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# Active Control of Edge-Localized Modes with a low $n$ Perturbation Fields in the JET Tokamak

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## ABSTRACT

Active control of edge localized modes (ELMs) by using static external magnetic perturbation fields with low toroidal mode number,  $n$ , has been demonstrated for both, ITER baseline ( $q_{95} \sim 3$ ) and high beta advanced tokamak scenarios at the JET tokamak. During the application of the low  $n$  field the ELM frequency increased by a factor up to  $\sim 4 - 5$ . Reduction in carbon erosion 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 frequency of the mitigated ELMs using a low  $n$  field is found to increase proportional to the total input heating power. Compensation of the density pump-out effect observed when the external low  $n$  field is applied has been achieved by gas fuelling in low triangularity plasmas.

## 1. INTRODUCTION

The standard tokamak H-mode, which is foreseen as the ITER baseline operating scenario [1], 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) [2,3]. The so-called Type-I ELMs lead to a periodic expulsion of a considerable fraction of the stored energy content onto the plasma facing components. Although ELMs may be beneficial in controlling the particle inventory and removing fusion products, the associated energy losses might cause severe problems regarding the life time expectations of plasma facing wall components. Melting or high erosion rates might occur under certain conditions, as it is derived from extrapolations based on present knowledge [4]. Therefore, reliable methods for the control of ELM power losses are required for operation of a future fusion machine, e.g. ITER [1].

Previous experiments on DIII-D have shown that the application of resonant magnetic perturbation fields (RMP) is a promising technique for the complete suppression of ELMs with an  $n = 3$  field induced by a set of in-vessel coils [5,6]. On JET, active control of the transient heat loads due to large type-I ELMs has been achieved with low- $n$  ( $n = 1$  and  $n = 2$ ) fields induced by the set of error field correction coils (EFCCs) [7] mounted outside of the vacuum vessel [8,9]. During the application of the  $n = 1$  field the ELM frequency increased by a factor of 4 - 5 for a duration of 10 times the energy confinement time. The energy loss per ELM normalised to the total stored energy,  $\Delta W/W$ , decreased from 7% to values below the resolution limit of the diamagnetic measurement ( $\approx 2\%$ ). The density pump-out effect [10], the reduction in ELM amplitude, the simultaneous increase in ELM frequency and braking of the plasma toroidal rotation [11] were observed independent on the toroidal phase (i.e. the direction in the tokamak midplane) of the  $n = 1$  field [8]. Recently, the operational domain for active control of type-I ELMs with an  $n = 1$  field has been developed toward more ITER relevant regimes with high plasma triangularity (up to 0.45) high normalized beta (up to 3.0), plasma current up to 2.0MA and  $q_{95}$  varied between 3.0 and 4.8. The minimum  $n = 1$  perturbation field amplitude above which the ELMs were mitigated increased when  $q_{95}$  was

lowered, but always remained below the  $n = 1$  locked mode threshold. The results of ELM mitigation experiments with  $n = 2$  magnetic perturbations on JET showed that the frequency of ELMs could be increased from 10Hz to 35Hz [9]. A wide operational window of  $q_{95}$  from 4.5 to 3.1 has also been found with  $n = 2$  field without observation of any locked mode even at the maximum value of EFCC coil current delivered from the present power supply system. Transport analysis using the TRANSP code [12] shows no or a modest reduction of the thermal energy confinement time,  $\tau_{\text{therm}}$ , mainly attributed to the density pump-out, but when  $\tau_{\text{therm}}$  was normalised to the IPB98(y,2) scaling [1] the confinement showed almost no reduction. However, for a possible application of this method for ELM control in a future reactor, the important question how the density pump-out could be compensated and the plasma confinement maintained, has to be resolved. In this paper, the application of active ELM control with a low  $n$  field in the ITER baseline ( $q_{95} \sim 3$ ) and high beta advanced tokamak steady state scenarios is discussed. The influence of mitigated ELMs on carbon erosion and the heat flux onto the divertor and limiter tiles are described. The heating power dependence of the ELM frequency of mitigated ELMs by an  $n = 1$  field is studied. Furthermore, the first experimental results of pump-out compensation with gas fuelling in a low triangularity plasma are presented.

