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Fusion Power Production in TFTR

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Fusion Power Production in TFTR

Abstract

Up to 9.3 MW of fusion power has been produced from deuterium-tritium (DT) fusion reactions in the Tokamak Fusion Test Reactor (TFTR). The total fusion yield from a single plasma pulse has reached 6.5 MJ. The experiments in TFTR with deuterium-tritium plasmas fuelled and heated by neutral beam injection span wide ranges in plasma and operating conditions. Through the use of lithium pellet conditioning to control the edge recycling, the plasma confinement in TFTR has been improved to the point where the stability of the plasma to pressure driven modes is limiting the fusion power for plasma currents up to 2.5 MA. The central energy and fusion power densities in these plasmas are comparable to those expected in a thermalized DT reactor, such as ITER.

1. Introduction

Since December 1993, the Tokamak Fusion Test Reactor (TFTR) has been operated with mixed deuterium-tritium plasmas at plasma densities and temperatures near those expected in a reactor such as ITER. To date, 1?0 plasmas have been heated and fuelled with tritium by at least one neutral beam source operating in pure tritium. A major thrust of the experiments being conducted with high concentrations of tritium is the study of the energetic DT fusion alpha-particles in the plasma, including their confinement and transport, their role in the energy balance and their potential for exciting instabilities. Since the possibilities for observing both self heating of the plasma by the DT fusion products and the collective instabilities excited by them generally increase with the DT fusion rate, the second area of interest has spurred efforts to maximize the fusion power production in TFTR.

This paper presents the techniques that have been used to produce high DT reactivity in TFTR. The optimization of the DT power within the constraints imposed by the available heating power, the energy confinement and the plasma stability are discussed. The modelling of the fusion reactivity based on measured plasma parameters is then addressed. Finally, the possibilities for further improvements in the DT fusion performance of TFTR are discussed.

2. Regime of DT Operation

For producing high DT fusion yields in TFTR, injection of high-power tritium and deuterium neutral beams (NBI) has proved most successful [1,2]. In the "preliminary tritium experiment" in the Joint European Torus (JET) [3], the tritium was also introduced through NBI. In TFTR, the twelve neutral beam sources inject almost tangentially; six of the sources inject co-parallel and six inject counter-parallel to the plasma current. For most of these experiments, each source was operated with either pure deuterium or pure tritium gas, although in an initial series of experiments, sources were also operated with a mixture of 2% tritium in deuterium. It has been possible to switch each source from deuterium to tritium operation and back on successive plasma shots without interruption of the normal TFTR operating cycle. This flexibility has minimized the tritium consumption for each experiment and enabled careful comparisons to be made between D-only and DT plasmas in otherwise similar conditions. The TFTR NB sources produce about 10% more injected power when operating in tritium: a maximum tritium NBI power from a single source of 3.6 MW has been achieved at an accelerating voltage of 116 kV. For tritium NBI at normal accelerating voltages, approximately 67% of the power is in the full-energy, 27% in the half-energy and 6% in the one-third-energy component whereas in deuterium at normal acceleration voltages, approximately 62% of the power is in the full-energy, 29% in the half-energy and 9% in the one-third-energy component. The total NBI power has reached 34 MW in both DT (using 6 T and 5 D sources) and D-only (12 sources) and 23 MW in T-only (8 sources). The NBI pulse has been typically 0.7 to 2.0 s in duration. Shorter NBI pulses were generally used to conserve tritium and to minimize the activation of the structure, except in experiments designed to study the accumulation of helium ash from DT reactions.

For deuterium NBI, the highest DD fusion rates in TFTR have been obtained in the supershot regime [4], characterized by very high central ion temperatures, $T_i(0) = 20 - 35$ keV >> $T_e(0) = 10 - 12$ keV, highly peaked profiles of the density and ion temperature, a broad electron temperature profile, and enhanced confinement relative to the predictions of L-mode scaling. This regime was also used for most of the high DT fusion yield experiments. In the DT experiment in JET, a similar mode of operation with $T_i(0) > T_e(0)$ was used, although in that case, the divertor plasma also showed characteristics of H-mode confinement [3]. Supershots in TFTR are produced with NBI heating when the edge recycling of hydrogenic species and carbon are reduced so that the plasma core is fuelled predominantly by the injected neutrals. In addition to the enhanced confinement, this provides the advantage for DT experiments that the central ion-species mix can be varied by changing the fraction of sources injecting tritium. In TFTR, the reduction in edge recycling that can be achieved by running repeated low-density ohmically heated plasmas has been extended through the injection of solid lithium pellets (1 – 4 pellets) into the ohmic phase of the discharge [5]. The plasma density perturbation from the pellets, which are injected 1.5 – 0.5 s prior to NBI, has largely decayed by the start of the NBI; even in plasmas with multiple conditioning pellets, lithium is not a significant source of plasma dilution during NBI. Each pellet contains typically 4×10^{20} atoms, which corresponds to coverage of roughly one monolayer of lithium on the limiter surface. The use of lithium-pellet conditioning has increased the plasma current at which the supershot characteristics are obtained to 2.5 MA and increased the highest energy confinement time achieved to 0.27 s in a plasma with 21 MW NBI. In deuterium supershots, there is a strong dependence of the peak fusion reaction rate on the total plasma energy, W_{tot}, during NBI [6] and similar dependence was expected with DT [7]. For maximum DT fusion yield, therefore, operation at high plasma current and toroidal magnetic field was necessary to maximize the β-limit, which has been found to scale in supershots similarly to the Troyon limit [8], so that $W_{tot,max} \propto I_p B_T$ for fixed plasma size.

