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The Role of RF in the Optimised Shear Scenario on JET

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ABSTRACT.

RF heating and current drive with ion cyclotron waves and Lower Hybrid waves have been crucial for the development of the Optimized Shear scenario on JET to high performance. Peaked electron temperature profiles and improved energy confinement could be obtained with electron heating both from LHCD and ICRH during plasma current ramp up. ICRH and NBI comparisons allow to separate heating and fueling and suggest a dominant role of core heating in the formation of an Internal Transport Barrier (ITB). ICRH and NBI powers are there equivalent. Pressure profile control by varying the composition of centrally peaked ICRF and broader NBI deposition improves MHD stability. Current profile modifications in a wide range have been obtained with LHCD and in combination with NBI during current ramp up. During the high performance phase, however, LH coupling degrades strongly due to the steep edge density gradient resulting in a drop of the density in front of the LH antenna to the cut-off density. High fusion performance achieving simultaneously high beta values and bootstrap currents is predicted in scenario modeling using pressure and current profile control with ICRF and LHCD.

INTRODUCTION

The Optimized Shear scenario has been one of the two routes to high fusion performance explored during the deuterium-tritium experiments in the DTE1 campaign on JET [1]. Strong Internal Transport Barriers (ITBs) have been established for the first time in DT operation and fusion power up to 8.2 MW has been produced in transient high performance pulses [2]. The perspective of an advanced steady-state tokamak operation mode has been opened by the combination of an ITB with an edge transport barrier in ELMy H-mode in first exploratory experiments in DD and DT [3]. This Double Barrier approach has become the main program of the experiments in the new gas box divertor configuration on JET in 1998/99 [4, 5]. Improved core confinement inside an ITB should reduce the minimum size and current of an ignition device. Moderately peaked density profiles as observed in Double Barrier mode discharges on JET relax the density limit issue by allowing higher central densities at the same edge density as in flat profiles characteristic for conventional ELMy H-modes. Improved MHD stability with reversed central magnetic shear gives access to higher beta values. This in turn should produce bootstrap currents large enough to supplement them with moderate external current drive for steady state operation. Key to this high performance route is a continuous control of pressure and current profiles in order to reliably form an ITB and maintain MHD stability at high pressure. RF heating and current drive are well suited to fulfill both requirements as their deposition inside the plasma can be widely varied by external adjustments, e.g. of phase and frequency. Experiments on pressure profile control with Ion Cyclotron Resonance Frequency (ICRF) waves and current profile control with Lower Hybrid Current Drive (LHCD) on JET are reported in this paper. The performance perspectives of the profile controlled Optimized Shear scenario have been investigated in MHD [6] and transport code modeling calculations [7].

IMPROVED ELECTRON ENERGY CONFINEMENT

Strong central electron heating and peaking of the electron temperature profile has been obtained upon application of LHCD or ICRH in the He^3 minority heating scheme early during the initial plasma current ramp-up phase at low density [8]. Transport code analysis shows a strong reduction of the heat conductivity in the core region and the formation of an ITB in electron heat transport. Slight electron density peaking and an increase in central ion temperature and neutron rate are also observed. Equilibrium reconstruction gives a slightly negative central magnetic shear during the improved core confinement phase [9]. These electron ITBs have been obtained already at low rf power in the range 1-2 MW. The improved confinement, however, could not be maintained when high power NBI with dominant ion heating was added.

IMPROVED PERFORMANCE WITH PROFILE CONTROL

High performance has been obtained in the so-called Optimized Shear scenario shown in Fig. 1 for a DT discharge [10]. The current profile evolution is controlled from the plasma formation phase onwards with a combination of an early short LHCD pulse, a fast plasma current ramp and low power ICRH. Both, ICRH and NBI are stepped up in power at low target density when the q=2 surface appears in the plasma core region. Formation of an ITB results then in high central ion temperatures and a strong rise in fusion power. The timing of heating and the power waveforms are of crucial importance to obtain an optimum match of current and pressure profiles allowing to trigger the ITB formation and to sustain MHD-stable high performance.

