ELM pace making and amelioration at ASDEX Upgrade

P.T. Lang*, J. Bucalossi^o, A. Degeling$^\diamond$, O. Gruber, G. Haas, L.D. Horton, J. Lister$^\diamond$,
S. Kalvin†, M. Kaufmann, G. Kocsis†, Y. Martin$^\diamond$, P.J. Mc Carthy‡, V. Mertens,
R. Neu, J. Neuhauser, T. Pütterich, W. Schneider, C. Sihler, A.C.C. Sips,
W. Suttrop, W. Treutterer, and the ASDEX Upgrade Team

Max-Planck-Institut für Plasmaphysik, EURATOM Association,
Boltzmannstr. 2, 85748 Garching, Germany
^{o} CEA Cadarache, 13108 St Paul-Lez-Durance Cedex, France
$^\diamond$ CRPP-EPFL, Assoc. EURATOM-Confédération Suisse, 1015 Lausanne, Switzerland
†KFKI-RMKI, EURATOM Association, P.O. Box 49, H-1525 Budapest-114, Hungary
‡ Physics Dept., University College Cork, Association EURATOM-DCU, Cork, Ireland
* Corresponding author; e-mail: ptl@ipp.mpg.de

1. Introduction

One key scientific program conducted at several major tokamak experiments is dedicated to further consolidation of the ITER reference scenario, the type-I ELMy H-mode. A main goal is to establish an operational scenario combining both high confinement and acceptable ELM imposed power loads on the divertor plates. ELM pace making enhancing the ELM frequency f_{ELM} beyond the intrinsic value f_0 and hence accordingly ameliorating ELMs is one option being considered for this task. Techniques currently under investigation aim to manipulate the ELM frequency by altering the pressure gradient and/or current profile in the steep gradient zone of the transport barrier at the plasma edge. Strong local perturbations are expected to trigger ELMs almost instantly on a sub-ms time scale. A gradual change of the ELM behaviour should take place in cases of control tools altering profiles over the entire toroidal circumference. Different techniques are under investigation currently at ASDEX Upgrade, recent results will be reported here.

2. Experimental setup

For the study presented, we usually used a lower single null (LSN) configuration with $I_P = 1MA$, $B_t = -2.7T$, $q_{95} = 4.9$, $\kappa = 1.6$, $\delta^u = 0.12$ and $\delta^l = 0.37$. The applied neutral beam injection (NBI) heating of about 5 MW, just above the L-H transition power threshold, results in stable and robust operation in the type-I ELM regime with rather low natural ELM frequency as desired for demonstration of active ELM frequency control. Depending on the actual wall conditions, discharges developed a natural ELM frequency in the range 25 to 45 Hz.

Different techniques were tried to trigger ELMs: injection of cryogenic solid pellets or a supersonic molecular gas jet composed of Deuterium (D) or magnetic triggering, relying on a fast motion of the plasma column in a spatially asymmetric flux configuration. The pellet injector is capable of delivering up to 120 pellets at a speed of 1 km/s. To prevent strong refueling smallest pellet sizes of about 1×10^{19} D-atoms, still keeping the delivery reliability high, were injected [1]. In this setting, pellet repetition frequencies $f_P = \frac{250}{n}, n = 3, 4, 5...$ can be obtained. The Supersonic Pulsed Injector (SPI) [2] delivered a molecular D jet of typically 2 ms duration, containing a particle amount of $1-5 \times 10^{19} D_2$. The diameter of the laval nozzle throat is 2 mm, the jet speed 1.8 km/s. It was installed at the torus low field side (LFS) slightly above the horizontal midplane, distances to the plasma separatrix were altered between 6 and 9 cm. Due to the low repetition rate of 2 Hz, only a trigger proof-of-principle experiment was feasible.

For the plasma movement required for magnetic triggering we relied on the feedback controlled plasma position and shape control system [3]. Actuators are the poloidal magnetic field (PF) coils. Two of them are fast position control coils with 1 ms response time. This allowed for a reliable and reproducible performance of the plasma position waveform with a control cycle time set to 3 ms. Chosen driving frequencies for the vertical (z) motion were in the range of about 50 Hz, higher frequencies suffered from a reduced realized amplitude with respect to the required one. To avoid resonant excitation of the whole vessel or partial structures, operation below 30 Hz and above 90 Hz was avoided. The system allows control to amplitudes of the plasma contour up to about 6 cm at an absolute precision of about 0.5 cm.

3. Results

3.1. Pellet injection

Using the pellet injection tool is the currently most advanced method to control ELMs. A dedicated study on operational features and the physics background of the trigger mechanism has recently been published [4], so just main results are highlighted in this context. It was demonstrated pellet induced ELM control can fulfill the three basic requirements required with respect to operational concerns:

• impose external ELM control and enhance f_{ELM} beyond f_{ELM}^0

• keep the plasma confinement high

• reduce the ELM power P_{ELM}.

