

Edge Stability Analysis and Pedestal and ELM Characteristics in I-Coil ELM Suppressed Discharges on DIII-D

T.H. Osborne¹, P.B. Snyder¹, T.E. Evans¹, R.A. Moyer², M.J. Schaffer¹, K.H. Burrell¹,
R.J. Groebner¹, A.W. Leonard¹, D.M. Thomas¹, G. Wang³, and L.Zeng³

¹General Atomics, San Diego, California, USA.

²University of California, San Diego California, USA.

³University of California, Los Angeles, California, USA.

Introduction

The Type I ELM remains a significant concern for reactor scale tokamaks. At the collisionality expected at the top of the ITER H-mode pedestal, $\nu_{*e} \sim 0.1$, present day tokamaks near ITER shape and q have ELM energy loss, $\Delta W_{ELM} > 0.15 W_{PED}$, where W_{PED} is the pedestal energy, $p_{PED}V$. ELMs of this size are expected to rapidly erode the divertor target plates in ITER [1]. The DIII-D I(internal)-coil has been used successfully to produce discharges free of Type I ELMs while maintaining good energy confinement and avoiding runaway density or impurity accumulation [2,3]. The I-coil is normally connected in $n=3$ configuration and is expected to create a region of stochastic field and a region of field line loss near the separatrix (Fig. 1). The extent of these regions and the degree of stochastic connection between magnetic islands increases with I-coil current and depends on the I-coil up-down parity and toroidal phasing. The latter is a result of interaction of the I-coil field with intrinsic field errors in DIII-D. The extent of the stochastic field region also depends on the safety factor, q , and to some extent on the plasma cross-sectional shape. The I-coil effectiveness for ELM suppression as a function of collisionality, I-coil parity, I-coil phasing,

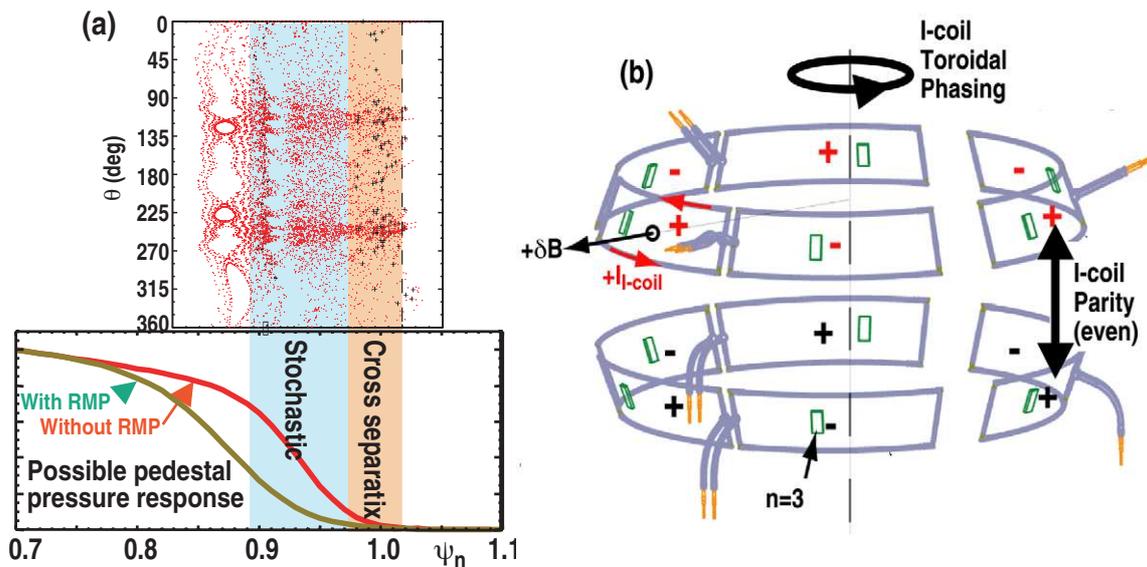


Fig. 1. (a) Magnetic field line puncture plot showing stochastic region and region where lines cross separatrix; possible effect on p profile. (b) $n=3$ I-coil setup and can be connected in even (same sign top and bottom loops), or odd parity, and 0 deg. or 60 deg. toroidal phasing.

and plasma triangularity, is shown in Table I. Conditions which might be expected to enhance the resonant field perturbation, RMP, effect are: (1) even I-coil parity, which increases the RMP amplitude (Fig. 2), (2) 60 deg. phasing making the I-coil and intrinsic field errors additive, (3) low collisionality giving longer mean free path, allowing particles to move

