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Modeling of low frequency MHD induced beam ion transport in NSTX[1]

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Beam ion transport in the presence of low frequency MHD activity in National Spherical Tokamak Experiment (NSTX) plasma is modeled numerically and analyzed theoretically in order to understand basic underlying physical mechanisms responsible for the observed fast ion redistribution and losses as reported by Medley [1]. In NSTX experiments of interest typical plasma parameters were major radius $R_0 = 0.85 - 0.9m$, minor radius $a = 0.67m$, plasma current $I_p = 0.3 - 1.5MA$, and toroidal field $B_T = 0.3 - 0.6T$. In NSTX Neutral Particle Analyzer (NPA) [1] was measuring energy spectrum signal of confined beam ions initially injected with maximum injection energies in the range $E_{b0} = 80 - 100keV$. Note that in NSTX Neutral Beam Injection (NBI) is characterized by multiple injection energies, E_{b0}, $E_{b0}/2$, and $E_{b0}/3$. After the transition of the plasma discharge to an H-mode with typical accompanied low frequency, low-n MHD activity NPA signal shows loss of selected energies fast beam ions in the energy range $E_b = 50 - 80keV$. Solid curve on Figure 1 taken in shot #108730 at $t = 400msec$ illustrates these NPA measurements with depletion region between two sources: $E_{b0}/2 = 40keV$ and $E_{b0} = 80keV$.

Loss time estimate

It is instructive to apply a simple analytical model to describe the measured ion distribution presented in Figure 1 in order to estimate the energetic ion "loss" time τ_{loss}. Note that this time is a characteristic confinement time of beam ions in the pitch angle of NPA viewline and may not describe actual particle loss to the wall. The steady state distribution function should satisfy the kinetic equation $St(f) - f/\tau_{loss} + Q - S = 0$, where $St(f)$ is the collisional operator, Q and S are the source and the sink of beam ions, respectively, τ_{loss} is their characteristic loss time, which we introduced following Ref.[2]. Beam ions are thermalized from the injection velocity until they become a background specie. During slowing down, the beam ion distribution function satisfies the equation [3]

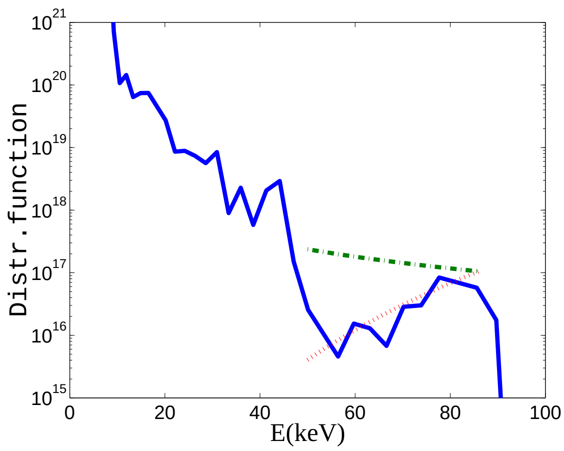

FIG. 1: NPA signal spectrum for shot #108730 at $t = 400msec$ (solid curve) and its approximation at high energies by the slowing down distribution without loss (dash-dotted line) and with finite loss time, Eq.(2) (dotted line).

$$\frac{1}{\tau_{se} v^2} \frac{\partial}{\partial v} \left(v^3 + v_*^3\right) f - \frac{f}{\tau_{loss}} = 0, \tag{1}$$

where τ_{se} is the slowing down time on electrons and v_* is the critical velocity. Equation (1) has a familiar slowing down distribution function $f \sim 1/\left(v^3 + v_*^3\right)$ if $\tau_{loss} \to \infty$. At finite

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τ_{loss} we obtain

$$f = \frac{Cn_b}{v^3 + v_*^3} \left(\frac{v^3 + v_*^3}{v_{b0}^3 + v_*^3} \right)^{\tau_{se}/3\tau_{loss}}, \quad (2)$$

where v_{b0} is beam ion birth velocity, C is the normalization constant, n_b is beam ion density. Shown in Figure 1 is an approximate fit of Eq.(2) velocity dependence to the measured spectrum, which is obtained by adjusting the loss time. This dependence translates to $\tau_{loss} = \tau_{se}/15$. Thus, estimating the electron drag time to be $60msec$, the loss time is about $4ms$ for the high-energy component of the beam ion distribution. Another interesting observation from Fig. 1 is that given a finite "loss" time, within the energy range affected by the stochastic diffusion, the distribution function at lower energies is more depleted than at higher energies. This is because lower energy ions are confined longer and more effected by the diffusion.

