Topic: EX-C

Optimization of Density and Radiated Power Evolution Control using Magnetic ELM Pace-making in NSTX

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The most promising confinement mode of present tokamaks—the H-mode—commonly exhibits edge-localized modes (ELMs). While they pose a threat to plasma facing components (PFCs), ELMs have the beneficial effect of purging impurities and particles from the plasma, allowing stationary discharge conditions to be achieved. This is part of the reason for adopting the ELMy H-mode as the reference scenario for ITER, and any alternative scenario must include a mechanism for providing sufficient particle and impurity transport. Recent experiments at the National Spherical Torus Experiment (NSTX) have shown that lithium coating of the PFCs leads to improved energy confinement [1], and also the complete suppression of ELMs [2,3]. Due to the lack of ELMs, however, such plasmas suffer from density and radiated power that increase throughout the discharge, often leading to a radiative collapse. Previous experiments have shown that ELMs can be controllably restored into these lithium-conditioned discharges using 3D magnetic perturbations, which reduces impurity accumulation [4]. Here we present the optimization of the use of magnetic ELM pace-making to control the evolution of the density and impurity content, aimed towards bringing lithium-enhanced plasmas to stationarity.

Previous experiments showed that when a threshold 3D magnetic perturbation is applied during an ELM-free H-mode, ELMs are destabilized [5]. The applied n=3 perturbation contains significant resonant as well as non-resonant components (Figure 1), and when applied leads to a steepening of the pedestal electron temperature gradient, which is calculated to destabilize low-n (2-4) edge modes [4,5]. To perform ELM pacing using magnetic triggering, the waveform of the applied field was optimized to maximize ELM frequency and minimize magnetic braking of the plasma rotation. Rather than DC fields, short duration large amplitude pulses were used, so that the threshold field inside the vessel (the coils are external, and the vessel penetration time is ~4 ms) was reached and ELMs triggered quickly, and the field then removed. A second improvement was made by adding a negative-going pulse to each of the triggering pulses. This second pulse was used to counteract the vessel eddy currents, bringing the 3D field inside the vessel towards zero more quickly following an ELM, reducing time-averaged braking.

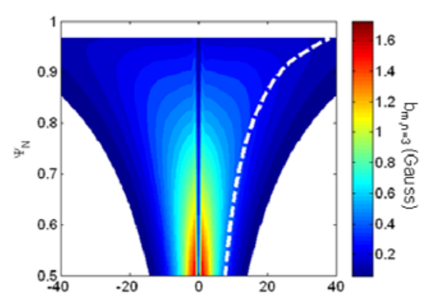

Figure 1: Poloidal spectrum of the applied n=3 perturbation, with resonant values highlighted by dashed white line

With these improvements to the triggering waveform, the frequency of the triggered ELMs was increased to over 60 Hz. This reduced the average ELM size from $\Delta W/W_{tot}$ ~ 15% at 10

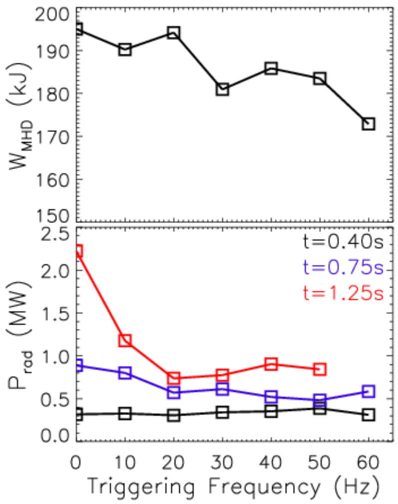

Figure 2: Dependence of the a) time-averaged stored energy and b) total radiated power on n=3 pulse frequency

Hz ELM frequency to the lowest achieved value of ~5 % at 60 Hz triggering. These ELM sizes are roughly consistent with sizes of natural, large type-I ELMs in NSTX. The optimum frequency for attaining impurity control while minimizing energy confinement reduction was determined (Figure 2). Fairly low frequency ELMs (20 Hz triggering) are sufficient to keep the total radiation under 1 MW throughout the discharge and avoid radiative collapse (although P_{rad} is not stationary), with little reduction in the plasma stored energy (Fig 2a). This confirms that ELM pacing by this technique can be used to increase the particle transport and provide impurity control while maintaining high energy confinement [5].

The optimized triggering was combined with improved particle fuelling to further improve control. In these experiments, the fuelling of the plasma during startup was partially done using a supersonic gas injector [6], which can be rapidly shut off to reduce fuelling during the current flat-top. The results are shown in Figure 3, where the red lines correspond the case with ELMs triggered (the triggering time can be seen in the magnetic pickup signal shown in the second frame, which exhibits the 3D field pulses beginning at t=0.4 s). When the triggering begins at t=0.4 s, the line-averaged electron density and total radiated power both become stationary, with the secular increase typically seen entirely arrested. This period of stationarity is terminated by the onset of a rotating n=1 MHD mode (panel b), which commonly arises during triggering experiments. While this optimized technique has been successful in achieving stationarity in these global parameters, the profiles of the density and radiation continue to evolve (the core values increase in time, the edge decreases). Control of the core evolution will be attempted by raising T_e with high-harmonic fast wave heating, as has been shown on ASDEX-Upgrade using central ECRH to avoid impurity accumulation [7].

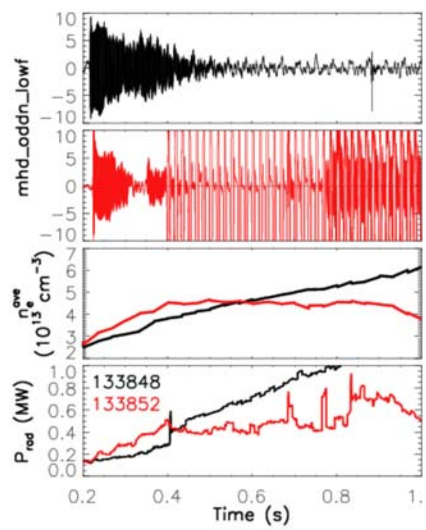

Figure 3: Discharges with improved fuelling only (black) and combined with ELM-pacing (red): a) and b) odd-n MHD activity, c) line-averaged electron density and d) total radiated power

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