Table I. Effectiveness of I-coil ELM suppression: complete suppression (green), strong reduction in ELM frequency or size (yellow), little change in ELM behavior (red), not tested (no color)

$\nu^* \sim 0.1$, p-even $\phi = 60$, $\delta < 0.5$	$\nu^* \sim 0.1$, p-even $\phi = 0$, $\delta < 0.5$	$\nu^* \sim 0.1$, p-even $\phi = 60$, $\delta > 0.5$	$\nu^* \sim 0.1$, p-even $\phi = 0$, $\delta > 0.5$
$\nu^* \sim 0.1$, p-odd $\phi = 60$, $\delta < 0.5$	$\nu^* \sim 0.1$, p-odd $\phi = 0$, $\delta < 0.5$	$\nu^* \sim 0.1$, p-odd $\phi = 60$, $\delta > 0.5$	$\nu^* \sim 0.1$, p-odd $\phi = 0$, $\delta > 0.5$
$\nu^* \sim 1$, p-even $\nu = 60$, $\delta < 0.5$	$\nu^* \sim 1$, p-even $\phi = 0$, $\delta < 0.5$	$\nu^* \sim 1$, p-even $\phi = 60$, $\delta > 0.5$	$\nu^* \sim 1$, p-even $\phi = 0$, $\delta > 0.5$
$\nu^* \sim 1$, p-odd $\phi = 60$, $\delta < 0.5$	$\nu^* \sim 1$, p-odd $\phi = 0$, $\delta < 0.5$	$\nu^* \sim 1$, p-odd $\phi = 60$, $\delta > 0.5$	$\nu^* \sim 1$, p-odd $\phi = 0$, $\delta > 0.5$

radially along the stochastic field, (4) low triangularity allowing effective divertor pumping required for reducing the density in H-mode. Although complete ELM suppression has been achieved in $\nu_{*e} \sim 1$, odd parity, 0 deg. phasing, and high triangularity, this is unexpected on the basis of the resonant field amplitude.

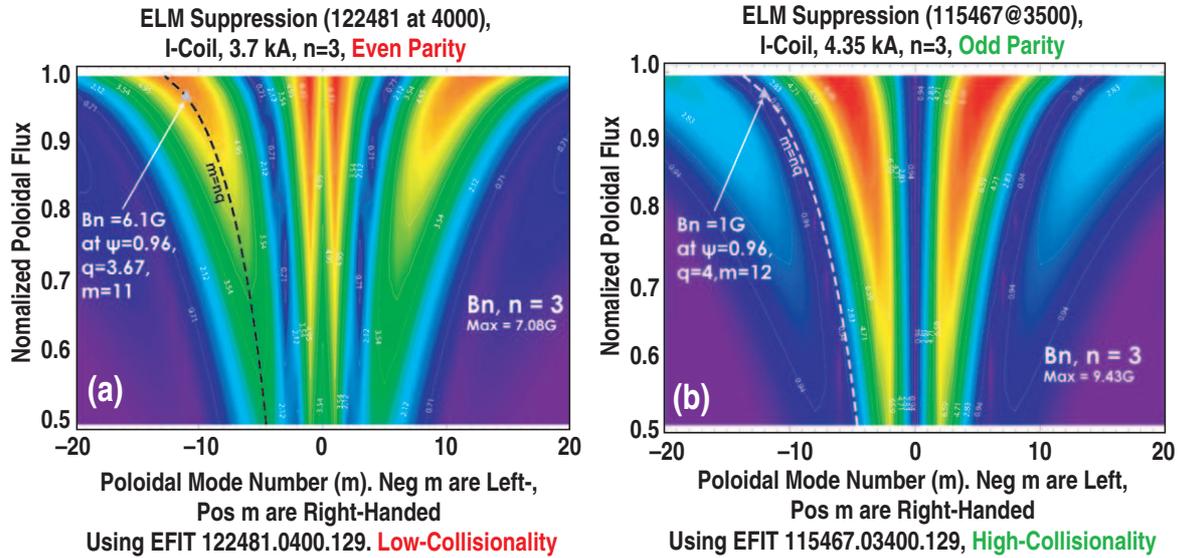


Fig. 2. Magnetic field created by the I-coil normal to a flux surface as a function of minor radius and poloidal mode number, m with colour contours ~ 0.8 G (blue) to ~ 10 G (red). (a) For even parity I-coil configuration resonance, $m=nq$, is near maximum in B_n , (b) for odd parity $m=nq$ is near minimum in B_n , giving little resonant field.

