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Y. Liang[1], C.G. Gimblett[2], P.K. Browning[3], P. Devoy[3], H.R. Koslowski[1],
S. Jachmich[4], Y. Sun[1], C. Wiegmann[1] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

*[1]Forschungszentrum Jülich GmbH, Association EURATOM-FZ Jülich, Institut für Plasmaphysik,
Trilateral Euregio Cluster, D-52425 Jülich, Germany*
[2]EURATOM-CCFE Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
[3]School of Physics and Astronomy, University of Manchester, Manchester, UK
*[4]Association EURATOM-Belgian State, Koninklijke Militaire School - Ecole Royale Militaire,
B-1000 Brussels Belgium*
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ABSTRACT.
Multiple resonances in the Edge Localized Mode (ELM) frequency (f_{ELM}) as a function of the edge safety factor q_{95} have been observed for the first time with an applied low n (=1,2) field on the JET tokamak. Without an n = 1 field applied, f_{ELM} increases slightly from 20 to 30Hz by varying the q_{95} from 4 to 5 in a type-I ELMy H-mode plasma. However, with an n = 1 field applied, a strong increase in f_{ELM} by a factor of 4-5 has been observed with resonant q_{95} values, while the f_{ELM} increased only by a factor of 2 for non-resonant values. A model, which assumes that the ELM width is determined by a localised relaxation triggered by an unstable ideal external peeling mode, can qualitatively predict the observed resonances when low n fields are applied.

1. INTRODUCTION.

The periodic and transient power load onto the plasma facing components caused by type-I Edge Localized Modes (ELMs) in high performance H-mode plasmas [1] is a critical issue for the integrity and lifetime of these components in future high power H-mode devices, such as the International Tokamak Experimental Reactor (ITER) [2]. Accordingly, significant effort on both experimental investigations [3, 4] and the development of theoretical models [5, 6] has been spent on a better understanding of ELM physics and the mechanism of ELM control. To date, ELMs are understood as a class of ideal Magneto-HydroDynamic (MHD) modes excited in a high-pressure-gradient region at the plasma edge (known as the pedestal) where pressure gradient driven ballooning modes can couple to current density driven peeling modes. When the pressure gradient in the edge pedestal reaches a critical limit, the type-I ELM is destabilised.

Recently, active control of ELMs using Resonant Magnetic Perturbation (RMP) fields has become an attractive method for application on ITER. DIII-D has shown that type-I ELMs are completely suppressed in a single narrow range of the edge safety factor (q_{95} = 3.5–3.9) when n = 3 fields induced by a set of in-vessel coils are applied [7]. A reduction in pedestal pressure with n = 3 field has been observed, and it can be attributed mainly due to a reduction in pedestal density (the so called density pump-out effect) rather than to an increase in the pedestal thermal diffusivity. Based on the successful ELM suppression experiments on DIII-D, the main criterion for ELM control with RMPs has been de¯ned to require the Chirikov parameter within the plasma edge layer ($\sqrt{\Psi} \geq$ 0.925) to be larger than 1 [8]. Here, the Chirikov parameter (*3/4*), which is a measure of magnetic island overlap, is used to define the stochastic layer as the region for which *3/4* is greater than 1.

On JET, recent experimental results have shown that both the frequency and the size of type-I ELMs can be actively controlled by application of a static low n = 1 or 2 field produced by four external Error Field Correction Coils (EFCC) mounted far away from the plasma between the transformer limbs [9, 10]. When an n = 1 field with an amplitude of a few mT at the plasma edge is applied during the stationary phase of a type-I ELMy H-mode plasma, the ELM frequency, f_{ELM}, rises from ~30Hz up to ~120Hz, while the energy loss per ELM normalised to the total stored energy, $\Delta W_{ELM} = W$, decreases from 7% to values below the resolution limit of the diamagnetic measurement (<2%). Although there are common observations like plasma density pump-out effect and magnetic rotation braking in RMP ELM suppression/control experiments on DIII-D and JET, no complete ELM suppression was observed to date with either the $n = 1$ and $n = 2$ fields on JET, even with a Chirikov parameter above 1 in the edge layer $\sqrt{\Psi} \geq 0.925$ [11]. The major difference in the RMP ELM suppression experiments on JET and DIII-D is the magnetic perturbation spectrum (not only the spatial distribution of Fourier components, but also the ratio of resonant to non-resonant components). This raises the question of the role of the perturbation spectrum in ELM control using resonant magnetic perturbations.

