Overview of ELM Control by Low *n* Magnetic Perturbations on JET

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(Received 8 December 2009 / Accepted 5 February 2010)

A series of ELM control experiments have been performed on JET aiming at a better understanding of the plasma response to applied magnetic perturbations. The dynamics of the edge profiles with applied $n = 1$ fields have been studied in the type-I ELM H-mode plasmas. Typically, the pedestal density decreased by about 20 % when the $n = 1$ perturbation field was applied (So called pump-out effect). However, there is no influence of the $n = 1$ fields on the recovery rate of the pedestal pressure, but the ELM crash occurs earlier and at a lower level of the pedestal pressure and pressure gradient. The compensation of the density pump-out has been demonstrated using either gas fuelling or pellets injection in low triangularity H-mode plasmas. Strong toroidal rotation braking by more than 60 % has been observed, and found to be independent on the safety factor. The calculated Neoclassical Toroidal Viscosity (NTV) torque profile in the ν regime including the boundary effect is in agreement with the observed torque profile induced by the $n = 1$ fields on JET. No complete ELM suppression was observed by application of either $n = 1$ or $n = 2$ fields with a Chirikov parameter above one at $\sqrt{\Psi} \geq 0.925$, which is one of the important criteria for the design of ITER ELM control coils.

Keywords: Type-I ELM, H-mode, RMP, Density pump-out, MHD stability

DOI: 10.1585/pfr.5.S2018

1. Introduction

The standard tokamak H-mode, which is foreseen as the ITER baseline operating scenario, is characterised by a steep plasma pressure gradient and associated increased current density at the edge transport barrier which exceeds a threshold value to drive magnetohydrodynamic (MHD) instabilities referred to as Edge Localized Modes (ELMs) [1]. Active control of ELMs by resonant magnetic perturbation (RMP) fields offers an attractive method for ITER. DIII-D has shown that type-I ELMs are completely suppressed when the $n = 3$ fields are applied [2].

On JET, the previous experimental results have shown that the type-I ELM can be actively controlled by application of a static low n $(1, 2)$ field produced by four external error field correction coils (EFCC) mounted far away from the plasma between the transformer limbs [3, 4]. When an $n = 1$ field with an amplitude of a few mT at the plasma edge (the normalized poloidal flux, Ψ, is larger than 0.95) is applied during the stationary phase of a type-I ELMy H-mode plasma, the ELM frequency rises from $\sim$ 30 Hz up to $\sim$ 120 Hz. The energy loss per ELM normalised to the total stored energy, $\Delta W_{\mathrm{ELM}}/W$, decreased from 7 % to values below the resolution limit of the diamagnetic measurement (< 2 %). Transport analysis using the TRANSP code shows up to 20 % reduction of the thermal energy confinement time because of density pump-out, but when normalised to the IPB98$(y, 2)$ scaling the confinement time shows almost no reduction. Stability analysis of the controlled ELMs suggests that the operational point with $n = 1$ field moves from the intermediate-n peeling-

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*See the appendix of F. Romanelli et al., Nucl. Fusion **49**, 104006 (2009) ballooning boundary to the low-n peeling boundary, and the radial width of the most unstable mode reduced from ∼ 3 % down to ∼ 1 % of the normalised minor radius [5,6]. The results of ELM control with the n = 2 fields on JET demonstrate that the frequency of ELMs can be increased by a factor of 3.5 with the present capability of the EFCC power supply. During the application of the n = 1, 2 fields, a reduction in the absolute ELM size (ΔW_{ELM}) and ELM peak heat fluxes on the divertor target by roughly the same factor as the increase of the ELM frequency has been observed. The reduction in heat flux is mainly due to the drop of particle flux, rather than a change of the electron temperature [7, 8].

In this paper, an overview of recent JET experimental results on *i*) investigation of ELM suppression with n = 2 field based on the criteria for the ITER ELM control coils, *ii*) dynamic of edge profiles, *iii*) compensation of density pump-out effect and *iv*) plasma rotation braking with the low n fields is presented.

2. ELM Control with n = 2 Field

Based on the ELM suppression results from DIII-D, the criteria for ELM suppression with RMP requires the Chirikov parameter number at the plasma edge layer ($\sqrt{\Psi} \geq 0.925$) larger than 1 [9]. Here, the Chirikov parameter (σ), which is a measure of island overlap, is used to define the stochastic layer as the region for which σ is greater than 1. On JET, the maximal EFCC coils current (I_{EFCC}) is limited by the capability of the power supply, and it is 32 kAt. In the previous JET ELM control experiments, the target plasmas are programmed in a normal JET operational regime with the plasma currents, I_p, from 1.4 to 2.5 MA and the toroidal field, B_t, from 1.7 to 2.2 T, while the Chirikov parameter numbers calculated based on those experimental parameters are below ∼ 0.85 at $\sqrt{\Psi} = 0.925$. To investigate the ELM suppression with n = 2 field induced by EFCCs on JET, a low current (I_p = 0.84 MA) type-I ELM H-mode plasma sustained by neutral beam injection (NBI) with an input power of 10.5 MW for 5 s has been established.

