Comparison of High-β_p Regimes between JET and JT-60U on Confinement and Fusion Reactivity

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INTRODUCTION

High-β_p regime has become a new paradigm of tokamak fusion reactor developments, since it has the significant potential of enhancing the economical attractiveness in a fusion reactor where the requirement for external sources of non-inductive current drive is very much reduced. The eventual goal of this regime is to maintain a high pressure plasma in a steady state with highly enhanced confinement and stability under a large fraction of bootstrap current. Such a plasma has been extensively developed in JT-60U high-β_p regime [1,2] and JET high-β_p regime [3,4] both with non-circular divertor configurations. In spite of the similar β_p domains explored, there have been many important differences in confinement properties and fusion performance between the two regimes, in particular concerning the steady ELMy plasmas in JET and the ELM-free plasmas in JT-60. This paper aims at comparing these regimes in the two machines including the operational conditions and the plasma characteristics for optimization and further extension of these regimes towards the advanced tokamak reactors.

JT-60U EXPERIMENTS

The high-β_p regime in JT-60U is produced in non-circular divertor discharges with an elongation typically 1.7 and an aspect ratio ~4.3 with the plasma volume V_p~48 m^3, as shown in Fig.1, configured to achieve central deposition of the nearly perpendicular neutral beam injection (NBI) (up to 24 MW). In addition to the perpendicular NBI system, JT-60U has two off-axis tangential NBI system (up to 12 MW) balanced to the co- and counter directions respective to the plasma current.

The experiments have been conducted to create a high performance plasma with a high bootstrap fraction. Control of the edge recycling is a prerequisite and has been achieved by a combination of the divertor action and boronization of the first wall where the vacuum vessel is baked at ~290 degrees. Suppression of sawtooth oscillations, reducing the internal inductance below ~1.2, and avoidance of locked MHD modes are necessary for the improvement in performance.

Under these conditions, the high-β_p mode plasma has been produced with a highly peaked pressure profile by concentration of the central beam fueling and heating and is sometimes combined with H-mode characteristics ("high-β_p H-mode"). As shown in Fig.2, the central electron density increases up to ~6×10^{19} m^{-3} during beam injection from the target plasma density below ~1×10^{19} m^{-3}.

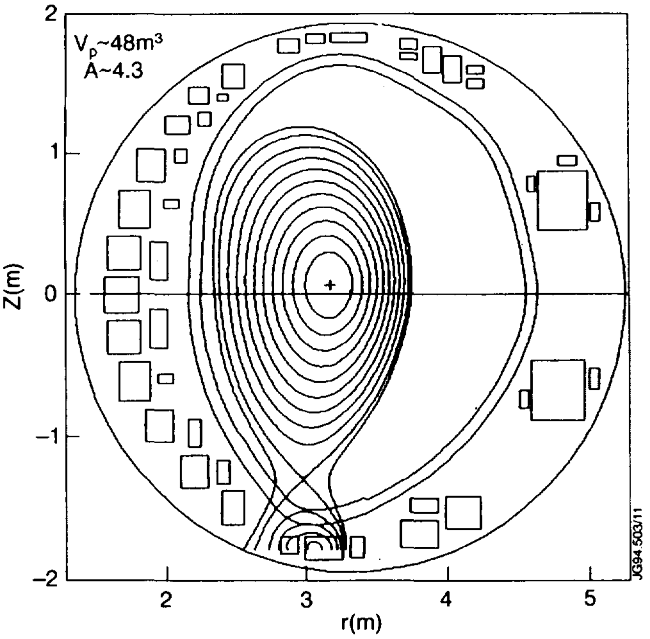


Fig. 1: High-β_p plasma configuration in JT-60U, indicating the plasma volume and aspect ratio of 48 m^3 and ~4.4, respectively.

