, (b) fast ion density profile in real space at t=28 ms, (c) volume averaged fast ion density profile in phase space at t=28msec, (d) temporal evolution of beam power deposition on electrons and ions, charge exchange loss, orbit loss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

III. Effects of neutral beam injection on bulk plasmas

III.1 NBI induced electron heating

Neutral beam born fast ions slow down through Coulomb collisions with both electrons and ions, which provides a classical mechanism for plasma heating. In typical MST plasmas, the beam energy is generally larger than the critical energy, thus the expected neutral beam heating on electrons is larger than on ions, as shown in Figure 5 (d). In order to maximize neutral beam heating on MST, neutral beam is injected during enhanced confinement period of PPCD plasmas, in which both fast ions and thermal particles are well confined. In addition, the background neutral density in PPCD plasmas is generally much lower (up to 10 times) than in standard RFP plasmas, the expected fast ions loss is much lower and more power should be available for heating. Figure 6 (a) shows the core electron temperature data collected in 200kA PPCD discharges with and without NBI. The plasma temperature ramps up quickly during the enhanced confinement period, and falls back down after that period is over. As shown in Figure 6 (b), there is about 100 eV electron temperature increase in the "NBI On" case compared with "NBI off" case. Note that during the enhanced confinement period, the electrons continue to be heated by the fast ions even though the beam is no longer firing. This is because the fast ions are still confined and continue to circle around the MST, dragging against the background electrons and heating them. The observed ~100eV electron heating is similar to the output of a 1-D classical heating model (see Figure 6 (b)), which starts from the stored energy balance equation of electrons. Note that no NBI induced electron or ion heating has been observed in standard RFP discharges, which are characterized by lower thermal confinement time and larger charge exchange loss.

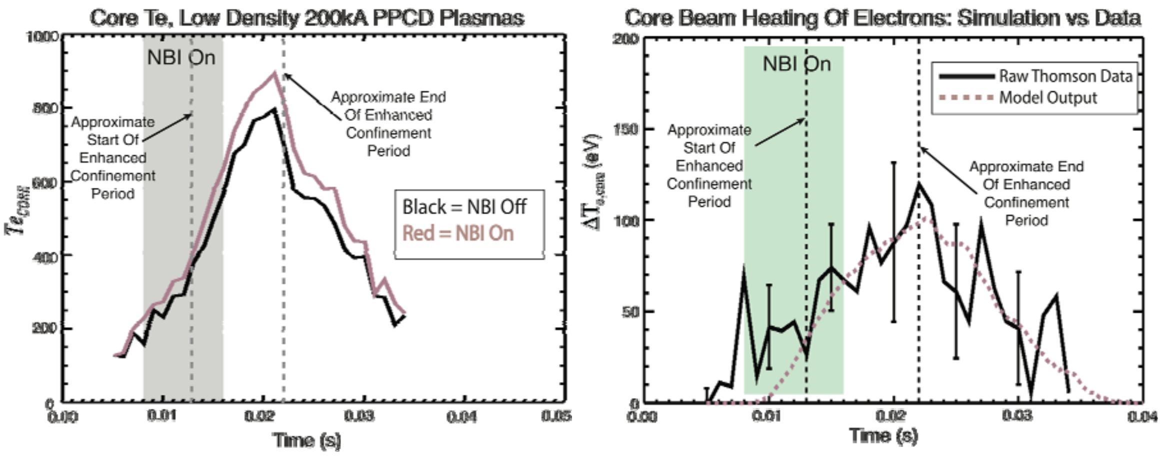

Figure 6 (a) Comparison of core electron temperature for the "NBI on" (red curve) and "NBI off" (black curve) in 200 kA PPCD plasma ensembles. Each dataset has 22 similar shots with plasma density about $0.5\times10^{13}cm^{-3}$. (b) The measured change of electron temperature between "NBI on" and "NBI off" ensembles is pretty similar to the output of a 1-D classical heating model.