In this letter, the first results on a multi-resonance ef- fect in f_{ELM} vs q_{95} observed on JET with the application of low n fields are presented. A possible explanation of this observation in terms of the ideal peeling/relaxation model of ELMs is given [12].

2. EXPERIMENTAL RESULTS.

On JET, the EFCC system was originally designed for compensation of the $n = 1$ harmonic of the intrinsic error field arising from imperfections in the construction or alignment of the magnetic field coils. Depending on the wiring of the EFCCs either $n = 1$ or $n = 2$ fields can be created. In the $n = 1$ EFCC configuration, the amplitude of the $n = 1$ harmonic is one to two orders of magnitude larger than other components ($n = 2, 3$). Comparison of the effective radial resonant magnetic perturbation amplitudes, $|b^{r,eff}_{res}| = |B^{r,eff}_{res}/B_0|$ calculated for $n = 1$ and $n = 2$ configurations shows that the amplitude of $|b^{r,eff}_{n=2}|$ in the n = 2 configuration is a factor of ~3 smaller than $|b^{r,eff}_{n=1}|$ in the $n = 1$ configuration for all radii[11]. Here, $B^{r,eff}_{res}$ and B_0 are the radial resonant magnetic perturbation field (calculated with a vacuum approximation) and the on-axis toroidal magnetic field, respectively.

A comparison of two JET ELM control pulses using the same $n = 1$ field but different q_{95} is shown in figure 1. Both target plasmas had a low triangularity shape (δ_{lower} ~ 0.2), a toroidal field (B_t) of 1.84T, a stationary type-I ELM H-mode phase sustained by the Neutral Beam Injection (NBI) with a total power of 11.5MW, a low electron collisionality at the edge pedestal (ν^* ~ 0.1), and a similar f_{ELM} of ~20*Hz* before the $n = 1$ field was applied. The plasma currents (I_p) in the two discharges were 1.4*MA* and 1.32*MA*, which correspond to edge safety factors q_{95} of 4:5 and 4:8, respectively. In this experiment, no additional gas fuelling was applied during the H-mode phase. The $n = 1$ field created by the EFCCs had a ramp-up phase of the coil currents (I_{EFCC}) for 300*ms* and a flat-top with I_{EFCC} = 32 *kAt* for 2,5*s*, which is about 10 energy confinement times. $|b^{r,eff}_{n=1}|$ calculated in the vacuum approximation is ~ 2.5×10^{-4} at the position of the edge pedestal. The Chirikov parameter calculated using the experimental parameters and neglecting screening of the $n = 1$ field is ~ 0.8 at $\sqrt{\Psi} = 0.925$, which indicates a weak ergodisation level at the plasma edge. When the $n = 1$ field was applied, f_{ELM} increased strongly by a factor of ~ 4.5 in the plasma with q_{95} of 4.8, while f_{ELM} increased only by a factor of ~2 in the plasma with a safety factor q_{95} of 4.5. Furthermore, an additional drop in the plasma stored energy by 7%, which is mainly due to an enhancement of the density pump-out effect (seen as an additional drop of the central line-integrated density by ~15%) rather than a change of the electron temperature (*Te*), was observed when the q_{95} was changed from 4.5 to 4.8. No clear difference in the toroidal rotation braking induced by the $n = 1$ field between either discharge can be seen. This result indicates a strong resonant effect in q_{95} of the RMP on both the ELM frequency and the density pump-out.

