Multiresonance Effect in Type-I Edge-Localized Mode Control With Low n Fields on JET

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

[1]*Forschungszentrum Jülich GmbH, Association EURATOM-FZ Jülich, Institut für Energieforschung—Plasmaphysik, Trilateral Euregio Cluster, D-52425 Jülich, Germany*

[2]*EURATOM/CCFE Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, United Kingdom*

[3]*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*

[4]*Association EURATOM-Belgian State, Koninklijke Militaire School—Ecole Royale Militaire, B-1000 Brussels, Belgium*

(Received 25 January 2010; published 3 August 2010)

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 30 Hz 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 nonresonant values. A model, which assumes that the ELM width is determined by a localized relaxation triggered by an unstable ideal external peeling mode, can qualitatively predict the observed resonances when low n fields are applied.

DOI: 10.1103/PhysRevLett.105.065001 PACS numbers: 28.52.−s, 52.35.Py, 52.55.Fa, 52.55.Rk

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 [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 magnetohydrodynamic 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 destabilized.

Recently, active control of ELMs using resonant magnetic perturbation (RMP) fields has become an attractive method for application on the International Tokamak Experimental Reactor. 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 the $n = 3$ 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 defined 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 (σ), which is a measure of magnetic island overlap, is used to define the stochastic layer as the region for which σ 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 (EFCCs) mounted far away from the plasma between the transformer limbs [9,10]. When an $n = 1$ field with an amplitude of a few milli-Tesla 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 $\sim$30 Hz up to $\sim$120 Hz, while the energy loss per ELM normalized to the total stored energy, $\Delta W_{\mathrm{ELM}}/W$, 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 or control experiments on DIII-D and JET, no complete ELM suppression was observed to date with either the $n = 1$ or $n = 2$ 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 nonresonant 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 multiresonance effect 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 or relaxation model of ELMs is given [12].

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 1–2 orders of magnitude larger than other components ($n = 2, 3$). Comparison of the effective radial resonant magnetic perturbation amplitudes $|b_{\rm res}^{r,\rm eff}| = |B_{\rm res}^{r,\rm eff}/B_0|$ calculated for $n = 1$ and $n = 2$ configurations shows that the amplitude of $|b_{n=2}^{r,\rm eff}|$ in the $n = 2$ configuration is a factor of ~ 3 smaller than $|b_{n=1}^{r,\rm eff}|$ in the $n = 1$ configuration for all radii [11]. Here, $B_{\rm res}^{r,\rm eff}$ 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 Fig. 1. Both target plasmas had a low triangularity shape ($\delta_{\rm lower} \sim 0.2$), a toroidal field ($B_t$) of 1.84 T, a stationary type-I ELM H-mode phase sustained by the neutral beam injection with a total power of 11.5 MW, a low electron collisionality at the edge pedestal ($\nu^* \sim 0.1$), and a similar $f_{\rm ELM}$ of $\sim$20 Hz before the $n = 1$ field was applied. The plasma currents (I_p) in the two discharges were 1.4 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 ($I_{\rm EFCC}$) for 300 ms and a flattop with $I_{\rm EFCC} =$ 32 kAt for 2.5 s, which is about 10 energy confinement times. Here, total current is given in terms of the current in one coil winding times the number of turns. $|b_{n=1}^{r,\rm eff}|$ calculated in the vacuum approximation is $\sim 2.5 \times 10^{-4}$ at the position of the edge pedestal. The Chirikov parameter calculated by using the experimental parameters and neglecting screening of the $n = 1$ field is $\sim$0.8 at $\sqrt{\Psi} =$ 0.925, which indicates a weak ergodization level at the plasma edge.