III.2 NBI increases plasma rotation and reduces core mode fluctuation

As shown in Figure 5, TRANSP modeling predicts that fast ions are centrally peaked with density up to 15% of local electron density. These fast ions can impart a significant torque on the plasma, and may change the stability of tearing modes. Figure 7 shows that in 300kA, F=0 discharges, co-current NBI significantly reduces the amplitude of the core-most resonant tearing mode (n=5) while counter injection has almost no effect (see Figure 7(b)). Modes resonant further from the core (n=6-10) are unaffected (see Figure 7(c)). The change in the toroidal rotation profile is indicated by the phase velocities of the *n*=5-7 modes, with n=5 mode rotation shown in Figure 7 (d). Similar analysis of n=6 and n=7 velocity show increased flow shear. The increased mode rotation suggests that the external torque is being applied by NBI. The larger increase in the *n*=5 rotation relative to the other modes evidences the flow profile is more strongly sheared. The mechanism of mode stabilization is not fully understood yet. There are few possible candidates: (1) altered parallel current profile affects tearing mode stability; (2) altered parallel current profile removes core mode resonance condition; (3)stabilization due to fast ions at tearing mode layer by finite Larmor radius effect. More experimental and theoretical studies are ongoing.

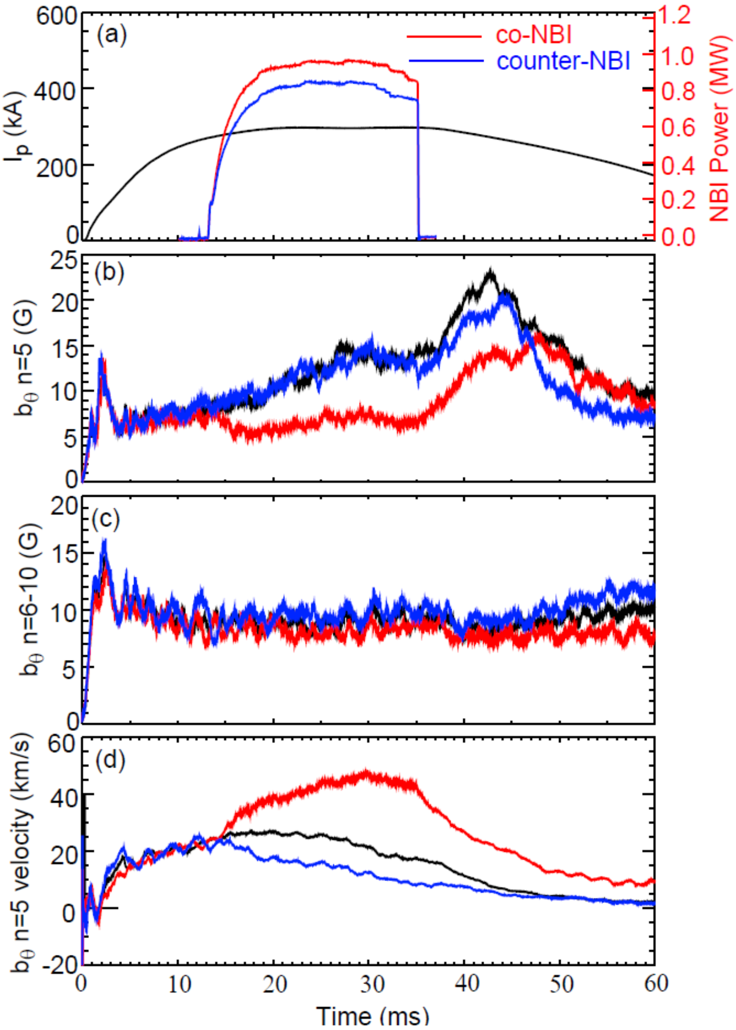

Figure 7 Temporal evolutions of (a) plasma current and neutral beam power, (b) the core tearing mode n=5, m=1 mode amplitude (c) the n=5,6, m=1 mode amplitude; (d) the n=5, m=1 mode rotation in 300 kA, $n_e = 0.7\times10^{13} cm^{-3}$ and F=0 standard RFP plasmas. The traces are from ensemble averaged datasets.

