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Pellet fuelling and ELM triggering investigations at JET

P. T. Lang[1], A. Alonso[2], B. Alper[3], A. Boboc[3], S.Devaux[1], T.Eich[1], R. Felton[3], D. Frigione[4],
K. Gál[5], L. Garzotti[3], A. Geraud[6], S. Gerasimov[3], M. Goniche[6], J. Hillairet[6], J. Hobirk[1],
S.H. Hong[7], K.M. Kim[7], G. Kocsis[5], R. Koslowski[8], Y. Liang[8], T. Loarer[6], A. Loarte[9],
P.J. Lomas[3], M. Maraschek[1], H.W. Müller[1], Y.S. Na[7], F. Nave[10], I. Nunes[10], G. Petravich[5],
F. Poli[11], G. Saibene[9], R. Sartori[9], H.Thomsen[1], M. Tsalas, M. Valovic[3], R. Wenninger[2],
and JET-EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
1 MPI für Plasmaphysik, EURATOM Association., Boltzmannstr. 2, 85748 Garching, Germany
2 Laboratorio Nacional de Fusion, Euratom-CIEMAT, 28040 Madrid, Spain
3 Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK
4 Associazione EURATOM-ENEA sulla Fusione, CP 65, Frascati, Rome, Italy
5 KFKI RMKI, EURATOM Association, P.O.Box 49, H-1525 Budapest-114, Hungary
6 CEA IRFM, 13108, St Paul-Lez-Durance, France
7 Department of Nuclear Engineering, Seoul National University, Seoul 151-742, Korea
8 Institut für Energieforschung - Plasmaphysik, Association EURATOM-FZJ, D-52425 Jülich, Germany
9 FUSION FOR ENERGY, Joint Undertaking, 08019 Barcelona, Spain
10 Association EURATOM–IST, Av. Rovisco Pais, 1049-001 Lisbon, Portugal
11 University of Warwick, Coventry CV4 7AL, UK
*See the Appendix of F. Romanelli et al., Fusion Energy (Proc. 22nd Int. Conf. Chengdu) IAEA, 2008

INTRODUCTION

ELM mitigation via pacing and plasma fuelling are the two main roles of pellet injection in ITER. ELM triggering by pellet injection provides a promising method for reducing the ELM size as demonstrated on ASDEX Upgrade (AUG). By pacing, the ELM impact on plasma-facing components can be reduced. This should be achieved with the smallest possible impact on all other plasma parameters (besides ELM frequency). Hence, pellet injection for ELM pacing should use the smallest possible pellets and a shallow injection. The use of pellets in ITER requires their integration in ITER plasma scenarios in an effective manner for both fuelling and ELM pacing. However, a successful scaling to ITER from results of present day tokamaks requires sound physics understanding. For this purpose, detailed investigations of the local impact of the pellet imposed perturbation are performed both at AUG and JET.

For fuelling purposes, pellet injection has to maintain the plasma density and allow high density operation with minimum detrimental effect on energy confinement. This requires pellet penetration as deep as possible into the core plasma. Investigations on JET are under way to identify the best approach to achieve this goal, e.g. by comparing injection from the torus magnetic high field to low field side launch. While the first approach benefits - in hot plasmas - from strong drift effects, the latter has the potential for higher launch speed.

INJECTION SYSTEM

To meet requirements of both fuelling and ELM pacing a novel pellet launching system is under development and commissioning at JET. The High Frequency Pellet Injector (HFPI) project originally aimed to deliver small (variable size containing $0.6 – 1.2 \times 10^{20}$ D) pellets at up to 60 Hz rate and speed 50 – 200 m/s or large ($21 – 42 \times 10^{20}$ D) pellets up to 15 Hz and 100 – 500 m/s [1]. Launch towards the plasma is possible from the magnetic low field side (LFS), the vertical high field side (VHFS) or obliquely from the high field side (HFS) of the torus. The set up of the launching system as operated during campaigns C20-C27 (2008/2009) with the HFPI integrated into the pellet guiding system is shown in figure 1. Until the end of C26 (April 2009) the fuelling part was operational on plasma at up to 10 Hz rate, showing high reliability for LFS launch and suitable for occasional VHFS launch. The speed range spans from 50 to 250 m/s. An optimized setting was found for LFS launch at a speed of about

160 m/s for nominal 30 × 10^{20} D pellet size, delivering to the plasma about 60% of this particle inventory at 10Hz, corresponding to a particle flux of 1.8 × 10^{22} D/s. Upgraded prior to C27 (starting June 2009) the system is currently under re-commissioning in order to approach closer its design parameters.

