Adaptive Real-Time Pedestal Control for DIII-D and Prospects for ITER

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Abstract: A comprehensive adaptive real-time (rt) ELM control system that exploits key properties of ELM physics, Resonant Magnetic Perturbation (RMP) ELM suppression physics, and an extensive set of diagnostic inputs to make real-time decisions about the control of multiple actuators to sustain ELM suppression/mitigation leads to improved performance at DIII-D. The control experiments showed the path dependence and hysteresis of plasma confinement and performance recovery: even for the same final perturbing 3D currents, starting with higher initial 3D currents leads to lower recovery down the path. This demonstrates the need for a control system to keep the ITER RMP perturbations close to the ELM suppression threshold at all times. The development at DIII-D initiates progress toward adaptive pedestal control, and includes pedestal profile control as well as ELM suppression/mitigation. 3D coil phasing for RMP ELM suppression is adjusted in real-time based on SURFMN calculations of the vacuum edge pitch-resonant, and kink-resonant harmonics of the applied 3D magnetic perturbation and offline IPEC data. The amplitude of the 3D coil is regulated to achieve a given ELM frequency (or none) using ELM detection based on the D_α measurements from the divertor region. For pedestal control, the Plasma Control System (PCS) acquires real-time Thomson scattering diagnostic data and fits the pedestal width/height for temperature and density profiles. Based on the Thomson fits, the PCS regulates the pedestal density by adjusting the gas-puffing rate to increase particle source and RMP density "pump-out" to reduce it. Real-time pedestal stability boundary calculation using a neural network based on EPED1 runs, and a real-time pellet injection control for turn on/off timing and ELM frequency are under development. These developments at DIII-D pave the way for ITER adaptive pedestal control.

1. Introduction

The high performance "H-mode" regime of tokamak operation offers attractive potential for fusion energy. However, the strong edge transport barrier present in this regime lead to Edge Localized Modes (ELMs). Heat flux due to ELMs necessitates ELM control at ITER and future fusion reactors for divertor protection. In order to help design and identify the requirements for such a system, we need to develop such ELM control systems in current fusion facilities. With this aim, we designed an adaptive real-time ELM control system at DIII-D. This system combines our knowledge from ELM physics, RMP ELM suppression physics, and real-time data we gather from an extensive set of diagnostic inputs and controls a set of actuators to sustain ELM suppression/mitigation regimes at DIII-D. The control system calculates the effect of 3D perturbing fields on the magnetic surfaces in real-time to optimize RMP ELM suppression, reduces the required 3D coil currents, and thus mostly recovers the $H_{98}(y,2)$ and β_N.

The control experiments showed the path dependence and hysteresis of plasma recovery: even for the same final perturbing 3D currents, starting with higher initial 3D currents leads to lower recovery down the path. This control is motivated by the experimental result that the H-factor decreases substantially with an RMP coil current exceeding that required for threshold conditions for ELM suppression [2]. This demonstrates the need for a control system to keep the ITER RMP perturbations close to the ELM suppression threshold at all times or risk locking in reduced performance for the remainder of the discharge. The DIII-D system proves that the concept of real-time pedestal profile control is feasible with real-time Thomson scattering and D_α diagnostics, and gas and 3D coil feedback regulation.

ITER has 27 individually controlled 3D coils (for ELM suppression), many gas valves, and pellet injectors that can be used for ELM avoidance and mitigation. As the plasma evolves in minutes-long discharges, preprogrammed feed-forward control becomes infeasible and a real-time decision process is needed. The development at DIII-D initiates this progress towards adaptive pedestal control, including pedestal profile control and ELM suppression/mitigation.

2. Adaptive ELM Control System on DIII-D

In order to enable real-time pedestal control, Thomson diagnostic acquisition and pedestal width/height fitting of temperature and density profiles were added to the DIII-D Plasma Control System (PCS). The system performs two different functions:

a) 3D coil current and phase control for ELM suppression
b) Pedestal pressure regulation via gas input and pellet injection, and RMP density "pump-out" for ELM avoidance.

