CHARACTERISTICS OF CONFINEMENT AND FUSION REACTIVITY IN JT-60U HIGH-β_P AND TFTR SUPERSHOT REGIMES WITH DEUTERIUM NEUTRAL BEAM INJECTION

BY

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ABSTRACT

The high performance regimes achieved in JT-60U and TFTR have produced peak DD fusion neutron rates up to 5.6 x 10^{16}/s for similar heating beam powers, in spite of considerable differences in machine operation and plasma configuration. A common scaling for the DD fusion neutron rate ($S_{DD} \propto P_{abs}^{2.0} H_{ne} V_p^{-0.9}$) is obtained, where P_{abs} and H_{ne} are the absorbed beam power and beam fueling peaking factor, respectively, and V_p is the plasma volume. The maximum stored energy obtained in each machine has been up to 5.4 MJ in TFTR and 8.7 MJ in JT-60U. Further improvements in the fusion neutron rate and the stored energy are limited by the β-limit in Troyon range, $\beta_N \sim 2.0 - 2.5$. A common scaling for the stored energy ($W_{tot} \propto P_{abs} V_p H_{ne}^{0.2}$) is also proposed.

1. INTRODUCTION

For an economically attractive tokamak fusion reactor, a centrally peaked profile of the plasma pressure is desirable to minimize the plasma energy for a given fusion power output and to maintain a large, useful bootstrap current component. Such profiles have been consistently obtained with intense neutral beam injection (NBI) in TFTR supershot [1] and JT-60U high-β_p [2] regimes. In both devices, peak ion and electron temperatures of 35-41 keVand 10-13 keV, respectively, have been achieved. The peak central electron density was ~7.5 x 10^{19} m^{-3} in JT-60U and ~9.5 x 10^{19} m^{-3} in TFTR. The maximum density peaking factors F_{ne} (= $n_e(0)/\langle n_e \rangle$) were greater than 3 in both regimes. Energy confinement times were up to 3 times the prediction of L-mode scaling with deuterium NBI powers up to ~30 MW. Recently deuterium and tritium (DT) supershot experiments [3] have been successfully demonstrated in TFTR. In JT-60U the confinement has been further improved when the high-β_p mode is combined with H-mode characteristics [4]. This paper presents the first comparative study of the wo regimes in the two devices, including the conditions necessary for their occurrence, the plasmas obtained and their limitations. In particular, a search for common plasma parameters describing the enhanced neutron yield and energy confinement for both regimes is conducted via a scaling study.

2. PRODUCTION OF HIGH β_p AND SUPERSHOT REGIMES

The high-β_p regime in JT-60U is produced in non-circular, diverted discharges with an elongation typically 1.7 and an aspect ratio ~4.3 with the plasma volume V_p = 42 ~ 51 m^3 configured to achieve central deposition of nearly perpendicular NBI (up to 24 MW). In addition to the perpendicular NBI system, JT-60U has two off-axis tangential NBI injectors (up to 12 MW) balanced in the co- and counter- directions with respect to the plasma current. The tangential NBI provides effective control of the heating beam profile and the plasma rotation. Control of the edge recycling is a prerequisite for high-β_p

regime and has been achieved by a combination of the divertor action and boronization of the first wall. Suppression of sawtooth oscillations by reducing the internal inductance below ~1.2, and the avoidance of locked MHD modes by using counter tangential NBI prior to the main beam power injection, are necessary for improved performance. This has now been achieved for plasma currents up to 2.8 MA. The improved confinement of the high-β_p regime occurs in combination with H-mode characteristics [4].

Supershots heated by tangential NBI have been extensively studied in DD plasmas in TFTR with nearly circular cross-sections, aspect ratios from 2.9 to 3.1, and plasma volumes ranging from $V_p = 27 \sim 48\ m^3$. TFTR is equipped with tangential NBI (up to 32 MW). Efficient central beam fueling can be achieved as long as a low edge plasma density is maintained. Supershots occur when the carbon limiter surface has been conditioned to reduce the recycling of the hydrogenic species. As techniques for decreasing the limiter recycling have been developed, the plasma current at which supershots can be produced has increased to 2.5 MA. Sawteeth are suppressed during beam injection in supershots even though they may be present in the preceding ohmically heated phase. Locked modes occur infrequently in TFTR and have not been a barrier to raising the current, despite the very low plasma densities of the ohmically heated phase. The typical ranges of plasma parameters in two regimes are illustrated in Table 1. Here, a set of TFTR supershot discharges with two different plasma volumes (V_p = 30 and 37 m^3) are shown in addition to JT-60U high-β_p discharges with $V_p = 48\ m^3$.

