# DEUTERIUM-TRITIUM TFTR PLASMAS IN THE HIGH POLOIDAL BETA REGIME

BY

S.A. SABBAGH, M.E. MAUEL, G.A. NAVRATIL, ET AL.

To be published in the Proceedings of the 15th International Atomic Energy Agency Conference on *Plasma Physics and Controlled Nuclear Fusion Research 1994* (September 26-October 1, 1994, Seville,Spain), to be published by IAEA, Vienna, 1995.

IAEA-CN-60/A-5-I-6



**Work supported by U.S. Department of Energy Contracts DE-FG02-89ER53297, DE-AC02-76CH0-3073, and DE-FG02-90ER54084**



**Princeton University**
**Plasma Physics Laboratory**

# DEUTERIUM-TRITIUM TFTR PLASMAS IN THE HIGH POLOIDAL BETA REGIME*

S. A. Sabbagh†, M. E. Mauel, G. A. Navratil
*Department of Applied Physics, Columbia University, New York, NY USA*

M. G. Bell, C. E. Bush, R. V. Budny, D. S. Darrow, E. D. Fredrickson, B. Grek, R. J. Hawryluk, H. W. Herrmann, A. Janos, D. W. Johnson, L. C. Johnson, B. LeBlanc, D. K. Mansfield, D. C. McCune, K. M. McGuire, D. Mueller, D. K. Owens, H. K. Park, A. T. Ramsey, C. Skinner, E. J. Synakowski, G. Taylor, R. M. Wieland, M. C. Zarnstorff, S. J. Zweben
*Princeton Plasma Physics Laboratory, Princeton, NJ USA*

S. H. Batha, F. M. Levinton
*Fusion Physics and Technology, Inc., Torrance, CA USA*

S. P. Hirshman, D. A. Spong
*Oak Ridge National Laboratory, Oak Ridge, TN USA*

J. Kesner
*Plasma Fusion Center, M.I.T., Cambridge, MA USA*

ABSTRACT

Deuterium-tritium plasmas with enhanced energy confinement and stability have been produced in the high poloidal beta, advanced tokamak regime in TFTR. Confinement enhancement $H \equiv \tau_E/\tau_{E\ ITER-89P} > 4$ has been obtained in a limiter H-mode configuration at moderate plasma current $I_p = 0.85 - 1.46$ MA. By peaking the plasma current profile, $\beta_{N\ dia} \equiv 10^8\langle\beta_{t\perp}\rangle aB_0/I_p = 3$ has been obtained in these plasmas, exceeding the $\beta_N$ limit for TFTR plasmas with lower internal inductance, $l_i$. Fusion power exceeding 6.7 MW with a fusion power gain $Q_{DT} = 0.22$ has been produced with reduced alpha particle first orbit loss provided by the increased $l_i$.

## I. Introduction

The economics of a fusion power plant based on the tokamak concept can be significantly improved if the plasma stability and energy confinement, usually parameterized by the Troyon normalized beta [1], $\beta_N \equiv 10^8\langle\beta_t\rangle aB_0/I_p$, and energy confinement enhancement factor [2], $H \equiv \tau_E/\tau_{E\ ITER-89P}$, could be enhanced. Present reactor design studies [3] show that 50% reductions in the cost of electricity and the capital cost of the plant can be obtained with "advanced tokamak" operation at high $H \leq 4$ and $\beta_N \leq 6$ compared to more conventional tokamak operating parameters. Advanced tokamak plasmas in steady-state operation have been considered in both the ARIES [4] and SSTR [5] designs.

Operation at high poloidal beta, $\beta_p$, has the additional benefit of reduced plasma current, $I_p$, which reduces the requirements for non-inductive current drive, increases the fraction of transport-induced bootstrap current, and reduces the adverse consequences of disruptions. The advantages of this operating regime have been understood for some time and large experimental tokamak programs including TFTR [6], JT-60U [7], and DIII-D [8] have produced and studied high $\beta_p$ plasmas. Operation at high $H$ and $\beta_N$ has been achieved by modifying the plasma current and pressure profiles [6, 9-10], and the shape of the outer boundary [11-12].

Prior to the use of deuterium and tritium (DT) in TFTR, high $\beta_{p\ dia} = 5.9$ (up to the equilibrium limit [13]), $\beta_{N\ dia} = 4.9$, $H \equiv \tau_E/\tau_{E\ ITER-89P} = 3.6$ (with $\beta_{N\ dia} = 4.5$, $H = 3.5$ reached simultaneously) conditions had been obtained in deuterium (D) plasmas at $I_p < 0.5$ MA by actively peaking the current profile and creating a plasma with increased internal inductance, $l_i$ [6]. Here, $\beta_{p\ dia} \equiv 2\mu_o\langle p_\perp\rangle/\langle\langle B_p\rangle\rangle^2$ where $\langle p_\perp\rangle$ is the volume averaged transverse plasma pressure and $\langle\langle B_p\rangle\rangle$ is the line average of the poloidal magnetic field over the outer flux surface. In addition, high $\beta_p$ plasmas with an on-axis safety factor, $q_0 > 2$, and low magnetic field shear in the core had been created with access to the second stability region [14]. Recently, a separate set of experiments has produced plasmas with high $q_0$ exhibiting a reversal in the magnetic field shear and enhanced confinement properties [15]. Similar "high $l_i$" and "high $q_0$" operating scenarios are planned to be produced and studied under steady-state plasma conditions in the proposed Tokamak Physics Experiment [16].

The experiments described in this paper are the first to utilize nominally equal concentrations of D and T in high poloidal beta plasmas in TFTR with current and density profiles optimized for high $\beta_N$ and high $H$. The purpose of these experiments is to demonstrate the ability to produce significant levels of fusion power with these plasmas and to examine the characteristics of these discharges in the presence of DT fusion alpha particles. Both "high $l_i$" and "moderate $q_0$" ($1 \leq q_0 \leq 1.5$) operating scenarios are considered in the present study.

The ability of high $\beta_p$ plasmas to generate significant levels of fusion power at reduced plasma current is illustrated in Fig. 1. Here, the peak DT fusion power, $P_F$, is plotted as a function of $I_p$ for TFTR supershot plasmas with $I_p \geq 1.5$ MA and high $\beta_p$ plasmas at lower $I_p$. Up to 6.7 MW of fusion power was produced in a non-disruptive high $\beta_p$ plasma with auxiliary heating power $P_{tot} = 31$ MW, $I_p = 1.46$ MA, and $q^* \equiv 5(a^2B_0/R_pI_p(\mathrm{MA}))(1+\kappa^2)/2 = 4.7$. This value of $q^*$ is in the range presently being considered in advanced tokamak reactor design studies. The fraction of fusion reactions by thermal ion collisions, beam ion collisions with other beam ions, and beam ion collisions with thermal ions, as computed by the TRANSP code [17] were 34%, 10%, and 56%, respectively. This level of fusion power is 90% of the maximum power produced in a non-disruptive supershot plasma, but at 2/3 of the plasma current.