The RMP ELM suppression decision-making process requires either the direct measurement or modeled calculation of the effects of the applied 3D fields on the plasma and the calculation of ELM stability as the plasma evolves. To enable this capability, a real-time system based on the SURFMN code [1] was implemented at DIII-D.

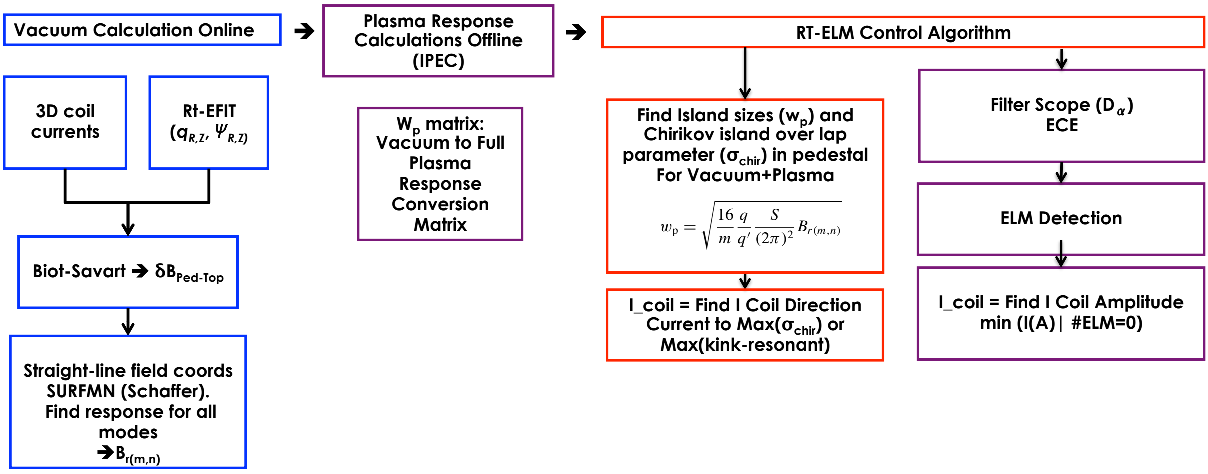

FIG. 1. Schematic of the real-time adaptive ELM control algorithm used on DIII-D

SURFMN code calculates the effect of 3D perturbing fields on the magnetic surfaces (see Fig. 1.) and decomposes it on different modes. Using this decomposition, the vacuum edge pitch-resonant and kink-resonant harmonics of the applied 3D magnetic perturbation, induced island sizes, and the Chirikov parameter, σ_{chir}, and are calculated for real-time use in the PCS. The relationship between the vacuum and the plasma responses for specific plasma regimes are approximated via off-line IPEC calculations and loaded to the PCS system. This system allows us to adjust the relative phase between upper and lower 3D coil sets as the plasma boundary and q-profile evolve to optimize the effectiveness of the 3D coils based on different theories of ELM suppression mechanisms (edge pitch- or kink-resonant etc.).

In addition, a real-time ELM detection algorithm based on D_α measurements from the divertor region finds the ELM frequency and adjusts the amplitude of the 3D coil currents to bring the plasma to a non-ELMy state (or a given ELM frequency) with minimum 3D currents. Fig. 1. shows the schematic of this real-time adaptive ELM control algorithm implemented on DIII-D.

A test of this system is shown in Fig. 2, where the control was able to reduce the amplitude of the 3D perturbation currents substantially while maintaining ELM suppression, which partially recovered the H98(y,2) and β_N. However, even though the final perturbing 3D coil currents are the same, the plasma recovery has path dependence (high initial 3D currents lead to lower recovery of confinement and performance down the path). The degrading effect of this hysteresis as a result of first achieving an ELM free regime with higher current level and then reducing it to the suppression threshold needs to be considered for high performance operation of ITER.

