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ELM SUPPRESSION BY RESONANT MAGNETIC PERTURBATIONS AT DIII-D

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***Abstract*— Edge localized mode (ELM) suppression by resonant magnetic perturbations (RMPs) is being studied at DIII-D with ITER-similar plasma shapes and edge collisionalities. Suppression at low collisionality correlates with overlap of vacuum magnetic field islands in a quantified edge layer at moderate *q*. Suppression is successful with *n*=3 perturbations from one or two rows of internal coils, but it fails for *n* < 3 and for poloidally-tall and distant coil arrays. These observations are interpreted in terms of differences of spatial helical harmonic spectra the different magnetic perturbations: excessive non-resonant harmonics may brake plasma rotation before the RMP is large enough to suppress ELMs.**

Keywords-edge localized mode; ELM; magnetic perturbations; RMP; DIII-D

I. OVERVIEW

Complete suppression of the Type-I edge localized mode (ELM) instability in high-confinement H-mode plasmas by application of weak ($\delta b/B_0 \sim 3\times10^{-4}$) normalized non-axisymmetric magnetic perturbations δb was first achieved in the DIII–D tokamak [1]. While ELMs are not a problem in present tokamak experiments, empirical and theoretical modeling predicts that Type-I ELM heat pulses will severely limit divertor target lifetime in ITER [2,3], unless the ELM pulse energy is reduced by a factor ~20 in the worst case. Extension of ELM suppression from DIII-D to ITER involves large extrapolations, and the physics of ELM suppression is incompletely known, but at low, ITER-like plasma collisionality, suppression is associated with modified pressure and current profiles in the plasma edge [4]. Continued research at DIII-D has extended the scope of the magnetic perturbation method and is now concentrated on studies of resonant magnetic perturbations (RMPs) in DIII-D plasmas having ITER-similar plasma shape and ITER-similar low-collisionality ($\nu_e{}^* \sim 0.1$) edge pedestals simultaneously [5]. Here $\nu_e{}^* = q_{95}(R_0/\lambda_e)(R_0/a)^{3/2}$ is the normalized neoclassical collisionality; R_0/a are the plasma major/minor radii; q_{95} is the tokamak safety factor at the 95% poloidal magnetic flux surface near the plasma edge; and λ_e is the electron Coulomb collision mean free path. This paper summarizes some recent DIII-D results and new insights.

II. EXPERIMENTAL CONFIGURATION

DIII-D [6] is a mid-sized tokamak with R_0 = 1.70 m, $a \approx$ 0.6 m, toroidal magnetic field up to B_0 = 2.14 T, and a flexible poloidal field plasma shaping system. ELM suppression experiments to date were conducted in H-mode plasmas made and sustained by neutral beam heating. Plasma density is controlled by a combination of between-shot helium glow wall conditioning and active deuterium gas puffing and divertor exhaust pumping. Nonaxisymmetric magnetic fields are applied by two separate coil sets, shown in Fig. 1. The C-coils are an array of six, approximately rectangular coils, ≈1.6 m tall, wrapped toroidally around the tokamak just outside the toroidal field coils, at $R \approx 3.2$ m. Two rows of six I-coils each are attached to the vacuum side of the vacuum vessel wall, one row above and the other below the mid body of the vessel. They are 0.5 m tall. I- and C-coils can be powered in various ways. Fig. 1 shows magnetic field signs for *n*=3 toroidal periods of radial magnetic field in the I-coils and *n*=1 in the C-coils. The I-coil field is said to have “even” or “odd” parity when the

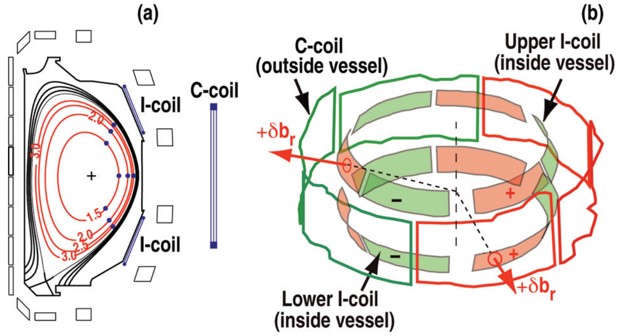

Figure 1. Geometry of I- and C-coils. (a) Cross section, and (b) perspective. Red loops make positive and green loops negative perturbations δb_r, shown as vectors for two coils. I-coil even parity current distribution shown.

up/down loop pair at a given toroidal angle makes the same or oppositely directed fields, respectively. The C-coil is usually used for n=1 error field correction when the I-coil is used for ELM control, and vice versa.