## II. Experimental parameters

The increase in $l_i$ required to produce high $\beta_N$ plasmas in TFTR was produced by rapidly decreasing the plasma current from $I_p = 1.65 - 2.5$ MA to $0.85 - 1.46$ MA in a deuterium plasma with toroidal field $B_t = 4.6 - 5.1$ T and major radius $R_p = 2.45 - 2.6$ m during a period of neutral beam injection (NBI) in the co-direction (Fig. 2a). Addition of counter-injected beams later in the discharge produced the desired power level $P_{tot} = 16 - 31$ MW with a nominally equal number of D and T sources. The fraction of $P_{tot}$ due to injected tritium neutral beam power was in the range 0.45 - 0.72. Electron and ion temperatures reached 11 keV and 35 keV respectively with peak electron densities of up to $8\times10^{19}$ m$^{-3}$. Non-inductive current of up to 55% has been computed by TRANSP at $I_p = 1.46$ MA with a 35% contribution from the bootstrap current. The thermal plasma comprised 65% of the total stored energy in the highest density plasmas. Determination of the $q$ profile using motional Stark effect (MSE) measurements of the magnetic field pitch angle indicate that $q_0 \leq 1$ for plasmas with $I_p \geq 1$ MA.

High $\beta_p$ DT plasmas with moderate $q_0$, $I_p = 0.85$ MA, $R_p = 2.6$ m, and $P_{tot} \leq 17$ MW were produced in a manner similar to that described above to test the recent theoretical result [18] indicating that the alpha particle driven toroidal Alfven eigenmode (TAE) [19] can be destabilized if $q_0$ could be raised to a value between 1.2 and 1.5. In this case, $\beta_{p\ dia} = 2.9$, $\beta_{N\ dia} = 2.8$, H = 4.2, and $P_F = 1.8$ MW were attained and preliminary equilibrium modelling using MSE data shows $q_0 = 1.4$.

Advanced tokamak operation in DT produced a relatively large alpha particle beta, $\beta_\alpha$, for a given plasma current. The on-axis value, $\beta_{\alpha 0}$, of $1.6\times10^{-3}$ was computed by TRANSP for the $I_p = 1.2$ MA DT plasma shown in Fig. 2. This value is the same as has been obtained in a DT supershot plasma with $I_p = 1.8$ MA. At $I_p = 1.2$ MA, the $\beta_\alpha$ profile is slightly broader. A $\beta_{\alpha 0}$ of $2.5\times10^{-3}$ was generated in the plasma with $P_F = 6.7$ MW. The plasma at moderate $q_0$ had a peak $\beta_{\alpha 0} = 0.9\times10^{-3}$.

## III. Enhanced confinement and the DT limiter H-mode

Producing enhanced energy confinement involved a reduction in particle recycling. This was obtained in both D and DT plasmas when the discharge made a transition to a limiter H-mode [20], or by lithium pellet conditioning [21] of the limiter. Limiter conditioning has allowed $\tau_E$ at $I_p > 1$ MA to reach a value of 0.2 s at 1.5 MA. This is a significant improvement compared to the maximum value of $\tau_E$ = 0.14 s reached before the use of Li pellets in high $\beta_p$ plasmas [22]. Similar increases in $\tau_E$ have been observed in sequences of D plasmas which utilize Li conditioning before and/or after NBI. The greatest improvements were obtained when pellets were injected before NBI. The combination of limiter conditioning, operation using DT, and transition to a limiter H-mode has produced a maximum value of $\tau_E = 0.26$s.

The general characteristics of edge localized modes (ELMs), precursor MHD activity to $\beta$-collapse, and disruptions are similar in D and DT plasmas. High frequency "grassy" ELMs occur in low power H-mode discharges, while large amplitude, low frequency (~40 Hz in Fig. 2) "giant" ELMs are more likely to occur in DT plasmas with relatively broad pressure profiles and high $\beta_N$. DT H-mode plasmas exhibit an earlier transition time, a longer ELM-free phase, and a greater drop in $D_\alpha$ light when compared to equivalent D plasmas.

*Transitions to the high $\beta_p$ H-mode in equivalent D and DT plasmas are* shown in Fig. 2 (c-e). While a significant increase in $\tau_E$ was observed in the D plasma during the MHD quiescent "ELM-free" phase of the H-mode, a greater increase (of approximately 40%) was observed in the DT plasma [23] and an $H$ factor of 4.3 (using an average isotopic mass of 2.3) was attained. This improvement was transient, since the onset of the first ELM caused a decrease in $\tau_E$. However, a recovery of enhanced energy confinement was observed during the relaxation period of the ELMs.

Since transition to the H-mode occurred during the initial rise of the plasma stored energy during NBI, the plasma density and temperature increased up to the onset time of the first ELM. However, while the edge electron temperature and density steadily increased, the edge $T_i$ displayed a more rapid increase in both DT and D plasmas at the time of the H-mode transition (Fig. 2(e)). At this time, the effective ion thermal diffusivity, $\chi_{i\,tot} \equiv -q_i/n_{i\,th} \nabla T_i$ as computed by TRANSP decreased in both DT and D comparison plasmas (Fig. 3). Here, $q_i$ is the ion heat flux, and $n_{i\,th}$ is the thermal ion density. A larger change in $T_i$ and $\chi_{i\,tot}$ occurred in DT plasmas as compared to equivalent D discharges.

After the onset of ELMs, the increase in both the edge temperature and density ceased. The edge $T_e$ decreased during an ELM burst but recovered its original value before the next ELM burst. In addition, the edge $T_i$ in DT plasmas decreased to the value reached in the equivalent D plasma. This matching of the $T_i$ profile, which appeared to be caused by the ELMs, generally extended from the plasma edge to a normalized minor radius $r/a = 0.65$.

The range of $H$ and $\beta_N$ achieved during the DT phase of TFTR operation is shown in Fig. 4. The highest values of $H$ (up to 4.5) were reached transiently during the ELM-free H-mode phase, during which time $(dW_{tot}/dt)/P_{NBI}$ was maximized (exceeding 40% in some discharges). While the largest value of $H$ occurred in a D plasma at $I_p = 1$ MA, DT plasmas produced the larger $H$ at equal $P_{tot}$ and $I_p$. Also indicated in Fig. 4 are the values of $\beta_N$ and $H$ for some plasmas at the time of maximum $\beta_N$ (where $dW_{tot}/dt = 0$). The high $\beta_p$ plasma with the highest fusion power output, $P_F = 6.7$ MW reached during the ELMing phase of the discharge, had $H = 3.1$ and $\beta_{N\,dia} = 3$.

