High Beta Plasmas and Internal Barrier Dynamics in JET Discharges with Optimised Shear

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Abstract. High β_N conditions have been sustained in JET discharges with Internal Transport Barrier by controlling edge conditions and pressure peaking. The behaviour of ideal and resistive MHD instabilities at high β_N has been studied as a function of pressure peaking. Duration of the high β_N phase was limited by interaction with the septum of the Gas Box divertor. ITB triggering and evolution are in good agreement with the condition for turbulence suppression by ExB shear flow.

1. Introduction

The realisation of advanced tokamak scenarios requires the simultaneous attainment of high confinement, high normalised beta and high bootstrap current fraction, i.e. high poloidal beta. Operation in the optimised shear and negative shear regimes has been successful in improving the confinement properties through the formation of Internal Transport Barriers (ITB). Plasmas with internal transport barriers can reach high normalised beta (β_N) and high poloidal beta (β_p), provided that the pressure profile is kept broad enough to avoid MHD instabilities [1]. High β_N values have been sustained for several confinement times in high performance JET discharges with ITB, as discussed in Section 2. The MHD behaviour of these plasmas will be presented in Section 3. Other factors that possibly limit the β_N values attained so far will be discussed in Section 4. ITB collapses that terminate the high performance phase without any MHD precursor are often observed; a possible cause of such collapses will be discussed in Section 5. The results of preliminary high β_p experiments will be presented in Section 6. The possible role played by ExB velocity shear in turbulence suppression and ITB evolution will be discussed in Section 7.

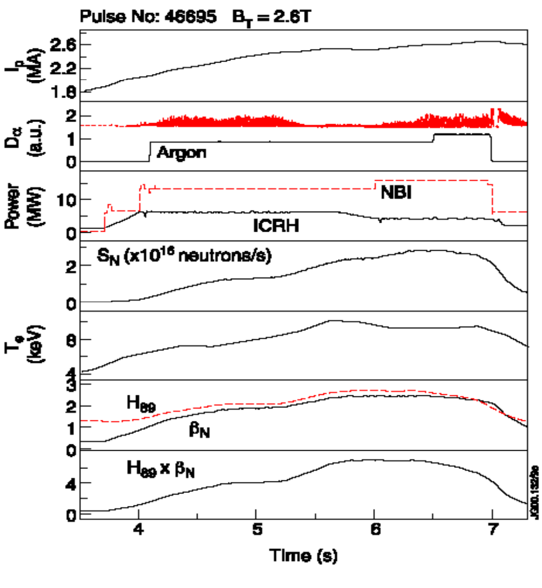

Fig. 1. Time traces of plasma current (I_p), D_α, argon puffing, heating waveforms, neutron rate (S_N), electron temperature (T_e), confinement enhancement (H_{89}), normalised beta β_N and quality parameter $H_{89}\times\beta_N$.

2. Optimised Shear High β_N Scenario with Steady ITB

Internal transport barriers are produced in JET with pre-heating and main heating during the current ramp-up phase of the discharge; in this way so-called optimised shear scenarios [2] are obtained, with flat or hollow core q-profile.

* See appendix to IAEA-CN-77/OV1/2, the JET Team (presented by C. Gormezano).

The neutral beam (NBI) and ion cyclotron resonance (ICRH) heating waveforms are adjusted to start the main heating having a q=2 surface in the plasma [3]. The power needed to form an ITB is several times larger than the H-mode power threshold [4]; for this reason the plasma tends to develop large ELMs which can destroy the ITB. In order to reduce the ELMs amplitude, the current ramp is continued during main heating and the divertor pumping is maximised by locating the separatrix strike points in the corners of the Gas Box divertor. Steady ITBs are only obtained when excessive peaking of the pressure profile is avoided (see Section 3.1); this is achieved by controlling the plasma edge with impurity injection (usually argon) and by adjusting the power waveforms to slowly build-up the plasma pressure [5]. In consequence of edge radiation the q=2 surface slowly broadens and wide ITBs are produced, allowing good confinement to be achieved. An example of a high beta steady pulse is shown in Fig. 1. The quality factor $H_{89} \times \beta_N$ has been maintained up to 7.3 for several confinement times. At B=3.4 T, fusion yield up to 10 MW of equivalent DT power has been achieved [6].

