Analysis of edge magnetic field line structure in ITER due to in-vessel ELM control coils

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Abstract
In this work we evaluated the ITER ELM coils design based on two metrics: the Chirikov vacuum magnetic island overlap parameter, and the vacuum field line loss fraction. The study was performed for a range of current amplitudes for three different $n = 4$ waveforms: square, cosine and sine. The results indicated that ITER ELM coils are designed with a high level of flexibility to accommodate different operation scenarios (H-mode and Steady State) with different values of q_{95} and q-profiles. The magnetic island overlap analysis showed that ITER ELM coils are capable of matching the DIII-D I-coil spectrum. The Field Line Loss analysis showed that edge vacuum stochastization might be achieved that is similar or greater than in DIII-D. Fault analysis of the coils indicated that ITER ELM coils are robust and show good characteristics even with 11% of dead coils.

1. Introduction

Resonant magnetic perturbations (RMPs) have proven to be successful for the suppression and mitigation of edge localized modes [1,2] (ELMs) in DIII-D [3,4], JET [5] and ASDEX-U [6]. ELMs drive impulsive energy losses and can be detrimental to plasma facing surfaces in future ITER high power experiments. Type-I ELM power fluxes on ITER divertor targets can be close to or above marginal for an acceptable divertor lifetime [19]. During the application of RMP fields from non-axisymmetric coils external to the plasma the vacuum topology of the magnetic field, excluding the plasma response, changes producing a stochastic region that is formed by overlapping magnetic islands. Experiments have shown that the application of RMP fields leads to increased particle transport in the pedestal and the suppression of Type-I ELMs [7]. Understanding ELM physics and developing the ability to control Type-I ELMs will improve the performance and longevity of ITER plasma-facing surfaces in high energy density tokamak-based fusion confinement.

In this work, we analyze the effect of the RMP coils on the magnetic topology in ITER since this is known to affect the stability of Type-I ELMs in DIII-D. The ITER RMP ELM control approach is based on the successful ELM suppression with DIII-D I-coils [8]. Thus, by comparing the magnetic topology in DIII-D with that in ITER we can extrapolate our knowledge of the DIII-D RMP ELM suppression strategy to the future ITER experiments.

One of the goals of this work is to provide data to fluid codes for calculating the distribution of heat loads on the divertor target plates. We do this by modeling the magnetic footprints on the divertor targets.

Previously, several ITER ELM coil designs were studied in order to optimize the coil mode spectra and magnetic island overlap [9,10]. In the present work we extend this research to a design that has 3 rows of coils with 9 toroidal loops located between the ITER blanket modules and wall on the low field side of the machine as shown in Figs. 1 and 2.

The work that is presented here is based on the perturbed vacuum magnetic field model. All calculations of B in the plasma are made with the conventional model where curl-free magnetic perturbations from accurate coil current models are added to the axisymmetric field of a Grad-Shafranov plasma equilibrium calculated with the corsica code [11]. This vacuum model does not include the effects of plasma response; no self-consistent perturbed fields in the plasma are calculated. Since the plasma response may play a very important role in the performance of the of the pedestal when small 3D magnetic perturbations are present, future work should include perturbed plasma currents since linear MHD models like MARS-F predict that they screen the field inside the plasma [12]. However, presently the vacuum model is the only way to consider and compare a large number of nonaxisymmetric perturbations including coil fault conditions.

In this work, we make use of two major metrics - the width of the magnetic island overlap region (typically associated with Chirikov parameter σ_{CHIR} = (sum of neighboring island half-widths)/(island separation)) and Field Line Loss Ratio. These metrics will be discussed in detail in the following sections. It has been shown previously that there exists a correlation between the ELM suppression in DIII-D and the width of the edge region in normalized poloidal magnetic flux where the Chirikov parameter profile is equal to or exceeds unity $(\sigma_{CHIR} > 1)$. Result from DIII-D ELM suppression were used to identify the criteria for designing the ELM suppression coils in ITER: $\Delta_{CHIR} = 0.165$ in normalized poloidal flux coordinates [13]. It should be noted here, that the underlying physics of RMP ELM suppression is not understood yet. An ongoing research at DIII-D and other tokamaks is focused on identifying the ELM suppression parameter space as well as validation of different theories of ELM suppression.

