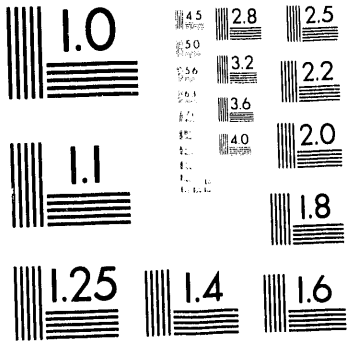
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HIGH-PERFORMANCE SUPERSHOTS IN TFTR WITH LITHIUM PELLET INJECTION

by

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ABSTRACT

Increasing the amount of lithium pellet injection during the supershot conditioning procedures has enabled reliable enhancement of supershot confinement at higher plasma currents. Some shots have exceptionally good performance, with peak global parameters up to τ_E = 205 ms, $S_n = 5.6\times10^{16}$ n/s and $Q_{DD} = 2.1\times10^{-3}$.

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Introduction

TFTR supershots are neutral-beam-fueled and heated plasmas with enhanced confinement characterized by highly peaked density profiles and relatively broad temperature profiles. The basic technique for achieving supershot operation is to inject high-power neutral beams into a low-density target plasma with a first wall/limiter that has been conditioned to achieve a low recycling coefficient [1]. Aggressive limiter conditioning procedures [2] have included Ohmic helium discharges to remove deuterium from the carbon limiter; repetitive high-power neutral-beam injection (NBI); disruptive discharge cleaning; and inducement of runaway sublimation of carbon from the limiter (a "carbon bloom") on the previous shot. For several years, supershots were limited to plasma currents, I_p, below about 1.5 MA, because higher I_p was apparently correlated with increased deuterium recycling and carbon influx from the limiter. However, supershot performance at lower I_p is limited by MHD constraints. In particular, the pressure limit (evidenced by minor or major disruption, often at $\beta_p \approx 1.2$) appears to increase with I_p in a manner similar to the Troyon limit [3]. The performance of supershots approaching the β limit tends to degrade after about 0.5 s of beam injection, often because of the start of coherent MHD (such as 3/2 or 4/3 modes), or because of a disruptive MHD event [3,4]. Thus the ability to operate at higher I_p is essential.

In 1990, with the aid of a single pre-beam lithium pellet injected 1.0 s before NBI, the carbon influx was significantly reduced, and the high-performance supershot range extended to 1.9 MA, with consequent increases in plasma stored energy, E_{tot}, and the maximum neutron rate, S_n [5]. Lower carbon-II emission from the target plasma and lower Z_{eff} during NBI suggested that pre-beam lithium pellet injection reduced the carbon influx by covering the active limiter surfaces with lithium. In 1992 this procedure was extended by injecting *two* lithium pellets in the Ohmic phase of each beam shot, by using pellets twice as large as in 1990, and also by operating a series of Ohmic shots with lithium pellet injection prior to the beam shots. This paper describes the best plasmas achieved during the 1992 campaign.

Experiment

The conditioning sequence for a supershot run often began with a series of 1.4-MA helium Ohmic plasmas that were repeated until the rate of carbon influx (which is characterized by the carbon-II emission level [6]) ceased dropping from shot to shot. This series was often followed by a series of 1.4-MA ohmic deuterium plasmas with Li pellet injection, also repeated until the magnitude of carbon-II emission stopped evolving. It is

assumed that this second phase established a preliminary coating of Li on the limiter. The methodology of the 1992 Li pellet conditioning is described more fully elsewhere [7].

Figure 1 shows the time evolution of the central and edge electron densities, as well as the D_α and CII emission, for one of the best Li-assisted supershots (#68244) and a comparison supershot plasma without Li pellets (#68206). Two Li pellets were injected into the Ohmic target plasma about 1 sec before the start of neutral-beam injection (NBI), so that the Li would transport out of the plasma and cover the carbon inner wall, which is employed as a bumper limiter. The plasma density, n_e, and carbon influx returned to levels slightly below the initial levels that would have occurred if the pellets were not injected [8]. Starting from this low-density target plasma, beam fueling resulted in a rapid rise in n_e and strong peaking of the density profile. The plasma evolution during beam heating also featured lower carbon and deuterium influxes as well as lower edge density when the plasma was aided by Li pellets. However, the Li-assisted plasma had significantly higher central density, $n_e(0)$.

For supershots, the neutron emission rate, S_n, is nearly proportional to E_{tot}^2 [3]. Higher performance at a given beam power (i.e., higher S_n and E_{tot}) is generally associated with higher energy confinement time, τ_E, as $E_{tot} \approx P_b\tau_E$, where P_b is the injected neutral-beam power. At a given P_b, the 1992 supershots with Li pellet conditioning generally gave higher S_n than the supershots of previous years [4]. The 1992 supershots often had higher τ_E than in 1990, and in particular, a much larger proportion had $\tau_E > 0.15$ s. This result is probably due to the larger number of Li pellet shots in 1992, the larger amount of Li in each pellet, and the use of 2 Li pellets per shot. In fact, as shown in Fig. 2, the supershot τ_E increases with Li light intensity from the target plasma. The light intensity is probably proportional to the amount of Li on the limiter and in the plasma edge, and there is apparently no saturation of τ_E with the levels of Li used to date.

