CCFE-PR(17)35

F.G. Rimini, D. Alves, G. Arnoux, M. Baruzzo, E. Belohony, I. Carvalho, R. Felton, E. Joffrin, P. Lomas, P. McCullen, A. Neto, I. Nunes, C. Reux, A. Stephen, D. Valcarcel, S. Wiesen and JET EFDA contributors

The Development of Safe High Current Operation in JET-ILW

The Development of Safe High Current Operation in JET-ILW

F.G. Rimini[1], D. Alves[2], G. Arnoux[1], M. Baruzzo[3], E. Belohony[4],
I. Carvalho[2], R. Felton[1], E. Joffrin[5], P. Lomas[1], P. McCullen[1], A. Neto[6],
I. Nunes[2], C. Reux[5], A. Stephen[1], D. Valcarcel[1], S. Wiesen[7] and JET
EFDA contributors

[1]CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[2]Instituto de Plasmas e Fusão Nuclear, IST,Universidade de Lisboa, Portugal
[3]Associazione EURATOM-ENEA sulla Fusione, Consorzio RFX Padova, Italy
[4]Max-Planck-Institut für Plasmaphysik, 85748 Garching, Germany
[5]IRFM-CEA, Centre de Cadarache, 13108 Sant-Paul-lez-Durance, France
[6]Fusion for Energy, 08019 Barcelona, Spain
[7]IEK-4, Forschungszentrum Jüulich GmbH, Partner in the Trilateral Euregio Cluster, Juelich, Germany

ABSTRACT

The JET tokamak is unique amongst present fusion devices in its capability to operate at high plasma current, providing the closest plasma parameters to ITER. The physics benefits of high current operation have to be balanced against the risks to the integrity of the machine due to high force disruptions. The installation of the ITER-Like Wall (ILW) has added risks due to the thermal characteristics of the metal Plasma Facing Components. This paper describes the operational aspects of the scientific development of high current H-mode plasmas with the ILW, focusing on disruption prediction, avoidance and amelioration. The development yielded baseline H-mode plasmas up to 4MA/3.74T, comparable to the maximum current achieved in JET in Carbon-Wall (CFC) conditions with similar divertor geometry.

1. INTRODUCTION

The JET tokamak is unique amongst present fusion devices in its capability to operate at high plasma current, providing the closest plasma parameters to ITER. High current operation opens the door to ITER relevant physics studies, e.g. dimensionless scaling to low ρ^*, and high performance H-mode studies in DT. Naturally the physics benefits of high current operation have to be balanced against the risks to the integrity of the machine due to high force disruptions. With the installation of the ITER-Like Wall (ILW) [1] additional risks have been introduced due to the characteristics of the metal Plasma Facing Components (PFC) and to the observed slower timescales of the disruption process, resulting in higher disruption forces.

As the dynamic forces on the vessel scale with current, operation at High current has always brought significant risks for the integrity of JET. The forces are a characteristics of the magnetic configuration, typically higher at high triangularity, δ, than low triangularity. They depend on the currents in the PF coils and the geometrical characteristics of the configuration. Statistical analysis of the historical JET data suggests that the lifetime to leak is ~ 134 disruptions for a low δ disruption with force of 3.5MN, decreasing to ~ 20 disruptions at the 4.5–5MN level. For example, even a relatively harmless low δ configuration, can produce disruptions with 4–5MN forces at 4–4.5MA.

In addition, when the JET First Wall was protected by CFC tiles, it was relatively safe from the high energy localised loads typical of disruptions and the subsequent loss of position control. CFC sublimates at temperatures above 3642°C, and this could result in local damage to the PFCs, potentially reducing its capability to tolerate heat loads in the long run. It would, nevertheless, not melt into macroscopic droplets like beryllium and tungsten do. These macroscopic debris can be re- deposited elsewhere around the tokamak and significantly undermine the power handling of the wall in normal operation. It is essential, therefore, to protect the PFCs from the worst thermal loads at disruptions.

