Role of Magnetic Configuration and Heating Power in ITB Formation in JET.

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Abstract. An extensive database of more than 250 OS plasmas with different power level, heating scheme and current profile control has been formed and used to determine the conditions for ITB formation. The results of the database analysis are presented which confirm the crucial role of excess power and other key plasma parameters. JET experiments have also shown that the magnetic configuration, particularly the q-profile and magnetic shear, also play an important role in the ITB formation. Different scenarios, which have been used on JET to tailor the q-profile, will be discussed. Results of the predictive modelling of a series of JET OS plasmas are presented alongside experimental results.

1. Introduction

Optimise Shear (OS) scenario is considered as one of perspective scenarios for ITER-type tokamak-reactor. The JET OS regime exhibits, amongst other conditions, a heating power threshold for the formation of a good quality Internal Transport Barrier (ITB). Some results of the power threshold dependence on toroidal magnetic field have been reported previously [1]. An extensive database of more than 250 OS plasmas with different power levels, heating schemes and current profile control methods has been formed and used to determine the conditions for ITB formation. The results of the database analysis will be presented which confirm the important role of both the heating power and of the magnetic configuration, particularly the q-profile and magnetic shear, for the ITB formation.

2. Role of Heating Power in the ITB Formation

It has been reported previously [1], like in many other Tokamaks, that the heating power plays a crucial role in an Internal Transport Barrier (ITB) formation in JET. In particular, it was shown that power threshold for the ITB formation scales almost linearly with toroidal magnetic field in discharges without negative magnetic shear (though the q-profile was not measured systematically). The claim that such a linear dependence $P_{th} \propto B_T$ is valid for discharges without negative shear comes from a few measurements and numerical simulations of the q-profile evolution for selected pulses. The extrapolation of this statement onto the entire database is supported by an apparent similarity of the heating waveform for all discharges in the database. In this respect 1999 campaign allowed us to extend the range of the toroidal magnetic field and to improve the statistics of the scan. The result of this study is shown in Figure 1 which confirms the trend.

3. Role of Magnetic Configuration

The 1999 campaign also addressed the role of the magnetic configuration in the ITB formation. Experimentally JET has exploited two different scenarios to tailor the q-profile. The first one uses low power ICRH preheating simultaneously with current ramp-up. By varying the starting time of the main heating, the emergence of the ITB could be associated with the q-profile evolution. Equilibrium reconstruction using polarimetry and MSE data, has shown that access power can be noticeably reduced in cases when the central q value crossed low order rational magnetic surface, particularly the q=2 surface [2]. In these cases the ITB emerges close to the low order rational magnetic surface. This effect (shown in Figure 2) tends to disappear when the heating power exceeds the threshold value.

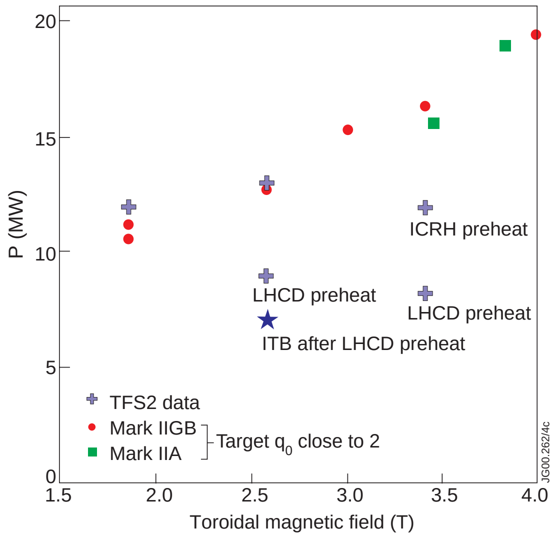

Fig.1: Power threshold of the ITB as a function of the toroidal magnetic field (TFS2 data comes from 2000 campaign)