Fig.1: High performance DT discharge on JET in the Optimized Shear scenario.

ITB Power Threshold

Formation of an ITB in the Optimized Shear scenario requires high heating power above a threshold of 10-15 MW depending on the toroidal magnetic field [4]. The role of the power deposition profile and of particle fueling versus heating has been studied by varying the composition of ICRH and NBI power and the geometry of the beam lines used in a series of consecutive discharges (I_p=2.6 MA, B_t=2.6 T). The results are summarized in Fig. 2. ITBs are formed in pulses 3 and 4, as seen from the larger and accelerating rise in neutron yield (S_n), compared with pulses 1 and 2. The two extreme cases 1 and 4 have the same NBI power of 10.4 MW applied but
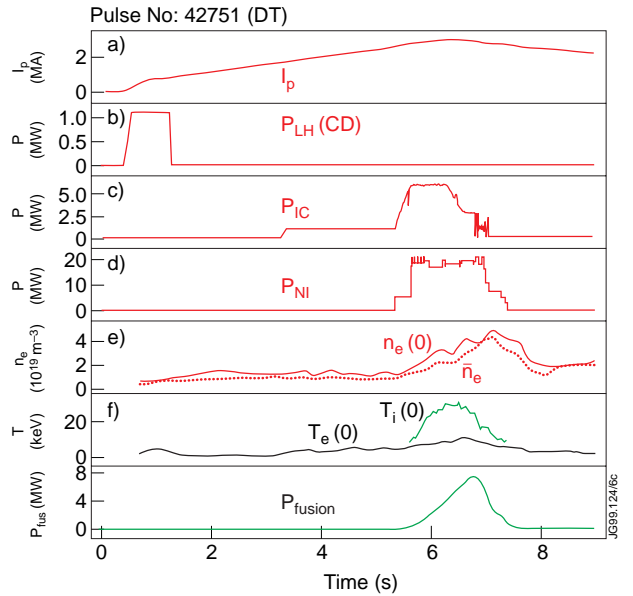
ITB Power Threshold: NI/ICRF Comparison				
	P_{NI} (MW)	P_{IC} (MW)	P_{tot} (MW)	Pulse No:
ITB	4: 10.4	5.6	16	47667
	3: 7.8 (on axis)	5.6	13.4	47668
no ITB	2: 7.8 (off axis)	5.6	13.4	47669
	1: 10.4	3.1	13.5	47670

Fig.2: Assessment of the ITB power threshold with ICRH and NBI on/off-axis.

different levels of ICRH power. With P_{IC}=5.6 MW an ITB is obtained in case 4 but not with P_{IC}=3.1 MW in case 1. The reduction by 2.5 MW corresponds to two NBI sources. By reducing the NBI power by the same amount to 7.8 MW and keeping the higher ICRH power P_{IC}=5.6 MW, an ITB is still formed in case 3 where all NBI sources retained have centrally peaked on-axis deposition. By replacing two on-axis sources by two off-axis sources, no ITB is formed in case 2 though the total power is the same as in case 2.

In conclusion, core power deposition is essential for the ITB formation. The power threshold is then 13.4 MW. ICRH and NBI power are equivalent. The critical quantity is core heating not fueling. This favors ICRH as preferred heating method to assure an ITB formation. By proper frequency tuning, all ICRH power can be directed to the plasma core with a narrow deposition profile. The ITB threshold power can thereby be minimized. The density also rises to 25% higher values in case 3 with an ITB with P_{NI}=7.8 MW, compared with case 4 with the higher P_{NI}=10.4 MW but no ITB. The density evolution therefore is more determined by confinement than by fueling.

The importance of ICRH core heating for the ITB formation has been also demonstrated in a series of discharges where the width of the ICRH deposition profile has been varied by spreading the frequencies of the emitters feeding the four antennae in JET. With multiple frequencies the deposition is broadened and the ITB forms later in this case [11].