3. FUSION NEUTRON RATES

The relationship $3/2 n_D(r) T_i(r) = \langle W_{ion} \rangle F(r) \approx \langle W_{tot} \rangle F(r)$ is often used to deduce the correlation between fusion neutron rate and stored energy, where $\langle W_{ion} \rangle$ and $\langle W_{tot} \rangle$ are volume averaged total stored ion energy and total energy, respectively, F(r) represents the pressure profile shape, and n_D and T_i are ion density and temperature, respectively. It was shown that $W_{ion}/W_{tot} \approx 0.75$ for TFTR supershots [5] and a similar relationship is also observed in the JT-60U high-β_p regime. In general the DD neutron rate for plasmas with the central ion temperature ranging from 20 to 40 keV can be represented as follows:

$$S_{DD} = 1/2 \int n_D^2 \langle \sigma v \rangle \, dV \approx G \frac{W_{tot}^2}{V_p}, \text{ where } G = \text{constant} \langle F(r)^2 \rangle. \quad (1)$$

Here, W_{tot} is the magnetically measured stored energy. Fig. 1 shows the measured neutron yield as a function of W_{tot}^2/V_p for both the TFTR supershot and JT-60U high-β_p regimes. For a given stored energy, the neutron yield in the JT-60U high-β_p regime is significantly less than that in the TFTR supershot regime. It should be remarked that the parametric dependence of the G factor is inconsistent among the data from the three different plasma volumes; this is addressed later in this section.

In the JT-60U high-β_p and TFTR supershot regimes, for fixed plasma size, magnetic field and current, the DD fusion rate increases almost with the square of the absorbed NBI power. In TFTR, it has also been found that, for fixed NBI power, there is a strong correlation between the DD fusion rate and the peakedness of the NBI power and particle deposition profiles [5], which is controlled by the configuration and energy of the NBI system and plasma geometry. Once these are fixed, it is further controlled by the plasma average density and density profile shape. The peakedness of the neutral beam fueling profile is described by the parameter $H_{ne}=S_{be}(0)/<S_{be}>$ where $S_{be}(0)$ and $<S_{be}>$ are, respectively, the central and volume averaged electron source rates originating from the heating beam [5]. For the subset of TFTR supershots at a major radius of 2.45 m (V_p = 30 m^3) which have been analyzed by the TRANSP code [6], H_{ne} may be described by the fitted expression $H_{ne} \propto F_{ne}e^{-\gamma n_e}$ where n_e is the plasma line average density, F_{ne} is the electron density profile peakedness, and γ is a proportionality constant. Applying this fitted expression for H_{ne} to the DD supershots (discharges with the energy confinement time improved by more than 1.5 times that of the L-mode scaling), it has been found that the DD fusion rate is proportional to $P_{abs}^{2.0}\ H_{ne}^{0.9}$. The fitted expression for H_{ne} is found to be a reasonable description for the plasmas with larger major radius in TFTR.

We now investigate whether a similar dependence on H_{ne} is apparent in the JT-60U high-β_p regime. The beam deposition in JT-60U is complicated by the use of both on-axis perpendicular and off-axis tangential NBI injectors. However, a study of H_{ne} in JT-60U high-β_p regime showed that the fitted expression was quite similar to that of the TFTR [7]. Since there is a difference in defining a line average density in two machines, the expression H_{ne} from TFTR is tested with $F_{ne}P_{abs}^{-0.5}$ and found to be a good fit for TFTR discharges. Therefore, it is assumed that the expression for H_{ne} for JT-60U is $H_{ne} \propto F_{ne}P_{abs}^{-0.5}$ and the constant of proportionality is normalized to a number of calculated values deduced from both the OFMC [8] and TRANSP [6] codes. Finally, a regression study is performed for TFTR and JT-60U data with P_{abs}, H_{ne}, and V_p as independent variables. The deduced common scaling for the DD neutron rate for both TFTR and JT-60U is as follows:

$$S_{DD} \propto P_{abs}^{2.0} H_{ne}^{1.0} V_p^{-0.9}. \qquad (2)$$

When the measured DD neutron rate is compared with the scaling, the agreement is quite good as shown in Fig. 2. Note that JT-60U H-mode high-β_p discharges are excluded in this study.

On the other hand, it is also found that the G factor in Eq. 1 is roughly proportional to $H_{ne}^{0.5}$ for both the supershot and high-β_p regimes. The dependence of the G factor for two different volumes in TFTR supershots is vastly different when JT-60U data are included as shown below.

$$G \propto H_{ne}^{0.5}\ V_p^{-0.7} \text{ for TFTR data} \qquad (3a)$$

and

$$G \propto H_{ne}^{0.5}\ V_p^{-1.7} \text{ for TFTR and JT-60U data.} \qquad (3b)$$

This difference in the G factor can not be explained by the small difference in observed pressure profiles in the two machines except in a few extremely broad pressure profiles in the JT-60U H-mode high-β_p discharges. Further investigation is needed to resolve the difference in G-factors. Possible candidates can be differences in the fraction of ion energy (W_{ion}/W_{tot}) and/or thermal and non-thermal components of W_{tot} for the two regimes.