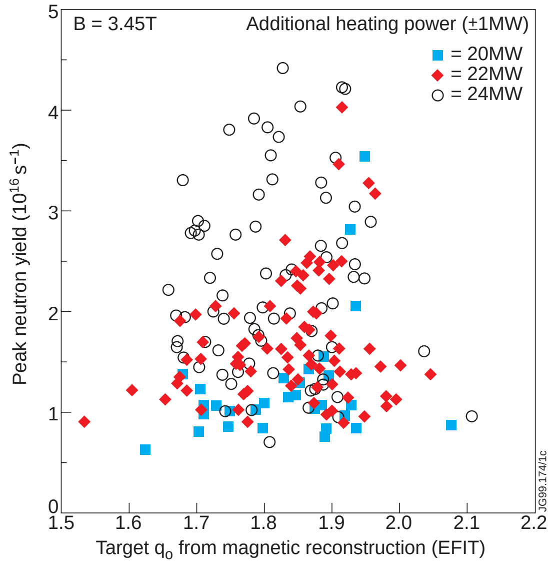

Fig.2: Peak neutron yield as a function of q_o for three levels of heating power

The second technique uses Lower Hybrid Heating/Current Drive (LHCD) which is applied during the current ramp up phase, prior to the main heating phase. Analysis shows that LHCD plays a dual role. First it heats electrons and therefore helps to prepare flat or hollow Ohmic current during current ramp up and freezes the current profile until main heating pulse. The LH system also provides plasma current drive, which may also contribute to the inversion of the q-profile. Experimental results from both the 1999 and 2000 campaign show that an early application of LHCD can significantly reduce the power threshold (see Fig.1). It was also found that an early application of the off-axis ICRH heating leads to a similar, although less pronounced effect (see Fig.1). Indeed Figure 3 shows that an early application of LHCD results in the formation of the ITB even before application of the full NBI and ICRH power. This result confirms the idea that negative magnetic shear can induce an ITB even without strong plasma rotation.

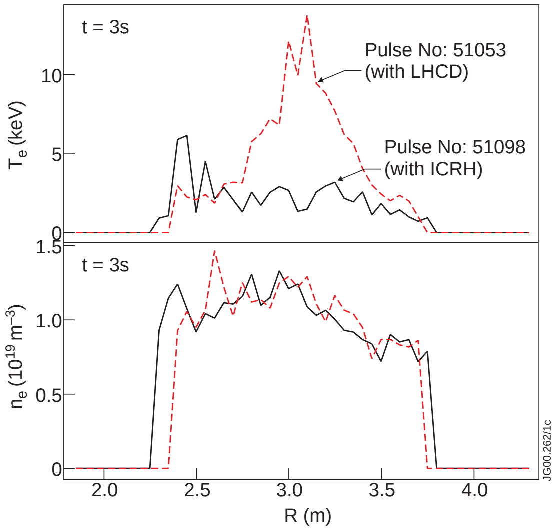

Fig.3: Electron temperature and density for two otherwise similar shots with either LHCD (dashed) or ICRH (solid) preheating

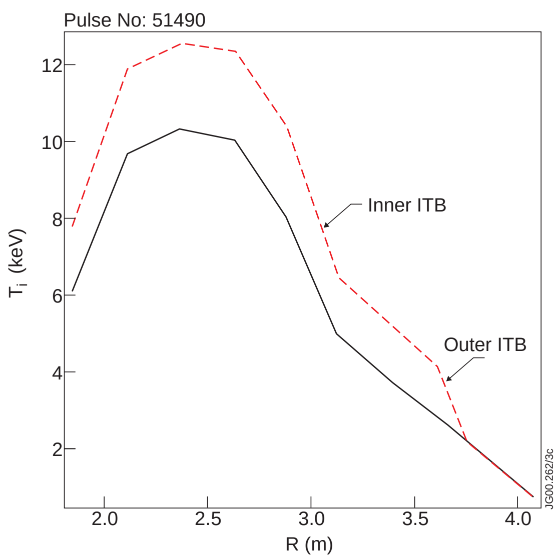

Fig.3: Ion Temperature before (solid) and after (dashed) formation of ITB

Probably the most intriguing result of an early application of LHCD was that such a scheme could lead to the formation of two ITBs (see Fig.4). The inner one, which remains almost stationary, is seen most strongly on the ion temperature and is probably confined within the negative magnetic shear region. The outer ITB is seen on both electron and ion temperatures, as well as on the electron density. It expands radially, which is characteristic of a single ITB, formed in discharges without LHCD by applying access power