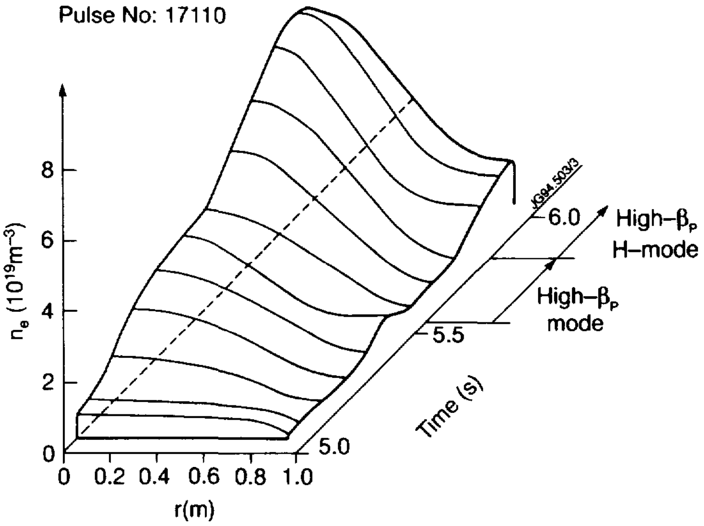


Fig. 2: Typical density evolution of a high-β_p discharge during intense neutral beam injection in JT-60U, where the density profile becomes centrally peaked during the high-β_p mode phase and the edge density also increases during the high-β_p H-mode phase.

JET EXPERIMENTS

The new experimental phase of JET with a pumped divertor configuration started operating in February 1994. The vacuum vessel is baked at ~250 degrees during operations, in which the first wall is conditioned with beryllium-evaporation and helium glow discharge cleaning. In the high-β_p campaign, a steady-state high-β_p regime has been aimed at and achieved with ELMy plasmas.

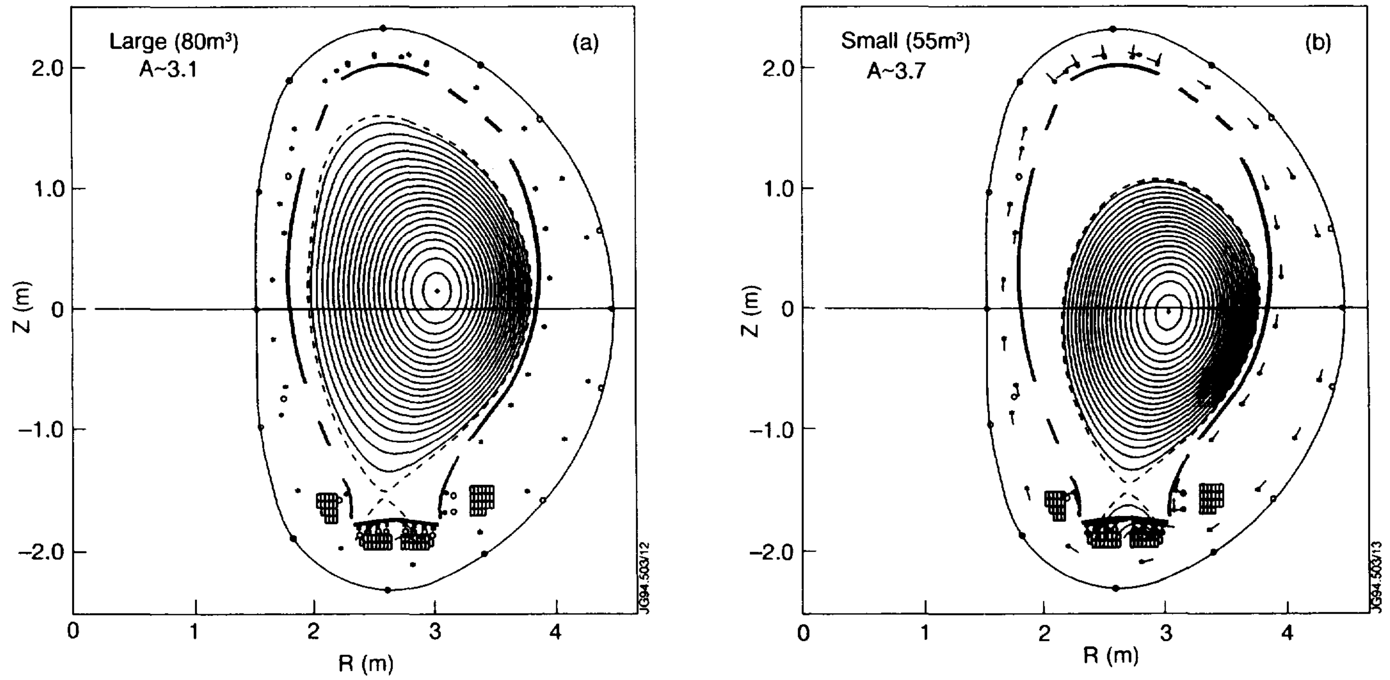


Fig. 3: Typical high-β_p plasma configurations in JET; (a) the 'large' volume configuration with an aspect ratio A~3.1 and a plasma volume V_p~80 m^3, and (b) the 'small' volume configuration with A~3.7 and V_p~55 m^3.