$\nu_{*e} \sim 1$, Odd I-coil Parity

Notwithstanding the fact that the RMP effect is expected to be small, complete Type I ELM suppression has been achieved in this case for the duration of the I-coil current (at least 1.5 seconds). There is little difference in T_e , T_i , or n_e with and without the I-coil under these

conditions, and $H_{98}(y2)$ remains near 1.0. There is an increase in Z_{eff} by about 0.5, and a strong reduction in the toroidal rotation speed over the entire plasma cross-section with the I-coil on. ELMs at $v_{*e} \sim 1$ are generally a mixture of large, Type I, ELMs and much smaller, possibly Type II [4], ELMs. The Type II ELMs persist with the I-coil on and appear to increase in amplitude [Fig. 3(a)]. In discharges where Type I ELMs continue at reduced frequency with the I-coil on, edge current density and pressure gradient evolve over a similar range as between ELMs with I-coil on or off, leading to similar modes and growth rates for peeling-ballooning mode at the ELM time [Fig. 3(b)]. These observations suggest the enhanced Type II ELMs may provide the transport which delays or avoids Type I ELMs under $v_{*e} \sim 1$, odd I-coil parity conditions.

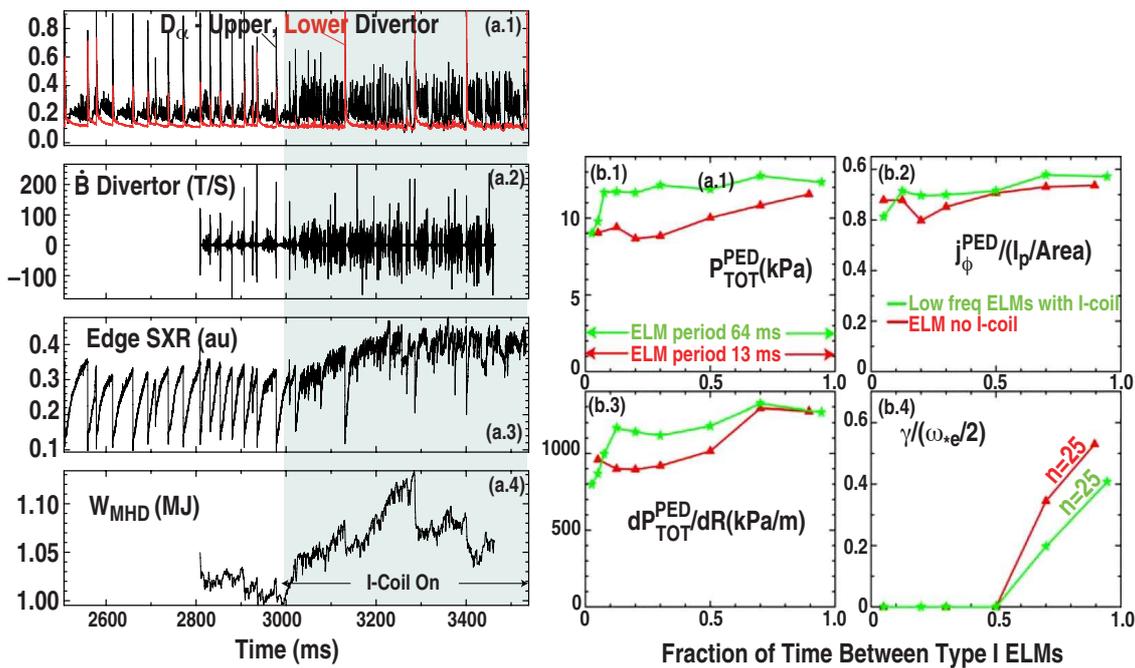


Fig. 3. (a) Size of small, Type II, ELMs increase with I-coil on in $v_{*e} \sim 1$, odd I-coil parity discharge on (a.1) D_{α} , (a.2) magnetic probes in divertor region, and (a.3) edge SXR. (a.4) Large Type I ELMs with I-coil on also appear as somewhat larger changes in plasma stored energy. (b.1) Pedestal pressure, (b.2) edge current density, and (b.3) edge pressure gradient evolve over similar range but at 5 times slower rate between Type I ELMs with I-coil on (green curves) compared to off (red). (b.4) Peeling-ballooning mode growth rates are similar at ELM time with I-coil on (green) or off (red).

