JET MULTI-PELLET INJECTION EXPERIMENTS* CONF-8810231--10

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CONF-8810231--10

DE90 011638

Abstract

The multiple injection of deuterium pellets into JET plasmas under various scenarios for limiter and X-point discharges with currents up to 5MA with pure ohmic, neutral beam and RF heating has been undertaken in a collaborative effort between JET and an USDoE team under the umbrella of the EURATOM-USDoE (US Department of Energy) Fusion Agreement on Pellet Injection using an ORNL built 3-barrel, repetitive multi-pellet launcher. The best plasma performance with pellet injection and additional heating so far has been obtained by injecting early into 3 MA, 3.1 T pulses while centrally depositing the pellet mass, with n_{eo} initially well in excess of 10^{20} m^{-3}. Subsequent central heating of this dense and clean core by ion cyclotron resonance heating (ICRH) with H and ^3He minorities in the 10 MW range yields T_{eo} up to 12 keV and T_{io} up to more than 10 keV, while n_{eo} is decreasing (within up to 1.5s) decaying to 0.6 x 10^{20} m^{-3}, suggesting an enhanced central energy confinement in limiter discharges with only modestly improved global L-mode confinement. In this plasma core electron pressures of more than 1 bar with gradients in the order of 4 bar*m^{-1} have been reached with the total pressure approaching ballooning stability limits. The resulting total neutron rate from D-D reactions of up to $4.5*10^{15}$ s^{-1} so far increases strongly with RF power and can exceed that of similar non-enhanced shots by factors of 3 to 5. $n_D(0)*T_i(0)*\tau_E(a)$ products in the range of 1 to $2*10^{20}$ m^{-3}keVs are obtained but combined power with neutral beams (up to 28 MW total), generally degrades the performance though leading to higher neutron rates of up to $7*10^{15}$ s^{-1}.

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* This work was performed under a collaboration agreement between the JET Joint Undertaking and the United States Department of Energy.

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1 Operated by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under contract DE-AC05-84OR21400.

DISCLAIMER

1. INTRODUCTION

Pellet Injection experiments on JET have started since 1986 with single pellet experiments establishing that peaked density profiles can be generated and that the central density is not closely tied to the global density limit experienced in tokamak operation [1]. With the installation of the multi-pellet injector, jointly built by JET and Oak Ridge National Laboratory (ORNL) the range of experiments could be enormously widened due to the flexibility of the injector capable of delivering 2.7, 4 and 6 mm pellets from three independent barrels (i.e. guns can be fired simultaneously) with up to 1.5 kms^{-1} speed and up to 5 s^{-1} repetition frequency. The number of pellets is at present limited to a maximum of 32 only by the control and monitoring system of the injector. More technical details are given in [2,3].

The experiments - jointly carried out and evaluated by the JET-US team - tried initially to probe predominantly ohmic plasmas in preparing the plasma for subsequent additional heating since it was known that at least the smaller pellets of the above choice would not penetrate far into very high temperature plasmas. However, a few experiments of the latter kind were also performed.

The paper will firstly give a short summary of these probing attempts and their (preliminary) results - for more information see [4,5] - and then turn to the more interesting phenomenon of a new confinement regime found in the plasma core when applying centrally deposited RF heating to particularly peaked density profiles in the early current flat-top phase. The very first indications of this effect came as a late entry to the EPS conference at Dubrovnik [4,6,7] and the newest results on the now broadened data base have been given at the recent IAEA conference at Nice [8].

