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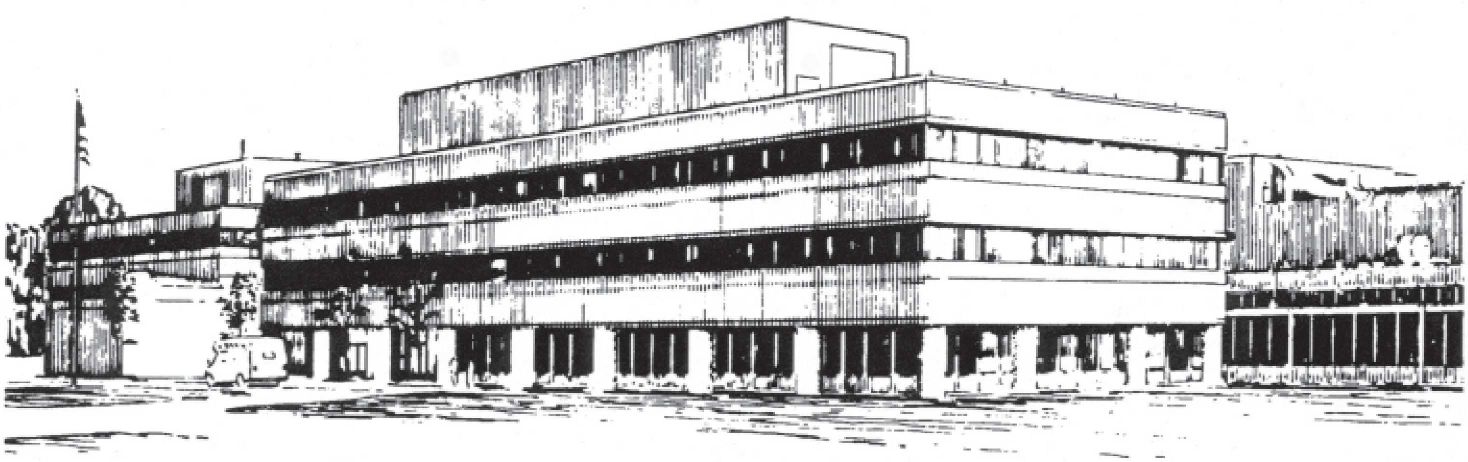

PRINCETON PLASMA PHYSICS LABORATORY
PRINCETON UNIVERSITY, PRINCETON, NEW JERSEY

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M. H. Redi[a], D. S. Darrow[a], J. Egedal[b], S. M. Kaye[a], R. B. White[a]

[a]*Princeton Plasma Physics Laboratory, Princeton, NJ 08543, USA*
[b]*Plasma Science and Fusion Center, MIT, Cambridge, MA 02139,USA*

Introduction

The spherical torus (ST) concept underlies several contemporary plasma physics experiments, in which relatively low magnetic fields, high plasma edge q, and low aspect ratio combine for potentially compact, high beta and high performance fusion reactors. An important issue for the ST is the calculation of energetic ion confinement, as large Larmor radius makes conventional guiding center codes of limited usefulness and efficient plasma heating by RF and neutral beam ion technology requires minimal fast ion losses. The National Spherical Torus Experiment (NSTX[1]) is a medium-sized, low aspect ratio ST, with R=0.85 m, a=0.67 m, R/a=1.26, I_p≤1.4 MA, B_t≤0.6 T, 5 MW of neutral beam heating and 6 MW of RF heating. 80 keV neutral beam ions at tangency radii of 0.5, 0.6 and 0.7 m are routinely used to achieve plasma betas above 30%. Transport analyses for experiments on NSTX often exhibit a puzzling ion power balance[2]. It will be necessary to have reliable beam ion calculations to distinguish among the source and loss channels, and to explore the possibilities for new physics phenomena, such as the recently proposed compressional Alfven eigenmode ion heating.

Calculations of Fast Ion Confinement

While anomalous transport is an important consideration for thermal ion confinement, fast ion confinement appears to be classical. A beam blip experiment scanning plasma current from 0.3 to 1.0 MA at B_t≤0.35 T showed that measured neutron rates were in rough agreement with that expected from classical behavior[3]. Several methods are being used to calculate the classical transport of neutral beam ions, needed for transport analysis and perfomance planning. Initial NSTX calculations are presently limited to collisionless transport. Collisionless fast ion losses, calculated with the EIGOL[4], GYROXY[5], and CONBEAM[6] codes, have been compared for a group of NSTX plasmas, which range in I_p from 0.6 to 1.0 MA and B_t from 0.3 to 0.45 T (Table 1.). EIGOL and GYROXY are full Larmor radius, Lorenz codes which compute neoclassical orbits in the (R, Z) laboratory coordinates. CONBEAM provides a rapid analysis of ion guiding center topology, to which is added the edge Larmor radius width (ρ_L), determining an estimate of loss for specific neutral beam parameters (Fig. 1). Diamagnetic effects lead to different edge ρ_L for shots with identical values of I_p and B_t. The beam ionization models, and thus the initial ion ensembles, are similar for the codes, which all include realistic antenna and plasma gap-to-wall geometries.

