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High Beta Plasmas with Internal Transport Barriers in JET

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Introduction.

The advanced tokomak scenarios might allow more effective reactor operation than the ITER ELMy H mode reference scenario. In addition to common requirements with the reference ITER scenario, advanced scenarios require operation with simultaneously: high confinement, high-normalised beta and high bootstrap current operation, i.e. high poloidal beta. So far, some of these conditions have been achieved in plasmas with Internal Transport Barriers (ITB) where turbulence is at least partly stabilised either at the location of the ITB or within the ITB. This paper will describe some development of high confinement, high beta plasmas with ITBs on JET.

Optimised Shear Scenario with Steady ITBs.

In JET ITBs are produced in the so-called optimised shear scenarios [1] with pre-heating and the main heating during the current ramp-up phase of the plasma. The timing of the main heating phase is adjusted to have a rational q surface, generally q=2, in the plasma [2]. In order to delay the triggering of an H-mode (the applied power being generally higher than the L to H-mode power threshold) the strike points of the last closed magnetic surface (LCMS) are located in the corner of the Gas Box divertor, in order to maximise the pumping. Steady ITBs are only produced when excessive peaking of the pressure profile is avoided [3],[4] which might otherwise lead to disruptive external kink modes or to creation of snakes [5]. This is achieved by controlling the plasma edge with impurity injection (argon or krypton) and by adjusting the power waveforms to slowly build-up the plasma pressure. The q=2 surface slowly increases and large ITBs are produced, allowing good confinement to be achieved. These ITBs being rather wide are very sensitive to the radial energy losses occurring during large ELMs [6],[7].

An example of a high beta steady pulse is shown in Figure1. The product $H_{89}x\beta_N$, the usual reference quality factor for advanced scenarios, have been maintained up to 7.3 for several confinement times. At 3.4T, fusion yield up to 10MW of equivalent DT power has been achieved with confinement and beta significantly exceeding the corresponding values obtained with an ELMy H-mode plasmas produced at similar magnetic field and plasma current [8]. It is to be noted that some event, especially at high beta, often interrupts the high

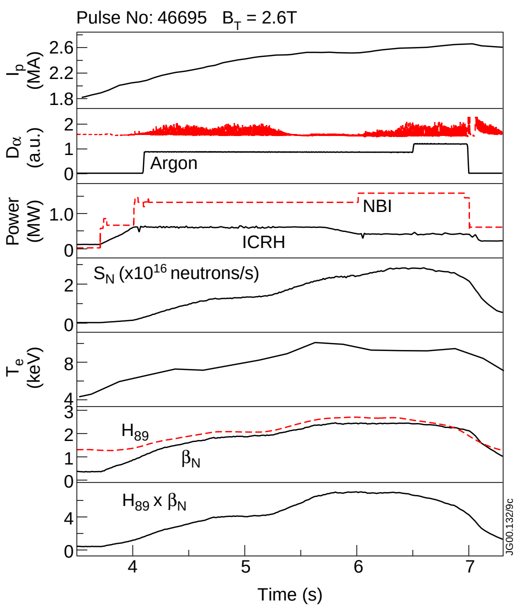

Fig.1: Time traces of typical signals for pulse 46695 (2.6T)

performance phase before the end of the additional heating power phase which does not corresponds to any MHD activity and induces a neutron rollover. A possible explanation is linked to interaction with the septum part of the Gas Box divertor

Interaction with the Septum.

The LCMS came very close to the septum when beta increases (Fig.2). In OS plasmas at relatively low betas produced when the LCMS is set very close to the septum, large ELMs are triggered, likely to be due to the gas release during the interaction with the septum. As a result ELMs change from very grassy to large ELMs (which seem like type I ELMs). This might be due from changing edge plasma conditions with high T_e and low n_e to edge plasmas with low T_e and high n_e.

Once the ITB is triggered, strike points are moved up on the divertor vertical target plates in order to avoid interference with the septum. The triggering of large ELMs can only be avoided when the clearance to the septum is sufficiently large. As a result plasmas with ITBs can be maintained without changes in the edge behaviour (Fig.3). When the septum is avoided, the edge density increases, probably due to lower pumping, but remains at a steady value allowing ITBs to be maintained. The ITBs are rather wide (about r/a~ 0.7) and the electron temperature outside the ITB is quite high. As a result, the pressure gradient in the ITB area tends to weaken. A weakening of the ITB can also be observed at a radius of about 3.5m. This can be linked to tearing modes and will be discussed later.

