EFDA–JET–CP(08)05/13

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High Beta$_N$ Regimes at JET: Progress Towards Steady-State Operation

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** See annex of F. Romanelli et al, "Overview of JET Results ",*
(Proc. 22 nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

Preprint of Paper to be submitted for publication in Proceedings of the
22nd IAEA Fusion Energy Conference, Geneva, Switzerland.
(13th October 2008 - 18th October 2008)

ABSTRACT.

High β_N plasmas, with or without an ITBs, have been studied in JET AT scenarios at high triangularity and high normalised density at I_p = 1.2-1.8MA /B_T = 1.8-2.7T. The current profile is tailored via a fast current ramp, ohmic or with Lower Hybrid Current Drive (LHCD), and early application of Neutral Beam (NBI) or NBI + Ion Cyclotron Resonance Heating (ICRH) power. The initial q profile has low or weakly reversed shear in the core. β_N approaching 3 has been achieved with $H_{IPB98(y,2)} \sim$ 1.0–1.2. The development of an ITB contributes by 20-25 % to – β_N, the best ITB performance being obtained when a barrier forms in both ion and electron temperature channels. In the absence of ITBs the global confinement and the core pressure decrease with increasing q_{min}. The total non-inductive current I_{NI} reaches transiently 75% of I_p, at the maximum values of β_N and > 60% I_p in a more stationary phase. Unlike previous JET experiments, where strong pressure peaking led to MHD limitations at relatively low values of β_N, the new data indicate that a viable route towards sustainable high β_N operation may exist, with different q profiles, with or without ITBs, as long as strong pressure gradients are avoided. Of particular importance for JET is the preparation of the AT scenario in view of the upgrade of the JET heating power, NBI and ICRH: modelling suggests that operation at high β will be achievable at higher toroidal field which, in turn, may improve the LH wave accessibility and increase the capability to tailor and sustain a non-monotonic the current profile for times comparable to the resistive diffusion time.

1. INTRODUCTION

One of the main challenges facing the research into future efficient steady-state tokamak fusion power plants lies in the development of plasma operating scenarios with high plasma pressure, at the limit of MHD stability and minimal recirculating power. In ITER, the so-called Advanced Tokamak (AT) regime at 9 MA, with confinement significantly higher than a standard H-mode, $H_{IPB98(y,2)} \approx 1.5$, plasma current driven fully non-inductively, with a dominant self-generated bootstrap component $I_{BS} \sim 0.5 \times I_p$, is one of the candidates to fulfil the steady-state requirements mentioned above [1]. An intensive and challenging research programme on this particular topic is, therefore, carried out in today’s tokamaks and will form an integral part of the ITER research plan.’

The study of AT scenarios has long been an important part of the JET experimental programme. Until recently, the experiments concentrated on low triangularity plasmas with deeply reversed q profiles, with’“strong” Internal Transport Barriers (ITB) and type III ELMs H-mode. Lately, starting in 2006, the focus has shifted towards the exploration and integration of ITER-relevant issues [2]. More precisely, the topics addressed include a) the operation at ITER-relevant safety factor $q_{95} \sim 5$ and high triangularity, b) the approach to high normalised pressure, the maximisation of the self-generated Bootstrap current and the investigation of MHD stability limits, c) the exploration of ITB physics at higher density and d) the investigation of weakly reversed q profiles and ITBs located at large minor radius. Eventually, the aim is the combination of core and edge conditions appropriate for future implementation of AT scenarios in an all-metal wall environment. In this paper we report on the experimental progress made, on the numerical extrapolation of these scenarios to future JET operation and on how these results can be used to firm up the foundation to predict the performance of AT steady-state scenarios in ITER.