3. MHD activity at high β_N

Optimised shear discharges exhibity a variety of MHD phenomena. Some of them, namely kink modes and q=2 snakes, are clearly beta-limiting factors. Tearing modes play a modest role of local profile flattening, but it is important to understand if these modes can seed neoclassical tearing modes.

3.1. Hard and Soft MHD Limits

Plasmas with peaked pressure profile are subject to disruptions at β_N<2 (Fig. 2). The identification of precursors with n=1 toroidal mode, and the comparison with ideal MHD calculations including some wall stabilisation effects clearly show that disruptions are caused by pressure driven kink modes [7].

Disruptions have been avoided by controlling the pressure peaking, i.e. by operating at high β_N with a broader ITB radius and with an H-mode pressure pedestal. By slightly delaying the high power heating phase, disruption-free discharges with intermediate pressure peaking result. These discharges may develop m=2, n=1 helical structures (the so-called q=2 snakes) near the barrier foot [8]. During the growth of a snake there is an erosion of the ITB from the outside inwards; the enhanced heat loss from such erosion usually results in an ELM-free period and a termination of the good confinement phase by a large ELM that perturbs the ITB. The effect of snakes is minimised by argon injection, which reduces the amplitude of the ELM and then avoids perturbation of the ITB region.

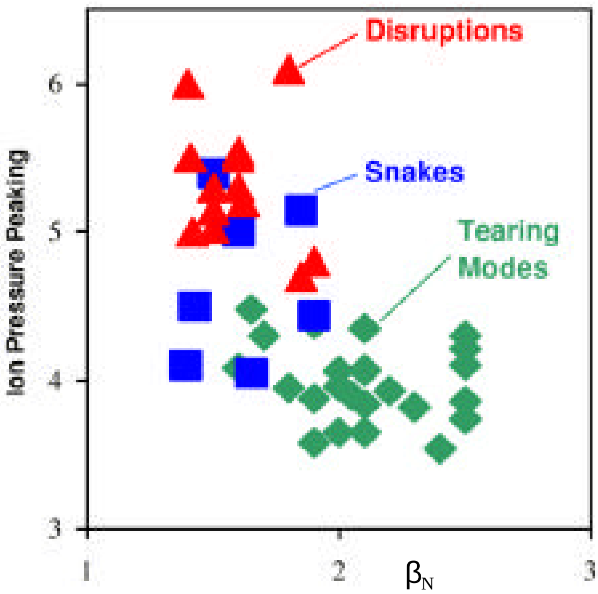

Fig.2. β_N values reached ad different values of the ion pressure peaking (peak to volume average ratio) and associated MHD phenomena.

Both disruptions and snakes can be avoided by further delaying the main heating, and by optimising argon puffing; in particular, ELMs size reduction through edge radiation is essential to achieve broad pressure profiles. In this way, a long high performance phase is obtained, in which the only significant MHD activity consists of tearing modes with n≥2 [9].

3.2. Tearing Modes

The observation of tearing modes in high β_N discharges raises the question of the possible role played by these modes in limiting the performance attained so far. Fig. 3 shows the comparison between two discharges with similar heating waveforms; both discharges attain β_N>2.5 in spite of a large difference in the modes amplitude. Moreover, the discharge with smaller MHD activity has the earlier ITB collapse, and in general no change in the modes is observed before ITB collapses. There is evidence that tearing modes locally weaken the pressure gradient, but this has small global effect as profiles are broad at high β_N.