## IV. Stability

Plasma stability limited the improvement in $\tau_E$ for plasmas with high $H$ factor. The first high $\beta_p$ DT experiments were concentrated on reaching enhanced performance while simultaneously minimizing the probability of major disruptions. Based on results from prior D plasma operation, the $\beta_{N\,dia}$ stability limit was determined for a given plasma current time history, and a value of $\beta_{N\,dia}$ 15% below this limit was chosen as a target value for DT operation. This technique was almost entirely successful. Out of 134 discharges in which neutral beams were injected, only 3 major disruptions were produced, each one occurring *below* the reduced target value of $\beta_{N\,dia}$. Two of these disruptions occurred in D plasmas for which the electron density profile peakedness, $F_{N_e} \equiv n_e(0)/\langle n_e \rangle_{volume}$ became excessively large. This observation of a reduced $\beta_N$ limit at increased density peakedness is consistent with ideal MHD stability analyses of $n = 1$ kink/ballooning modes performed for TFTR deuterium plasmas [22]. The result of these calculations showed that the increase in $\beta_{N\,dia}$ observed in plasmas with increased internal inductance can be eliminated by increased peaking of the plasma pressure profile. The excessive density peaking was created by excessive limiter conditioning using Li. This conditioning typically caused a reduction of particle recycling that allowed increased neutral beam penetration and caused $F_{N_e}$ to rise (with a corresponding increase in $\tau_E$). The disruptions that occurred below the target value of $\beta_{N\,dia}$ had $F_{N_e} = 3.4$, while a more common value for high $\beta_p$ plasmas is 2.5.

The peakedness of the DT neutron source strength as measured with a neutron collimator (an indicator of the pressure profile peakedness) was found to be a useful diagnostic in examining the MHD stability. DT plasmas either disrupted or suffered a $\beta$-collapse when the neutron profile peakedness rapidly increased to a value of $P_{S_N} \equiv S_N(0)/\langle S_N\rangle_{volume} \sim 10$ (Fig. 5). Such large values of $P_{S_N}$ were obtained only with DT operation or Li pellet injection. These $\beta$-limiting events occurred at $\beta_N$ less than the observed disruptive limit of D plasmas with less peaked pressure profiles.

A "secondary ballooning instability" [24] was clearly observed as a precursor to the DT disruption and the toroidally localized nature of this mode was established by observing $T_e$ fluctuations at two distinct toroidal locations. Details of this instability can be found in a companion paper by Fredrickson, *et al.* [25].

Alpha-driven TAE instabilities have not yet been observed in high $\beta_p$ DT plasmas. TAE mode stability analysis of plasmas with high $l_i$ and $q_0 \lesssim 1$ is consistent with this observation. The $\beta_{\alpha 0}$ required to drive the least stable toroidal mode number, $n$, was computed to be $9.0\times10^{-3}$ for the $n = 4$ mode in the DT plasma shown in Fig. 2. This level is 5.6 times greater than the peak $\beta_{\alpha 0}$ reached in this discharge. High $\beta_p$ plasmas at moderate $q_0$ that were also observed to be stable are computed to be stable, but have $\beta_{\alpha 0}$ significantly closer to the unstable boundary. Preliminary analysis of the DT plasma with $q_0 = 1.4$ yields an instability threshold of $\beta_{\alpha 0} = 2.1\times10^{-3}$ for the $n = 1$ mode, which is a factor of 2.2 larger than the peak $\beta_{\alpha 0}$ generated in this discharge.

## V. Alpha Particle Confinement

Confinement of alpha particles in high poloidal beta plasmas appears to be classical and large losses due to collective effects have not been observed. The alpha particle loss fraction does not increase as the fusion reactivity increases (Fig. 6). High poloidal beta plasmas with $I_p = 1.5$ MA and higher plasma internal inductance experience alpha loss similar to 2.0 MA supershot plasmas with a lower plasma internal inductance. Due to the peaked current profile produced in the high $\beta_p$ plasmas, first orbit losses are less than in a plasma with lower $l_i$ and equal $I_p$. Modelling of experimental DT plasmas using TRANSP shows that at $I_p = 1$ MA, 17% of the alpha particles are lost with $l_i = 2.2$ as opposed to 34% with $l_i = 1.2$.

The ELMs also have a small but measurable effect on the DT fusion alpha particle loss. The alpha particle detector mounted at a poloidal position 90° below the outboard midplane of the torus measured a fluctuation in amplitude of less than

10%, approximately in phase with the ELM bursts. The detector mounted at 45° below the outboard midplane showed a 15% fluctuation that was out of phase with the ELM bursts. This modest poloidal redistribution of particle loss may be important for ITER, in which even a few percent loss of the alpha particle population could damage first wall components.

## VI. Conclusion

The initial TFTR DT experiments performed in the high $\beta_p$ "advanced tokamak" regime have begun to address issues important to future tokamak reactors designed to operate in this regime. Significant fusion power production (6.7 MW) has been demonstrated at $\beta_{N\ dia} = 3$, $H = 3.1$, and $q^* = 4.7$ with a central fusion power density (1.6 $MW/m^3$) at the level of the present ITER design (1.7 $MW/m^3$). In these plasmas, peaking the current profile allowed fusion power production similar to supershot plasmas, but at 2/3 of the plasma current. Operation with DT produced an increase in $\tau_E$ of approximately 40% in an enhanced limiter H-mode. Confinement of alpha particles was classical, with no large loss due to collective effects. Alpha particle losses due to ELMs are small, but are at a level that may be significant to the operation of ITER. The alpha particle driven TAE has not been observed to date in these plasmas. DT plasmas with high $l_i$ and $q_0 \leq 1$ are computed to have an adequate margin against TAE instability. However, plasmas at moderate $q_0$ might encounter TAE instability at higher $P_{tot}$ since TFTR DT plasmas are presently about a factor of two below the computed instability boundary. Future experiments are planned to test the TAE thresholds at $q_0 \sim 1.4$ by increasing $\beta_{\alpha 0}$ in these plasmas.

---

* *Supported by US DoE Contracts DE-FG02-89ER53297, DE-AC02-76-CH03073, and DE-FG02-90ER54084.*

† *Present address: Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ 08543, USA*

[1] F. Troyon, *et al.*, Phys. Lett. **110A** (1985) 29.
[2] P. N. Yushmanov, *et al.*, Nuclear Fusion **30** (1990) 1999.
[3] R. J. Goldston, *et al.*, European Physical Society Meeting, Montpellier, June 1994, and references therein; L. J. Perkins, *et. al.*, submitted to Nuclear Fusion.
[4] F. Najmabadi, *et al.*, in Proceedings of the 13th International Symposium on Fusion Engineering, Knoxville (1989) 1021.
[5] M. Kikuchi, *et al.*, Nuclear Fusion **30** (1991) 265.
[6] S. A. Sabbagh, *et al.*, Phys. Fluids *B* **3** (1991) 2277.
[7] S. Ishida, *et al.*, Plasma Phys. and Contr. Nucl. Fus. Res., **1** (1993) 219.
[8] P. Politzer, *et al.*, Phys. Plasmas **1** (1994) 1545.
[9] J. R. Ferron, *et al.*, Phys. Fluids B **5** (1993) 2532.
[10] Y. Kamada, *et al.*, "Noninductively Current Driven H-mode with High and High values in JT-60U", submitted to Nucl. Fusion.
[11] G. A. Navratil, *et al.*, Plasma Phys. and Contr. Nucl. Fus. Res., **1** (1991) 209.
[12] L. L. Lao, *et al.*, Phys. Rev. Lett. **70** (1993) 3435.
[13] M. E. Mauel, *et al.*, Nuclear Fusion **32** (1992) 1468.
[14] S. A. Sabbagh, *et al.*, Bull. Am. Phys. Soc. **38** (1993) 1984.