Confinement time also appears to be associated favorably with density peakedness, $n_e(0)/\langle n_e \rangle$, and higher peakedness probably results from a larger fraction of the central density fueled by the beams. Higher peakedness has generally been correlated with lower carbon emission from the target plasma, and often with lower target density [3,4,7]. With reduced recycling apparently a result of Li covering the limiter, Li pellet injection enables still higher peakedness (and sometimes lower Z_{eff}). These correlators are not unique, but the important feature is that the Li-assisted plasmas comprise an extension of supershot performance and are not an intrinsically new phonomenon.

Exceptional Shots

During 1990-92, the median τ_E for Li-assisted supershots was about 150 ms, compared with 135 ms for all supershots (excluding those with RF power). While only 9.5% of all supershots had Li conditioning, these accounted for 37% of supershots with $\tau_E > 170$ ms and 50% with $\tau_E > 180$ ms. In 1992, several plasmas had exceptionally good performance with maximum $\tau_E = 185$-205 ms. (Note that the largest τ_E during NBI usually occurred somewhat earlier than the time of maximum S_n.) Each of these exceptional shots came after sequences of plasmas aimed at successively accumulating more Li on the limiter. However, the occurrence of such plasmas was sporadic, and presently not fully understood. Table 1 gives the parameters of 4 of these shots, which were obtained after different sequences of Li conditioning [7] (on different days), and they are characterized by different levels of I_p and P_b. The parameter values shown are taken at peak S_n. Also shown are the parameters for #68206, a comparison shot that had the same machine settings as #68244, but that occurred during the early part of the sequence before any Li pellets were injected (see also Fig. 1). Evidently, $n_e(0)$, $T_e(0)$ and $T_i(0)$ are substantially larger for the high-τ_E plasmas.

Figure 3 compares the time evolution of several parameters for shots 68206 and 68244, as well as for shot 68522, which gave record E_{tot} and Q_{DD} but at substantially higher P_b and I_p than 68244. T_e was determined from cyclotron radiation (ECE), T_i from charge-exchange recombination spectroscopy (CHERS), and n_e from multi-channel laser interferometry. The following is a discussion of the performance of the 4 exceptional shots of Table 1.

Shot 68244. On this run day there were no Ohmic shots with Li pellet pre-conditioning. However, shot 68244 was preceded by a series of beam shots with 1 pre-beam and 1 post-beam Li pellet, this series having $\tau_E \approx 160$-170 ms. Shot 68244, as well as the immediately preceding two shots (68242 and 68243), had 2 pre-beam Li pellets. Shot 68242 attained $\tau_E = 190$ ms, but suffered MHD problems beginning at 0.4 s after NBI, while τ_E for #68243 was 170 ms. Shot 68244 proceeded with $\tau_E = 180$ to 190 ms for a longer time than in 68242, so that $n_e(0)$ and S_n could continue to build up until about 0.6 s into the beam pulse, when β_p reached 1.20 and the central plasma parameters began to degrade.

Figure 4 compares some radial profiles for #68244 with the corresponding profiles for the non-pellet shot 68206. The Li-conditioned shot has central electron density 35% higher for essentially the same average density, 25% higher $T_e(0)$, and 37% higher $T_i(0)$. While $T_e(r)$ has the same FWHM for both shots, $T_i(r)$ is slightly broader for the pellet shot. The 30%

higher τ_E of #68244 is reflected in the much larger density in a higher temperature central region. The larger $n_e(0)$ results in a reduction in the (calculated) beam-ion density and the beam-beam reaction rate, but the total neutron rate is dominated by increases in the thermal and beam-target rates. The more highly peaked density profile and higher T_i enhance the thermal reaction rate, while the higher T_e and T_i tend to increase the beam slowing-down time. (The density effect cancels out of the beam-target rate.) The resultant neutron rate is 60% higher for the shot aided by Li pellet conditioning.

Shot 68436. The series of shots around 68436 had the same I_p as the 68244 series, but used lower P_b in an attempt to reduce MHD problems. A large τ_E (160-180 ms) was obtained in the first beam shots after a sequence of Li-conditioned ohmic shots. Shot 68436 had an unusually large τ_E that reached 205 ms, but its S_n was matched by two others in the sequence. Despite the lower P_b, salient parameters such as S_n began to degrade at 0.5 s into the beam pulse, when β_p was still only 1.06. The apparent cause was a minor disruption followed by increased MHD activity and carbon influx.

