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ENHANCED D-T SUPERSHOT PERFORMANCE AT HIGH CURRENT USING EXTENSIVE LITHIUM CONDITIONING IN TFTR

BY

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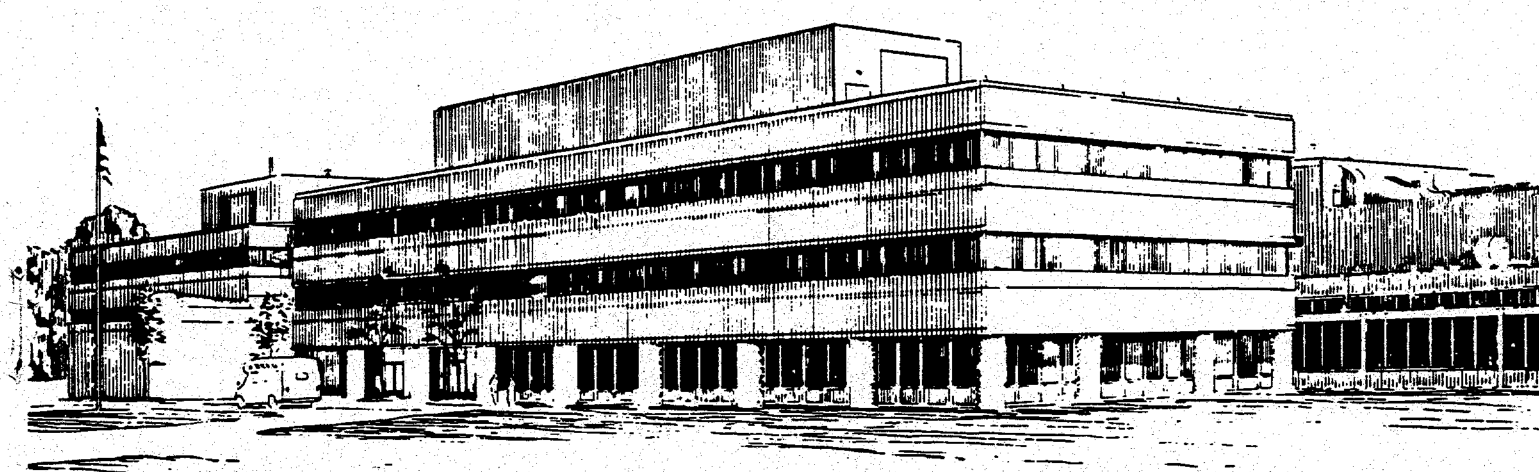

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Enhanced D-T Supershot Performance at High Current using Extensive Lithium Conditioning in TFTR

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Abstract

A substantial improvement in supershot fusion plasma performance has been realized by combining the enhanced confinement due to tritium fueling with the enhanced confinement due to extensive Li conditioning of the TFTR limiter. This combination has resulted in not only significantly higher global energy confinement times than had previously been obtained in high current supershots, but also the highest ratio of central fusion output power to input power observed to date.

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Recently, it has been observed that in the Tokamak Fusion Test Reactor (TFTR) energy confinement in discharges fueled by both deuterium (D) and tritium (T) is improved compared to similar discharges fueled only by deuterium [1,2]. This improvement has been attributed to favorable isotopic scaling of energy confinement in tokamaks [3,4,5]. The majority of experiments with D-T discharges in TFTR have been carried out in the "supershot" mode of plasma operation. The enhanced energy confinement, peaked density profiles and high fusion reactivity that characterize supershots are known to depend sensitively on the surface condition of the TFTR carbon inner limiter [6]. Moreover, it has been demonstrated that, in D-only supershots, energy confinement can be improved by depositing lithium (Li) onto the limiter [7,8,9,10]. In this work, the high energy confinement associated with supershot operation has been enhanced by combining tritium fueling with the deposition of large amounts of Li onto the TFTR limiter. This combination has been carried out at high plasma currents ($\geq$ 2 MA) and has led to the attainment of the highest supershot confinement time ($\tau_E \approx 280$ ms) observed to date as well as the highest ratio of central fusion output power to input power ($Q_{DT}(r=0) \approx 0.6 - 0.8$).