2. SUMMARY OF PROBING RESULTS

2.1 2.7 and 4 mm deuterium pellets have penetration depths in line with previous single pellet results, and single pellets as a rule of thumb will reach the center of JET plasmas with central electron temperatures $T_e(0)$ of 1.5 and 2.5 keV, respectively; according to our experience only then strong density peaking is to be expected. Fig. 1 shows the normalised peaking factor $n_e(0)/\langle n_e \rangle$ (central over volume averaged electron density, ratio of this factor before - usually 1.5 - to that 0.2 s after the pellet event)

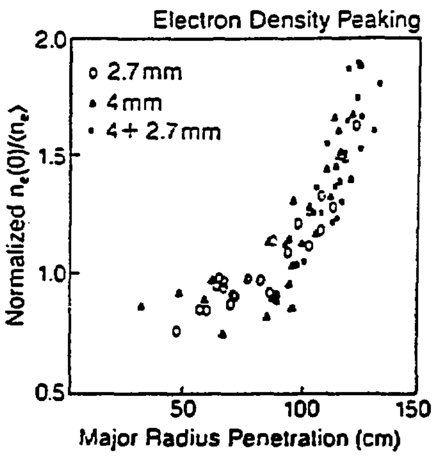

Fig.1

versus penetration depth as derived from the end of the D_α-trace (minor horizontal radii of JET plasmas are a = 1.15 to 1.25 m). As can be seen from the figure, pellets in the case of JET must reach the center within 0.3 m before significant peaking will occur.

2.2 Since JET plasmas of ≥ 3 MA develop usually already higher $T_e(0)$ than the ones quoted above, pellets are either injected at the beginning of the pulse into the current ramp or early flat top (these cases will be dealt with in chapter 4 more extensively) or a string of pellets preceeding the one to facilitate the peaking have to be applied to cool the plasma suitably. An example of the latter case (pulse # 13572) is given in fig. 2 where a 4 mm pellet at 4.5 s controls the temperature such that a close (ca 10^{-3} s apart) combination of a 4 and a 2.7 mm pellet at 5.5 s leads to strong peaking of density, starting with a maximum of $1.3*10^{20}$ m^{-3} decaying slowly in this ohmic shot to $0.9*10^{20}$ m^{3} within 2 s; the well confined core is still recognisable after 3 s and sawtooth activity is supressed well beyond the timescale of fig. 2.

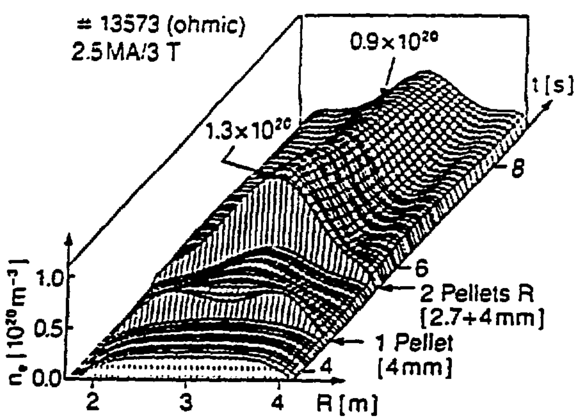

Fig.2

2.3 Multiple pellet injection in the current flat-top, early as well as late, has in limiter discharges quite often led to the excitation of quasi-stationary modes (QSM or locked modes) which usually destroy the density peakedness quite rapidly and can easily lead, in particular with subsequent heating attempts, to disruptions [9]. No general recipe has yet been found to avoid QSMs; they seem largely but not uniquely to depend on the conditioning of walls and limiters. In one of the few attempts to heat plasmas with RF (16 MW) after flat-top injection of three successive (2 s^{-1}) 4 mm pellets the neutron rate ($7*10^{14}$ s^{-1}) came out higher than with comparable RF shots at that time: a hint for the higher deuterium contents despite the lack of central pellet deposition in this case.

2.4 Recently some preliminary attempts of fuelling into RF heated (ca 6 MW) limiter discharges have been performed in a quasi-centrifuge mode: in one case 32 pellets of 2.7 mm at 2.5 s^{-1} and in another six 4 mm pellets at 1 s^{-1} have not created any sign of peaking of the density profile which has rather exhibited the features of gas fuelled pulses.