4. OPERATING BETA REGIONS

For fixed operating parameters, the strong dependence of the fusion neutron rate on the total plasma energy implies that the highest fusion rates are always obtained near the β–limit in both the TFTR supershot and JT-60U high-β_p regimes. It is particularly interesting that similar β_N limits ($\beta_N \sim 2.5$) are observed in both regimes in spite of differences in plasma operation and configurations. The similarity is apparent in Fig. 3. In TFTR this limit is manifested either by the onset of quasi-continuous MHD instabilities, which degrade the global confinement, or by minor or major disruptions. In JT-60U, fast collapses, named "β_p collapses", sometimes resulting in major disruptions, occur at the β-limit [2]. The operating beta domains of the JT-60U high-β_p and TFTR supershot regimes almost overlap within a relatively high q region ($q^* = 3$ - 10) in the β_N - $\varepsilon\beta_p$ diagram with similar heating power, plasma current and toroidal field as shown in this figure. Here q^* is defined as $\pi a^2 B_t(1+\kappa^2)/(\mu_0 I_p R_p)$. Transient peaking of the current profile shape, produced by decreasing the plasma current on a time scale less than the global resistive diffusion time, has increased β_N well beyond its usual limit for low current plasmas ($q^* > 5$) in both TFTR and JT-60U. These experiments demonstrate the possibility of increasing the β-limit through current profile control and eventually leading to further improvement of performance in fusion reactivity and energy confinement in both regimes [9].

5. ENERGY CONFINEMENT

TFTR supershots have been studied over a wide range of plasma currents (0.8 - 2.5 MA) and heating power (5 - 33 MW) where the maximum heating power for each current is restricted by the β-limit. The major radius has been varied from 2.45 to 2.62 m (corresponding minor radius from 0.80 to 0.97 m). At fixed plasma size, the global energy confinement time is influenced by neither the heating power nor the plasma current. In reference [5], it is pointed out that the ion stored energy ($W_i = W_{tot} - W_e$) is strongly correlated with P_{abs} and H_{ne} whereas the electron energy (W_e) is not influenced by H_{ne} at all. For supershot discharges operating near the β-limit, where W_i/W_{tot} is constant (~0.75), $W_{tot} \propto P_{abs}^{1.1} H_{ne}^{0.5}$. The toroidal field does not affect the confinement time of supershots provided the β-limit is not approached too closely. Under otherwise constant conditions, the confinement time improves as the plasma size is increased. For fixed machine settings, the stored energy is always obtained near the β-limt for both regimes. The measured W_{tot} as a function of $V_p I_p B_t/a$ is shown in Fig. 4 along with normalized-β lines of $\beta_N = 2$ and 3 defined as $\beta_N = \beta_t a B_t/I_p$ where a is the minor radius. The stored energy was increased from 5.4 MJ in TFTR to 8.5 MJ in JT-60U with the plasma volume (V_p) due to the similar β-limits.

The energy confinement time in the JT-60U high-β_p regime with a fixed divertor geometry at a typical major radius of 3.05 m (corresponding minor radius 0.70 m) has a more complicated dependence on plasma parameters. Figure 5a and 5b show two different energy confinement times for both regimes as a function of the plasma current. $\tau_E = W_{tot}/P_{net}$ where $P_{net} = P_{abs} - dW_{tot}/dt$ (P_{abs} is the heating power absorbed in the plasma) is the standard definition for the global energy confinement time. Thus, $\tau_E = W_{tot}/P_{abs}$ when the transient energy variation (dW_{tot}/dt) is excluded or negligible. The upper bound of the energy confinement time of the JT-60U data differs by a factor of 2 in two figures whereas that of the TFTR data remain the same. This is due to the fact that TFTR supershots have no appreciable dW_{tot}/dt (< less than ± 5 %) at the time of analysis whereas discharges in JT-60U high-β_p regime have significant values of dW_{tot}/dt (up to 50 % of P_{abs}). Despite the higher energy confinement time at higher plasma current with H-mode characteristics in Fig. 4a, the energy confinement time is not influenced by the variation of plasma current. Under the assumption that the ratio (Wi/W_{tot}) is similar for the two machines, a regression study for the stored energy (W_{tot}) employing the same sets of independent parameters used in the previous section is performed. The common scaling for W_{tot} is

$$W_{tot} \propto P_{abs}^{1.0} V_p^{1.0} H_{ne}^{0.2}. \qquad (4)$$

This correlation indicates that the increased global stored energy is largely due to the variation of the plasma volume for a given heating beam power. The reduction of the exponent in H_{ne} from 0.5 (TFTR data) to 0.2 may arise from the differences in confinement characteristics of electrons in the two regimes. The derived scaling for the stored energy for both regimes is compared with the measured stored energy in Fig. 6.