Small volume experiments have been also conducted with NBI heating up to 17 MW and NBI+ICRF combined heating up to 26 MW. While the normal 'large' plasma configuration has a plasma volume V_p~80 m^3, an elongation κ~1.7 and an aspect ratio R_p/a~3.1, the 'small' plasma configuration has Vp~55 m^3, κ~1.6 and a relatively large aspect ratio R_p/a~3.7 as shown in Fig.3. In both configurations, the injected beam lines pass near the plasma center and the outside curvature of the plasma surface is shaped to make the ICRF coupling to the plasma improved.

In comparison with the JT-60U high-β_p operation, generally, there has been marked difference in JET that the target plasma for main beam injection has sawtooth oscillations and relatively high electron density ~2.5×10^{19} m^3 to suppress shinethrough of the tangential beams facing the ICRF antennas. Thus, the electron density profile tends to become flat or even hollow during ELMy H-mode even if the plasma volume is significantly reduced as shown Fig.4.

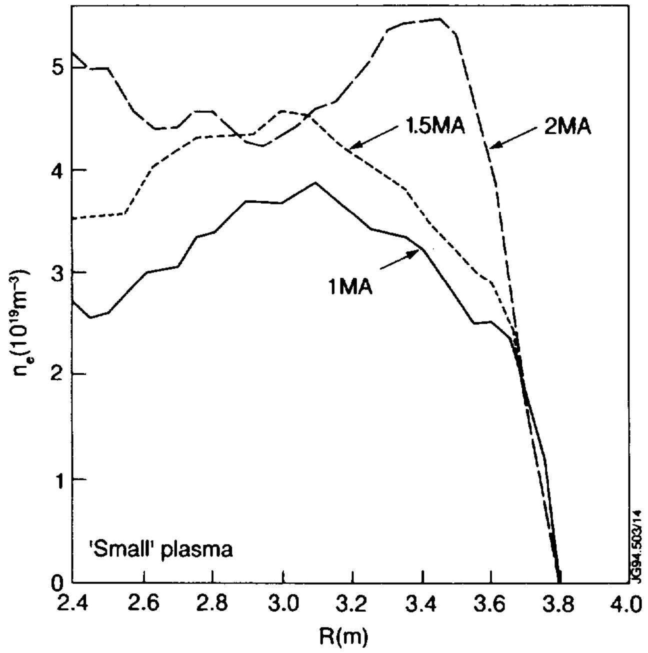


Fig. 4: Electron density profiles during neutral beam injection for the small volume plasma measured by LIDER Thomson scattering system in JET, where the cases at I_p=1.0, 1.5 and 2.0 MA are shown.

SMALL VOLUME PLASMAS IN JET

The small/large volume experiments in JET have been conducted for the range of $\beta_p \leq 1.5$ in the light of size scaling of confinement and comparison with the JT-60U high-β_p regime under the following conditions: 1.5 MA/2.8 T for 'large' case; 1.0, 1.5 and 2.0 MA/2.8 T and 1.0 MA/1.4 T for 'small' case. The NBI and ICRF heating up to P_{NBI}~17 MW and P_{IC}~6 MW, respectively, are applied in power scans. In some cases of the combined heating experiment, preheating by ICRH and/or beams before the main beam injection has been utilized to increase the target electron temperature.