High current H-mode operation is, also, carried out at high levels of input power. The development of such scenarios cannot, therefore, neglect to limit thermal excursions, in steady-state, on the First Wall and the Divertor to the safe limits for the integrity of the various components. In JET this translates in keeping the temperature of the Be main chamber tiles below their melting point of 1287°C. For the Tungsten the melting temperature is considerably higher, 3422°C, the main problems being thermal cycling and carbidisation risk for the W-coated tiles [1,2], limiting their useful max. temperature to about 1300°C. The assembly of the bulk- W tile has also energy limits to avoid thermal fatigue.

This paper describes the operational aspects of development of high current H-mode plasmas with the ILW, focussing on disruption prediction, avoidance and amelioration, as well as the handling of the steady state heat load during high power operation. We will look in turn at the various issues linked to disruptions and how we plan to mitigate them. We'll also investigate the main disruption causes for this specific scenario and the means we have at JET to respond, in real time, to off-normal events which, if left unchecked, would inexorably lead to a disruption. In this paper we'll look only briefly to the limited set of high current pulses done in the first ILW campaigns [3,4], and we'll concentrate on the more extensive and ambitious experiments carried out in the 2013/14 campaigns. An in-depth analysis of the confinement and plasma physics results for this experiments, as well as implications for extrapolations to future devices, is found in [5].

2. DISRUPTION FORCES

The worst disruptions at JET, both in terms of forces and heat loads, are the so-called Vertical Displacement Events (VDE) when plasma vertical stabilisation is lost and plasma intercepts locally a PFC on a timescale of few milliseconds, before both thermal collapse and current quench. In these cases the force depends on the plasma vertical growth rate, on some of its geometrical characteristics, like elongation and wall clearance and, more generally, on the currents in the poloidal field coils.

As dynamic disruption forces scale with I_p^2, they can be measured by doing deliberate VDEs at low current and in ohmic plasmas, thus minimising the risks to the PFCs. Overall the results of these tests confirm the increase in dynamic disruption forces with the ILW when comparing with the same magnetic configurations in CFC conditions [6,7]. For example, the low δ configurations used in 2009 for high current experiments, with strike points either on the bulk-W tiles (LBSRP) or in the lower corners of the Divertor region, when run in ILW resulted in forces increasing from an average of 0.28–0.30 MN/MA^2 to 0.46–0.47MN/MA^2 (Figure 1).

In the 2011/12 first ILW campaign, initial scoping studies of high current operation were carried out and achieved H-mode pulses up to 3.5MA/3.2T with combined Neutral Beam (NBI) and Ion Cyclotron Resonance (ICRF) Heating in the range of 24–26MW [3, 4]. The scientific plan for the 2013/14 campaign was more ambitious, including extensive use of H-mode plasmas up to 4–4.5MA for potentially more dangerous experiments, e.g. extrinsic impurity seeding for heat load control. Work has, therefore, been done to develop new magnetic configurations with lower intrinsic force at the disruption. Decreasing the Poloidal shaping currents does somewhat decrease elongation and disruption forces but, also, decreases the clearance between the Last Closed Flux Surface and the

PFCs. By exploiting the fact that configurations are naturally thinner at lower internal inductance, e.g. during the Ip ramp-up and in H-mode, one can produce configurations that have sufficient clearance even at reduced shaping currents.

Some attention has also been given to the magnetic equilibria to be used after a “stop”, i.e. an early forced termination of the H-mode phase in case of detection of abnormal plasma behaviour. With the CFC wall, the strategy in case such a fast termination was needed, for example if a disruption was deemed to be imminent and unavoidable, was to decrease rapidly the Poloidal shaping and divertor currents, thus reducing the disruption forces even at the cost of making a transition from a diverted to a limiter configuration. This could result in high heat loads to the first wall, when the plasma became limited on some part of the PFCs. While acceptable in CFC First Wall conditions, this is clearly too dangerous with an all-metal wall. In ILW abnormal plasma terminations it is, therefore, essential to keep a diverted magnetic configuration as long as possible during the fast ramp down of the plasma. The VDE tests indicate that the new configurations for the high power phase have, indeed, forces lower than in the 2011/12 campaign and comparable to the CFC values. As expected, the configurations (FASTCC) to be used for abnormal, fast, plasma termination have higher normalised force. However, since they are to be used in a phase with a relatively fast ramp down to lower plasma current, the absolute force will be of the same order or less than in the flat-top.