III. Some Recent DIII-D Results in Low Collisionality Plasmas

A. Dependence on Toroidal Periods

To date, ELMs have only been suppressed in DIII-D by I-coil fields with n=3 toroidal periods. Renewed attempts using n=1 and n=2 I-coil fields and also n=1 and n=3 C-coil fields failed to produce ELM suppression. These attempts were frustrated by the appearance of a plasma instability or the loss of plasma rotation and onset of a locked mode, all of which degrade plasma confinement, often to the point of triggering a return to low-confinement L-mode.

B. Dependence on q_{95}

In all cases of ELM suppression by n=3 I-coil perturbations using the two coil rows simultaneously, a distinct range of q_{95} values or "resonant window" over which the ELMs are suppressed is observed, at high and low ν_e*, and for ITER similar shapes and others [5]. At low collisionality, suppression occurs most easily for the I-coils operated at even parity [4,8], and suppression correlates strongly with the nearness of q_{95} to ≈3.5.

The I-coil even-parity magnetic field has a strong peak in its Fourier harmonic spectrum [7] at m/n = 10/3 or 11/3 near the 95% flux surface of elongated, diverted, $R_0/a \approx 3$ plasmas. Coincidence of q and m/n is the Resonance condition for a Magnetic Perturbation to make a magnetic island chain, hence "RMP". The spectral calculations simply add the perturbation vacuum field to the axisymmetric plasma equilibrium magnetic field without any amplification, screening or other self-consistent response from the plasma.

The DIII-D I-coil odd-parity field has a weak spectral peak centered at m/n = 23/3, and it just barely suppressed ELMs with $q_{95} \approx 7.5$ at its full allowable current [8]. This demonstrates that ELMs can be suppressed over a range of q_{95} at low ν_e* by adjusting the perturbation spectrum for resonance. This technique was proposed for ITER to ameliorate ELMs in experiments over a range of q_{95} [7].

C. Correlation with Vacuum Island Overlap

A useful empirical correlation for ELM suppression has been obtained for moderate $q_{95} \approx 3.6$. Fig. 2 from [8] displays the variation of ELM magnitude, measured by the peak intensity of their visible H_α light pulses, as a function of the width of the edge layer in which the Chirikov parameter σ exceeds 1. This island overlap layer width is called $\Delta_{chir>1}$. σ is the sum of the half-widths of two adjacent magnetic islands, divided by the radial separation between the two island centers. It tells whether the calculated islands overlap each other ($\sigma > 1$) and is a qualitative indicator of possible stochastic magnetic lines. σ depends not only on $\delta b_r/B_0$, but also on q and its radial derivative q'. In Fig. 2, a threshold for the disappearance of most of the large ELM pulses is seen at $\Delta_{chir>1} \approx 0.165$, but ELM suppression can dither, and suppressed ELM points are seen at narrower overlap layer widths. In this data set, the gas puff rate, δb_r and B_0 were varied while keeping the ratio B_0/I_p constant, where I_p is the toroidal plasma current. The radial profiles of q were carefully computed using all available diagnostic data [8]. For the sharp threshold to appear from the data, it was necessary to include δb_r and the islands from all known non-axisymmetric sources, including the tokamak's magnetic field errors [6] and the (imperfect) C-coil correction field. Additional shots in which the C-coil n=1 harmonic was deliberately varied (not included in Fig. 2) supported the reality of a "fill in" effect by the extra harmonics. Thus, harmonics of more than one n periodicity can be combined usefully.

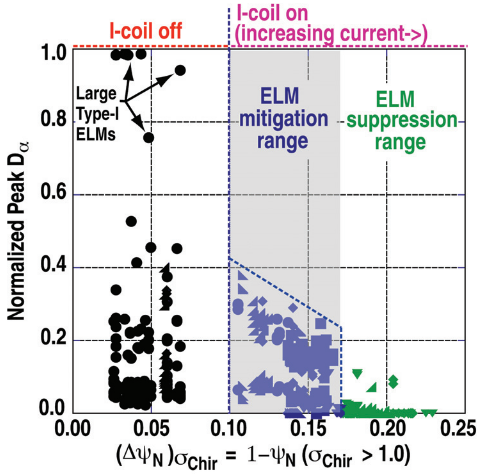

Figure 2. Peak magnitude of ELM light pulses versus the width of the island overlap region, $\Delta_{chir>1}$. ELM light is normalized to the largest pulse, $\Delta_{chir>1}$ is in radius units of normalized poloidal flux.