When the $n = 1$ field was applied, $f_{\rm ELM}$ increased strongly by a factor of $\sim$4.5 in the plasma with q_{95} of 4.8, while $f_{\rm ELM}$ increased only by a factor of $\sim$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 $\sim$15%) rather than a change of the electron temperature (T_e), 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(a) shows $f_{\rm ELM}$ 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 Fig. 1. Without an $n = 1$ field, $f_{\rm ELM}$ changed slightly from 20 to 30 Hz, and there was no visible large increase of $f_{\rm ELM}$ at any specific q_{95}. However, multiple peaks appeared in the q_{95} dependence of $f_{\rm ELM}$ when the $n = 1$ fields were applied. We term the multiple strong increase of $f_{\rm ELM}$ 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 nonresonant q_{95} are the values at the gaps between resonances where there is a weak influence of the perturbation field on $f_{\rm ELM}$. The resonant peaks of $f_{\rm ELM}$ are not equally distributed in the range of q_{95} from 4 to 5, and the difference in q_{95} between two neighboring resonance peaks is in the range of Δq_{95} from 0.2 to 0.3.

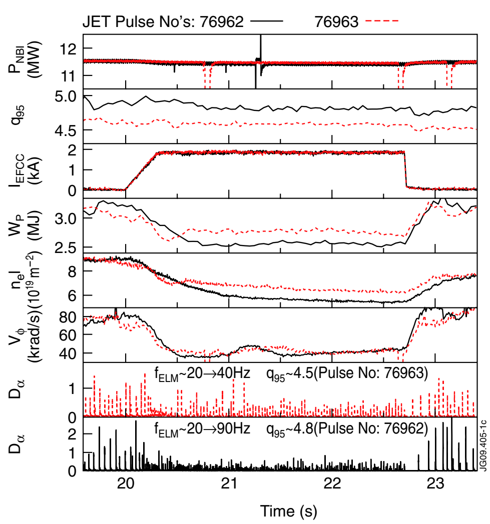

FIG. 1 (color online). Comparison of two ELM control discharges using the $n = 1$ field with different values of q_{95} of 4.5 and 4.8. The traces from top to bottom are the neutral beam injection input power, the edge safety factor q_{95}, the EFCC coil current, the stored energy, the central line-integrated electron densities, the plasma central toroidal rotation measured at $R =$ 3.05 m, and the D_α signals measured at the inner divertor.

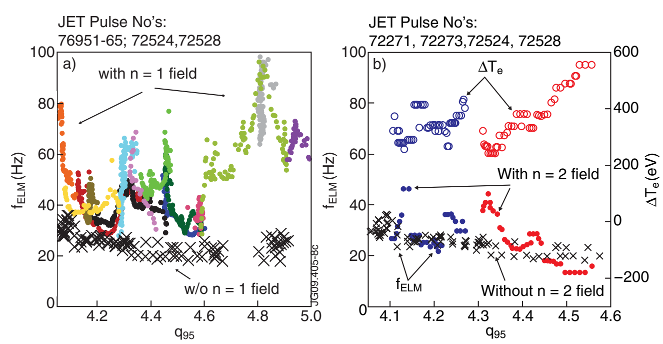

FIG. 2 (color online). Frequency of ELMs as a function of q_{95} for the H-mode plasma (a) with (closed circles) the $n = 1$ field and (b) with (closed circles) the $n = 2$ field and without (crosses) perturbation fields. The amplitude of the periodic drops of the edge pedestal temperature due to ELMs ΔT_e (open circles) dependence on q_{95} for an identical plasma with the $n = 2$ field has been plotted in (b).

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 Fig. 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 Letter. These two effects are most likely due to different physics mechanisms.

The multiresonance effect in f_{ELM} vs q_{95} has also been observed with $n = 2$ fields as shown in Fig. 2(b). 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. $|b^{r,\mathrm{eff}}_{n=2}|$ calculated with a vacuum assumption is $\sim 0.7 \times 10^{-4}$ 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 multiresonance effect is still clearly observed. The size of ELMs, which is indicated by a drop of pedestal T_e due to the ELM crash (ΔT_e), follows the change of f_{ELM}, and it is strongly reduced at resonant q_{95} values as shown in Fig. 2(b). Comparison of the multiresonance 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 or control have focused on the idea that a nonaxisymmetric 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 or 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. Furthermore, 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 by using the experimental parameters and the vacuum approximation of the perturbation field indicates that the ergodization zone may appear only at the far plasma boundary ($\sqrt{\Psi} > 0.95$). The mechanism of edge ergodization, which is used to explain the results of the ELM suppression with the $n = 3$ field on DIII-D, may explain the global effect of the $n = 1$ field on f_{ELM} on JET, but it cannot explain the multiresonance effect observed with the low n fields.