3. DISRUPTION HEAT LOADS

As discussed in details in [6,7], some of the disruptions characteristics have been significantly altered by the installation of the all-metal ILW with respect to the CFC conditions. The radiation level during the disruption process has been strongly reduced leading to an increase both of the current quench timescales, and of the resulting forces on the vessel, and of the heat loads. To reduce the impact of the disruptions in the ILW the Massive Gas Injection (MGI) system has been used extensively since the 2012 campaign as “active” protection system at JET [8] in cases where a disruption is judged to be unavoidable. The Real-Time Protection Sequencer (RTPS)[9] incorporates a detection of the large plasma current excursions or voltage spikes, following the thermal quench, as well as high levels of MHD activity, which are likely to lead to a thermal collapse.

The reliable Real-Time triggering of the MGI via the Disruption Mitigation Valves (DMV), together with an intelligent detection of off-normal events which could be precursor to a disruption (see section 3) proved very successful in avoiding, in this specific set of experiments, overheating of the main chamber at disruption. In the 143 pulses carried out in the framework of the high current H-mode scenario development in 2013/14, none produced disruptions challenging the integrity of the main chamber PFC. In particular, even though a significant number of these disruptions evolved, at some point during the current quench, in an upwards VDE, only 3 disruptions at low I_P didn’t have the MGI. None of the disruptions in this experiment produced any significant overheating of the beryllium-clad Upper Dump Plate, one of the most delicate and at risk of the JET PFCs.

4. DETECTION OF OFF-NORMAL EVENTS AND EARLY H- MODE TERMINATION

Although the presence of MHD activity or other abnormal plasma behaviour can lead to a disruption, it does not necessarily follow that a disruption is so imminent that no other action can be taken by the Real Time systems apart from triggering the DMV and actually causing the disruption. When operating at high current a better strategy might be to use the time before the disruption occurs naturally to try and take further mitigating or disruption avoidance actions. These include a fast switch off of the additional heating power, thus exiting the H-mode on confinement timescales, << 1s, and decreasing the plasma stored energy. In addition, it is very desirable to force a relatively fast decrease of the plasma current and, if possible, make a transition to a magnetic configuration with lower disruption forces. For example, a full disruption at 4MA could have forces in the range of 5.5–6MN which could be reduced to ~ 3–3.5MN if the current can be quickly decreased to the 3–3.2MA level. As mentioned in section 1, this latter strategy may or may not be compatible with minimising the heat loads to the main chamber PFCs in this transient phase. In the experiments considered here, a compromise has been chosen between minimising forces and minimising the thermal loads on the delicate beryllium First Wall components.

In certain conditions, the link between off-normal behaviour and disruption might be weaker and suitable actions may help delaying significantly or, even, avoiding the disruption itself.

4.1. CORE HIGH-Z IMPURITY CONTAMINATION

An interesting case is the pollution of the core plasma by high-Z impurities, typically tungsten and/or nickel. With the CFC JET Wall this was an uncommon event in low δ H-mode scenarios but it has become a significant constraint during ILW operation [2,4,10] as it has been for other all-metal devices like ASDEX-Upgrade [11]. Excessive high-Z radiation in the plasma core leads to core thermal collapse and highly MHD unstable conditions. In JET two fairly distinct types of behaviour have been identified in H-mode plasmas.