Figure 1 shows an overview of an ELM control pulse, with n = 2 field, from this experiment. The target plasma had a low triangularity shape (δ_{lower} ∼ 0.2). The electron collisionality at the edge pedestal is ∼ 0.25. No additional gas fuelling was applied during the H-mode phase. The n = 2 field created by the EFCCs had a flat-top with I_{EFCC} = 32 kAt for 2 s, which is about 8 energy confinement times. The Chirikov parameter calculated using the experimental parameters and the vacuum approximation of the perturbation field is above 1.1 at $\sqrt{\Psi} \geq 0.925$. When an n = 2 field was applied, a drop of density by ∼ 20 % (so called density pump-out effect), braking of plasma toroidal rotation (V_ϕ) by 60 %, reduction of ion temperature (T_i) by 20 %, no drop of electron temperature (T_e), and reduction of the stored energy (W_p) by ∼ 20 % have been observed.

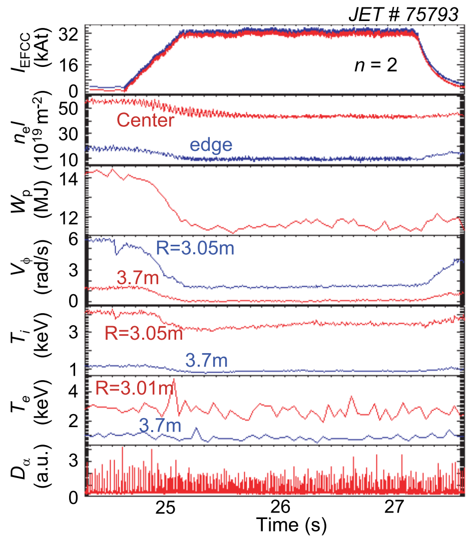

Fig. 1 Overview of an ELM control discharge with n = 2 field in a low triangularity plasma. The traces from top to bottom are the EFCC coil current (I_{EFCC}), the line-integrated electron densities ($n_e l$), the stored energy (W_p), the plasma toroidal rotation (V_ϕ), the ion temperature (T_i) and electron temperature (T_e) in the plasma center (R = 3.05 m) and near the edge pedestal (R = 3.7 m), and the D_α signal measured at the inner divertor. Here, the line-integrated electron densities are measured with an interferometer along two lines of sight, one close to the magnetic axis (upper trace) and the other near the pedestal top (lower trace).

Though no ELM suppression was observed with the n = 2 fields, the ELM frequency increased from ∼ 50 to ∼ 90 Hz. Furthermore, a scan of q_{95} from 3.0 to 5.5 with a small step of Δq_{95} of 0.2 has been performed pulse by pulse. However, no ELM suppression has been observed in this q_{95} window. The major difference in the RMP ELM suppression experiments from JET and DIII-D is the magnetic perturbation spectra (not only the mode number, but also the ratio of the resonant to the non-resonant components). This result suggests that ELM suppression using the RMP depends on the perturbation spectrum, and a model that uses this idea is being developed using the ELM theory of [10], to address the q-dependence of the ELM frequency.

3. Dynamic of Edge Profiles

On JET, although ELM suppression has not been observed to date, ELM control both, in frequency and in size with a low n field has been achieved. To understand the mechanism of ELM control with a magnetic perturbation, the dynamics of the edge pedestal with and without n = 1 field have been studied.

Figure 2 shows comparison of the edge pedestal recovery after a normal type-I ELM crash and a mitigated ELM crash with n = 1 field. Here, the pedestal electron density, temperature and pressure are measured by the high resolution Thomson scatting and averaged over several ELM cycles [5]. With n = 1 field, the ELM frequency

