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HIGH-PERFORMANCE JET PLASMAS WITH PELLET INJECTION

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1. INTRODUCTION

At the last IAEA Technical Committee Meeting at Gut Ising in October 1988, JET reported on the generation of confinement improved PEP (Pellet Enhanced Plasmas) modes by early injection of 4 mm deuterium pellets and subsequent central heating with about 8-10 MW of Ion Cyclotron Radio frequency Heating (ICRH) or combined ICRH/Neutral Beam Injection (NBI) Heating in otherwise L-mode type 3 MA discharges [1]. Since then, JET has expanded these pulses to higher plasma currents, higher additional heating power levels, employment of larger pellet size and particularly has combined the PEP modes with H-mode plasmas (1990/91) obtaining transiently plasma performances approaching those of the best competing scenarios [2,3]. Essentially this paper reports is an excerpt from [3] expanded by more recent experiments and findings; it does not intend to give a full review of the JET pellet experiments nor even of the immense variety of the PEP-mode phenomena. The evaluation of the pellet data is ongoing and has allowed some insight into the reason for the PEP confinement and its transient nature. The JET pellet data base contains a good 200 shots with pellet injection of which about 120 show clear PEP indications; its review has revealed some trends which are now being followed up.

2. EXPERIMENTS AND RESULTS - 4 MM PELLETS

The combination of PEP- and H-mode was obtained by injecting 4 mm pellets early into initially 3 to 3.6 and later 4 MA X-point discharges and by immediately applying central ICRH heating in the order of 8-12 MW into these non-sawtoothing plasmas. Usually, the PEP mode starts soon following the injection very closely followed by the onset of the H-mode and the combination reaches its highest performance level in somewhat less than 1 second which then persists for up to .6 s before the plasma falls back, sometimes featuring significant MHD activity, into the H-mode state. One of the better examples is shown in fig. 1 for pulse # 22490. The X-point configuration is formed immediately after the end of the current rise to 3 MA and a pellet is injected soon after and well before the onset of sawteeth. The pellet creates a peaked density profile with a central value of $1.6.10^{20}$ m^{-3}. The pellet injection is immediately followed by additional heating on a level of about 8-10 MW of ICRH (10-15 % hydrogen minority and central resonance position). This leads in less than 1 second to temperatures equally for electrons and ions of about 9-11 keV at a central electron density of 7.10^{19} m^{-3} and a central electron pressure of up to 1.2 bar at

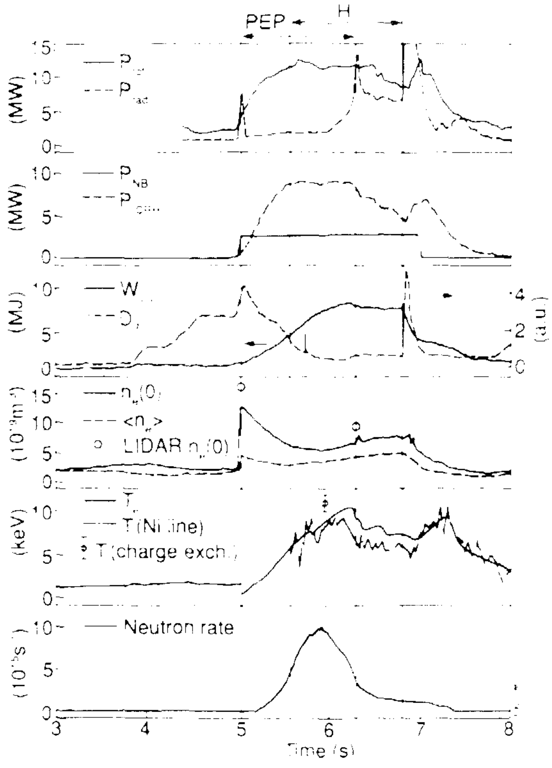

Fig. 1: Time history of pulse # 22490

This work has been performed under a collaboration agreement between the JET Joint Undertaking and the US Department of Energy.

the time of the maximum D-D neutron rate of 1.10^{16} s^{-1}. 80% of these neutrons are of thermonuclear origin. This is clearly the highest observed thermonuclear neutron rate on JET for plasmas with $T_i \approx T_e$. The maximum value of the fusion product $n_{D(0)} \bullet \tau_E \bullet T_{i(0)}$ is in the range of $5\text{-}7.10^{20}$ $m^{-3} \bullet s \bullet keV$ and is among the highest seen on JET. After about .5 seconds an L to H transition takes place, as can be seen from the typical signature of the edge D_α light and the total plasma energy now reaching 7-8 MJ. The plasma is in the combined mode for about .5 s, then the PEP-mode terminates and the plasma adopts ordinary H-mode behaviour. The plasma is not saw-toothing before or during the PEP phase, nor in the subsequent H-mode.