Impurity cooling (Figure 2) can be linked to the observation of the so-called Transient Impurity Events (TIE), i.e. a sudden increase in radiated power due to high-Z, mostly W and/or Ni, dust particles or poorly attached debris reaching the confined plasma [12]. The consequences of a TIE depend on the plasma parameters: in particular for H-mode conditions it is crucial for the plasma to remain in ELMy H-mode to avoid a radiation collapse For example, plasmas with high ELM frequency are more likely to survive a TIE than low ELM frequency cases. High power plasmas have better probability of recovering from the transient high radiation without reverting to L-mode than similar cases at lower power.

Slow impurity accumulation has, also, been observed. It is thought to be linked to high W source from the divertor combined with low ELM frequency conditions This behaviour can be avoided by raising external gas fuelling during the H-mode to increase both the edge density, thus cooling the divertor and reducing the W source, and the ELM frequency, thus enhancing the W flushing effect from the main plasma. Core heating via ICRH, typically above ~ 3MW for most JET H-mode conditions, has also proven to be very beneficial in increasing anomalous transport and control the concentration of high-Z impurities once they have reached the plasma core [13]. It is, however, unfortunate that most high H-mode performance scenarios have, historically, been obtained at low gas fuelling, low ELM frequency and hot divertor conditions. Needless to say, one of the main challenges for the operation of present and future all-metal tokamaks is to combine high plasma performance with tolerable divertor conditions and minimum high-Z core contamination. The initial high current 2011/12 experiments remained deliberately in the safe high gas fuelling domain. In order to progress in these studies the high current JET 2014 experiments have chosen to explore the inherently more dangerous operations with lower gas fuelling.

For the real-time detection of the plasma evolving towards high core radiation, and the subsequent core cooling and radiative collapse, a very simple system has been recently implemented. It is based on bolometric line integrated radiation measurements and on the real- time computation of a *radiation peaking* as the radio between the radiation measured on a line of sight going through the core and one intercepting only the upper edge of the plasma, and avoiding the divertor region. The choice of a suitable level to actively stop the pulse is non trivial. If the level is too high, and the stop is issued when the core has already undergone a significant cooling, experience suggests that a disruptive plasma termination is almost unavoidable. On the other hand, pulses that could eventually recover from a high radiation phase may be stopped un-necessarily on a low “radiation peaking” level.

The real-time *radiation peaking* detection has been implemented only towards the end of the high current development and the alarm level has been varied. The related work needed to optimise the response to the *radiation* peaking alarm has barely started. For the time being, a standard response based on rapid current ramp down and fast H-mode exit whilst keeping high electron temperature with ICRF heating has been tested (Figure 3). Statistics on the success of this detection method will be given in section 4.

As additional protection, the JET Session Leader, i.e. the expert who designs the JET pulses on the basis of the experiment requirements and the machine constraints, has a push button to use in case he/she notices something abnormal in the video images relayed live in the Control Room. The human reaction times are such that, usually, one of the real-time protections systems acts before the Session Leader has had time to stop the pulse. Exceptions are low ELM frequency pulses, which can develop towards a slow impurity accumulation. Since, for this experiment, we had not implemented a stop based on detection of low ELM frequency the SL stop has been a useful way to recognise the problem occurring. To be noted that a real-time ELM frequency measurement and control via gas injection has, indeed, been developed at JET and used in low plasma current conditions [14] and it could be a powerful tool for future high current experiments.

4.2. FIRST-WALL HEAT LOAD PROTECTION

Aside from risk of disruption, there are other cases where it is advisable to stop the pulse earlier than programmed. Amongst the most notable examples is the heating of any of the main chamber or divertor components beyond the “safe” limits for steady-state operations, established in the JET Operating Instructions to protect the integrity of the long term investment in the ILW. The Real-Time monitoring of the temperature of various ILW components is entrusted to a set of near-Infrared (IR) cameras [15] co-ordinated via a Vessel Thermal Map system (VTM) which raises alarms to RTPS if any temperature exceed the operational limits or if cameras stop transmitting data, the so-called “blind” alarm [16]. In addition to the IR measurements, an independent system called WALLS [17] computes in real-time distances between the Last Closed Flux Surface and the main chamber components as well as carrying out model-based calculations of the thermal loads on PFCs. WALLS raises alarms to RTPS if distances are deemed to be too low, based on the level of the input additional heating power, or if the energy to a component becomes too large. RTPS then transmits the alarm and it is up to the JET Session Leader to programme an appropriate response.