The experiments described in this paper were conducted in plasmas with major radii of 2.45 – 2.52 m (minor radius 0.80 – 0.87 m, nominally circular cross-section, with a toroidal carbon limiter on the inboard side) at a toroidal magnetic field 4.6 – 5.1 T. The plasma current was in the range I_p = 1.0 – 2.5 MA, held constant during NBI, and the total NBI power was in the range 5 – 34 MW. In a companion paper by Sabbagh *et al.* [9], experiments in which the plasma current was ramped during NBI to modify the current profile are described.

The DT fusion yield from TFTR is measured with a number of detectors for the 14 MeV neutrons [10]. The total rate is measured by ^{4}He-recoil detectors, silicon surface barrier detectors, ZnS scintillators and a set of fission detectors (^{235}U and ^{238}U) with overlapping operating ranges to provide wide dynamic range. Most of these detectors have been absolutely calibrated using a standard DT neutron source *in situ* [11]. The total yield for each pulse is measured by an elemental sample activation analyzer which provides neutron energy discrimination and which, coupled with a neutron transport code, is also absolutely calibrated [12]. The scintillators and ^{4}He-recoil detectors are collimated along ten lines of sight across a poloidal cross section to provide data on the neutron source profile. The various detectors have different sensitivities to the 2.5 MeV neutrons from the d(d,n)^{3}He reaction and the 14.1 MeV neutrons from the d(t,n)^{4}He reaction, allowing the rates of the two reactions to be separated for plasmas with a small tritium content. The DT neutron rates used in this paper are generally derived from one of the fission detectors operating in its current-measurement mode. The calibration of this mode, which is expected to be linear for DT neutron rates up to 10^{19} s^{-1}, was derived from an uncertainty-weighted mean of four absolutely calibrated measurements for the first high-power tritium shots in December 1993 [10]. From time to time since then, variations of up to 10% have been observed between this and other measurements of the total DT fusion rate. The overall accuracy of the DT neutron rates is believed to be ±7%.

Figure 1 shows the time evolution of the DT fusion power (using the total reaction energy of 17.6 MeV per DT neutron) and plasma stored energy for four plasmas from a sequence leading up to the shot producing the highest instantaneous power of 9.3 ± 0.7 MW. The plasma energy is determined from magnetic data and includes the energy in the unthermalized injected deuterons and tritons. In this sequence, the neutral beam power and the amount of lithium conditioning were progressively increased. Only shots with tritium NBI are shown in Fig. 1; shots with deuterium NBI only were interspersed between the tritium shots. The final shot in the sequence disrupted after 0.44 s of NBI when the plasma reached the β-limit at a total plasma stored energy of 6.5 MJ, corresponding to a Troyon-normalized-β, β_N ($=10^8 \beta_T a B_T / I_p$ where β_T is the total toroidal β and a is the plasma minor radius) of 2.0. A similar β-limit has been found to apply to deuterium "High-β_P" plasmas in JT-60U, which exhibit many similarities to TFTR supershots, including high ion temperatures and peaked pressure profiles [13].

Figure 2 shows the peak fusion power, averaged over a 40 ms interval, as a function of total heating power (NBI plus ohmic power: the latter is, however, negligible for $P_{tot} > 10\,MW$) for the data set of supershots with NBI auxiliary heating only and with more than 20% of the NBI power in tritium. Plasmas with extensive lithium pellet conditioning are distinguished. A non-linear dependence of the DT fusion power on the heating power is apparent in these data. The highest ratio Q of the fusion power to the total heating power, Q ~ 0.27, was obtained on two shots, one being the highest power shot. In this shot, immediately before the disruption, the rate of increase of plasma energy was still 7.5 MW out of a total heating power of 34 MW, demonstrating that stability rather than energy confinement now imposes the limit on the DT performance in TFTR. The central toroidal-β is calculated to have reached 5% in this plasma. A rapidly growing, toroidally localized mode with ballooning character was detected in the electron temperature profile immediately before this disruption [14]. The shot producing 5.6 MW with only 21 MW NBI was conditioned with four lithium pellets in the ohmically heated phase prior to the NBI and achieved a transient confinement time of 0.27 s (averaged over an energy confinement time) which is approximately 2.4 times the prediction of ITER-89P scaling [15], based on an average ion mass of 2.5.

The peak fusion powers from DT and nominally D-only supershots at the same NBI power under similar conditions have been compared. Since there is a small amount of tritium present in any nominally D-only plasma taken soon after a DT shot, as a result of tritium influx from the limiter, the DT reaction component is subtracted from the nominally D-only data in calculating this power ratio. In the experiment to maximize fusion power, the DT component of the reaction rate in the D-only plasmas tended to increase secularly through the NBI pulse whereas the DD component generally peaked after about 0.5s. Comparison of the plasmas shown in Fig. 1 with D-only shots from the same experiment having the same plasma current (2.5 MA) and number of Li pellets, yields a ratio P_{DT}/P_{DD} of 135 ± 7 *at constant neutral beam power*. A similar ratio is obtained for the subset of shots with the same major radius (2.52m) but at a plasma current of 2.0 MA.