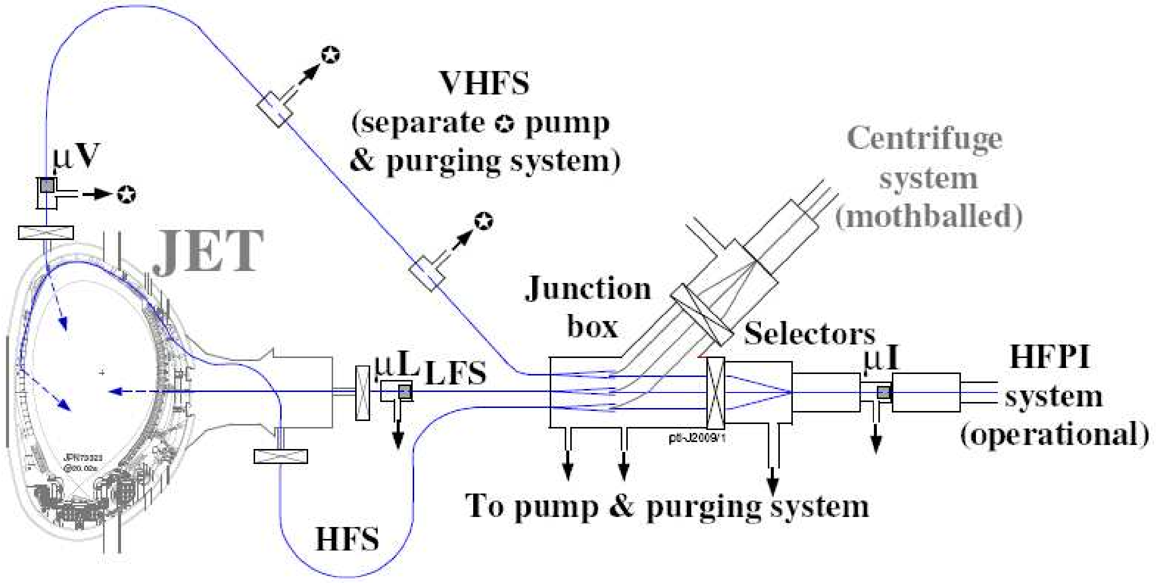
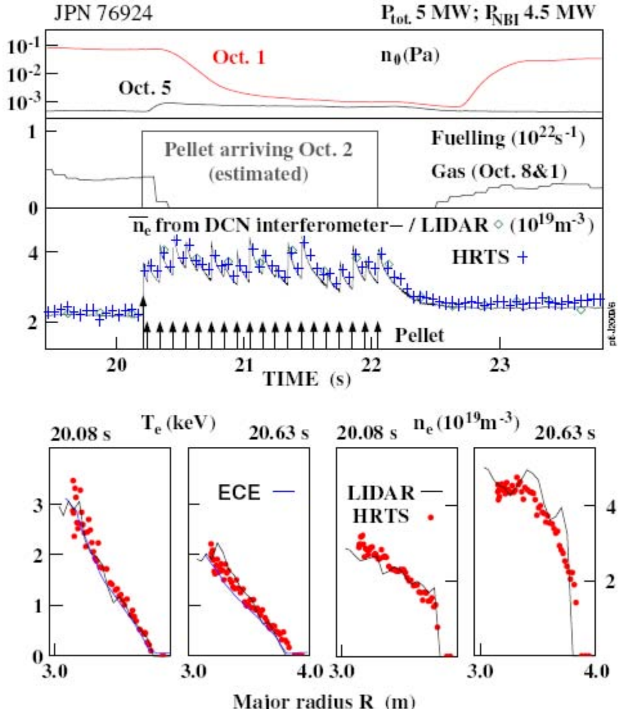


Figure 1: Pellet launcher set up as operated during campaigns C20-C27. Location of microwave cavities used for pellet measurements are indicated.