[15] F. M. Levinton, *et al.*, Americal Physical Society Division of Plasma Physics meeting (1994); R. J. Goldston, *et al.*, European Physical Society Meeting, Montpellier, June 1994.
[16] G. H. Neilson, *et al.*, in Proceedings of the 11th Topical Meeting on the Technology of Fusion Energy, 1994, to be published in Fusion Technology.
[17] R. J. Goldston, *et al.*, J. Comput. Phys. **43** (1981) 61.
[18] ~~D. A. Spong, *et al.*, these proceedings, paper~~ IAEA-CN-60/D-P-II-3.
[19] C. Z. Cheng, *et al.*, Ann. Phys. **161** (1985) 21.
[20] C. E. Bush, *et al.*, Phys. Rev. Lett. **65** (1990) 424.
[21] J. Snipes, *et al.*, J. Nucl. Mater. **196-198** (1992) 686.
[22] M. E. Mauel, *et al.*, Plasma Phys. Contr. Nucl. Fus. Res., **1** (1993) 205.
[23] C. E. Bush, *et al.*, 21st EPS Conference on Controlled Fusion and Plasma Physics, Montpellier, 1994.
[24] Y. Nagayama, S. A. Sabbagh, J. Manickam, *et al.*, *Phys. Rev. Lett.* **69** (1992) 2376; M. N. Bussac and R. Pellat, *Phys. Rev. Lett.* **59** (1987) 2650.
[25] E. D. Fredrickson, *et al.*, these proceedings, paper A-2-II-5.

# Figure Captions

Fig. 1. DT fusion power vs. plasma current for TFTR high $\beta_p$ and supershot plasmas

Fig. 2. Time history waveforms for a high $\beta_p$ DT H-mode plasma and comparison to an equivalent D discharge. Shown in this figure are a) the plasma current, plasma internal inductance, and neutral beam heating, b) diamagnetic normalized beta and DT fusion power c) Energy confinement enhancement factor and confinement time, d) $D_\alpha$ emission, e) edge ion temperature.

Fig. 3. Reduction in $\chi_{i\ tot}$ for the DT and D plasmas shown in Fig. 2 before the H-mode transition and during the ELM-free H-mode phase. The largest change was observed during the ELM-free phase of DT H-mode plasmas at a normalized minor radius $r/a \geq 0.5$.

Fig. 4. Range of $\beta_N$ and $H$ reached by high $\beta_p$ plasmas during the DT phase. The different symbols indicate varying $I_p$. The majority of the data shown was taken at the time of peak $H$. The data shown by the arrow was taken at the time of peak $\beta_N$. Solid or bold symbols indicate a plasma in which DT was used. None of the plasmas represented terminated in disruption.

Fig. 5. Time evolution of DT neutron peakedness in plasmas of varying MHD stability. Plasma with $P_{S_N} \sim 10$ encountered major and minor disruptions at reduced $\beta_{N\ dia}$. Plasmas with lower peakedness were stable at greater than 90% of the anticipated $\beta_{N\ dia}$ limit.

Fig. 6. Alpha particle loss as a function of DT neutron reactivity in high performance TFTR plasma regimes.

