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Measurements of Prompt and MHD-Induced Fast Ion Loss from National Spherical Torus Experiment Plasmas

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Abstract. A range of effects may make fast ion confinement in spherical tokamaks worse than in conventional aspect ratio tokamaks. Data from neutron detectors, a neutral particle analyzer, and a fast ion loss diagnostic on the National Spherical Torus Experiment (NSTX) indicate that neutral beam ion confinement is consistent with classical expectations in quiescent plasmas, within the ~25% errors of measurement. However, fast ion confinement in NSTX is frequently affected by magnetohydrodynamic (MHD) activity, and the effect of MHD can be quite strong.

1. Introduction

Spherical tokamaks (STs) operate at significantly lower magnetic field than do most tokamaks at ordinary aspect ratios, e.g. B_T=0.3 T in NSTX compared to 2–5 T in similarly-sized conventional tokamaks. As a consequence, the gyroradii of fast ions (e.g. neutral beam (NB) ions, ion cyclotron heated tail ions, and charged fusion products) can be a significant fraction of the plasma minor radius, contributing to possible degraded confinement of these ions. In this work, we examine diagnostic data from NSTX (B_T=0.3–0.6 T, I_p~1 MA, n_e~2–8x10^{19} m^{-3}, T_e~T_i~600-1000 eV) to determine whether NB ion confinement departs from classical expectations in quiescent plasmas. In addition, we describe some observed effects of MHD activity on the fast ion diagnostic signals.

2. Implications of low B on fast ion confinement

As noted above, the relatively low magnetic field strength in STs means that fast ions will have large gyroradii. For example, the 80 keV D (co-injected) NB heating ions in NSTX can have a gyroradius of ~0.3 m at the outboard midplane of the plasma. This is a sizable fraction of the 0.68 m minor radius of a typical plasma. Additional prompt loss to the walls from the large gyroradius is therefore expected and seen in numerical simulations.[1] The large fast ion gyroradius in an ST also can be comparable to the gradient scale length of the magnetic field, meaning that the fast ion magnetic moment (μ) may not be well conserved. If μ invariance is broken, then it is possible that orbit stochasticity can cause fast ions to be lost. Indeed, stochasticity in NB ion orbits in NSTX has been observed in orbit modeling, due to resonant interaction between gyromotion and bounce motion.[2] However, other theoretical work[3] indicates that the net effect of the loss of invariance is quite small, apparently because another invariant arises.[2]

The large gyroradius of fast ions in STs can also augment MHD-induced loss because a smaller radial displacement is required in an ST to bring a fast ion orbit from the plasma interior to the point where it can intersect the wall. Finally, the low magnetic field means that fast ions can easily be present at velocities above the Alfvén velocity, possibly driving Alfvén-type instabilities.[4] These could then cause expulsion of the fast ions

3. Beam blip measurements

The deviation of fast ion behavior from classical was investigated by analyzing neutron emission resulting from short (3 ms) beam pulses ("blips") injected into NSTX plasmas. This method[5] provides two measurements of possible losses of neutral beam ions. First, the absolute height of the resulting neutron pulse can be compared to the rate expected from the beam injection power and the plasma density to obtain a measure of the loss fraction of the beam ions arising from short time scale (<3 ms) processes, typically prompt loss. Second, the decay constant of the neutron rate vs time after the beam blip ends can be compared with the decay rate expected due to collisional slowing down of the beam ions. Any faster than classical decay indicates an additional loss mechanism is operative on a time scale comparable to the slowing down time (typically a few tens of milliseconds).

Beam blip measurements were made in plasmas with 0.5 MA ≤ I_p ≤ 1.0 MA and 0.25 T ≤ B_T ≤ 0.55 T, with each of the three NSTX NB sources (tangency radii of 0.487, 0.592, and 0.694 m). The data exhibited the expected variation in loss fraction with current and with beam tangency radius, the two variables which most strongly influence prompt loss. There was, however, significant scatter, amounting to +/-25% in some cases. When the ratio of measured peak neutron rate to the rate computed by the TRANSP[6] transport code is plotted as a function of plasma current, the data show no systematic dependence on plasma current. This indicates that the prompt losses are purely orbit loss as this is the dominant fast ion loss mechanism in TRANSP under these conditions. In some cases, excellent agreement between the measured neutron rate and the calculated neutron rate is observed (Fig. 1).