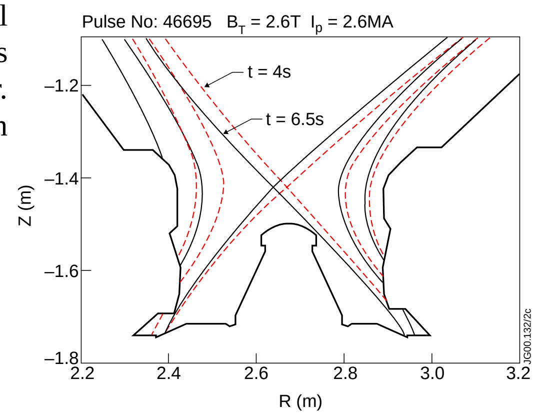

Fig.2: Last closed magnetic surfaces for a high normalised beta pulse at B_T=2.6T (pulse 46695) during the low and the high beta phases of the discharges (from EFIT)

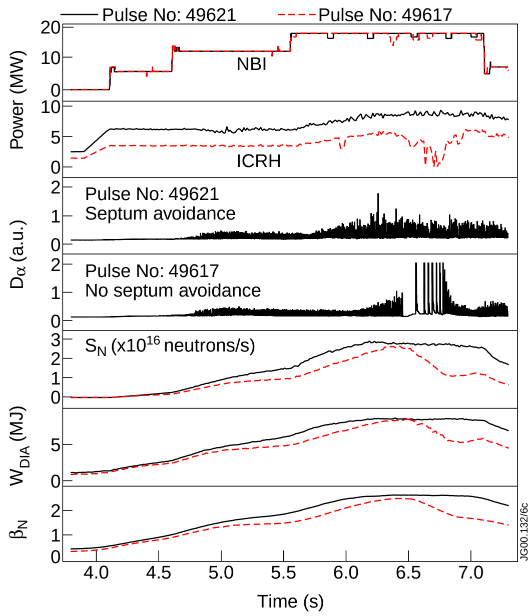

Fig.3: Time evolution of typical traces for pulses 49617 and 49621 with and without septum interaction.

High Normalised Beta Plasmas.

Two sets of databases have been set-up for 2.6 and 3.4T, for which a large number of pulses exist. Selected pulses are disruption free, do not show snakes, have an ITB triggered when a q=2 magnetic surface exist, show a steady value of β_N and total power is maintained more or less constant for about 0.5sec before the steady phase of β_N. Argon seeding at the edge has been used for most of the pulses in the database. ITBs so produced are wide and the pressure peaking is moderate. The dependence of β_N versus additional power is shown on Fig.4. In spite of data scattering due to varying conditions for OS, a weak saturation is clearly observed. To be noted that β_N achieved with septum avoidance technique are slightly below the trend of the other data. A similar plot of normalised beta versus additional power for a magnetic field of 3.4 T is shown in Fig.5. Here also some scatter of the data is observed but there is no clear indication of beta saturation. Power in excess of the available power: 18 MW of NBI and 10 MW of ICRH is really necessary to assess the beta limit.

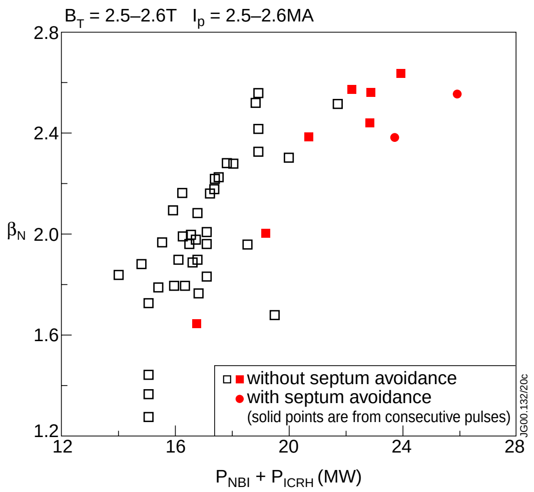

Fig.4: Normalised beta versus additional heating power for B_T = 2.6T. Open circles correspond to data achieved with septum avoidance technique. Solid points correspond to a set of consecutive pulses with very similar conditions but for septum avoidance.

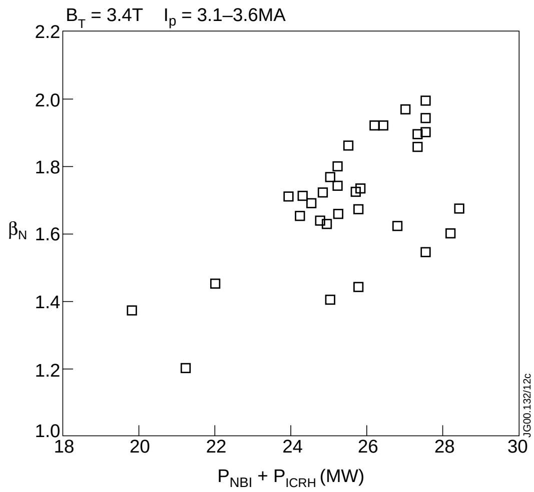

Fig.5: Normalised beta versus additional heating power for B_T = 3.4T.