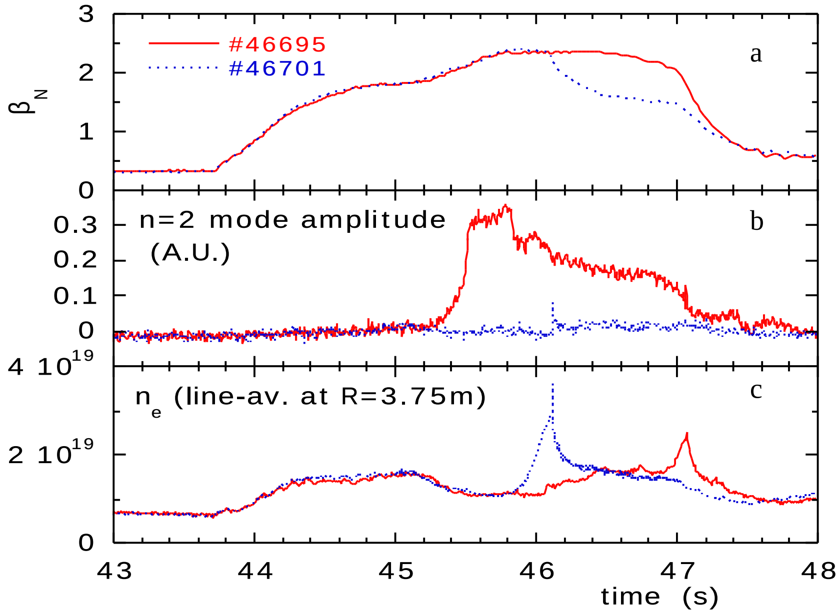

Fig.3. a) Time traces of normalised beta for two discharges with similar heating conditions. b) Qualitative indicator for the amplitude of modes with even n. c) Line average density at R=3.75 m, near the plasma edge.

The signals shown in Fig. 3b result from the superposition of all the modes with even toroidal number. Magnetic signals analysis performed for the discharge with stronger activity shows two main coherent modes, one at 42 kHz with toroidal number n=2 and another at 62 kHz with n=6. The poloidal (m) numbers were inferred from temperature oscillations as measured by a multichannel ECE radiometer with off-equatorial line of sight, i.e. with each channel sampling a different poloidal angle. Cross-phase analysis gives m=3 for the n=2 mode and m=9 for the n=6 mode, i.e. both modes resonate with the same rational q=1.5. The analysis of ECE oscillations also gives the island position, which is identified as the radius where the phase changes by π, and the radial displacement profile (Fig. 4). The island positions on the outer midplane are R=3.23 m for the m/n=3/2 mode and R=3.58 m for the m/n=9/6 mode. This indicates that there is a pair of q=1.5 surfaces, i.e. a reversed shear profile. The equilibrium reconstruction gives a monotonic q-profile, but the uncertainty of such

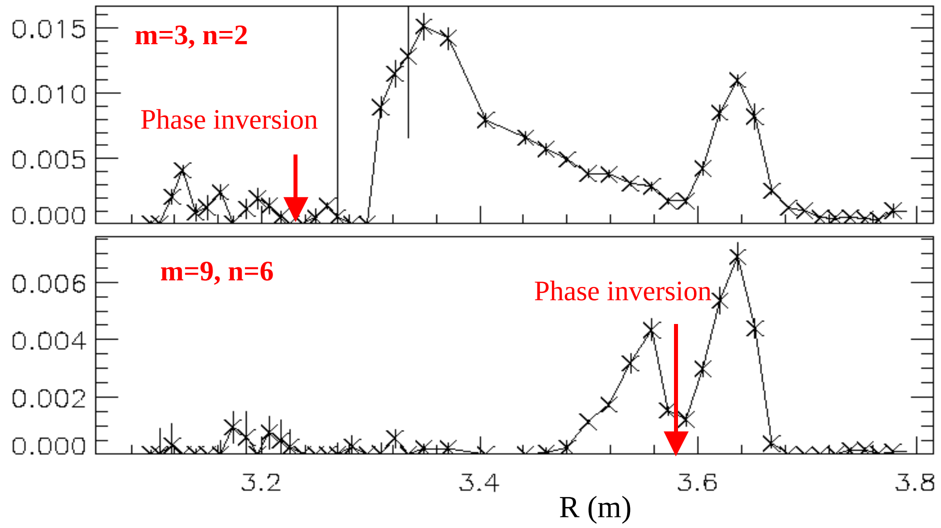

Fig. 4. Radial displacement (in meters) induced by tearing modes in pulse #46695 as a function of major radius coordinate. As both modes have m/n=1.5, a pair of q=1.5 surfaces is expected to be localises at the positions marked by arrows. Data refer to the time interval 46.26÷46.39 s.

reconstruction in the absence of motional Stark effect data for this pulse does not allow to exclude the presence of a central region with negative magnetic shear.