In fig. 2 the peak neutron production rate of L- and H-mode plasma with and without PEP-mode is plotted versus plasma energy, demonstrating that the PEP H-modes are typically a factor of 5 better than the ordinary H-modes. They also extend the trend curve of neutron production rate by a factor of 2 as compared to the limiter PEP pulses (see also fig. 6 for a more up-to-date ensemble of PEP shots). It should be remarked here that the higher neutron rates of the PEP + H-mode shots in comparison to the PEP + L-mode shots are likely to result from the higher ion temperatures which may be due to the better confinement. However, the PEP H-mode experiments were also conducted with a better ion heating efficiency of the ICRH because of higher H minority fraction: PEP L-modes with < 5 % of H with about 30 % against 10-15 % of H with about 50 % of power coupled to the ions.

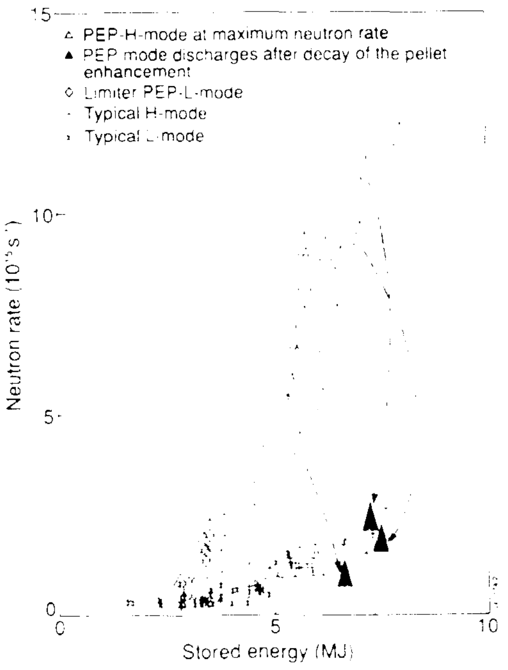

Fig. 2: Neutron rate vs plasma energy

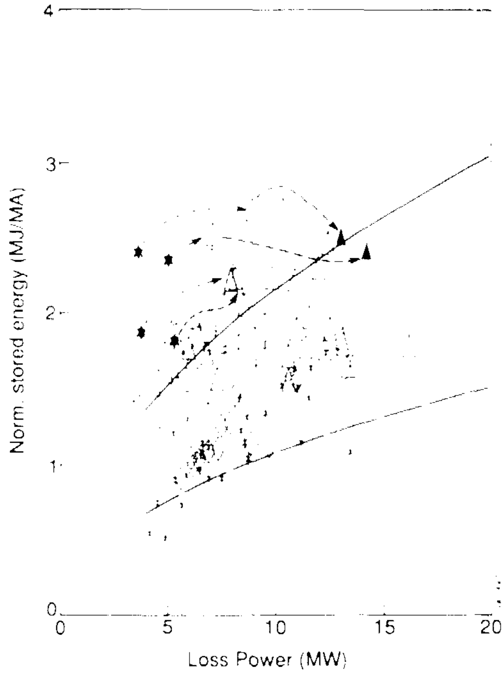

Fig. 3: Plasma enrgy vs power loss

In fig. 3 the normalised plasma energy content is plotted against the loss power for a similar selection of shots, at the time of maximum energy; the lines indicate one and two times Goldstone confinement scaling. The PEP data in the figure contains both discharges with clear PEP H-mode signatures and discharges in which the H-mode signature is less clear (PEP H- or PEP elmy H-modes). The figure shows the global energy confinement of good PEP H-modes is comparable or slightly better than that of ordinary H-modes. The figure further shows in the transition to the solid triangles that the confinement of the H-mode that remains after the decay of the PEP phase is similar to that of ordinary H-modes.

In the following experimental phase 1991/92 more experiments were carried out and the data base on 4 mm PEP shots was widened (for 6 mm pellets see below). In particular, it could be shown that the additional heating pulse can be delayed against the pellet injection for as much as 1 s and the PEP confinement state is still established. Fig. 4 shows an example of a 3 MA pulse with $T_i = T_e = 16$ keV by virtue of good confinement in combination with relatively low density due to the time delay and very central heating of ca 8 MW of ICRH (likely to have created a non-thermal ion population at this density) and 140 keV NBI (previously 80 keV). The peak neutron rate for this shot is $1.2.10^{16}$ s^{-1}.