The ICRH deposition profile and the ITB formation depend also on the phasing of the ICRH antennae. Central ion temperatures and neutron yield are lower with -90° and symmetric phasing than with +90° phasing. Also a larger delay in the ITB formation is observed in this case. Monte-Carlo calculations show that the fast ion pressure in the core is much lower when the ion orbits are driven outwards in -90° phasing [11, 12].

In the initial phase of the ITB formation most of the ICRH power is damped onto hydrogen minority ions, building up fast particle pressure which can amount to about half the total plasma pressure. With the core pressure rapidly rising after the ITB formation, direct ion heating through second harmonic damping on deuterons increases continuously. The central ion heating power densities from ICRH can then rise to a multiple of the NBI heating power density for the same total input power [13].

Pressure Profile Control

The strong pressure peaking inside the ITB can trigger various MHD instabilities They lead either to a saturation in performance or to a degradation of the ITB or to disruptions caused by pressure driven kink modes [14]. Pressure profile broadening with an ELMy H-mode edge has alleviated the MHD stability problem and allowed to steer discharges along the marginal stability boundary [10]. Most effective has been a control of the pressure profile by varying the power composition of narrow ICRH and broader NBI deposition. High performance with an H-factor $H^{89} \approx 3$ and a normalized beta value $\beta_N \approx 2.5$ could then be sustained for three energy confinement times in the discharge shown in Fig. 3. The ITB expands to $r/a \approx 0.65$. The ion heat conductivity in the core region drops to the neo-classical level and reaches values as low as $\chi_{i,eff}=0.2$ m^2/s. The ICRH power, instrumental for the initial ITB formation, is reduced in the flat-top phase and replaced by a step-up in NBI power. A slow gradual growth of neo-classical tearing modes, seen in the growing level of D_α fluctuations after 6.0 s still leads to a soft roll-over and limits the duration of the high performance phase. The change-over in heat deposition profiles is illustrated in Fig. 4 with a comparison of two time slices at 4.5 and 6.5 s. The power deposition onto ions from NBI increases while the ICRH power deposition mostly going to the electrons is reduced.
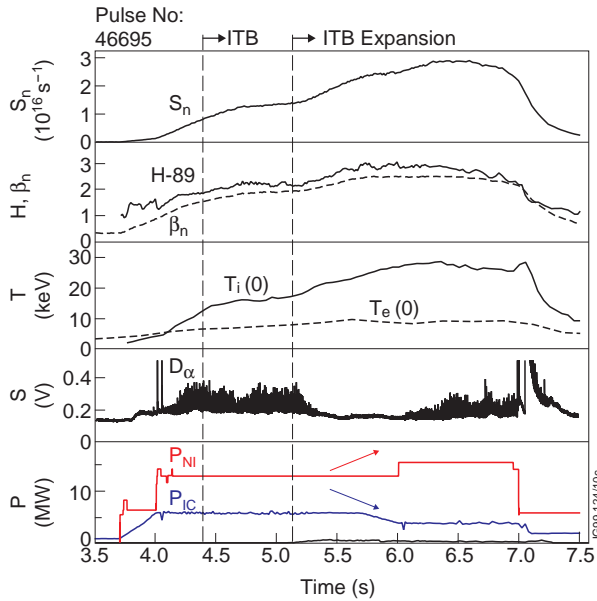