2. The high β_N experiments

All experiments considered here were carried out in the range I_p = 1.2-1.8MA/B_T = 1.8-2.7T, at high triangularity, $\delta \approx$ 0.35-0.5, and relatively high density, $n_e \approx$ 50-80% of the Greenwald density. Plasma current and toroidal field were chosen so as to be close to the value of $q_{95} \approx 5$, as foreseen for ITER steady-state operation at Q~5. The current profile is tailored in a *prelude* phase, before the high power heating is applied, via a fast current ramp, ohmic or with Lower Hybrid Current Drive (LHCD), and early application of Neutral Beam (NBI) or NBI + Ion Cyclotron Resonance Heating (ICRH) power. Three experimental lines have been followed, and will be addressed separately: a low toroidal field scenario, typically with no or weak ITBs, to explore the highest β_N domain (section 3), one at higher field, current and density to develop ITB scenarios for exploitation with the ITER-Like Wall (ILW) and the power upgrades (section 4), and a third line specifically aiming at studying the compatibility of ITBs with so-called “grassy” mild ELMs (section 5).

3. NO-ITB SCENARIO

The scenario without ITB (Fig.1(a)) has been developed up to 1.2MA/1.8T [3]. Discharges are heated by NBI alone, the actual power being controlled in real-time to achieve and maintain a pre-set value of β_N. The q profile is tailored via the fast ohmic current rise, 0.2-0.4MA/s, in order to have conditions of low or weakly reversed shear in the core and the initial value of q_{min} can be adjusted by the timing of the NBI application. The experimental q profile is derived by the EFIT magnetic reconstruction code, constrained by Motional Stark Effect (MSE), polarimetric and kinetic measurements and, for the 2008 data, including the information on the appearance and radial position of various types of well identified MHD activity, such as Alfven Cascades (AC), q = 2 fishbone activity or q = 1 sawteeth. The target q profiles explored range from reversed shear conditions with $q_{min} \approx 2$-3, via flat shear with $q_{min} \approx 2 - 1.5$, to monotonic conditions with q_{min} around and below 1. This range of current profiles not only covers the ITER-relevant cases but also extends, for completeness, towards more extreme cases It is assumed in the following that the target q_{min} value can be used as representative of the q profile even during the high ≤ phase, although it is clear that the current profile will evolve and may actually evolve differently according to the time evolution of ≤. The plasmas are characterised by a type I H-mode edge, with no ELM mitigation being applied, and global confinement up to $H_{IPB98(y,2)} \approx 1.0$–1.2 at density corresponding to 50-70% of the Greenwald value. The total normalised pressure reaches – $\beta_N \approx 3$, sustained for $\sim 18 \times f_E$, and $\beta_N \approx 2.8$ for $35 \times f_{E\,Rmin}$, making the access to high β_N more difficult in the high q_{min} parameter space (fig.2).

Measurements of the plasma response to an applied low level n=1 helical magnetic perturbation are used to probe the proximity to a stability threshold [4]. The threshold for increased plasma response with increasing $\leq_N$ is attributed to Resonant Field Amplification (RFA) and linked to, although not necessarily equal to, the “no-wall” limit. Discharges are transiently obtained with total β_N up to 50-70% above the RFA threshold and 20% above it for times comparable to resistive diffusion timescales. The high beta phase is often, but not always, terminated by the appearance of a continuous $n = 1$ mode. At the highest beta values this mode starts with an ideal kink-like (no reconnection) structure; in all cases it evolves into an $m = 2$ tearing mode [5]. Both the measured RFA threshold and the achievable β decrease with increasing q_{min}, as do the global confinement and the core pressure even in the absence of MHD activity (fig.3). The behaviour of the measured RFA threshold can be compared to theoretical predictions for the no-wall limit in JET using the MARS-F code [6]: the simulations confirm a link between the RFA threshold and the ideal no-wall limit, with the RFA threshold being, however, systematically lower than the calculated ideal no-wall limit. It is interesting to note that in DIII-D the ideal no-wall limit has also been observed to degrade with increasing q_{min} [7]. The challenge of achieving high β_N in the region $q_m \approx 1.5\text{-}2$ has recently been tackled by a careful optimisation of the discharge evolution, and consequently of the pressure and current profiles. In this new set of data it has been shown that, starting from $q_{min}>2$, the discharge can *cross* $q_{min}=2$ at high $\beta_N \approx 3$: the slow evolution of the q profile, even though full non-inductive conditions are not attained, allows increased stability of high q_{min} domain for several confinement time. In these conditions β_N has been found to exceed, transiently, the RFA threshold by up to 50-70%, significantly more that the 20% expected from the relationship between no-wall limit and RFA threshold. The possibility of RFA well below the no-wall limit and the conditions under which this could happen have been investigated numerically with linear ideal MHD stability codes and appear to be linked to marginally stable current driven modes [4].