For the data discussed here, only soft events, such as tearing modes, are present. Spectrograms of MHD activity show the presence of high n tearing modes, including n=2, 3 and 4 modes with no indication of a precursor for ITB collapses when large ELMs are triggered. The phase inverts at about 3.38 m indicating an island of about 2 cm width. This mode also couples to another mode near 3.6m with only a 0.5cm displacement. This mode may be the cause of the weakening of the electron ITB. Modes with even higher n number have been observed with n up to 8 and frequencies up to 100 kHz. These modes might produce a slight local weakening of the transport barrier but they are no indications that they are causing the neutron rollover.

The neo-classical nature of these modes is debatable. An MHD analysis has been made of pulse 46695 [9]. Modes (n=2 and n=6) grow out of the noise without any obvious trigger event, and the n=2 mode amplitude seems to be well correlated with beta. This might point out towards a neo-classical nature for this mode. But there is no inversion in phase (from ECE channels) for this n=2 mode, therefore indicating kink mode type behaviour. So, the nature and drive of these modes remains an issue for further study. Irrespective of their origin these modes seems to affect the quality of the ITB and therefore the achievable beta [10] (but do not lead to beta saturation).

High Poloidal Beta Plasmas.

Increasing the relative value of β_p implies operating at lower plasma current. With the same current ramp up rate, the main heating then takes place in the plateau phase of the current. Therefore, the problem is not only to develop a configuration avoiding septum interaction at higher Shafranov shift, but also to prevent the appearance of too strong ELMs which are likely to be triggered without current ramp-up and with a power higher than the L to H-mode power threshold. By controlling the plasma shape with the outermost divertor coils, a large interaction with the septum can be avoided but the LCMS is still rather close to the septum. Good ITBs are formed (Fig.6) but a significant ELM activity takes place with some temporary collapses of the barrier. Some steady high beta conditions were established in spite of the ELM activity. Significant steady neutron yield and a ratio β_N / β_p of about 1.6 have been established.

From a preliminary TRANSP analysis, it has been estimated that 60% of the plasma current is non-inductively driven, the bootstrap fraction being 35%. The remaining non-inductive current is due to neutral beam current drive. It appears that the total non-inductive current is rather well aligned with the total current.

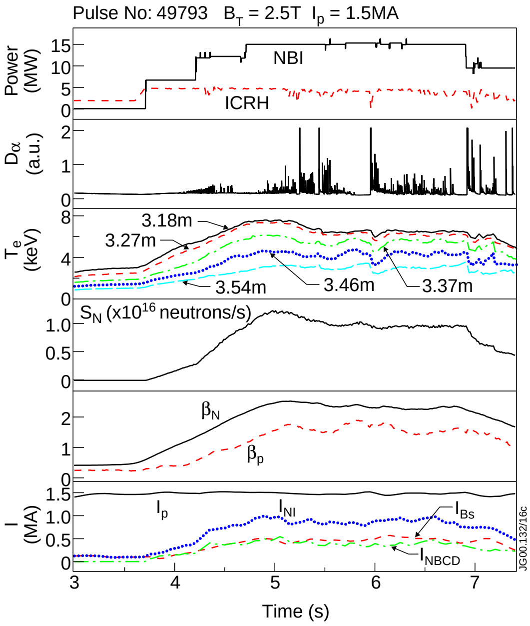

Fig.6: Time traces for a typical high β_p pulse (49793)

Conclusions.

Steady plasmas with wide ITBs, high confinement high-normalised beta (H_{89}x β_N up to 7.3) have been achieved with optimised shear plasmas by controlling edge conditions and pressure peaking. Interaction with the septum is likely to induce large ELMs and a subsequent collapse of the ITB.

By moving up the strike points on the vertical plates once the ITB is formed, septum avoidance techniques have been developed and steady high-normalised beta plasmas have been obtained. But these plasmas with raised strike points have a somewhat lower β_N, probably due to too high an edge pressure caused by the lack of pumping. A real long-term solution appears to be the removal of the septum. High n MHD modes seem to locally affect the ITB but do not cause a saturation of $\beta_{N.}$. Their neo-classical nature is debatable and should be the subject of further study. Total present available power (28 MW) is not sufficient to really assess β_N limits in the presently developed OS scenarios in JET. High β_p scenarios with ITBs have been developed at lower plasma current but so far septum interference cannot be avoided. Non-inductive plasma current up to 60% of the total current including with 35% of bootstrap current and well aligned with I_p have been achieved. These data are very encouraging for the future of advanced scenarios.

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