CONCLUSION

Significantly improved neutron rate and energy confinement have been produced from two different regimes (TFTR supershot and JT-60U high-β_p) in two considerably different machines. Ther has been an extensive collaboration between the JT-60U and TFTR teams. The characteristics of each regime are studied, and common scalings for the fusion neutrons and stored energy are proposed for both regimes. Here the fusion neutron rate and stored energy in both regimes are characterized by the absorbed beam power, fueling peaking parameter and plasma volume. The performance in fusion reactivity and stored energy is presently limited by a β-limit ($\beta_N = 2.0 \sim 2.5$). Energy confinement times used in this paper have a significant transient component (dW_{tot}/dt) in JT-60U high-β_p data whereas this term is negligible in TFTR supershot data; otherwise the dependence on the plasma current is quite similar in both regimes. However, the highest energy confinement times in JT-60U has been obained at higher plasma current when a high-β_p mode is combined with H-mode characteristics.

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TABLE 1

	TFTR (V_p=30 m^3)	TFTR (V_p=37 m^3)	JT-60U (V_p=48 m^3)
a_0	0.8 m	0.86 m	0.7 m
R_0	2.45 m	2.52 m	3.05 m
B_t	4.0 - 5.2 T	4.7, 5.0 T	4.3 - 4.5 T
I_p	0.9 -2.0 MA	1.5 - 2.0 MA	1.0 - 2.5 MA
P_{abs}	5 - 33 MW	12 - 32 MW	5 - 30 MW
q*	3.5 - 6.5	3.5 - 4.6	3 - 7
H_{ne}	1.5 - 4.0	2 - 4.5	1.2 - 4.0
κ	1.0	1.0	1.7

FIGURES

Fig. 1: Fusion reactivity for TFTR and JT-60U is shown as a function of W_{tot}^2/V_p in the TFTR supershot and JT-60U high-β_p regimes. For a given stored energy, fusion reactivity in TFTR supershots is significantly higher than that of the JT-60U high-β_p discharges. TFTR supershot discharges (x : $V_p = 30\ m^3$, and Black ◊ : $V_p = 37\ m^3$) and JT-60U high-β_p discharges (Square: high-β_p discharges, and square with x : high-β_p H-mode discharges, $V_p = 48\ m^3$).

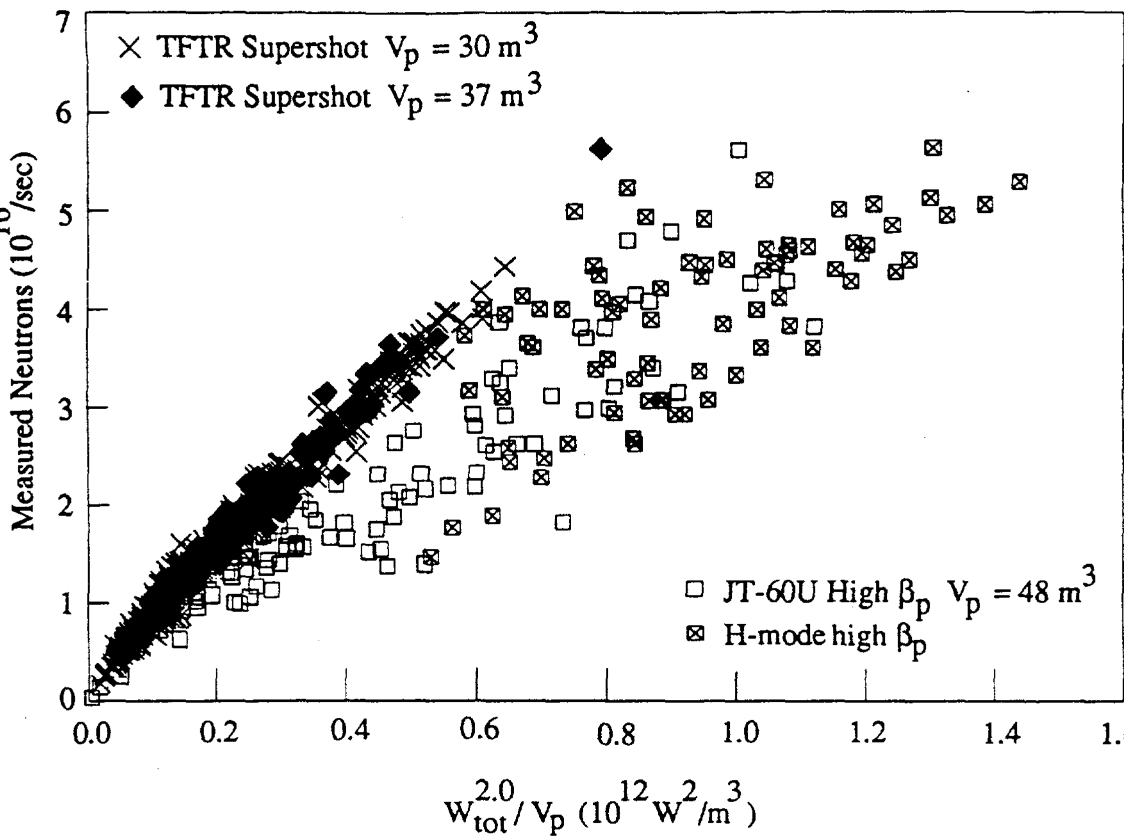
Fig. 2: The measured fusion neutron rate is compared with the common scaling for both TFTR supershot and JT-60U high-β_p regimes. The fusion reactivity is a strong function of the heating beam power and fueling profile shape. C is a proportionality constant. The symbols are the same as in Fig. 1.