Although there is little direct experimental evidence for magnetic islands and stochasticity, except possibly in an edge layer only a few cm wide, the island overlap threshold correlation is much clearer than in plots of just $\delta b/B_0$. $\Delta_{chir>1} \approx 0.165$ has been used to extrapolate from DIII-D to ITER RMP ELM control requirements since late 2007 [9]. However, ELM suppression is observed to also depend on some combination of beam heating power, its toroidal torque, plasma β, and rotation that is not yet untangled. Additional scans are being done this year.

D. Single Row of Coils

Until recently, fields applied by a *single* toroidal row of coils had not obtained ELM suppression. Single-row n=1 fields had reduced Type-I ELM amplitudes, but plasma instability, locked modes or H-to-L-mode transitions arose before ELM suppression, in DIII-D, JET [10] and NSTX. Similarly, single-row n=2 fields reduce but do not suppress ELMs in JET [11]. Single-row n=3 fields from the DIII-D C-coil cause locking [12,13], but from the NSTX error correction coil they *trigger* ELMs in previously ELM-free plasmas [14]. In contrast, recent DIII-D experiments showed ELM suppression by *single* n=3 I-coil rows at low ν_e*, either the upper or lower alone [12,13].

Suppression occurred for approximately the same level of resonant δb_r near the plasma edge as with two rows of I-coils, but with a narrower $\Delta_{chir>1} \approx 0.13$ [13]

The C- and I-coil physical geometries differ by: 1) poloidal location, 2) vertical aperture, and 3) distance from plasma. Poloidal location (centered with the plasma equator vs. above or below it) does not affect the magnetic spectrum strongly. Short vertical aperture and nearness to the plasma cause the δb_r field distribution to be poloidally localized at the plasma surface, which makes a spectrum with relatively strong high-$|m|$ harmonics. In contrast, a tall vertical aperture and greater distance from the plasma cause δb_r to be broadly distributed at the plasma surface, making a spectrum with strong low-$|m|$ harmonics. The single-row I- and C-coil spectra and the "conventional" 2-row I-coil spectrum are compared in Fig. 3. The 2-row, even-connected I-coil spectrum has peaks and valleys, and a spectral peak is aligned with the resonance condition $m = -nq$. The three non-resonant peaks are not much larger than the RMP peak. The single-row spectra do not have peaks near the resonance locus. However, the single-row I-coil spectrum is broad out to resonance, especially in the important outer 15% layer of poloidal flux (radius). The single-row I-coil result shows that a local RMP peak is not necessary for ELM suppression at low ν_e*. The C-coil spectrum is narrow in m, and although coil current can be increased to make the same δb_r at the resonance locus, the low-$|m|$ non-resonant harmonics are ~4 times stronger than the RMP, often leading to a locked n=1 mode. The perturbation coils at JET and NSTX are similar in geometry to the C-coils.

IV. DISCUSSION

The Chirikov parameter σ, which is empirically correlated with ELM suppression, increases as $\sigma \sim (n\ \delta b_r)^{1/2}$. The favorable n dependence is qualitatively consistent with the failure to suppress ELMs in any experiment with $n < 3$ RMPs. Meanwhile, resonant and non-resonant magnetic braking of plasma rotation both increase as $(\delta b)^2$. We conjecture that if non-resonant harmonics are sufficiently greater than the ELM-suppressing RMPs, braking dominates and the plasma tends toward instability. This is also qualitatively consistent with experiment. This conjecture must be tested by future experiments, but if correct, it means that RMP coils for ELM control must be poloidally short and close to the plasma, so that they can apply a resonant field without non-resonant field harmonics that are too large.

The ITER organization plans to have redundant ELM amelioration methods, using pellet pacing and RMP coils [9]. The present RMP coil design has three toroidal rows (upper, equatorial, lower) of nine coils each (consistent with the nine ITER vacuum vessel segments) [9]. Fig. 4 shows a simplified concept drawing, but the design is not yet final [9]. Fig. 5 shows a corresponding magnetic spectrum with a non-resonant peak only about 15% larger than the RMP. The planned coils can make n=3, n=4, or mixed n=3 and n=4 RMPs with a resonant spectral peak that can track q_{95} from 3 to 5, the anticipated range of high-power H-mode operation.