In the experiments described here we have chosen to respond to high PFCs temperature detection or lower- than-tolerable proximity to main chamber PFCs with:

- immediate switch-off of the additional NBI power and consequent exit from H-mode conditions
- reduction of the ICRF power to a level enough to control high-Z impurities, that may be present in the core, during the transition from H- to L-mode (~ 2s)
- transition to a slimmer plasma configuration, with increased clearance from the main chamber PFCs and different Strike Points positions in the Divertor to cope with either or both types of high temperature alarms
- rapid decrease of the plasma current, ~ 0.35MA/s, to decrease the remaining ohmic heat load and the forces in case of disruption during the exit from H-mode.

Figure 4 shows a case of early plasma termination due to a high temperature alarm on the W-coated horizontal part of the Divertor.

4.3 CORE MHD ACTIVITY

The presence of high levels of MHD activity, although potentially deleterious for the energy confinement and the plasma performance, is not always a good indication of a disruption precursor. In JET baseline H-mode scenario the response to real-time detection of high levels of n = 2 activity, typically linked to (3/2) Neoclassical Tearing Modes, is normally a fast decrease of the NBI power, to decrease the drive to the NTMs, while keeping some ICRH power to ward against core accumulation of the impurities. In our development, we chose to make this response the same as a PFC high temperature or *radiation peaking* alarm.

Conversely, the detection of a high level of non- rotating n = 1 activity is considered to have a very high probability of disruptive consequences. The response chosen for this alarm is a total switch-off of all heating power, a drastic reduction of the Shaping and PFX currents and a very fast, ~ 0.6 MA/s, ramp-down of the plasma current. To be noted that, if the mode amplitude continues to grow despite the fast stop, the remedial action is deemed to have failed and the MGI is triggered, albeit at lower current than at the time of the first alarm.

5. EXPERIMENTAL RESULTS

For the development of the baseline H-mode scenario towards high current a total of 143 pulses were carried out over a period of about 2 months, withe the current ranging from 1.4MA to 4MA and using up to 27MW of NBI power and ~ 6MW of ICRF minority heating. The programmed duration of heating phase is between 12s, at low current, and 3–3.5s at the highest current levels. Most pulses used sweeping of the strike points across the divertor to increase the available pulse length with respect to surface and bulk PFCs temperature limits. In a limited number of cases extrinsic seeding with Neon was also tested [5].

An analysis of the reasons for early termination of the heating phase is shown in Figure 5. Almost 43% of the pulses, and 50% of the pulses with flat-top current above 2.75MA, arrive successfully to the end of their heating phase. Of those that terminate early, the majority are stopped by alarms related to protection of the PFCs (WALLS or VTM).

A limited number of pulses were stopped on detecting that, due to technical faults, the delivered NBI power was below the acceptable level to keep the plasma in good H-mode conditions (Figure 6), while 7 pulses were stopped due to detection of n = 2 activity.

The rest of the pulses not completing the full programmed H-mode phase, roughly 12% at all currents and 9% above 2.75MA, was stopped on detection of an increase of the radiation peaking or by the Session Leader recognising that the ELM frequency had decreased to dangerously low levels, in the 1Hz range.

Although the number of pulses in this set is too small to yield a statistically relevant result, it is still interesting to analyse how successful the strategy for handling the different types of abnormal terminations has been. The results shown in table I suggest that pulses stopped by the protection of the PFCs have a good probability to terminate without a disruption. The same applies to pulses stopped because of n = 2 activity or low NBI power. The H-modes terminated on detection of impurity peaking or high radiations, however, escape a disruption only in 50% of the cases.