In Fig. 1 is shown the central line-averaged electron density from the best D-T supershot attained in initial experiments designed to maximize Li deposition on the TFTR limiter (shot #77309 : major radius = 2.52 m, minor radius = 0.87 m). In these experiments Li was deposited by the injection and ablation of four Li pellets in the Ohmic phase of supershot discharges immediately before D-T neutral beam injection (NBI). Each cylindrical pellet ($\approx$ 2 mm long x 2 mm diameter, $\approx 5 \times 10^{20}$ atoms) was large enough to coat the inner geometric surface area of the TFTR vacuum vessel with about one monolayer of Li. Pellets were injected radially at the horizontal midplane at speeds of 0.4 - 0.6 km/s. The timing of injection was determined by three considerations: (1) The injector required a 1.3 s delay between the second and third pellets for magazine repositioning. (2) A 200 ms delay was needed between successive pellets to allow the plasma to re-heat. This re-heat prevented the second pellet of each pair from passing through a quenched plasma column and striking the inner wall. (3) A 500 ms delay just before NBI allowed the injected Li to diffuse out of the plasma and onto the limiter. Additional conditioning of the limiter was accomplished by injecting a total of fourteen pellets into six Ohmic discharges preceding shot #77309. The efficacy of this pre-conditioning was inferred from the carbon (CII) emission in these plasmas because successful Li conditioning suppresses the influx of carbon from the limiter [9]. Further, in TFTR supershots, reduced carbon influx in the Ohmic phase prior to NBI correlates with increased energy confinement times during NBI [11]. However, excessive Li pre-conditioning can occasionally cause a disruption during the Ohmic phase of TFTR supershots. Hence, before attempting a D-T supershot experiment, the carbon emission was reduced by a factor of 2 - 4 in a series of Ohmic D-only pre-conditioning discharges, but not reduced so low as to risk a disruption.

In these experiments, NBI power was limited to 20.8 MW to maintain the Troyon-normalized beta (β_n) below 2.0 thus minimizing the risk of a major disruption [12]. Indeed, β_n of shot #77309 approached only 1.7. Of the total NBI power for this discharge, 14.0 MW was injected in the direction of the plasma current and 6.8 MW was injected in the opposite direction. Further, tritium beams totaled 12.3 MW while deuterium beams accounted for 8.5 MW.

Shown in Fig. 2 are traces of the global energy confinement time, the neutron production rate with the alpha particle loss, the central ion and electron temperatures, injected beam power, edge density and average Z_{eff} for shot #77309. The ion and electron temperatures were measured by charge exchange recombination spectroscopy and electron cyclotron emission, respectively [13,14,15]. The alpha loss was measured by a scintillation detector located at the bottom of the vacuum vessel [16]. The hatched areas in Fig. 2 represent ranges of performance observed in supershots with externally-controlled plasma parameters similar to shot #77309 (plasma current, major and minor radii, toroidal field and NBI power) but without the benefit of either extensive Li conditioning or tritium fueling. * The confinement time was measured magnetically and includes the energy in unthermalized beam-injected ions [17]. The energy confinement time is defined as:

$$\tau_E \equiv \frac{W_{TOT}}{P_{OH} + P_{NB} - \dot{W}_{TOT}} \quad , \qquad (1)$$

Where W_{TOT} is the total stored energy of the discharge, P_{OH} and P_{NB} are the Ohmic and neutral beam input powers, respectively, and $\dot{W}_{TOT}$ is the time rate of change of the total stored energy. Using the isotopic scaling detailed in Refs. 3,4 & 5, it has been estimated that the confinement time shown in Fig. 2(a) was enhanced by 10-15% because of tritium fueling. Hence, in that figure, roughly 1/3 of the improvement in τ_E as compared to the hatched area can be attributed to isotopic scaling while 2/3 is due to Li conditioning.