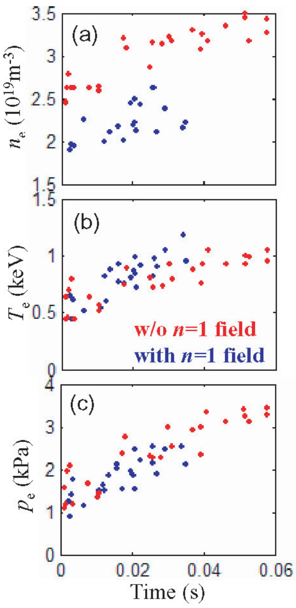

Fig. 2 Temporal evolution of (*a*) pedestal electron density, (*b*) temperature and (*c*) pressure after an ELM crash measured for the type-I ELMs with (blue) and without (red) $n = 1$ field. This data is averaged over about 20-30 ELMs

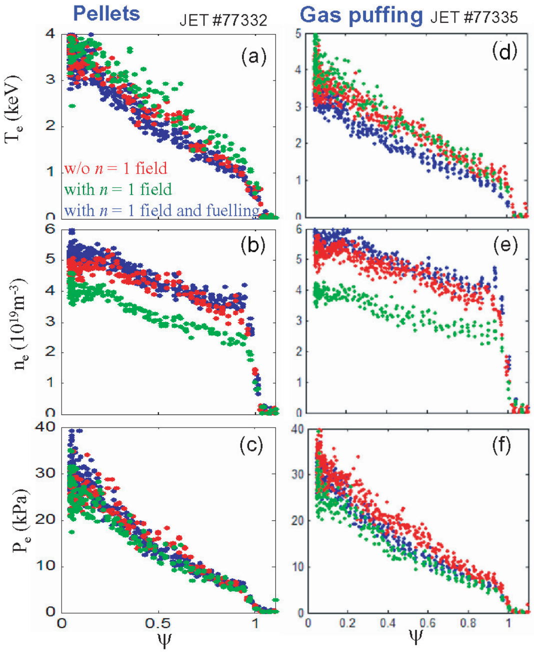

Fig. 3 Radial profiles of electron temperature (a, d), density (b, e) and pressure (c, f) measured in the phases without (red) and with (green) $n = 1$ field, and with additional fueling (blue) by pellet injection (left) and gas puffing (right). All data points are taken during the inter ELM phase averaged from 70 % of ELM cycle up to the ELM crash.

increased by a factor of ~ 2 (from ~ 15 Hz to ~ 30 Hz), and the pedestal density recovered only up to ~ 80 % of that in the case without $n = 1$ field. However, the pedestal electron temperature in both cases, with and without $n = 1$ field, recovered to the same value. These result in a decrease of both the edge pedestal electron pressure and the pedestal pressure gradient by ~ 20 % with the application of $n = 1$ field. However, the mitigated pedestal pressure with the $n = 1$ field recovers approximately at the same rate in respect to the one without $n = 1$ field applied, but the ELM crash occurs earlier at a lower pedestal pressure level.

This result suggested that the ELM stability threshold might be reduced with the application of an $n = 1$ field. It should be emphasized that although the pedestal recovery rate is similar, the individual changes of the pedestal density and temperature are different.

4. Compensation of Density Pump-Out

One of the important questions for the application of the RMP ELM suppression/control for the next generation of fusion devices, e.g. ITER, is the compensation of the density pump-out effect. On JET, previous experiments have shown that the compensation of density pump-out effect with $n = 1$ field can be achieved by means of gas fuelling [7, 8]. An optimised gas fuelling rate to compensate the density pump-out effect without an additional drop in the plasma stored energy has been identified by means of gas fuelling up to a Greenwald fraction of 0.73 in a ITER-like shaped plasma. Depending on the configuration of target plasmas the optimized gas fuelling rate can be different in value. Recently, the compensation of the density pump-out effect due to the application of the $n = 1$ field has been demonstrated using both gas puffing and pellet injection.

Figure 3 shows radial profiles measured from two examples of the compensation of density pump-out effect with $n = 1$ field by means of pellets injection and gas fuelling, respectively, in a same low triangularity target plasma ($I_p = 2.0$ MA, $B_t = 1.85$ T). Both edge and central density can be recovered during the flat top of I_{EFCC} by either pellets injection with a pellet size of 3.5 mm and injection frequency of 10 Hz, or gas fuelling with a fuelling rate of $12{\times}10^{21}$ el/s. A smaller drop of electron temperature has been observed in the discharge with pellet injection when the density pump-out with $n = 1$ field is compensated. The ELM frequency controlled by the $n = 1$ field can remain high even though the density profiles recovered by either of those two fuelling methods as shown in Figure 4. No recovery of the total stored energy in respect to that before the $n = 1$ field was applied has been found with these two methods in low density and low triangularity plasmas. However, the compensation of density pump-out with pellets injection is much faster than that with gas fuelling due to a deeper particle penetration with pellet injection.