Fig. 3: The domains of operating beta for both devices are shown in β_N - $\varepsilon\beta_p$ space. The best performance of the discharges is obtained near the beta limit (β_N~2.5) in both machines. The symbols are the same as in Fig. 1.

Fig. 4: Magnetically measured stored energy (W_{tot}) is shown as a function of $V_p I_p B_t/a$. The stored energy near the β-limit (β_N ~ 2.5) is increased as the plasma volume is increased. The symbols are the same as in Fig. 1.

Fig. 5: (a) The global energy confinement time ($\tau_E = W_{tot}/P_{net}$) is shown as a function of plasma current for both TFTR supershot and JT-60U high-β_p regimes, where P_{net} is defined as (P_{abs} - dW_{tot}/dt). (b) The energy confinement time excluding dW_{tot}/dt (W_{tot}/P_{abs}) is shown as a function of the plasma current. In general, the energy confinment time is not influenced by the variation of the plasma current in either the TFTR supershot or JT-60U high-β_p regimes. However, the highest energy confinement time in JT-60U was obtained at high plasma current when the JT-60U high-β_p regime is combined with H-mode characteristic. The symbols are the same as in Fig. 1.

Fig. 6: The measured global stored energy (W_{tot}) is compared with the common scaling for both TFTR supershot and JT-60U high-β_p regime. The stored energy has a strong linear correlation with the plasma volume. C is the proportionality constant. The symbols are the same as in Fig. 1.



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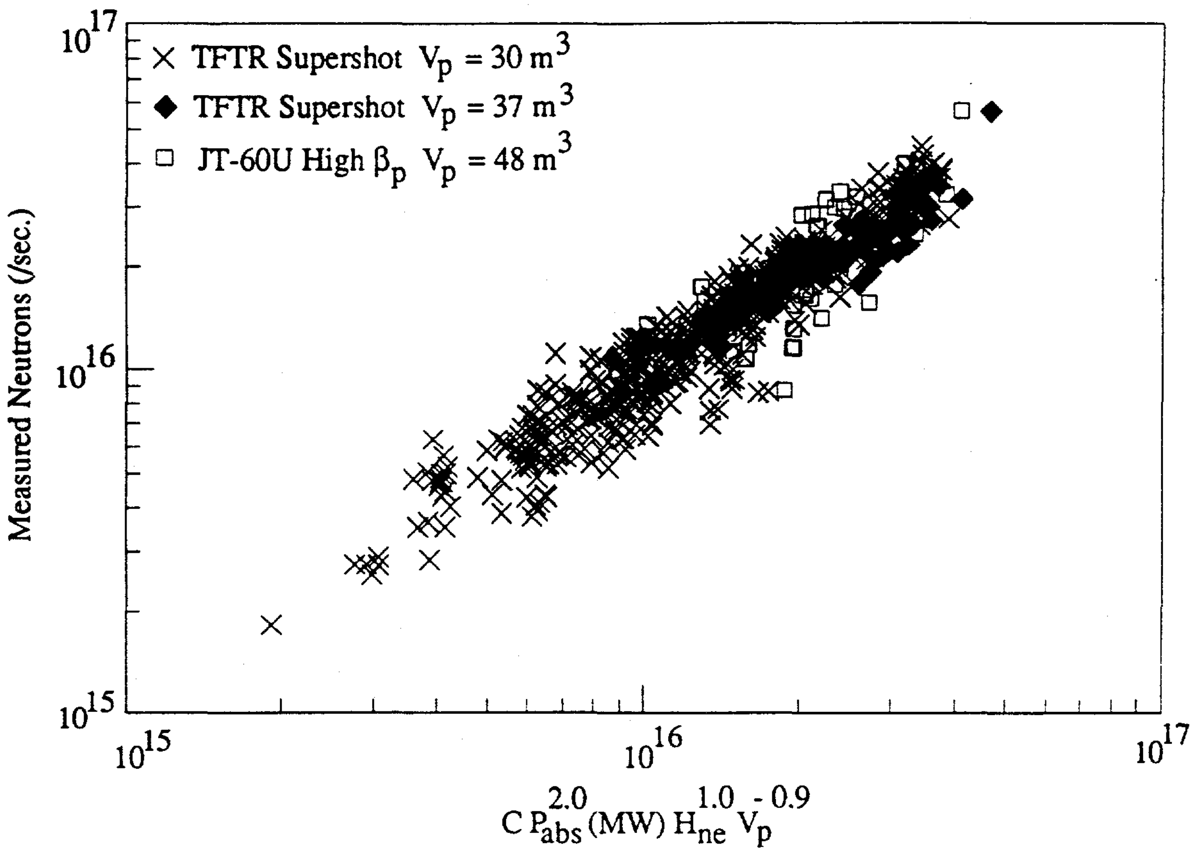