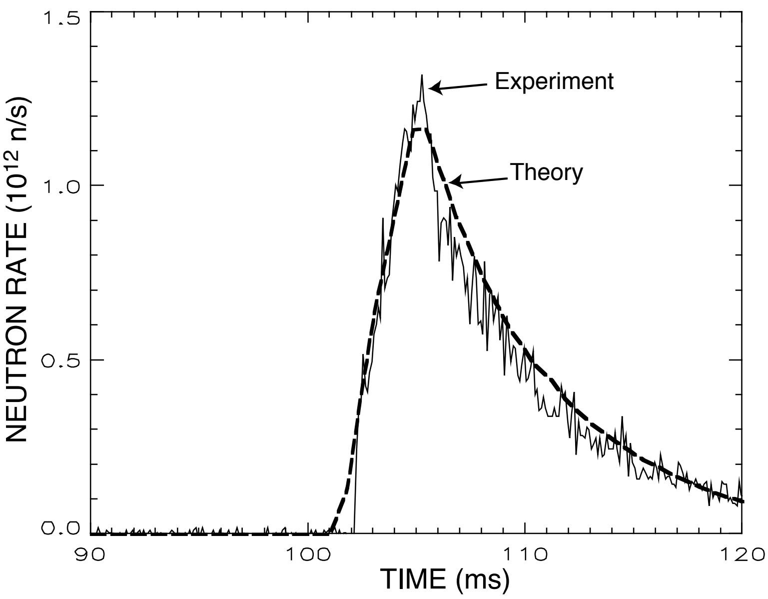

FIG. 1: Measured and modeled neutron rate vs time for an NSTX beam blip.

The ratio of measured neutron decay time to that computed by TRANSP was also plotted as a function of plasma current and toroidal field. The ratios are scattered uniformly about a ratio of 1, with a standard deviation of ~0.25. This implies that the slower time scale losses are also strictly classical. The data taken as the toroidal field varied set a limit on the loss rate that may be present due to non-conservation of , namely that it is no larger than the 25% scatter cited above. The amount of scatter in both the neutron pulse amplitude and decay time is larger than anticipated and is present in spite of removal of shots with obvious MHD activity from the data set. We conjecture that the scatter may be attributable to low level MHD activity.

4. Loss measurements

Losses of ions with energy >1 keV in NSTX have been measured with a Faraday cup probe located at the vessel midplane. These can be compared with a numerical model of prompt orbit loss from NSTX plasmas. However, because the numerical model does not yet take into account some effects of the beam deposition profile, only general conclusions may be drawn from the comparisons. Except during MHD activity, observed losses are at or below the rate predicted by the model, indicating that there are no large non-classical loss processes active.

5. NPA data

NSTX is equipped with a neutral particle energy analyzer (NPA) capable of looking at neutrals with tens of keV of energy. The NPA line of sight can be scanned in the midplane from tangency radii up to 1.28 m for co-going particles and 0.75 m for counter-going particles. With the NPA viewing co-going particles at a tangency radius of 0.70 m, the time evolution of the fast neutral energy spectrum was observed over the course of NB injection in a quiescent shot, 106099. The energy spectrum evolved with time, but reached a steady distribution after ~25 ms. For the parameters of this plasma, the interval required for equilibration, calculated from the collisional slowing down time, was 23 ms, meaning that the observed equilibration time was consistent with classical collisional processes.