2.5 Injection into single and double null X-point discharges can be dealt with like in limiter discharges: we have achieved strong peaking before the onset of the additional heating and an H-mode could be created thereafter. However, the limited penetration of the JET neutral deuterium beams cannot heat this central dense core and RF antennae and plasma geometry in this configuration are incompatible at present. Also small pellets into an H-mode (without destroying it) and into supershots (with slightly increasing the highest neutron rate on JET so far) have been facilitated.

2.6 Most of the above experiments have been performed on plasma currents close to 3 MA for reasons of higher stability (i.e. higher safety factor q(a)) and less severe disruptions. The extension of the schemes to be described in item 4. to plasma currents of 4 and 5 MA proved quite tricky because it is difficult to control the $T_e(0)$ appropriate for peaking by a suitably timed pellet string over the long time to reach the respective current (e.g. ca 7 s for 5 MA). Scenarios have been developed but until now there was insufficient time to perform the subsequent heating.

2.7 Suitable plasmas for the injection of 6 mm pellets ($T_e(0)$ = 5-6 keV and total plasma energy > 5 MJ) have not readily been available and the few attempts made in marginal conditions have ended in disruptions.

3. EARLY INJECTION AND HEATING - ENHANCED MODE

3.1 The peaked density profiles with peaking factors around 3 (after 0.2 s) with injection into the current ramp and early flat-top can be facilitated as demonstrated in the two examples given in figs. 3 and 4: a string of 7 2.7 mm pellets leads to $n_e(0) = 0.9*10^{20}$ m^{-3} when 8.5 MW of RF (H minority ICRH) and 5 MW of neutral beam (NB) are applied (# 14550) raising $T_e(0)$ to 8 keV; in # 16211 a single 4 mm pellet created an initial $n_e(0)=1.4*10^{20}$ m^{-3} before 8 MW of RF only (again H minority) boost $T_e(0)$ and $T_i(0)$ up to maximum values of 11 and 8 keV, respectively, while the central density is decaying towards $0.6*10^{20}$ m^{-3}. Both pulses - Fig. 4, lower - exhibit after an initially steep and smooth slope of $T_e(0)$ some hesitation in this rise and end the increase in a sudden loss of electron temperature by several keV (still no sawtoothing present, and for # 16211 analysed to be accompanied by MHD modes, predominantly m=3, n=2). Fig. 4, upper shows the development of the central safety factor q(0) for both pulses as derived from Faraday rotation and shows it to be >1 (even through the crash of $T_e(0)$ in # 16211) and to be higher for the multiple pellet shot which may be of advantage if ballooning instability is a problem. In the last period we concentrated on "single" pellet peaking (and achieved here the maximum value of $n_e(0) = 2*10^{20}$ m^{-3}) but it will be of interest to return to the other scheme.