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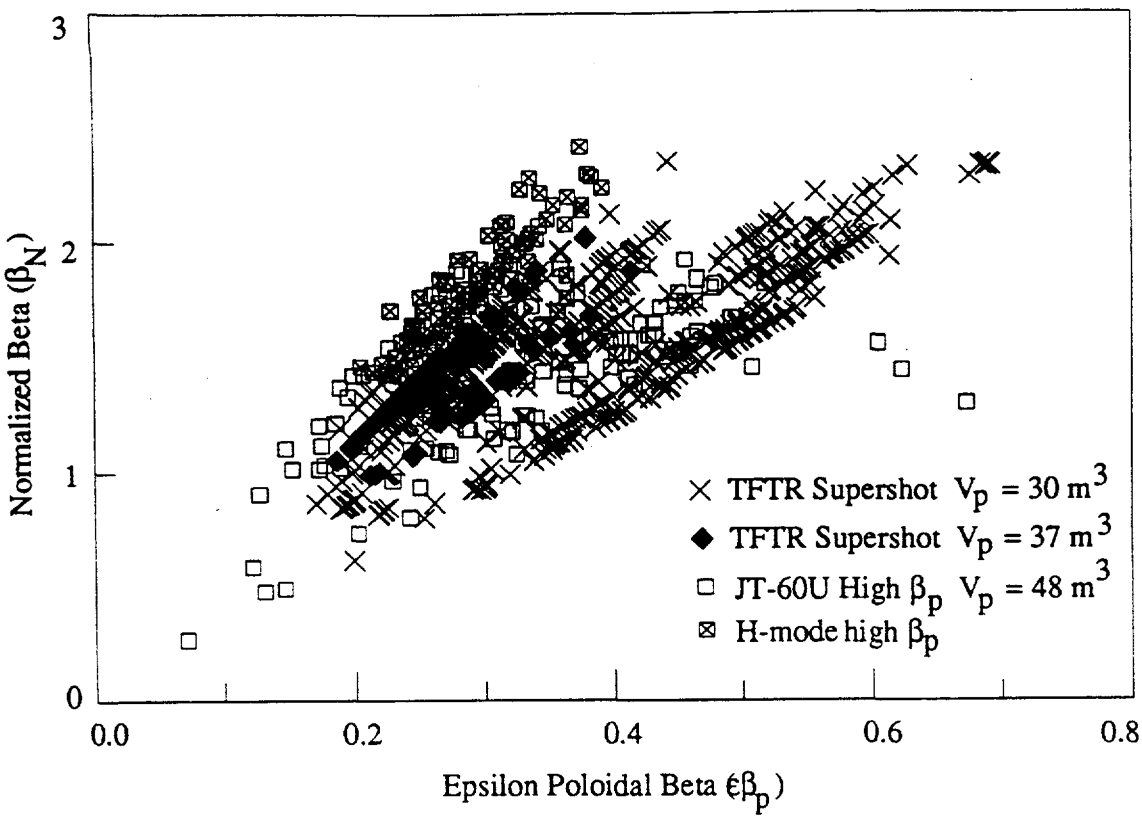