Interpretative numerical analysis of the current profile evolution has been carried out with the TRANSP code [8]. In general, although the initial q_{min} value may be different, the profiles during the high $\leq$ phase evolve towards conditions with q_o”<1 and positive shear in the plasma core (fig. 4a). The total non-inductive current I_{NI} can reach 75% of I_p, transiently at the maximum values of β_N, and $\geq$ 60% I_p in a more stationary phase; the thermal Bootstrap current and the beam driven current are equally important components of the total non-inductive current. The contribution of the ion temperature gradient to the bootstrap current driven in the confinement zone, inside $r/a<0.8$, is small compared to the terms due to the electron temperature and density gradients, with the density gradient term dominating only in the few discharges with the leargest density peaking, $n_{eo}/\langle n_e \rangle \sim 1.6$. This observation suggests that a possible route to increase the bootstrap current in this scenario, which has so far been dominated by ion NBI heating, would be increasing the electron heating and, thus, the electron temperature. Finally, the capability of the theory-based GLF23 transport model to describe thermal transport in the MHD stable phase of these discharges has been assessed. The predictive accuracy is good, within 22%, for both electron and ion temperature (fig. 4b): major discrepancies are observed only in the very core of the plasma, and especially when there are signs of weak ion ITBs. The agreement is worse for the electron temperature, the calculated profiles being generally under-predicted in the gradient region. The GLF23 simulations also highlight the stabilising effect of the ExB rotation shear on ion thermal transport in this high ≤ scenario, while its influence on thermal electron transport is negligible.

4. ITB SCENARIO

High β_N H-mode plasmas with an ITBs have been studied to investigate specifically the viability of AT scenarios based on ITBs located at as large minor radius as compatible with an ELMy edge, r/a > 0.5, to attain confinement $H_{IPB98(y,2)} \approx 1.5$, significantly higher than a standard H-mode at similar plasma parameters. The issues of MHD stability and compatibility of core and edge transport barriers in these weak ITB cases have also been addressed.

The scenario has been explored (fig.1(b)) in 2006/2007 up to 1.5MA/2.23T, heated by a combination of NBI and (H)D ICRH, the latter resonant on the hfs of the magnetic axis [9,10]. In line with the aim of avoiding strong ITBs located at small minor radius the target q profile is characterised by a weakly negative shear in the centre, with q_{min} between ~1.5 and β 2. LHCD is used in some of the discharges to further broaden the current profile but, since accessibility and current drive efficiency are limited at this low toroidal field, the fraction of LHCD absorbed power inside $\rho \leq 0.85$ could be as low as 20%. In this set of data the confinement is in the range $H_{IPB98(y,2)} \approx 0.9\text{-}1.1$: the development of an ITB is estimated to contribute by 20-25 % to confinement, the best performance being obtained when an ITB forms in both ion and electron temperature channels (fig.2). The total β_N reaches 2.8 (fig.3) which, as in the no-ITB case, is consistently ~ 20% above the RFA threshold. A statement on the effect of the ITBs, at large radii, on ≤ stability cannot be made at the moment because the characterisation of the ideal no-wall limit with and without ITBs has not been done in this scenario. However, because of the limitations to the present JET additional heating power, ITBs are needed in this scenario to provide the necessary confinement for β_N to approach the no-wall limit. The highest confinement phase is often, but not always, terminated by the appearance of a continuous n = 1 mode, identified as an m = 2 tearing mode [5].