In discussing the relative fusion reactivity, it is also necessary to consider the confinement differences between DT and D-only plasmas, since the fusion rate varies strongly with plasma energy [6]. As discussed in detail by Zarnstorff *et al.* [16], the global energy confinement of plasmas with significant tritium NBI is substantially higher than in equivalent plasmas with deuterium NBI only. Figure 3 shows the fusion power production from comparable DT and D-only plasmas plotted against the scaling $W_{tot}^{1.91} q_a^{0.32} V_p^{-1}$, where V_p is the plasma volume and q_a the edge q, and the exponents on W_{tot} and q_a were determined by regression analysis. The exponent of W_{tot} is close to that expected for thermalized DT plasmas with ion temperatures in the range 10 – 20 keV (where the local DT fusion power density varies approximately as $n_i^2 T_i^2$) having similar pressure profile shapes and in which the electron stored energy is a constant fraction of the total. The factor $q_a^{0.32}$ represents a tendency for the pressure profile to broaden and the fraction of the total energy in the ions to decrease with plasma current. The data include supershots both with and without lithium pellets. The DT plasmas are restricted to those with a tritium NBI power fraction between 0.35 and 0.75. The root-mean-square deviation of the data about the fit is about 7% for the whole data set. From this data, the ratio of the fusion power between the DT and D-only supershots *at constant plasma energy* is 115 ± 15. This ratio is less than the maximum of about 210 expected for thermalized DT and D-only plasmas at a temperature of 10 keV, because in supershots, the ion temperatures are higher and the non-thermal ion component increases the reactivity in D-only plasmas, and because there are small systematic differences in the profiles between DT and D-only supershots.

3. Modelling of the DT Reactivity

The time evolution of the fusion reactivity in TFTR has been analyzed with the TRANSP code [17]. The deposition, orbit loss and slowing down of the injected T and D neutrals are calculated using the measured profiles of the electron density and the electron and ion temperatures. The beam-injected ions are transferred to the thermal ion population when their energy reaches $^3/_2 kT_i$, where T_i is the local ion temperature. The profile of the total ion density is calculated using the visible bremsstrahlung for the total Z_{eff} and x-ray measurements of the metallic contribution to Z_{eff}. Spectroscopy shows that carbon is the dominant low-Z impurity. A source of uncertainty in the analysis is the role of the edge fuelling in determining the overall mix of deuterium and tritium in the center. High-resolution spectroscopy of the hydrogen isotope line radiation from the plasma edge [18] has confirmed that, as expected from the history of the limiter exposure to plasmas, the edge fuelling is dominated by deuterium, with a smaller component of hydrogen, typically 10 – 20%, and relatively little tritium influx, <10%. Comparisons between plasmas with varying fractions of D and T injection have demonstrated that the fuelling of the core of supershots by this edge recycling is quite significant. The DT neutron rate normalized to the scaling $W_{tot}^{1.91} q_a^{0.32} V_p^{-1}$ is shown in Fig. 4 as a function of the tritium NBI fraction, $F_T = P_T/(P_T + P_D)$ where P_T, P_D are the tritium and deuterium NBI powers, for plasmas with $P_{NBI} >$ 10MW and at least one source injecting tritium. The fitted parabola, which is constrained at $F_T = 0$ to the level typical for D-only plasmas in DT experiments, peaks at $F_T \approx 0.6$ and is broader than would be expected in the absence of edge fuelling. In plasmas with T injection only, the normalized DT neutron rate averages about 65% that for the optimal mix of D and T sources and shows more variability since it depends on the edge influx. In plasmas with deuterium NBI only, the tritium content is small and depends on the tritium exposure of the limiter during the preceding discharges. However, because of its much larger fusion probability, the tritium in D-only plasmas can produce a DT reactivity comparable to or larger than the DD reactivity. A model for the T and D transport which describes reasonably well the dependence of the DT and DD neutron rates on the tritium fuelling fraction has been developed [19].

The measured and calculated time evolutions of the total DT fusion power and plasma energy are compared in Fig. 5 for the shot (76771) producing 7.2 MW (Fig. 1). The slight decay of the DT power after 0.45 s of heating is reproduced by the calculation, indicating that this decay arises from the classical effects which are included in the model (in particular, changes in temperature and density profiles) and is not caused by an anomalous loss of injected beam ions. The data from the collimated neutron detector array is also used to constrain the fuelling and particle transport models. At the time of peak fusion power, the central electron and ion temperatures in this plasma were 11 and 30 keV and the central electron and fuel (deuteron plus triton) densities were 7.3×10^{19} and $5.0 \times 10^{19}\,m^{-3}$ respectively. The peakedness of the fuel ion pressure profile, which is appropriately characterized by the parameter $\langle U_{DT}^2 \rangle / \langle U_{DT} \rangle^2$, where U_{DT} is the energy density of the deuterons and tritons and $\langle\rangle$ represents the volume average, reached 2.1.