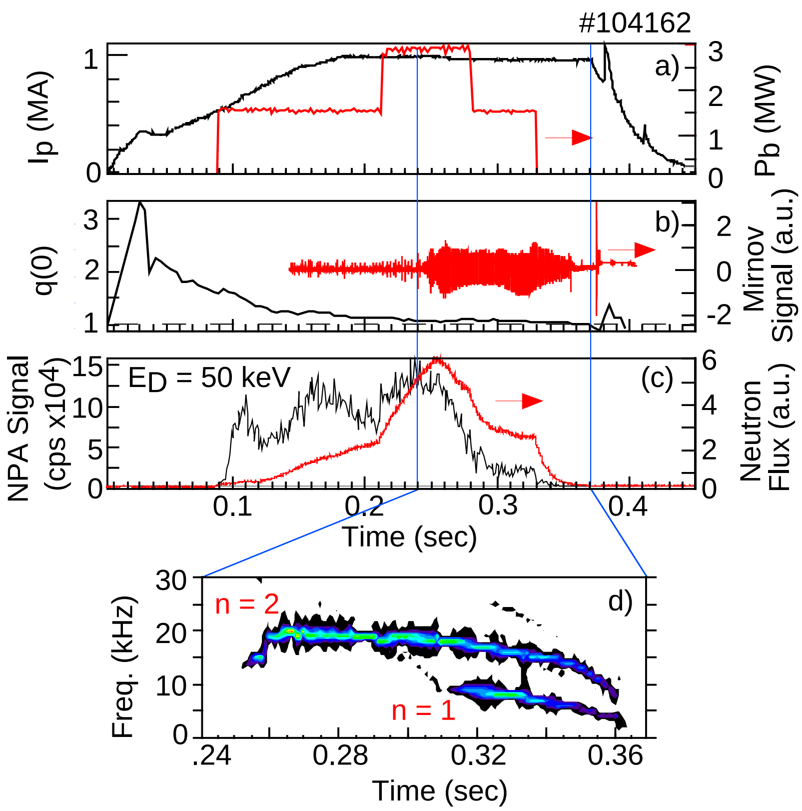

FIG. 2: Influence of MHD activity on beam ion confinement in NSTX. (a) Plamsa current and neutral beam power. (b) Central q value and Mirnov coil signal. (c) 50 keV neutral D efflux and neutron emission. (d) Mirnov spectrogram.

Similarly, the rate of collisional pitch angle scattering was assessed by setting the NPA to view the plasma near perpendicularly (tangency radius of 0.15 m) during a set of beam injected plasmas. It was seen that the population of perpendicular particles at and below the critical energy (~15 keV) was initially empty. It increased to reach a steady value on the time scale of ~50 ms, in good agreement with the computed pitch angle scattering time of 56 ms for that condition. So, in both these examples and many similar discharges, the NB ion behavior inside the plasma appears consistent with classical collisional processes.

6. MHD effects on beam ion confinement

MHD activity can have a strong effect on the fast ion population in NSTX, as shown in Fig. 2. In this discharge, an n=2 mode at ~20 kHz becomes prominent at 0.26 s, joined by an n=1 mode at ~10 kHz at 0.31 s. Note that q_0 remains above unity throughout the MHD activity. Simultaneous with the development of the n=2 mode, the neutron and energetic neutral flux begin to diminish gradually. At the point just before one of the neutral beams switches off, at 0.28 s, the neutron rate has diminished by ~25%, and the fast neutral flux has diminished by ~50%. In the interval where the neutron rate declines, n_e and T_e continue to rise, indicating that the diminishing neutron rate arises from degraded beam ion confinement, not degraded plasma conditions.

In contrast with the MHD mode in the case above, sawteeth and reconnection events in NSTX cause very rapid loss of beam ions in less than 2 ms. Figure 3 shows an example of this. Reconnection events are characterized by sudden upward spikes in both the plasma current trace and q_0 and are delineated by solid vertical lines in Fig. 3. These are preceded by two sawteeth or other events at earlier times, marked by dashed vertical lines. Simultaneous with the reconnection events are brief spikes in the Mirnov coil signal, which contrast with the steady Mirnov activity in Fig. 2. As Fig. 3 shows, sawteeth and reconnection events cause rapid depletion of the fast neutral flux over a range of energies, resulting in ~50% drops in the neutron rate. Because beam injection continues after the events in this discharge, the neutral flux and neutron rate do recover. In other discharges, the neutron rate never recovers to more than about half its initial value. This lack of recovery is not understood, but may result from decreased plasma density and impurity influx induced by the event. The volume within the q=1 surface is a significant fraction of the plasma volume, and the reconnection events probably generate magnetic field stochasticity over that whole volume, affecting a large fraction of the beam ions in the plasma.