The exploration of AT scenarios with ITBs has been pursued in 2008, at higher values of plasma current and toroidal field of 1.8MA/2.7T (fig.5). This development targets specifically conditions where the forthcoming JET additional power upgrade, ICRH and NBI [11], will provide the means to achieve high β_N as well as higher density, relevant for operation in JET with an all-metal wall [12]. Another advantage of going to higher toroidal field, provided the density does not increase more than proportionally to the plasma current, could be an improvement in the LH wave accessibility resulting in increased capability to sustain a weakly reversed shear profile for times comparable to the resistive diffusion time. In designing these experiments the experience from both the no-ITB and the ITB scenarios in 2006/2007 has been invaluable; elements have been incorporated, in addition, from other experiments like the studies on inter-ELM heat load mitigation by impurity injection in AT scenarios [13]. To ensure the optimal power handling in the ITER-like Wall phase, 2010 and beyond, the magnetic configuration in the 2008 experiment has been adapted so that the

Outer Strike Point lies on the specific divertor tile which will be solid tungsten once the ITER-like Wall is installed. In addition, to minimise the NBI shine-through and, thus, limit the power deposited on the Innerwall tiles, the density has been increased in the *prelude* phase of the scenario. This is a delicate balancing act between decreasing shine-through losses whilst keeping a relatively low resistivity and current tailoring capability; experimentally, a suitable current profile has been achieved up to n_e~$1.5\times10^{19}\,m^{-3}$, as compared to n_e~0.8-$1.2\times10^{19}\,m^{-3}$ in previous experiments, by optimising the plasma current ramp-up rate in a purely ohmic *prelude*. The target current profile has typically weakly reversed/flat core shear with q_{min}~1.5-2, as judged particularly interesting on the basis of the recent studies of stability and confinement at high β_N reported above.

The preliminary 2008 experiments, the main thrust on this scenario being planned for the end of 2008, yield a good baseline confinement $H_{IPB98(y,2)} \approx 1$, rising to ~1.2 when a weak ion-ITB is triggered at mid-radius, with 20MW of NBI power but only ~2MW of ICRH and LHCD power respectively. The density in the high power phase increases up to n_e~$4.8\times10^{19}\,m^{-3}$, corresponding to roughly 60% of the Greenwald density. The total beta reaches $\beta_N \approx 2.5$ with $\beta_p \approx 1.4$; the high beta phase lasts 2s ~ 10xf_E but the current profile evolves, though slowly, throughout this period. In the discharges reaching the highest beta a burst of n=1 MHD activity is observed around the time of the ITB collapse and termination of the $H_{IPB98(y,2)} > 1$ phase. The nature of this activity is still under investigation, but it should be noted that at this time β_N is approaching the estimated no-wall limit $4\times l_i$. Care is taken, in these discharges, to optimise the edge pedestal conditions so as to achieve the best compromise between good pedestal confinement and minimum interference with the ITBs. As a new feature of the scenario, use is made of rapid varying radial field, the so called VS-kicks, as an ELM pacing actuator to minimise the length of the initial ELM-free phase, at the application of the high power, and the potentially deleterious effects of a first large ELM [13,14]. In parallel, experiments are continuing on mitigation of inter-ELM heat load via injection of extrinsic impurities (Neon, Nitrogen) following the promising results obtained in 2007 [13].

Simulations with the Cronos code [15], computing the time evolution of the ohmic and non-inductive components of the current profile on the basis of the measured plasma temperature and density profiles, indicate that of the ~1.8MA of total plasma current up to 0.6MA are accounted for by bootstrap current, ~0.4MA are driven by NBCD and ~0.15MA are driven by LHCD (fig.6). The LH wave, launched in the specific discharge modelled with a spectrum peaked at $n_{//}$=1.8, is deposited around mid-radius : the wave becomes less accessible with increasing density during the pulse, and the simulation indicates that the contribution of LH to the non-inductive driven current decreases throughout the pulse.