For the subset of DT plasmas in Fig. 2 that have been analyzed in detail by TRANSP (46 shots), the model generally matches the total plasma energy within 10% and the total DT neutron rate within 25%. The discrepancies in the DT rate and the plasma energy are correlated so that the modelled and measured ratios P_{fus}/W_{tot}^2 agree within a 10% standard deviation for the DT plasmas. For similar D-only plasmas run during the DT campaign, the TRANSP calculations of the plasma energy are generally in agreement with the measurements but the fusion rates do not agree quite as well. As a result, the TRANSP code predicts that there should be a ratio of about 135 between the fusion powers from DT and D-only supershots at constant plasma energy, which is about 20% higher than the measured ratio.

4. Discussion

For shot 76771, the local Q, defined as the ratio of the fusion power density to the total heating power density (neutral beam and ohmic power) was about 0.4 at the plasma center. The plasma with exceptional confinement produced by lithium conditioning which achieved a global Q of 0.27 (shot 77309, Fig. 2), is calculated to have reached a central Q of 0.5. The central fusion power densities achieved in the high-performance TFTR supershots, typically $\sim 1.5\,MWm^{-3}$, are essentially the same as those for pure, isothermal DT plasmas at the optimum temperature for reactivity ($T_e = T_i \approx 15\,keV$) having the same total energy density. For shot 76771, this "equivalent thermonuclear" plasma would have $n_e = n_T + n_D \approx 1 \times 10^{20}\,m^{-3}$. Although the NBI provides the dominant heating and fuelling in supershots, at the plasma center, the non-thermal ion distribution does *not* increase the DT reactivity compared to that of a plasma having a locally Maxwellian ion distribution with the same total fuel energy and particle densities. The hot-ion ($T_i > T_e$) nature of these plasmas essentially compensates for the dilution of the fuel density relative to the electron density.

Assuming that the central plasma energy density is limited, either by confinement or the local β-limit for the present magnetic field strength, the reactivity is currently being reduced below that which could be achieved both by the presence of impurities ($Z_{eff}(0) = 2.0$ typically at the time of peak fusion power) and by the hydrogen component fuelled by the limiter. In the shot that achieved exceptional confinement and Q (77309), the fraction of hydrogen in the edge recycling was particularly high. Modelling with TRANSP suggests that increases of 20% in the central fusion power density might be possible in similar plasma conditions to this shot with the normal recycling composition. Experiments to modify the contact of the plasma with the limiter to control the recycling during the NBI pulse are also planned.

Since the β-limit is now providing a fundamental limitation on the achievable DT performance in TFTR, plans are also being made to increase the toroidal magnetic field by up to 16% for a limited number of pulses. Such an increase could raise the central plasma energy density at the β-limit by up to 30% and, if the present scaling is maintained, the achievable DT fusion power by up to 70%.

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References

[1] STRACHAN, J.D. *et al.*, Phys. Rev. Lett. 72 (1994) 3526

[2] HAWRYLUK, R.J. *et al.*, Phys. Rev. Lett. 72 (1994) 3530

[3] JET TEAM, Nucl. Fusion 32 (1992) 187

[4] STRACHAN, J.D. *et al.*, Phys. Rev. Lett. 58 (1987) 1004

[5] SNIPES, J.A. *et al.*, J. Nucl. Materials **196–198** (1992) 686;

JASSBY, D.L. *et al.*, "High Performance Supershots in TFTR with Lithium Pellet Injection", report PPPL-2940, Princeton Plasma Physics Lab. (1993).

[6] BELL, M.G. *et al.*, Plasma Physics and Controlled Nuclear Fusion Research 1988 (Proc. 12th Int. Conf., Nice, France) Vol. 1, p. 27

[7] BUDNY, R.V. *et al.*, Nuclear Fusion **32** (1992) 429

[8] TROYON, F. *et al.*, Plasma Phys. Control. Fusion 26 (1984) 209

[9] SABBAGH, S.A. *et al.*, paper IAEA-CN-60/A-5-I-6, these Proceedings

[10] JOHNSON, L.C. *et al.*, Rev. Sci. Instrum. **66** (January 1995), *to appear*

[11] JASSBY, D.L. *et al.*, Rev. Sci. Instrum. **66** (January 1995), *to appear*

[12] BARNES, C.W. *et al.*, Rev. Sci. Instrum. **66** (January 1995), *to appear*

[13] PARK, H.K. *et al.*, paper IAEA-CN-60/A-2/4-P-1 these Proceedings

[14] FREDRICKSON, E.D. *et al.*, paper IAEA-CN-60/A-2-II-5, these Proceedings

[15] YUSHMANOV, P. *et al.*, Nucl. Fusion **30** (1990) 1999

[16] ZARNSTORFF, M.C. *et al.*, paper IAEA-CN-60/A-2-I-2, these Proceedings

[17] BUDNY, R.V., "A Standard DT Supershot Simulation", Nucl. Fusion, *to appear*

[18] SKINNER, C.H. *et al.*, "First Measurements of Tritium Recycling in TFTR", report PPPL-2993, Princeton Plasma Physics Laboratory, June 1994, *submitted to Nucl. Fusion;*