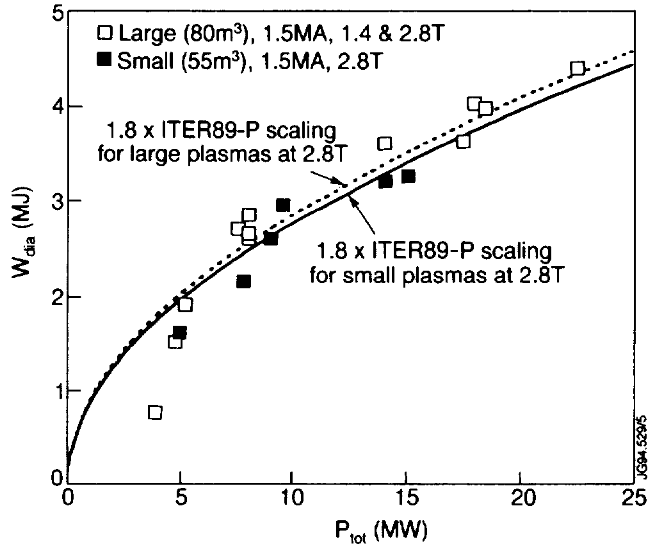


Fig. 5: Diamagnetic stored energy W_{dia} as a function of total heating power P_{tot} for the small and large volume discharges at 1.5 MA along with the predictions from the ITER89-P scaling, in which the confinement is not changed in spite of vast differences in plasma conditions.

The results show that the energy confinement is not changed though the plasma configuration is vastly different at the same radius.The confinement enhancement factor (H-factor) against the ITER89-P L-mode scaling reaches ~1.8 for ELMy plasmas at 2.8T for both plasmas as shown in Fig.5 where the W_{dia} value is plotted against the total heating power at 1.5MA. The evidence suggests that the major radius is the dorminant size parameter for determining the energy confinement for ELMy plasmas at high β_p. The fact of the higher pressure plasma with the same τ_E in the small plasma would also support the argument that the high aspect ratio is beneficial to the fusion triple product in ELMy plasmas at high-β_p, which is quite favorable for advanced tokamak concepts with a high aspect ratio.

ENERGY CONFINEMENT TIMES

Energy confinement times for the two high-β_p regimes in JT-60U and JET are shown in Fig.6 as a function of the H-factor. Noted that the τ_E values have the non-thermal components of the stored energy, typically, ~30% at 2MA in JT-60U and ~20% at 1.5MA in JET and the transient component ($dW/dt/P_{tot}$) up to ~50% in JT-60U whereas this term is negligible in the JET data. The energy confinement in the JET high-β_p regime accords with ~1.8 times the ITER89-P scaling for ELMy plasmas and sometimes exceeds it to some extent when the ELM-free phase is sufficiently prolonged using different plasma shaping such as double-null configurations and higher triangularity (up to $\delta \leq 0.4$).

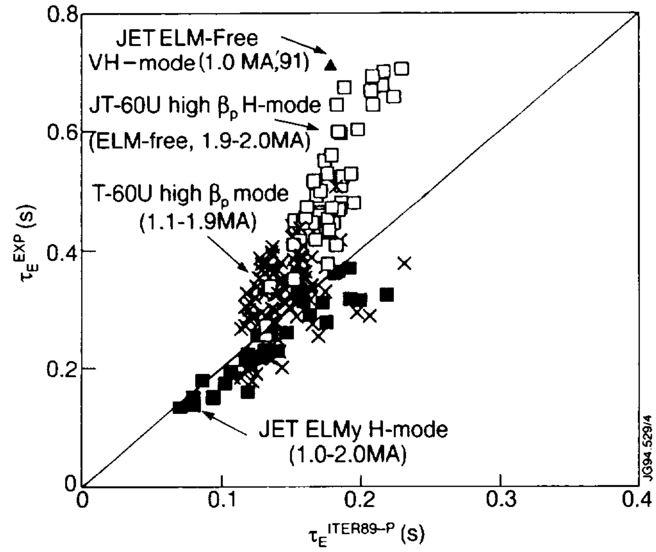


Fig. 6: Energy confinement times magnetically measured as a function of the predicted confinement times from the ITER89-P scaling for the high-β_p discharges in JET and JT-60U.

CONFINEMENT ENHANCEMENT FACTORS

Figure 7(a) shows the dependence of β_p on the H-factor for the JT-60U high-β_p regime. The high-β_p mode is characterized by enhanced core confinement with a peaked pressure profile inside an internal transport barrier [2]. The high-β_p H-mode during ELM-free phase shows higher confinement enhancement than the high-β_p mode for a given β_p value. The JT-60U results are promising for the high-β_p tokamaks since it would be possible to achieve such an enhanced confinement with a large bootstrap current fraction.

