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The confinement of dilute populations of beam ions in the national spherical torus experiment

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Abstract
Short ∼3 ms pulses of 80 keV deuterium neutrals are injected at three different tangency radii into the national spherical torus experiment. The confinement is studied as a function of tangency radius, plasma current (between 0.4 and 1.0 MA), and toroidal field (between 2.5 and 5.0 kG). The jump in neutron emission during the pulse is used to infer prompt losses of beam ions. In the absence of MHD, the neutron data show the expected dependences on beam angle and plasma current; the average jump in the neutron signal is 88 ± 39% of the expected jump. The decay of the neutron and neutral particle signals following the blip are compared to the expected classical deceleration to detect losses on a 10 ms timescale. The temporal evolution of these signals are consistent with Coulomb scattering rates, implying an effective beam-ion confinement time ≳100 ms. The confinement is insensitive to the toroidal field despite large values of ρ∇B/B (≲0.25), so any effects of non-conservation of the adiabatic invariant µ are smaller than the experimental error.

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1. Introduction
Dilute populations of energetic ions exhibit excellent confinement properties in conventional tokamaks [1]. A spherical tokamak (ST) has a smaller major radius R relative to the minor radius a than a conventional tokamak; for example, in the national spherical torus experiment (NSTX), a/R ≃ 0.7. This difference has several implications of potential importance for fast-ion confinement. First, the magnitude of the poloidal field can be comparable to the toroidal field, altering the orbit topology [2, 3] and particle drifts [4]. Second, the relatively weak magnetic field B implies a large fast-ion gyroradius ρ, while the small value of the major radius implies rapid field variations (B ∝ 1/R in a torus). Because ρ∇B/B is appreciable, the magnetic moment µ = W⊥/B, which is a robust adiabatic invariant in a conventional tokamak, need not be conserved in a ST [5–10]. In addition to these theoretical considerations, the confinement of fast ions in a ST is of considerable practical importance. Neutral beams are the primary heating system for thermal confinement studies in NSTX, so it is vital to understand their performance. Moreover, the normalized beam-ion gyroradius ρ/a in NSTX is comparable to the expected normalized gyroradius of alpha particles in a deuterium–tritium ST reactor, so measurements of beam-ion confinement in NSTX address the viability of the ST as a fusion reactor.

The first study of fast-ion confinement in an ST was performed on the START ST [5]. The measured neutral particle spectra were consistent with predictions based on orbit calculations in the presence of Coulomb scattering alone. Short neutral-beam pulses (beam “blips”) are a convenient technique [11] for the study of the confinement of dilute populations of beam ions. The technique has verified classical deceleration [11, 12] and weak diffusion [13,14] of beam ions in conventional tokamaks, has measured anomalies associated with field ripple in conventional tokamaks [15–17] and has diagnosed poor confinement of perpendicular beam ions in the CHS helical device [18]. This paper reports the first application of the beam-blip technique to a ST. Although the scatter in the data is larger than expected, the absolute magnitude, time evolution and parametric dependences of the resulting neutron signals are consistent with classical beam-ion behaviour.

2. Experimental conditions and techniques for analysis
All the data in this paper were acquired during two consecutive days of operation in July 2001. Three neutral beam sources...
injected approximately 1.6 MW of ~80 keV deuterons into deuterium NSTX plasmas ($a \simeq 0.66 \text{ m}$, $R \simeq 0.95 \text{ m}$, elongation $\kappa \simeq 1.8$) at tangency radii of 0.69 m (Source A), 0.59 m (Source B), and 0.49 m (Source C). The gyroradius of a typical orbit is quite large, as illustrated in figure 1.

In a typical discharge (figure 2), several beam blips of ~3 ms duration are injected into a nominally steady-state portion of the discharge. The electron temperature and density are measured by a ten-point Thomson scattering diagnostic.