On DIII-D, strong dependence of the edge pedestal electron pressure on the edge safety factor q_{95} has been observed in high confinement, high rotation plasmas during application of an $n = 3$ field [17]. Reference [17] concluded that the resonances in the edge pressure were consistent with achieving good alignment of the magnetic field with the perturbation, suggesting the resonant formation of a stochastic layer. However, the results from JET presented in this Letter are not consistent with this interpretation, as demonstrated in Fig. 3. The width of the edge ergodization zone $\delta\sqrt{\Psi}|_{\sigma>1}$ (with a Chirikov parameter σ larger than 1) increases slightly from 0.038 to 0.048 when q_{95} increases from 4.1 to 4.8 and then saturates as q_{95} is further increased from 4.8 to 5.0. There are no multiresonance features in the graph that can explain the JET results.

Reduction of the pedestal pressure and pressure gradient up to 20% has been observed in ELM H-mode plasmas with the application of a low n field on JET. Previous modeling results from the ELITE code show that the ELM triggering instability moves from the peeling-ballooning corner of the stability diagram towards the low n peeling mode region, which is driven only by the current density [18]. Therefore, the dependence of the current driven peeling modes on the edge safety factor is important for an understanding of the experimental observations.

A possible explanation of the multiresonance effect has been investigated by using the ideal external peeling mode or relaxation model [12]. 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 [19] 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 destabilizes the peeling mode; however, this is countered by the formation of a stabilizing negative edge current sheet, and it is the balance of these two effects that determines the predicted width of the relaxed region. Unlike the ballooning mode, the peeling mode does not depend on toroidicity to be unstable and is driven by edge current density. In a simple cylindrical model, the plasma is peeling unstable whenever [20]

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

where m is the poloidal mode number, Δ' is the familiar jump in $(r/b_r)db_r/dr$ across the plasma-vacuum interface

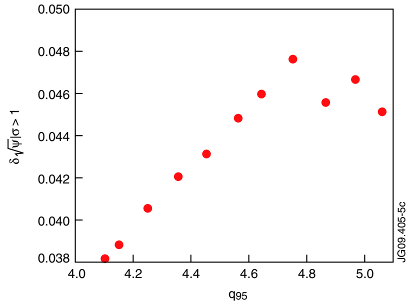

FIG. 3 (color online). Width of the edge ergodization zone $\delta\sqrt{\Psi}|_{\sigma>1}$, with a Chirikov parameter σ larger than 1 as a function of the edge safety factor q_{95}. Here, the Chirikov parameter is calculated by using the experimental parameters as seen in Fig. 2(a) and a vacuum approximation for the $n = 1$ perturbation field.

(b_r is the perturbed radial field) which encapsulates information about the equilibrium current profile ($\Delta' = -2m$ for a vacuum response [20]), and J_a is the driving edge current density (normalized to the on-axis value). A similar criterion can be obtained for an arbitrarily shaped toroidal plasma [21].

In the peeling or relaxation model [12,20], the ELM width (the extent of the relaxed region d_E) is determined by requiring that external peeling modes are stabilized 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. The dominant unstable peeling mode also depends on the normalized edge current J_a. Multiresonance naturally exists at small edge current density [20], while for larger J_a the low n modes given by Eq. (1) dominate over extended regions of q_a and multiresonance disappears. By 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 $f \sim 1/d_E^2$, and this is plotted for low edge current density in Fig. 4.