Inspection of the displacement profile (Fig. 4) reveals that the 3/2 mode has a very unusual shape, very broad and asymmetric, probably due to the presence of a very low shear region. The 9/6 mode has a more usual tearing structure, with localised and antisymmetric displacement. The island width as estimated from the displacement profile is w≈5 cm. Such island size should be enough to give a significant bootstrap current perturbation, but the application of simple estimates derived in neoclassical tearing mode theory is not sthaightforward, due to the non-standard shape of the current profile in the optimised shear regime. A progress in this field is needed in order to predict the behaviour of tearing modes at higher β_N values.

4. Limits on the β_N Value

In order to get insight in the nature of the normalised beta saturation encountered so far (β_N <2.6), two databases have been set-up for optimised shear discharges at magnetic field values 2.6 T and 3.4 T respectively. All the selected discharges are not affected by kink modes or snakes, have an ITB triggered when a q=2 surface exists, and show a plateau of normalised beta. Within each database plasma current, density and geometric parameters are nearly constant. The confinement enhancement with respect to the ITER89-P scaling law can then be directly evaluated in a diagram representing β_N versus the heating power. Most of the data, including high power ones, are in line with H_{89}≈2.5, as shown in Fig. 5, where the experimental data are plotted together with two lines corresponding to H_{89}=2 H_{89}=3. Low power data fall below H_{89}=2, possibly due to closeness to threshold conditions, the power needed to trigger an ITB being around 15 MW at B=2.6T [4]. High confinement data at intermediate power correspond to plasmas with very small ELM activity and strong gradients in the outer plasma region (the discharge shown in Fig. 1 belongs to this group). Two points

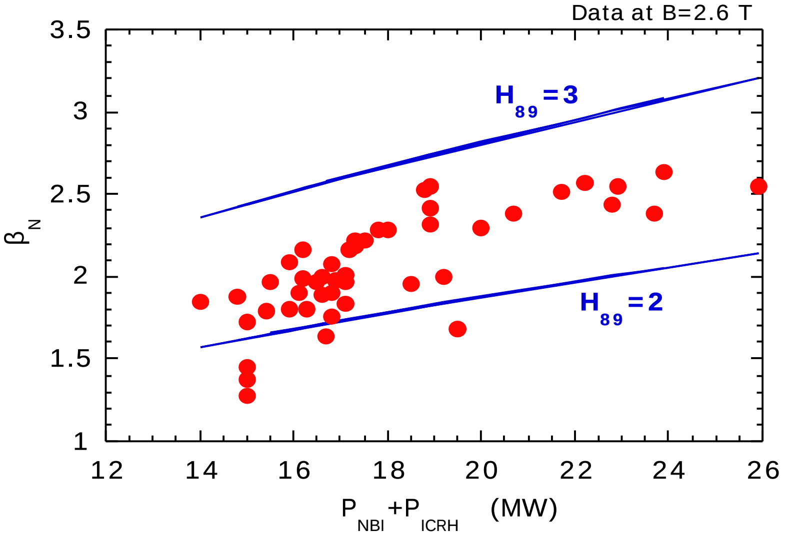

Fig. 5. Normalised beta as a function of the heating power. Dots represent experimental data from the B=2.6 T database; lines correspond to fixed values of the confinement enhancement factor.

at P>23 MW that fall below H_{89}=2.3 result from discharges with special edge conditions (septum avoidance, see Section 5). The observation of good confinement conditions at the maximum power indicates that the β_N values achieved so far with broad pressure profiles are transport limited.