5. GRASSY ELMS SCENARIO

In parallel to the “active” ELM mitigation methods described in section 4, an experimental line on “passive” ELM mitigation has also been pursued, in Quasi-Double-Null equilibria at 1.2-1.5MA/ 2.3-2.7T (fig.1c) , to study specifically the compatibility of ITBs with so-called”*grassy* mild ELMs conditions [16]. The interest of such regimes of small grassy ELMs is in their potential to combine good core and pedestal confinement at high density with acceptably small ELM losses. In an earlier set of experiments, in 2003/2004, mild *grassy* ELMs had been observed at high β_{pol} in Quasi Double-Null (QDN) equilibria with high l_i, in the range typical of baseline H-modes, and high $q_{95} \sim 7$ plasmas but not in similar β_{pol} Single-Null (SN) low l_i discharges. In 2006/2007 the low l_i database was extended to QDN configurations and an extensive q_{95} scan was carried out down to the AT-relevant range of q_{95}~5. In this new set of discharges when $\beta_{pol} > 1.6$, a transition is observed from clear type I ELMs to *grassy* ELMs, with features decorrelated with stored energy or pedestal temperature losses. *Grassy* ELMs are observed at q_{95} as low as 5.8 and high edge collisionality, but not at the highest current values, where β_{pol} only reaches 1.5 with the available NBI+ICRH power. In this set of discharges the target current profile, tailored via an LHCD assisted *prelude,* is weakly reversed in the core with $q_{min} \approx 2$. For the first time at JET mild ELMs conditions have been combined with an ion-ITB located at mid-radius $r/a \approx 0.5$, while there is no obvious sign of electron ITBs. The total β_N approaches 2.6, but the global confinement corresponds only to $H_{IPB98(y,2)}$ ~0.8. This could be consistent with the observation, in the other high ≤ scenarios considered in this paper, of confinement degradation with increasing q_{min} and limited performance when only ion-ITBs are observed. In addition, strong recycling in this particular QDN equilibrium may have an important negative effect on pedestal confinement.

6. WHAT NEXT ?

The experimental results described in this paper form the basis on which the research on Advanced Tokamak scenarios will be built at JET in the forthcoming years. A significant upgrade of the NBI power up to 35MW/20s together with the addition of ~10-15MW of ICRH power, delivered by both conventional and ITER-like antennas, will result in power well in excess of 40MW to be available for times comparable to the resistive diffusion timescales [11]. This extra power opens the route on JET to optimisation of the actual fusion performance of Advanced Tokamak scenarios, and not just of the normalised parameters. Unlike previous JET experiments, where strong pressure peaking led to MHD limitations at relatively low values of β_N, the new data presented above indicate that a viable route towards sustainable high β_N operation may exist, with different q profiles, with or without ITBs, as long as strong pressure gradients are avoided. The choice of q profiles, as expected, is crucial for both confinement and stability at high b_N. Avoiding the $q_{min} = 2$ surface is, in general, advantageous for stability while the baseline confinement, without ITBs, is more interesting at q_{min}~1.5 and lower. For ITB scenarios weakly reversed/flat shear in a region covering at least half of the minor radius should be privileged. The additional ingredient of ELM mitigation via approach to QDNX equilibria could, also, be included in the scenario, although it is more difficult to see how such equilibria could be safely accommodated at high power in the all-metal ILW environment. Essential for operation with the ILW will also be the minimisation of NBI shine-through losses to the Innerwall. This additional constraint will require increasing density not only in the *prelude* phase, as already mentioned in section 4, but also during the high power phase, especially when considering extending the pulse length towards resistive diffusion timescales. The question of optimising fuelling in the high power phase of the AT scenarios has not been addressed yet in 2008.

Interpretative modelling of these discharges highlights the role of the various non-inductive components of the current profile and predictive modelling can, thus, be employed to optimise the scenario. Extrapolations carried out with the Cronos code point at possible ways to improve the current tailoring and non-inductive current drive capability by LHCD, not just by increasing the toroidal field or the injected LHCD power, but also by varying the launched spectrum from $n_{//}$=1.8 to $n_{//}$=2.3. As suggested by the predictive TRANSP modelling, it may also be interesting to increase the electron heating power to increase the bootstrap current driven by the electron temperature gradient. Adding electron heating by ICRH to the high ≤ no-ITB scenario almost doubles the electron temperature but, unfortunately, is accompanied by a large reduction of ion temperature, probably due to the destabilising effect of increasing T_e/T_i on the ITG threshold. Indeed, extending the high ≤ scenarios, with or without ITBs, to conditions of dominant, or at least significant, electron heating is in itself an extremely interesting task because it addresses some crucial and ITER-relevant issues like the confinement, or even the basic feasibility, of AT scenarios in an electron heating dominated plasma. In this context JET, with its unique mix of powerful electron and ion additional heating systems, without forgetting its non-inductive CD by LH system, is clearly in a privileged position to investigate experimentally these ITER-relevant issues in high fusion performance conditions.

