Control of Type-I ELMs by Resonant Magnetic Perturbations in ITER Similar Shaped Plasmas on DIII-D

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Abstract. Using the new high triangularity pumping capability on DIII-D, suppression of large Type-I edge localized modes (ELMs) by n=3 resonant magnetic perturbations (RMPs) from an internal coil (I-coil) was extended to ITER similar shape (ISS) plasmas with the ITER pedestal collisionality, $\nu_e^* \sim 0.1$. Comparison of a series of ISS plasmas with different n=3 RMPs, n=1 field-error correction, and residual intrinsic field-errors showed that for complete ELM suppression, the region of island overlap in the edge, calculated with vacuum fields, was greater than approximately 3-4 times the width of the total pressure pedestal.

I. Introduction and Motivation

Tokamak plasmas operating with the high confinement (H-mode) edge also produce transient bursts of particles and energy known as edge localized modes (ELMs) that are projected to be large enough to severely limit the operation of future devices due to material erosion [1]. One of the techniques shown to completely suppress large ELMs in present experiments is application of edge resonant magnetic perturbations (RMPs) using magnetic coils [2-5]. The applied RMPs produce a region of overlapping magnetic islands in the edge plasma. This paper explores the possibility that a minimum required width of the island overlap region could be an RMP coil criterion that can be extrapolated to determine the requirements for full suppression of large Type-I ELMs in ITER and future tokamak reactors.

In DIII-D, the island overlap widths during full ELM suppression were compared for various combinations of magnetic perturbations from internally mounted RMP coils (I-coils), externally mounted field-error correction coils (C-coils), and residual intrinsic field errors. Section II presents the results in terms of vacuum field calculations for the experimental conditions. Section III discusses improvements in the calculations needed to convert this simplified island overlap picture into a real predictive threshold condition for extrapolation to ELM suppression coil requirements in ITER.

II. Experimental Results

Complete suppression of Type-I ELMs was obtained in DIII-D plasmas with an ITER similar shape (ISS) at the ITER pedestal collisionality $\nu_e^* \sim 0.1$ using the new high triangularity lower single null (LSN) pumping capability combined with sufficient magnetic perturbations from the internal I-coils [2], external C-coils [4] and measured residual field errors [6-7]. Figure 1 shows a comparison of a plasma with a 4 kA I-coil RMP and an optimum global n=1 error field correction (EFC) by the C-coil that had ELMs (black), vs a matched plasma with a 6.3 kA I-coil RMP that achieved full ELM suppression. Both had q_{95}=3.6, i.e., optimum for pitch resonance with the n=3 I-coil. Pedestal plasma profiles for these two cases, compared to a case without RMP (green), show a significant difference in the gradient of the total plasma pressure inside the steepest gradient region but very minor differences of the profiles outside the steepest gradient region [Fig. 1(g)].

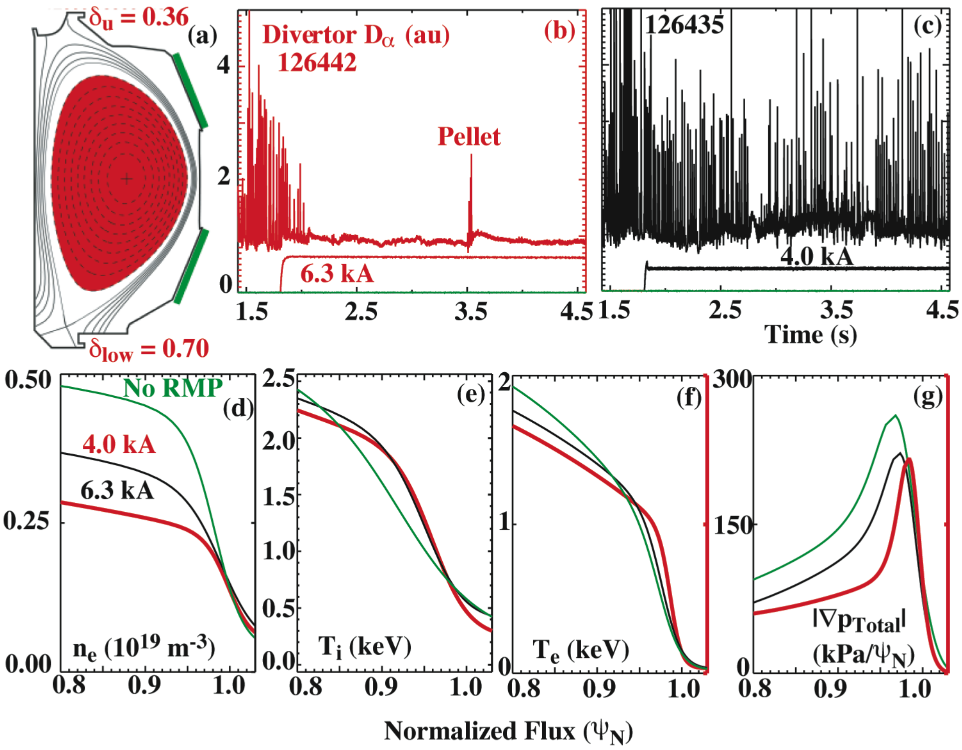

FIG. 1. Results from RMP H-mode plasmas in (a) the ISS with (b) full ELM suppression and (c) an H-mode at lower RMP amplitude that is still ELMing. Pedestal profiles of (d) n_e (10^{20} m^{-3}) (e) T_i (keV), (f) T_e (keV) and (g) gradient of total pressure (kPa/Ψ_N) are shown for the case in (b - red) and (c - black) plus a case with zero RMP amplitude (green),