2. ITER coil sets and ITER equilibria

ITER is currently projected to have several sets of internal coil [21]. The coil sets of interest for this work include the internal ELM coils – three rows by nine coils each shown in Figs. 1 and 2 in green.

Fig. 1 shows a view of the ELM coils located on the inside wall viewed from inside the vessel. The size and location of the ELM coils is dictated by complex design and space limitations in ITER. Additional elements shown in Fig. 1 include leads (blue) and vertical stability coils (orange).

The other coil set of interest is the three by six array of Error Field Correction (EFC) coils (shown as dotted line in Fig. 2). These coils are located outside the vessel, away from the plasma. Figure 2 shows the relative position of ELM and EFC coils. The limiter geometry is shown as a black solid line for reference. We have performed the analysis of the EFC coils alone and the effect of $n = 1$ current on ELM suppression, and observed only a small effect of the EFC-coils even at maximum current amplitude. This is due to the low levels of stochasticity created by EFC coils. This conclusion agrees with the previous experimental observations on DIII-D [22].

We performed the modeling using the ITER equilibria that were generated on 257 by 513 grid using the CORSICA code [11]. These equilibria represent the ITER 15MA H-mode and 9MA Steady State scenarios as shown in Fig. 3. Both equilibria include the bootstrap current that reduces the magnetic shear in the pedestal (flattening the safety factor radial profile). These equilibria provide a wide range of edge safety factor q_{95} parameter from 3.2 (H-mode) to 5.9 (Steady state).

For the current distribution in the RMP coils, we looked at three different waveforms. The first waveform is an $n = 4$ square wave as shown in Fig. 4. The current in the middle row of coils in this configuration reinforces the return flux from top and bottom rows. This is achieved by shifting the middle row current distribution by 40 degrees toroidally. Additionally, since the ITER ELM coil set consists of 9 coils in each row, and the $n = 4$ square form is typically constructed using 8 toroidal coils, that left us with a choice of currents for the ninth column of ELM coils. Two natural solutions are to switch the 9th coils off $\left(I_c = 0\ kAt\right)$, or to copy currents from neighboring column (1st or 8th). Both solutions create a significant $n = 5$ component (as do the sine and cosine wave forms described later). Both solutions will also create a small $n = 1$ component (this was confirmed in our analysis) that will not have a significant impact on RMP ELM suppression, nor create comparable addition to $n = 1$ EFC coils. We have chosen to fill the 9th coil column with currents equal to currents in the 1st column of ELM coils. This gives us the advantage of more flexibility and uses all available coil currents.

The other waveforms studied in this work are the $n = 4$ cosine waveform (shown in Fig. 5) and the $n = 4$ sine waveform (shown in Fig. 6). These waveforms were developed and studied previously [10]. The sine waveform was optimized for ITER H-mode, and the cosine waveform was optimized for the ITER Steady state scenario. The details of the sine and the cosine waveforms are given in Appendix A. In both cases, the optimization was done by matching the coil current phase shift with the magnetic field line pitch angle in the pedestal region. The $n = 4$ square waveform produces larger perturbation fields because the current amplitude in the coils is maximized. Additionally, the shape of this waveform produces a large number of magnetic islands with different toroidal mode numbers $n = 1$, 2, 3, 4 and 5, that help to achieve desired levels of stochastization in the plasma and meet the coil design criterion. The advantage of the sine and cosine waveforms over the square waveform is that they can be smoothly rotated toroidally. This allows for rotation of helical separatrix lobes and their associated footprints on the divertor [14] to reduce heat loads. This is important for the reduction of material degradation. An application of the present research to study the magnetic footprints on the ITER divertor will be discussed in the final section of the paper.

3. Chirikov parameter and Field line loss analysis

In the vacuum model, magnetic islands are formed on resonant surfaces inside the separatrix. The stochastic region inside the separatrix is associated with the region of overlapping magnetic islands. The width of the magnetic island overlap region is typically denoted as Δ_{CHIR} and is defined as the width of the region near separatrix where Chirikov magnetic island overlap parameter σ_{CHIR} is greater than one: $\Delta_{CHIR} = 1 - \psi_N\left[\sigma_{CHIR} > 1.0\right]$. The Chirikov magnetic island overlap criterion was developed for a single toroidal harmonic case. Its application in case of multiple toroidal harmonics can be very complicated and possibly misleading.