The neutron rate is measured by a ZnS scintillator that was cross-calibrated to a 1.3 g $^{235}$U detector, which was directly calibrated by a standard $^{252}$Cf radioactive source [21]. At a typical beam blip (figure 3), the neutron emission $I_n$ rises nearly linearly during the beam pulse, then decays approximately exponentially following the pulse. Under these conditions, the beam–plasma reaction rate is over an order of magnitude larger than the beam–beam or thermonuclear rates. The maximum possible rate of change of neutron emission is

$$\dot{I}_n \simeq N_b n_d \langle \sigma v \rangle,$$

(1)

where $N_b$ is the rate at which full-energy beam ions are injected into the device, $n_d$ is the deuterium density in the centre of the device, and $\langle \sigma v \rangle$ is the d–d reactivity. For these beam–plasma reactions with injection energy $E_{\text{inj}} \gg T_i$ (and negligible toroidal rotation), the reactivity is well approximated by the reactivity of an 80 keV deuteron that collides with cold target ions, $\langle \sigma v \rangle \simeq \sigma v = 3.39 \times 10^{-18} \text{ cm}^2 \text{ s}^{-1}$. In a large, conventional tokamak with excellent confinement, nearly all the injected neutrals become centrally confined beam ions, so $N_b \simeq f_{\text{full}} P_{\text{inj}} / E_{\text{inj}}$ where $f_{\text{full}} \simeq 0.66$ is the fraction of the total power carried by full-energy beam ions and $P_{\text{inj}}$ is the injected power. For NSTX parameters, the maximum expected rate of

\[ I_n \simeq N_b n_d \langle \sigma v \rangle. \]
rise of the neutron emission is typically $I_n = 279n_d$ ($n_d$ is in cm$^{-3}$ and $I_n$ is in neutrons s$^{-1}$).

Following the blip, the neutron emission decays approximately exponentially. Because the reactivity decreases rapidly with energy, the expected neutron decay rate, $1/\tau_n$, is faster than the energy deceleration rate $\nu_E$. A simple but accurate estimate of the expected decay time is given by a 'typical particle model' [22] using average values of $T_e$ and $n_e$ in the central third of the plasma:

$$\tau_n = (2.63\nu_E)^{-1}, \quad (2)$$

where $\nu_E$ is the classical deceleration rate [23, 24] of 80 keV deuterons.

In an ideal beam blip experiment, the duration of the beam blip is short compared to the deceleration time, so an approximately monoenergetic population of beam ions is studied. In practice, $\tau_n$ can be comparable to the pulse duration $t_{\text{blip}}$. The resulting slight curvature of the rate of rise is evident in figure 3. To include this effect, the neutron signal is fit to the equation $I_n = c - I_0/\tau_n$ during the beam blip and to $I_n = -I_0/\tau_n$ after the pulse. The constant $c$ reflects the prompt confinement of the injected beam ions and should equal the right-hand side of equation (1) if all the injected beam ions are confined in the plasma centre. The decay time $\tau_n$ should agree with the classical expectation (equation (2)) if delayed losses on the deceleration timescale are negligible. Empirically, the fit of the neutron signal to the temporal evolution predicted by this simple model is usually excellent (reduced $\chi^2 < 1$), as illustrated in figure 3.

Deviations from this model behaviour are sometimes observed, especially in the presence of violent MHD activity. In the example shown in figure 4, the plot of the rate of increase of the neutron signal is slightly concave (in contrast to the usual convex one) because of the bursts at 181 and 182 ms and the decaying signal abruptly terminates at the minor disruption at 191 ms, evidently indicating a total loss of beam ion confinement. (Minor disruptions were common during the 2001 experimental campaign but are now less prevalent due to improved vacuum conditions, reduced error fields, and increased operational experience [25].) Beam blips with concurrent low-frequency MHD activity are excluded from the data presented in the next section.