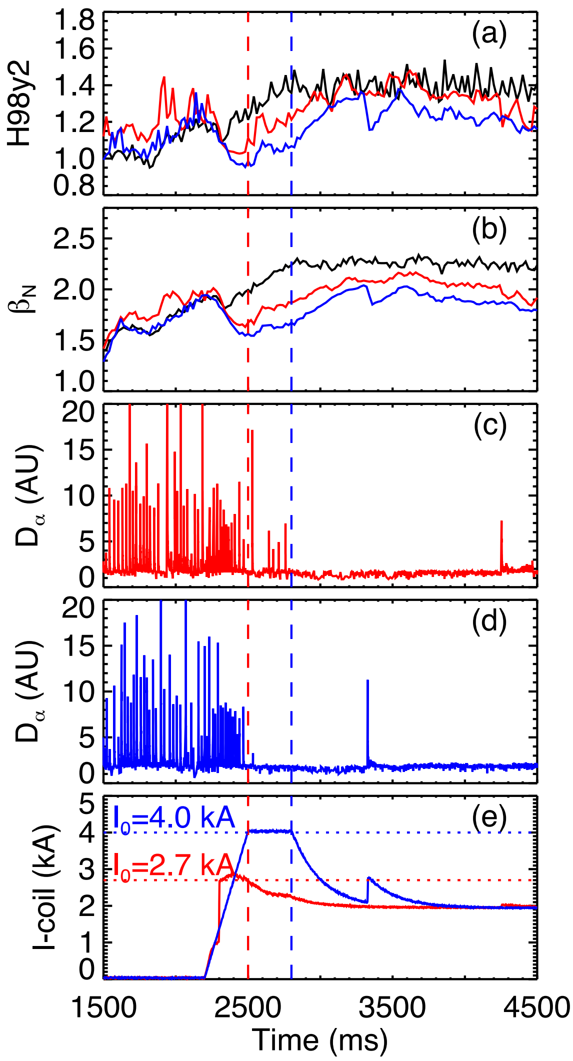

FIG. 2. Adaptive ELM Control: I-Coil control (starting at dashed lines) obtains ELM free regime with minimum 3D perturbation: No-control shot in black; with-control shots with different initial I-coil currents in red and blue.

The versatility of this control system also allowed us to implement a fast (20-250 ms) non-perturbative adaptive Error Field Correction (EFC) based on the minimization of the plasma resonant response, which is shown to predict the optimal EFC configuration (amplitude and phase) [3] for the I and C coils. This fast control was implemented and tested for n=1 and n=2 EFC for evolving plasma, finding the same optimal 3D coil currents as the detailed offline analysis in real time.

3. Pedestal Regulation Algorithm

Combined peeling-ballooning and kinetic ballooning mode physics can be used to predict the stability boundaries for ELMs. The EPED1 model [4], which predicts the limiting height of the pedestal before ELMs, shows pedestal density variation is a strong ELM control actuator. Thus, we implemented two real-time control strategies to adjust pedestal height: gas puff feedback and RMP density "pump-out". The gas feedback system increases gas flow when the rt-Thomson pedestal density fit falls below the target value as shown in Fig. 3. As this system is only able to increase the density, the I-coils can be used in a complementary system to control RMP density "pump-out" and limit the pedestal pressure as shown in Fig. 4. Here, I-coils in n=3 RMP configuration were used to regulate the global confinement by keeping the pedestal pressure constant. In combination, these systems can adjust the pedestal up and down and achieve the requested pedestal height.

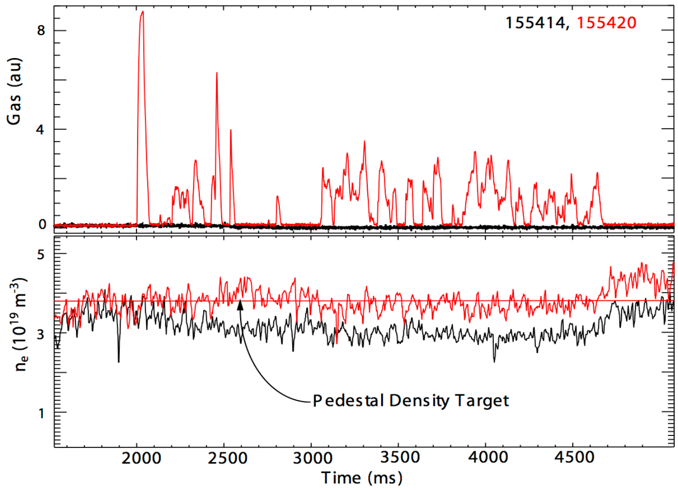

FIG. 3. Actuators for pedestal control using gas injection: Pedestal density height feedback using D2 fueling: black uncontrolled and red controlled shot.