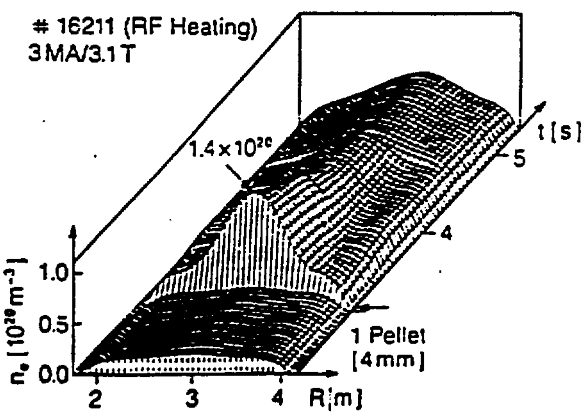

Fig.3

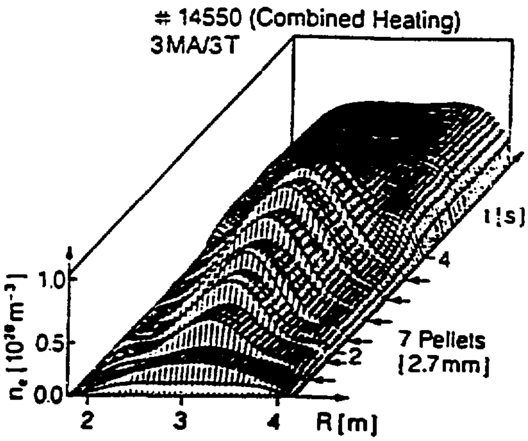

Fig.4

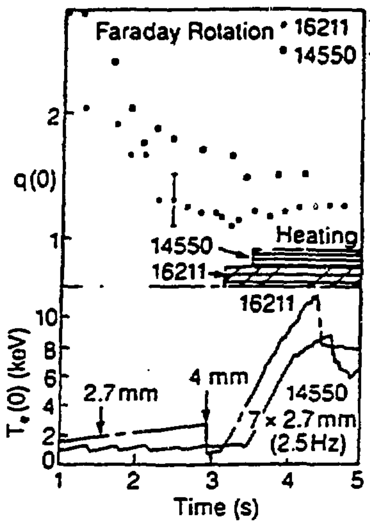

Fig. 5

3.2 The comparison of a pellet shot (I = # 16211) with a non-peaking pellet shot (II = # 16206 resembling very much a gas fuelled one) in fig 6 (a to e) clarifies why we speak of enhanced performances: When central ICRH is applied the rates of electron and ion temperature rise as well as the obtained maximum values are superior to those of the shot lacking the density peaking. This is particularly evident from the neutron rate due to D-D reactions being increased by factors of 3 to 5 and that due to D-T reactions of the generated tritons being larger by an order of magnitude; it is important to note that the D-T reaction is maintained steadily through the T_e crash documenting that the tritons are not expelled.

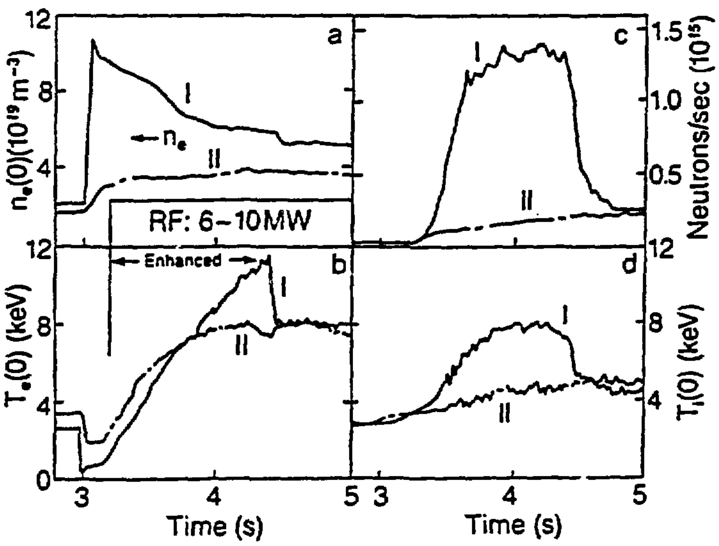

Fig. 6 (a,b,c,d)

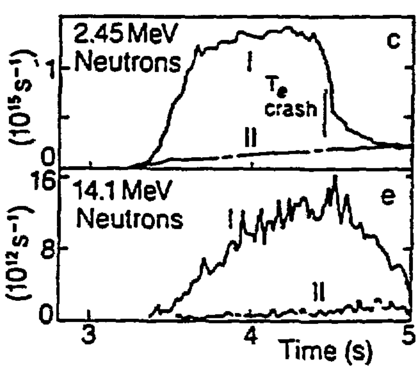

Fig. 6 (c,e)

3.3 Fig. 7a shows a comparison of radial profiles of density from LIDAR Thomson scattering at the time of pellet injection and 1.2 s thereafter (the central density peaking still recognisable and shifted to a larger radius because of β-effects) for # 17749, marked (P), in comparison with the flat non-pellet profiles of # 17747, marked (NP). Underneath in fig 7b, the comparison is seen for T_e from LIDAR and T_i from charge exchange