In most of the previously published work, only the first three toroidal modes ($n = 1$, 2 and 3) were included in the vacuum spectral analysis with the SURFMN code, which is used to calculate the Chirikov parameter profile [10]. In the present work we have included five toroidal modes ($n = 1,2,3,4$, and 5). This was dictated by our preliminary study that indicated that the ELM coils in ITER would be capable of producing a large variety of magnetic islands of comparable size. Thus, we needed to include all of the significant toroidal modes for correct calculation of the Chirikov magnetic island overlap parameter and the width of the magnetic island overlap region. This, however, creates a complication because the Chirikov parameter profile in this case cannot be approximated by a low-order spline. This is shown in figures 7 and 8 for ITER H-mode scenario with RMP coils at 50 kAt and 90 kAt $n = 4$ square waveforms. The Chirikov magnetic island overlap parameter σ_{CHIR} is represented by blue dashed lines. The solid horizontal line indicates $\sigma_{CHIR} = 1$. The value of ψ_N at which Chirikov profile crosses $\sigma_{CHIR} = 1$ is associated with the extent of the vacuum magnetic island overlap region. Thus, in this case the width of the magnetic island overlap region increases from $\Delta_{CHIR} = 0.18$ to $\Delta_{CHIR} = 0.21$ when the ELM coil current is increased from 50 kAt to 90 kAt.

The second metric used in this study is the Field Line Loss Fraction. It is the ratio of the field lines that hit the divertor in less than 200 toroidal revolutions to the total number of field lines launched at a particular flux surface. The FLLF analysis is performed with the vacuum magnetic field line tracing code TRIP3D [15]. As shown previously [16], a good accuracy of the FLLF requires 512 lines per normalized poloidal flux surface, but it is possible to achieve a good approximation of the field line loss ratio when launching 128 lines per normalized poloidal flux surface. The error in field line loss ratio computation in this case is on the order of 1-2 percent. In the Field Line Loss analysis, the field lines are followed for 200 toroidal transits, comparable to approximately 2 electron mean free paths, which is sufficient to characterize the lost field lines [17]. For the radial distribution we launched field lines at 64 normalized poloidal flux surfaces equally distributed between ψ_N of 0.68 and 0.995.

The Field Line Loss Fraction radial profiles for ITER H-mode scenario with ELM coils at 50 kAt and 90 kAt $n = 4$ square waveforms are shown as a solid line in Figs. 7 and 8, respectively. Both FLLF profiles show that we can achieve high levels of vacuum Field Line Loss in the H-mode pedestal. This was shown previously to be correlated with ELM suppression in DIII-D [18].

As it can be seen in Figs. 7 and 8, Field Line Loss Fraction radial profile is more sensitive to the changes in ELM coil current amplitude than the Chirikov parameter. When we find only a mild increase in Chirikov magnetic island overlap width (from 0.18 to 0.21), we see a more significant change in FLLF profile. The inner boundary of lost field line region moves from $\psi_N = 0.74$ to below $\psi_N = 0.68$ (limited by computational boundaries). The fraction of the lost field lines also increases significantly across the profile.

Taking into account these differences in Chirikov parameter and FLLF metrics, we use the first one as a quick proxy to identify conditions and parameters for a more detailed study using Field Line Loss analysis. For example, we can use the Chirikov parameter to look at the dependence of the width of magnetic island overlap region on the amplitude of ELM coil current. As a next step, we perform the FLLF analysis at different ELM coil current amplitudes.