The performance of shot #77309 is noteworthy not only because of the high energy confinement, but also because of the high fusion reaction rate ($S_n \approx 1.9 \times 10^{18}$ s^{-1}) and high temperatures ($T_i \approx$ 38 keV, $T_e \approx$ 12 keV) attained at only 21 MW input power. The magnetically-measured stored energy for this discharge reached a maximum value of 4.8 MJ.

Although all the mechanisms by which Li conditioning contributes to plasma performance are not understood, reduced particle (mostly carbon and deuterium) influx from the limiter during NBI appears to play an important role in determining energy confinement in TFTR supershots [6,18]. In this regard, a clear result of Li conditioning can be seen on the edge electron density. Shown in Fig. 2(e) is the line-integrated density measured on a vertical chord located 15 cm from the TFTR inner limiter [19]. Due to reduced particle influx brought about by extensive Li conditioning, the edge density is clearly suppressed during most of the beam-heating phase.

The suppression of particles from the limiter generally has led to a peaking of the plasma profiles in Li-conditioned discharges. Indeed, shot# 77309 exhibited the most peaked density profile observed to date in a TFTR supershot. Other examples of this peakedness, are seen in Fig. 3 in which are plotted radial profiles of density, neutron emissivity, electron and ion temperatures, fusion power multiplier as well as the calculated power inputs to ions and electrons. All curves are given at the time of maximum neutron emission (t = 4.4 s). The profile of neutron emissivity was determined from neutron collimator measurements [20]. The fusion power multiplier shown in Fig. 3(d) is the ratio of fusion output power to input power and is defined by :

$$Q_{DT}(r) \equiv \frac{\int_0^r P_{fusion}(r)\,dV}{\int_0^r (P_{NB}(r) + P_{OH}(r))\,dV} \quad . \qquad (2)$$

Here P_{fusion} is the instantaneous fusion power released as a function of flux-averaged minor radius r and is determined from S_n, the measured local D-T neutron emissivity, by:

$$P_{fusion}(r) = S_n(r) \times 17.6 \text{ MeV / DT reaction} . \qquad (3)$$

In Eq. (2), P_{NB} and P_{OH} are the local external heating powers due to neutral beams and Ohmic heating, respectively. The beam heating power includes beam-electron, beam-ion and beam-thermalization terms. The value of $Q_{DT}(r)$ at the plasma edge is defined to be the global Q_{DT} and is the ratio of the total fusion power output to the total plasma input power. The central ratio of fusion output power to input power in shot # 77309 attained a value of 0.6 - 0.8, while the global Q_{DT} was 0.27 (Fig. 3(d)). Both of these are the highest values produced to date and correspond to a volume-integrated instantaneous fusion output power of ≈ 5.5 MW.

The profile of the fusion power multiplier was calculated using TRANSP, the 1 1/2 D transport analysis code [5,21]. The local value of this parameter was then mapped onto the major radius as $Q_{DT}(R)$ and is shown as a range of values representing Monte Carlo noise and measurement uncertainties. TRANSP uses measured plasma profiles to calculate the neutral beam deposition and heating profiles. The calculated beam-ion, thermalization and Ohmic heating rates for shot #77309 were used in the denominator of Eq. (2). TRANSP is also used to calculate fusion reaction rates. The resulting profile of the calculated chordal D-T emissivity for this discharge was compared to that measured by the neutron collimator and agreed within experimental error. Shown in Fig. 3(b) is a comparison of the Abel-inverted neutron emissivity from the collimator and the local emissivity calculated by TRANSP. The calculated local emissivity was used in the numerator of Eq. (2). Following the prescription given above, TRANSP was also used to calculate the heating power to ions and electrons due to fusion alpha particles. These power inputs are shown in Fig. 3(e & f); however, there is no experimental confirmation of this heating owing to the lack of reproducible D-only and T-only comparison discharges.

Although the discharges in these experiments attained a noteworthy level of fusion performance, further improvements can be realized. In particular, due to a water leak in a neutral beam source, the D-T mixture in all plasmas studied was diluted with high levels of hydrogen (H). Spectroscopic measurements have shown the fractional influx, H/(H+D) $\approx$ 30% [22]. Employing this level of influx, it has been calculated by TRANSP that the D-T mixture in the core of shot #77309 had about 10% hydrogen dilution. This level of dilution could have signifcantly limited the D-T fusion reaction rate.