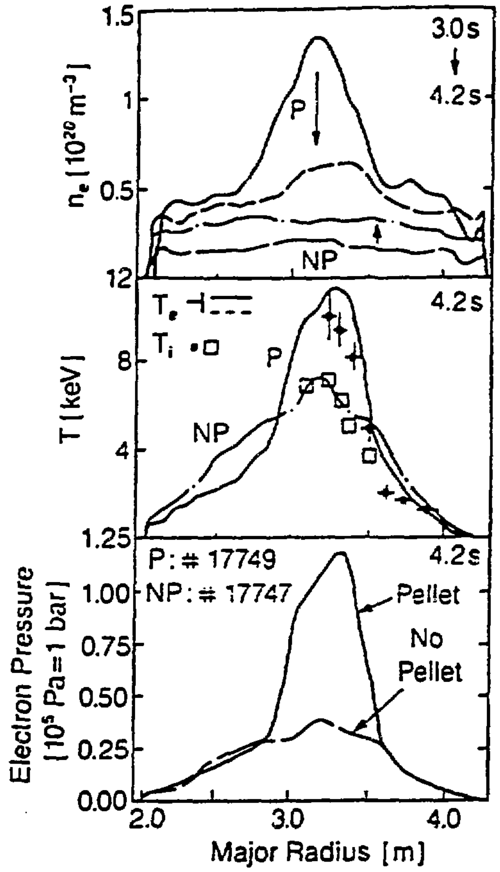

Fig.7

spectroscopy documenting that the temperatures for the enhanced performance are tracking each other well concerning the radial profiles and are well into the reactor relevant range. The resulting electron pressure (1.2 bar with a gradient of 4 bar*m^{-1}) in fig. 7c leads to an plasma pressure estimate of close to 2 bar and poses the question of stability: Although this pressure approaches only 40% of the Troyon limit for idealised profiles more detailed calculations show that - taking into account the uncertainty for q(0) - the stability limit is at least approached if not exceeded (fig. 8); This is one possible explanation for the deterioration of the enhanced performance. Fig. 9 presents $\eta_e = \delta \ln T_e / \delta \ln n_e$ values from LIDAR measurements whereby we assume that $\eta_i = \eta_e$ at least for the first 0.75 s because of the proximity of temperature profiles of electrons and ions and the low Z_{eff}; the indications that η_i is below 1.5 for the central half of the plasma radius may contribute to the enhancement but the progression of the $\eta(r)$ curve with time towards the axis would then also point to the transient nature of this phenomenon. In transport modelling with a single fluid model the thermal conductivity for the central core had to be assumed to be 2 to 3 times lower than is compatible with the modelling of other non-pellet shots (reduction also in χ_e)[10]. With regard to the plasma stored energy and global energy confinement time these shots are only marginally (20% on average) better than the gross of the RF heated limiter discharges at the same current (L-mode); this is understandable since the markeably improved central energy density (by a factor of 2 to 3) fills only a small (10-20%) part of the total plasma volume.