A demonstration that pellet injection can resolve the intrinsic deadlock between confinement and f_{ELM}/P_{ELM} was performed in the matching experiment shown in figure 1. A gradually increasing gas puff was employed in the reference discharge in order to match a phase containing a pellet sequence of maximum repetition rate $f_{Pel} = f_{ELM} = 83.3 Hz$. Highlighted phases show almost perfect matching, as can be seen e.g. by the virtually identical density and temperature profiles. Clearly, $f_{ELM}^0 = 51 Hz$ realized in the gas puffed discharge is less than $f_{ELM} = 83 Hz$ imposed by ELM pace making. Thus, f_{ELM} was established as a free parameter in the ELM control approach. Pace making results also in a smoother evolution of W_{MHD} and less pronounced ELM losses.
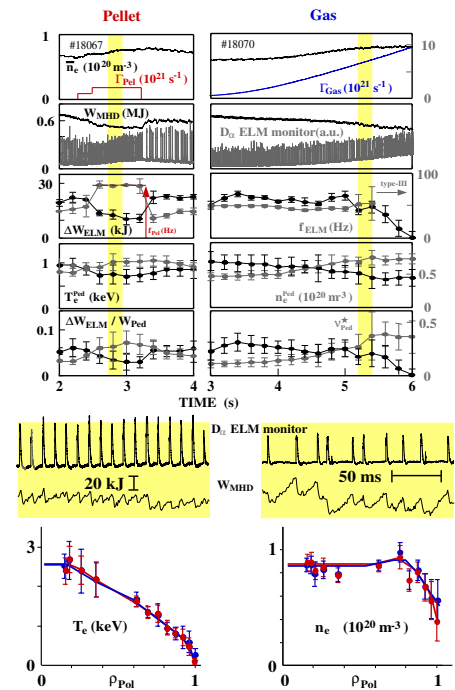

Figure 1: Plasma parameter matching (according periods marked by shading) of discharge with pellet ELM pace making and with gas ramp. There is a striking difference in the ELMing behavior as the pace making establish $f_{ELM} = 83 Hz > f_{ELM}^0 = 51 Hz$.

Several investigations dedicated to ELM physics showed that, at least at the available spatial and temporal resolution, the evolution of a triggered ELM is indistinguishable from an intrinsic one in case of sufficiently small pellet sizes.

3.2. Supersonic molecular beam

A main intention of the investigation of the supersonic gas jet was the wish to avoid the technical complexity of a cryogenic pellet system. It was hoped the strong local perturbation initiated by the molecular gas beam would be sufficient to provoke an ELM. As the low repetition rate of SPI does not allow for real ELM controlling, we investigated its impact on the subsequent ELM. Therefore, we performed gas jet injection in long phases with a stable but low intrinsic ELM frequency otherwise stable against the impact of the gas pulse. We found the gas jet does not immediately trigger an ELM but can result in premature ELM release. The stronger the applied particle flux, the earlier the appearance of the next ELM. This can be clearly from figure 2. Here, the time elapsed at the ELM onset since the gas jet was injected is correlated with the density enhancement induced by the gas jet.

Variation of the distance SPI to separatrix does not alter this situation. We conclude the local perturbation of the gas jet not yet strong enough to trigger an instant ELM. However, strong edge fuelling causes an accelerated pressure increase in or close to the plasma pedestal region finally resulting in a somewhat faster onset of the next ELM event. Of course this mechanism can be used to enhance the ELM frequency as well. However, gas amounts required in order to sufficiently fast response would about equal the gas bleed particle flux resulting already in an enhancement of the intrinsic ELM rate to the same amount. Thus, at least at ASDEX Upgrade, gas jet injection seems to offer no advantage for ELM frequency controlling.
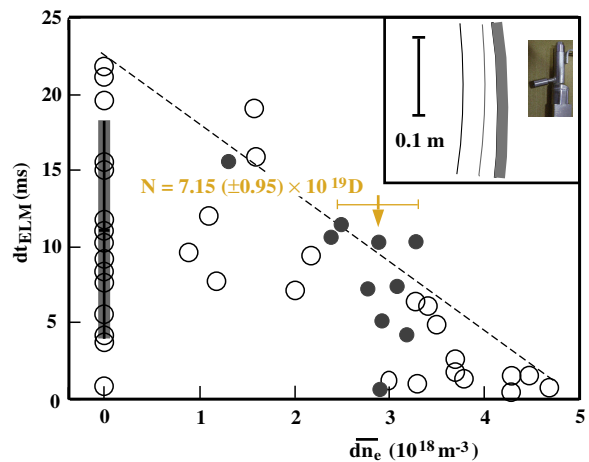

Figure 2: Time elapsed between gas jet injection and consecutive ELM versus applied gas amount. Variation of the distance SPI - separatrix (9 cm open circles, 6 cm grey dots, see also inset) does not show significant impact.