ACKNOWLEDGEMENTS

The work was undertaken within the framework the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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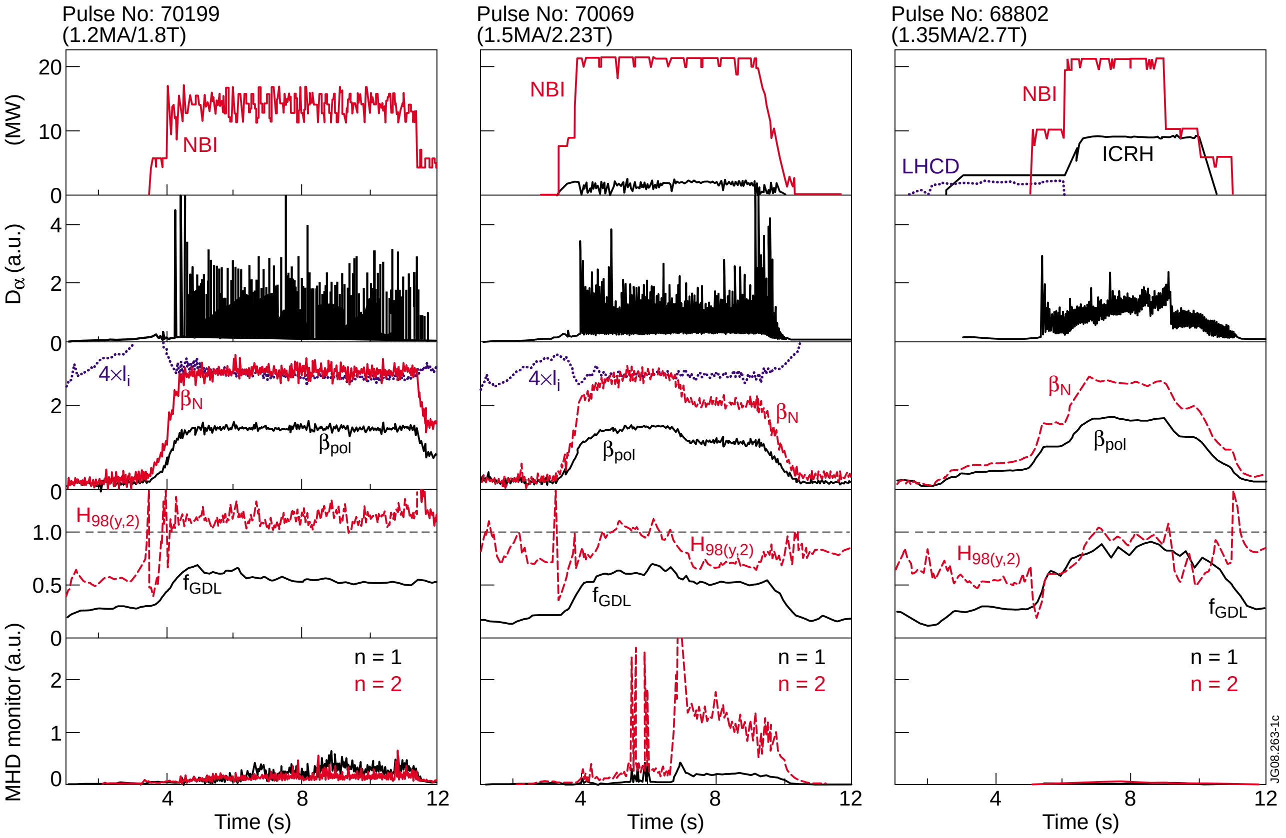

Figure 1: Overview of the 3 high ″ scenarios, no-ITB (Pulse No: 70199), ITB (Pulse No: 70069) and grassy-ELMs in Q_{DN} equilibrium (Pulse No: 68802).