Shot 69162. This shot was the last of a long sequence of beam shots with 2 Li pellets in the pre-beam phase. The preceding shot (#69161) differed in that 2 Li pellets were injected into the *post-beam* phase, at t = 3.9 and 4.3 s. Thus #69162 benefited from 4 Li pellets and its τ_E was 20% larger than for most of the preceding shots. (A similar arrangement with a total of 2 pellets was made for #55806, the highest-S_n shot of 1990 [4].) The 69162 plasma disrupted at 0.48 s into the beam pulse, as the large τ_E allowed β_p to rise to 1.26 and β_N to 2.2.

Shot 68522. This shot was the 2nd beam shot following a sequence of ohmic shots with Li pellet conditioning. The 1st beam shot (#68521) had a carbon bloom, probably aiding the conditioning process in a manner that has been well-documented on TFTR but not understood [2]. (A similar event occured before #47394, which in 1990 gave the record Q_{DD} for non-Li-conditioned shots.) Shot 68522 gave the highest E_{tot}, S_n and $Q_{DD} = S_n/P_b$ of any TFTR shot to date, before disrupting at 0.5 s into the beam pulse, at $\beta_p = 1.20$ and $\beta_N = 2.1$.

These results show that major or minor MHD events or carbon bloom can restrict the period of maximum stored energy and neutron rate of the best supershots to about 0.5 s or less. Thus there is a need to increase the stability margin by operating supershots at still

higher I_p. The maximum I_p for which supershot confinement was obtained during 1992 was 2.45 MA, in plasmas that used Li pellet conditioning [7]. At this I_p, τ_E = 160 ms was observed at P_b up to 28.5 MW (shot 69060). However, density peakedness was a relatively moderate 2.3, β_p was only 0.6, and S_n at 3.4×10^{16} n/s was somewhat smaller than the best values obtained at this P_b using lower I_p (see Fig. 2). The low β_p does indicate considerable potential for improved performance, probably by injecting greater Li mass per pulse.

Code Simulations

The TRANSP code [9] was used to calculate the time dependence of thermal, beam-thermal, and beam-beam reactions. As indicated in Fig. 5 for shot 68522, the total neutron rate calculated by TRANSP, using the measured temperature and density profiles, is in good agreement with the measured rate. Initially, beam-beam reactions are dominant, until the target density builds up by beam fueling. After about one-half second of beam injection, this highest performing shot acquires the canonical supershot distribution of reaction rates: Beam-target reactions account for 55% of the total rate, with the balance shared roughly equally by beam-beam and thermal-ion reactions [4].

Using the measured radial profiles of plasma parameters, the SNAP code [10] determines particle and heat transport coefficients, D_e, χ_e, and χ_i. Both heat diffusion and convection are included in χ_e, and χ_i. Figure 6 compares, for each transport coefficient, the radial profile of the median value for 5 exceptional shots (3 of the 4 discussed herein, plus 2 shots fairly similar to #68436), with the profile of the median value for 180 supershots with no Li conditioning, also from the 1992 campaign. The profiles are shown at the time of peak neutron emission. While the radial profiles of n_e, T_e and T_i are distinctly different for the two categories (see Fig. 4), the calculation of gradients necessary for determining transport coefficients results in a large spread in values at each r/a, within. each category.

The values of D_e and χ_e for the exceptional Li-conditioned shots are fairly similar (within statistical deviation) to the values for the non-Li shots, but the exceptional shots have somewhat smaller D_e and χ_e at r/a < 0.5. (There was incomplete T_e data at r/a > 0.5.) The values of χ_i for the exceptional Li- conditioned shots are as much as a factor of 2 smaller than those for the non-Li shots at r/a < 0.6. Thus the improvement in τ_E appears to be due mainly to a large reduction in ion heat transport.

The radial profiles of the average values of the transport coefficients for 30 other supershots with Li pellet injection in 1992 generally fall between those shown in Fig. 6. These

results are consistent with the measurements of substantially larger global τ_E for supershots with Li pellet conditioning, and especially for the exceptional shots.

Conclusions

Supershot performance in TFTR can be enhanced substantially by the use of lithium pellet injection to condition the inner wall during the ohmic phase of the beam pulse. In such cases the global energy confinement time can reach 200 ms for exceptional shots, and the peak neutron rate can exceed the nominal supershot envelope by 20%, even at I_p = 1.8-2 MA where previous performance without Li pellets had been lower than for I_p < 1.5 MA. Exceptional shots were sometimes preceded by a shot having a special conditioning feature, such as a carbon bloom or Li pellet injection in the post-beam phase. The best shot achieved 5.6×10^{16} n/s and $Q_{DD} = 2.1 \times 10^{-3}$ just before disruption.

More work is required to achieve superior supershots at I_p up to 2.5 MA, in order to avoid the β limit that restricts performance at lower I_p. Increases in τ_E are generally correlated with greater amounts of injected Li, and no saturation of the benefits of lithium injection has yet been observed, so that future experiments will utilize greater Li mass injection per pulse.

