Experiments on Plasma Fuelling and ELM Control by Pellet Injection on JET

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First plasma injection experiments with the pellet centrifuge, which came into operation on JET during the last year, have been conducted. The centrifuge has been designed and built at JET, using a Garching type of rotor/stop cylinder arrangement, for injection of long-pulse pellet trains or sequences of order 1 minute at moderate pellet speeds and is therefore equipped for the appropriate gas handling requirements. Two pellet extruder units of novel design - with an ice reservoir of up to 150 cm^3 - are capable of launching cubic deuterium pellets of 2.7 and 4.0 mm at velocities ranging from 50 to 600 m/s with repetition rates so far up to 5 Hz. Problems with the acceptance of pellets in the rotor hub have lead to pellets missing from the sequence delivered to the plasma. Injection is performed from the plasma outboard side and along the curved pellet track horizontally about 300 mm below the midplane of the plasma, co-injecting at 15°. Pellets are characterised with regard to timing, speed and size when they traverse and de-tune two μ-wave cavities on the flight to the torus; the absolute size calibration has been checked against the highest achieved plasma content increase in ohmic plasmas. The arrival of pellets in the plasma is detected by a diode collecting light from the pellet plume (due to a marginal solid viewing angle this signal indicates a minimum penetration depth). For nominal 4 mm pellets the average particle flux to the plasma was up to 1.4×10^{22} deuterons/s and this fuelling rate can be sustained for up to 20 s (i.e. 100 pellets).

For reference and comparison to past pellet experiments with a pneumatic launcher, the centrifuge fuelled ohmic plasmas with pellets which showed very high fuelling efficiencies of up to 88 %, despite the shallow deposition to about 1/3 of the minor radius. Together with the build-up of the plasma density its profile peaked and this lasted for about 1 s after the termination of the pellet string: in so far the pellets acted like in the earlier JET experiments.

Various refuelling scenarios were probed with the aim to enhance the flexibility in density control, in particular, to increase the density over and above what has been achieved with strong gas puffing. Pellet trains, without and with additional gas puffing, were injected during quasi-stationary L- and H-mode phases of neutral beam and ICRH heated discharges up to a level of 12 MW in total. Generally, the commonly observed decrease in penetration with increasing auxiliary heating power is accompanied by a decrease in fuelling efficiency. In particular, in the cases with 2.7 mm pellet trains into 12 MW ELMy H-mode plasmas the pellets can hardly be noticed in the noise of the ELM activity. With 4 mm pellets, in general, pure pellet fuelling acted faster and more efficiently than gas puffing in the density build-up but did in the end only marginally exceed the density obtained by gas fuelling. Combining both methods has shown advantages for fast density rises to maximum values of of 85% of the Greenwald limit so far. At these power levels, pellet induced particle losses do not seem to contribute significantly to the bulk plasma energy losses connected with ELM activity.

These main features can be seen in the following examples of 2.5 MA / 2.5 T high-triangularity (δ=0.3) type I ELMy H-mode discharges: 4 mm pellets of about 3.10^{21} deuterons each are injected at 240 m/s and 5 Hz into shots # 39988/91 without gas fuelling and # 39992 combined with gas fuelling (at a rate of about 5.10^{21} deuterons/s) during the phase of 8-9 MW of neutral injection (starting at 17 s). Fig.1 shows the torus outer divertor Dα-signal for the 3 pellet shots adjacently with their pellet train and those for the comparison shots # 39989/90 without pellets nor additional gas feed where "natural" ELMs do not start before 18.4 s. From the pellet Dα-light a penetration depth of 35 to 38 cm into the plasma is derived which is surprisingly deep (compared to code predictions) but otherwise in qualitative agreement with the plasma temperature profile development seen in fig. 2 below. Each pellet appears in the torus Dα-signal as a giant ELM of about 1.5 msec duration, starting with some delay of up to 1.5 msec after the pellet reaches the plasma, and a similar signature is found in the camera pictures of the divertor in the light of Bremsstrahlung, Carbon II (C II), and in the infra-red camera (measuring mainly the tile surface temperature), with the main activity showing up near the inner divertor strike zone as is typical for the ELMs on JET. We are unable to distinguish the pellet signature from that of a natural ELM, except for the fact that, expanded in time, a pellet

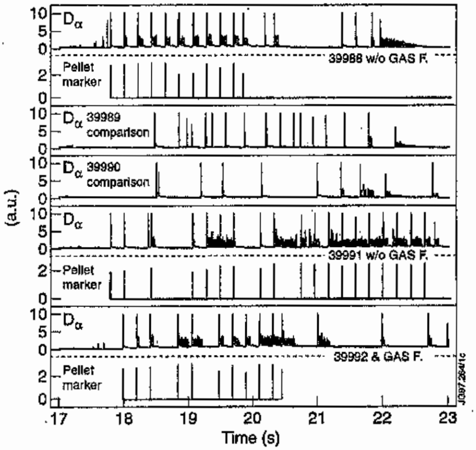

Fig.1: Dα and pellet marker traces for 5 JET pulses

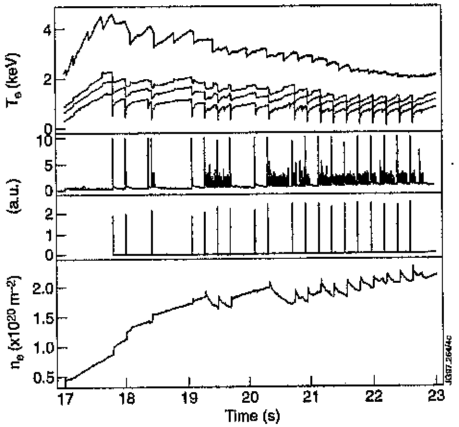

Fig. 2: Electron temperature and line density versus time in relation to the pellet sequence for # 39991

