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# Neutral Beam Ion Loss Modelling for NSTX

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## Abstract

A numerical model, EIGOL, has been developed to calculate the loss rate of neutral beam ions from NSTX and the resultant power density on the plasma facing components. This model follows the full gyro-orbit of the beam ions, which can be a significant fraction of the minor radius. It also includes the three-dimensional structure of the plasma facing components inside NSTX. Beam ion losses from two plasma conditions have been compared: $\beta$=23%, $q_0$=0.8, and $\beta$=40%, $q_0$=2.6. Global losses are computed to be 4% and 19%, respectively, and the power density on the rf antenna is near the maximum tolerable levels in the latter case.

## Introduction

Spherical tokamaks have a number of favorable properties that scale well to a reactor-sized device, including high beta. the National Spherical Torus Experiment NSTX is a new spherical tokamak at PPPL which is intended to explore the properties of these plasmas at an intermediate scale. First plasma was obtained in February 1999, and the initial experimental campaign will begin in the summer of 1999. The plasma will be heated with up to 6 MW of high harmonic fast waves (HHFW) in the ion cyclotron range of frequencies and eventually with up to 5 MW of neutral beam injection (NBI). Although NBI will not commence until the 2000 campaign, we have started to model the orbits of fast ions arising from NBI in order to learn about rates of loss that may arise under various experimental conditions.

Beam ion loss rates are of interest and concern for a number of reasons. From the engineering point of view, knowing the power density expected on various in-vessel components allows them to be designed to withstand that heat flux. Loss rates also affect plasma efficiency. Loss distribution information is useful in planning the location of diagnostics to measure the loss rate. Modelling also provides a basis for interpreting observed wall heating patterns and fast ion losses as it indicates whether they can arise from prompt orbit losses or whether some other mechanism must be invoked to explain them. At present, the primary goal of this effort is to compute the expected prompt loss power density on the HHFW antenna and passive stabilizer plates which are close to the plasma near the midplane and therefore, given the shape of orbits in the machine, can receive a significant heat load.

## Model Description

The modeling for NSTX has been done with a newly developed code, EIGOL (Energetic Ion Global Orbit Loss). Beam ion losses in some NSTX cases (next section) have already been computed with the LOCUST code[1]. The purpose of the latter code is to model the fast ion velocity distribution in the plasma and as it would be observed by a neutral particle analyzer. Thus, it incorporates orbit-following along with collisional pitch angle scattering and slowing down, and atomic cross-sections for ionization and charge exchange. Because LOCUST can follow a population of fast ion orbits, it readily can compute the fast ion loss to the wall. However, EIGOL has been developed to provide a less sophisticated but potentially faster evaluation of which discharges may result in excessive wall heating by focusing on the prompt loss of fast ions. It may also, in the future, be extended to handle non-axisymmetric plasmas.

The EIGOL code follows the complete gyromotion of the beam ions in the magnetic field using the orbit integrator kernel from the PPPL Lorentz Orbit code[2]. For accurate computation of losses in NSTX this is essential, since the 80 keV D beam ions can have a gyroradius ($\rho$) of ~30 cm, giving $\rho/a$~0.4. In this large Larmor radius regime, simply following the particle guiding centers would not give an accurate measure of the particle loss rate.[3]

The magnetic field structure of the plasma is taken from EFIT[4], and does not include ripple arising from the discreteness of the toroidal field coils (~0.5% maximum, at the outer midplane of NSTX). The code starts ions on a regular rectangular three-dimensional grid that fills the volume where the neutral beam intersects the plasma volume. Each particle is assigned a weight based upon the source strength expected at its initial position. That source strength is determined by the beam density profile in the two transverse dimensions of the beam. Along the axis of the beam, deposition is computed based upon an input density profile. Specifically, the neutral beam flux at the i-th grid location is given by $S_i$, where

$$S_i = S_{i-1} \exp(-\Delta y/\lambda).$$

Here $\Delta y$ is the distance between grid points, and $\lambda$ is the mean free path of beam neutrals at the injection energy. For this work, we take $\lambda=3.99\times10^{14}\ E^{1.3}/n_e$, where $\lambda$ is given in m, E is the particle energy in eV, and $n_e$ is the electron density in $m^{-3}$. The local beam ion deposition at the i-th grid point is taken to be $S_{i+1} - S_i$.