The surface condition of the graphite inner wall at the start of these experiments imposed another limitation on the ultimate fusion performance of shot # 77309. Some indication of this surface condition can be seen in the response of the inner wall to magneto-hydrodynamic activity (MHD) in the plasma column. Because of the high stored energy attained in this discharge, four episodes of MHD activity occurred during NBI and appear to have adversely affected fusion performance. Each of the four episodes of MHD activity had strong ballooning characteristics as contrasted to the "fishbone" activity and low frequency modes more commonly seen in TFTR supershots [23]. Further, each of these MHD episodes terminated in an event which caused a transient increase in the power flux to the limiter resulting in a particle influx to the plasma (Fig. 2(e)). The fourth of these events appears to have been a minor disruption and was clearly the most damaging to plasma performance. This minor disruption was accompanied by a particularly large influx of wall particles and a pronounced decrease in energy confinement, electron temperature and neutron production rate (Fig. 2 (a, d and f)). Such a large influx of particles at such modest beam power is not typically observed in TFTR and suggests that the initial surface condition of the limiter was less than optimal at the time of the experiment. The condition of the limiter may have been determined by the residual effects of a 6 MJ major disruption which occurred prior to these experiments.

It is interesting to note that the loss of fusion alpha particles to the vessel bottom appears to be consistent with the level expected from first-orbit losses ($\approx$ 5%), although this loss increased slightly during the four episodes of MHD activity in shot #77309 (Fig. 2(f)) [16]. This level of MHD-induced alpha particle loss should not significantly affect the global alpha particle heating rate.

The level of fusion performance in these experiments, and in particular shot #77309, clearly benefited because of the combined effects of Li conditioning and favorable isotopic scaling. Moreover, remedies exist for each of the fundamental limitations on fusion performance discussed above (viz.: hydrogen dilution, MHD activity and initial limiter condition). Future efforts to achieve high-confinement supershots in TFTR using extensive Li conditioning will be carried out under conditions of better vacuum integrity, of better initial wall conditioning and at the highest toroidal field strength attainable (≈ 6.0 T). This increased field strength will increase the stability of these discharges and may allow the central Q_{DT} to increase.

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* Ideally, a direct comparison of shot #77309 should be made to D-only, 2.1 MA supershots which have experienced no Li conditioning. However, this is problematic because the supershot mode of operation has not been attainable in TFTR at plasma currents higher than ≈ 1.9 MA except with the assistance of Li conditioning. The shots represented by the hatched areas (shots #78507, #78508, #75889, #75939) are ≈ 2.1 MA, D-only supershots which did not experience the direct benefit of Li pellet injection. Instead, each of these comparison shots experienced some residual benefit from single Li pellets injected into preceding discharges. Hence these supershots are considered to be "lightly" conditioned. These are to be contrasted with the "extensively" Li-conditioned discharges detailed in this work. The performance of comparison shots which did not experience the benefit of any Li conditioning would be significantly worse than that shown by the hatched areas.