Experience has shown that, even if there is no obvious detectable sign of ongoing impurity accumulation, the exit from the H-mode phase is always particularly delicate in ILW. We rely on ICRH to maintain high electron temperature until the plasma returns to L-mode conditions, when slow impurity accumulation becomes unlikely. If, for any technical problem, ICRF fails to deliver the requested power the plasma becomes more vulnerable. In addition, should a TIE occur in this phase, one cannot rely on the ELM flushing mechanism and a sudden radiation cooling is more probable. These reasons explain most of the disruptions observed in pulses which arrive safely to the end of the H-mode phase but do not survive to the programmed end of the current ramp-down.

Finally, we can look at some of the statistics for the disruptions in these experiments. Out of the 143 pulses, 24.5% disrupt [6]. This number decreases to 17.9% if we consider only pulses with flat-top current above 2.75MA. Even if a significant number of pulses disrupted, only in one case did the stop strategy fail to decrease the current and the disruption takes place at the full flat-top value. More importantly, in most of the high current cases (Figure 7), the fast termination strategy reduces the current to a level around 3MA, where the forces become less threatening for the machine integrity. In the course of this experiment, the highest disruption force was measured at 3.36MN at 3.1MA, corresponding to ~ 0.35MN/MA^2, well within the predicted range. In total only 3 disruptions exceeded 3MN, with 2 more disruptions above 2.5MN.

6. CONCLUSIONS

A dedicated experiment was carried out at JET in all- metal wall conditions to explore the performance and confinement physics characteristics of baseline H-modes at high plasma current. Because of the significant danger to the integrity of the machine in case of disruptions at high current and to the PFCs when operating at the maximum available levels of input power, the main threats to the plasma have been separately addressed and different Real-Time disruption avoidance and mitigation methods have been integrated into the scenario development.

This work successfully delivered an H-mode scenario up to 4MA, as well as a more routine 3.5MA H-mode, the vehicle for physics studies that varied from dimensionless parameter scaling, to L-H threshold experiments and extrinsic impurity seeding for divertor heat-load control [4].

ACKNOWLEDGMENTS

The authors wish to thank the JET Chief Engineer and her Team for their support throughout this challenging experiment. The very useful discussions with Dr. T. Pütterich on real-time detection of impurity accumulation are, also, gratefully acknowledged.

This work was supported by EURATOM and 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

REFERENCES

[1]. G. Matthews et al., 2009 Physica Scripta **T138** 014030
[2]. V. Riccardo et al., Fusion Engineering and Design **89** (2014) 1059–1063
[3]. E. Joffrin et al., Nuclear Fusion **54** (2014) 013011
[4]. F. Romanelli et al., Nuclear Fusion **53** (2013) 104002
[5]. I. Nunes et al., Proceedings 25th IAEA FEC Conference
[6]. M. Lehnen et al, Nuclear Fusion **53** (2013) 093007
[7]. P. De Vries et al., Physics of Plasmas **21**, 056101 (2014)
[8] C. Reux et al., Fusion Engineering and Design **88** (2014) 1101–1104
[9] A. Stephen et al., Proceedings 13th ICALEPCS, Grenoble 2011
[10] T. Pütterich et al., Proceedings 24th IAEA FEC Conference, San Diego, USA
[11] R. Neu et al., 2003, Journal of Nuclear Materials **313–316** 116–26
[12] M. Sertoli et al., Physica Scripta **T159** (2014) 014014
[13] E. Lerche et al., Proceedings 25th IAEA FEC Conference

[14] M. Lennholm et al., Proceedings 25th IAEA FEC Conference
[15] G. Arnoux, Review of Scientific Instruments **83** (10) (2012)
[16] D. Alves et al., Accelerators and Beams **15** (5) (2012) 054701
[17] D.F. Valcarcel et al. , Fusion Engineering and Design **89** (2014) 234–258

Termination type	No. of pulses	Disrupting
WALLS, VTM	46	8
n = 2	7	1
Impurity related	18	9
Low NBI power	11	1
Full pulse	61	14

Table I : Statistics on H-mode termination.