In Table 1 are given parameters for sixteen NSTX equilibria representing the range of I_p, B_t, K found on NSTX. CONBEAM predicts 20% to 50% losses for 80 keV neutral beam ions for the full energy component. Not surprisingly, best confinement occurs at high I_p, B_t and small ρ_L. Figure 2 shows the confined fraction contours for a high current NSTX plasma, #105572, I_p=1.0 MA, B_t=0.45, as a function of Z and tangency radius. In Fig. 3 is shown the confinement fraction of 80 KeV neutral beam ions calculated for the three beams at 0.5, 0.6 and 0.7 m tangency radii, as a function of ρ_L for the equilibria. Confinement improves at small ρ_L and large injection radius, with more variability at small tangency radius.

GYROXY and EIGOL have been benchmarked for identical source profiles modeling a 80 KeV, 0.5m tangency radius beam, in a NSTX 23% beta equilibrium. The two codes are in excellent agreement at short times: 21% loss of 54,000 ions after 7.5×10^{-5} sec. GYROXY has been used to examine losses after longer orbit integration times, with 26% loss found at 7.5×10^{-4} sec. 26% loss is also found with CONBEAM; however, the fractional loss computed by GYROXY increases linearly with time. This integration time corresponds to $1/20^{th}$ of an ion slowing down time; for longer integration times energy slowing down effects will be included. Although not yet parallelized, as is the parent code ORBIT, GYROXY provides detailed information about ion paths, initial and final pitches and positions as well as ion lifetimes. For the benchmark case, the final ion density is flat, with ions being preferentially lost near the magnetic axis. The ions which leave the plasma at later times are found to have more pitches near co-passing, rather than between co-passing and trapped. Convergence studies of the equilibria are important for validation and have been carried out, along with checks on the energy conservation criteria.

Conclusions

Benchmarking of EIGOL and GYROXY validate the results of both codes and are in good agreement with CONBEAM. These present calculations of collisionless beam ion losses confirmed loss of ~20% for high beta on NSTX, using results from three methods of calculating the confinement fraction. CONBEAM provides fast estimates of confinement without details of ion orbit paths (in minutes) and predicts good confinement with high I_p, B_t, $1/\rho_L$, and high R_{tan}. Using EFIT analyses of NSTX equilibria, CONBEAM finds that small ρ_L at the limiter is the best guarantor of good fast ion confinement. GYROXY can provide long integration time calculations of collisionless confinement (days) and can also be used to address nonadiabatic and collisional losses. Slowing down is expected to improve fast ion confinement[7]. These calculations for present experiments, will support ion power balance analyses and the understanding of new phenomena on NSTX.

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Table 1. Confined beam fraction for $Ne=(2x10^{13}/cm^3)(1-(r/a)^2)^{0.3}$ using CONBEAM

Shot ID	Ip(MA)	κ	B_t(T)	Edge ρ_L	frac(0.5m)	frac(0.6m)	frac(0.7m)
23% beta	1.0	1.7	0.30	0.2309	0.7418	0.7700	0.7779
104370	1.0	1.7	0.29	0.2333	0.7660	0.7759	0.7817
104282	1.0	2.0	0.30	0.2806	0.7333	0.7445	0.7516
102442	0.8	2.0	0.30	0.2927	0.7142	0.7326	0.7401
103275	0.6	1.7	0.30	0.2794	0.6408	0.7315	0.7412
106382	1.0	1.6	0.34	0.2098	0.7768	0.7897	0.7937
106382(c)	1.0	1.8	0.34	0.2000	0.7319	0.7375	0.7378
104391	0.8	1.7	0.30	0.2691	0.7373	0.7489	0.7558
104879	1.0	1.7	0.30	0.2592	0.7503	0.7600	0.7653
105542	0.8	1.7	0.45	0.2044	0.7386	0.7806	0.7853
105572	1.0	1.7	0.45	0.1989	0.7732	0.7873	0.7913
105582	0.8	2.0	0.45	0.2192	0.7409	0.7739	0.7762
105631	0.6	2.0	0.45	0.2264	0.6362	0.7611	0.7641
105632	0.6	1.7	0.45	0.2091	0.6447	0.7685	0.7747
105645	0.6	2.0	0.30	0.3054	0.4780	0.6833	0.7143
105917	1.0	2.0	0.45	0.2051	0.7473	0.7823	0.7866