Figure 2 shows f_{ELM} as a function of q_{95} for plasmas with (closed circles) and without (crosses) the $n = 1$ fields. A q_{95} scan from 4 to 5 was carried out by varying I_p only, keeping all other parameters of both discharges identical to the ones shown in figure 1. Without an $n = 1$ field, f_{ELM} changed slightly from 20 to 30*Hz*, and there was no visible large increase of f_{ELM} at any specific q_{95}. However, multiple peaks appeared in the q_{95} dependence of f_{ELM} when the $n = 1$ fields were applied. We term the multiple strong increase of f_{ELM} at different values of q_{95} the 'multi-resonance' effect. The q_{95} values corresponding to each of those peaks are called resonant q_{95}, and the non-resonant q_{95} are the values at the gaps between resonances where there is a weak influence of the perturbation field on f_{ELM}. The resonant peaks of f_{ELM} are not equally distributed in the range of q_{95} from 4 to 5, and the difference in q_{95} between two neighbouring resonance peaks is in the range of Δq_{95} from 0.2 to 0.3. In this experiment, the q_{95} scan has been carried out in two ways, both slow ramp-up and slow ramp-down of I_p, during the application of the $n = 1$ fields. The ramp rate of q_{95} is 0.2 in 2 seconds, which is ~8 energy confinement times. There is good agreement in the values of those resonant q_{95} values observed in the different q_{95} scans. In addition, with a constant q_{95} at either resonant or non-resonant q_{95}, a stationary influence on f_{ELM} has been observed as shown in figure 1, and the results also agree well with the pulses where q_{95} has been varied even more slowly.

This result suggests that there are two effects of the RMP on the ELM frequency, one which has no q_{95} dependence, resulting in a relatively weak increase of f_{ELM}, and a second which depends strongly on q_{95} and causes a stronger increase of f_{ELM}. We may call the first one a global effect, and the second one is the so-called multi- resonance effect described in this paper. These two effects are most likely due to different physics mechanisms.

The multi-resonance effect in f_{ELM} versus q_{95} has also been observed with $n = 2$ fields as shown in figure 3. In this experiment, a q_{95} scan from 4 to 4.6 was performed with target plasmas similar to those used in the $n = 1$ field case. However, the EFCC current was limited to 24*kAt* due to technical reasons. $|b^{r,eff}_{n=2}|$ calculated with a vacuum assumption is ~0.7×10^{-4} at the plasma edge pedestal. A weaker global effect of the $n = 2$ fields on f_{ELM} is seen compared to the $n = 1$ fields, nevertheless the multi-resonance effect is still clearly observed. The size of ELMs, which is indicated by a drop of pedestal *Te* due to the ELM crash (ΔTe), follows the change of f_{ELM}, and it is strongly reduced at resonant q_{95} values as shown in figure 3. Comparison of the multi-resonance effect observed with $n = 1$ and $n = 2$ fields in a q_{95} window of 4 to 4.6 shows that the values of q_{95} at the resonances are similar. However, it should be emphasized that the q profiles are rather steep at the plasma edge, and the q goes to infinity at the plasma separatrix from a finite value q_{95} at $\Psi = 95\%$. So, a small difference of q_{95} could result in very different q values at given radii near the plasma boundary.

DISCUSSION.

To date, many attempts to model ELM suppression/control have focused on the idea that a non-axisymmetric perturbation field penetrating into the edge plasma region would interact with the plasma equilibrium field to produce an outer 'ergodic' magnetic field structure. This would enhance edge thermal and particle losses, weaken the edge transport barrier and its gradients, and thus reduce the peeling/ballooning instabilities thought to underlie ELM formation [13]. An objection to this interpretation is that either bulk plasma or diamagnetic rotation [14, 15] can screen the RMP fields from the plasma whenever they encounter a resonant surface. Fur- thermore, it is important to note that many calculations of the Chirikov parameter [16] model the plasma as producing a *vacuum* response to the RMP, and the resulting total field will not be in magnetostatic equilibrium.