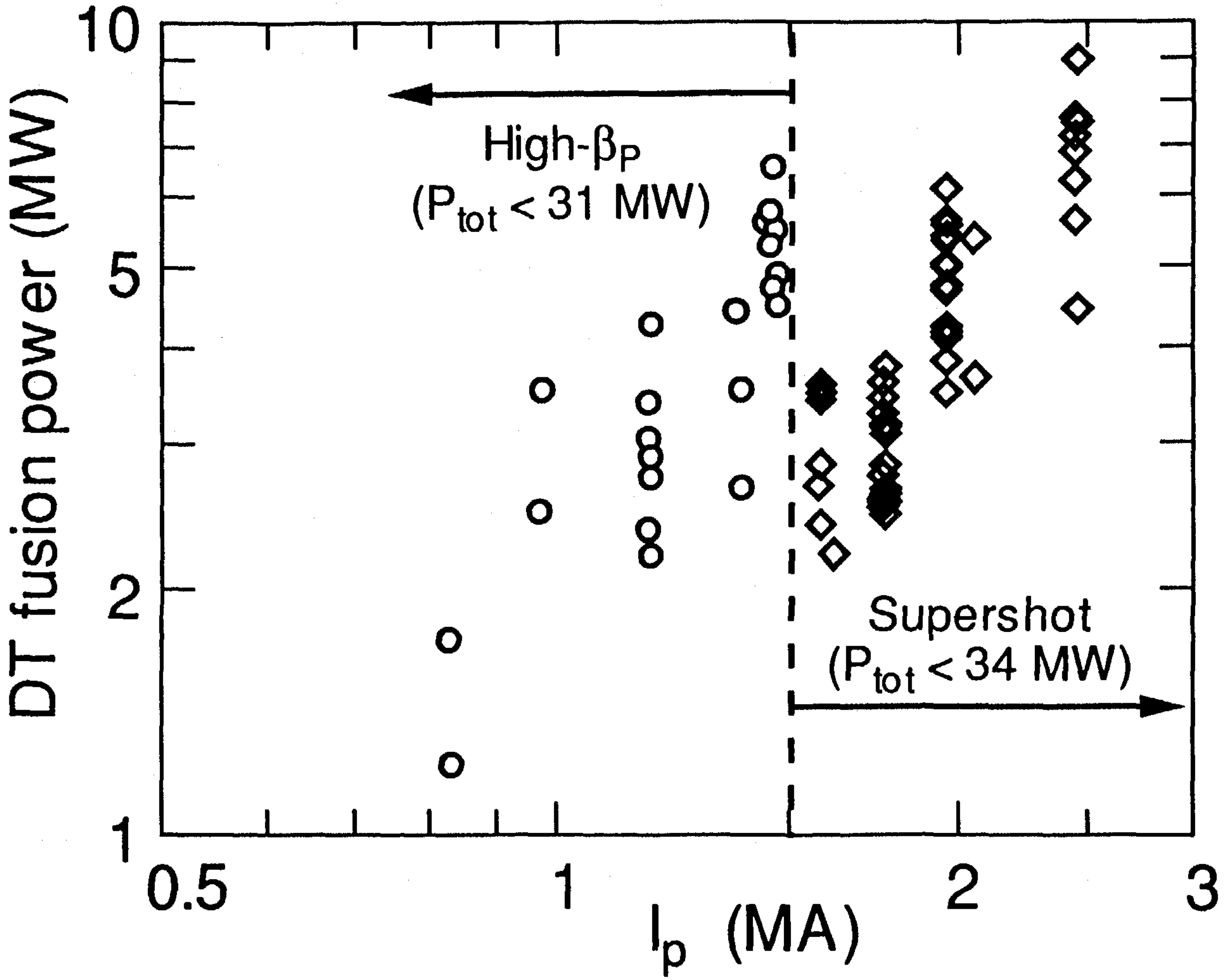
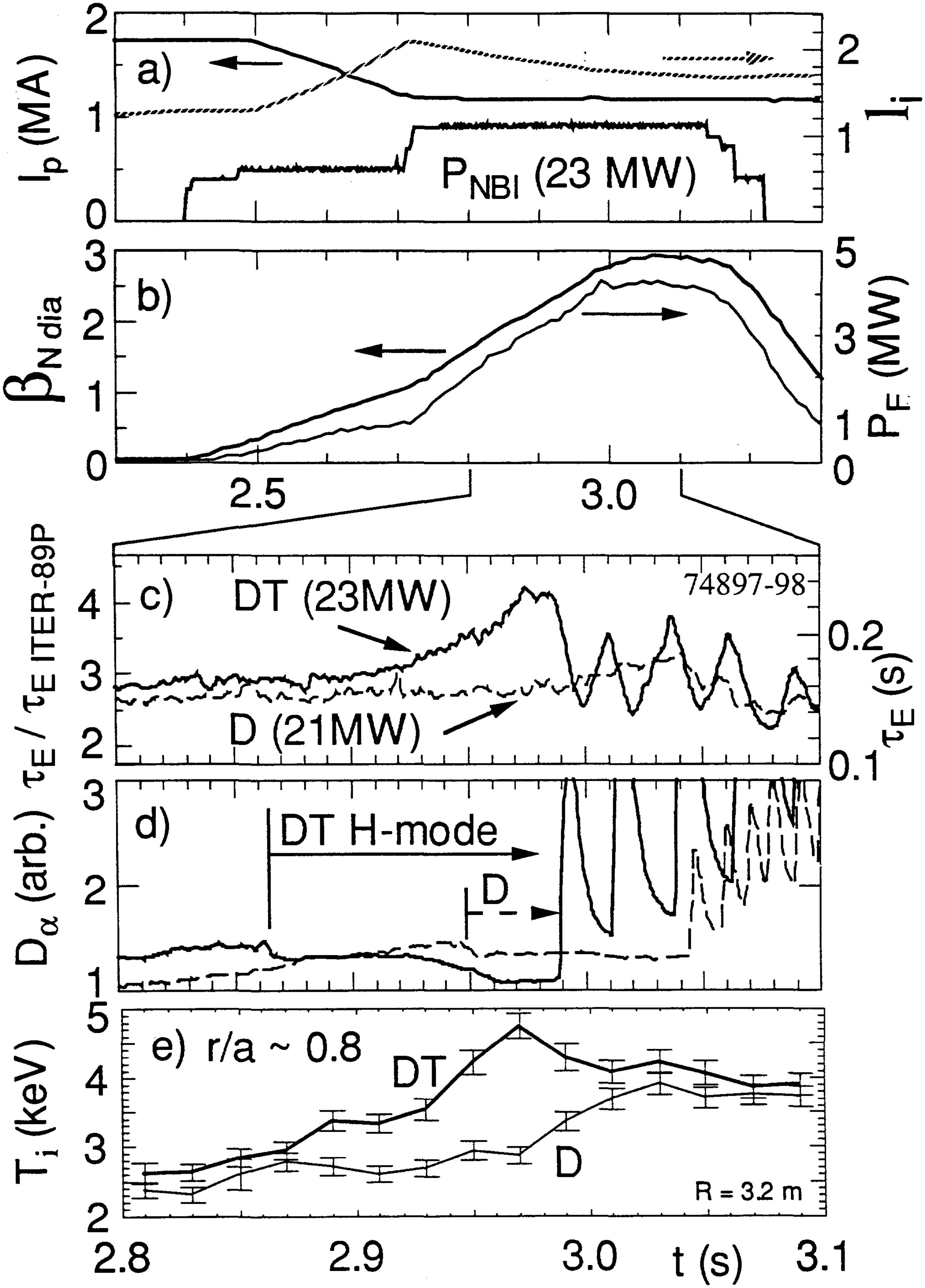
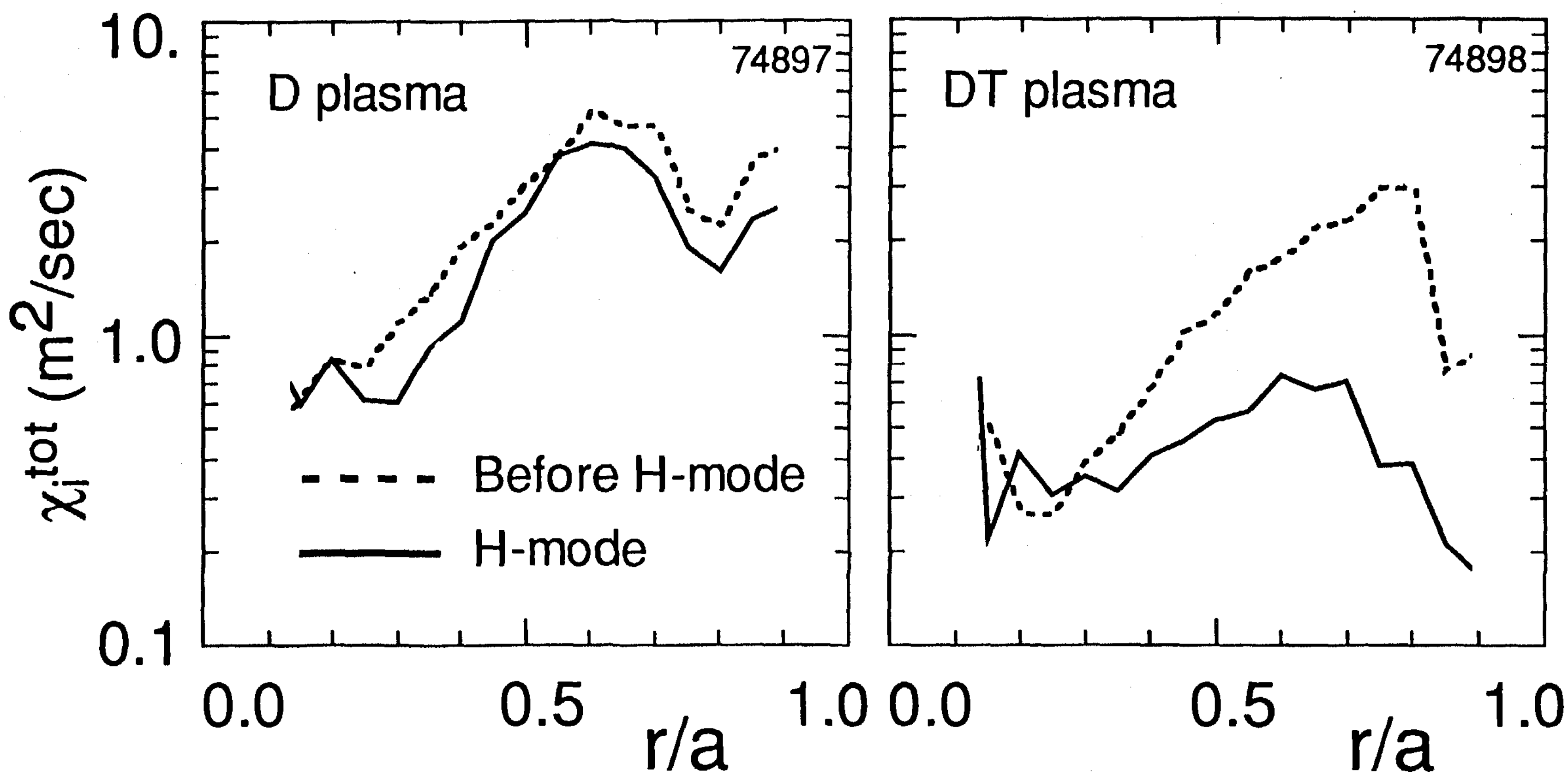