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Table 1

PARAMETERS OF BEST 1992 LITHIUM PELLET SUPERSHOTS

	#68436	#69162	#68522	#68244	(Ref.shot) #68206
B_t (T)	4.73	5.0	5.0	4.73	4.73
R_o (m)	2.45	2.54	2.52	2.45	2.45
I_p (MA)	1.64	1.75	2.0	1.64	1.64
P_b (MW)	17.8	28.2	30.8	20.6	20.8
Li pellets	2	2 (+2)	2	2	0
E_b (keV)	100	103	107	102	102
$T_i(0)$, keV	30		27	28	20
$T_e(0)$, keV	9.4	10.0	10.5	10.6	8.4
$n_e(0)$, m^{-3}	5.8 E19	10.5 E19	9.7 E19	7.6 E19	5.6 E19
$n_e(0)/\langle n_e \rangle$	2.6	3.2	3.25	2.9	2.1
τ_E (ms) *	195	185	195	185	140
Z_{eff}	2-3	2-3	2-3	2-3	3-4
Plas.En'gy (MJ)	3.0	4.6	5.5	3.6	2.8
β_p	1.06	1.26	1.20	1.20	0.92
S_n (n/s)	2.2 E16	4.3 E16	5.6 E16	3.1 E16	1.9 E16
Q_{DD}	1.45 E-3	1.78 E-3	2.13 E-3	1.76 E-3	1.07 E-3
Comment:	Minor Disrup. 0.5 s into beam pulse	Major Disrup. 0.48 s into beam pulse	Major Disrup. 0.5 s into beam pulse	Rollover at 0.6 s into beam pulse	Slow improv. through beam pulse

