Isotopic Mass and Alpha Heating Effects in TFTR DT Plasmas

R. V. Budny, M. G. Bell, D. K. Mansfield, J. D. Strachan, S. Zweben,
H. Adler, C. E. Bush,[a] Z. Chang,[b] D. Ernst,[c] E. Fredrickson, B. Grek,
L. R. Grisham, R. J. Hawryluk, D. L. Jassby, L. C. Johnson, D. C. McCune,
M. Murakami,[b] H. Park, A. T. Ramsey, J. Schivell, S. D. Scott,
C. H. Skinner, E. Synakowski, G. Taylor, and M. C. Zarnstorff

Princeton University Plasma Physics Laboratory
P. O. Box 451, Princeton NJ 08543, USA

1. Introduction

Experiments with deuterium-tritium (DT) plasmas started in TFTR during 1993 [1,2]. Recent results with neutral beam injection (NBI) heated DT discharges have produced 9 MW of fusion power with a peak power density of 1.8 MW/m^3. The stored energy and the energy confinement time in these plasmas is observed to increase up to 30 % above the values in comparable D-only NBI discharges. The central ion and electron temperatures also increase.

The thermonuclear fraction of the neutron emission rate reaches 35% of the total. At the times of peak stored energy and neutron emission, the beam energy is 25-45 % of the total. The beam ion deposition, slowing down, and plasma heating change as the isotopic mix of the beam ions varies, so it is important to include beam ion effects in assessing isotopic scaling and alpha heating.

This paper analyzes the phenomenology of these increases in energy, confinement, and temperatures using the TRANSP time-dependent plasma analysis code [3]. The modeling provides detailed information about the beam ions, as well as profiles of the D and T densities, the hydrogenic isotopic mass, and the alpha heating. These are correlated with the observed increases.

To study the isotopic effect and alpha heating, sets of similar discharges with varying amounts of D and T are compared. The T content is altered by varying the mix of D and T NBI at approximately constant total NBI power, P_B. The total plasma current I_p, toroidal field B_T, central Z_{eff}, and wall conditions are very similar in each set. The electron density profiles are approximately similar. The sets contain pairs of discharges with D-only and DT-NBI. Several sets also contain discharges with T-only NBI.

2. TRANSP modeling and comparisons with measurements

The TRANSP code uses measured plasma parameters and minimal additional assumptions to model discharges. The time evolutions of particle and energy profiles are computed in one dimension. For the results described here, the modeling includes the thermal H, D, and T, the fast D and T ions from the NBI, the fusion alpha particles, and carbon impurity. Measured profiles of the electron density (from infrared interferometry), electron temperature (from electron cyclotron emission) and of the carbon temperature and toroidal rotation velocity (from charge-exchange recombination spectroscopy) are used. The Z_{eff} is deduced from the visible bremsstrahlung emission. The neutral beam parameters are calculated using Monte Carlo techniques.

Hydrogenic recycling has important effects, such as introducing D into T-only NBI discharges, and relatively small, but significant amounts of T into D-only NBI discharges. The hydrogenic recycling rates are calculated from the measured $H_\alpha + D_\alpha + T_\alpha$ emission, converted to ionization rates using the DEGAS neutrals code [4]. Spectroscopy indicates that about 18-35 % of this emission is from H, and at most $\approx$ 7 % is from T [5]. For the TRANSP modeling of D-only NBI discharges, the T fraction is assumed to be constant during each discharge, and is adjusted from discharge to discharge to match the measured peak DT neutron emission rate. The resulting values are within 30 % of the values measured using a Fabry-Perot

interferometer [5]. The modeling of DT- and T-only NBI discharges is insensitive to the choice of this parameter.

There are uncertainties about the particle transport of the hydrogenic species. Several classes of models are available in TRANSP. Only one is successful in modeling all the discharges. The thermal hydrogenic density is determined from the symmetrized electron density, and the computed Z_{eff}, and beam ion density. The relative H, D, and T fluxes can be specified by assuming either 1) their profile shapes are the same, 2) their radial velocities are the same, or 3) by constraining D_j and V_j in

$$\Gamma_j(x,t) = -D_j * \text{grad} (n_j) + V_j * n_j, \text{ with } j = H, D, T$$

The choice 1) is unsuccessful in modeling the neutron emission, especially for the T-only NBI discharges. Choice 2) is numerically unstable in the case of three thermal hydrogenic species, and has not been studied in detail. A non-unique set of constraints for choice 3) gives good agreement with measurements, and is used for the results presented here.

Examples of comparisons that test the accuracy of the modeling are the neutron emission rates and profiles, which test the accuracy of the calculated beam and thermal ion density distributions, and the stored energy and the Shafranov shifts, which test the calculated beam ion energy. The results generally agree with measurements to 1.5 σ. Examples of neutron emission comparisons for one of the discharges in a triplet are shown in Fig. 1. Each discharge in this triplet has R = 2.52 m, a = 0.87 m, I_p = 2.1 MA, B_T = 5.1 T, P_B = 21 MW, and lithium pellet wall conditioning. The agreement shown is typical of the results achieved, even for the D-only and T-only NBI discharges.