## 2. APPLICATION OF $N = 1$ FIELDS FOR ELM MITIGATION AT AT SCENARIO

Advanced Tokamak steady state (AT) scenarios operate at a normalised beta close to or above the no-wall beta limit. In this scenario ELM mitigation is needed to keep ELM amplitudes small which otherwise may erode the internal transport barrier and reduce the confinement [13,14]. Figure 1 shows an example where the  $n = 1$  fields have been applied for ELM control in AT scenarios at high  $\beta_N$  ( $B_t = 1.8\text{T}$ ;  $I_p = 1.2\text{M A}$ ;  $q_{95} = 4.5$ ). Real-time beta control has been applied to maintain a prescribed  $\beta_N \sim 2.5$  (approximate no-wall beta limit  $4 \times \ell_i$ ) by controlling the NBI input power. The ELMs in the target plasma have the standard Type I characteristics with an edge transport barrier that provides a normalized thermal confinement of  $H_{\text{IPB98}(y;2)} \sim 1$ . When the current in the EFCCs is ramped up the  $D_\alpha$  spikes show a strong decrease and the ELM frequency increases. Although the density decreases due to the pump-out effect, transport analysis using the TRANSP code shows that the thermal energy stays almost constant. Another indication for the constant energy content is given by the unchanged heating power request from the real-time beta control. This is due to the fact that both, ion and electron temperatures,  $T_i$  and  $T_e$ , increase, similar to the previous observation in standard ELMy H-modes [8].

Figure 2 shows that the influence of the  $n = 1$  field on  $T_i$ ,  $T_e$  and  $n_e$  in the plasma core ( $R = 3.05$  m) and near the edge pedestal ( $R = 3.70$  m). The dashed curves indicate a constant plasma thermal pressure. Due to application of the  $n = 1$  field, the edge plasma pressure dropped by  $\sim 20\%$  caused by the reduction of edge  $n_e$  while both, edge  $T_i$  and  $T_e$  stay almost constant. However, the ion pressure increase in the plasma core due to the rise of  $T_i$  from  $\sim 5$  to  $\sim 7.5$  keV over compensated the drop of  $n_e$ , while the core electron pressure remains constant. Active control of type-I ELMs

with the  $n = 1$  field was successfully applied in similar discharges with  $\beta_N$  up to 2.9, but further technical development will be required to increase the pulse duration capability of EFCC system at the required large coil currents. It is also important to note that in these experiments no locked modes were seeded by the perturbation field. It is quite likely that the strong beam heating keeps the toroidal plasma rotation high enough to prevent the field from penetration [15,16].

### 3. HEAT LOAD AND CARBON EROSION OF MITIGATED ELMS

The heat loading and carbon erosion of the divertor target due to mitigated ELMs by an  $n = 1$  field has been studied in a series of high triangularity discharges ( $\delta = 0.45$ ) [17]. During the flat top of a the type-I ELMy H-mode phase ( $I_p = 1.8$  MA,  $B_t = 2.16$  T,  $q_{95} = 4.4$ ,  $P_{\text{NBI}} = 9.5$  MW,  $n_e l = 1.3 \times 10^{20}$  m<sup>-2</sup>) the error field correction coils at a current of 32 kAt have been applied. The ELM frequency increases from 30Hz up to 90Hz, while the loss of stored energy per ELM,  $\Delta W$  decreases from  $\sim 130$ kJ to very small values which lie within the noise of the diamagnetic measurement. Figure 3 shows profiles of (a) particle flux, (b) electron temperature and (c) heat flux measured near the outer strike point for the cases with and without the application of the  $n = 1$  field. Here, the heat fluxes are measured by Langmuir Probes embedded in the divertor tiles. When the magnetic perturbation field is applied, a reduction in the ELM peak heat fluxes on the divertor target by roughly the same factor as the increase of the ELM frequency has been observed. The loss of core and edge density (density pump-out effect) during the application of the  $n = 1$  field is not seen as an increased particle flux at the divertor in neither the inter-ELM phase nor at the ELM-peak as shown in Fig. 3. The reduction in heat flux is mainly due to the drop of particle flux rather than the change of the electron temperature. It is important to note that the electron temperature remains unaffected (Fig. 3), also in the inter-ELM phase. No clear changes in heat flux during the inter-ELM phase has been observed, which is consistent with the observation of only small changes of the global plasma confinement. A similar observation has been made by a fast IR camera viewing the divertor targets. These observations do not depend on the toroidal phase of the  $n = 1$  perturbation field. Further more, the particle flux measured with the outer wall guard limiter probes shows that the interaction of the ELMs with the outer wall is also significantly reduced.