In contrast , as shown in Fig.7(b), the JET results for ELMy plasmas in the high-β_p regime show that the confinement enhancement factor is kept constant within βp values up to 2.5, although the long ELM-free H-mode plasmas in the 1991 high-β_p campaign show a similar dependence to the above JT-60U results. While a theoretical model has been proposed to explain such a positive correlation between confinement and β_p or bootstrap fraction [5], the correlation mechanisms are not comprehensively understood yet including these contradictory results.

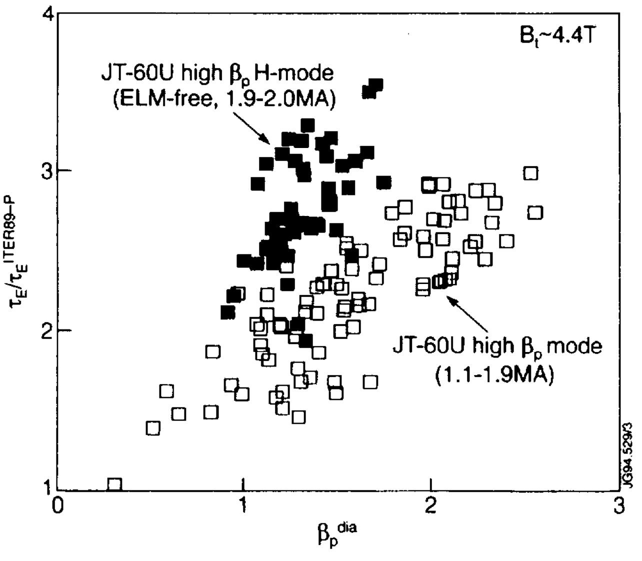


Fig. 7(a): Confinement enhancement factor against the ITER89-P scaling as a function of diamagnetic poloidal beta β_p^{dia} for high-β_p mode and high-β_p H-mode plasmas at 4.4 T in JT-60U.

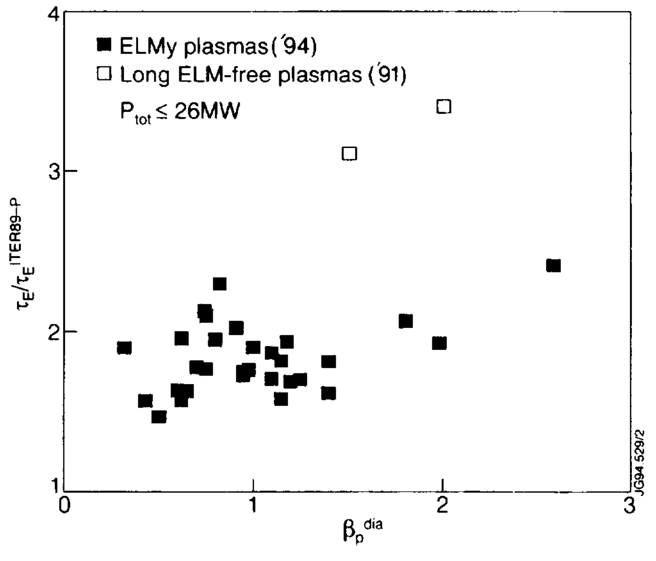


Fig. 7(b): Confinement enhancement factor against the ITER89-P scaling as a function of bpdia for high-β_p discharges with ELMy plasmas ('94) and long ELM-free plasmas ('91) in JET.

FUSION NEUTRON YIELD

An important effect of difference in the profiles between the two regimes in JT-60U and JET is manifest on the DD fusion neutron yield. Figure 8 shows the neutron rate as a function of the total additional power into the plasma in comparison with the JT-60U and JET high-β_p regimes. It is shown here that the peaked profile plasmas obtained in JT-60U produce much higher fusion power than the broad profile plasmas in JET for a given input power at the similar plasma volume and current ranges.