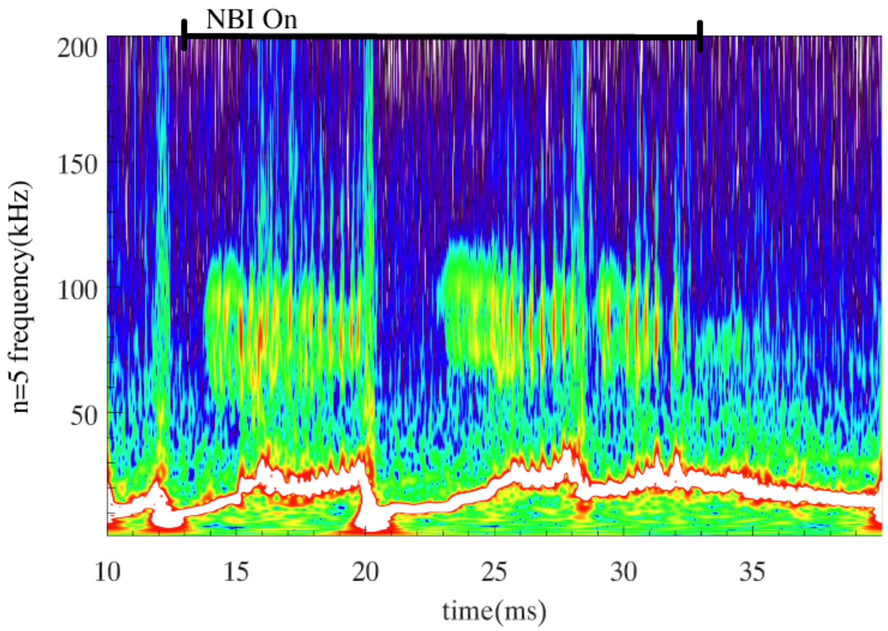

Figure 8 Wavelet spectrum of n=5 and m=1 mode observed in 300 kA F=0 plasmas with NBI. The high frequency (60`120kHz) magnetic activity occurs only in F=0 plasmas with NBI.

III.3 NBI induced bursting mode

The 25 keV ions created by NBI are super-Alfvénic. It is therefore possible that the energetic ions could excite Alfvén eigenmodes or energetic particle modes. Figure (8) shows one example that fast ions have induced some bursty, fast-chirping coherent magnetic activity in the frequency range of 60~150 kHZ when neutral beam is injected into I_p=300kA and F=0 standard plasmas. The mode appears to be core-localized with mode number n=4 or n=5, m=1. The frequency is much less than the predicted TAE frequency (~300kHz) from linearly analysis with codes developed for stellarator and tokamak research and the RFP magnetic equilibrium. The strongest coherence activity scales inversely with density, but does not scale with magnetic field strength. The high-bandwidth interferometer-polarimeter will be used to study the internal structure of these modes. More experiments and data analysis are underway.

IV Conclusion

The confinement of fast ion in the stochastic magnetic field of the MST RFP has been studied with beam "blip" technique. Analysis of the neutron flux decay after beam turn-off and neutron absolute value at beam turn-off suggests the fast ions behave roughly classically in spite of stochastic magnetic field. The estimated fast ion confinement times range from several times to ten times the thermal particle and energy confinement time. Direct evidence of fast proton slowing down is observed on the ANPA. These results are largely in agreement with TRANSP modelling. Several influences of NBI on bulk plasmas are also observed. About 100 eV increase of the electron temperature has been detected by Thomson scattering system in the plasma core during improved confinement periods. NBI also has induced a substantial reduction of core tearing mode amplitude, a robust increase of mode rotation and some bursting high frequency modes.

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