5. Limits on Duration at High β_N

The steady phase at high performance is often interrupted before the end of the main heating phase by some event that does not correspond to any change in the MHD activity. The duration of the steady phase, defined as the period with β_N exceeding 90% of the top value,

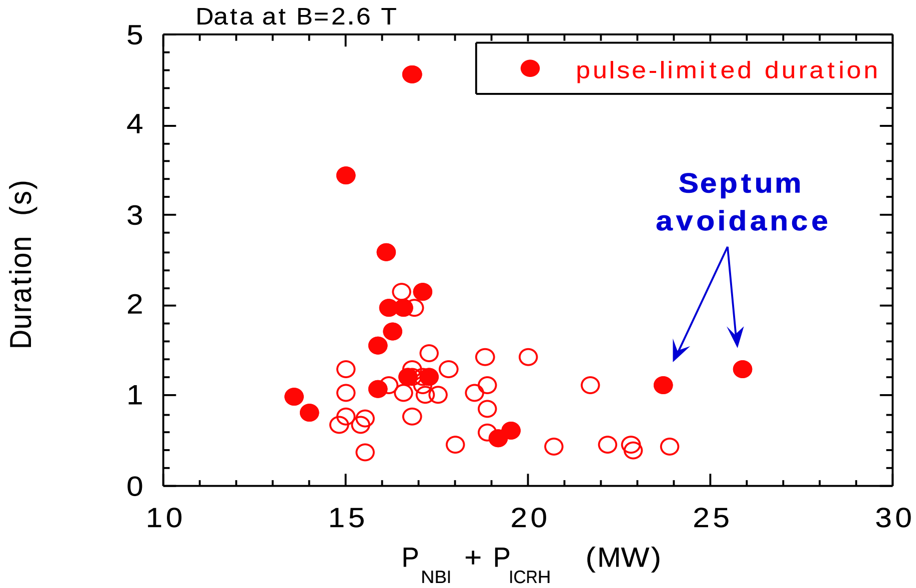

Fig. 6. Duration of the high β_N phase versus heating power. Open circles represent cases with the steady phase terminated by an ITB collapse.

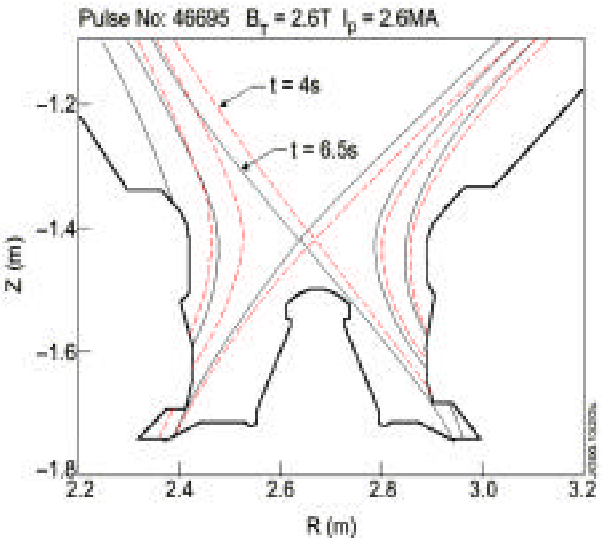

Fig. 7. Magnetic surfaces in the divertor region. The normalised beta is β_N=0.84 at t=4 s and β_N =2.52 at t=6.5 s, when septum interaction occurs.

clearly decreases at high power and high β_N (Fig. 6). ITB collapses are generally preceded by an increase of density at the plasma periphery (Fig. 3c), indicating that some edge phenomenon is taking place. A possible explanation can be found from the inspection of magnetic surfaces in the divertor region: with the constraint of placing the strike points in the divertor corners, at high β_N the separatrix comes very close to the septum part of the Gas Box divertor (Fig. 7). In order to assess the effects on the plasma associated with such an interaction, discharges have been developed in which the magnetic configuration has been modified by moving the strike points on the divertor vertical plates once the ITB was triggered. Fig. 8 shows the septum avidance discharge together with a reference discharge with strike points in the divertor corners. In the reference discharge, strong ELMs appear after a period of edge density increase and provoke the ITB collapse. In the discharge with septum avoidance, the edge density is higher, probably due to lower pumping, but remains at a steady value, allowing the ITB to be maintained. Energy confinement is slightly reduced in discharges with septum avoidance, but heating pulse limited duration at the maximum power levels is obtained (Fig. 6).