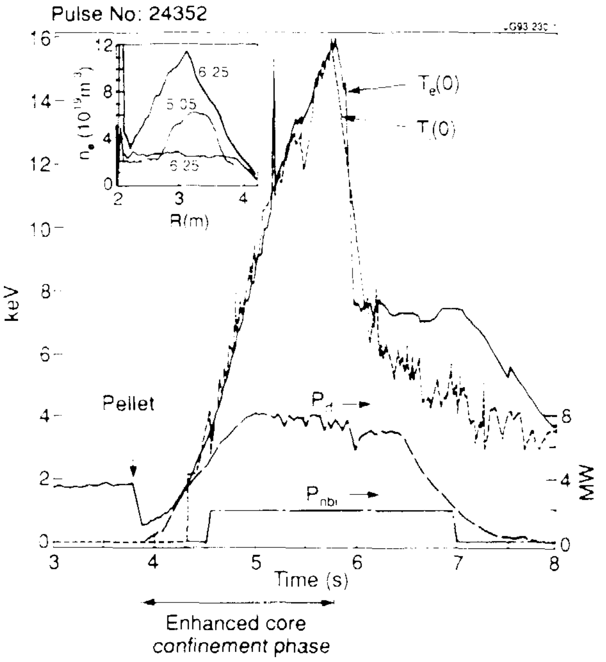

Fig. 4: Time history of pulse # 24532

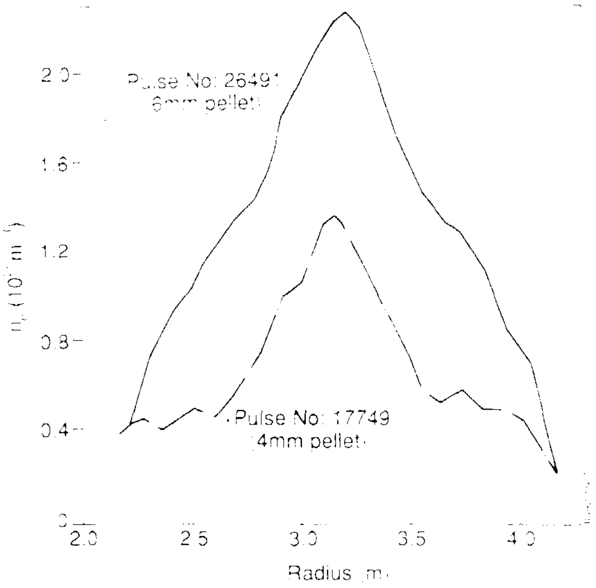

Fig. 5: Initial density profiles after pellet deposition

3. AIMS, EXPERIMENTS AND PRELIMINARY RESULTS - 6 mm PELLETS

Since the attempts with 4 mm pellets (average ne increase of $2.7.10^{19}$ m^{-3}) result in well-confined central cores reaching out to about 1/3 of the smaller plasma radius - i.e. covering only about 1/10 of the plasma volume - it was hoped that 6 mm (average ne increase of 8.10^{19} m^{-3}) would generate triangular density profiles with large density gradients throughout the full plasma cross section. This would permit to find out whether the PEP confinement can be extended to larger plasma volumes, with then corresponding increases in neutron rate and total plasma energy, or it would still be limited to a more central core because the shear cannot be made sufficiently low over the full volume (see chapter 5); details of the development of profiles would give further indications about the nature of the PEP-mode.

The operational problems with this scenario lie in the problem that on the one hand the central electron temperature is not to exceed 2.5-3 keV to permit central deposition of the 6 mm pellet but that on the other hand the total plasma energy at the time of pellet injection need to be sufficiently high - of order 3 MJ - to avoid a radiation collapse which will occur if the post-pellet electron temperature falls below ca 250 eV. For JET this target plasma can only be obtained in an X-point discharge with modest amounts of NBI, preceding the pellet injection and leading to a relatively broad electron temperature profile.