ORBIT modeling of MHD effects on beam ions

We have applied an ORBIT code [4] to model the effect of MHD modes on the confinement of beam ions in NSTX. ORBIT is a guiding center code, which follows beam ion drift orbits. For realistic simulations we employ numerical equilibrium and model MHD activity based on the experimental observations [1]. In the analyzed discharge $\#108730$ MHD activity was measured as being dominated by one $m = 4$ poloidal harmonic with the toroidal mode number $n = 2$. The vector of the perturbed magnetic field is described by the formula $\delta \mathbf{B} = \nabla \times \alpha \mathbf{B}$, where the scalar function α is approximated in a following manner consistent with the MHD model

$$\alpha \sim (1 - nq/m) (r/r_s)^m \sin (n\varphi - m\theta), \text{ if } r < r_s,$$

and decreases fast with minor radius at $r > r_s$, where r_s is the minor radius (square root of the normalized toroidal magnetic flux) of the rational magnetic surface, φ is the toroidal angle. Note that in the simulations α is normalized at its maximum to the amplitude α_0. The magnetic field amplitude is approximately $\delta B/B \sim m\alpha_0$ if the shear is small. In the simulations the plasma toroidal rotation is included in the form of the radial electric field potential $\phi[keV] = -54.3\bar{\psi} \left(1 - 0.93\bar{\psi}^{0.1}\right)$, which is monotonic function changing from zero at the center to $-3.8keV$ at the edge. This provides strong central rotation of $\omega_\varphi = 2.4 \times 10^5 rad^{-1} sec^{-1}$ at the center, which modifies the beam ion MHD mode interaction through the local Doppler shift due to the $E \times B$ drift

$$\omega - \omega_{E\times B} - \left(k_{||} + l/qR\right) v_{||} = 0, \quad (3)$$

where ω is the MHD mode frequency, and in the limit of high aspect ratio one can approximate $k_{||} = (m - nq)/qR$, and $l = \pm 1$ due to the poloidal modulation of the ion drift velocity components. Note that in NSTX due to large radial width of the beam ion drift orbit, comparable with the minor radius and on the order of the mode width, $|l|$ may be larger than 1 [3]. MHD activity has approximately constant low frequency $|\omega - \omega_{E\times B}| \ll \left|v_{||}\right|/qR$. Hence for the passing particles (representing the majority of particles measured by NPA) the resonance in Eq.(3) is possible if $\left| k_{||}qR + l\right| \ll 1$. For example for $m = 4$, $n = 2$ mode and $l = \pm 1$ the local resonance is possible near $q = 2.5$ surface. However due to the large orbit width high energy ions interact with perturbations even if they satisfy the resonance condition on the part of drift trajectory, which leads to high l's. Note that the resonance condition Eq.(3) is velocity dependent, so that the low energy particles should have less response from the mode due to the smaller orbit width and smaller $v_{||}$ term, which leads to narrower radial locations of possible resonances.

In the ORBIT code runs we launch beam ions in the phase space where NPA signal peaks. The pitch angle of the observed particles at the moment when it exchanges an additional electron with the neutrals is approximately given by the dependence $\chi \equiv v_{||}/v = 1.5125 - 0.629R_{cx}[m]$. Two groups of particles are under investigation: passing and trapped. When the passing particles are launched they are redistributed within the pitch angle range $0.8 < \chi < 0.9$ with flat distribution. Trapped particle are distributed within the window $0.55 < \chi < 0.7$. At the end of the run particles are recorded within ± 0.02 pitch angle range from the NPA view line (note that the results are only slightly sensitive to this number). Beam ions are started with the single energies $E_{b0} = 80,\ 40keV$ and are allowed to slow down and scatter due to collisions for $10msec$. Figure 2 shows the results of simulations for passing particles with two values of injected energies. It clearly shows that as expected high energy particles are more strongly affected by the perturbations. The signal from high energy ions is reduced by as much as 60% from the unperturbed case. For the $40keV$ energies beam ions are less affected with the signal falling within the statistical error, which was less than or around 5%. It is interesting to note from Fig. 2(right) the correlation of the expected NPA signal with the value of the safety factor, which was scaled by multiplying the whole q-profile with a scaling factor, so that the factor 1 corresponds to the experimentally analyzed plasma. As we argued above this sensitivity is expected due to $k_{||}$ dependence on q. Indeed, as the numerical modeling shows NPA measured beam ions propagate through the region of the mode location, $q = 2$. Therefore Eq.(3) is not satisfied neither for $l = 0$ due to finite mode frequency nor for $l = \pm 1$ and low energy ions with smaller drift orbit width. High energy ions as we argued have higher harmonics due to large orbit width.

