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by

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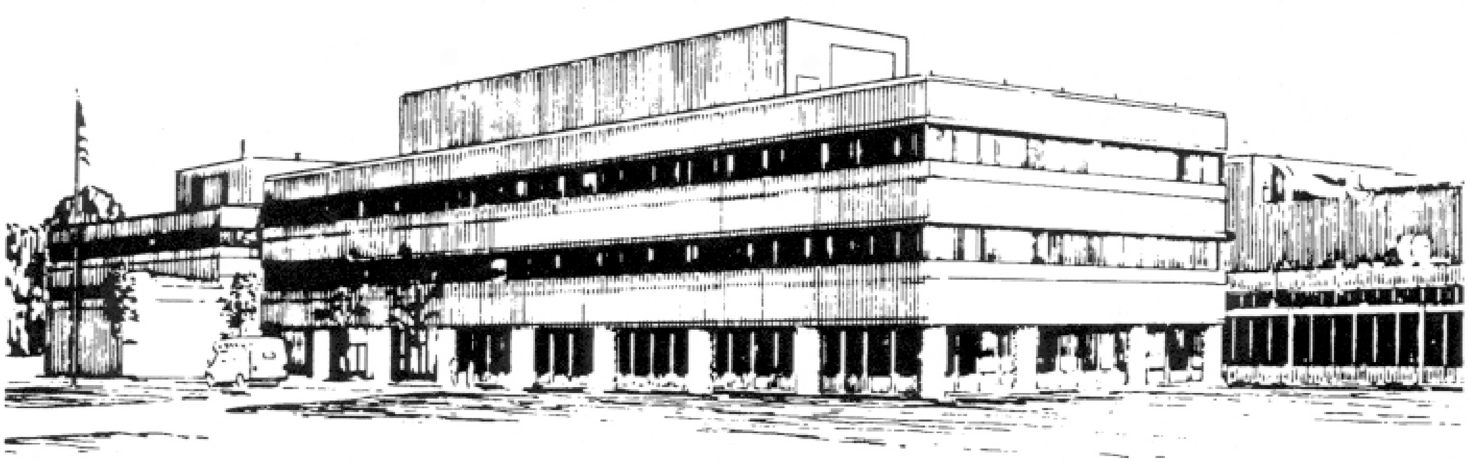

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Confinement of Neutral Beam Ions in the National Spherical Torus Experiment

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Abstract

The loss of neutral beam ions to the wall has been measured in the National Spherical Torus Experiment (NSTX) by means of thermocouples, an infrared (IR) camera, and a Faraday cup probe. The losses tend to exhibit the expected dependences on plasma current, tangency radius of the injector, and plasma outer gap. However, the thermocouples and the Faraday cups indicate substantially different levels of loss and this difference has yet to be understood.

Introduction

Spherical tokamaks (STs) have been found, both theoretically[1] and experimentally[2], to be capable of confining plasmas at high beta, a quality attractive for prospective fusion reactor applications. NSTX[3] is an ST with typical parameters of R=0.86 m, a=0.68 m, κ=2, B_T=0.3 T, I_p=1 MA, $n_{e0}=3\text{x}10^{19}$ m^{-3}, and T_{e0}=1 keV. To reach fusion temperatures and high beta, auxiliary heating is needed, the simplest form being neutral beam (NB) heating. NB heating has been applied to NSTX, commencing in September 2000, and has resulted in toroidal beta values of up to ~25%. On NSTX, deuterium ions are injected at 80 keV from three sources, yielding a maximum possible injection power of 5 MW. The sources have tangency radii of 0.487, 0.592, and 0.694 m.

Because efficient NB heating depends upon good confinement of the injected ions, we have undertaken measurements of the loss rate of NB ions. In addition to assessing the quality of confinement, this study should also reveal if there are any conditions of extreme losses in which the limiters or walls might be damaged. Loss measurements also reveal details of the physics of events that cause loss and aid in benchmarking numerical models of loss processes. Finally, understanding the loss of NB ions in NSTX provides a good framework for prediction of alpha particle losses in at deuterium-tritium fueled ST in that the dimensionless parameters (ρ/a and β_{fast}) are similar between the two systems.