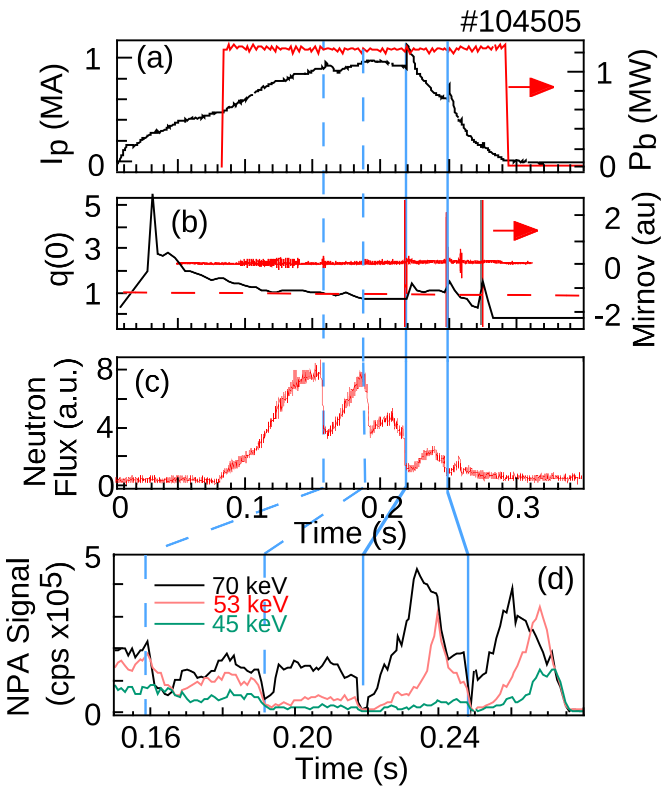

FIG. 3: Influence of sawteeth and reconnection events on beam ion confinement in NSTX. (a) Plasma current and neutral beam power. (b) q0 and Mirnov coil signal. (c) Neutron rate. (d) Neutral D efflux at 70, 53, & 45 keV. The first two events, marked by dashed vertical lines, are sawteeth, and the latter two, marked by solid lines, are reconnection events.

In reviewing the neutron signals from all NSTX NB plasmas, it has been noted that a large fraction of them show some evidence of an MHD-related effect on the neutron rate. In particular, in a data set of ~400 NB shots from the 2002 experimental campaign, ~90% exhibited some degradation of the neutron rate, most frequently from bursting n=1, 2, or 3 modes that are probably fishbone modes (see next section).

7. Observations of fast ion driven MHD

Several MHD instabilities driven by the NB ions have been identified in NSTX plasmas: compressional Alfvén eigenmodes (CAEs)[7,8], toroidicity-induced Alfvén eigenmodes (TAEs)[9], and fishbones.[10] Of these, the CAEs have no discernable effect on the neutron rate or beam ion loss rate. In some cases, the TAEs cause transient neutron drops of ≤10%. The fishbones, however, can have a noticeable effect on the neutron rate, causing it to drop by ~25% in the worst cases. Further study of the TAEs and fishbone modes is warranted to understand their global effect on the discharge.

8. Summary

We have examined data from the NSTX neutron monitors, NPA, and fast ion loss probe to assess the degree to which the loss rate of neutral beam ions from NSTX plasmas conforms to classical losses and collisional slowing down and pitch angle scattering. Beam blip experiments indicate that beam ion confinement is in reasonable agreement with the prompt orbit loss model. However, the scatter in the data is ~25% and mechanisms producing loss at that level or smaller might not be evident. NPA data also indicates that the beam ions are slowing down and pitch angle scattering at the classically-expected collisional rates. However, we have found that ~90% of NSTX discharges show some evidence of MHD effect on the neutron rate. In many cases, the effect on the neutron rate and the NPA signals are strong, indicating that MHD activity is can have a strong adverse effect on fast ion confinement. These observations suggest that attention must be paid to MHD suppression and control in STs if they are to be heated by fast ions and used for neutron sources or fusion reactors.

Acknowledgements

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