Indeed, in 1992 the desired type of initial deposition profile with a peak value of around $2.3.10^{20}$ m^{-3} was achieved in a number of cases in 4 MA discharges, and an example is shown in fig. 5 some 20 msec after injection in comparison with a corresponding typical 4 mm pellet deposition profile. (note: The 4 mm deposition profile in the small insert of fig. 4 is atypical in its triangularity but the further development of thisdensity profile may indicate a preference of the plasma to develop a central core only). A total of nine 6 mm pellet shots approaching the above initial deposition profile were successfully heated with varying combinations and levels of ICRH and NBI (140 keV). Commonly they feature a central density decay similar to those of the 4 mm shots and develop in a combined PEP- and H-mode plasma with about 10 MJ of total plasma energy at only $T_i \cong T_e \cong 5$ keV; the ones with predominantly ICRH heating around 10 MW achieve a D-D neutron production rate of 6.10^{15} s^{-1} - almost half the values of comparable 4 mm shots at much higher temperatures. Although the detailed code evaluation of these shots is still outstanding their global data seem to suggest that they show a high performance but not to the extent that the above questions can be answered. Their total particle content is higher than that of the 4 mm plasmas and therefore regarding the applied power the ion temperature and neutron yield are low despite favourable $n\tau$

T-values. Fig. 6 shows the neutron production rate plotted versus the total plasma energy of 6 mm pellet shots in comparison to an updated data set of 4 mm shots. Future experimental work will also have to consider the merits of an intermediate pellet size for which the JET additional heating capability would be more appropriate.

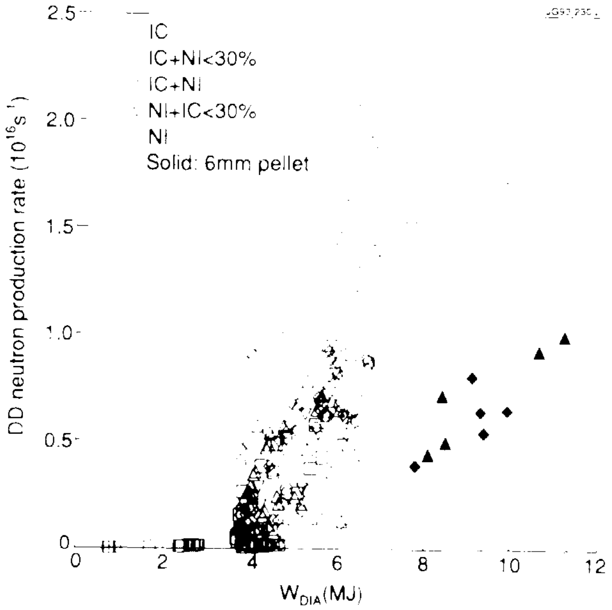

Fig. 6: Neutron rate vs plasma energy

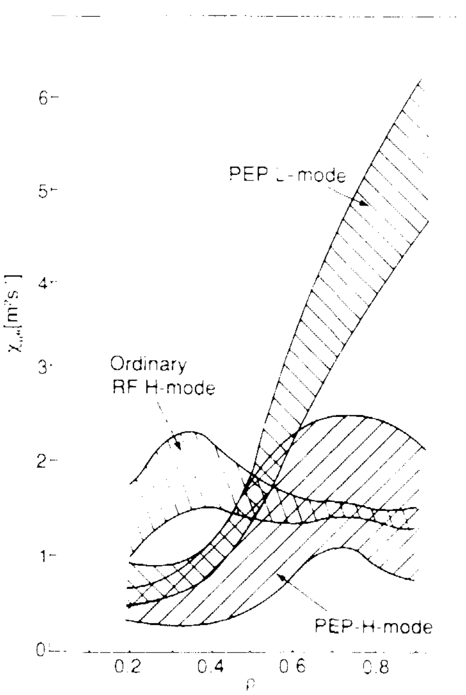

Fig. 7: Eff. heat conductivity vs radius

4. MORE DETAILED EVALUATIONS

The confinement features found in L-mode and H-mode PEP pulses alike suggest that the PEP mode is more or less independent of the state of the background plasma it is superimposed upon. During the overlapping period of the PEP- and H-mode, local transport calculations using the FALCON and TRANSP codes have shown central values of ($r \leq 0.4$ a) of the electron diffusion coefficient $D_e \approx 0.1$ m^{2}s^{-1} and the effective heat conduction coëfficient $X_{eff} \approx 0.5$ m^{2}s^{-1} (these central values are also typical for the old limiter L-mode PEPs); outside the central region X_{eff} values characteristic for H-modes are found in the range of 1 -2.5 m^{2}s^{-1} as shown in fig. 7. Code calculations for some early shots show consistency with the thermonuclear neutron production rate up to a point, however in many cases it is observed that the neutron rate decays significantly before the termination of the PEP phase. This can be explained by three possible causes or their combination: decaying central density, deuterium dilution in combination with impurity accumulation during the good confinement , and in some cases degrading confinement due to MHD activity. Indeed, there is experimental evidence for all of them in such an abundance that it is difficult to catalogue. Statistically of the 120 or so PEP shots only around 50 are terminated by MHD events, about one third of those by locked modes and ELMs, the remainder by n = 1, 3 and 2 modes (according to their frequency). Regarding the impurity / dilution issue the cataloguing is still incomplete but there are pulses with pronounced impurity accumulation close to that expected by neo-classical theory as well as cases with stagnant impurity contents or even expulsion of impurities without termination of the PEP-mode for a considerable period of time. Since any of these issues can also influence the duration of the PEP-mode (or for that matter of the combined PEP- and H-mode) it is not clear from the statistical evidence that the PEP-mode needs to be transient because there are a few pulses with a duration of the mode for a few seconds. This diversity may have to do with the subtleties of the generation and decay of the PEP-mode as suggested in the next chapter.