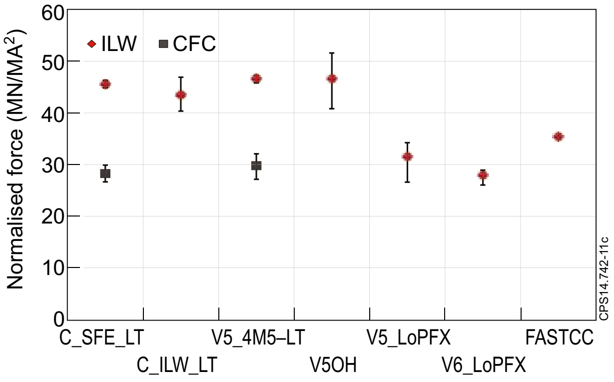

Figure 1: Normalised disruption forces for different JET equilibria: C_ is for strike points in the corner, V5 and V6 for ISP on vertical and OSP on the LBSRP or Horizontal.

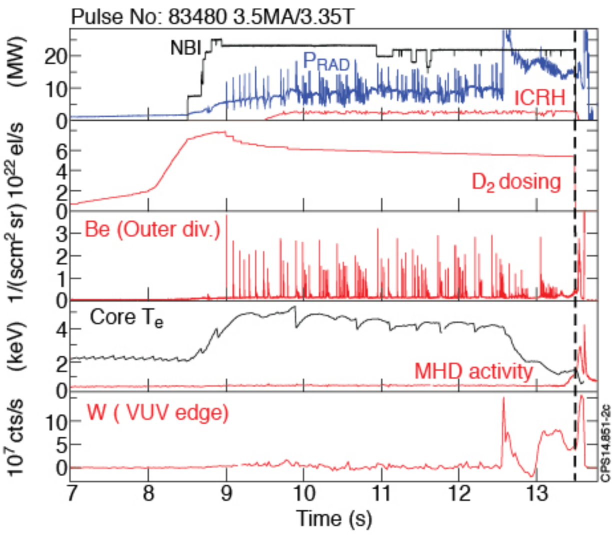

Figure 2: Pulse No: 83480 – example of TIE.

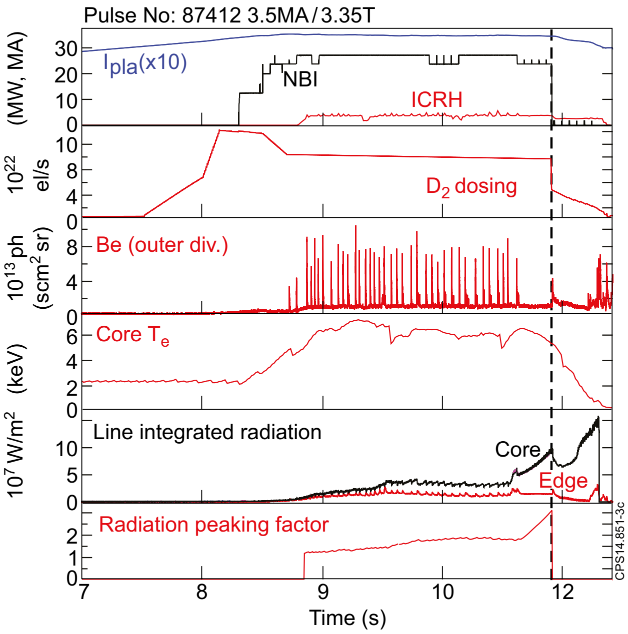

Figure 3: Pulse No: 87412 : real-time radiation peaking detection.