3. Isotopic Mass Effects

The computed thermal hydrogenic profiles are dissimilar for the hydrogenic particle model used due to their different sources. An example is shown in Fig. 2 for the discharge in Fig. 1 at the time of peak neutron emission. The discharges in this triplet have an unusually large amount of H recycling, with measured H_α / $(H_\alpha + D_\alpha + T_\alpha)$ = 35%. The relative T density can be summarized by the average isotopic mass of the thermal hydrogenic species,

$$A \equiv (n_H + 2n_D + 3n_T) / (n_H + n_D + n_T)$$

Profiles of A at several times for the triplet are shown in Fig. 3.

Since there is uncertainty about the degree to which the beam ions contribute to the isotopic effect, we consider also A_{tot} defined analogously to A, but with the D and T beam ion densities included with the thermal densities. The volume average of A increases approximately linearly with the fraction of T-NBI power, P_T / P_B. At 0.5 sec of NBI, which is near the time of peak neutron emission, it increases as

$$<A> \approx 1.9 + 0.7*(P_T/P_B)$$

At this time $<A_{tot}>$ is approximately 15% higher than $<A>$.

The magnetically determined total energy confinement time, τ_E increases with $<A>$ and $<A_{tot}>$. The ratios of τ_E with DT-NBI to τ_E in comparable D-only NBI discharges are plotted versus $<A_{tot}>$ in Fig. 4. The least squares fit gives a power of 0.72 for this enhancement. The power for the fit to $<A>$ is 0.75.

The plasma plus beam energy and the total energy confinement time increase ~ 15-20 % in changing the NBI mix from D-only to ≈ 50:50 D:T, and again another ~ ~ 8-10 % in changing further to 100 % T-NBI. Effects contributing to these changes are 1) increased stored energy in the NBI ions, 2) altered heating of T beam ions, 3) stored energy of the fast alpha particles, 4) alpha heating, and 5) an isotopic mass effect. Simulations made before the DT campaign [6] incorporating 1-4 indicated the change would be about half of what is observed.

The fraction of the total energy stored in the beams is large during the first 0.3 sec of NBI, and decreases in time as the electron density increases and more of the beam ions thermalize. At 0.5 sec of NBI, the beam fraction decreases to 40-50 %. This fraction is plotted versus $<A_{tot}>$ in Fig. 5 for the sets of discharges used in Fig. 4. It does not vary significantly with $<A_{tot}>$, so changes in the beam ion energy do not have a significant direct effect on the increase in total energy with $<A_{tot}>$. The energy fraction in thermal ions shows a slight increase with $<A_{tot}>$, and the fraction in electrons shows a slight decrease. The energy fraction in alphas peaks near 5 % for intermediate $<A_{tot}>$, which is where the fusion yield is largest.

The profiles of A in DT-NBI, and especially in T-only NBI discharges peak near the plasma center. The profiles of the increase in total energy density, $\Delta w_{tot}^{DT} \equiv w_{tot}^{DT} - w_{tot}^{D}$ and $\Delta w_{tot}^{T} \equiv w_{tot}^{T} - w_{tot}^{D}$ have shapes that are similar to the profiles of $\Delta A_{tot}^{DT} \equiv A_{tot}^{DT} - A_{tot}^{D}$ and $\Delta A_{tot}^{T} \equiv A_{tot}^{T} - A_{tot}^{D}$. This suggests that the strong isotopic scaling exists throughout the plasma profile.

4. Alpha Heating Effects

Although the volume-integrated electron energy is relatively insensitive to $<A_{tot}>$, as shown in Fig. 5, the central T_e measured by ECE increases up to 2 keV in DT plasmas. Except in plasmas with extreme lithium pellet conditioning, the central electron density is relatively constant, and $w_e(0)$ increases significantly. Significant increases in T_i profiles are also observed with DT-NBI. The increase in T_e could be caused by 1) alpha heating, 2) ion-electron coupling, and 3) an intrinsic isotopic effect. The computed peak alpha-electron heating is 0.15 MW/m^3. The beam-electron heating with T-NBI is calculated to decrease $w_e(0)$.

These various effects can be studied by comparing modeling results for D-, DT-, and T-NBI discharges. The electron thermal conductivity, χ_e deduced by TRANSP from D-only and DT-NBI discharges can be cross substituted for predicting T_e. Also the NBI parameters can be cross substituted, and alpha heating can be turned on or off. The results of this modeling indicate that the isotopic and the alpha heating effects each cause about 1/2 of the observed Δw_e^{DT}. The profiles of Δw_e^{DT} and Δw_e^{T} are peaked at the plasma center, similar to the computed profiles of the alpha-electron heating, and more peaked than the broad profiles of ΔA_{tot}^{DT} and ΔA_{tot}^{DT}.