Results for this current amplitude scan are shown in Figs. 9a and 9b for the ITER H-mode scenario with ELM coils with $n = 4$ square and cosine waveforms respectively. The top plots in both figures show the width of the magnetic island overlap region as function of applied current amplitude. The horizontal blue line in both plots is the DIII-D suggested criterion above which a statistical correlation for ELM suppression was seen for some discharge conditions. The bottom plots in Figs. 9a and 9b show FLLF as a function of normalized poloidal flux coordinate. The data in Figs. 9a and 9b suggests, that an $n = 4$ square waveform will probably allow us to exceed the coil design criterion suggested by the DIII-D statistical correlation studies [13] with $I_c = 25$ kAt in ITER ELM coils. In the case of a cosine waveform, the criterion will be exceeded at a higher value $\left(I_c = 65 \text{ kAt}\right)$ of ELM coil current.

The comparison of the two metrics shown in the top and bottom plots in Figs. 9a and 9b indicates that the island overlap parameter is very insensitive to changes in ELM coil current amplitudes. For example, in case of the square waveform (Fig. 9a) the values of the magnetic island overlap width change very little when the coil current is increased from 25 kAt to 65 kAt (Fig. 9a, top). On the other hand, we see a large difference in FLLF radial profiles at 25 kAt and 50kAt (Fig. 9a, bottom).

The bottom plots in Figs. 9a and 9b also suggest that the design of the ITER ELM coils allows for a great flexibility. While satisfying the coil design criterion $\left(\Delta_{CHIR} > 0.165\right)$ we can change the ELM coil current amplitude so that the predicted vacuum FLLF profiles vary from narrow (25 kAt, square waveform) to broad (90 kAt, square waveform). This range includes ELM coil currents at which the vacuum ITER ELM coil performance is compatible with that of the DIII-D I-coils.

The ITER ELM coils are designed to have a maximum coil current of 90 kAt. We performed a detailed Field Line Loss analysis to compare the effect of different waveforms at maximum current amplitude. The conditions for the FLL analysis were set as described previously: 64 normalized poloidal flux surfaces between ψ_N of 0.68 and 0.995 with 128 field line per surface, the lines were traced for 200 toroidal transits.

The results for ITER H mode scenario are summarized in Fig. 10 for 90 kAt in the $n = 4$ waveforms in ITER H-mode. FLLF radial profile from DIII-D ELM-suppressed ITER similar shot 126006 at 3600 ms is given for reference. At maximum allowed ELM coil current all three studied waveforms (square, cosine and sine) produce Field Line Loss Fractions that are larger and wider than in the DIII-D case. The square $n = 4$ waveform produces the largest field line loss; cosine and sine waveforms also give FLLF profiles that are broader than FLLF profile in DIII-D case.

The results for ITER Steady State scenario are shown in Fig. 11. In this case, the sine waveform produces a narrow FLLF radial profile. This is due to the fact that the sine waveform was not optimized for the ITER Steady State Scenario. The other two waveforms produce broad Field Line Loss Fraction profiles in the ITER Steady State scenario with $q_{95} = 5.9$. This indicates that the ELM coils in ITER can provide significant FLLF over a wide range of q_{95}.

4. Coil failure analysis

The ITER ELM coils are designed to work for an extended period of time without repairs. In this case, it is very important to be able to maintain RMP ELM control in the event of a possible coil failure. In this section we present the results of an analysis of the impact of isolated coil failures in the ITER ELM coils on the ability of the coil set to satisfy the design criterion $\Delta_{CHIR} \geq 0.165$.

The first step is the quick Chirikov parameter analysis. Let us suppose that all 27 ELM coils are working normally. If we apply a 90kAt $n = 4$ square waveform in an ITER H-mode discharge, the predicted Chirikov magnetic island overlap width parameter Δ_{CHIR} is equal to 0.23, as shown by the solid horizontal line in Fig. 12. This value is higher than the Chirikov magnetic island overlap width in DIII-D ITER similar shape ELM suppressed shots which has been adopted as the ITER coil design criterion. The solid, dashed and dotted lines in Fig. 12 show the values of the Chirikov magnetic island overlap width as function of the position of the single failed coil in bottom, middle, or top row of the ELM coil set respectively. As the results show, the single coil failure in the top or bottom coil rows leads to a very small decrease of less than 1% in the width of the island overlap. The largest effect on the Chirikov magnetic island overlap width is produced by the coil failure in the middle row of coils. In this case, the width of the magnetic island overlap region shrinks to approximately 0.21 in normalized poloidal flux coordinates. This value is still well within the guidelines given to ITER for possible ELM suppression.