5. INTERPRETATION AND CONJECTURES.

Our level of understanding of the PEP mode - in particular why the high confinement mode develops in the centre, gently deteriorates or often ends in spectacular crashes of central electron and ion temperatures as well as neutron rates - is still roughly that of [3] , some of it still speculative. Earlier work has been performed considering ballooning [Galvao, 1988] or infernal modes [Charlton, 1991] due to high pressure gradients to be responsible for the observed MHD phenomena. However, in many cases PEP modes display similar MHD phenomena without having reached similarly high levels of pressures / neutron rates or gradients. This suggests that the current density and q-profile might be the dominant variable in the stability game. We have diagnosed by magnetic analysis of developing instabilities for a particular pulse the existence of a $q = 1.5$ surface inside a $q = 1$ surface [4]; this is supported by soft X-ray diagnostics; therefore, a region of negative shear $dq/dr<1$ must exist. This non-monotonic q-profile can be created during the cold shock during pellet injection expelling a central portion of the current; this particular profile is then aided by the bootstrap current due to the steep density gradient $dn_e/dr = -(5 \text{ to } 1.10^{20} \text{ m}^{-4})$ concurrent with the pellet deposition and increasing with the temperature gradient due to the centrally applied heating, eventually freezing the current density profile when the temperature becomes sufficiently large. Calculations of the bootstrap current densities indicate a value of the order of 1 MAm^{-2} in the region of $r = 0.4$ a, comparable to the ohmic current density. It has been speculated that the enhanced central confinement is associated with the reversal of shear. Simulations using the Rebut-Lallia critical temperature gradient model outside and assuming neo-classical transport inside the negative shear region show qualitative agreement with the experiments, in the time window between the pellet injection and the onset of MHD phenomena. These simulations were done by treating the ions neo-classically in the core and assuming the electron heat conduction coefficient either itself neo-classical or equal to that of the ions. A current density distribution not challenged by high pressure or pressure gradients might also survive for quite some time explaining the performance of pulses with delayed onset of the additional heating pulse. On the other hand, if the plasma performance, i.e. the pressure or pressure gradients are limited by other effects like dilution and impurities or the current distribution is influenced by other phenomena like current drive, plasma rotation or electric fields then the MHD stability might not be challenged and this would explain the more gentle roll-over appearance of the other shots. Accepting these hypothetical interpretation, the key to a more tailored behaviour of the PEP-mode would lie firstly in the ability to better shape the onset of the desired current distribution and then secondly to maintain it during the heating phase to preferably last into the flat top. Measures for the first class are to create a higher q on axis by advancing pellet injection earlier into the current rise (at lower internal inductance l_i), work at higher toroidal field (limited in the case of JET) or shape the early current distribution by non-inductive current drive. Measures for the second class are the immediate freezing of the desirable current density profile once achieved by raising the electron temperature as fast as possible after pellet injection and using active means for desirable corrections of the current density profile by either density profile shaping (NBI and pellets) or selective current drive (e.g. NBI or application of radio frequency in the form of lower hybrid or ICRH phased antenna configuration). Any of the tasks is experimentally difficult because it means guiding a plasma with an inherently unstable current distribution profile through the pitfalls of onsets of instabilitiesin the absence of (preferentially real-time) diagnostics permitting to tightly monitor and possibly feedback control the q-profile.

6. CONCLUDING REMARKS

Apart from providing an interesting and potentially useful insight into the physics governing the central core of a tokamak plasma, the PEP-mode may have a technical application as an operational start-up mode for a future fusion reactor with a minimum additional heating power or at least a minimum additional heating energy before its plasma after ignition is permitted to relax into a mode without impurity accumulation and with suitable particle loss for ash removal. For this to happen it will require still a lot of work and it would also be necessary to tailor the PEP-mode for a ramp time period sufficiently long to adapt the poloidal field to the rapid change of β.

7. REFERENCES

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