On the other hand, the Chirikov parameter calculated using the experimental parameters and the vacuum approximation of the perturbation field indicates that the ergodisation zone may only appear at the far plasma boundary ($\sqrt{\Psi} > 0{,}97$). The mechanism of edge ergodisation, which is used to explain the results of the ELM suppression with $n = 3$ field on DIII-D, may explain the global effect of the $n = 1$ field on *fELM* on JET, but it cannot explain the multi-resonance effect observed with the low n fields.

In this paper, the ELM model proposed in reference [12] has been used to interpret the experimental results. In this model it is assumed that an unstable ideal external peeling mode triggers a turbulent relaxation process which produces a post-ELM relaxed force-free configuration [17] that is stable to all possible external peeling modes. The flattening of the current profile by the relaxation process generally produces an increase in the edge current density which in itself further destabilises the peeling mode; however this is countered by the formation of a stabilising negative edge current sheet, and it is the balance of these two effects that determines the predicted width of the relaxed region. It should be noted that, unlike the ballooning mode, the peeling mode does not depend on toroidicity to be unstable and it is driven by edge current gradients. In a simple cylindrical model, the plasma is peeling unstable whenever [18]

$$\Delta' \,(1/q_a - n/m) + J_a > 0 \tag{1}$$

where m is the poloidal mode number, Δ' is the familiar jump in $(r/b_r)dbr/d_r$ across the plasma-vacuum interface (b_r is the perturbed radial field) which encapsulates information about the equilibrium current profile ($\Delta' = -2m$ for a vacuum response [18]), and J_a is the driving edge current density (normalised to the on-axis value). A similar criterion can be obtained for an arbitrarily shaped toroidal plasma [19].

In the peeling/relaxation model [12, 18], the ELM width (the extent of the relaxed region, d_E) is determined by requiring that external peeling modes are stabilised for all modes (m, n). Hence, for a given current profile, the mode (m, n) requiring the largest d_E determines the width. A key quantity in the calculation of d_E is the $\Delta = (1/q_a - n/m)$ of Eq. 1, and as m and n must be integers, Δ exhibits detailed structure. It is indeed this fact that gives rise to the 'resonances' in the model predictions.

We now ask how this picture is affected by the application of an $n = 1$ RMP. The RMP will force the plasma into a non-axisymmetric equilibrium with $n = 1$ toroidal variation. Now, an external peeling instability of an axisymmetric field would saturate at modest amplitude with the field in such a non-axisymmetric state, having lower energy [20]. However, this energy-lowering transition is not available if an $n = 1$ distortion already exists. We thus propose that the RMP eliminates the triggering effect of any peeling modes with the same toroidal mode number. Hence, the (m, n) peeling mode with $n \neq 1$ having the next smallest d_E becomes the appropriate trigger. Thus, if the original ELM width were determined by a mode with toroidal mode number $n = 1$, the width is then reduced. Taking the ELM repetition time to be the time taken for the relaxed state to diffuse in a classical manner back to the initial state, a simple qualitative measure of the ELM frequency is given by $f \sim 1/d^2_E$.

Figures 4(a) and (b) show the result of applying these ideas to ELM control modelling. In the example shown we examine a region of edge q just below $q_a = 4$, where the model without an applied $n = 1$ field predicts that an $(m, n) = (4,1)$ mode produces the largest ELMs. Figure 4(a) indicates that there is little variation in predicted ELM size, and hence frequency, in this region (blue curve). When the $n = 1$ is removed, however, we see that a sequence of higher n modes are now revealed to be operative (Fig.4(b), red curves). These produce smaller ELMs and hence higher frequencies (Fig.4(a) red curves). (Corresponding figures can be produced for $n = 2$, with q_a taking values below a half integer value). This simple model reproduces many qualitative aspects of the multi-resonance effect. A full quantitative explanation would require a toroidal model which includes separatrix geometry.