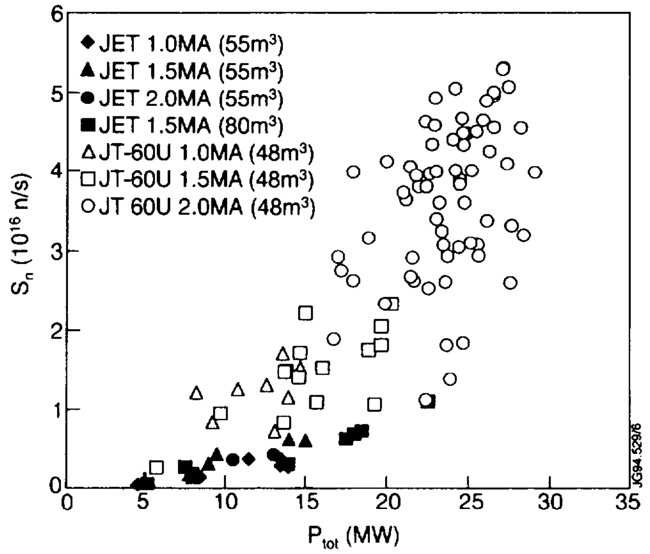


Fig. 8: Neutron emission rate as a function of total heating power for the high-β_p regimes in JT-60U and JET.

When the total ion stored energy is dominant in the plasma stored energy, the DD thermal neutron rate $S_n=(1/2)\int n_D^2<\sigma v>dV$ within the central ion temperature of interest can be approximately expressed as $G<p>^2V_p$ where $<p>$ is the total volume-averaged plasma pressure and G is a peaking factor of the pressure profile written as $<p(r)^2>/<p(r)>^2$. Figure 9 shows the neutron rate as a function of $<p>_{dia}^2 V_p$ for the JT-60U and JET high-β_p regimes, indicating that the high-β_p plasmas in JT-60U produced higher neutron rates for a given stored energy than the high-β_p plasmas in JET. This evidence may result from the differences not only in the pressure profile but also in the fraction of ion energy and/or non-thermal components of the stored energy.

In the JT-60U high-β_p regime, the concentration of the beam heating and fueling into the plasma center is found to induce a highly peaked ion pressure profile coinciding with significant reduction of ion thermal transport in the core plasma region and sometimes combined with H-mode characteristics at the edge. Without such the condition, the JET results show that the profile becomes broader with the H-mode even at the similar q and β_p regions and the resultant neutron rate is relatively low though the beam power density is increased with decreasing the plasma volume. Characteristics of the peaked profile plasmas are discussed in detail in comparison between the JT-60U high-β_p discharges and the TFTR supershots in Reference [6].

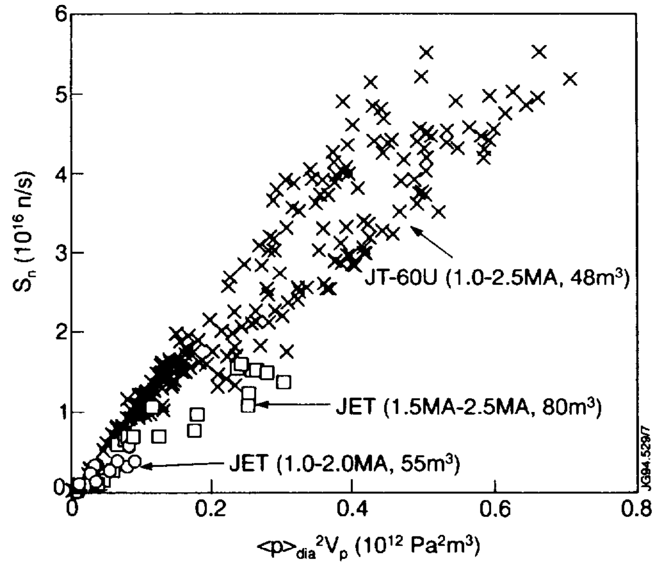


Fig. 9: Neutron emission rate as a function $<p>d_{ia}^2 V_p$ for the high-β_p regimes in JT-60U and JET including high current data up to 2.5 MA of 1994.

LONG PULSE PERFORMANCE AND OPERATING DOMAINS

A very long pulse ELMy discharge with high-β_N has been demonstrated in the JET high-β_p regime as shown in Fig.10, where a plasma at β_N~3 and β_p^{dia}~1.6 is sustained for ~7 sec. On the other hand, a high performance plasma with a peaked profile and continuous ELM activity has been sustained for ~2 sec at 1.8 MA/4.4 T in the JT-60U high-βp regime as shown in Fig.11, where β_p and β_N reached 1.4 and 1.8, respectively. In both machines, the ELMy plasma appears to be beneficial to maintain the plasma performance in a steady state since it could moderate the wall-plasma interaction preserving the core confinement unlike giant ELMs, X-events and other collapses.