5. Summary

The approximate agreement of the TRANSP modeling with various measured parameters indicates that the profiles of the computed beam ion and D and T densities are realistic. The beam fraction of the total energy at 0.5 sec of NBI remains relatively constant, $\approx 40 - 50$ % as the isotopic mass varies. The total energy and the total energy confinement time increase approximately linearly with the mass by up to 30 %. The isotopic and alpha heating effects contribute in roughly equal amounts to the increase in central T_e.

[a]Oak Ridge National Laboratory
[b]University of Wisconsin
[c]Massachusetts Institute of Technology

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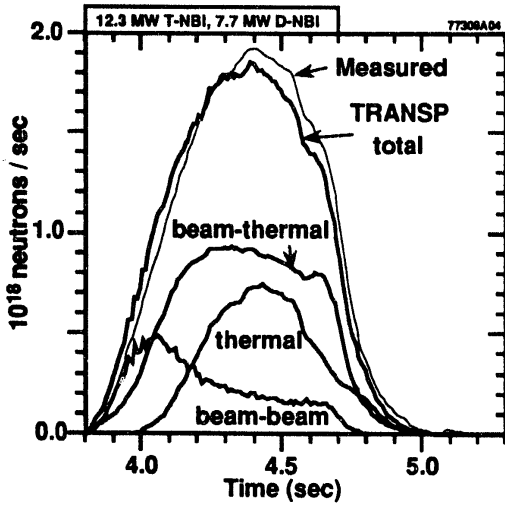
Fig 1a - Neutron Emission Components

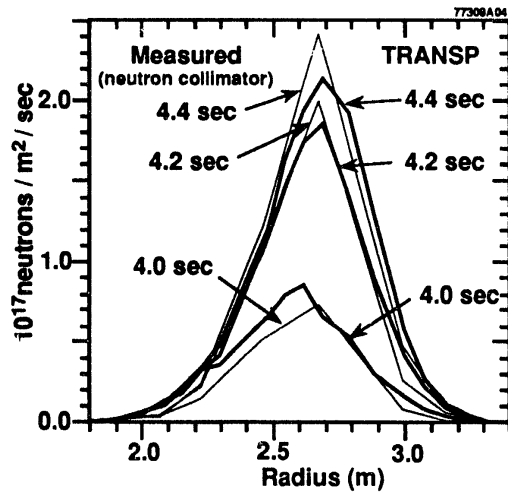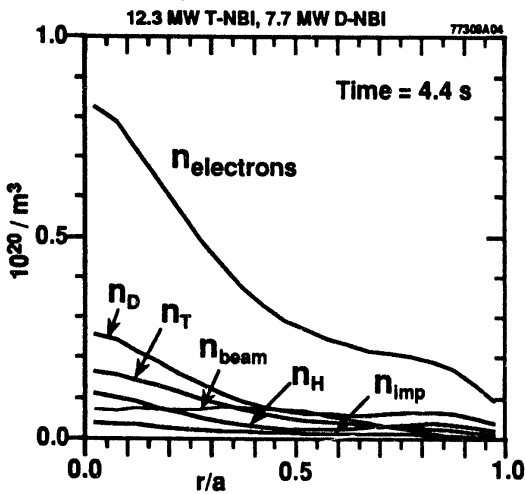## Fig 1b - Chordal DT neutron emission profiles

Fig 2 - Density profiles
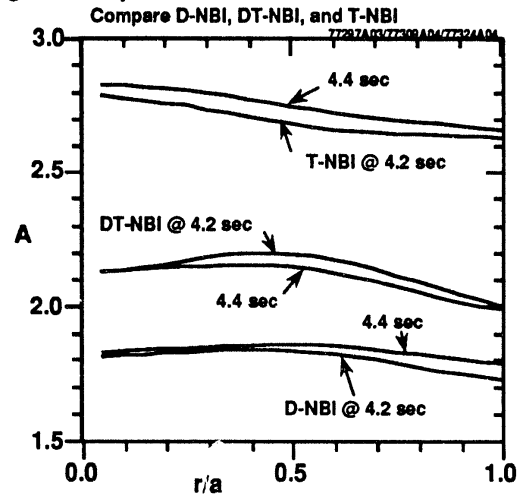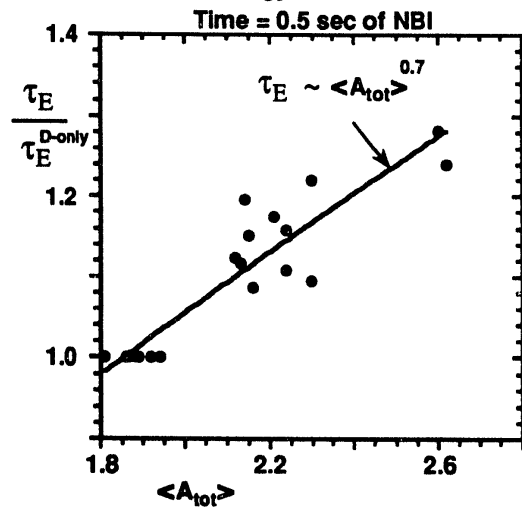

Fig 3 - Isotopic Mass Profiles

Fig 4 - Enhanced Energy Confinement

Fig 5 - Stored Energy Fractions