FUELLING RESULTS

Although not yet achieving its design criteria even for the fuelling part and in particular missing the option for high speed launch from the VHFS which is regarded as the most efficient, the pellet system provided reasonable performance for LFS fuelling at moderate speed and was hence applied in this mode on several occasions.



An example of the corresponding fuelling capabilities is shown in figure 2. Injection was performed at a speed of 102 ± 34 m/s (1.5 bar He propellant gas pressure). The arriving particle flux was estimated to be about 10^{22} D/s. During a phase with modest beam heating, pellets cause a massive increase in the density across the entire plasma cross section. Temperature profiles are changed almost adiabatically as the kinetic electron energy content remains essentially unchanged at half of the diamagnetic energy's magnitude.

Figure 2: Pellet fuelling from the LFS at moderate speed during phase with modest heating power. A significant elevation of the density level is achieved without causing a localized strong increase of the neutral gas pressure in the torus vessel.

Compared to gas puffing efficient particle deposition in the plasma is achieved without causing a burden on the unconfined neutral density in torus vessel. This can clearly be seen from the evolution of neutral gas pressure measured in the mid plane of Octants 1 and 5. While already a modest gas bleeding obviously results in a strong localized pressure increase, even strong pellet fuelling causes only a small and more homogeneous rise. This also allows efficient removal of the pellet induced particle flux out of the plasma, confirming an earlier finding for plasma configurations as applied here again with strike points placed close to the divertor pumping slots.

Baseline ELMy H-mode regimes (Comparison of gas and pellet fuelling)

Dedicated investigations were performed in the baseline ELMy H-mode regime to compare gas to pellet fuelling and also investigate combined gas and pellet fuelling. Two distinct plasma configurations were chosen, both at the same plasma current (2.5 MA) and edge safety factor (q_{95}=3.6, B_t=2.7 T) but one at low and one with high triangularity. In this first attempt the plasma response to an increasing gas rate injected from the divertor high field side was investigated, mainly in terms of density (monitored by the Greenwald density fraction f_{Gw}) and confinement (monitored by the ratio H98 to the value predicted by the IPB98(y,2) scaling). Taking the pure gas puff examples as basis and reference, LFS pellet injection was employed to replace the gas either partially or entirely.

For the low triangularity configuration (elongation κ=1.68, upper δ_u=0.18 and lower δ_l=0.35 triangularity) the expected performance was found ($f_{Gw}\approx0.7$, H98≈1.0) in the case of marginal fuelling, but it deteriorated when gas puffing in the range 0.6-1.8 × 10^{22} D/s was applied with no significant density enhancement. Stronger gas puffing even reduced f_{Gw}. This confinement reduction correlated with a changing ELM behavior from clear type-I into a regime with compound type-I/type-III events despite heating powers applied (up to 16.5 MW NBI and 6.6 MW ICRH) which are normally regarded as sufficient to stay in the type-I ELMy H-mode scenario. This behavior turned out rather typical for these plasma configurations at plasma currents beyond about 2.0MA while at lower currents still successful gas fuelling was observed. For the pellet fuelling case the same behavior was found with only about half the particle flux causing the same impact. Transport modeling of the post pellet phases indicated a reduction of the particle confinement when approaching higher densities.

Increasing the gas fuelling rate in configurations with high triangularity (κ=1.75, δ_u=0.43, δ_l=0.39) and ~16 MW heating power (dominant NBI and ~2 MW central ICRH); first it results in higher density at the expense of a modest confinement reduction while the type-I ELM frequency rises. Further raising the gas rate leads to (here with 2.6 × 10^{22} D/s) a regime with enhanced particle and energy confinement ($f_{Gw}\approx1.05$, H98≈1.0) while the ELM frequency drops, but a further enhancement causes a transition into the type-III regime and significant confinement reduction. Operation in the regime with enhanced confinement was a deliberate reproduction of the so called HT3 scenario found as one of the options to establish high density and confinement at JET in a recent investigation [2]. High performance and low ELM frequencies correlated with a broadband MHD fluctuation in the range around 20 kHz, identified as a wash board mode and regarded as mixed type-I/II ELM regime. Pellet injection terminated this MHD activity and no access to the regime showing highest performance could be achieved any more. Operating outside this regime, pellets could enhance the density efficiently replacing the gas puff. And as for low triangularity, compared to gas puffing significantly less particle flux was required to achieve the same fuelling impact.