Beam ions in NSTX often destabilize modes with frequencies between 50 kHz and several megahertz. In these experiments, the beam population is intentionally kept small in order to study classical confinement. No evidence of any TAE [26] or CAE [27] activity is observed by magnetic diagnostics for any of the discharges reported here.

In addition to comparisons with simple test particle models, the data are compared to the predictions of the TRANSP code [28], which has been modified for NSTX to properly average plasma parameters over the relatively large beam-ion gyroradius [29]. The TRANSP code assumes conservation of the magnetic moment $\mu$. The same algorithm used for the experimental data is used to fit the neutron signals predicted by TRANSP. This model is generally an excellent fit to the predicted time evolution.

3. Results

In a tokamak, the prompt losses of beam ions decrease with increasing plasma current because the poloidal gyroradius decreases. These losses are greater for perpendicular ions than for parallel ions. These expected trends are evident in figure 5, which shows the measured rate of rise of the neutron signal as a function of the plasma current. As expected, the jump in the neutron signal is larger for beam ions injected tangential to the field (Source A) than for beam ions injected at a more perpendicular angle (Source C). (This difference is also evident in the raw signal shown in figure 2). As expected, the signal strength increases with plasma current for all angles of injection.

The scatter of the data in figure 5 is large. Known sources of error include the following:

- Uncertainties associated with fitting the neutron data to the model rise and decay equations are $\sim 10\%$.
- The rise depends on the deuterium density $n_d$, which itself depends on both the electron density $n_e$ and $Z_{\text{eff}}$. The random error in the Thomson scattering measurements

Figure 5. Measured rate of increase of the neutron signal divided by the ideal rate (equation (1)) vs $I_p$ for all beam blips with undetectable MHD activity and $B_t > 0.3$ T. The symbols denote the angle of beam injection. The error bars are derived from estimates of the uncertainties in the model fit and in the deuterium density. The curves are from polynomial least-square fits to the data.
of electron density is typically 5%; the systematic error is estimated as $\sim 5\%$. In addition, measurements are only acquired every 17 ms. In the analysis, the average of the density measurements before and after the blip is employed but rapid changes in density introduce additional errors.

- The $Z_{\text{eff}}$ measurement is an average value. The uncertainty is difficult to quantify but could be substantial. It is also assumed that carbon is the dominant impurity, so $n_A/n_e = (Z_{\text{eff}} - 1)/(6 - 1)$, but this may not always be the case.

- The neutral beams were not calibrated to measure the time evolution of the beam power throughout the beam blip at the time of this experiment. Generally, the beam voltage and power are only available for a single time point during the blip. Any power fluctuations or error in this single measurement contributes to the overall error.

- The relative error in the neutron measurement is small and is included in the fitting uncertainties given above. On the other hand, the absolute error is estimated to be 25%.

For currents above 0.5 MA and fields above 0.25 T, the normalized rise in neutron rate is 0.42 $\pm$ 0.04 for Source A, 0.32 $\pm$ 0.10 for Source B, and 0.32 $\pm$ 0.06 for Source C. The absolute magnitude of the normalized rise is a factor of three smaller than the ideal value of unity but, as discussed below, this discrepancy is principally caused by the deficiencies of the typical particle model.

To investigate any effects associated with the large beam-ion gyroradius, the toroidal field is varied between 0.25 and 0.50 T. Any systematic variation in prompt losses is obscured by the relatively large scatter in the data (figure 6). Losses due to non-conservation of $\mu$ are more likely to appear as an effect on the decay rate but no systematic variation with toroidal field is observed (figure 7). There is also no difference in decay rates for different angles of injection. The ratio of $\tau_D$ to the prediction of the typical particle model (equation (2)) is 1.16 $\pm$ 0.25 for Source A, 1.06 $\pm$ 0.17 for Source B, and 1.05 $\pm$ 0.35 for Source C. Theoretically, the decay rate is not expected to depend significantly on the injection angle in a regime where Coulomb drag on electrons predominates, since pitch-angle scattering onto loss orbits is negligible for nearly all initially confined orbits. In contrast to the rise in neutron emission, the decay time is in good agreement with the simple theoretical prediction, indicating that well-confined, centrally born beam ions slow down classically.

