Anomalous Beam-Ion Loss in TFTR Reversed Magnetic Shear Plasmas

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Anomalous beam-ion loss has been observed in an experiment with short tritium beam pulses injected into deuterium-beam-heated Tokamak Fusion Test Reactor plasmas ($P_{\mathrm{NBI}} = 15$ MW) with reversed magnetic shear (RS). Comparisons of the measured total 14 MeV neutron emission, the neutron flux along eight radial locations, and the perpendicular plasma stored energy with predictions from an extensive set of TRANSP simulations suggest that about 40% beam power is lost on a time scale much shorter than the tritium beam pulse length $\Delta t = 70$ ms. In contrast with recent results [K. Tobita *et al.*, Nucl. Fusion **37**, 1583 (1997)] from RS experiments at JT-60U, we were not able to show conclusively that magnetic field ripple is responsible for this anomaly. [S0031-9007(98)07412-2]

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Tokamak plasmas with reversed magnetic shear have been identified as promising candidates for designing economically attractive fusion reactors [1]. Theoretical calculations [2–4] and experiments at major tokamak facilities [5–7] indicate that simultaneous achievement of high energy confinement time τ_E, high bootstrap current, and high Troyon normalized β is possible in plasmas with nonmonotonic q profiles. Under the best conditions, highly peaked central pressure profiles have been achieved, and they are explained with the creation of transport barriers. Turbulent microinstabilities inside the barriers are suppressed [8] resulting in near neoclassical transport levels.

Reversed shear (RS) in the Tokamak Fusion Test Reactor (TFTR) is created during the plasma startup phase, with staged current ramp-up and early injection of several megawatts of neutral beam power (NBI). The initial electron heating to $\sim$5 keV provides current diffusion times longer than the ramp-up time, thus creating hollow current profiles [5]. Later in the discharge much stronger beam heating is applied. For beam power lower than 18 MW, the observed electron density, ion, and electron temperature profiles are similar to those in supershots [9]. If more beam power is injected, transport barriers develop, and their most striking feature is the rapid rise of the central electron density. This improved confinement regime in TFTR is known as enhanced reversed shear (ERS) [10,11].

However, the fusion reaction rate in TFTR RS plasmas has been below the expectations. Parametrization based on the electron density peakedness shows [12] that the stored energy and neutron production in these plasmas is 20% and 35% below the level in discharges with monotonic q profiles, respectively. Time dependent transport simulations with the TRANSP code [13] predict significantly better performance, as described in this paper. With standard modeling assumptions, the stored energy during the high power heating phase is typically 20%–25% above the measurements, and the DT neutron emission S_{DT} from RS plasmas fueled with deuterium and tritium beams is typically 50%–100% above the measurements (in a few extreme cases of ERS plasmas S_{DT} is 250%–300% above the measurements).

Clarification of these discrepancies has been sought in an experiment where short tritium beam pulses are injected into deuterium beam heated RS plasma. This “beam-blip” technique has been used previously in confinement studies of trace populations of beam ions in Ohmic plasmas [14–16]. Here we exploit the 2 orders of magnitude difference in the cross section between the DT and DD fusion reactions to analyze the deuterium and tritium beam ion confinement in a NBI heated discharge. The tritium beam pulse is a small perturbation of the background plasma and the plasma stored energy reflects the deuterium beam ion confinement. Since the tritium beam pulse duration is shorter than the tritium beam ion energy slowing down time, the peak value of the S_{DT} signal reflects the tritium beam ion loss. The subsequent S_{DT} decay rate is a measure of the tritium beam ion diffusive transport.

A typical set of RS discharges is shown in Fig. 1. The DD shot is heated with 15 MW of deuterium beams, and the other two shots have superimposed tritium beam pulses; in one case the tritium beam is injected parallel to the plasma current (CO), and in the other case antiparallel (CTR). These discharges are created with parameters common for TFTR reversed shear plasmas: $I_p = 1.6$ MA, $B_T(0) = 4.3$ T, $R = 2.60$ m, $a = 0.94$ cm, and they have similar q profiles ($q_0 \sim 5.5, q_{\min} \sim 3, q_a \sim 6$). No significant MHD activity is detected in any of them. The TRANSP calculated Shafranov shifts (i.e., the outward displacement of the magnetic axis with respect to the geometric center of the plasma) are $\Delta \sim 21$ cm.

