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

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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, νᵦₑ ~ 0.1, present day tokamaks near ITER shape and q have ELM energy loss, ΔWₑLM > 0.15 WₑPED, where WₑPED is the pedestal energy, pPEDV. 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.

![Field line puncture plot](image)

**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.
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, 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 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.

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)

<table>
<thead>
<tr>
<th>Condition</th>
<th>Effectiveness</th>
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<tbody>
<tr>
<td>$\nu^* \sim 0.1$, p-even</td>
<td>complete suppression</td>
</tr>
<tr>
<td>$\phi = 60, \delta &lt; 0.5$</td>
<td></td>
</tr>
<tr>
<td>$\nu^* \sim 0.1$, p-odd</td>
<td>strong reduction</td>
</tr>
<tr>
<td>$\phi = 60, \delta &lt; 0.5$</td>
<td></td>
</tr>
<tr>
<td>$\nu^* \sim 1$, p-even</td>
<td>little change</td>
</tr>
<tr>
<td>$\phi = 60, \delta &lt; 0.5$</td>
<td></td>
</tr>
<tr>
<td>$\nu^* \sim 1$, p-odd</td>
<td>not tested</td>
</tr>
<tr>
<td>$\phi = 60, \delta &lt; 0.5$</td>
<td></td>
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</tbody>
</table>

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.
\( v_e \sim 1 \), 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 \( H98(y2) \) remains near 1.0. There is an increase in \( Z_{\text{eff}} \) 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.

\( v_e \sim 0.1 \), 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. \( Z_{\text{eff}} \) 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-balloonng 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 $v_{ce} \sim 0.1$, 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 $p_{\text{PED}}$ averaged over ELMs (red square); H-factor (blue) is less affected than $p_{\text{PED}}$. (b) Contour plot of peeling-balloonng mode normalized growth rate versus edge current density and normalized pressure gradient, $\alpha$. 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, $v_{ce} \sim 0.1$, and even I-Coil parity, where RMP effects should be strong, the pedestal pressure is controlled and maintained below the peeling-balloonng 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 $p_{\text{PED}}$ above the time-averaged value with ELMs. In the case of ELM suppression at $v_{ce} \sim 1$, 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.