The width of the magnetic island overlap region, for these plasmas with optimum pitch resonant q_{95}, is significantly greater for the case with complete ELM suppression. The widths of the vacuum magnetic islands due to the I-coil, C-coil and measured intrinsic field errors for the two plasmas of Fig. 1 are shown in Fig. 2. The islands overlap in to about $\Psi_N = 0.865$ for the plasma that is still ELMing. Complete ELM suppression is achieved in the plasma with vacuum islands overlapped in to about $\Psi_N = 0.78$. This increase in overlap region width is obtained by a combination of larger n=3 RMP from the I-coil operated with higher current, and slight increases in the n=1 island widths due to changes in the C-coil current from the optimum global EFC algorithm.

From a collection of binary comparisons between ELMing and ELM suppressed discharges, the minimum ratio of the required vacuum island overlap width for full ELM suppression (Δ^{vac}_{stoc}), normalized to the width of the total pressure in the pedestal (Δ^{ptot}_{ped}), is in the range 3–4. Figure 3(a) shows the case for the plasmas of Fig. 1. In this case at q_{95}=3.6, $\Delta^{vac}_{stoc}/\Delta^{ptot}_{ped}$ was 1.9 for the ELMing case (4 kA I-coil) and 4.4 for the ELM suppressed case (6.3 kA I-coil). Figure 3(b) shows a comparison for plasmas with q_{95} = 3.2 (i.e. not optimum for pitch resonance with the n=3 I-coil RMP alone) in which the ELMing plasma had 3 kA in the I-coil and optimum n=1 global EFC current in the C-coil. The ELM suppressed case had 4 kA in the I-coil and 2x times the optimum EFC current in the C-coil. Here $\Delta_{stoc}^{vac}/\Delta_{ped}^{ptot}$ was 2.4 in the ELMing case and 4.5 in the ELM suppressed case. Several other comparisons are given in Table 1. At q_{95} = 3.8 the ELMing case had $\Delta_{stoc}^{vac}/\Delta_{ped}^{ptot}$ =3.75 and the ELM suppressed case had $\Delta_{stoc}^{vac}/\Delta_{ped}^{ptot}$ = 7.1. ELM suppression was even obtained using odd parity in the n=3 I-coil [4] for a pitch resonant q-profile with q_{95} = 7.2. In this configuration the plasma with ELM suppression had $\Delta_{stoc}^{vac}/\Delta_{ped}^{ptot}$ = 3.8.

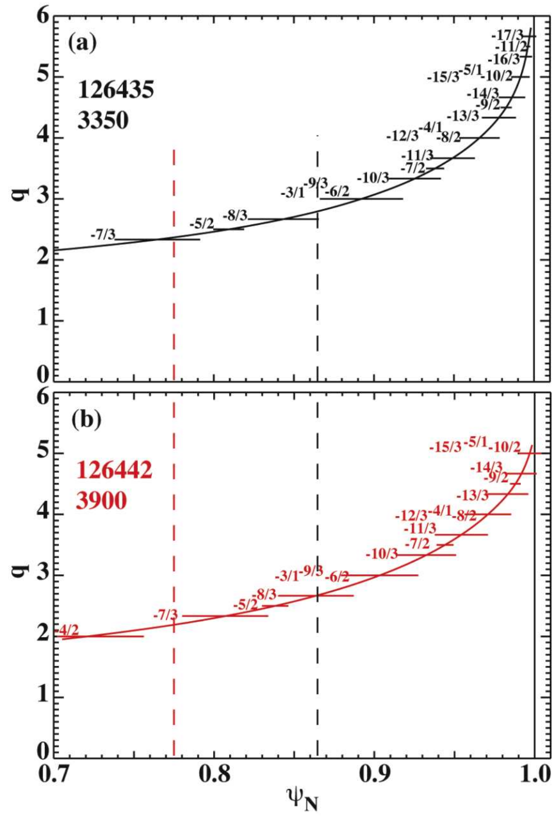

FIG. 2. Resonant island widths from n=3 I-coil RMP, n=1 C-coil and measured error fields overlaid on q-profiles for plasmas of Fig. 1 that are (a) ELMing (black) and (b) ELM suppressed (red). Vertical dashed lines indicate boundaries of island overlap regions for the two cases.