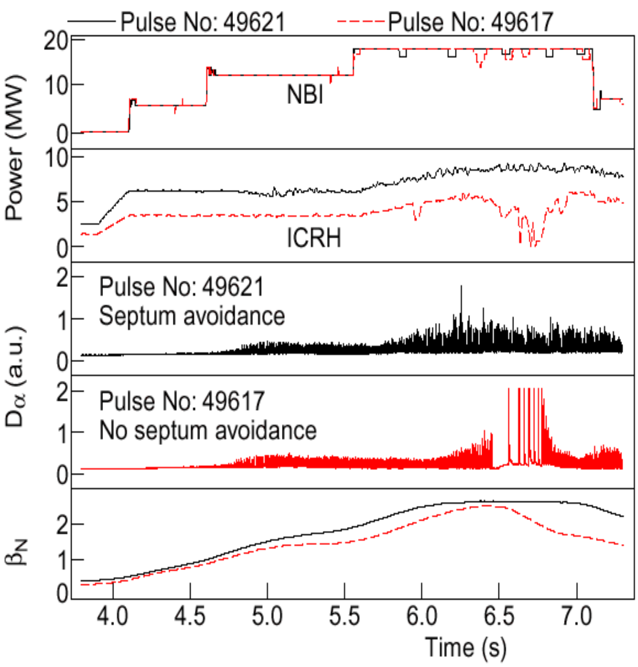

Fig. 8. Time traces for pulses 49617 and 49621, with and without septum interaction.

6. High β_p Plasmas

Preliminary optimised shear experiments have been performed at plasma current I_p=1.5 MA and magnetic field B=2.6 T, corresponding to $q_{95}\approx6$. This relatively high q_{95} value was chosen in order to increase β_p values without requiring too high β_N values; in these conditions, $\beta_N=1.6\beta_p$. The magnetic field was kept low in order to have a threshold power for ITB formation well below the available heating power. A careful plasma configuration optimisation was necessary in order to avoid spurious plasma-wall interaction, as at high β_p the problem of septum interaction worsens. In addition, due to the low flat-top current, the current ramp duration was short and then countinued ramping during the main heating could not be applied. Despite these difficulties, a value of β_p =1.6 was maintained for several confinement times. Transport analysis gives 35% bootstrap current fraction and 60% total non-inductive fraction. There is a good alignment between non-inductive and total current profiles.

7. Analysis of ExB Flow Shearing Rate During ITB Evolution

The formation of internal transport barriers has been found in agreement with theories based on turbulence suppression by ExB shear flow [10]. Turbulence suppression is expected to be effective when the ExB shearing rate (ω_{ExB}) exceeds the growth rate of ion temperature gradient driven modes (γ_{ITG}). The shearing rate has to be calculated from the radial force balance of a single impurity, including flows and pressure gradient. As no direct measurements were available for the poloidal flow velocity, this quantity was calculated from the parallel momentum balance equation in the framework of neoclassical theory [11]. A simple model expression was used for the ITG growth rate [11]. Both triggering and radial expansion of the ITB were found in good agreement with the condition for turbulence suppression ($\omega_{ExB}>\gamma_{ITG}$). The main contribution to the feedback mechanism leading to the ITB onset was given by toroidal rotation. Fig. 9 shows an example of ITB evolution during power step-down: the shearing rate takes several confinement times to drop below the ITG growth rate, and the ITB contraction occurs on the same time scale, as shown in Fig. 10.