DT fusion power (MW)
10
5
2
1
0.5
1
2
3
$I_p$ (MA)
High-$\beta_P$
($P_{tot}$ < 31 MW)
Supershot
($P_{tot}$ < 34 MW)

Fig. 1

Fig. 2



a)
$I_p$ (MA)
$l_i$
$P_{NBI}$ (23 MW)
b)
$\beta_{N\,dia}$
$P_F$ (MW)
2.5
3.0
c)
$\tau_E / \tau_{E\ ITER\text{-}89P}$
$\tau_E$ (s)
DT (23MW)
D (21MW)
74897-98
d)
$D_\alpha$ (arb.)
DT H-mode
D
e) r/a ~ 0.8
$T_i$ (keV)
DT
D
R = 3.2 m
2.8
2.9
3.0
3.1
t (s)



10.
1.0
0.1
$\chi_i^{tot}$ (m$^2$/sec)
D plasma
74897
Before H-mode
H-mode
0.0
0.5
1.0
r/a
DT plasma
74898
0.0
0.5
1.0
r/a


Fig. 3

Fig. 4

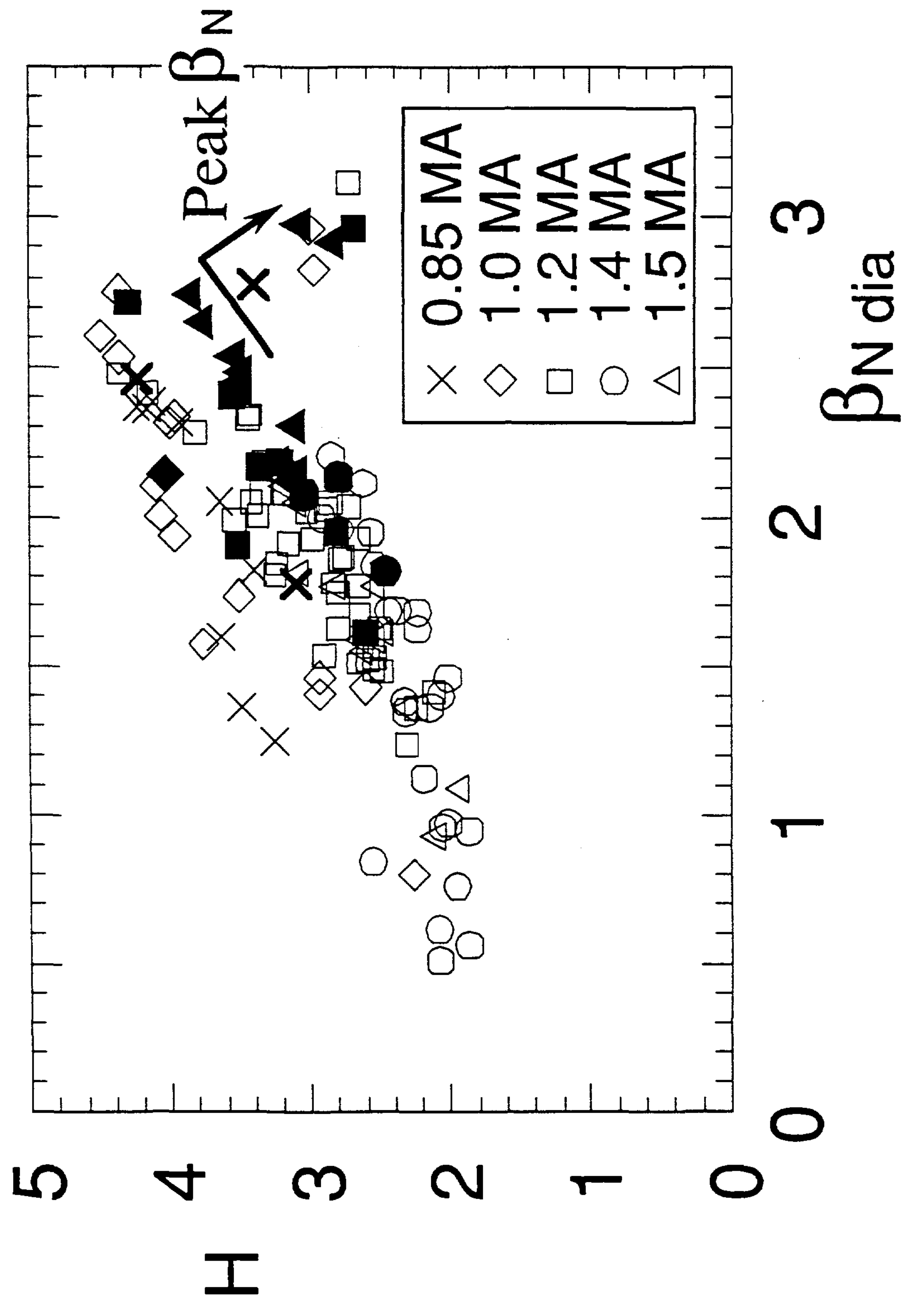
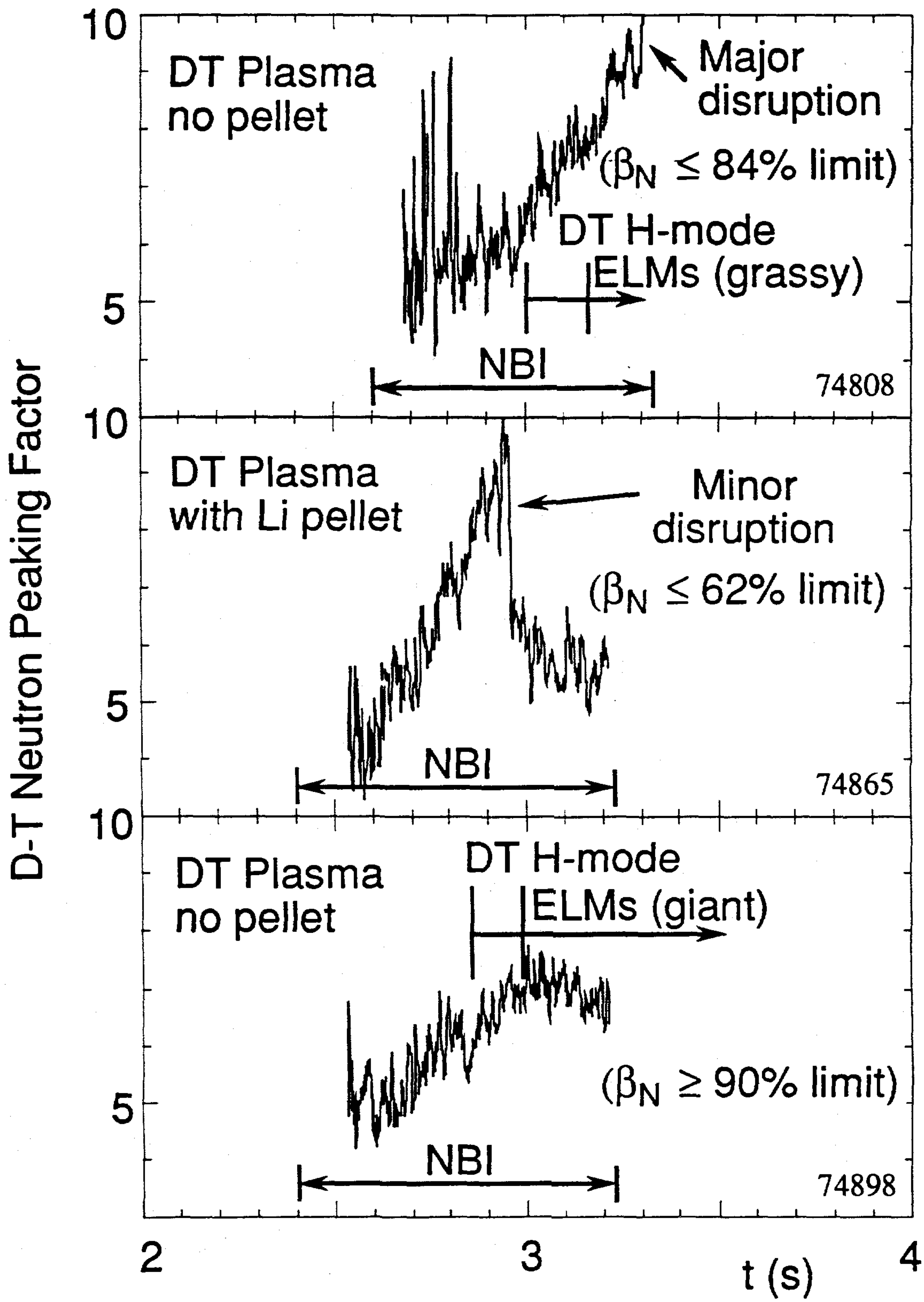