*Measured at peak S_n

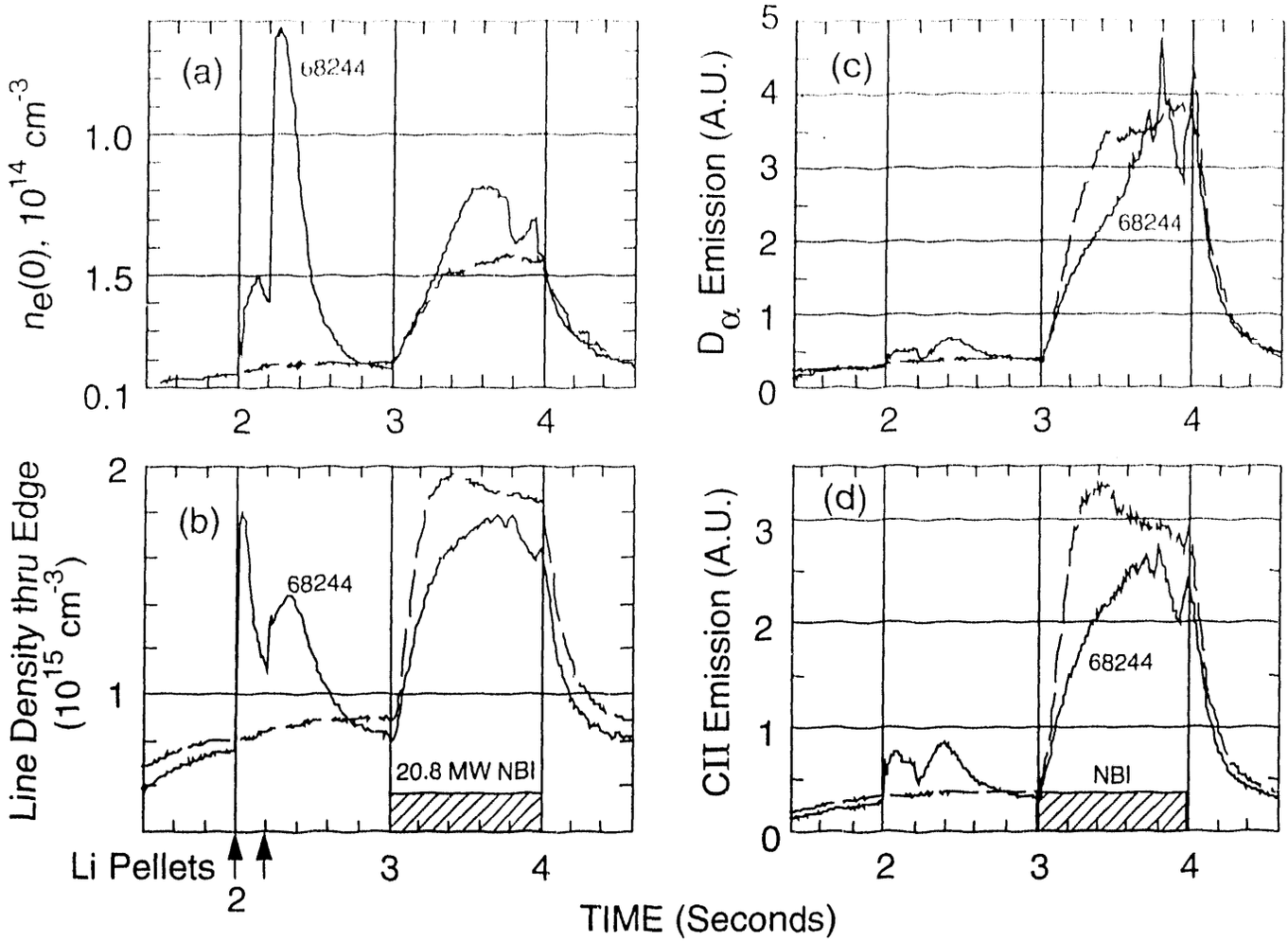

Fig. 1. Time dependence of (a) central electron density, (b) line-averaged density through the plasma edge, (c) D_α emission, and (d) C-II emission for shot 68244 with lithium pellet injection at 2.0 and 2.2 s, and comparison shot 68206 with no pellets. Neutral beams are injected from 3.0 to 4.0 s in both cases.

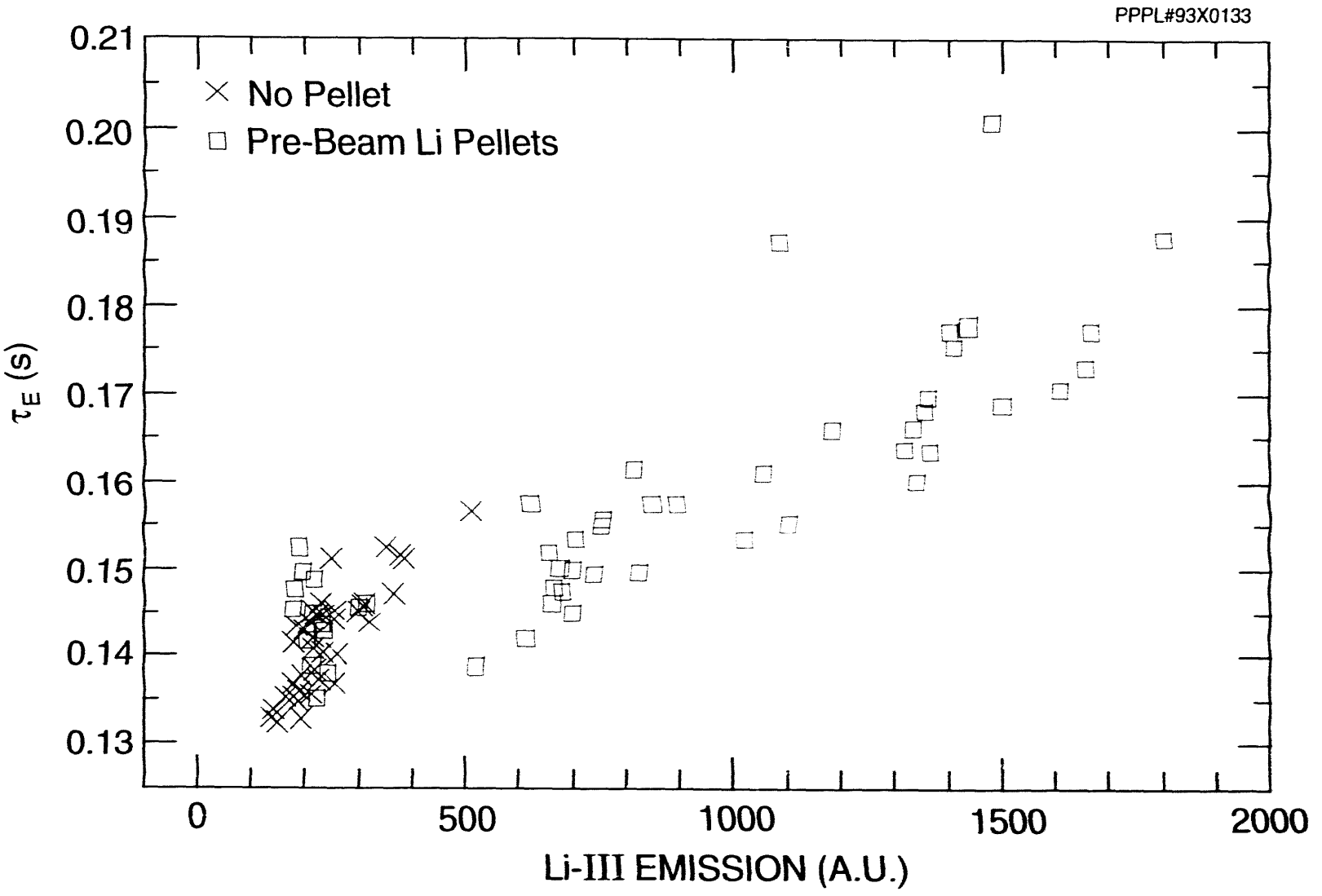

Fig. 2. Peak energy confinement time, τ_E, during NBI as a function of Li-III emission from the target plasma just before start of NBI. All shots at I_p = 1.6 MA and R_p = 2.45 m.