In addition, the results from the Quartz Micro Balance (QMB) [18] measuring the amount of carbon deposited in the inner divertor louver indicates clearly less erosion of carbon from the divertor in phases with mitigated ELMs. In type-I ELMy H-mode plasmas, net-deposition of carbon on the QMB with a growth rate of  $\sim 0.6$  nm/s was observed. However, when the large ELMs were mitigated by  $n = 1$  field, net-erosion of carbon from the QMB ( $\sim 0.25$ nm/s) was observed, which is mainly due to a significant deuterium flux even when the carbon flux shows a strong reduction.

### 4. APPLICATION OF N = 1 FIELDS FOR ELM MITIGATION IN THE ITER BASELINE SCENARIO

Active ELM control has been investigated in the ITER baseline scenario operated at  $q_{95} \sim 3$ . For

the  $n = 1$  field, it is more critical since the previous experimental results show that the operational window for the ELM control becomes narrow because the minimum value of perturbation field to effect ELMs increases and the locked mode threshold decreases at lower  $q_{95}$ .

In this experiment, the target plasma was heated by NBI with a power of 14MW.  $q_{95}$  is  $\sim 3:2$  at  $I_p$  of 2MA and  $B_t$  of 1:85 T. Due to the I2t thermal rating limit of power supplies, the EFCCs coil current was programmed with a quick jump to 8 kAt within 200ms followed by a slow ramp of  $I_{EFCC}$  up to 34 kAt with a duration of 3 s as shown in Fig. 4, to get a longer duration of the mitigated ELM phase at higher amplitude of  $I_{EFCC}$ . It seems that  $I_{EFCC}$  of 8kAt is already above the threshold of ELM mitigation (the minimum value of  $I_{EFCC}$  to get an increase in the ELM frequency) in this plasma configuration. The ELM frequency,  $f_{ELM}$ , increased from  $\sim 20$ Hz to  $\sim 70$ Hz following the slow rise of  $I_{EFCC}$ . No locked mode was observed in this plasma even at the maximum  $I_{EFCC}$ , which is different to the locked mode threshold observed previously with a same value of  $q_{95}$  [9]. The increase in locked mode threshold can be attributed to the higher plasma density (30%) in this discharge caused by a change of strike points positions on the divertor plates [11]. The strike points of the previous discharges in reference [9] were located in the corners close to the divertor louvre yielding a high pumping efficiency.

To identify the character of the mitigated ELMs a heating power scan with four different levels of NBI power,  $P_{NBI}$ , of 10, 11.2, 14, 15.2MW has been carried out. Figure 5 shows the ELM frequency as a function of  $P_{NBI}$ . The frequency of the mitigated ELMs increases when  $P_{NBI}$  is increased. The power dependence of the ELM frequency is similar to normal type-I ELMs (as shown in the case without  $n = 1$  field). However, the mitigated ELMs with  $n = 1$  field have a higher frequency and are smaller in size.

## 5. COMPENSATION OF DENSITY PUMP-OUT WITH GAS PUFFING

Compensation of the density pump-out effect due to the application of the external  $n = 1$  field has been performed with gas putting on JET. The target plasma in this experiment is chosen from the power scan in the ITER baseline scenario described in the previous section. The gas putting started just after the injection of NBI and  $\sim 1$  s before the  $n = 1$  field was applied. The total gas putting rate has systematically increased from discharge to discharge from 4.2, 7.8, 11.9, up to  $15.4 \times 10^{21}$  el/s keeping the same NBI input power of  $\sim 11:2$ MW.

Figure 6 shows that the central line integrated electron density as function of  $I_{EFCC}$ . Without additional gas fuelling, the electron density starts to drop at  $I_{EFCC} = 13$ kAt. The reduction of  $n_{e,l}$ ,  $\Delta n_{e,l}$ , due to the pump-out effect does linearly depend on the amplitude of  $I_{EFCC}$ . However, a contiguous drop in  $n_{e,l}$  is observed even after  $I_{EFCC}$  reached the flat top value, which may indicate that full stationarity hasn't been reached in the unfuelled case. The Greenwald fraction,  $f_{GW}$ , drops from 0.68 to 0.55. When gas putting is applied with a total gas rate of  $7.8 \times 10^{21}$  el/s, the target plasma density increased ( $f_{GW} = 0.73$ ) and maintains a constant value even with application of the  $n = 1$  perturbation field. The further increase of the gas fuelling rate up to  $15.4 \times 10^{21}$  el/s yields a