Fig. 5


D-T Neutron Peaking Factor
10
5
DT Plasma
no pellet
Major
disruption
($\beta_N \leq 84\%$ limit)
DT H-mode
ELMs (grassy)
NBI
74808
10
5
DT Plasma
with Li pellet
Minor
disruption
($\beta_N \leq 62\%$ limit)
NBI
74865
10
5
DT Plasma
no pellet
DT H-mode
ELMs (giant)
($\beta_N \geq 90\%$ limit)
NBI
74898
2
3
4
t (s)

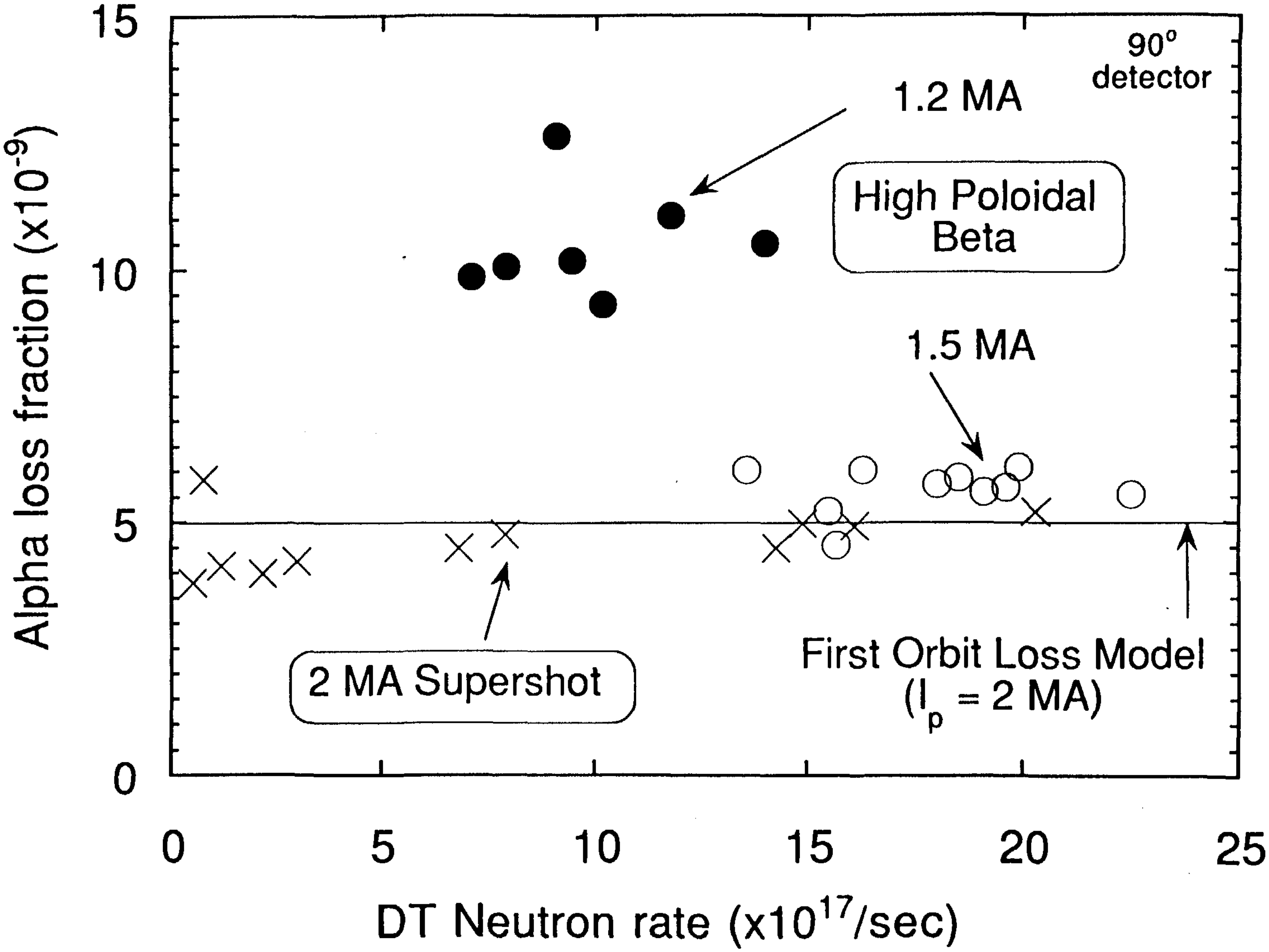

90°
detector
1.2 MA
High Poloidal Beta
1.5 MA
2 MA Supershot
First Orbit Loss Model
($I_p$ = 2 MA)
Alpha loss fraction ($\times 10^{-9}$)
DT Neutron rate ($\times 10^{17}$/sec)
0
5
10
15
20
25