Prompt Orbit Loss Modeling

The most fundamental and irreducible loss of fast ions arises from prompt orbit loss, meaning that beam ions are born onto orbits that intersect the limiters or vessel wall. This loss process has been modeled by the EIGOL code[4], which follows the full gyroorbits of NB ions using EFIT-generated magnetic equilibria, a detailed description of the internal structures in the vacuum vessel, and an accurate model of the beam deposition profile. It is important to retain the full gyromotion of the beam ions because their typical gyroradius is 0.2 m, which is non-negligible compared to the plasma minor radius of ~0.7 mEIGOL simulations show that I_p, q_0, and δ_{outer} (the distance between the separatrix and the limiter) have the strongest effect on the loss rate. Other parameters, such at B_T and n_{e0}, have considerably less influence. Figure 1 depicts the computed global loss fraction for a number of different cases with varying I_p, q_0, and δ_{outer}. The loss fraction rises as the plasma current is reduced, going from ~15% at I_p=1 MA to ~85% at 0.25 MA. However, if the outer gap is increased from 3.7 cm to 14.4 cm, the loss fraction at 1 MA drops to ~2%. Conversely, if q_0

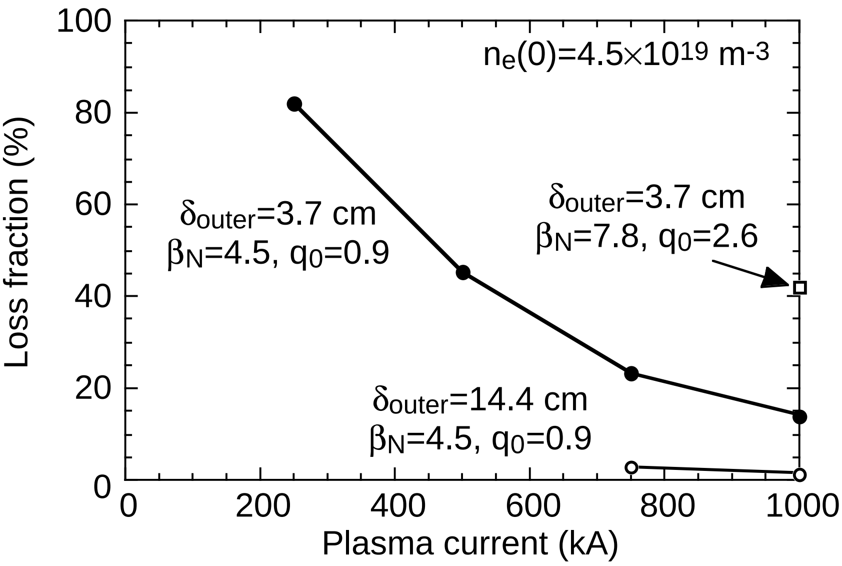

Figure 1 EIGOL computed loss fraction as a function of plasma current, outer gap, and q_0.

is raised from 0.9 to 2.6 at I_p=1 MA, the global loss fraction rises from ~15% to 42%. The loss fraction varies only a few percent at constant I_p as $n_e(0)$ changes.

Beam Ion Loss Diagnostics

On NSTX, there are several diagnostics that can provide information concerning NB ion loss rates. The first two of these diagnostics are associated with the high harmonic fast wave (HHFW) antenna. The antenna is the largest object in the vicinity of the midplane; it projects inward from the vessel wall by 10 cm, to R=1.58 m at the midplane, and it subtends 90° toroidally. Because the orbits of beam ions reach their farthest from the magnetic axis in the vicinity of the outboard midplane, the antenna is the place where many beam ions are lost. On the side of the antenna where beam ions strike there are boron nitride protective plates, 1 cm thick. By measuring the temperature rise of the protective plates during a shot, either with thermocouples or an IR camera, the total integrated flux of beam ions to the plate can be inferred. The thermocouple temperatures are digitized once every few seconds, and hence are useful only to measure the integrated energy absorbed by the protective plates. The IR camera can, in principle, give time-resolved surface temperature measurements, but requires calibration for the emissivity of the protective plate surface.