Differences in the particle flux, radiation, and heat loads on the outer divertor target between those two fuelling methods for the compensation of density pump-out have been observed. In these experiments, the maximum

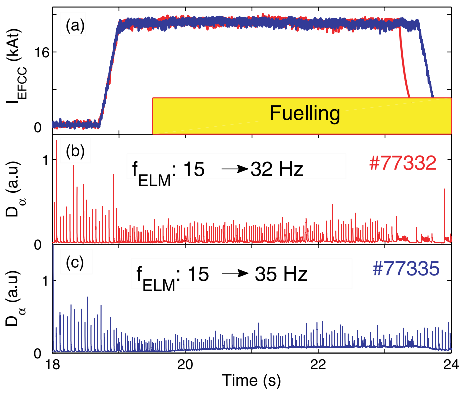

Fig. 4 Temporal evolutions of (*a*) I_{EFCC}, (*b*) (*c*) D_α signals for the discharges with (*b*) pellets injection and (*c*) gas fuelling. The duration of the fuelling is indicated.

deposited power per ELM reduced by about 35 % with $n = 1$ field applied. When the density is restored by pellet injection, the maximum deposited power per ELM is reduced additionally. A weaker effect on the peak heat load has been found when the discharge was re-fuelled by gas. During the inter-ELM phase, the average power deposited on targets is reduced with pellet injection but increases with gas fuelling. The average wetted area on the target increased up to a factor of 2 by both pellet injection and gas fuelling.

5. Plasma Rotation Braking

Self-similar braking of plasma toroidal rotation, i.e., reduction of toroidal rotation in different radii by the same factor ($\frac{\Delta v_\varphi}{v_\varphi}$ = constant), has been observed in the plasma core during the application of an $n = 1$ field while a stronger rotation braking appears near the edge pedestal as shown in Figure 5. A critical value of I_{EFCC}, which needs to be exceeded before the plasma rotation starts to decrease, is different than the threshold of density pump-out effect [8]. Here, no density pump-out effect has been observed in the discharge used to study the rotation braking with $n = 1$ field. No q_{95} dependence of the plasma braking has been observed. The change of core plasma rotation depends on the amplitude of I_{EFCC} as well as B_t after the critical value has been exceeded. The torque profile of the perturbation field induced by the $n = 1$ field, T_{EFCC}, is determined by momentum transport analysis using the JETTO code. T_{EFCC} has a global profile and the maximum torque is at the plasma central region.

A similar magnitude of plasma braking has been observed with $n = 1$ and $n = 2$ fields when the same amplitude of the I_{EFCC} was applied. A detail comparison of T_{EFCC} profile induced by the $n = 1$ field between the experimental observation and calculation based on neoclassical toroidal viscosity (NTV) theory [11] has been investigated [12]. The NTV torque profile calculated in the ν regime including the boundary layer effect agrees well with the measured one.

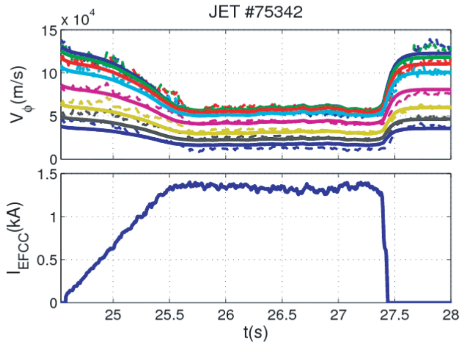

Fig. 5 Comparison of the temporal evolution of the plasma toroidal velocity (top) measured from different radii (star dashed lines) and simulation (solid line) with the calculated torque profile induced by the $n = 1$ field. The bottom shows the time trace of the EFCC coil current. Here, the rotation signals plotted from top to bottom correspond to the radii from the plasma center ($R = 3.0$ m) to the edge ($R = 3.7$ m).

6. Conclusions

In conclusion, the pedestal pressure with $n = 1$ field applied recovers approximately at the same rate compared to that without $n = 1$ field, but the ELM crash occurs earlier at a lower pedestal pressure level. Compensation of the density pump-out effect has been achieved by means of both pellet injection and gas fuelling in low triangularity plasmas. However, no recovery of stored energy was observed. The optimised fuelling rate to compensate the density pump-out effect depends on the plasma configuration. The torque profiles induced by the $n = 1$ field has been measured, and it can be explained by the NTV torque calculated in the ν regime including the boundary layer effect. No ELM suppression was observed to date with either the $n = 1$ and $n = 2$ fields on JET, even with a Chirikov parameter above 1 at $\sqrt{\Psi} \geq 0.925$.

This work, supported by the European Communities under the contract of Association between EURATOM and FZJ, 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.

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