Particles are started in their orbits with a velocity exactly along the direction of beam injection, i.e. the velocity spread of the beam (typically ~1°) is not taken into account. Also note that no effects of collisions are taken into account in this code. Orbits are followed until one of two conditions is satisfied: (1) the orbit reaches a maximum length set by the user (25–50 m for results described herein), or (2) the orbit intersects one of the plasma facing components inside the vessel. A three-dimensional representation of the major structures within the NSTX vessel is contained within the code. As each orbit computation is completed, the starting and ending points are written to an output file, along with the particle's weight and a flag indicating whether the orbit struck the wall. A post-processor then reads this output file and can construct a map of the beam ion power density on the plasma facing components.

## Cases for Comparison

For the initial study, calculated beam ion losses in two NSTX equilibria were computed. Both had $I_p$=1 MA, $B_T$=0.3 T, and were limiter discharges with their contact point on the center stack. For Case 1, $R_{axis}$=1.025 m, $q_0$=0.8, $q_a$=10.3, $\beta_T$=23%, $\kappa$=1.92, and $\delta$=0.39; for Case 2, $R_{axis}$=1.172 m, $q_0$=2.6, $q_a$=14.0, $\beta_T$=40%, $\kappa$=2.02, and $\delta$=0.44. Case 1 represents a typical first stability regime discharge in NSTX. Case 2 represents a high-$\beta$, high bootstrap fraction discharge with optimized pressure and current profiles. An approximately parabolic density profile, with taken from TRANSP[5] run number 11112P62 was used for computing the beam ion deposition in both cases. This profile has a central density of $3.5\times10^{19}\ m^{-3}$ and an edge density of $3.1\times10^{18}\ m^{-3}$. The density rises steeply at the outer edge such that 0.05 m inward from the last closed surface it has already reached $2\times10^{19}\ m^{-3}$.

For the TFTR beam injector that will be used on NSTX, there are three separate beam sources. Each source produces a beam whose cross-section is 0.22 m wide and 0.605 m high. Within that cross-section, the beam density is modeled as a gaussian with a horizontal full width at half maximum of 0.12 m, and a vertical full width of 0.43 m. The three beams have tangency radii of 0.487, 0.592, and 0.694 m, and their successive points of tangency are each separated by 4° toroidally. They are referred to as the "inner," "middle," and "outer" beams below, and their centers lie in the midplane. When operated in deuterium at 80 kV, these beam sources produce 78% of the total power in full-energy particles, 16% in half-energy particles, and 6% in one-third energy particles. Each beam source is capable of producing ~1.7 MW when operated at 80 kV, for a total power to the plasma of ~5 MW. The neutral output power of each source scales as $\sim V^2$ for V~80 kV.

Table I shows the computed global beam ion losses from the two equilibria, tabulated according to beam source and energy component. In this table, losses are tabulated as a percent of the power deposited in the plasma. Each beam has a typical shine-through, at these densities, of 1–2%. For these results, the code was run with grid spacings as follows: horizontal direction, 0.022 m; vertical direction, 0.03025 m; in the direction of beam propagation, 0.0459–0.0488 m. The simulation runs for all cases used ~11,800 particles, of which 454 to 6471 were lost, depending upon the equilibrium and beam source. The maximum orbit length was restricted to 50 m, and evidence from LOCUST runs indicates that larger loss fractions result when that figure is increased. This effect is produced by orbits whose outer midplane crossing radius is larger than 1.58 m, the radial position of the antenna at the midplane. The HHFW antenna subtends only 90° toroidally, and the wall location at the midplane over the remaining 270° toroidally is at R=1.69 m, allowing these orbits to remain confined until they precess toroidally to the point where their outer midplane crossing point intersects the antenna volume. LOCUST runs indicate that it can be up to ~20 poloidal transits (orbit length of ~500 m) before that intersection occurs.