Greenwald density of  $f_{GW} = 0.95$  before application of the  $n = 1$  field, however, the plasma density drop with increasing  $I_{EFCC}$  appears again after the critical  $I_{EFCC}$  of 13 kAt was exceeded. These results demonstrate that there is an optimized fuelling rate for the compensation of the density pump-out effect. Nevertheless, the plasma confinement becomes worse when the plasma density is chosen too high (close to Greenwald Limit) in the low triangularity target plasma. There is a limitation to achieve a high plasma density without degradation of plasma confinement with an  $n = 1$  field in low triangularity plasmas. Further investigation of the ELM mitigation with an  $n = 1$  field will be performed in high density, high triangularity plasmas in the near future. However, it should be noted that there is no further drop of the density during the flat top of  $I_{EFCC}$  in the discharges with gas fuelling.

Figure 7 (a)-(f) show the influence of an  $n = 1$  field on the profiles of  $n_e$ ,  $T_e$  and  $P_e$  for the discharges with (a – c) no gas fueling and (d – f) optimised gas fuelling at a rate of  $7.8 \times 10^{21}$  el/s. Without gas fueling, the application of an  $n = 1$  field lets the density drop everywhere from core to edge while the electron temperature increases in the core stronger than that at the plasma edge. By application of gas fueling, both, plasma density and temperature in the plasma core remain the same as before. However, an increase of the edge density and a drop in the edge temperature are observed. The electron density profile is getting flatter with gas fueling, while the temperature profile becomes steeper in the plasma core. A similar influence of an  $n = 1$  field on the electron pressure profile has been observed in plasmas with and without gas fuelling as shown in fig. 7 (c) and (f). With an  $n = 1$  field, the core electron pressure keep in constant while the profile becomes steeper slightly due to a modest reduction of the electron pressure at plasma edge. The measurement of the diamagnetic loop shows that there was about  $\sim 10\%$  drop in plasma stored energy when the  $n = 1$  field was applied. No difference in the stored energy between the discharges with and without an optimized gas fueling has been found. However, a further increase in the gas puffing rate above the optimized value will result in a large reduction of the plasma stored energy up to 20 – 25%.

The influence of gas fueling on the frequency of ELMs is plotted in Fig.8 for both cases, with and without application of the  $n = 1$  field. Below the optimised fuelling rate, the mitigated ELM frequency stays almost at a similar frequency of 50 – 60 Hz, while the target plasma has an ELM frequency of 20 – 25 Hz. Once the gas rate increases over the optimised value, a rise of the ELM frequencies is observed in both cases. Figure 9 shows a comparison of the total radiation between the discharges with and with out an  $n = 1$  field, and with and without a gas fueling during the ELM mitigation phase. For the discharge with no gas fuelling, no clear change in the total radiated power measured in the inter-ELM phase cause by the application of the  $n = 1$  field could be detected, even when the ELM frequency increased by a factor of  $\sim 4$ . However, the ELM-peak radiation dropped significantly for the mitigated ELMs, which is mainly due to a reduction of carbon erosion when the ELMs become smaller in size. With an optimised gas putting, the total radiated power measured in the inter-ELM phase increased by a factor of 2, which is about  $\sim 30\%$  of the total heating power while the decrease of the ELM-peak radiation is not that pronounced.

## SUMMARY AND CONCLUSION

Active ELM control by using static external magnetic perturbation fields with low  $n$ , has been demonstrated for both, ITER baseline ( $q_{95} \sim 3$ ) and high beta advanced tokamak steady state scenarios at the JET tokamak. ELM control was found to work in high beta plasmas ( $\beta_N$  up to 2.9) without degradation of the energy confinement time. These results confirm that the ELM mitigation using an low  $n$  perturbation has a wide operational window for different target plasmas. An increase of the frequency of mitigated ELM with increasing NBI heating power has been observed, which shows that mitigated ELM with  $n = 1$  field have a similar power scaling as type-I ELMs. The ELM mitigation with the  $n = 1$  field has been performed in low triangularity plasmas with additional gas fuelling. The plasma density can be maintained during the flat top of  $I_{EFCC}$ , while a contiguous drop in density even at a constant  $I_{EFCC}$  in discharges without gas fueling has been observed.

In conclusion, the experimental results from JET show that both the frequency and the amplitude of type-I ELMs can be actively controlled with an acceptable reduction in plasma confinement by the application of an  $n = 1$  perturbation field generated by external coils. During the application of the low  $n$  field the ELM frequency increased by a factor of  $\sim 4 - 5$ . Reduction in carbon erosion and ELM peak heat fluxes on the divertor target by roughly the same factor as the increase of the ELM frequency has been observed. Compensation of the density pump-out effect has been achieved by means of gas fuelling in low triangularity plasmas. An optimised fuelling rate to compensate the density pump-out effect has been identified.