CONCLUSION.

The multi-resonance effect in f_{ELM} versus q_{95} has been observed for the first time with either an n = 1 or an n = 2 magnetic perturbation field on JET. At the resonant q_{95} a strong increase in f_{ELM} and an enhancement of the density pump-out effect has been observed. The difference in q_{95} between two neighbouring resonant peaks is in a range of $\Delta q_{95} = 0.2–0.3$. A model in which the ELM width is determined by a localised relaxation to a profile which is stable to peeling modes can qualitatively predict this multi-resonance effect with a low n field.

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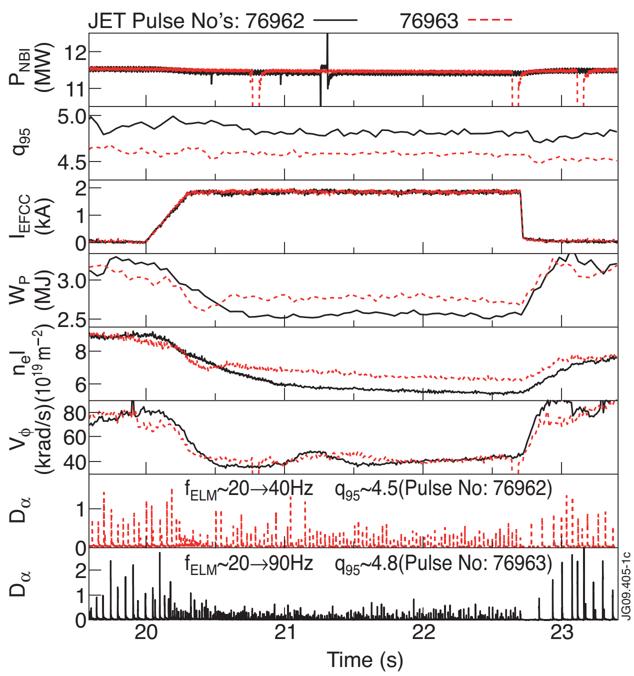
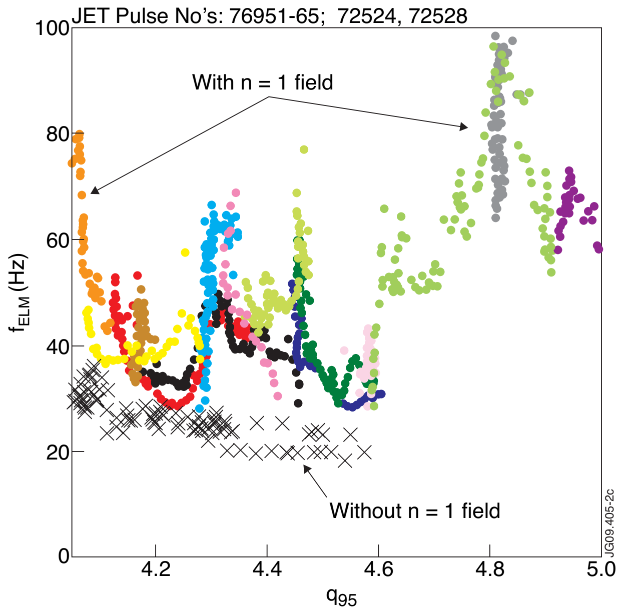


Figure 1: Comparison of two ELM control discharges using the n = 1 field with different values of q_{95} of 4.5 (Pulse No: 76962) and 4.8 (Pulse No: 76963). The traces from top to bottom are the NBI input power (P_{NBI}), the edge safety factor q_{95}, the EFCC coil current (I_{EFCC}), the stored energy (W_p), the central line- integrated electron densities (nel) with integration length of ~3.2m, the plasma central toroidal rotation (v_ϕ) measured at R = 3.05m, and the D_α signals measured at the inner divertor.