Beam ion loss at the vessel midplane is also measured by a Fast Lost Ion Probe (FLIP), which utilizes Faraday cups[5]. The probe has three apertures, at R=1.607, 1.632, and 1.661 m. These Faraday cups are located behind apertures that prohibit D ions with energies below 1 keV from reaching the cups. In addition, a cylinder internal to the probe is biased to –50 V to suppress secondary electrons that may result from beam ion impact on the Faraday cups. Signals from this diagnostic are typically digitized at 10 kHz and are absolutely calibrated.

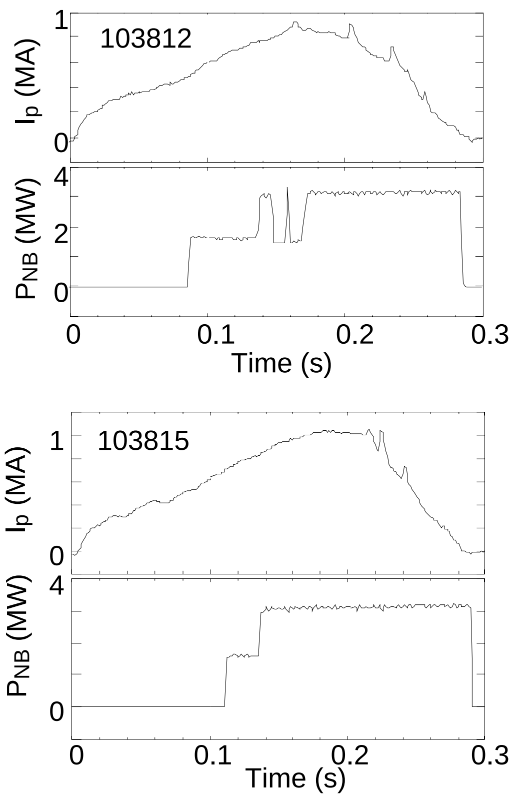

Figure 2 Plasma current and NB power waveforms for two shots with thermocouple data. For shot 103812, a temperature rise of 17° C was observed in the antenna protective plates and for shot 103815, a rise of 3.5° C was seen.

Beam Ion Loss Measurements

The protective plate thermocouples show no discernable temperature rise during ohmic shots, but do register a temperature increase during NB injection. EIGOL simulations predict a protective plate temperature rise of 8° C/(MW-s). Shown in Fig.2 is shot 103815 with I_p=1 MA, had 3 MW NBI for 0.17 s, including some injection during the plasma current rampdown. If the current had been held at 1 MA throughout the injection period, the EIGOL result would predict a temperature rise of 4° C in the protective plates, suggesting that the actual temperature rise should have been >4° C. The observed rise was 3.5° C, less than would be expected. However, a shot also shown in Fig. 2, 103812, with 3 MW injection for 0.2 s gives a temperature rise of 17° C, about five times the temperature change for a very similar discharge. This temperature rise is probably in excess of what EIGOL would predict for this plasma current waveform, and may be the result of MHD activity and internal reconnection events (IREs) during NBI.

IR camera images have been digitized during NBI. Since the surface emissivity calibration for the protective plates has not yet been done, absolute temperatures and temperature rises cannot be reported. However, the scrape off profile of the NB ions on the side of the HHFW antenna has been recorded for a number of shots. Preliminary analysis shows a scrape off length of ~2 cm, somewhat shorter than the 4.2 cm predicted by EIGOL.

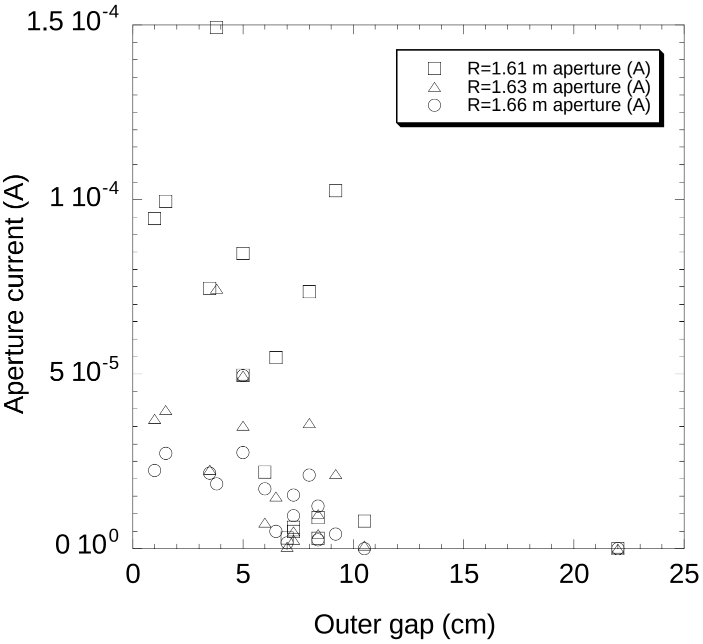

Figure 3 Beam ion loss as a function of outer gap distance for 0.7 MA, 0.3 T plasmas.