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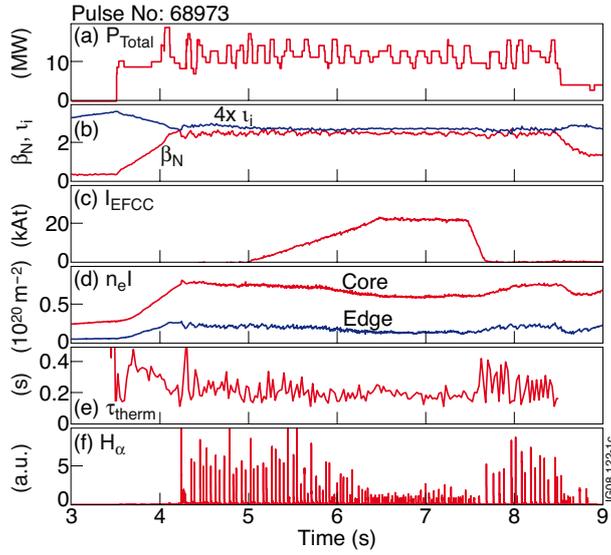


Figure 1: Time evolution of (a) the total input power,  $P_{Total}$ , (b) normalized beta,  $\beta_N$  and internal inductance,  $t_i$ , (c)  $I_{EFCC}$ , (d) line integrated electron densities,  $n_e l$ , measured with an interferometer along two lines of sight, one close to the magnetic axis (upper trace) and the other near the pedestal top (lower trace), (e) thermal energy confinement time,  $\tau_{therm}$ , (f)  $D_\alpha$  signal measured at the outer divertor for a high beta discharge.

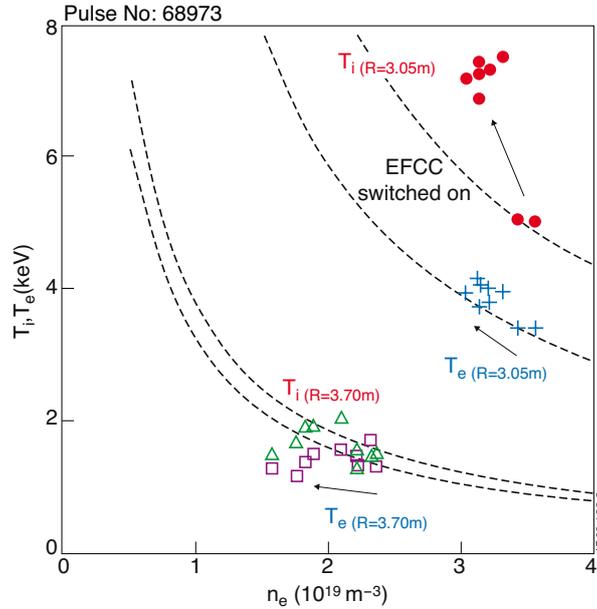


Figure 2: Evolution of  $T_i$  and  $T_e$  as a function of electron density,  $n_e$ , for the same high beta discharge as shown in Fig.1