SKINNER, C.H. *et al.*, Rev. Sci. Instrum., *to appear*

[19] BUDNY, R.V. "Analysis of a High Fusion Power Supershot", *to be published*

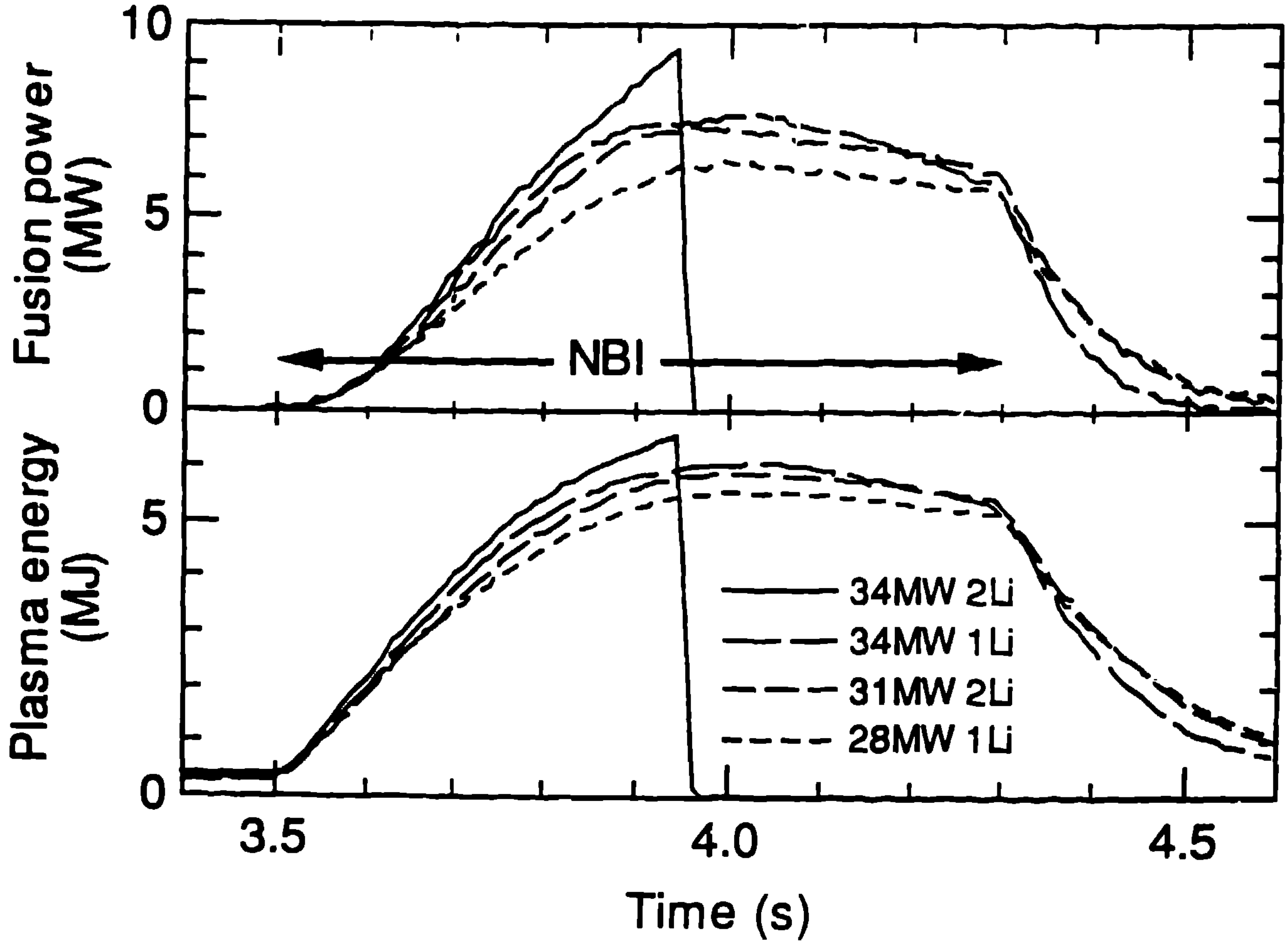

Fig. 1 Evolution of the DT fusion power and the plasma stored energy for a series of plasmas with mixed D and T NBI leading up to the shot which produced the highest instantaneous fusion power. Discharges with D-NBI only were interspersed in this sequence. One or two lithium pellets were injected into the plasma prior to NBI. Plasma parameters: major radius 2.52m, minor radius 0.87m, toroidal magnetic field 5.1T, plasma current 2.5MA.