In ITER, the gas puff will not penetrate the plasma; pellet injection control is needed both for fueling and ELM triggering. With this aim, real-time feedback control of DIII-D's pellet system is under development. EPED1 is used to train neuped, a fast algorithm neural network [5], which in turn obtains pedestal stability thresholds in real time. The PCS then adjusts the plasma conditions to stay below this limit. The system will turn the pellets on and off as needed and control the pellet injection frequency based on the neuped calculation, to adjust the pedestal density and the ELM frequency.

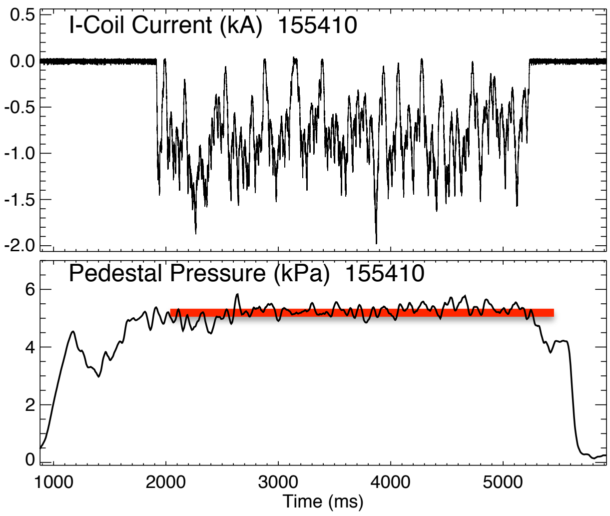

FIG. 4. Actuators for pedestal control using I-Coils (Non-axisymmetric coils): Pedestal electron pressure in RMP regulation.

4. Conclusions

In order to avoid the hysteresis effect of the RMP on confinement, ITER would need to have an adaptive ELM control algorithm that keeps the 3D perturbations to a minimum at all times. DIII-D has demonstrated that an adaptive system consisting of pedestal and ELM controllers can effectively enable high performance ELM free operations that can be applied to ITER in the future. The system dynamically adjusts perturbation structure based on plasma response based modeling, to optimize for ELM suppression, as well as adjusting to optimize the degree of suppression without excessive confinement degradation. Optimization of RMP levels to the minimum needed for suppression leads to improved performance. A further system also monitors the pedestal in real time in order to control pedestal height through gas puff and RMP pump out. The system shows the effectiveness of combining physics modeling of the pedestal phenomena and control applications to achieve high performance ELM free plasma operations. Further control development and multi-machine comparisons are needed to achieve the goal of reliable ELM control for ITER.

Acknowledgment

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References

[1] M.J. SCHAFFER, et al., “Study of in-vessel nonaxisymmetric ELM suppression coil concepts for ITER”, Nuclear Fusion 48 024004 (2008).

[2] R. NAZIKIAN, et al., “Advances in the Understanding of ELM Suppression by Resonant Magnetic Perturbations (RMPs) in DIII-D and Implications for ITER”, Proceedings of IAEA (2014), EX1-1.

[3] C. PAZ-SOLDAN, et al., “Equilibrium drives of the low and high field side n = 2 plasma response and impact on global confinement”, Nuclear Fusion, 54, 073013 (2016).

[4] P.B. SNYDER, et al., “A first-principles predictive model of the pedestal height and width: development, testing and ITER optimization with the EPED model”, Nuclear Fusion 51, 103016 (2011).

[5] O. MENEGHINI, et al., “Modeling of transport phenomena in tokamak plasmas with neural networks”, Physics of Plasmas, 21, 060702 (2014).