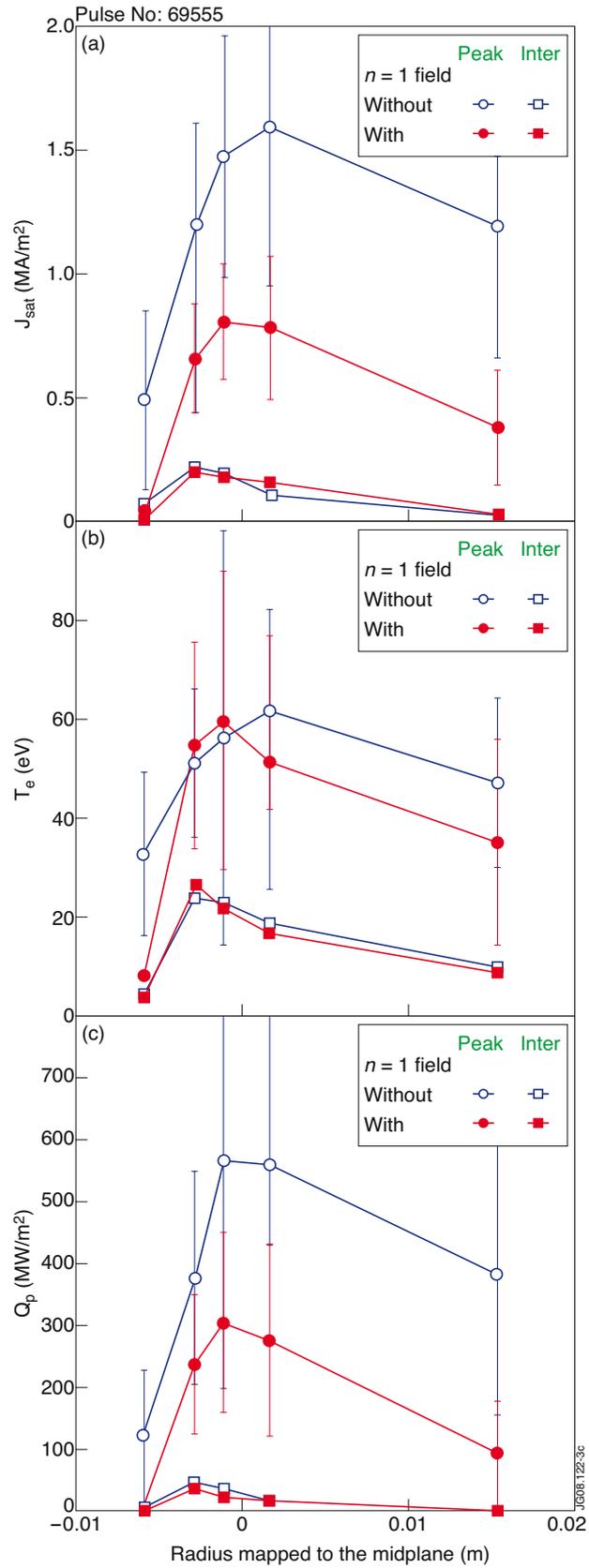


Figure 3: Profiles of (a) particle flux, (b) temperature and (c) heat flux at the outer divertor strike point.