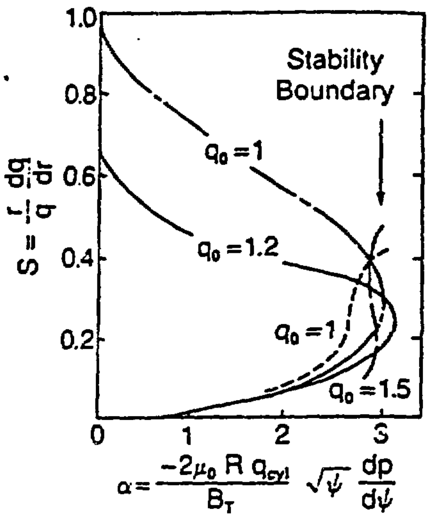

Fig.8

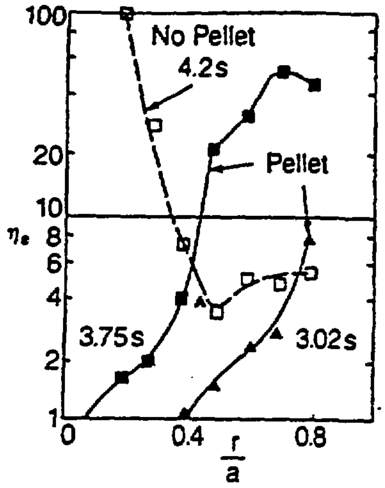

Fig.9

3.4 Fig. 10 shows the peak neutron yields of peaked and non-peaked profile shots and the strong increase with the RF power. The neutron rate is usually at maximum before, and in decline when, the temperature maxima are reached and this is roughly in line with impurity accummulation encountered in these shots. At the moment of pellet injection global Z_{eff} from Bremsstrahlung assumes values of 1.3 to 1.5 which increase on the time scale of about 1 s to values around 3-4 suggesting, supported also by conventional and charge exchange spectroscopy and neutron diagnostics, that n_D/n_e may be of the order of 50% to 80% only at the temperature maximum. Total radiation is not yet terminal for the total power balance, but it is certainly a candidate to limit the core performance.

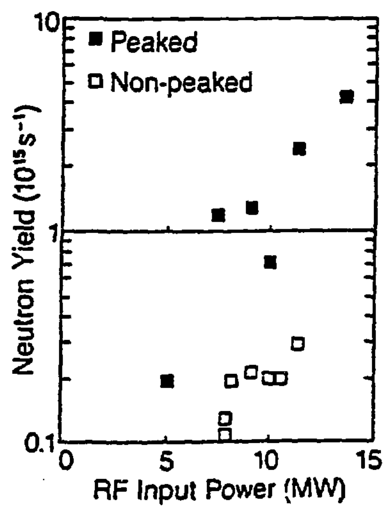

Fig.10

3.5 The $n_D(0)\ T_i(0)\ \tau_E(a)$ product rises up to maximum values in the order of $2\text{-}3{\times}10^{20}\ m^{-3}$keVs for the better ones of these shots but the correlation with the D-D neutron peak is not unique and more detailed work has to be carried out to understand the plasma conditions in the central core.

3.6 The above shots have in common that the ICRH has to be centrally deposited (off-axis heating did fail to exhibit the enhancement signature); most of them have been heated using the H minority scheme but ^3He minority heating can achieve the same effects suggesting that direct deuterium second harmonic heating does not seem to play a dominant role; also the choice of antenna configuration (most shots used dipoles, some however monopoles) does not seem to have a large influence.

3.7 The addition of neutral beams to the RF power does either little to boost the performance as judged from the T_e, T_i behaviour (the injected beam cannot reach the central core of these high density plasmas) or even deteriorates the performance in relative terms ((e.g. with respect to the $n_D(0)\ T_i(0)\ \tau_E(a)$ product). However, with the application of 28 MW of combined heating for this type of pulse (half of it RF, half of it NB) the highest neutron rates $7{*}10^{15}\ s^{-1}$ for these kind of shots have so far been obtained.

4. CONCLUSIONS

This enhanced regime, though transient on the time-scale of one second, is interesting because of its potential to permit in-sight into reactor relevant tokamak and plasma physics, and may provide an operational help of potentially igniting a tokamak. More work has to be done on the questions of stability in conjunction with appropriately tailored pellet deposition and heating profiles in space and time, and on impurity control.

Also work has to resume on the fuelling aspects of long-pulse high temperature plasmas, and it is hoped that the use of the 6 mm gun and the employment of a new high-speed launcher with pellet speeds around 5 kms^{-1} will allow in the next year to make progress in this field.

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