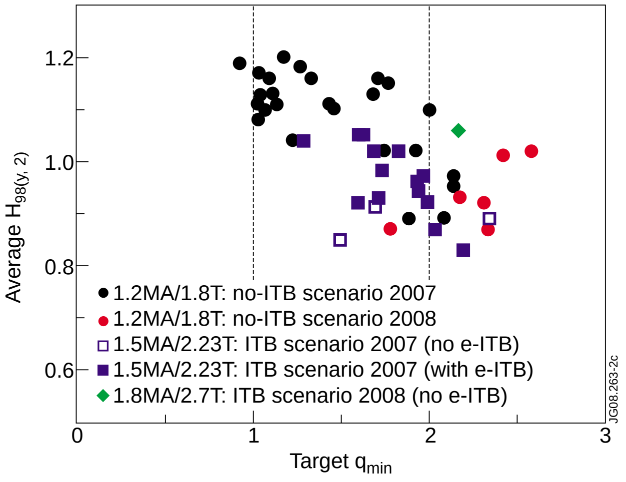

Figure 2: Normalised confinement $H_{IPB98(y,2)}$ versus target q_{min} for both ITB and no-ITB cases.

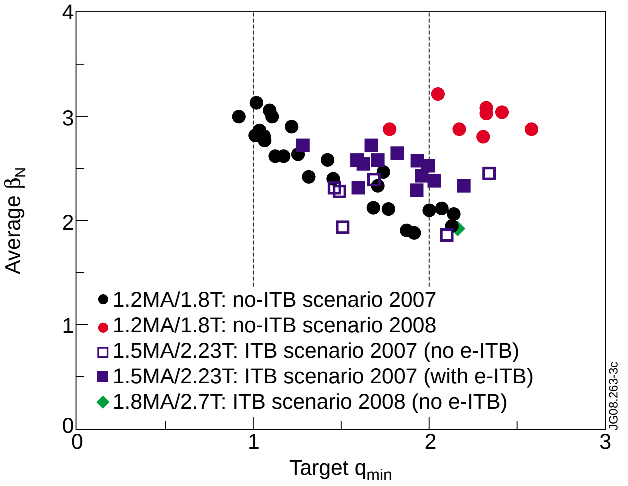

Figure 3: normalised β versus target q_{min} for both ITB and no-ITB cases.