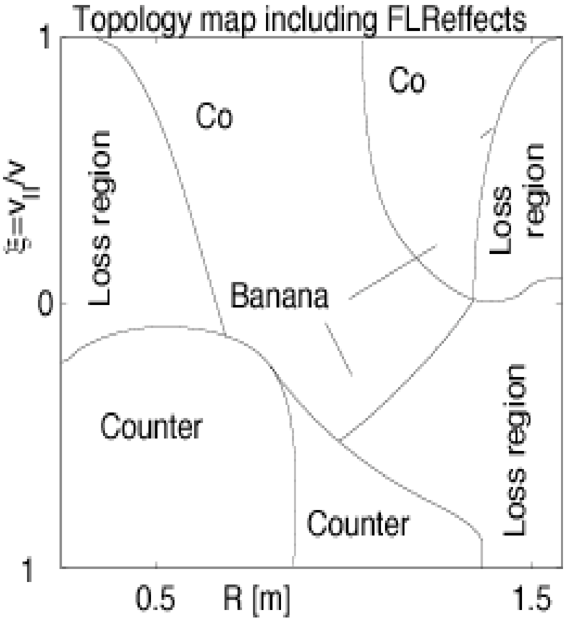

Fig. 1 Ion orbit topology diagram from CONBEAM, as a function of $\xi = v_{//}/v$ versus R(m). Loss regions occur at low and high R.

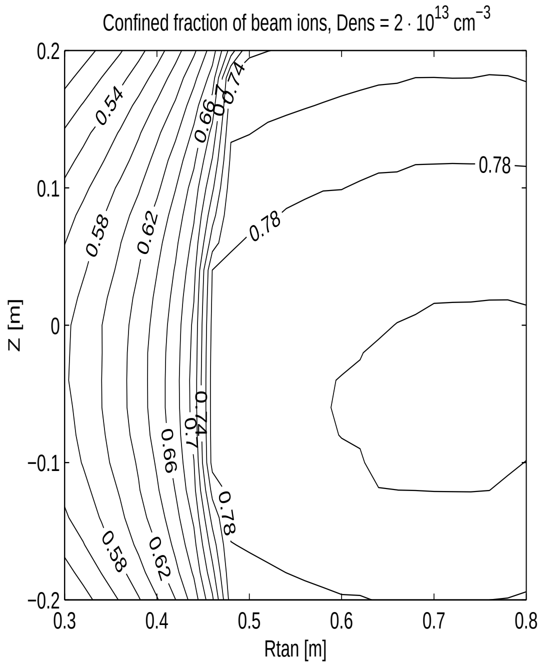

Fig. 2 Confined beam fraction of high current NSTX plasma, shot #105572, Ip=1.0 MA, Bt = 0.45 T, for Z versus beam tangency radius.

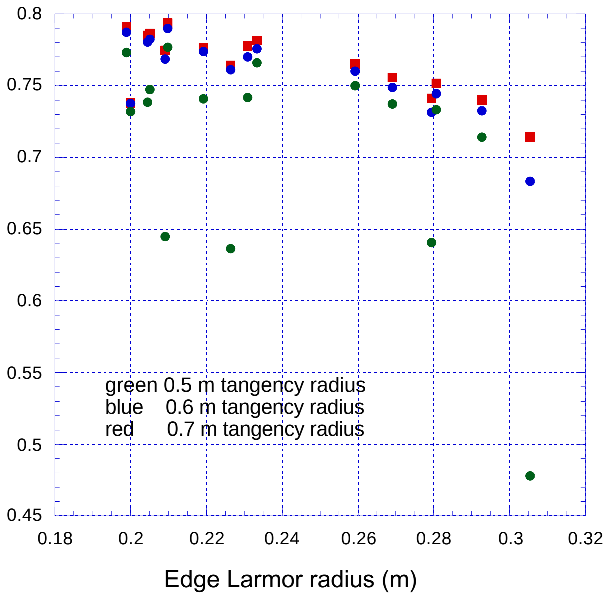

Fig. 3 Confinement fraction of 80 keV beam ions improves at small Larmor radius and large injection radius.

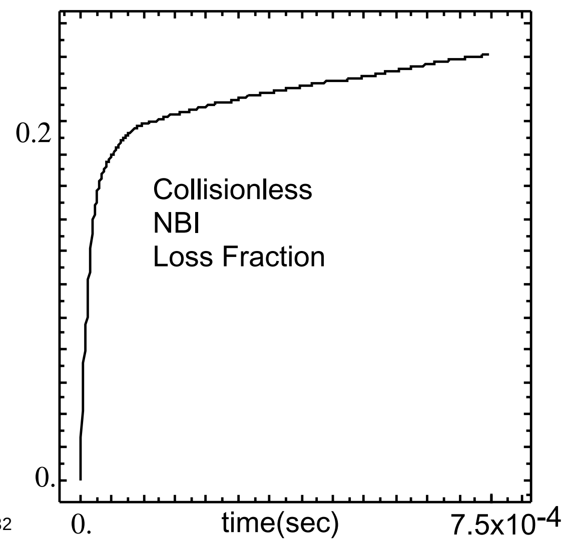

Fig. 4 GYROXY calculation of NBI loss fraction evolution over ~1/20th of a slowing down time, for 54,0000 beam ions (Ip = 1 MA, Bt = 0.34 T.

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Information Services
Princeton Plasma Physics Laboratory
P.O. Box 451
Princeton, NJ 08543

Phone: 609-243-2750
Fax: 609-243-2751
e-mail: pppl_info@pppl.gov
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