As can be seen in Table I, the total loss in Case 1 is ~4%, while in Case 2 it is ~19%. The losses in Case 2 are larger for two main reasons: first, because there is less total poloidal flux in the discharge to confine fast ion orbits and, second, because the last closed flux surface lies closer to the passive stabilizer plates, causing more ions to scrape off there. The results from this effort are ~25% lower than those of LOCUST, which computes an average power loss of ~25% in Case 2. It is reasonable that LOCUST computes a higher loss fraction due to the orbit precession effect noted in the preceding paragraph and due to the fact that the grid spacing used for these EIGOL simulations did not adequately resolve beam deposition in the steep density gradient region at the plasma edge where most lost orbits originate. In addition, the LOCUST simulation was done with a higher edge density than that used here.

| | *80 keV D* | *40 keV D* | *27 keV D* | *Total loss* |
|---|---|---|---|---|
| Power fraction | 0.70 | 0.21 | 0.09 | |
| β=23% (Case 1) | | | | |
| Outer beam | 2.4 % | 0.4% | 0.2% | |
| Middle beam | 3.5% | 0.7% | 0.3% | |
| Inner beam | 10.6% | 1.1% | 0.4% | |
| Average loss | 5.5% | 0.7% | 0.3% | 4.0% |
| β=40% (Case 2) | | | | |
| Outer beam | 8.2% | 2.7% | 0.8% | |
| Middle beam | 27.4% | 4.4% | 0.9% | |
| Inner beam | 41.9% | 7.4% | 1.3% | |
| Average loss | 25.8% | 4.8% | 1.0% | 19.2% |

*Table I: Beam ion loss fractions for the two equilibria studied, as a function of beam source and energy component of the beam. The figures in the right-most column are the weighted total of the average loss fractions at each energy.*

The losses computed in these EIGOL simulations are concentrated principally on the HHFW antenna and, to a much lesser extent, the lower outer passive stabilizer plate. On the antenna, the losses are approximately uniform in toroidal angle, with slight evidence of peaking at the edges of the antenna. In poloidal angle, the losses are concentrated near the midplane, over the middle 60% of the vertical extent of the antenna. The antenna has a surface area of $\sim 2.5\ m^2$, meaning that the average beam loss power density is $\sim 0.7\ MW/m^2$. This is near upper limit in the design criteria for the antenna for the full 5 s pulse. LOCUST simulations predict

~0.6 $MW/m^2$ on the face of the antenna, in reasonable agreement with these results, but with potenially troublesome peak loads around 1.1 $MW/m^2$ at the edges of the antenna.

To reduce the large loss fraction from the inner beam, it was suggested that the voltage on that beam be reduced to 50 keV, and the voltage on the other two beams be increased to 85 to keep the total beam power roughly constant. Table II shows EIGOL loss fraction calculations for this arrangement for Case 2 and reveals that such a combination reduces the power to the wall by ~480 kW, or 37%. The power absorbed by the plasma drops by ~100 kW, which is ~3%. If such a high-$\beta$, high-$q_0$ discharge can be created in NSTX, this permutation of beam source voltages could diminish the amount of power deposited on the HHFW antenna and the passive stabilizer plates.

| **Case 2** | *Voltage (kV)* | *Loss Fraction* | *Lost Power (MW)* | *Plasma Power (MW)* |
|---|---|---|---|---|
| All 80 kV | | | | |
| Outer | 80 | 8.2% | 0.14 | 1.53 |
| Middle | 80 | 27.4% | 0.46 | 1.21 |
| Inner | 80 | 41.9% | 0.70 | 0.97 |
| **Totals** | | 25.9% | **1.30** | **3.71** |
| Mixed Voltages | | | | |
| Outer | 85 | 9.3% | 0.18 | 1.71 |
| Middle | 85 | 29.5% | 0.56 | 1.33 |
| Inner | 50 | 11.9% | 0.08 | 0.57 |
| **Totals** | | 18.5% | **0.82** | **3.61** |

*Table II: Comparison of beam power absorbed in plasma and deposited on walls for Case 2 with two different configurations of the beam voltages. The mixed configuration of voltages results in a slightly smaller power absorbed by the plasma, but a significantly lower loss to the walls.*

## Summary

We have developed a gyro-orbit following code to evaluate the global loss rate of neutral beam ions from NSTX plasmas and the resultant power density on the plasma facing components. Losses from a “typical” NSTX equilibrium with $q_0$=0.8 and $\beta_T$=23% are only 4%, but are ~19% in an equilibrium with $q_0$=2.6 and $\beta_T$=40%. A proposed decrease of the inner beam voltage, combined with a small increase of the voltages for the other beams, results in significantly lower losses to the wall with only slightly lower power absorbed by the plasma.

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