4. Transport Analysis and Predictive Modelling

Present theory contains at least two main ingredients, which could influence ITB formation. The first one is strong shear in plasma rotation, which should suppress drift type of plasma turbulence if the shearing rate ω_{ExB} exceeds the maximum turbulence growth rate $\gamma_{\max}$ [3]:

$$\omega_{ExB} \approx \frac{(RB_\theta)^2}{B} \times \frac{\partial}{\partial\psi}\left[\frac{1}{RB_\theta}\left(\frac{\nabla n_i T_i}{en_i} - V_\theta B_\phi + V_\phi B_\theta\right)\right] \geq \gamma_{max} \propto \frac{V_{i,th}}{\sqrt{R\cdot(L_n + L_T)}} \qquad (1)$$

Since the poloidal plasma rotation V_θ is controlled by neo-classical viscosity, it has a structure similar to that of the pressure gradient. We can therefore conclude, that the first two terms on the right hand side (1) are controlled by the heating power and by the particle source. On the other hand it is mainly a torque, applied by tangential NBI injection, which controls the toroidal rotation V_ϕ . It is worth noting that the ratio of the pressure gradient term in (1) over toroidal rotation scales as

$$\frac{|\nabla n_i T_i|}{en_i} \Big/ V_\phi B_\theta \propto \rho_{\theta beam} \big/ L_{nT} \,,$$

where $\rho_{\theta beam}$ is the poloidal Larmor radius of beams' ion. This formula suggests that the relative role of toroidal rotation will rise with the tokamak size. Following formula (1) we can expect the ITB appearance would require certain access power or/and central fuelling. A very simple dimensionless analysis shows that threshold power should scale as $P_{th} \propto B^\alpha n^\beta$, where $\alpha \geq 1$, $\beta \geq 1$.

The second important ingredient of the ITB formation is the magnetic configuration. The role of the low/negative magnetic shear ranges from stabilisation of some ballooning-type instabilities by negative shear to the decoupling of toroidally linked vortices by small shear. Since a region with a negative magnetic shear could be obtained by using current ramp-up together with moderate heating and/or current drive, one might expect a very low power threshold for this kind of ITB.

To assess the relative role of ω_{ExB} shearing rate and that of the magnetic shear s, 13 ITB JET pulses in H-mode, 3 pulses with L-mode edge and 3 pulses where conditions for sustained ITBs were not satisfied were selected. The plasma parameter range of the analysed pulses is very wide, i.e. B_ϕ varies between 1.8-4.0 T, the input power in the range 10-30 MW and the diamagnetic energy in the range 3-12 MJ. The magnetic shear has been calculated by transport code JETTO with the assumption of the neo-classical electrical conductivity and all other parameters taken from experiment. The neo-classical formula was used to calculate the poloidal ions velocity. All relevant plasma parameters have been taken 50msec before and after ITB formation close to a position of the ITB footpoint (or potential footpoint). Figure 5 shows the positions of the normalised shearing rate $\omega_{ExB}/\gamma_{ITG}$ and of magnetic shear *s* for selected discharges.

One can observe a systematic separation of the discharges before and after the ITB formation. Regression analysis gives the following form for the separation line:

$$s = 1.47\,\frac{\omega_{ExB}}{\gamma_{ITG}} + 0.14 \qquad (2)$$

with the standard deviation for the slope and intercept terms 0.13 and 0.031 respectively. We therefore can conclude that both the shearing rate and small/negative magnetic shear contribute to the formation of the ITB.

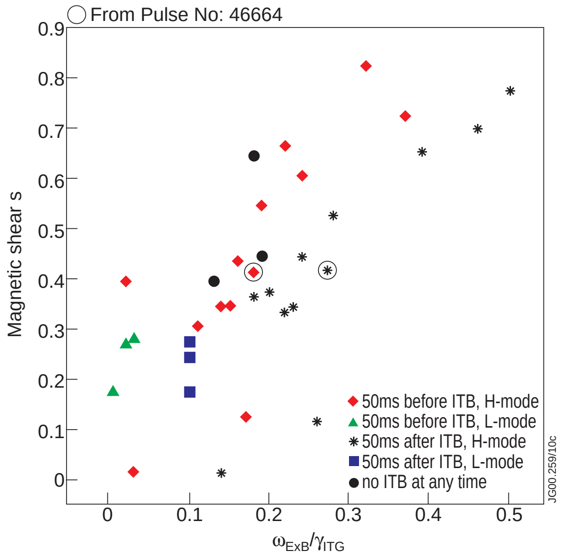

Fig.5: Magnetic shear (simulated) and Ω (measured) at the ITB location

Further assessment of the applicability of condition (2) has been done by using it in a predictive numerical modelling of a selection of JET OS plasmas with the toroidal field ranging from 1.8 to 4 T. An empirical JET mixed Bohm/gyroBohm transport model [4] has been used in this simulation with the formula (2) applied to the Bohm coefficient only. All the relevant plasma parameters, including toroidal velocity, have been calculated self-consistently. The results of this modelling is summarised briefly in Table 1 and allows us to conclude that the present model reproduces JET experiments with time averaged prediction errors of the order of 10%-25%. The simulated times of the onset of the ITB, as compared to the experimental ones are typically within 0.4 s and the simulated ITB widths within 0.1 of r/a throughout the whole simulations.