We now turn to the transport modeling of these discharges. Base line TRANSP simulations were established by using measured ion temperature and impurity density

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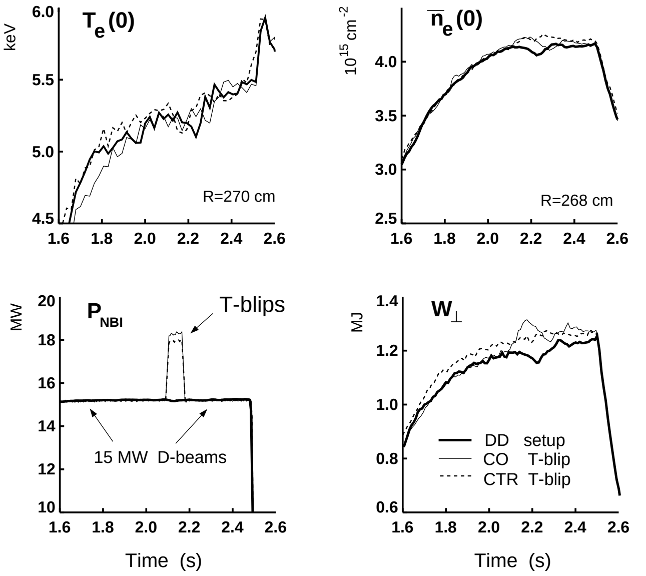

FIG. 1. Basic plasma parameters measured in three consecutive, nearly identical reversed shear discharges: Central electron temperature and line integrated electron density; beam power and transverse energy.

profiles, assuming only first orbit beam ion loss. They overestimate the perpendicular stored energy between 25% (when the D-beam ion energy component is dominant) and 10% (at the end of the beam heating interval, when the thermal energy component catches up with the perpendicular beam ion energy component). The 14 MeV neutrons are measured with silicon diodes [17] and the overestimate for the CO (CTR) case is 80% (110%). These overestimates are much larger than the 10% uncertainty in the 14 MeV neutron measurement. The comparison of the measured and TRANSP calculated DT neutron flux along four central sight lines (Fig. 4) also indicates large overestimates when only first orbit beam ion loss is assumed.

The DT neutron components shown in Fig. 2 clearly point out that the problem with the simulation is the excessive number of tritium beam ions which fuse with the thermal and beam deuterium ions. We will discuss several physical processes which may decrease the DT neutron rates. Beam ion loss due to magnetic field ripple or charge exchange reduces the T-beam/D-beam and T-beam/thermal-D components. Higher impurity levels decrease the thermal deuterium density, resulting in lower T-beam/thermal-D component.

Charge exchange (CX) between beam ions and neutrals in the plasma core is a loss mechanism that has to be considered. The neutral density profiles in TRANSP are calculated either from specified particle confinement times, or from the number of recycled hydrogenic species from the tokamak limiters. In the second approach, the measured H_α light from the inner bumper limiter is multiplied by a constant computed with the DEGAS code [18]. By arbitrarily increasing this constant it is possible to increase the core neutral density. We found that the predicted DT neutron emission cannot be lowered sufficiently without violating the energy conservation of the plasma discharge. This result is expected, because beam ions have to slow down to $\sim$60 keV before any significant charge exchange loss takes place. The velocity slowing down time for the 100 keV T-beam ions is $\sim$200 ms and their energy cannot drop sufficiently during the short blip duration to affect their CX loss. On the other hand, CX loss from thermalized D-beam ions increases as the neutral density increases. At all times, this loss plus the bremsstrahlung radiation from the electrons has to be lower than the deposited beam power.

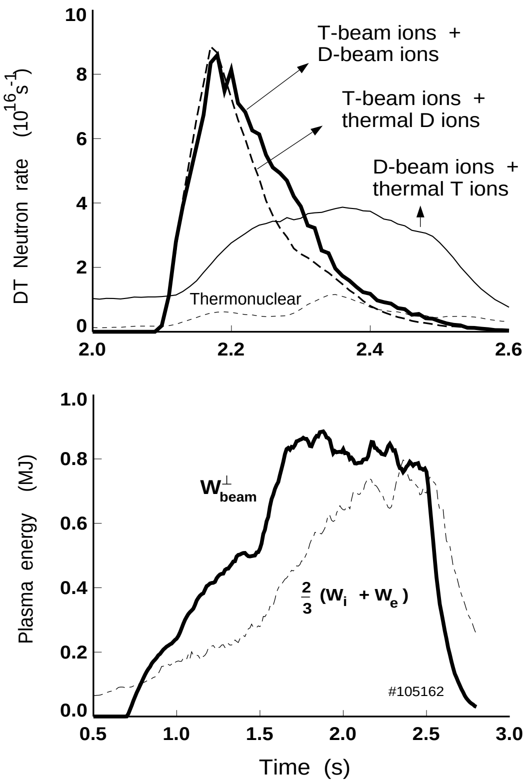

FIG. 2. Components of the DT neutron rate and transverse energy calculated with the TRANSP code. The peak measured DT neutron rate is 11.8×10^{16} s^{-1}.