ELM signal in comparison may have an initial small Dα-step on the time-scale of the pellet penetrating the outer plasma layers and that the outer plasma region is left after the induced ELM with an excess of particles rather than a deficiency as in the "natural" ELM case. The first pellet induced ELMs show a relatively clean signature whereas the later ones are successively followed by small or extended periods of small ELMs. Figure 2 shows on top 4 temperatures versus time at positions of 6, 13, and 36 cm into the plasma as well as on axis: The 3 outer traces clearly exhibit the direct pellet impact whereas the center is mildly affected but is also saw-toothing asynchronously. The lowest trace is from the central line density chord of the interferometer: The first three pellets show positive density steps followed later by positive short-lived excursions only, these usually accompanied by the small ELM activity. Smoothed line averaged density traces of the five pulses in Fig.3 indicate that the early regular pellet pattern of # 39988 and 39992 leads to a slightly faster density rise. However, the plasma particle content is on average already nearly constant 1.5 s into the heating pulse - approaching 85 % of the Greenwald limit marked on top of the diagram - although each pellet has sufficient particles to raise the entire plasma density instantaneously by at least 50 %. The radial density profile is for the first seconds very flat and the density reflectometer confirms that the outer indicating profile is hardly affected by the pellets on the time scale of >10 msec. Fig.4 shows the development of the radial temperature profile for the 3rd pellet in # 39988 as seen by the ECE which shows a dramatic temperature drop on the millisecond

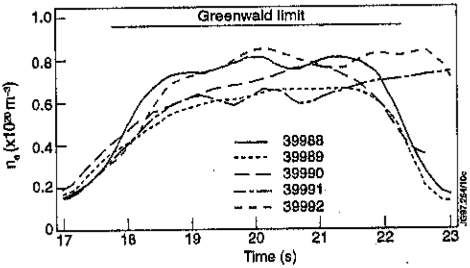

Fig. 3:Line averaged densities (smoothed) versus time

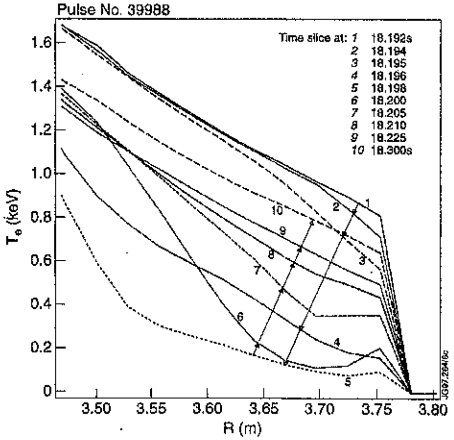

Fig. 4: Outer radial electron temperature profile of a pellet induced ELM for # 39988

scale with comparatively slow re-heating. Apart from the astounding fact that the plasma tolerates so large disturbances at all the pellet induced ELM - ejecting roughly the equivalent of the particles injected with the pellet - the ITER H89 scaling factor is 1.8 ± 0.2 and the convective loss per pellet are in the order of 5-10 % of plasma energy (ca 4-5 MJ), both as inferred from the negative jump of diamagnetic loop signal and estimates from the drop in the electron temperature, and is therefore of the same order as that by giant ELMs. However, the CII camera signal from the divertor looks qualitatively much less dramatic. We presume that the energy transported into the divertor by a quantity of particles at least an order of magnitude larger than by natural ELMs may have a beneficial effect for the instant load onto the divertor plates. This is also supported by the observation that with larger gaps in the pellet train the subsequent pellet induced ELM creates a larger CII signal. Moreover, the size of the pellet induced ELM may depend on pellet size, penetration and repetition frequency and this leaves some room for further optimisation attempts. There is also good evidence that the high flow of pellet material towards the divertor does wash out Nickel impurities which otherwise will build up in the plasma.

<u>In conclusion:</u> First pellet injection experiments with the new centrifuge have demonstrated for these medium power type I ELMy H-mode discharges that ELMs can be triggered by large pellets without the plasma reverting to L-mode and with possible beneficial effects for the instant divertor power loading. If this can be shown also for higher performance discharges, possibly with more optimised pellet parameters, this would give some perspective for ELM control on ITER. Despite the launching of pellets clearly beyond the confinement barrier and the recycling zone the investigated plasmas resist the build-up of much higher densities than can be achieved with gas puffing.