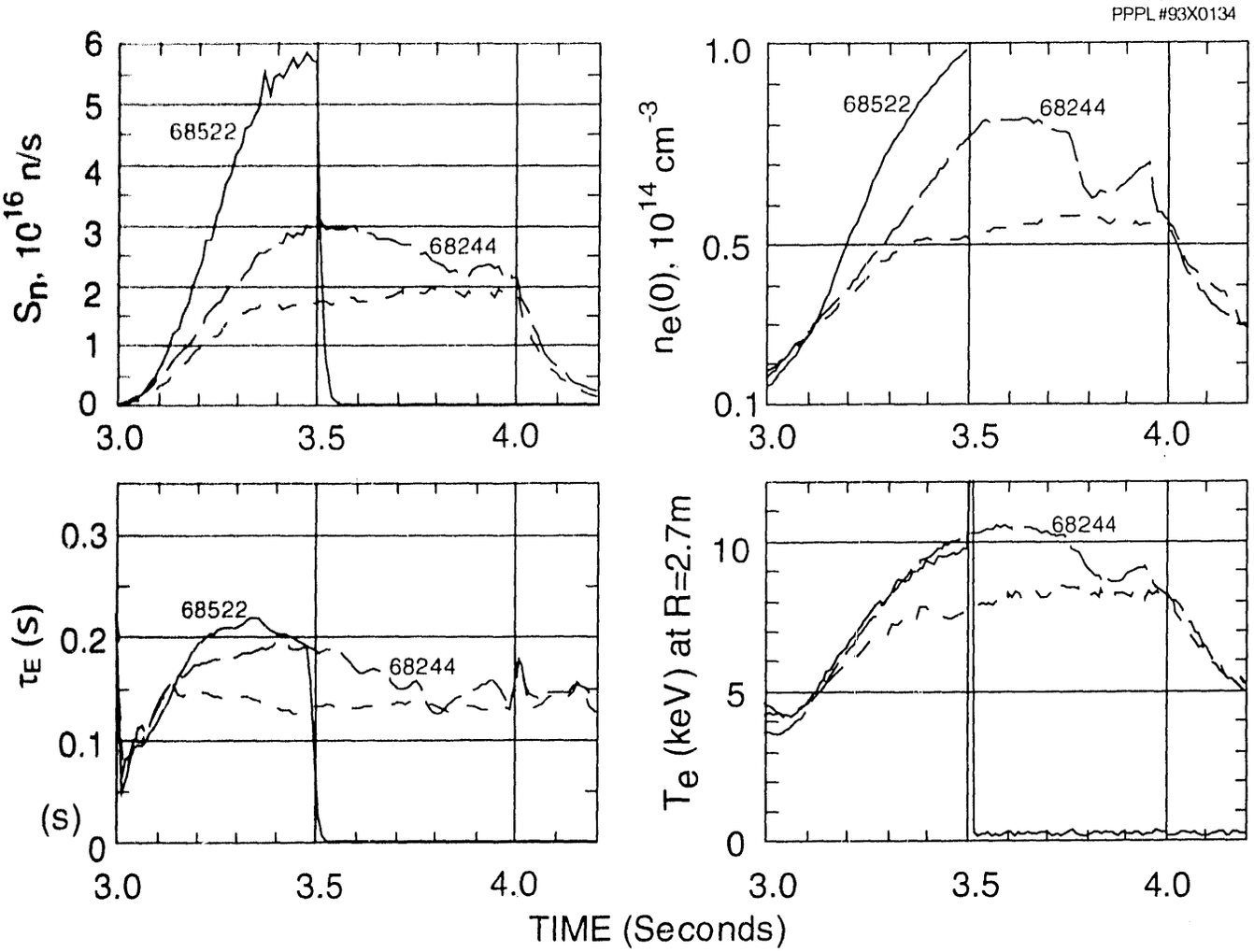

Fig. 3. Time dependence of S_n, τ_E, $n_e(0)$ and T_e at $\bar{R}$ = 2.7 m (near the plasma center) for shot 68244 with Li pellet injection, comparison shot 68206 (no pellets), and the shot with record values of S_n and E_{tot}, #68522, which disrupted at 3.5 s. Neutral beams are injected from 3.0 to 4.0 s.