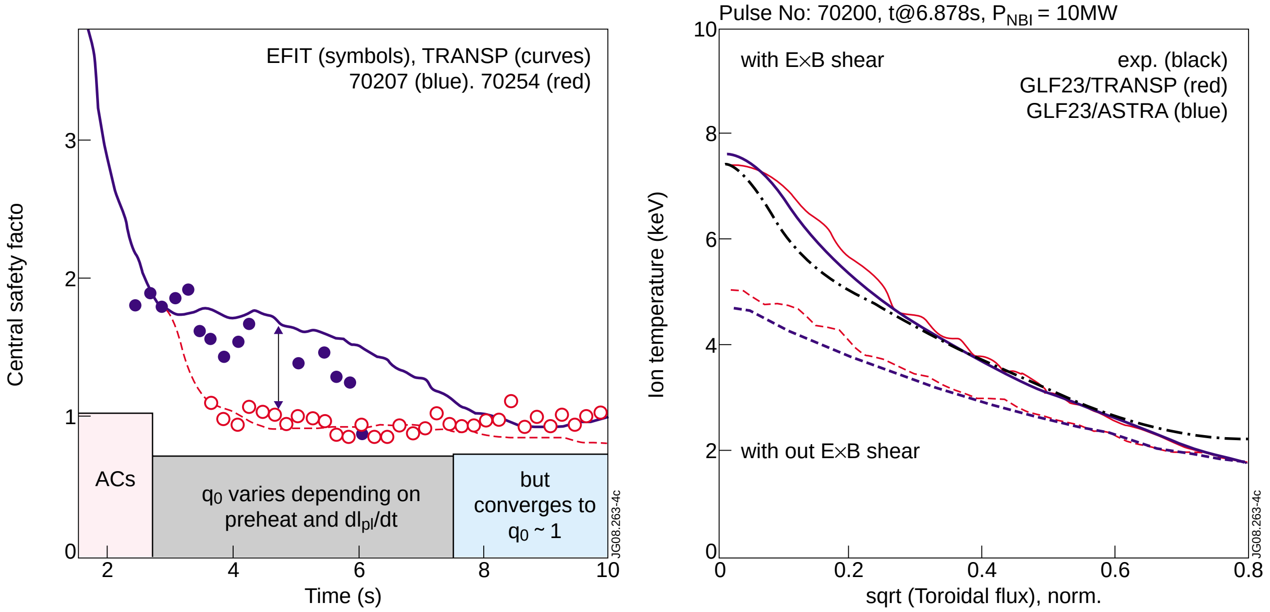

Figure 4 : Numerical modelling – a) TRANSP interpretative evolution of qo for early versus late–heating pulses and b) GLF23 simulation of ion temperature profiles, with & without E×B shear effect. AC denotes observation of Alfven Grand Cascades

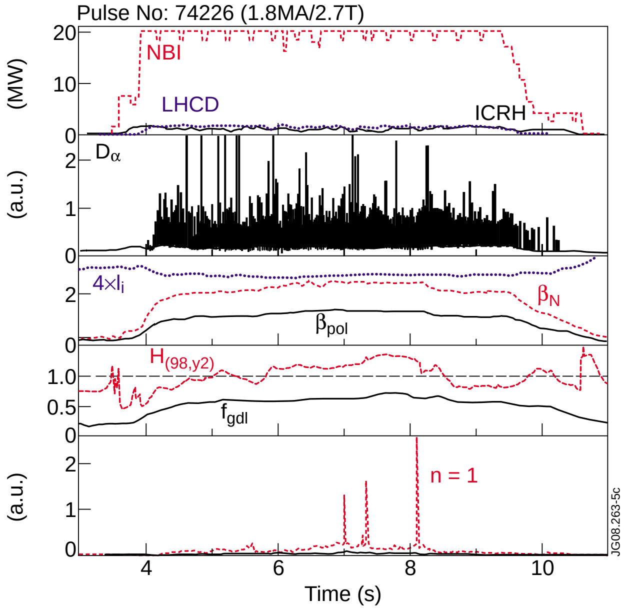

Figure 5: Overview of the ITB 2008 scenario

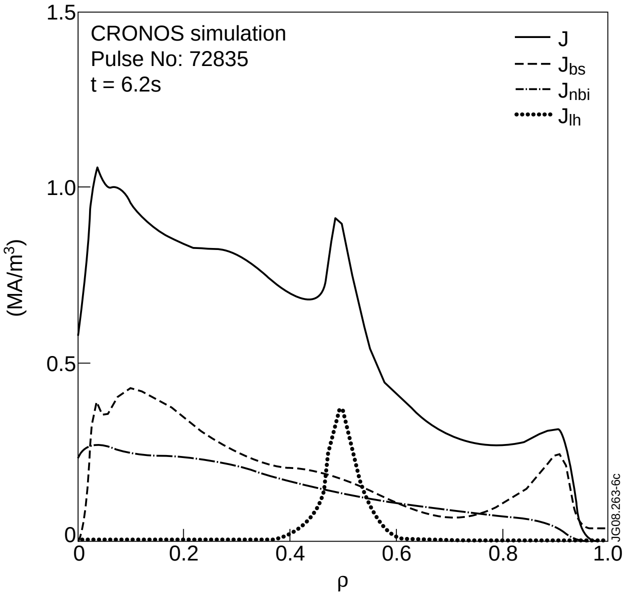

Figure 6: CRONOS simulation of total, Bootstrap, NBCD and LH current density profiles for Pulse No. 72835 t=6.2s