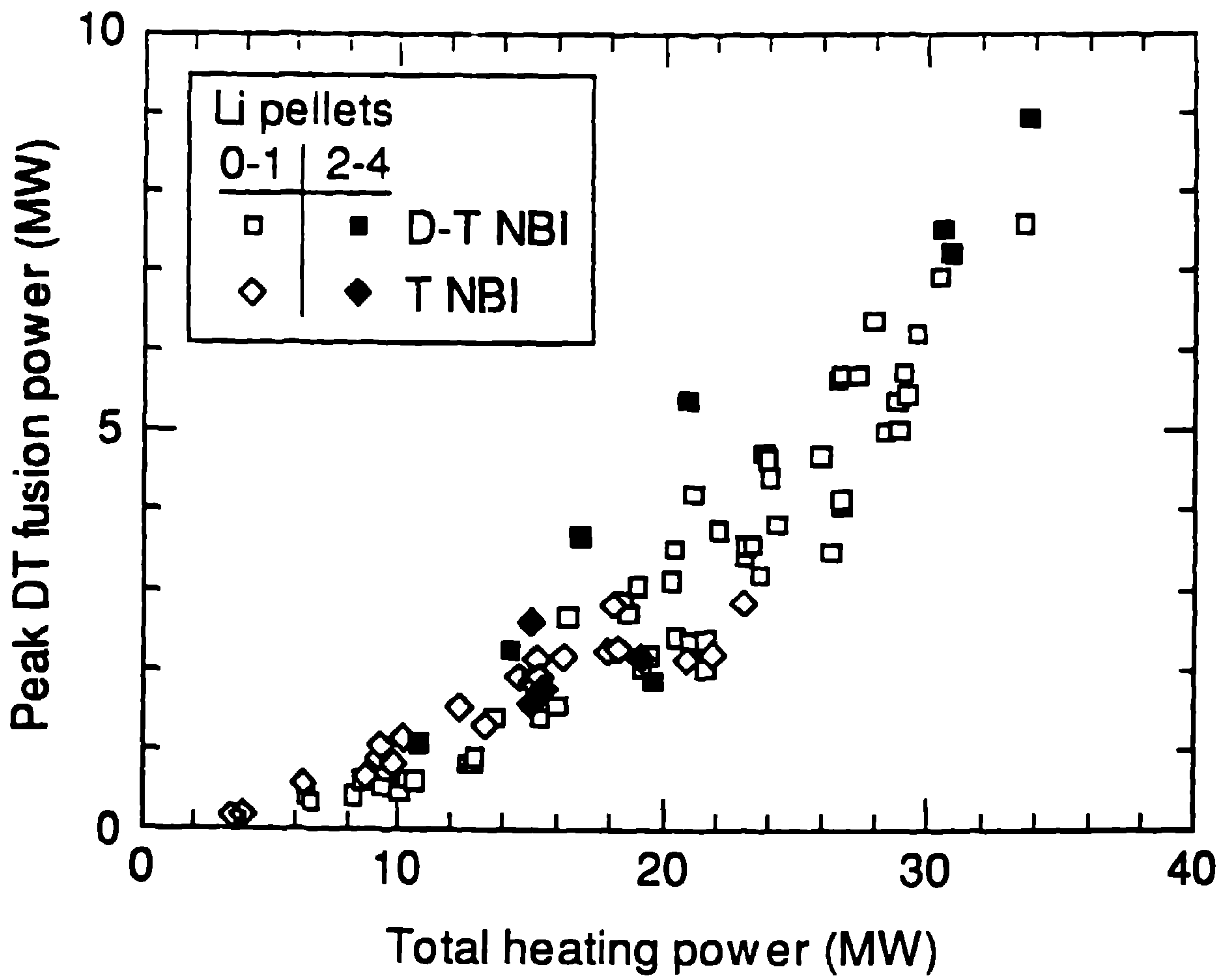

Fig. 2 Peak DT fusion power as a function of total input power (NBI plus ohmic power). The data is for supershots with at least one NBI source injecting pure tritium. Shots with tritium NBI only are distinguished. Improved performance is made possible by Li pellet injection.