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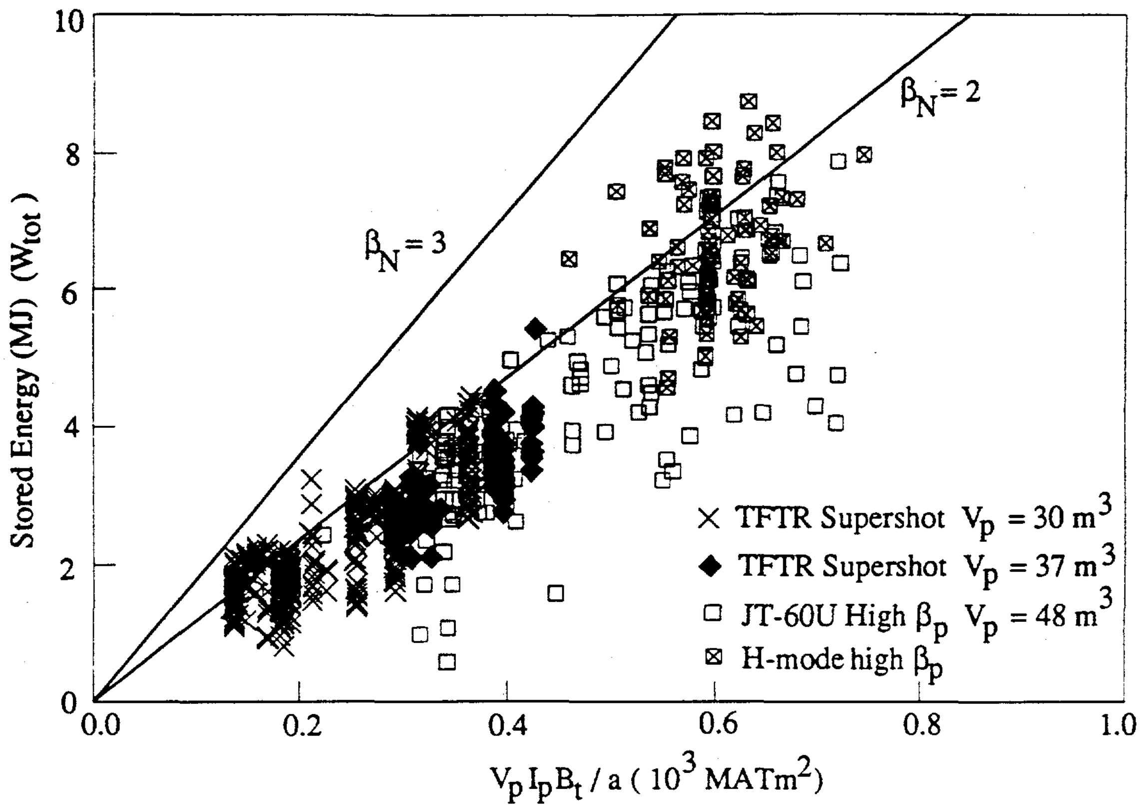

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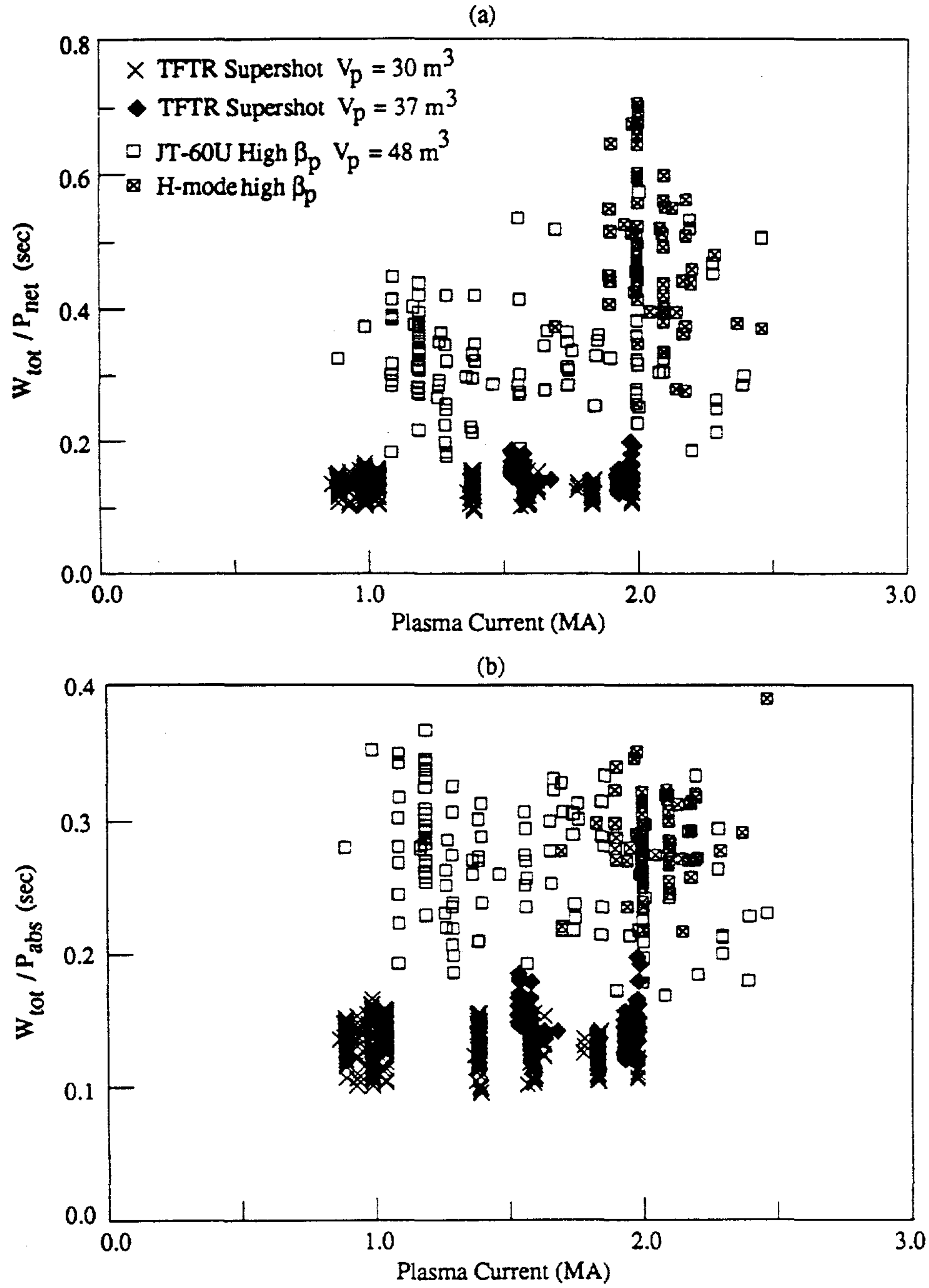