Anomalous transport of beam ions in TRANSP can be modeled with various presumptions for the fast ion diffusion coefficients [15,19]. The slow decay rate of the measured 14 MeV neutron emission indicates that the tritium beam ion diffusive transport is low: $D_f \leq 0.1$ m^2/s for CO, and $D_f \sim 0.2$ m^2/s for CTR injected T-beam ions. Much larger diffusion constants are needed ($D_f = 2$–3 m^2/s) to sufficiently lower the peak value of the DT neutron emission, and they grossly deform its shape [20].

The uncertainty in the impurity profiles and $Z_{\rm eff}$ may contribute to the discrepancy in the TRANSP simulations, since higher concentrations of impurities dilute the fusion fuel. Our nominal TRANSP simulation indicates that the plasma is rather clean, with $Z_{\mathrm{eff}}(0) \sim 2$ and $Z_{\mathrm{eff}}(0.8) \sim 2.5$. We tried various approaches to artificially increase Z_{eff}: the impurity radiation was scaled up by factors well above the measurement error bars, constant Z_{eff} profiles with values of 3.5 and 4.5, and profiles that modeled impurity accumulation in the plasma core were tested, but none of them was able to reproduce the shape and peak value of the DT neutron emission.

Since beam power in TFTR is determined to within ±15% [21], the only viable simulation alternative left is that a fraction of this power is promptly lost resulting in lower effective heating power. The integrity of this model has to be checked against the central electron fueling rate and the plasma energy conservation. There are two independent parameters that can be varied: Decrease of the effective D-beam power lowers the predicted $W_\perp$, and decrease of the T-blip power lowers S_{DT}. We find that 20% reduction in D-beam power brings $W_\perp$ within the measurement error bars (30%–40% reduction improves the agreement). Then we lower the T-blip effective power and compare the predictions with the measured 14 MeV neutron emission, as shown in Fig. 3. The simulation with ~50% T-blip power loss is in excellent agreement with the measurement. However, the exact percentage difference (if any) between the D- and T-beam ion loss cannot be precisely determined: good S_{DT} and neutron flux predictions are possible with common 40% deuterium and tritium beam ion loss.

The comparison (Fig. 4) of the measured and TRANSP predicted neutron flux along four central radial locations at one toroidal cross section [22] confirms that T-beam ions are lost from the plasma and not merely redistributed outside from the core. The measured neutron flux along the four peripheral chords in this cross section, and four other central chords at a different toroidal cross section [23], is also in good agreement with the 40%–50% T-blip power loss model.

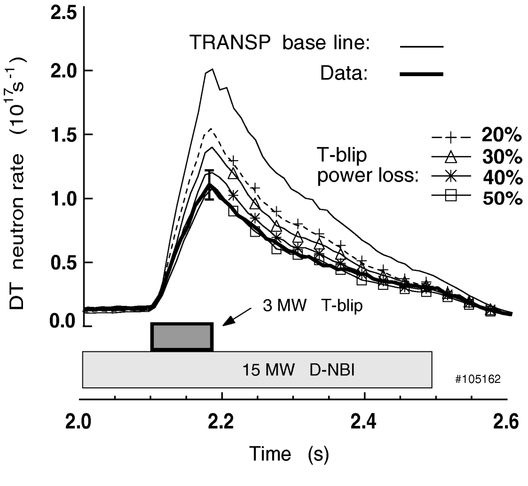

FIG. 3. Comparison of TRANSP predicted DT neutron emission from a 70 ms CO-injected tritium beam pulse. The base line model has only first orbit beam ion loss, and the other models have additional, fixed 20% D-beam power loss.

It is well established that ripple in the magnetic field due to the finite number of toroidal field coils degrades the confinement of fast ions [24]. TRANSP has a stochastic ripple model implementation [25] based on the Goldston, White, and Boozer criterion [26], multiplied by a constant obtained from benchmarks against a Hamiltonian coordinate guiding center code ORBIT [27,28]. Simulations of DT supershots in TFTR, with $R = 2.6$ m, indicated 10%–20% beam ion loss [25]. However, our attempts at using this model for predicting the 14 MeV neutron emission in RS plasmas were not successful, even when we increased the benchmarking constant so that all trapped ions were lost.

We modified both codes for accurate calculation of the beam ion loss. The TRANSP code was modified so that at a user specified time the internally calculated energy, pitch angle, and the position at the outer midplane crossing point, of each Monte Carlo deposited beam ion can be written in an output file. This file was then input in the ORBIT code. ORBIT was modified for first principle calculation of beam ion slowing down and pitch angle scattering on electrons, hydrogenic, and impurity ions. Input in these calculations was measured (T_e, T_i, N_e, Ω) and base line TRANSP calculated profiles (N_D, N_H, N_{imp}).