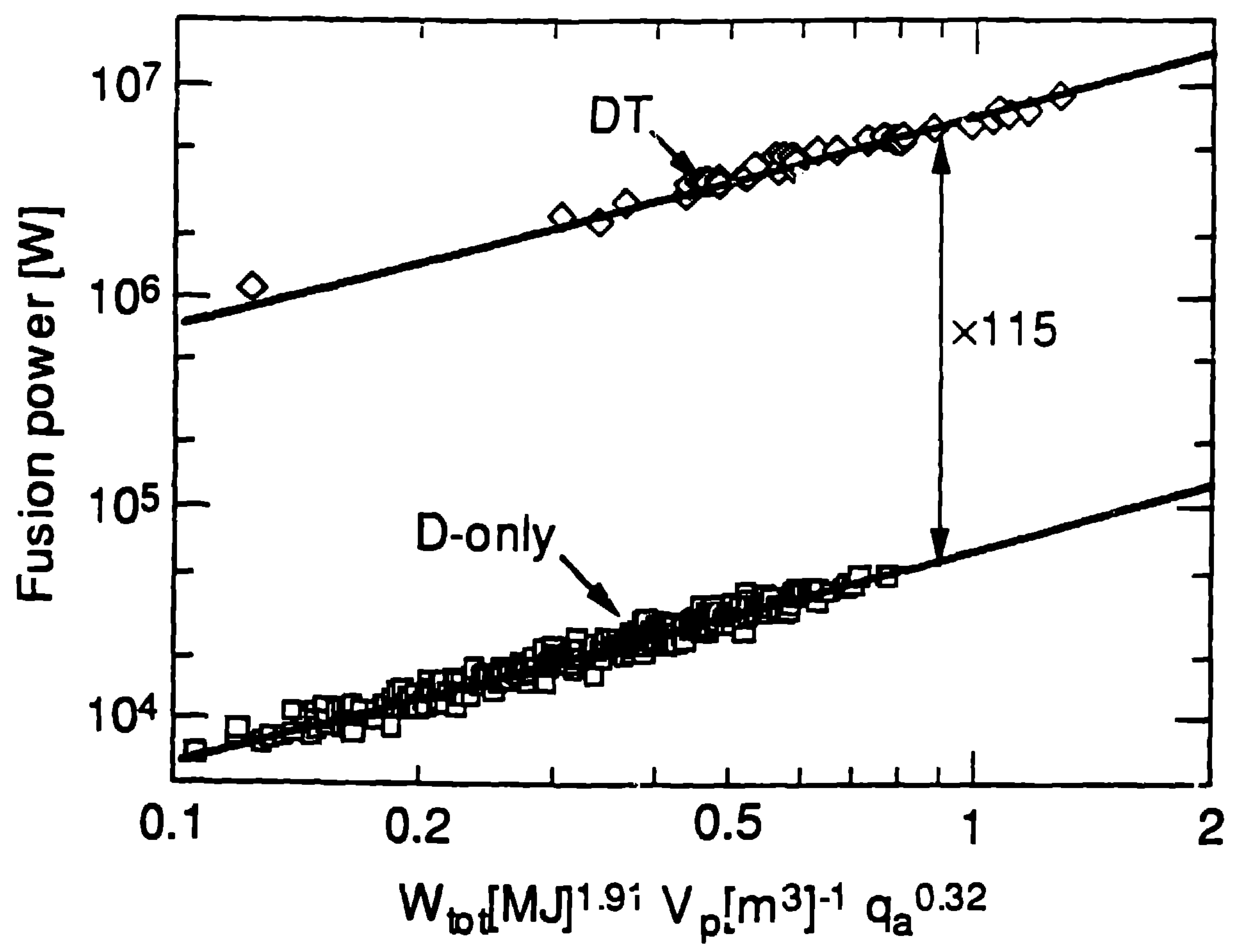

Fig. 3 Peak fusion power from both DT and D-only supershots with NBI heating plotted against the common scaling expression. The DT plasmas are restricted to those with close to the optimum fraction of T-NBI.