Next, we analyze double and triple RMP coil failures. In these scenarios we have used the same initial conditions to see the effect of consecutive coils failing in the top, middle or bottom rows. Fig. 13 shows the width of the island overlap as function of the position of the failed pair of coils in the triple coil failure scenario. Again, the effect of coil failures in the top and bottom rows is relatively small, and the largest effect is created by the coil failure in the middle row of RMP coils. As can be seen from these plots, even in this case of three consecutive coils failing in the middle row of ELM coils in ITER, the magnetic island overlap region width predicted by the vacuum field model of 0.18 is still larger than the island overlap width in the DIII-D ELM-suppressed plasma shots. These results indicate that the proposed ELM coils are capable of meeting the coil design criterion even in case of three dead coils in one row of coils.

The Chirikov island overlap parameter analysis indicated that the worst case scenario occurs when three consecutive coils fail in the middle row $\left(\Delta_{CHIR} = 0.187\right)$. This condition was chosen for a more detailed study using the Field Line Loss Fraction metric. The Field Line Loss analysis was performed for two current amplitudes of 50kAt and 90kAt and square, cosine and sine waveforms in the ITER H-mode and Steady state scenarios.

The results for the ITER H-mode scenario with an $n = 4$ square waveform in ELM coils are shown in Fig. 14 as radial field line loss fraction profiles. For both 50kAt and 90kAt, the Field Line Loss Fractions are smaller in cases with three dead coils, but the decrease is relatively small. The same behavior was also observed for the $n = 4$ sine and cosine waveforms in ITER H-mode scenario.

The FLLF results for the ITER Steady State scenario with an $n = 4$ square waveform in the ELM coils are shown in Fig. 15. The data is presented for 50 kAt (dashed lines) and 90 kAt (solid lines) cases. It is interesting to note that in the ITER Steady State scenario $\left(q_{95} = 5.9\right)$ we observe higher Field Line Loss Fraction values in case of a reduced ELM coil set with 3 dead coils. This is due to the fact that the $n = 4$ square waveform was not optimized for the Steady State scenario, and by turning off three consecutive coils in the middle row, we created $n = 1$ islands which are favorable for field line loss.

The results of the ITER ELM coil failure Field Line Loss Fraction analysis are summarized in Tables 1 and 2 for the average pedestal Field Line Loss Fraction. The averaging for the Field Line Loss Fraction was done in the plasma pedestal region between $\Psi_N = 0.95$ and $\Psi_N = 1.0$. The three columns of data correspond to the square, cosine and sine waveforms respectively. The data is the average pedestal FLLF values for 50kAt and 90kAt RMP coil currents with all 27 coils working normally and with a reduced set of ELM coils with three dead coils. The average pedestal FLLF value in a similar DIII-D H-mode ITER similar shape ELM suppressed shot 126006 at 3600 ms is $\mathrm{FLLF} = 0.7763$.

The corresponding results for the ITER Steady State scenario are shown in Table 2. The results show high values of average pedestal FLLF for the square and cosine waveforms, and quite moderate values for the sine waveform in the ELM coils.

5. Magnetic footprints

The proposed design of the ITER divertor target includes a high heat flux handling near the inner and outer strike zones $\left(\sim 10 MW/m^2\right)$ and a low heat flux handling zone away from the strike zones $\left(\sim 5\ MW/m^2\right)$ [19]. In the first divertor, the high heat flux zone plasma facing components (PFCs) will be made of carbon-fiber-composite (CFC) and the low heat flux zone will be made of tungsten, while in the second divertor (which will be used to explore DT plasmas) both PFC zones will be made of tungsten.

Vacuum field modeling provides efficient way to simulate magnetic footprints on the divertor that agree well with experimental observations [20]. In this work we look at the footprints near the inner (ISP) and outer (OSP) strike points in the ITER H-mode Scenario with 90kAt $n = 4$ square and cosine waveforms. The results of this modeling are shown in Fig. 16. The horizontal axis represents the toroidal angle, and the vertical axis represent the distance from the strike point along the divertor wall. The square waveform produces lobes with interior regions of larger connection lengths L_C (length of the magnetic field line from low field side target plate to high field side target plate) from further up in the pedestal (green) that extend from the CFC-high power handling area to the tungsten-low power handling area of the divertor. This might lead to larger power loads away from the divertor strike zone than originally expected and an increase in tungsten impurity production from these regions. Impurities produced at these locations would have an easier access to the bulk plasma than for those produced at the strike zone and may lead to higher impurity contamination of the confined plasma.