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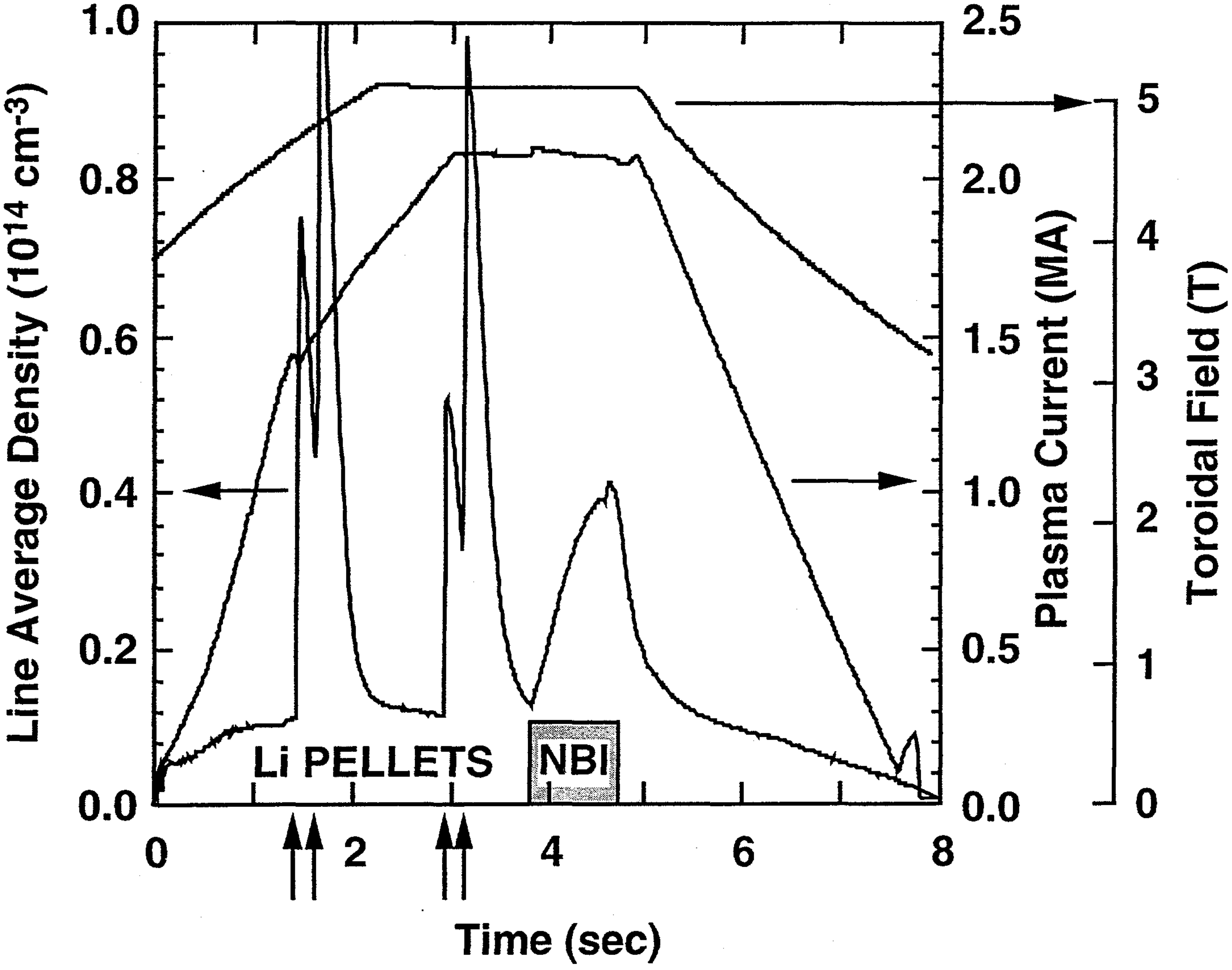
Figure captions

Fig. 1 The central line average density for shot #77309 showing the effects of four Li pellets as well as neutral beam injection. Also shown are the plasma current (2.1 MA) and toroidal magnetic field (5.1 T).

Fig. 2 Shown are expanded traces of the (a) gross energy confinement time, (b) neutron production rate and alpha particle loss to the vessel bottom, (c) central ion temperature, (d) central electron temperature and NBI power (e) line integral density measured 15 cm from the limiter surface and (d) Z_{eff}. The MHD events which took place during this discharge are indicated by dashed vertical lines while the minor disruption is represented by a solid line. The hatched areas represent the range of performance observed in lightly conditioned D-only supershots with similar externally-controlled plasma parameters.

Fig. 3 Shown are radial profiles of the (a) density (b) measured neutron emissivity compared to that calculated by TRANSP, (c) electron and ion temperatures, (d) calculated fusion power multiplier mapped onto the major radius and the calculated power inputs to the (e) ions and (f) electrons. All curves are given at t = 4.4 s. The dashed vertical line indicates the calculated position of the Shafranov-shifted magnetic axis.