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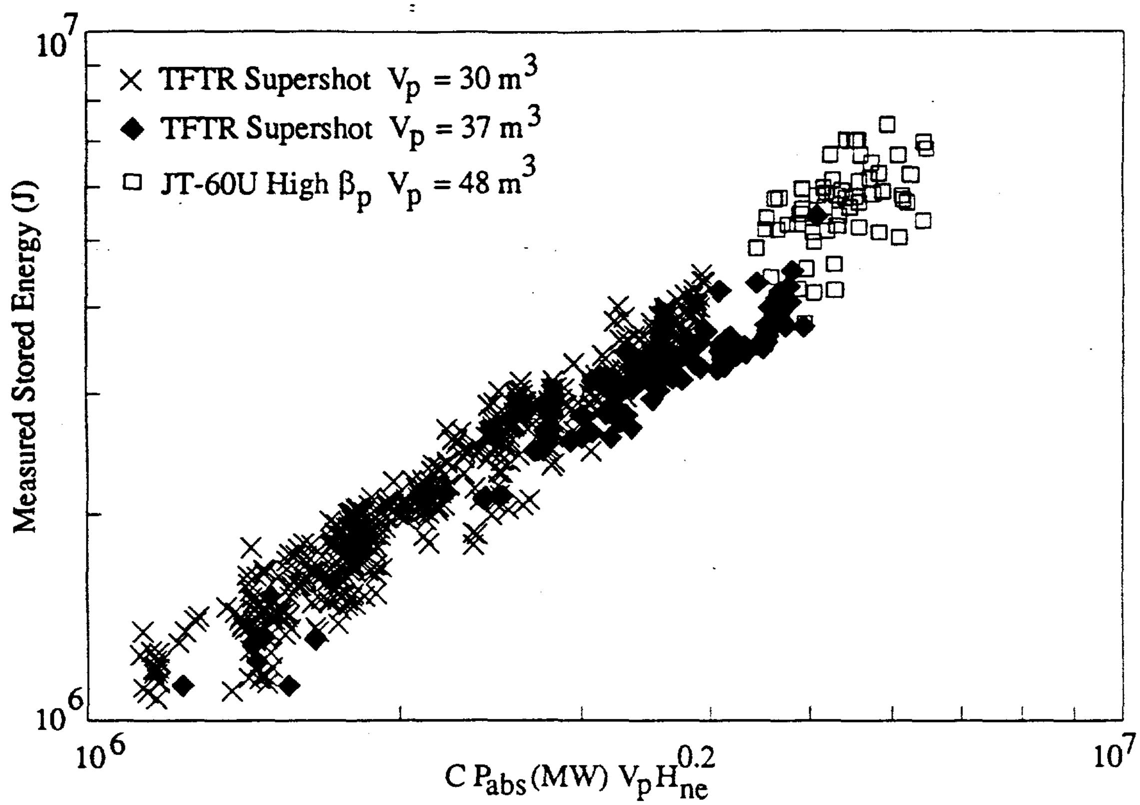

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