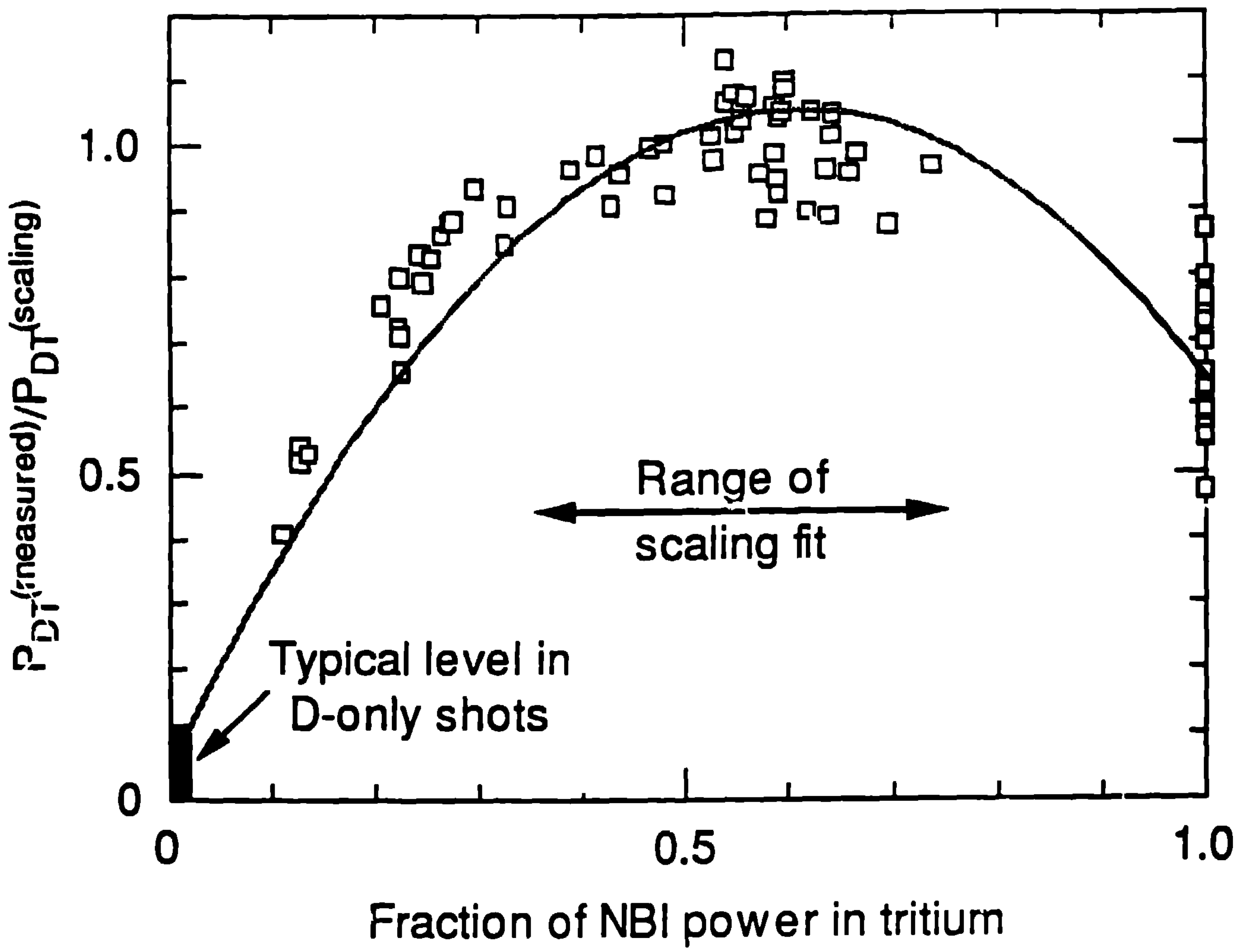

Fig. 4 Dependence of the normalized DT fusion power on the fraction of T-NBI in the total NBI power. The DT fusion rate is normalized to the scaling expression (Fig. 3) to remove the effect of the energy confinement on the DT power. The range over which the scaling expression was fitted and the range of DT power for D-only plasmas are indicated.

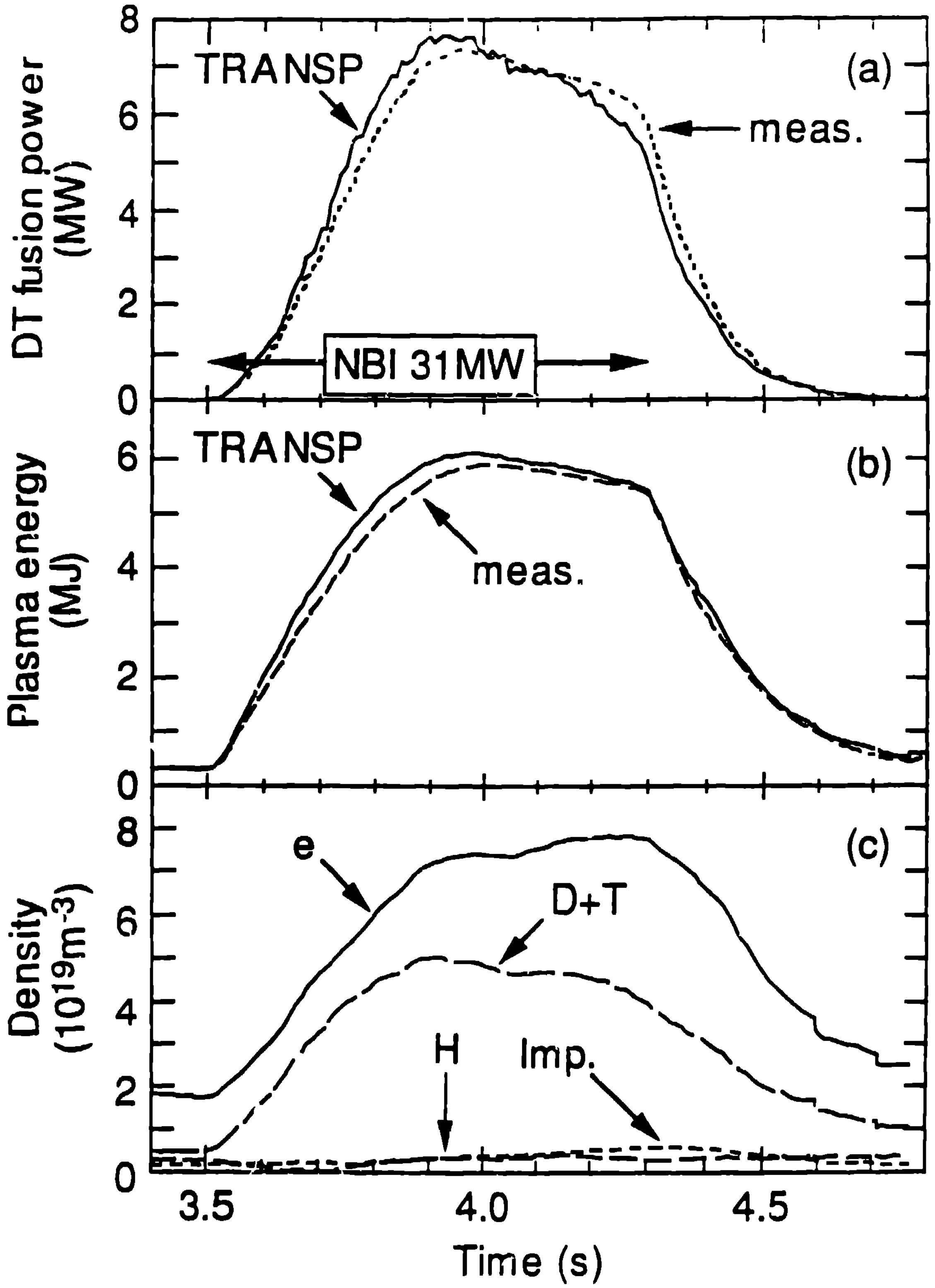

Fig. 5 Comparisons of a) the DT fusion power and b) the plasma energy calculated by TRANSP with measurements for shot 76771. Panel c) shows the inferred densities of the various plasma species.