1.0
0.8
0.6
0.4
0.2
0.0
2.5
2.0
1.5
1.0
0.5
0.0
5
4
3
2
1
0
0
2
4
6
8
Line Average Density (10^{14} cm^{-3})
Plasma Current (MA)
Toroidal Field (T)
Li PELLETS
NBI
Time (sec)

Fig. 1

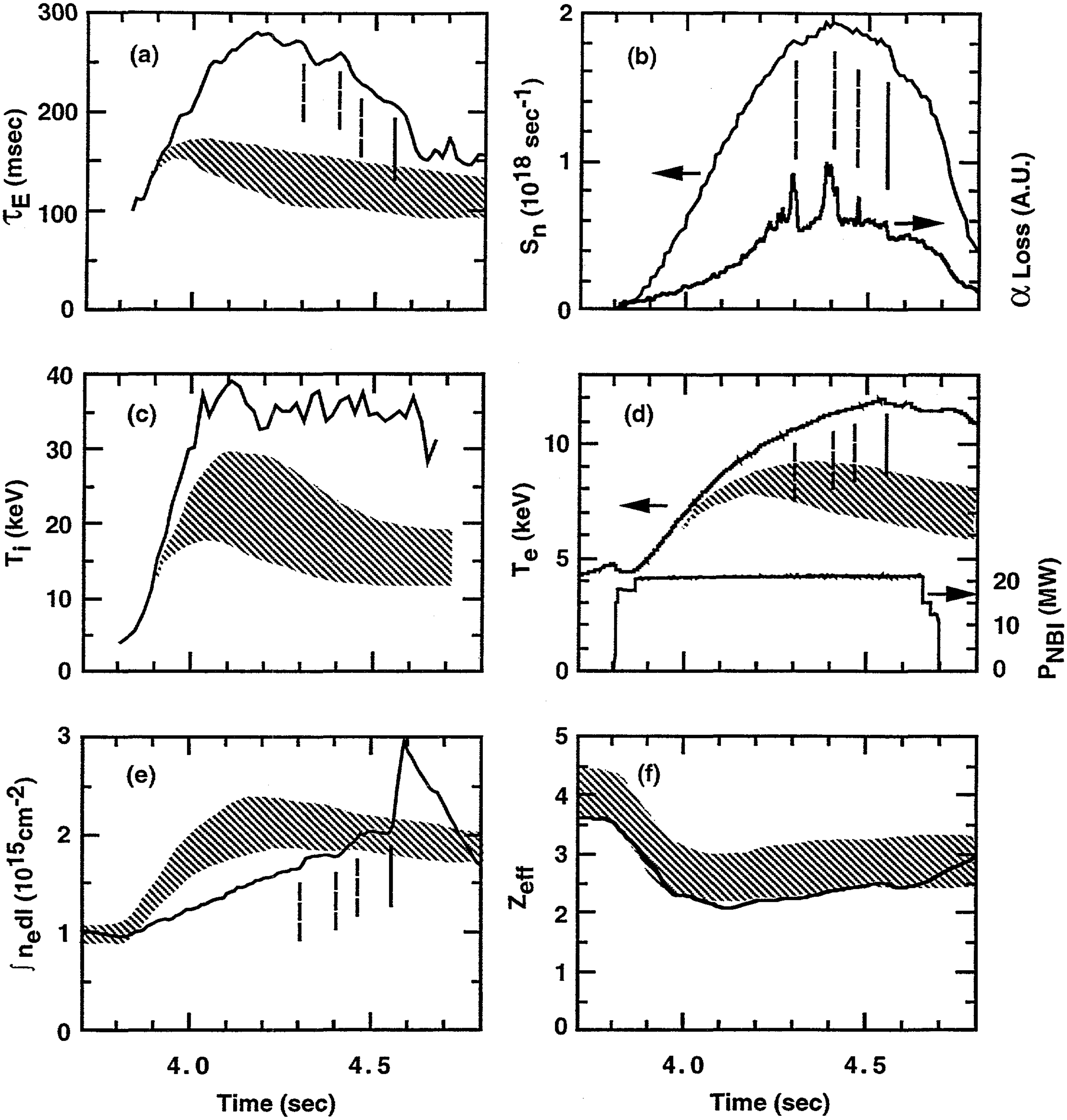


Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d

Fig. 2e

Fig. 2f

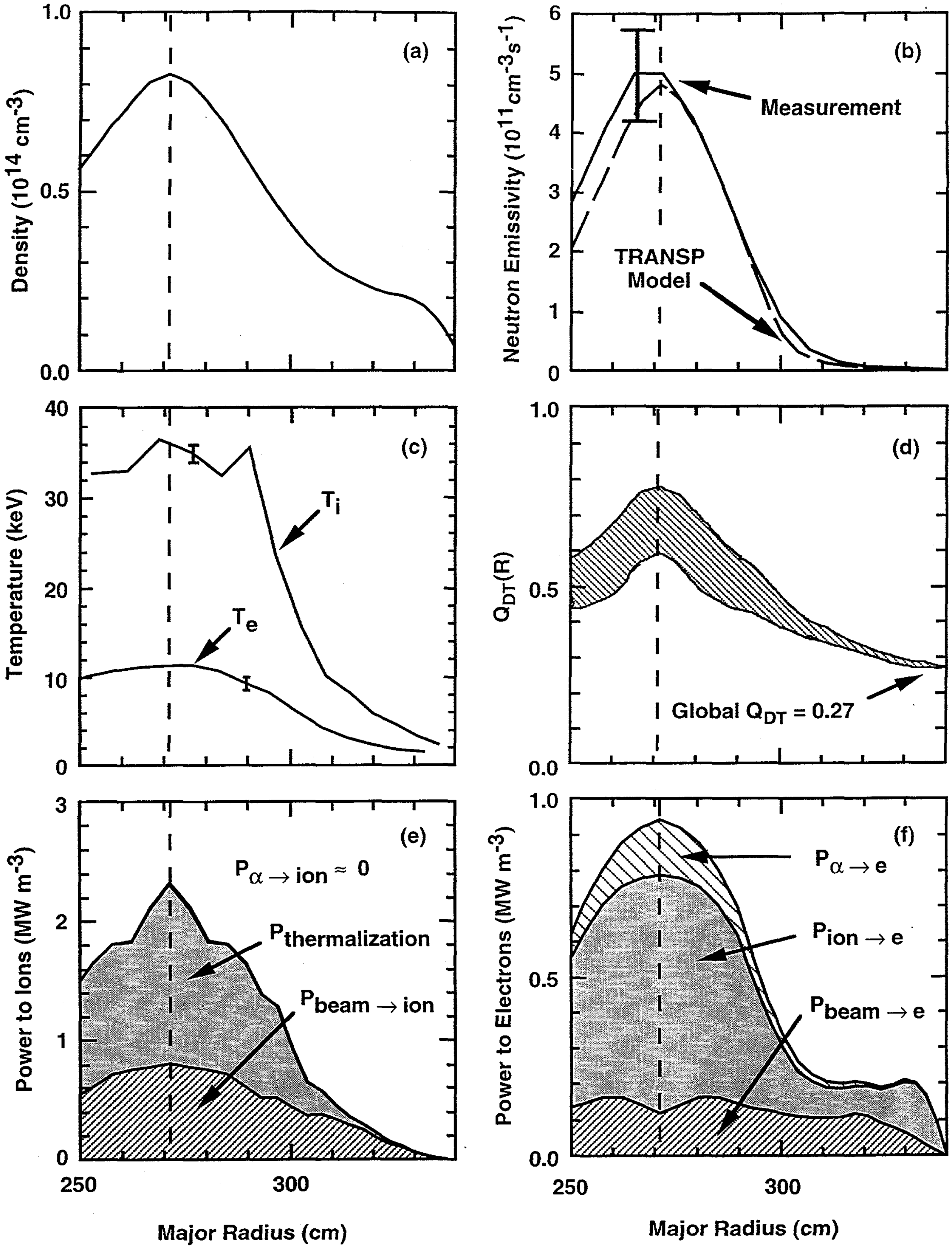


Fig. 3a

Fig. 3b

Fig. 3c

Fig. 3d

Fig. 3e

Fig. 3f

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