Table 1

Pulse No	**47843**	**49196**	**47170**	**46664**	**47413**	**46998**
B_T **[T]**	1.8	2.5	3.0	3.4	3.4	4.0
P_{in} **[MW]**	14	16	25	22	30	20
W_{dia} **[MJ]**	3	4	11	10	12	6
Exp/Sim ITB onset time [s]	2.1/2.3	4.4/4.1	5.6/5.4	5.6/5.2	6.2/6.1	6.3/5.7
Exp/Sim ITB width at onset [r/a]	0.42/0.44	0.28/0.28	0.50/0.42	0.44/0.48	0.53/0.42	0.32/0.38
σ_{Ti} **[%]**	23	17	20	18	17	29
σ_{Te} **[%]**	24	9	7	13	15	12
σ_{ne} **[%]**	13	11	6	6	7	17
$\sigma_{V\phi}$ **[%]**	13	9	16	13	19	17

Finally, a predictive modelling of recently obtained JET plasma with an early ITB, produced during LHCD assisted preheating phase, has been performed. To do this, the JET transport code JETTO has been upgraded to incorporate a recently developed fast ray tracing code for LHCD[5].

The main rational behind such a modelling was to investigate whether we need a Lower Hybrid current drive capability to explain an observed emergence of the ITB, or whether simple heating can lead to the same result. Figure 6 shows a comparison between experimental and simulated time evolution of a central electron temperature. The difference between four simulated cases is in their current drive capability. Best agreement with experiment has been achieved with an assumption that LHCD current drive capability is equal to theoretically predicted value. One can observe that the level of agreement between experiment and simulation reduces rapidly when we arbitrary reduce LH current drive capability from theoretical level to zero.

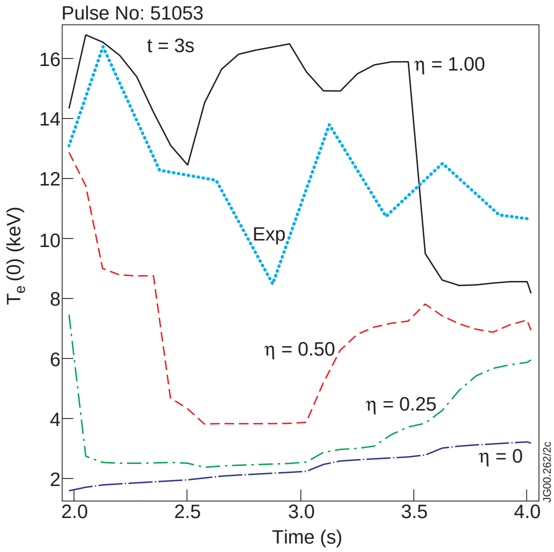

Fig.6: Time evolution of the central electron temperature as a function of a normalised current drive efficiency

For the sake of completeness, our analysis shows as well, that strong electron heating can generate an inverted q-profile by itself, without any involvement of the current drive. However, it requires a heating power in excess of $P_e \geq 5\ MW$ in standard JET OS scenario (instead of commonly used 2-3MW).

5. Conclusions

The results of recent experiments on JET with optimised shear plasmas confirm the almost linear dependence of the power threshold for the ITB formation with the toroidal magnetic field. However, recent experiments with LHCD preheating show that a proper tailoring of the current profile during preheating and current ramp up can significantly reduce the threshold power. These experiments with LHCD preheating also demonstrate the possibility of generating two separate ITBs, one of which remains stationary within the region with a negative magnetic shear while the other expands radially.

A transport analysis and predictive modelling of a series of JET OS plasma has been performed to elucidate the relative role of the plasma rotation and that of the negative magnetic shear in the ITB formation.

6. Acknowledgements

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