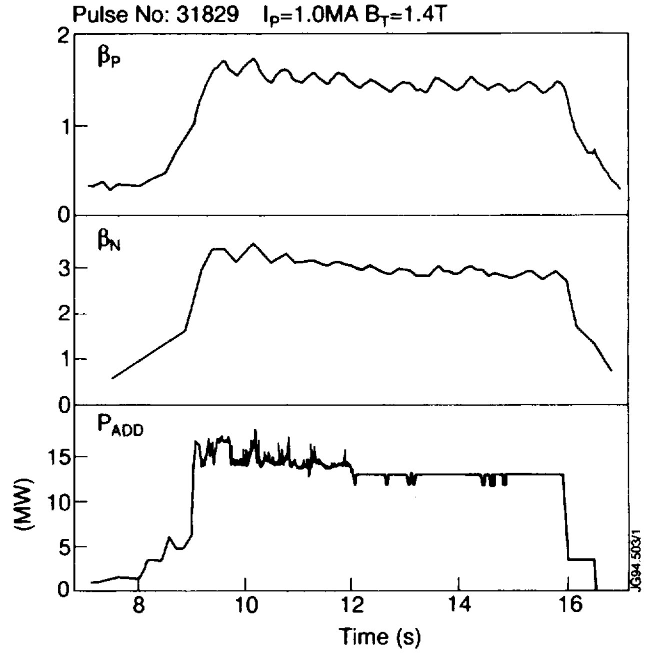


Fig. 10: Time history of a long-pulse high-β_N discharge in JET, where a high normalized beta β_N~3 is sustained for 7 sec.

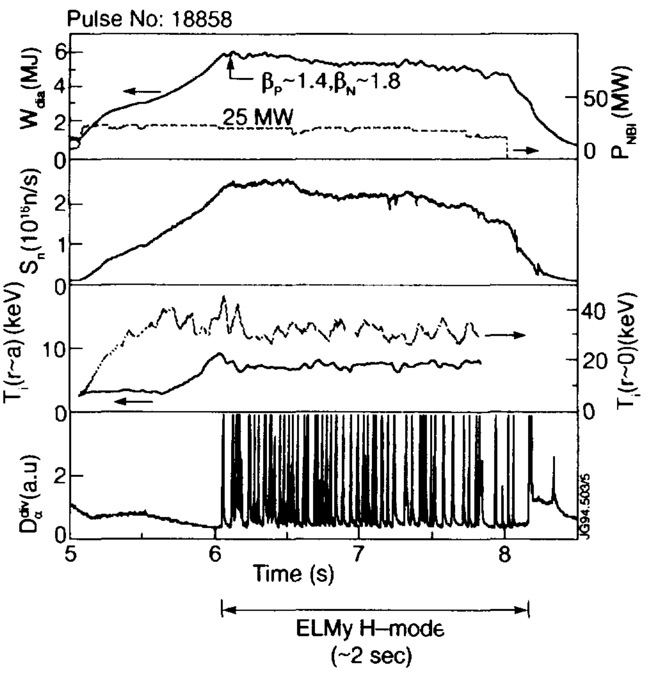
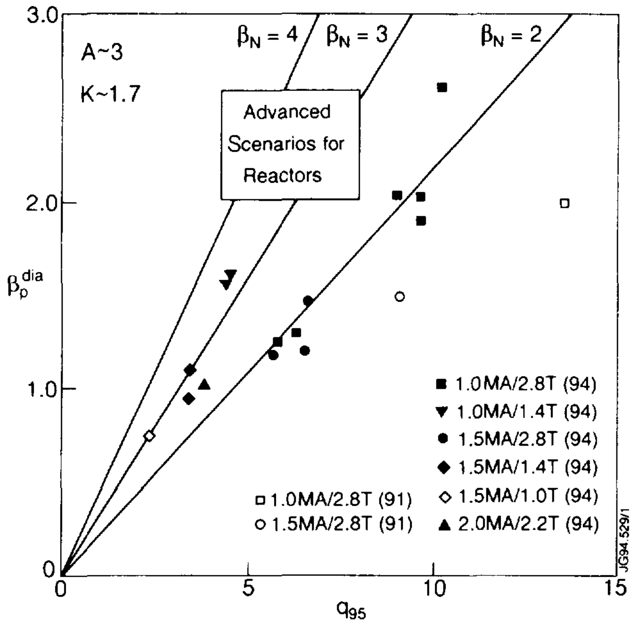


Fig. 11: Time history of a high performance discharge at 1.8 MA/4.4 T in JT-60U, where the performance is maintained for 2 sec until the beams are turned off.