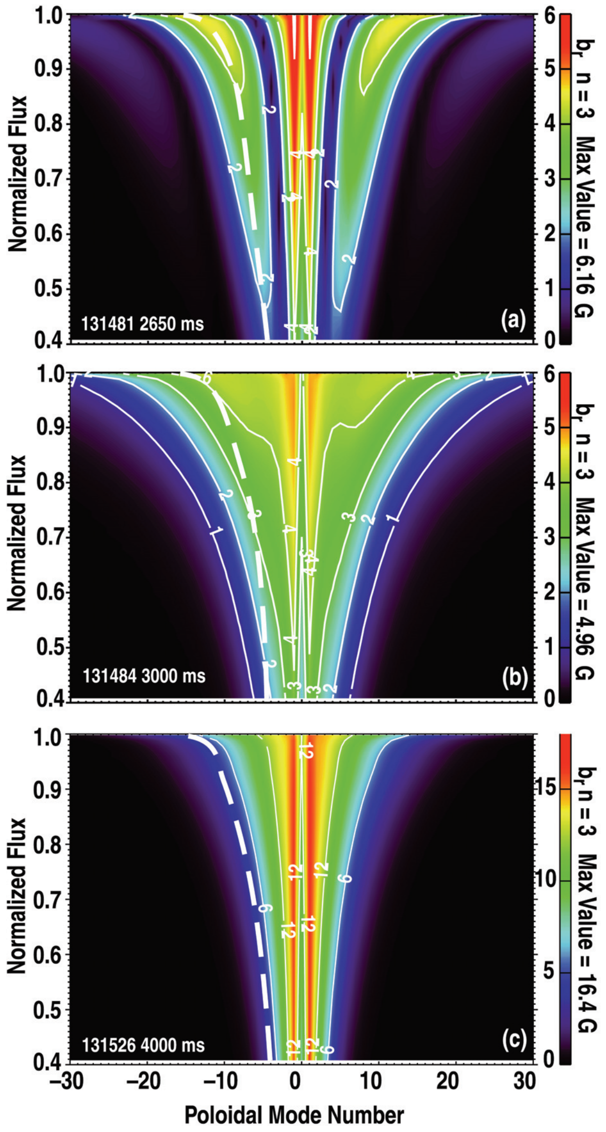

Figure 3. Comparison of $m/n = m/3$ helical harmonics of the vacuum δb_r field [7] of (a) two I-coil rows with even parity, (b) I-coil upper row alone, and (c) C-coil. ELM suppression occurs with (a) and (b), but not (c). Vertical axis is plasma radius in normalized poloidal flux units. White dashed line shows locus of pitch resonant modes, $m = -nq$. $q_{95} \approx 3.5$. Figure from [11].

Although the DIII–D RMP ELM suppression results are encouraging, the extrapolation to ITER is large, and this technique has not yet succeeded at other tokamaks. Magnetic spectra based on vacuum fields ignore important plasma amplification and shielding responses. In this paper we suggest a new insight that might explain why RMP ELM suppression has only be found so far with the DIII–D I-coil, namely, that excessively large non-resonant helical harmonics of the perturbing magnetic field might be braking plasma rotation and degrading the plasma stability. Additional experimental and theoretical research is necessary.

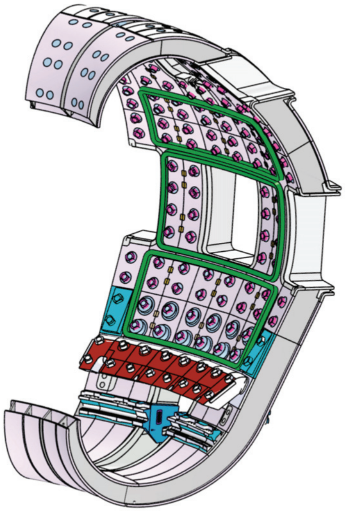

Figure 4. A concept for RMP coils (green) in ITER. Each 40° vacuum vessel sector carries an upper, mid and lower coil.

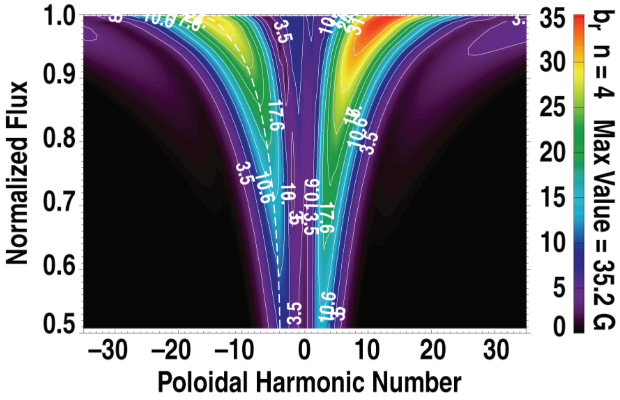

Figure 5. Calculated δb_r helical harmonics from an ITER RMP array of three rows of nine coils each. Coil currents are phased to apply a large, edge resonant peak.

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