On the other hand, lobes produced by the cosine waveform are shorter and tend to stay on the CFC-high power handling area completely thus avoiding the problems discussed above. In addition, the cosine waveform also allows for toroidal rotation that can be applied to reduce the average heat load on the divertor and produce a net uniform erosion pattern thus extending the divertor target lifetime.

Reduction of the current amplitude in the ELM coils will lead to reduction in the extent of the lobes. This is shown in Fig. 17 for the 50kAt $n = 4$ square waveform in ITER H-mode Scenario. The lobes in this case are shorter, and stay in CFC-high power handling area completely as well.

The vaccuum footprint modeling suggests three possible solutions (besides rotation of the perturbation) for reduction of heat loads on the tungsten-low power handling area of the divertor: to use cosine/sine waveforms, to use lower current amplitudes in square waveforms, or to increase the extent of the area with high power handling capability at the divertor. Simulation of heat and particle fluxes to the ITER divertor with ELM coil targets are needed to estimate properly the expected heat loads and erosion of the divertor and to chose the optimum strategy for heat flux reduction and erosion control in ITER for ELM-suppressed plasma scenarios.

6. Conclusion

The most recent ITER ELM coil design was evaluated in terms of a coil design criterion based on the width of the magnetic island overlap region for H-mode $(q_{95} = 3.2)$ and Steady state $(q_{95} = 5.9)$ scenarios using 3 distinct $n = 4$ coil toroidal waveforms (square, cosine, and sine). ITER ELM coil design was found to compare favorably to DIII-D I-coils. The results of the modeling indicate that it is possible to exceed the DIII-D ELM suppression criterion with all three ELM coil toroidal waveforms. The waveforms studied show good vacuum magnetic island overlap region widths $(\Delta_{CHIR} > 0.165)$ and field line loss radial profiles for both H-mode and Steady State operations in ITER that are compatible with FLLF radial profiles in DIII-D I-coil experiments. The results indicate that ITER ELM coils are sufficiently flexible to accommodate a variety of operating scenarios with different values of q_{95} and q-profiles. The coil configurations and current distributions are robust and show good characteristics over a range of RMP coil current amplitudes and phases. A detailed coil failure analysis also shows that the ITER ELM coil design will provide a significant operational margin with respect to Δ_{CHIR} and FLLF in the event of up to 3 isolated coil loop failures.

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Appendix A

The coil currents in case of the sine waveform are given as $A_{ri} = A_0 \cdot \sin(4 \cdot (\varphi_{ri} + \Delta\varphi_r + \Delta\varphi_0))$,

where $i = 1 \ldots 9$, subscript r represents top (t), middle (m) or bottom (b) row of ELM coils, A_0 is the magnitude of the applied coil current, the toroidal positions of the ELM coils are given at the center of each coil as $\varphi_{ti} = 28.5^\circ + i \cdot 40^\circ$, $\varphi_{mi} = 20.2^\circ + i \cdot 40^\circ$, $\varphi_{bi} = 30^\circ + i \cdot 40^\circ$, the phase shifts in the rows are $\Delta\varphi_t = 54^\circ$, $\Delta\varphi_m = 0^\circ$, $\Delta\varphi_b = -64^\circ$, and the phase shift for alignment with the first coil is $\Delta\varphi_0 = -20.2^\circ$.