Fig. 6

EXTERNAL DISTRIBUTION IN ADDITION TO UC-420

Dr. F. Paoloni, Univ. of Wollongong, AUSTRALIA
Prof. R.C. Cross, Univ. of Sydney, AUSTRALIA
Plasma Research Lab., Australian Nat. Univ., AUSTRALIA
Prof. I.R. Jones, Flinders Univ, AUSTRALIA
Prof. F. Cap, Inst. for Theoretical Physics, AUSTRIA
Prof. M. Heindler, Institut für Theoretische Physik, AUSTRIA
Prof. M. Goossens, Astronomisch Instituut, BELGIUM
Ecole Royale Militaire, Lab. de Phy. Plasmas, BELGIUM
Commission-European, DG. XII-Fusion Prog., BELGIUM
Prof. R. Boucique, Rijksuniversiteit Gent, BELGIUM
Dr. P.H. Sakanaka, Instituto Fisica, BRAZIL
Prof. Dr. I.C. Nascimento, Instituto Fisica, Sao Paulo, BRAZIL
Instituto Nacional De Pesquisas Espaciais-INPE, BRAZIL
Documents Office, Atomic Energy of Canada Ltd., CANADA
Ms. M. Morin, CCFM/Tokamak de Varennes, CANADA
Dr. M.P. Bachynski, MPB Technologies, Inc., CANADA
Dr. H.M. Skarsgard, Univ. of Saskatchewan, CANADA
Prof. J. Teichmann, Univ. of Montreal, CANADA
Prof. S.R. Sreenivasan, Univ. of Calgary, CANADA
Prof. T.W. Johnston, INRS-Energie, CANADA
Dr. R. Bolton, Centre canadien de fusion magnétique, CANADA
Dr. C.R. James,, Univ. of Alberta, CANADA
Dr. P. Lukác, Komenského Universzita, CZECHO-SLOVAKIA
The Librarian, Culham Laboratory, ENGLAND
Library, R61, Rutherford Appleton Laboratory, ENGLAND
Mrs. S.A. Hutchinson, JET Library, ENGLAND
Dr. S.C. Sharma, Univ. of South Pacific, FIJI ISLANDS
P. Mähönen, Univ. of Helsinki, FINLAND
Prof. M.N. Bussac, Ecole Polytechnique,, FRANCE
C. Mouttet, Lab. de Physique des Milieux Ionisés, FRANCE
J. Radet, CEN/CADARACHE - Bat 506, FRANCE
Prof. E. Economou, Univ. of Crete, GREECE
Ms. C. Rinni, Univ. of Ioannina, GREECE
Preprint Library, Hungarian Academy of Sci., HUNGARY
Dr. B. DasGupta, Saha Inst. of Nuclear Physics, INDIA
Dr. P. Kaw, Inst. for Plasma Research, INDIA
Dr. P. Rosenau, Israel Inst. of Technology, ISRAEL
Librarian, International Center for Theo Physics, ITALY
Miss C. De Palo, Associazione EURATOM-ENEA , ITALY
Dr. G. Grosso, Istituto di Fisica del Plasma, ITALY
Prof. G. Rostangni, Istituto Gas Ionizzati Del Cnr, ITALY
Dr. H. Yamato, Toshiba Res & Devel Center, JAPAN
Prof. I. Kawakami, Hiroshima Univ., JAPAN
Prof. K. Nishikawa, Hiroshima Univ., JAPAN
Librarian, Naka Fusion Research Establishment, JAERI, JAPAN
Director, Japan Atomic Energy Research Inst., JAPAN
Prof. S. Itoh, Kyushu Univ., JAPAN
Research Info. Ctr., National Instit. for Fusion Science, JAPAN
Prof. S. Tanaka, Kyoto Univ., JAPAN
Library, Kyoto Univ., JAPAN
Prof. N. Inoue, Univ. of Tokyo, JAPAN
Secretary, Plasma Section, Electrotechnical Lab., JAPAN
Dr. O. Mitarai, Kumamoto Inst. of Technology, JAPAN
Dr. G.S. Lee, Korea Basic Sci. Ctr., KOREA
J. Hyeon-Sook, Korea Atomic Energy Research Inst., KOREA
D.I. Choi, The Korea Adv. Inst. of Sci. & Tech., KOREA
Prof. B.S. Liley, Univ. of Waikato, NEW ZEALAND
Inst of Physics, Chinese Acad Sci PEOPLE'S REP. OF CHINA
Library, Inst. of Plasma Physics, PEOPLE'S REP. OF CHINA
Tsinghua Univ. Library, PEOPLE'S REPUBLIC OF CHINA
Z. Li, S.W. Inst Physics, PEOPLE'S REPUBLIC OF CHINA
Prof. J.A.C. Cabral, Instituto Superior Tecnico, PORTUGAL
Prof. M.A. Hellberg, Univ. of Natal, S. AFRICA
Prof. D.E. Kim, Pohang Inst. of Sci. & Tech., SO. KOREA
Prof. C.I.E.M.A.T, Fusion Division Library, SPAIN
Dr. L. Stenflo, Univ. of UMEA, SWEDEN
Library, Royal Inst. of Technology, SWEDEN
Prof. H. Wilhelmson, Chalmers Univ. of Tech., SWEDEN
Centre Phys. Des Plasmas, Ecole Polytech, SWITZERLAND
Bibliotheek, Inst. Voor Plasma-Fysica, THE NETHERLANDS
Asst. Prof. Dr. S. Cakir, Middle East Tech. Univ., TURKEY
Dr. V.A. Glukhikh,Sci. Res. Inst. Electrophys.l Apparatus, USSR
Dr. D.D. Ryutov, Siberian Branch of Academy of Sci., USSR
Dr. G.A. Eliseev, I.V. Kurchatov Inst., USSR
Librarian, The Ukr.SSR Academy of Sciences, USSR
Dr. L.M. Kovrizhnykh, Inst. of General Physics, USSR
Kernforschungsanlage GmbH, Zentralbibliothek, W. GERMANY
Bibliothek, Inst. Für Plasmaforschung, W. GERMANY
Prof. K. Schindler, Ruhr-Universität Bochum, W. GERMANY
Dr. F. Wagner, (ASDEX), Max-Planck-Institut, W. GERMANY
Librarian, Max-Planck-Institut, W. GERMANY