The good agreement of the measured decay time with classical Coulomb scattering theory is corroborated by neutral particle measurements (figure 8). For these measurements, the analyser [30] is oriented to measure the same tangency radius as injected by Source A. The spectra are produced by...
beam injection. The symbols denote the angle of
profile and the beam ions, so the spatial dependence of the
charge-exchange between the ambient neutral density
signal is complicated. If one assumes that the signal originates
behind the TRANSP prediction vs the TRANSP prediction for all beam blips
neutral particle data for Source A appears in figure 8.) Also shown
is the classically predicted peak of the distribution using core values of
beam power is deposited in the plasma for the discharges with
the TRANSP predictions (figure 11). (For decay times that are
room temperature of the plasma and 90% occur within
The neutron data are also compared to the predictions
the foils at
The neutron emission rate is smaller than that predicted by the
For all three injection angles, the prompt confinement is
Confinement of beam ions in the NSTX
for any of the beam blips. When current is detected, it is largest on
during the beam blip; no detectable current is observed after
any of the beam blips. When current is detected, it is largest on
of the plasma and 90% occur within
half of the reactions occur in the central quarter of
any systematic variation in prompt confinement with toroidal field is obscured by the relatively large scatter of the results.
The ratio does not vary systematically with tangency radius
plasma current, indicating that the principal variations associated with the beam-ion drift orbits are properly modelled by TRANSP. The average ratio is 88 \pm 39%.

The measured decay time is in excellent agreement with
the TRANSP predictions (figure 11). (For decay times that are
than remaining at a constant value of unity, the normalized
decay time is now expected to decrease as

Direct beam-ion losses to the midplane of the outer vacuum vessel wall are measured by a set of foils that act as Faraday cups [31]. In some cases, positive current is measured
during the beam blip; no detectable current is observed after
of the beam blips. When current is detected, it is largest on
of the plasma and 90% occur within
of the plasma and 90% occur within

4. Conclusions
For all three injection angles, the prompt confinement is
 degraded for currents below 0.5 MA, as expected. The effect

is strongest for the most perpendicular injection angle, also as expected.

The magnitude of the jump in neutron emission is comparable to the expected value for all injection angles and values of poloidal and toroidal fields. On the other hand, the scatter in the neutron jump data is larger than that expected based on known uncertainties. A possible reason for this scatter is that the deuterium density may not be accurately inferred from a single visible bremsstrahlung chord. Alternatively, variable prompt losses on a timescale much shorter than 1 ms may be occurring.

The temporal evolution of the neutron signal is in excellent agreement with the expectations of classical theory. Any delayed losses of initially confined beam ions are small (≤15%) on a 20 ms timescale. The good agreement between the measured decay time and Coulomb scattering theory confirms the accuracy of the Thomson scattering measurements of central $T_e$ and $n_e$ (to within ~15%).

Many NSTX plasmas have higher values of ion temperature than expected from classical energy transfer rates and neoclassical ion confinement [32]. The good agreement between the measured decay rates and classical Coulomb scattering theory suggests that the initially confined beam ions transfer their energy to electrons rather than to thermal ions, as expected. If any anomalous energy transfer to thermal ions occurs, it must occur on a sub-millisecond timescale.

Statistically significant variations in either prompt or delayed confinement with $\rho V B / B$ are absent in these data (for values between 0.12 and 0.25). Recent theoretical studies [5–9] predict reductions that are smaller than the experimental uncertainty so, although this result is consistent with theory, it does not constitute a rigorous test of the predictions.