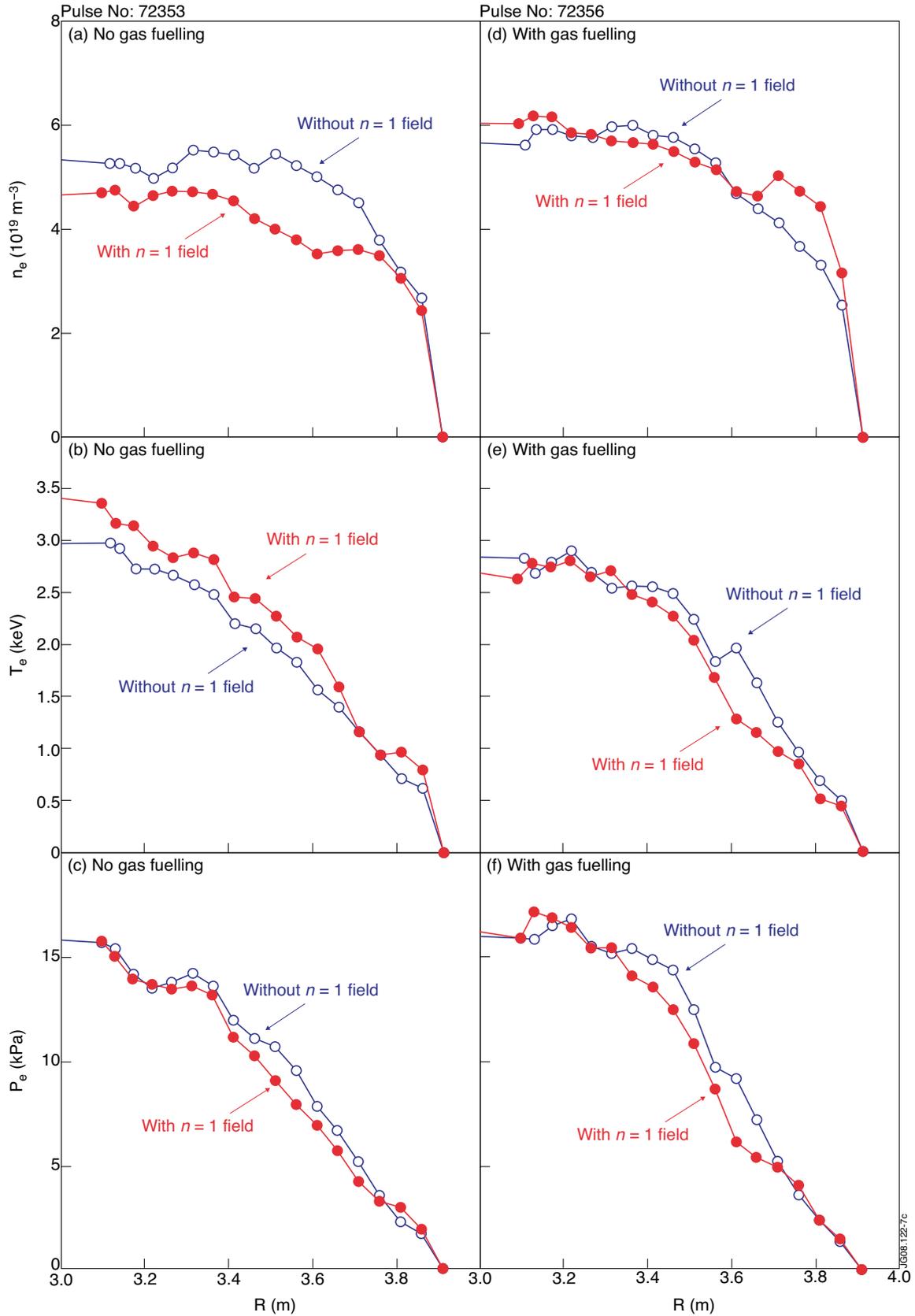


Figure 7: The profiles of (a, d) electron density,  $n_e$ , (b, e) electron temperature,  $T_e$ , and (c, f) electron pressure,  $P_e$  in discharges with and without gas fuelling before and during the  $n = 1$  EFCC application. The total gas rate is  $7.8 \times 10^{21}$  e/s for the fuelled discharge.

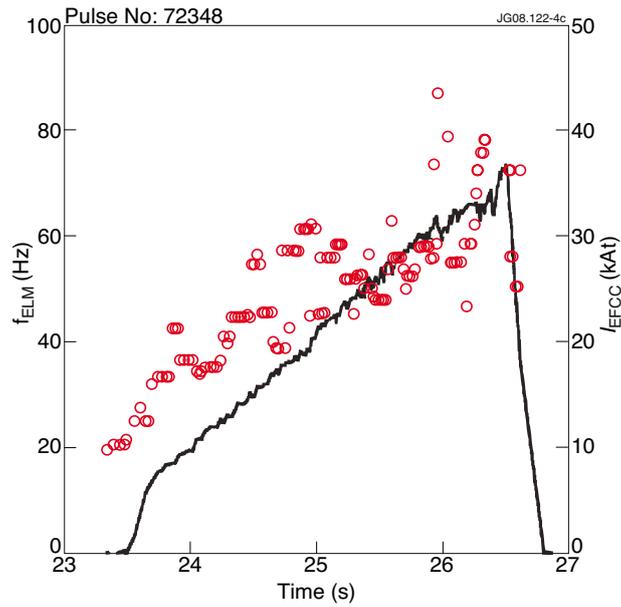


Figure 4: Time evolution of ELM frequency,  $f_{ELM}$ , and EFCC coil current,  $I_{EFCC}$ .

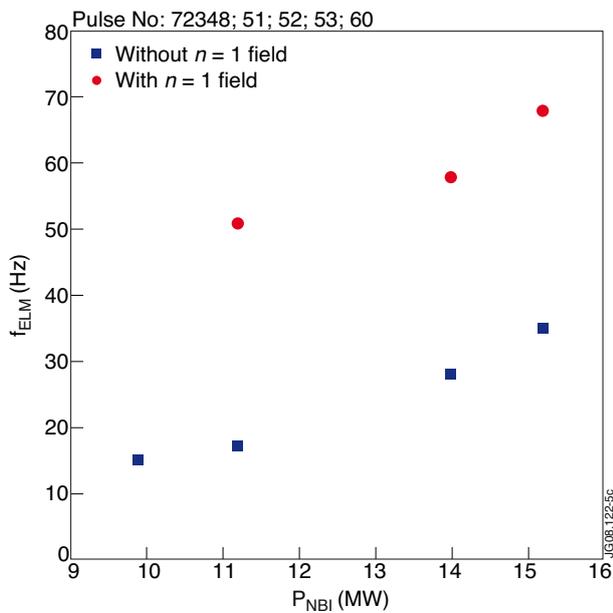


Figure 5: Heating power dependence of ELM frequency measured during the phases with and without an  $n = 1$  field.