3.3. Electromagnetic triggering

The method of magnetic triggering has been discovered and developed at TCV in ohmic plasmas for type-III ELMs [5]. We have applied this method successfully now also in auxilliary heated plasmas reaching the ITER reference type-I ELM regime. Our experiments at ASDEX Upgrade showed successful locking of the ELM frequency to the plasma motion. In steady state, one ELM is triggered per cycle, the ELM frequency thus becoming identical to the driving frequency. By this means, the ELM frequency can be shifted both up and down, in this first approach a range of $0.75 - 1.8$ times the initial ELM frequency was achieved. The amplitude of the imposed vertical motion required to gain complete control was found to be about 12 mm, twice the value of the plasma motion observed during an intrinsic ELM event. This value required could not be realized for the highest requested driving frequencies, so the achieved frequency range seems to be restrict rather by technical than physics limits. Triggered ELMs still show clearly type-I features, with respect to their dynamics and spatial structure no difference with respect to intrinsic ELMs was found.

Further, energy loss and divertor power flux measured for triggered ELMs agree well with scalings derived from intrinsic ELMs. Thus, ELM mitigation seems feasible in case of external ELM frequency enhancement by magnetic triggering. Figure 3 displays the ELM probability and plasma density and energy evolution during a motion cycle, obtained by boxcar averaging an entire control sequence lasting for 0.5 s. In this case, the retardation of plasma motion by change results in an almosted inverted evolution of requested and realized plasma motion. ELMs were found to be triggered at highest probability when the plasma down shift velocity reaches its maximum. Due to a CLISTE analysis [6] this corresponds to the minimum in the pedestal current evolution. Destabilization of the ELMs by reducing the pedestal current is opposite the behaviour expected from the peeling-ballooning nature attributed to the ELM boundary and as well to TCV observations. The reason for this behaviour is not yet clear.
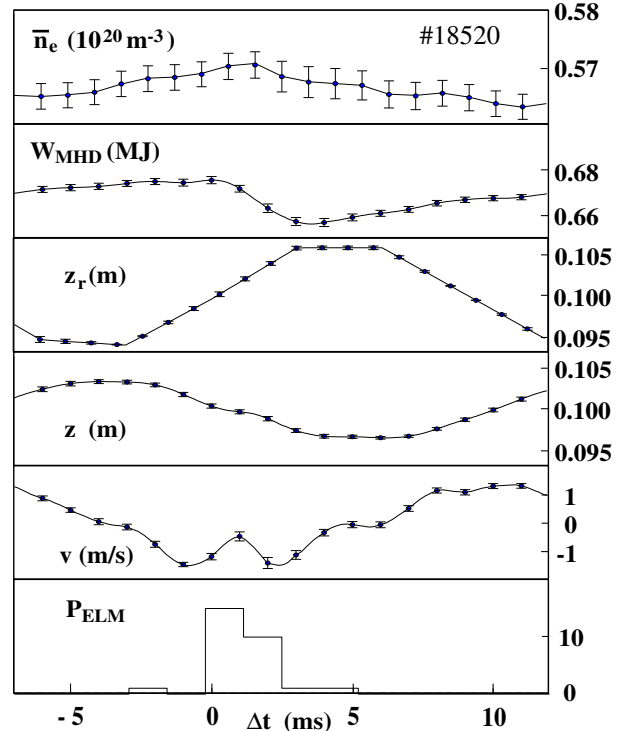

Figure 3: Requested and achieved plasma motion and resulting ELM occurrence probability obtained by boxcar averaging (1 ms bin width). In LSN configuration ELM triggering happens preferentially while the plasma moves downwards.

4. Conclusions

Our investigations prove externally imposed control techniques can change the ELM frequency. Frequency enhancement can result in amelioration of the single ELMs. Moreover, the approach can maintain plasma operation at a high performance level. Several different techniques were investigated. Both pellet injection and magnetic triggering have been shown their potential to act as useful control tools. This yields the option to choose eventually the most appropriate technique for a given scenario. Furthermore, results obtained can provide a better insight in the physics and dynamics of ELM events.

References
[1] P.T. Lang et al., Nucl. Fusion **41** (2001) 1107.
[2] J. Bucalossi et al., 19th IAEA, Lyon (2002) EX/P4-04.
[3] V. Mertens, G.Raupp and W.Treutterer, Fusion Technology **44** (2003) 593.
[4] P.T. Lang et al., Nucl. Fusion **44** (2004) 665.
[5] A.W. Degeling et al., Plasma Phys. Control. Fusion **45** (2003) 1637.
[6] P.J. Mc Carthy et al., 30th EPS , St.Petersburg (2003) P1.064.