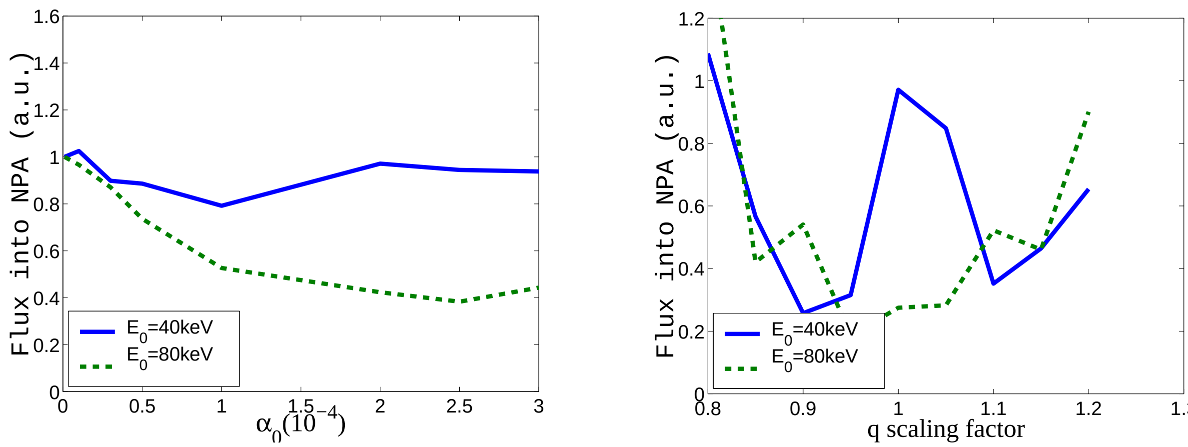

FIG. 2: Results of NPA signal flux modeling for two energies $E_{b0} = 80keV$ and $40keV$ used at the start of numerical runs. The modeled fluxes are shown as functions of mode amplitude α_0 (left) and the scaling factor for the safety factor profile (right).

Introduction of the electric field as simulations show changes the nature of the mode particle resonance interactions so that the introduced $E \times B$ drift induced Doppler shift is a function of a particle position. This is different from the recent modeling [5] in which the electric field and mode rotation frequency have been ignored. It can be seen from Eq.(3) that the zero mode frequency wave particle resonance is reduced to the following condition $k_{||}qR = l$, which does not involve beam ion velocity, so that the corresponding phase space island is reduced to the island in the real space ($l = 0, \pm 1$ in Ref.[5]). In our analysis due to large orbit width the interaction is much broader and forms many islands in the phase space. In fact high harmonics $|l| \gg 1$ plays an important role in energetic ion diffusion.

With the ORBIT code one can study the losses of beam ions. Here we specify the initial distribution of beam ions assuming the tangential injection at $E_{b0} = 80keV$ similar to the one used in the experiment. In these simulations beam ions were allowed to slow down and experience collisional scattering. Without the perturbation beam ions are lost promptly with the loss fraction about 9%. MHD activity enhances these losses by almost doubling them at $\alpha_0 = 3 \times 10^{-4}$. Note that the amplitude of the measured MHD activity at the edge, $\delta B/B \sim 2 \times 10^{-4}$, is much less than the value required for the quantitative agreement with the experiment based on the ORBIT modeling and NPA measurements $\delta B/B \sim m\alpha_0$. That is expected because the edge amplitude is smaller due to the envelope of MHD mode decays strongly toward the plasma edge and further in the vacuum region.

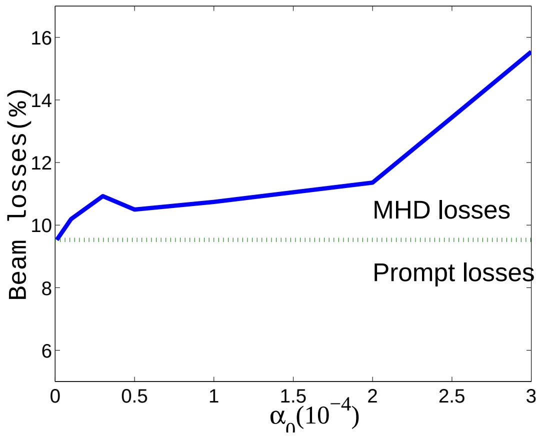

FIG. 3: Orbit modeling of beam ions loss due to low frequency MHD activity.

Conclusions

Numerical modeling of the beam ions flux into the NPA in NSTX shows that after the onset of low frequency MHD activity high energy part of beam ion distribution, $E_b > 40keV$, is redistributed radially due to stochastic diffusion. Such diffusion is caused by high order harmonics of the transit frequency resonance overlap in the phase space. Large drift orbit radial width induces such high order resonances. Characteristic confinement time is deduced from the measured NPA energy spectrum and is typically $\sim 4msec$. Considered MHD activity may induce losses on the order of 10% at the internal magnetic field perturbation $\delta B/B = O\left(10^{-3}\right)$, which is comparable to the prompt orbit losses.

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