A high-β_p plasma with enhanced confinement (high H-factor) and stability (high β_N) required for the advanced tokamak concepts can be achieved and sustained. However, as shown in JET and JT-60U, it most often occurs when the plasma pressure is reduced at low current and toroidal field, and has not yet been achieved for the highest performance discharges. Indeed, active profile control mechanisms would make it possible to sustain such a high performance plasma in the required β_p and β_N domains, but searching for a stable route to the high-β_p plasma will become a critical issue for the development of advanced tokamak concepts [4].



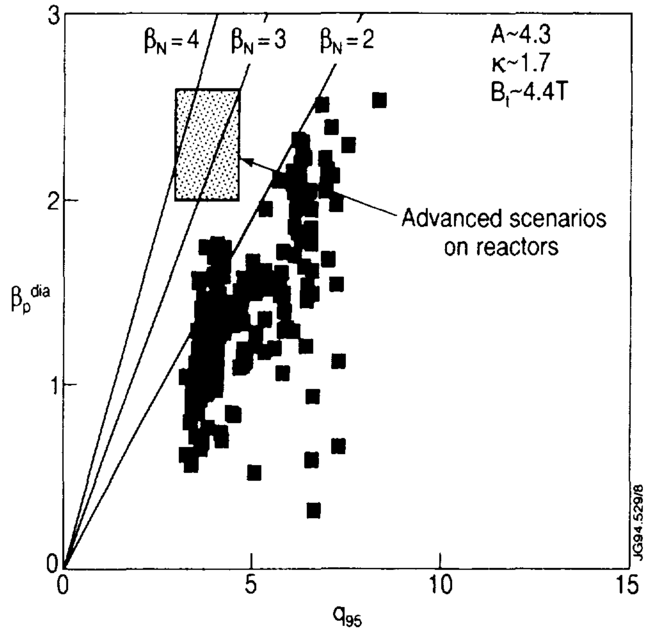


Fig. 12(a): Diamagnetic poloidal beta as a function of q_{95} for the JET high-β_p regime.

Fig. 12(b): Diamagnetic poloidal beta as a function of q_{95} for the JT-60U high-β_p regime.

The operating domains of the high-β_p regimes in JET and JT-60U are illustrated together with a goal of the advanced scenarios on reactors in Fig.12(a) and (b), respectively. In the JET high-β_p regime, the goal is approached with ELMy H-mode plasmas sustained much longer than the energy confinement times in terms of steady state whereas the JT-60U high-β_p regime aims at the goal with high performance plasmas which are often transiently terminated by MHD β-limits [7]. While there has been the clear differences in the experimental approach between the two regimes, the coincidence of the two approaches will be required for determining whether the reactor scenarios are workable.

CONCLUSIONS

- The high-β_p regimes in JET and JT-60U have for the first time been compared, in which steady state and high performance plasmas at high-β_p have been explored, respectively.
- The confinement enhancement factor against the ITER89-P scaling is significantly increased with β_p for ELM-free plasmas in a transient state both in JT-60U and JET, but is constant for JET ELMy plasmas in a steady state.
- Results from small/large volume experiments in JET show no difference in energy confinement in spite of reducing the plasma volume with the same major radius, suggesting that the major radius can be the dominant size parameter for determining the energy confinement and the high aspect ratio be beneficial to the fusion triple product in ELMy plasmas at high-β_p since the higher pressure <nT> was obtained at the same τ_E values for the high aspect ratio plasma.
- The peaked profile plasmas are found to produce much greater neutron rate than the broader profile plasmas in comparison between the two regimes, which may result from the differences in the ion pressure profile and fraction of ion pressure and non-thermal components in the stored energy.
- A steady state plasma has been produced at β_N~3 and β_p^{dia}~1.6 for ~7 sec in JET. A high performance plasma has been achieved for ~2 sec in JT-60U. However, long sustainment of a high-β_p plasma at high-β_N with high performance has not been demonstrated yet in both machines.

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