The coil currents in case of the cosine waveform are given as $A_{ri} = A_0 \cdot \cos(4 \cdot (\varphi_{ri} + \Delta\varphi_r + \Delta\varphi_{r0}))$,

where $i = 1 \ldots 9$, subscript r represents top (t), middle (m) or bottom (b) row of ELM coils, A_0 is the magnitude of the applied coil current, the toroidal positions of the ELM coils are given at the center of each coil as $\varphi_{ti} = 28.5^\circ + i \cdot 40^\circ$, $\varphi_{mi} = 20.2^\circ + i \cdot 40^\circ$, $\varphi_{bi} = 30^\circ + i \cdot 40^\circ$, the phase shifts in the rows are $\Delta\varphi_t = 70^\circ$, $\Delta\varphi_m = 0^\circ$, $\Delta\varphi_b = -70^\circ$, and the phase shifts for alignment with the first coil in the rows are $\Delta\varphi_{t0} = -28.5^{\circ}$, $\Delta\varphi_{m0} = -20.2^{\circ}$, $\Delta\varphi_{b0} = -30^{\circ}$.

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Figure Captions

Fig. 1. (color) Schematic of ITER internal ELM coil (view from inside the vessel). Top, middle and bottom RMP coils are shown in green. Leads are shown in blue, vertical stability coils are shown in orange.

Fig. 2. (color) ITER internal ELM coil (green) and Error Field Correction Coil (blue) models used in this work. ITER limiter geometry is shown in black for reference.

Fig. 3. (color on line) ITER 15 MA H-mode based on CORSICA equilibrium file g900003.00230 (dashed) and 9 MA Steady state based on Corsica equilibrium file g900004.00230 (solid) equilibria generated with the CORSICA code: contours of constant poloidal magnetic flux surfaces (left), radial profiles of current (top right) and safety factor (bottom right).

Fig. 4. (color on line) Current distribution for top, middle and bottom rows of the ITER ELM coils for an $n = 4$ square waveform. The top and bottom rows are shifted by 40 degrees to reinforce the return flux. Circles indicate current amplitudes in individual coils. Dotted lines are given to guide eye.

Fig. 5. (color on line) Current distribution for top, middle and bottom rows of the ITER ELM coils for an $n = 4$ cosine waveform. The waveform was optimized for ITER H-mode scenarios with $q_{95} = 3.2$. Circles indicate current amplitudes in individual coils. Dotted lines are given to guide eye.

Fig. 6. (color on line) Current distribution for top, middle and bottom rows of the ITER ELM coils for an n=4 sin waveform. The waveform was optimized for ITER Steady State scenarios with $q_{95} = 5.9$. Circles indicate current amplitudes in individual coils. Dotted lines are given to guide eye.

Fig. 7. (color on line) Chirikov parameter (star-hash-marked line) and Field Line Loss Fraction (solid line) radial profiles for an ITER H-mode equilibrium with an $n = 4$ square waveform and 50 kAt in the ELM coils. The solid horizontal line corresponds to Chirikov parameter $\sigma_{chir} = 1$.

Fig. 8. (color on line) Chirikov parameter (star, dashed line) and Field Line Loss Fraction (solid line) radial profiles for an ITER H-mode equilibrium with an $n = 4$ square waveform and 90 kAt in the ELM coils. The solid horizontal line corresponds to Chirikov parameter $\sigma_{chir} = 1$.

Fig. 9a. (color on line) Width of magnetic island overlap region as function of ELM coil current amplitude (top) and radial profiles of field line loss fraction (bottom) in the ITER H-mode scenario with $n = 4$ square waveform. DIII-D ELM suppression criteria shown by horizontal line.

Fig. 9b. (color on line) Width of magnetic island overlap region as function of ELM coil current amplitude (top) and radial profiles of field line loss fraction (bottom) in the ITER H-mode scenario with $n = 4$ cosine waveform. DIII-D ELM suppression criteria shown by horizontal line.

Fig. 10. (color on line) Comparison of radial profiles of Field Line Loss Fraction for the ITER H-mode scenario (q_{95} = 3.2) with ELM coils at 90kAt for $n = 4$ square (dot, dashed line), cosine (open diamonds, dashed line) and sine (cross, dashed line) waveforms. The FLLF radial profile of ITER Similar Shape DIII-D ELM-suppressed discharge 126006 at 3600 ms is shown for reference.

Fig. 11. (color on line) Comparison of radial profiles of Field Line Loss Fraction for the ITER Steady State scenario $(q_{95} = 5.9)$ with ELM coils at 90kAt for $n = 4$ square (open circled line), cosine (stars, dashed line) and sine (plus, dashed line) waveforms.