Although minor disruptions do degrade the beam-ion confinement, it seems unlikely that low-frequency MHD is responsible for the large scatter in the data. The level of MHD activity in the analysed data is at a much lower level than that which degrades beam-ion confinement in a conventional tokamak. Moreover, inclusion of beam blips taken during stronger (but still low) MHD activity does not significantly alter the results presented in section 3.

Future work should focus on understanding the large variability in the signal levels. Similar studies for higher beta plasmas are also desirable.

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References

[1] Heidbrink, W.W. and Sadler G.J. 1994 Nucl. Fusion 34 535
[2] Mikkelsen D.R. et al 1997 Phys. Plasmas 4 3667
[3] Redi M.H., Darrow D.S., Egedal J., Kaye S.M. and White R.B. 2002 Calculations of neutral beam ion confinement for the national spherical torus experiment 2002, EPS Princeton Plasma Physics Laboratory Report PPPL-3714
[4] Kolesnichenko Y.I., Marchenko V.S. and White R.B. 2001 Phys. Plasmas 8 3143
[5] Akers R.J. et al 2002 Nucl. Fusion 42 122
[6] Carlsson J. 2001 Phys. Plasmas 8 4725
[7] Kolesnichenko Y.I., White R.B. and Yakovenko Y.V. 2002 Phys. Plasmas 9 2639
[8] Yakovenko Y.V., Kolesnichenko Y.I. and White R.B. 2002 Lagrangian description of nonadiabatic particle motion in spherical tori Technical Report PPPL-3712 Princeton Plasma Physics Laboratory 2002
[9] Egedal J., Redi M.H., Darrow D.S. and Kaye S.M. 2003 Phys. Plasmas 10 2372
[10] Yavorksj V.A. et al 2002 Nucl. Fusion 42 1210
[11] Heidbrink W.W., Kim J. and Groebner R.J. 1988 Nucl. Fusion 28 1897
[12] Heidbrink W.W. 1990 Phys. Fluids B 2 4
[13] Heidbrink W.W. et al 1991 Phys. Fluids B 3 3167
[14] Ruskov E., Heidbrink W.W. and Budny R.V. 1995 Nucl. Fusion 35 1099
[15] Tani K., Nishitani T., Nagashima K. and Kusama Y. 1994 Nucl. Fusion 34 1097
[16] Isobe M., Tani K., Nishitani T., Kusama Y. and Sasao M. 1997 Nucl. Fusion 37 437
[17] Ruskov E. et al 1999 Phys. Rev. Lett. 82 924
[18] Isobe M. et al 2001 Nucl. Fusion 41 1273
[19] Leblanc B.P. et al 2003 Rev. Sci. Instrum. 74 1659
[20] Ramsey A.T. and Turner S.L. 1987 Rev. Sci. Instrum. 58
[21] Johnson L.C. et al 1995 Rev. Sci. Instrum. 66 894
[22] Strachan J.D. et al 1981 Nucl. Fusion 21 67
[23] Trubnikov B.A. 1965 Review of Plasma Physics vol 1 (New York: Consultants Bureau)
[24] Book D.L. 1990 NRL Plasma Formulary (Washington, DC: Naval Research Laboratory)
[25] Menard J.E. et al 2003 IAEA 2002 paper
[26] Wong K.-L. 1999 Plasma Phys. Control. Fusion 41 R1
[27] Fredrickson E.D. et al 2001 Phys. Rev. Lett. 87 145001
[28] Budny R.V. 1994 Nucl. Fusion 34 1247
[29] Pankin A., Mccune D., Andre R., Bateman G. and Kritz A. 2003 The tokamak Monte Carlo fast ion module NUBEAM in the national transport code collaboration library Comput. Phys. Commun. submitted
[30] Medley S.S. and Roquemore A.L. 1998 Rev. Sci. Instrum. 69 2651
[31] Darrow D.S. et al 2001 Rev. Sci. Instrum. 72 784
[32] Leblanc B.P. et al 2002 IAEA Lyon paper EX/C5-2