NB ion loss measurements have been made with the Faraday cup diagnostic for nearly every NBI plasma to date in NSTX. Figures 3 & 4 display this data. These figures show the typical measured loss levels, which vary from a few μA to ~200 μA. EIGOL calculations for a 1 MA, 0.3 T plasma predict a beam ion flux of 10 MW/m^3, which corresponds to a current of 1 mA in each aperture. So, the loss currents measured are in many cases much smaller than expected. This is in contrast to the thermocouple data, which indicates losses of the same order or slightly less than EIGOL predicts.

Figure 3 shows the most obvious correlation of the loss rate found so far—the correlation with the outer gap spacing. This data is taken from discharges in which single neutral beam sources were injected for 3 ms long “blips” (shots 105692–105749). Even after screening this data set to eliminate cases with obvious MHD activity, there is still significant scatter in the data. A more careful screening of the data for MHD is planned.

Figure 4 displays the variation of the loss as a function of plasma current. Shown are the losses measured in the apertures at R=1.61 and 1.63 m. The losses in both apertures exhibit the trend of increasing loss as I_p decreases. Figure 4 includes a plot of power law curve fits to the data that did not appear to have enhanced loss from MHD activity (solid curves). The fitted exponents are –2.82 and –4.04 respectively for the 1.61 and 1.63 m aperture data. On the same axes are plotted a power law fit to the EIGOL global loss calculation. The fits to the global loss are then scaled to coincide with the measured loss in each aperture at 1 MA. It is necessary to scale the fits because, as described above, the Faraday cup currents observed are significantly smaller than predicted by the model. This fit has an exponent of –1.90, meaning that the model loss varies less rapidly with current than does the observed loss. This set of data includes plasmas with outer gap positions varying between 3.2 and 10.5 cm. Given the strong dependence of the loss fraction on the outer gap distance, as seen in Fig. 3, this plot may not reflect the true variation of the loss with I_p.

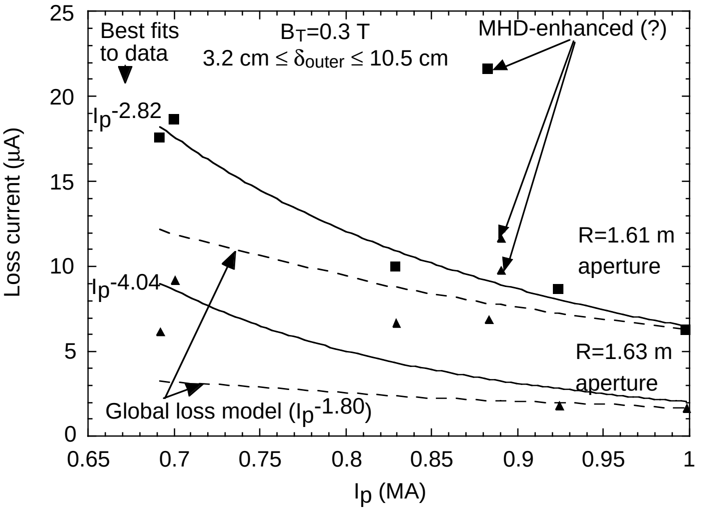

Figure 4 Loss as a function of I_p for two apertures. δ_{outer} varies between 3.2 and 10.5 cm for the shots shown.

Summary

Neutral beam ion losses in NSTX have been measured with thermocouples, an IR camera, and Faraday cups. Thermocouple data shows a loss rate at or somewhat below that predicted by the EIGOL code. Faraday cup measurements of the loss are substantially lower than predicted by the code. The loss rate varies strongly with the outer gap distance, and also with the plasma current.

Acknowledgements

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