Development of high confinement regimes without ELMs: A strength and priority of the US MFE program

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Summary: Fusion's success could hinge on the avoidance of transient divertor loading from ELMs. Multiple avenues for ELM amelioration are desirable, in order to ensure a viable solution exists for ITER and beyond. The US program is a world leader in developing high-confinement regimes that are naturally free of ELMs, and should consider their continued development a high priority. Future advances will require maintaining expertise, experimental capabilities and operational time.

When burning plasma devices operate in future years, they will be constrained severely by two requirements. They must possess high energy confinement, leading to substantial fusion gain, and they must avoid triggering macroscopic MHD instabilities that could lead to loss of plasma quality or, worse, damage to the device itself. ITER is at serious risk of failing to satisfy both of these requirements. This is because the design of the ITER Q=10 scenario, essential to completing its mission, is based on the conventional H-mode confinement regime [1], which almost universally exhibits edge-localized modes, or ELMs. These are explosive instabilities originating in the steep gradient region at the plasma edge, and while they do little to no harm on existing experimental devices—and indeed are usually necessary in order to flush the plasma core of radiating impurities—projections of natural ELM size to ITER indicate significant damage to divertor surfaces is a near certainty [2,3]. Projections to DEMO and beyond become even direr, given the need for continuous operation at three times ITER's energy density; *ELMs are simply unacceptable in a reactor*.

In order to make ITER successful, the fusion community has been working busily to develop ELM amelioration and avoidance techniques. Here the challenge is to simultaneously: (1) prevent the origination of *any ELMs* with energy loss greater than about 0.5% of the total plasma stored energy, (2) maintain a value of normalized confinement near that characteristic of conventional H-modes, which have ELM energy losses closer to 10—20%, and (3) provide a mechanism for regulating particle and impurity transport such that the core plasma does not become overly radiative, leading to confinement collapse. Active control techniques being pursued include application of resonant magnetic perturbations [4] and the injection of pacing pellets [5]. While both techniques have been shown to mitigate, and in some cases, completely suppress, ELMs, there remain serious questions about extrapolating the techniques to burning plasmas. Particular concerns for ITER include compatibility with divertor power handling requirements, consequences for core fueling and effects on energy confinement. [3] The size of the penalty paid in confinement is of primary concern; because both techniques by necessity reduce the peak edge plasma pressure, there is inevitably some reduction in energy confinement, *which has not yet been realistically accounted for in ITER scenarios*. Finally, extrapolating these techniques to DEMO becomes even more challenging, due for example to limitations on placing complex coils close to the plasma and the even lower requirement for fractional ELM energy loss (~0.1%).

An alternative approach to the ELM problem, which should be pursued in parallel, is to develop high confinement regimes that avoid ELMs through continuous pedestal transport regulation, which can be generated naturally in tokamak plasmas under some circumstances, and which *does not require* *sophisticated engineering of external control systems*. Leadership in this area has been strongest in the US, which has seen the development of high performance EDA H-mode [6], I-mode [7] and QH-mode [8] plasmas; the first two were pioneered on Alcator C-Mod and the third developed on DIII-D. These are examples of regimes which routinely satisfy all three of the above requirements, accessing stationary, high performance pedestals through continuous edge relaxation mechanisms. They represent a class of plasmas which provide an attractive alternative to conventional ELMy H-mode, when projected to burning plasma operation. QH-mode and I-mode both appear naturally compatible with the collisionless pedestal required in a burning plasma. EDA H-mode is less prevalent at low collisionality, although recent advances are extending its operation to lower-density, hotter plasmas, using ITER-relevant wave heating tools [9]. These types of confinement regimes merit serious consideration for ITER scenario development, and the capability to extrapolate them to burning plasmas should be sought aggressively. Other solutions may await discovery.

The importance of this issue was evidently recognized by the community and OFES, which plans a Joint Research Target on the topic in FY13. Now this effort is put in jeopardy by OFES's proposal to cease operations at Alcator C-Mod and severely reduce utilization of DIII-D. Resources for edge theory and modeling are also facing steep declines. Under these constraints, US investigators will find it difficult, if not impossible, to meet the following research requirements:

- Exploration and assessment on multiple devices of different scales and parameters. *It is impossible to confidently extrapolate to ITER and beyond based on a single device.*
- Sufficient run time to vary plasma parameters, and flexibility to explore promising new phenomena and regimes that may be observed. *Medium scale facilities such as Alcator C-Mod are ideal in this regard. With ITER relevant parameters but lower operating costs, and smaller teams, they can readily adapt campaign plans to investigate interesting new phenomena*
- Collaboration with theory and simulation to understand the physical mechanisms underlying the regimes.
- Development and retention of experts familiar with these scenarios. *US researchers are already working to replicate I-Mode and QH-mode on international devices. Their expertise is at risk of being lost if domestic research is terminated.*

In summary, development of high performance regimes without ELMs may prove essential to the success of fusion. The US is currently, and should remain, a world leader in this area. Progress has been significant, but future advances will go only as far as available personnel, experimental capabilities and operational time allow.

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