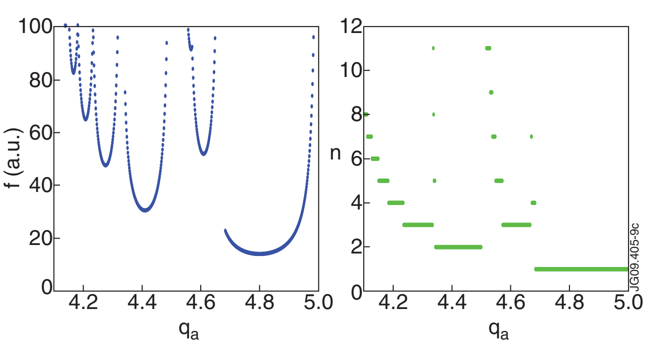

FIG. 4 (color online). Model predictions of ELM frequency and trigger n number against edge q_a. The equilibrium chosen has low edge current density ($J_a = 0.1$).

This simple model reproduces many qualitative aspects of the multiresonance effect. A full quantitative explanation would require a toroidal model which includes separatrix geometry and mode coupling between the peeling mode and the EFCC field. In principle, any current driven peeling modes model that predicts resonances due to the factor Δ could lead to structures like those observed here.

Conclusion.—The multiresonance effect in f_{ELM} vs 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 neighboring 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 localized relaxation to a profile which is stable to peeling modes can qualitatively predict this multiresonance effect with a low n field.

This work, supported by the European Communities under the contract of Association between EURATOM and FZJ and CCFE, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was done under the JET-EFDA workprogramme [22].

*y.liang@fz-juelich.de;
www.fz-juelich.de

[1] F. Wagner *et al.*, Phys. Rev. Lett. **49**, 1408 (1982).
[2] A. Loarte *et al.*, J. Nucl. Mater. **313–316**, 962 (2003).
[3] G. Saibene *et al.*, Nucl. Fusion **45**, 297 (2005).
[4] P.T. Lang *et al.*, Nucl. Fusion **44**, 665 (2004).
[5] J.W. Connor, Plasma Phys. Controlled Fusion **40**, 531 (1998).
[6] H.R. Wilson *et al.*, Phys. Rev. Lett. **92**, 175006 (2004).
[7] T. Evans *et al.*, Nature Phys. **2**, 419 (2006).
[8] M.J. Schaffer *et al.*, Nucl. Fusion **48**, 024004 (2008).
[9] Y. Liang *et al.*, Phys. Rev. Lett. **98**, 265004 (2007).
[10] Y. Liang *et al.*, Plasma Phys. Controlled Fusion **49**, B581 (2007).
[11] Y. Liang *et al.*, Nucl. Fusion **50**, 025013 (2010).
[12] C.G. Gimblett, R.J. Hastie, and P. Helander, Phys. Rev. Lett. **96**, 035006 (2006).
[13] M. Becoulet *et al.*, Nucl. Fusion **48**, 024003 (2008).
[14] M. Heyn *et al.*, Nucl. Fusion **48**, 024005 (2008).
[15] R. Fitzpatrick, Nucl. Fusion **33**, 1049 (1993).
[16] B.V. Chirikov, Phys. Rep. **52**, 263 (1979).
[17] O. Schmitz *et al.*, Phys. Rev. Lett. **103**, 165005 (2009).
[18] S. Saarelma *et al.*, Plasma Phys. Controlled Fusion **51**, 035001 (2009).
[19] J.B. Taylor, Rev. Mod. Phys. **58**, 741 (1986).
[20] C.G. Gimblett, R.J. Hastie, and P. Helander, Plasma Phys. Controlled Fusion **48**, 1531 (2006).
[21] A.J. Webster and C.G. Gimblett, Phys. Rev. Lett. **102**, 035003 (2009).
[22] F. Romanelli *et al.*, Nucl. Fusion **49**, 104006 (2009). (All the members of the JET-EFDA Collaboration appear in the appendix of this paper.)