Results from these simulations are summarized in Fig. 5. With nominal collisionality ($\tau_\perp \approx 250$ ms), the cumulative CTR T-beam ion loss at the end of the

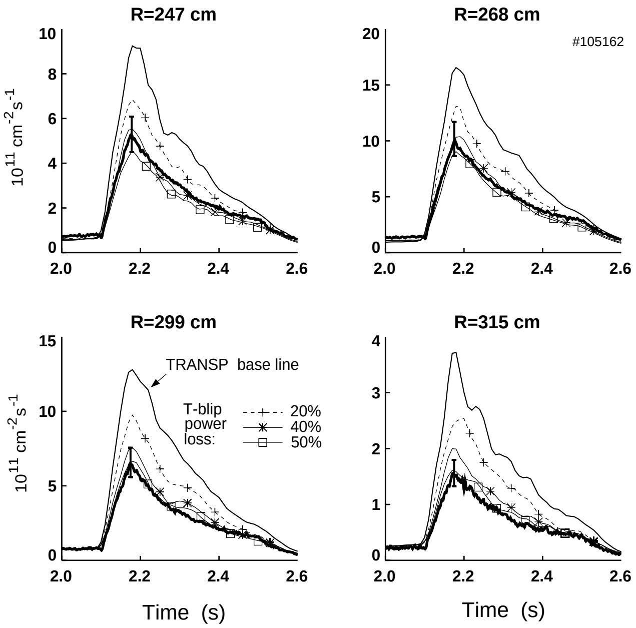

FIG. 4. Measured neutron flux along four central radial locations for the discharge shown in Fig. 3, and corresponding TRANSP predictions from models with 20%, 40%, and 50% T-blip power loss (20% common D-beam power loss).

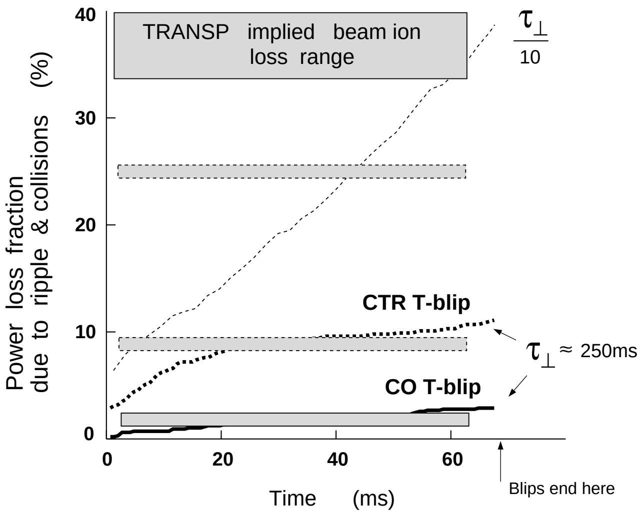

FIG. 5. Cumulative full energy T-beam ion loss fraction over the 70 ms CO/CTR tritium beam pulse duration calculated with the ORBIT code. A hypothetical case of CTR injected T-beam ions and 10 times increased collisionality is shown as well.

tritium beam pulse was 11%, and the time averaged loss was about 9%. When the beam ion collisionality was increased by tenfold, the time averaged CTR T-beam ion loss grew to 25%, which was still lower than the TRANSP implied ~40% power loss. The problem with the CO case was much more severe: the cumulative loss after 70 ms was *just* 3%. We believe that the uncertainties in the q profile and the tritium beam ion distribution function cannot explain the gap between the TRANSP implied and ORBIT calculated loss. We also believe that the combined effect of high impurity concentration in the plasma core, increased charge exchange loss, and first orbit beam ion loss cannot explain the TRANSP implied 35%–40% beam power loss.

The anomaly reported in the present analysis is surprising in light of a recent paper by the JT-60U group, which reports a good agreement between the loss of 1 MeV tritons in RS discharges and orbit-following Monte Carlo simulations [29]. This apparent discrepancy may be due to several differences between the two experiments: the ratio of the pitch angle scattering time to the slowing down time is 10 times larger for 1 MeV tritons than for the 100 keV NBI ions, the orbit size relative to the plasma size is 4 times larger, the birth velocity distribution functions are considerably different, and the diagnostic technique is completely different. As far as we can tell, the analysis of the toroidal field (TF) ripple loss is at least as complete and accurate in the present paper as in Ref. [29]. A complete discussion of ORBIT code calculation methodology is given in [20].

In addition to the possibility of more peripheral beam ion deposition in TFTR, we can speculate on two new physical effects which might be causing the anomalously large triton loss observed in the present experiment. One is the coincidence between the plasma turbulence time and size scales and the TFTR NBI triton transit time and gyroradius (7 μs, and 1 cm), which could result in turbulent pitch angle scattering of passing tritons into the large TF ripple loss cone. Another is the uncertain effect of the plasma itself on the TF ripple, which might affect the classical estimates of single-particle ripple loss. Neither of these effects has been evaluated quantitatively.

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