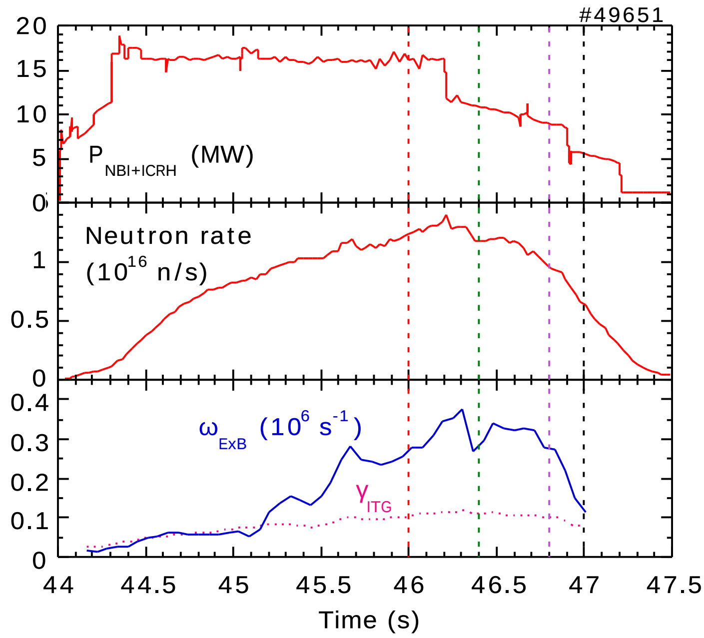

Fig. 9. Time evolutionof total power, neutron rate, shearing rate ω_{ExB} and turbulence growth rate γ_{ITG}. Both ω_{ExB} and γ_{ITG} are evaluated at R=3.35 m. The ITB contracts between t=46.8 and t=47 s.

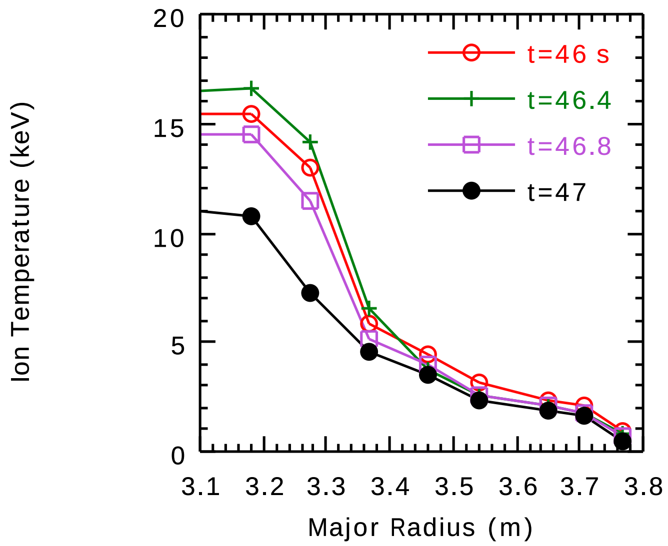

Fig. 10. Ion temperature profiles corresponding to times marked by vertical bars in Fig. 9.

8. Final Remarks

Significant prograss has been done in the development of integrated scenarios with high beta, Internal Transport Barrier and steady conditions. The quality factor $H_{89}\times\beta_N$ has reached steady values up to 7.3 in conditions of high neutron yield. Steady conditions have been achieved by controlling edge conditions and pressure peaking. The beta values achieved so far ($\beta_N \leq 2.6$) have been limited by the available heating power. The duration of the steady phase at high β_N was limited by plasma interaction with the septum of the Gas Box divertor.

The role of turbulence stabilisation by ExB velocity shear has been analysed in plasmas with Internal Transport Barrier. Both the time of ITB onset and the ITB radial extent coincide with the ExB shearing rate exceeding the linear growth rate of Ion Temperature Gradient driven turbulence. Also the ITB contraction following power step-down is in agreement with the same condition.

In the exploration of MHD boundaries, disruptions or q=2 snakes at $\beta_N<2$ have been found with peaked pressure profiles. Plasmas with broad pressure profile (the peaking factor ranging between 3.5 and 4.5) show tearing modes with $n\geq 2$. Tearing modes co-exist with steady ITBs, and cause at most some local profile flattening; nevertheless, the stability of these modes could be a crucial element in the progress to higher β_N.

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