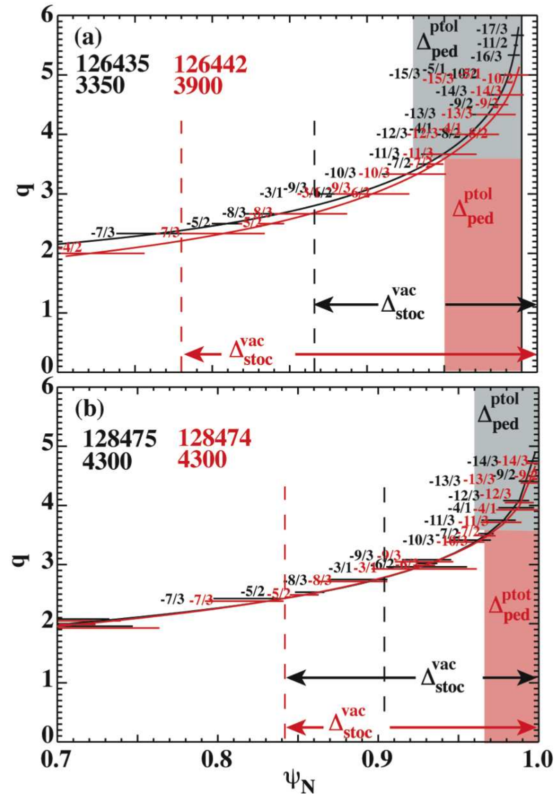

FIG. 3. Comparison of island overlap region widths (dashed line) and pedestal widths (shaded regions) for plasmas (a) of Fig. 1 and (b) with different I- and C-coil currents. ELMing case (black/grey) vs ELM suppressed case (red/pink). Island widths and q-profile overlays as in Fig. 2. Coil currents given in Table 1.

III. Discussion and Conclusions

The initial results from these experiments are consistent with a required overlap of the vacuum islands from RMPs of approximately 3–4 times the pedestal pressure width in order to achieve full suppression of ELMs in H-mode, ISS plasmas. This criterion is obtained from calculations using the sum of the vacuum fields from the internal RMP coils plus the fields from the external EFC coils and the measured intrinsic field errors in DIII-D. In several of the binary comparisons, if only the n=3 I-coil perturbation was considered, the Chirikov parameter was ≥1 throughout the pedestal and the width of the island overlap region was similar in plasmas with ELMs and those with full ELM suppression. A clear correlation between minimum required island overlap region width and ELM suppression was obtained only when the sum of all the non-axisymmetric fields in the edge was taken into account.

Table 1. Comparison of matched plasmas with different combinations of I-coil (n=3) and C-coil (n=1 EFC) magnetic perturbations for several q_{95} values. The normalized island overlap region width $\Delta_{stoc}^{vac}/\Delta_{ped}^{ptot}$ needed for full ELM suppression (red) is in the range 3–4.

Shot	**126435**	**126442**	**128371**	**128372**	**128376**	**128377**	**128475**	**128474**	**128466**	**128464**
q_{95}, I-coil, C-coil	3.6 4.0 kA 1xEFC	3.6 6.3 kA 1xEFC	3.8 3.0 kA 1xEFC	3.8 3.0 kA 1.2xEFC	3.8 3.0 kA 1xEFC	3.8 4.0 kA 1xEFC	3.2 3.0 kA 1xEFC	3.2 4.0 kA 2xEFC	7.2 0.0 kA 1xEFC	7.2 6.4 kA 4xEFC
ELMs	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
$\Delta_{stoc}^{vac}(\psi_N)$	0.135	0.222	0.10	0.14	0.15	0.2	0.09	0.16	0.03	0.228
$\Delta_{\rho}^{ped}\ (\psi_N)$	0.07	0.05	0.04	0.04	0.04	0.028	0.04	0.035	0.06	0.06
$\Delta_{stoc}^{vac}/\Delta_{\rho}^{ped}$	1.9	4.4	2.5	3.5	3.75	7.1	2.4	4.5	0.4	3.8

Two effects which are not included here must be added to the analysis to generate a predictive criterion for the required island overlap to assure ELM suppression in future devices, namely: 1) the effect of the edge bootstrap current peak due to the strong edge pressure gradients in H-mode plasma on the edge safety factor profile, and 2) the effect of plasma rotation on the actual perturbed magnetic fields in the edge plasma (rotational screening) [8,9]. Initial equilibrium reconstructions using the edge bootstrap current from the measured edge pressure gradients show that the *q*-profile in the region of vacuum island overlap is modified sufficiently by this bootstrap current to change the overlap region width by 10%–20%. Plasma screening of the perturbation fields could have a larger effect on the inferred island overlap width if predictions from theory for low m/n single-modes [8,9] prove applicable to the situation of multiple overlapping higher m/n perturbation fields in the edge. However, the indications from the experiments are that the predictions of single mode screening are not being realized in the edge during RMP application, perhaps due to the inability of the plasma to generate the internal currents necessary to screen out the complicated superposition of all the modes applied simultaneously in a given edge region by the RMP coils, EFC coils and the field errors. Incorporating the radial dependence of plasma screening of the RMP fields into full field line loss calculations will ultimately convert the simple picture of required island overlap into predictions of the required RMP coils for ELM suppression in future devices.

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