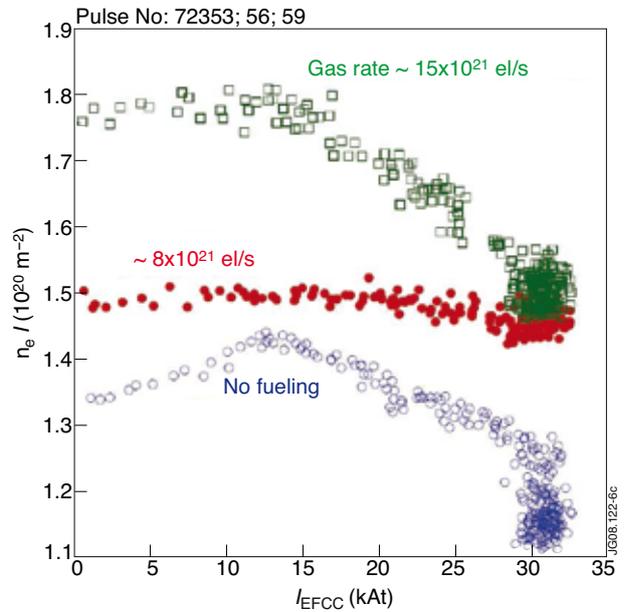


Figure 6: Central line-integrated density as a function of  $I_{EFCC}$  for the discharges with and without gas fuelling.

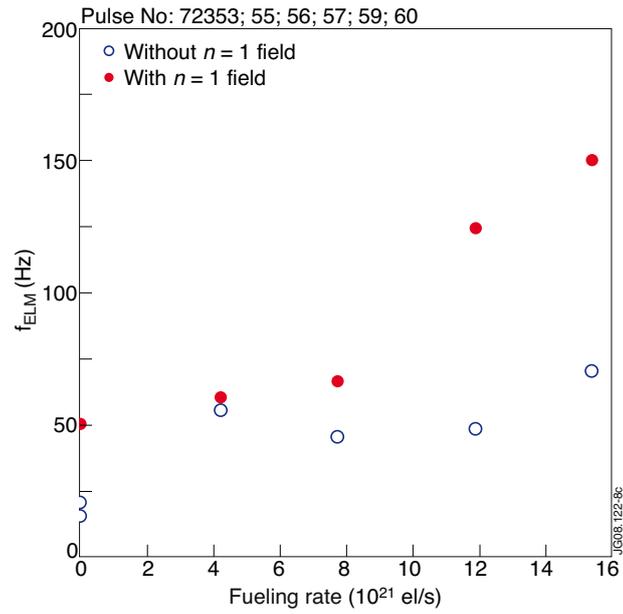


Figure 8: ELM frequency as a function of the total gas fuelling rate measured with and without an  $n = 1$  field.

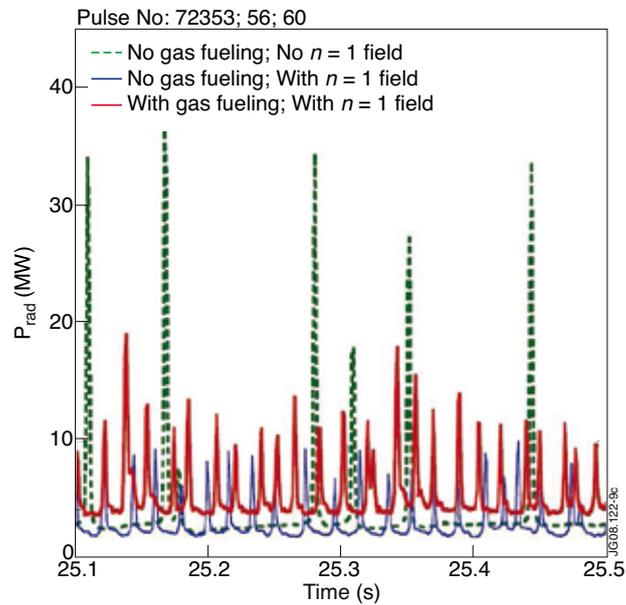


Figure 9: Time trace of total radiation,  $P_{\text{rad}}$ , during application of an  $n = 1$  field for discharges with and without fuelling. The total gas rate is  $7.8 \times 10^{21}$  el/s for the fuelled discharge.