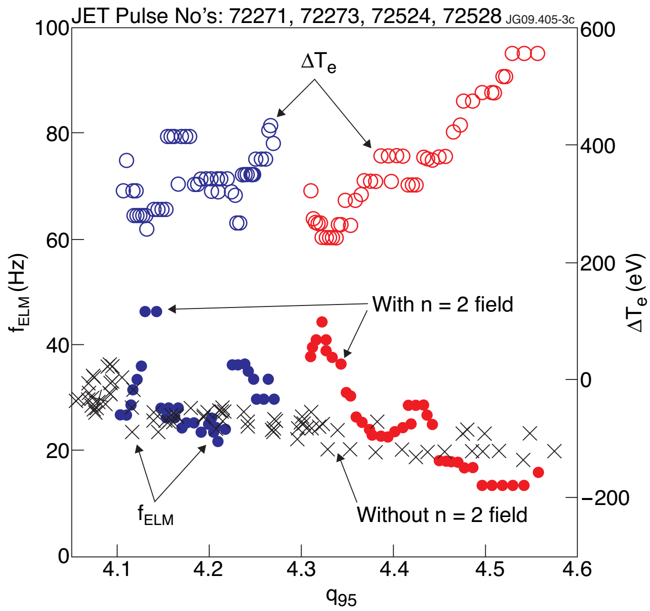


Figure 2: Frequency of ELMs (f_{ELM}) as a function of q_{95} for the H-mode plasma with (closed circles) and without (crosses) n = 1 field.

Figure 3: Frequency of ELMs, f_{ELM} (closed circles) and the amplitude of the periodic drops of the edge pedestal temperature due to ELMs, ¢Te (open circles) as a function of q_{95} for H-mode plasmas with n = 2 field. The f_{ELM} dependence on q_{95} for a identical plasma without n = 2 field has been plotted as a reference.

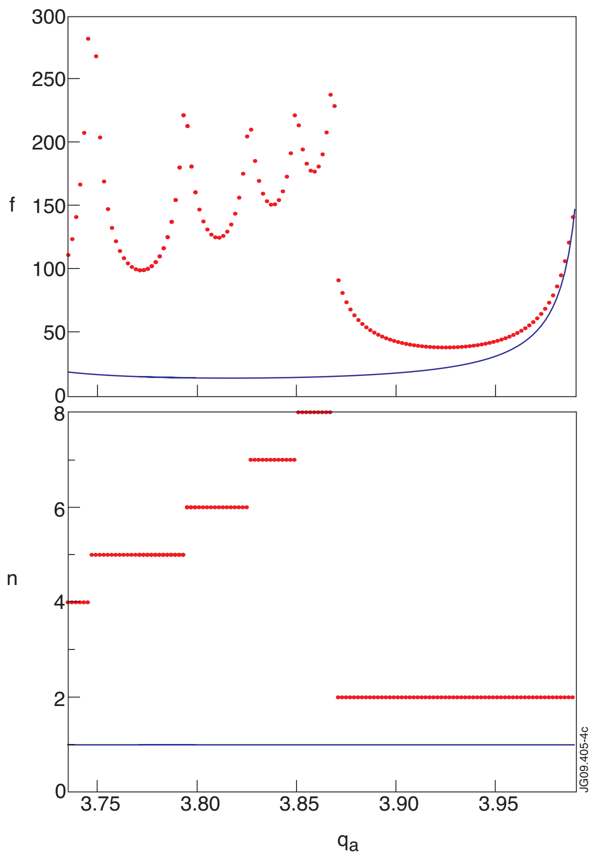


Figure 4: (a) Model ELM frequency (a.u.) and (b) most unstable toroidal mode number against edge q_a with (red) and without (blue) n = 1 removal.