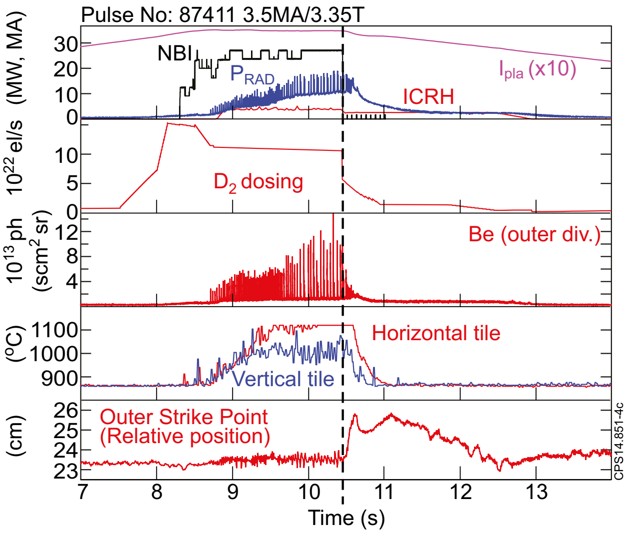

Figure 4: Pulse No: 87411 - response to PFC (W-coated tile) high temperature alarm.

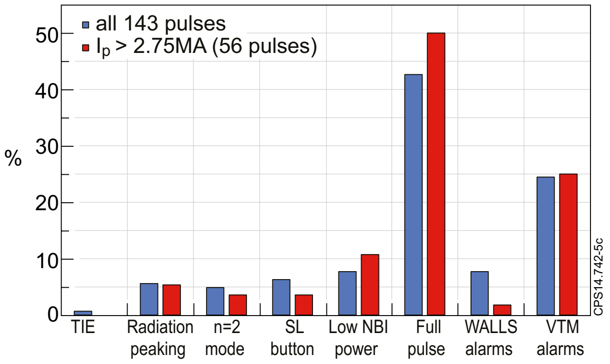

Figure 5: Statistics, for H-mode normal and off-normal terminations.

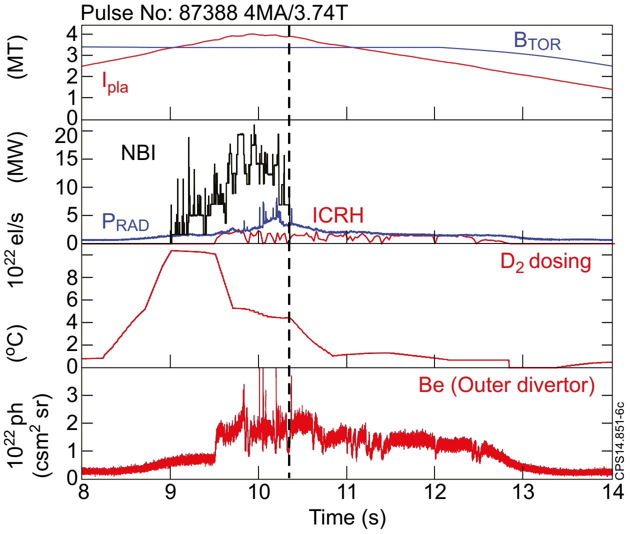

Figure 6: Pulse No: 87388 – response to a low NBI power at 4MA.

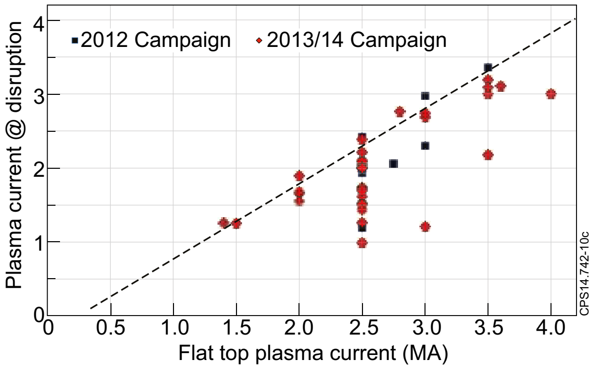

Figure 7: Plasma current at disruption vs. its value during the Flat-Top H-mode phase.