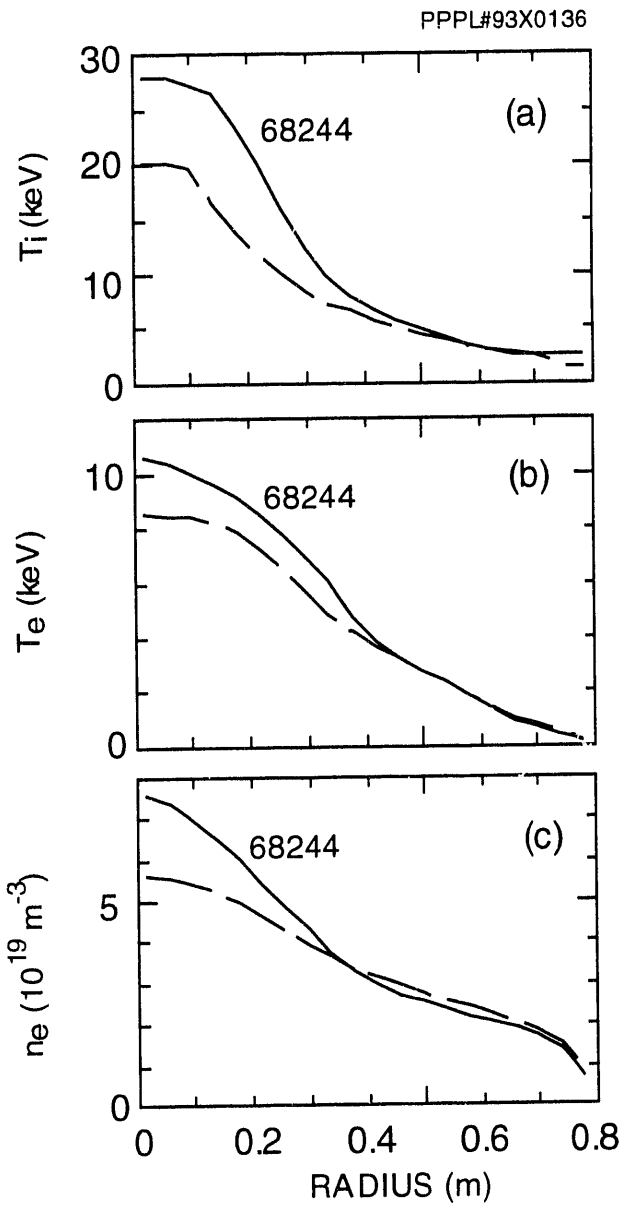

Fig. 4. Radial profiles of n_e, T_e and T_i for shot 68244 with Li pellet injection and comparison shot 68206 with no pellets.