Fig. 12. Width of the magnetic island overlap region (Δ_{CHIR}) as a function of the position of the single failed coil in the top (open squares, solid line), middle (filled circles, dashed line) and bottom rows (open circles, dotted line) for the ITER H-mode scenario with ELM coils at 90kAt and an $n = 4$ square waveform. Horizontal line indicates the width of magnetic island overlap region for the case with all 27 RMP coils working properly $(\Delta_{CHIR} = 0.23)$. The ITER coil design criterion from DIII-D ELM suppression experiments $(\Delta_{CHIR} = 0.165)$ is not shown.

Fig. 13. Width of the magnetic island overlap region (Δ_{CHIR}) as a function of the position of three failed coils $(\mathrm{N},\ \mathrm{N}+1,\ \mathrm{N}+2)$ in the top (open squares, solid line), middle (filled circles, dashed line) and bottom rows (open circles, dotted line) for the ITER H-mode scenario with an $n = 4$ 90 kAt square waveform in the RMP coils. Horizontal line indicates the width of magnetic island overlap region for the case with all 27 ELM coils working properly (Δ_{CHIR} = 0.23). The ITER coil design criterion from DIII-D ELM suppression experiments (Δ_{CHIR} =0.165) is not shown.

Fig. 14. (color on line) Radial profiles of the Field Line Loss Fraction for the ITER H-mode scenario with the ELM coils at 50kAt (dashed line) and 90kAt (solid line) with an n=4 square waveform. The FLLF profile for the full set of all 27 ELM coils working properly is shown in dotted line; the FLLF profile for the reduced set with 3 failed coils (coils 5,6 and 7 in the middle row) is shown in a dot, dashed line.

Fig. 15. (color on line) Radial profiles of the Field Line Loss Fraction for the ITER Steady State scenario with the ELM coils at 50kAt (dashed) and 90kAt (solid) with an n=4 square waveform. The FLLF profile for the full set of all 27 ELM coils working properly is shown in blue; the FLLF profile for the reduced set with 3 failed coils (coils 5,6 and 7 in the middle row) is shown in red.

Fig. 16. Magnetic footprints on ITER divertor (CFC $\left(\sim 10 MW/m^2\right)$ and W $\left(\sim 5 MW/m^2\right)$) as computed with the vacuum field model. Colors represent the magnetic field line connection length in kilometers. Results are shown for the Inner (left column) and Outer (right column) Strike Points with 90kAt in n=4 square (top) and cosine (bottom) waveforms.

Fig. 17. Magnetic footprints on ITER divertor (CFC $\left(\sim 10 MW/m^2\right)$ and W $\left(\sim 5 MW/m^2\right)$) as computed with the vacuum field model. Colors represent the magnetic field line connection length in kilometers. Results are shown for the Inner (left column) and Outer (right column) Strike Points with 50kAt in $n = 4$ square waveforms.

Table 1.

Field Line Loss Fraction averaged over the pedestal $(0.95 < \psi_N < 1.0)$ in the ITER H-mode scenario with the full 27 coils and with three dead coils for 50kAt and 90kAt $n = 4$ square, cosine and sine waveforms. The average pedestal FLLF in DIII-D ITER Similar Shape discharge 126006 at 3600ms is 0.7763.

Table 2.

Field Line Loss Fraction averaged over the pedestal $(0.95 < \psi_N < 1.0)$ in the ITER Steady State scenario with the full 27 coils and with three dead coils for 50kAt and 90kAt $n = 4$ square, cosine and sine waveforms.

Table 1.

	Square	Cosine	Sine
50 kAt – full set	0.8146	0.6499	0.7053
50 kAt – 3 failed coils	0.7855	0.5980	0.5703
90 kAt – full set	0.9354	0.8175	0.8224
90 kAt – 3 failed coils	0.8764	0.7578	0.7642

Table 2.

	Square	Cosine	Sine
50 kAt – full set	0.6449	0.6818	0.3793
50 kAt – 3 failed coils	0.7408	0.6257	0.5980
90 kAt – full set	0.8040	0.8196	0.5810
90 kAt – 3 failed coils	0.8501	0.7919	0.7578