$v_{*e} \sim 0.1$, Even I-coil Parity

Under these conditions, which give a good resonance between the I-coil generated and plasma equilibrium fields, there is a dramatic effect on the pedestal pressure [Fig. 4(a)]. n_e is strongly reduced with the I-coil on, while T_e remains relatively fixed. Z_{eff} increases with the I-coil on, while toroidal rotation is reduced in the core, and increased in the pedestal region consistent with enhanced electron loss. A strong increase in the T_i , perhaps due to reduced electron-ion coupling at lower density, limits the effect of the pedestal pressure reduction on the H-factor to 10%-20%. The width of the steep gradient region in pressure decreases in the I-coil on ELM free phase, however the edge pressure gradient is still reduced and the edge is calculated to be stable to peeling-ballooning modes [Fig. 4(b)]. No Type II ELMs or edge

localized coherent MHD are observed with the I-coil on under these conditions suggesting that the enhanced transport from the I-coil RMP may directly be keeping the pedestal below the instability limit, thus avoiding ELMs.

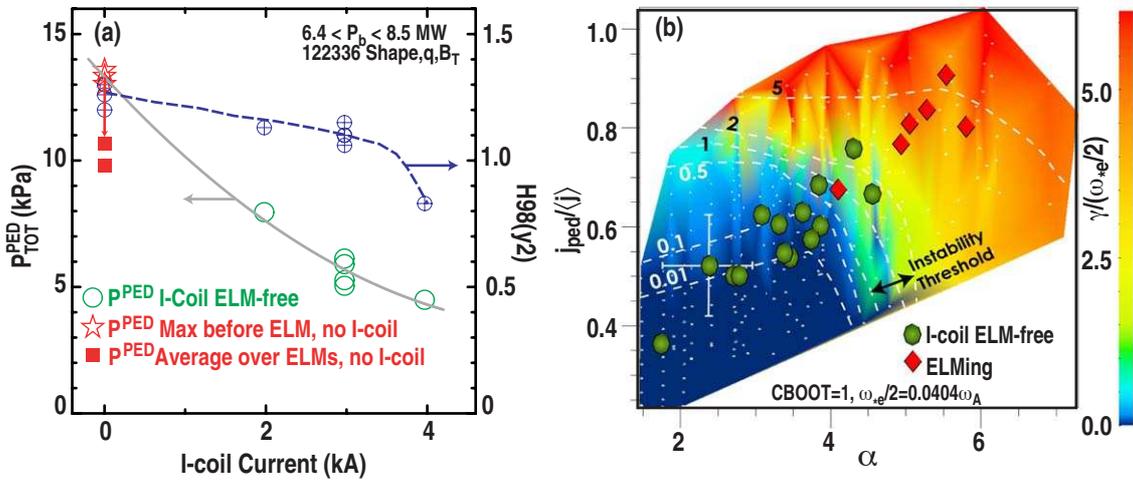


Fig. 4. (a) Pedestal pressure is reduced with increasing I-coil current at $v_{*e} \sim 0.1$, even I-coil parity, comparing pressure just before ELM (red star) to I-coil ELM free (green circle), difference is not as great compared to p^{PED} averaged over ELMs (red square); H-factor (blue) is less affected than p^{PED} . (b) Contour plot of peeling-ballooning mode normalized growth rate versus edge current density and normalized pressure gradient, α . I-coil ELM suppressed discharges lie in the stable zone.

Conclusions

The ability of a relatively simple external coil set to suppress Type I ELMs while maintaining good energy confinement is a positive result for future tokamaks. At ITER relevant collisionality, $v_{*e} \sim 0.1$, and even I-Coil parity, where RMP effects should be strong, the pedestal pressure is controlled and maintained below the peeling-ballooning mode stability limit while providing enough particle transport to avoid density or impurity accumulation. Enhancements of the technique could, in principle, allow I-coil ELM-free operation with p^{PED} above the time-averaged value with ELMs. In the case of ELM suppression at $v_{*e} \sim 1$, and odd I-coil parity, where the part of the I-coil field resonant with the equilibrium is small, the large non-resonant component might be interacting with the ELM instability, enhancing Type II ELMs to provide sufficient transport for avoiding Type I ELMs.

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