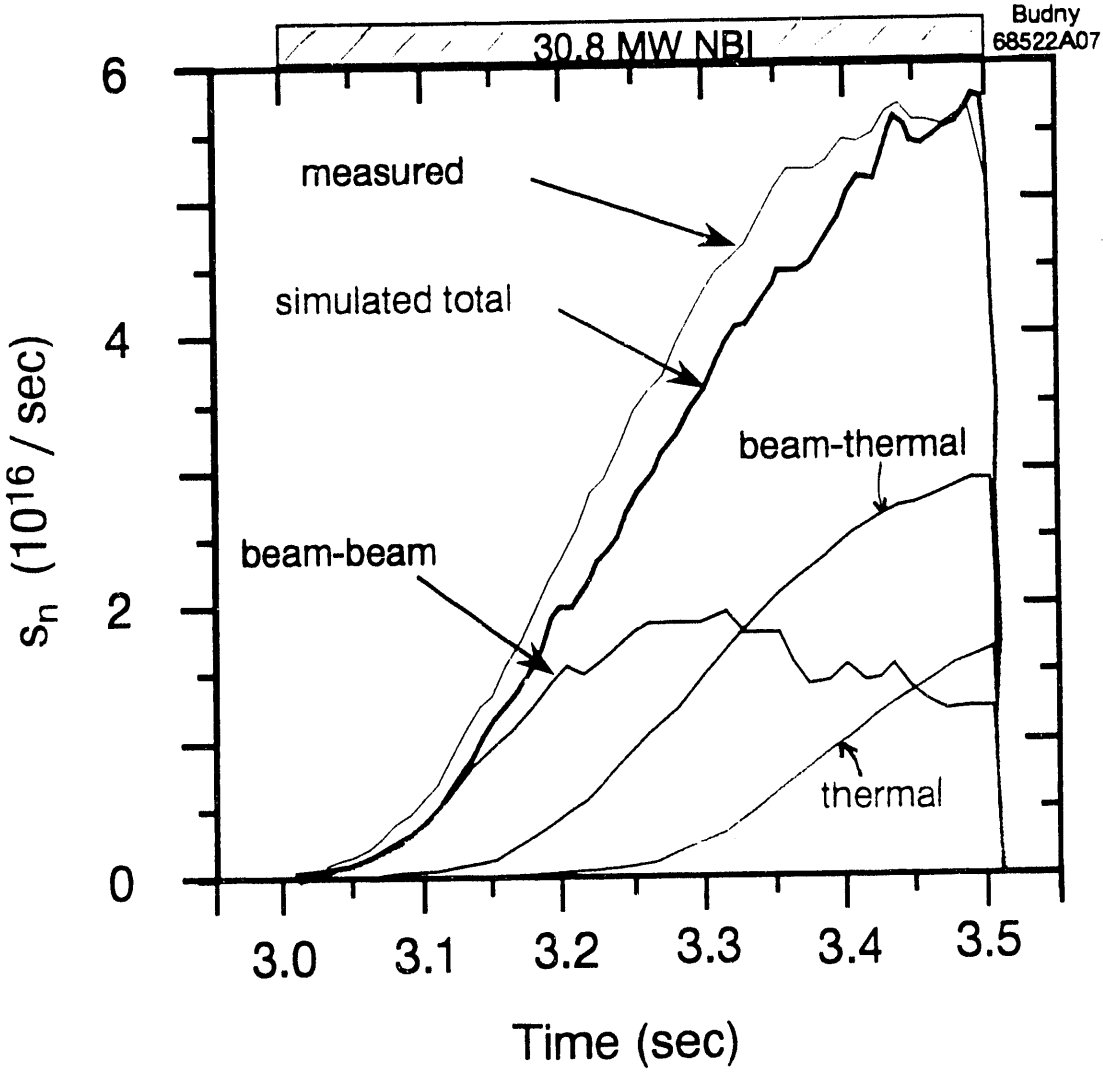

Fig. 5. TRANSP simulation of shot 68522 showing the time dependence of the 3 sources of fusion reactions.

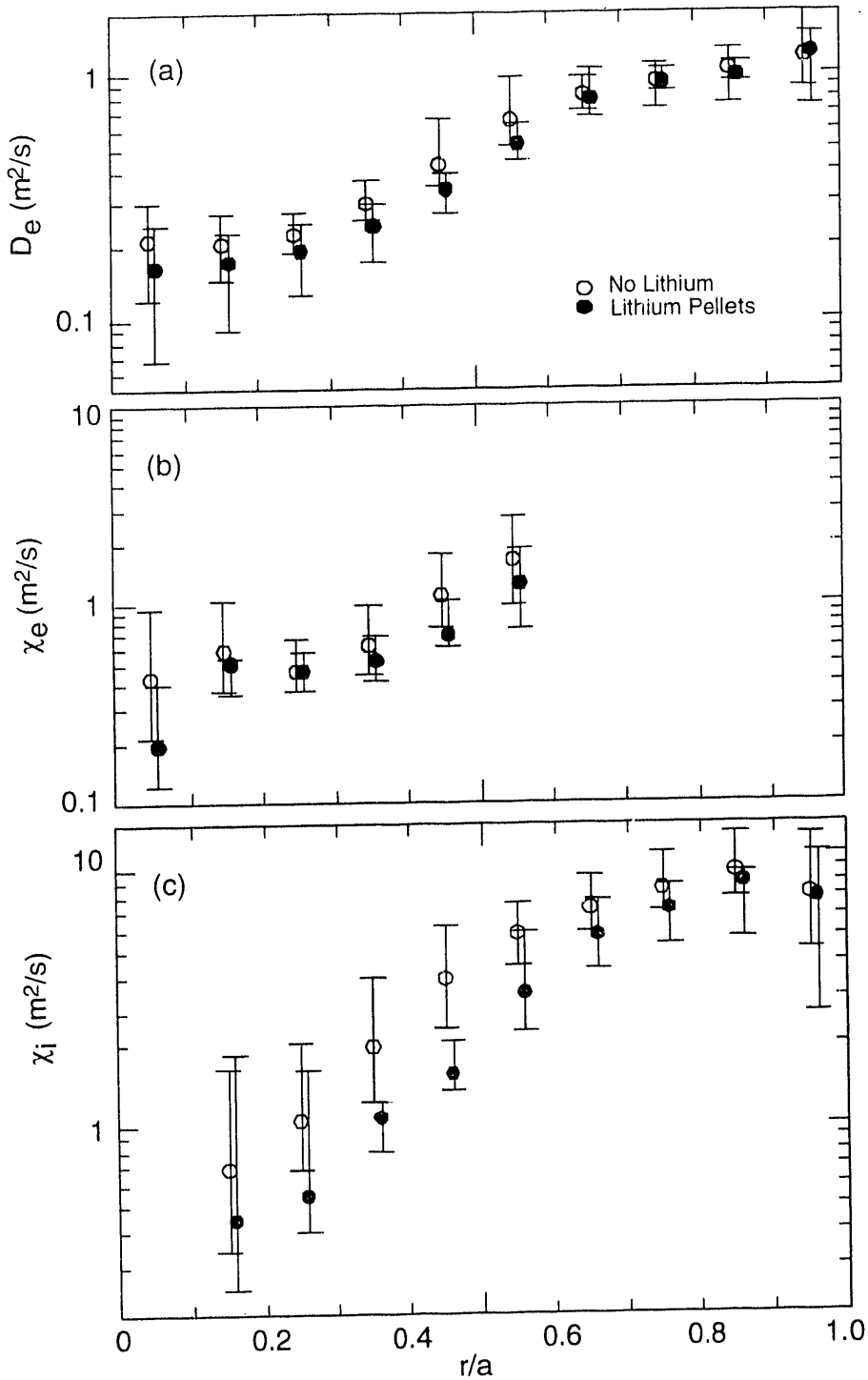

Fig. 6. Median transport coefficients calculated by SNAP for 180 supershots with no Li conditioning and for 5 exceptional shots with Li conditioning.

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