Compensation of density pump-out in ELM mitigation scenarios

Creating static low n (1,2) resonant magnetic field perturbations (RMP) by a set of four error field correction coils (EFCC) was found to mitigate ELMs by increasing their frequency. However, this correlates with a significant reduction of the density due to the EFCC density pump-out effect for ELMy H-mode plasmas. Recent experiments (reported in detail elsewhere [3]) achieved a full density compensation up to f_{Gw}=0.73 in low triangularity plasmas by gas fuelling and pellet injection. Yet again pellets showed higher efficiency since less particle flux was required to establish full density recovery for the reference scenario (pellets 0.8:, gas: 1.2 × 10^{22} D/s). In addition, full density recovery to the initial value was achieved much faster (about 0.7 s instead of 2.2 s) by using pellet re-fuelling.

RESULTS FROM ELM CONTROL AND ELM TRIGGER EXPERIMENTS

First attempts on ELM pacing were made with the available system parameters restricted to fuelling size pellets, thus oversized for pacing. Applying pellets at the maximum rate of 10 Hz and the smallest possible size pacing was tried in both the low and high triangularity configurations described above with heating powers adjusted to achieve low spontaneous ELM frequencies. In both scenarios sufficiently low values below 10 Hz could be achieved, however the high triangularity plasmas responded too positively to pellet fuelling. In this case the density induced ELM rate increased too far beyond 10 Hz for reasonable pacing.

ELM pacing demonstration at 10 Hz

For the low triangularity case lower confinement less efficient fuelling restricted the pellet impact on the plasma density and on the spontaneous ELM frequency just leaving a marginal operational window to establish pacing at $f_{Pel} = f_{ELM} = 10$Hz. This example is shown in figure 3.

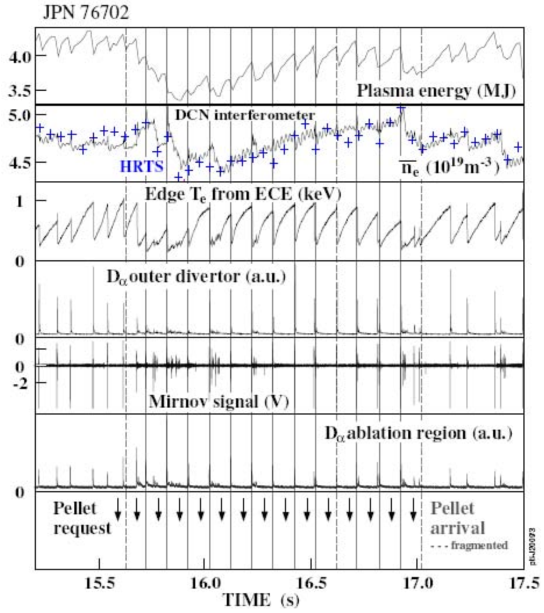


Figure 3: Confirmation of the ELM pellet pacing technique at JET. Pellets injected at 10 Hz rate establish a full control of the ELM frequency. Using the fuelling system results in significant density enhancement and convective losses reducing the confinement. With the pacing system under commissioning a pellet frequency of 60 Hz is envisaged applying only 15% of the pellet particle flux requested here.

ELM triggering investigations

A direct comparison of spontaneous and triggered ELMs can be obtained by comparing phases with pacing within reference discharges. In addition, phases where the spontaneous ELM frequency exceeds the pellet rate, like during the pacing attempt in a high triangularity configuration, can be used for such an analysis. Here, the pellet perturbation triggers an ELM or at least an ELM-like event within a spontaneous ELM cycle and phases where a mixture of triggered and spontaneous ELMs co-exists also occur. More detailed results from these investigations can be found elsewhere [3-6]. There is no significant impact on the pellet ELM trigger potential in cases where the magnetic configuration is perturbed by field ripple or the EFCCs [3]. The triggered ELMs look like the spontaneous ELMs in the type-I and type-III regimes, for example the toroidal mode number spectrum of the magnetic perturbation during the ELM are the same [4]. Triggered ELMs show a reduced peak power arriving at the outer divertor target with a slower rise and decay [5]. A filament originating from the pellet ablation location sets on at the same time as the ELM induced MHD activity recorded by the Mirnov diagnostics [6].

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