Fig.3: Sustained high performance with pressure profile control by variations of the ICRH / NBI power composition.
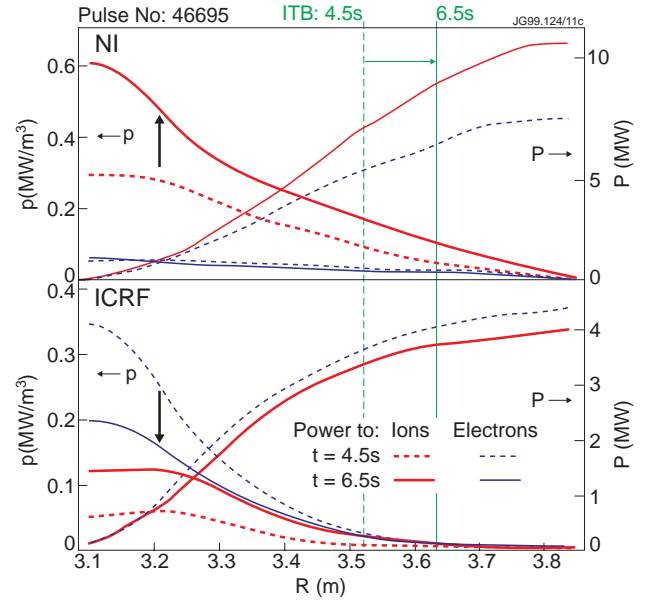
Fig.4: NBI and ICRH power deposition profiles in the pressure profile controlled discharge shown in Fig.3.

The ICRF power deposition profile is much more peaked and localized than the NBI power deposition profile. All ICRF power is deposited well inside the ITB, while up to about 30% of the NBI power is deposited outside the ITB into the ELMy H-mode edge pedestal, as seen from the radially integrated power profiles. In the plasma core the power densities from

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ICRH are comparable with the NBI power densities though the total NBI power injected is more than a factor 2 higher than the coupled ICRF power. The total power transferred to electrons and deuterons is the same at 6.5 s after the ICRF power step-down as at 4.5 s at the ITB formation time because the power transfer from minority hydrogen ions to electrons has increased by about 2 MW during this time due to the increase in electron temperature from $T_e(0) \approx 6.5$ keV to $T_e(0) \approx 9.0$ keV and a simultaneous increase in the electron density.

Pressure profile control, however, limits the available heating power and provides only a transient solution to the MHD stability problems while the current profile keeps evolving.

Current Profile Control

Scenario studies with combined transport code modeling and MHD stability analysis have shown that the shape of the current profile must be kept self-similar from the initial low-ß plasma formation phase into the high performance phase in order to avoid MHD instabilities [15]. LHCD during the plasma current ramp-up phase can efficiently modify the current profile as seen from Fig. 5. The internal inductance l_i decreases compared with an Ohmically driven reference pulse. The current profile therefore is broadened through off-axis LHCD. Additional high power NBI enhances the broadening strongly. A wide range of q-profiles with low or strongly reversed central shear can be generated by the end of the current ramp-up phase as shown in Fig. 6. No or only late ITBs have been formed with high power heating into reversed shear profiles [10]. The best performance has consistently been obtained on JET with wide regions of low central shear. Off-axis current drive with LHCD during the high performance phase has contributed to freeze in a q-profile with this shape [5].
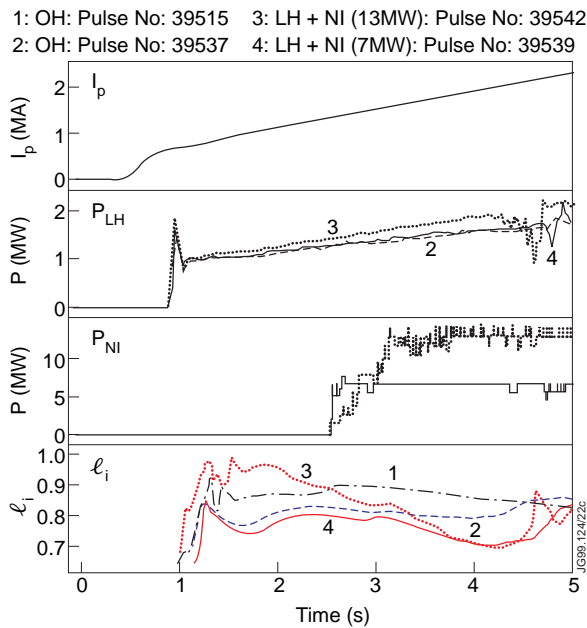

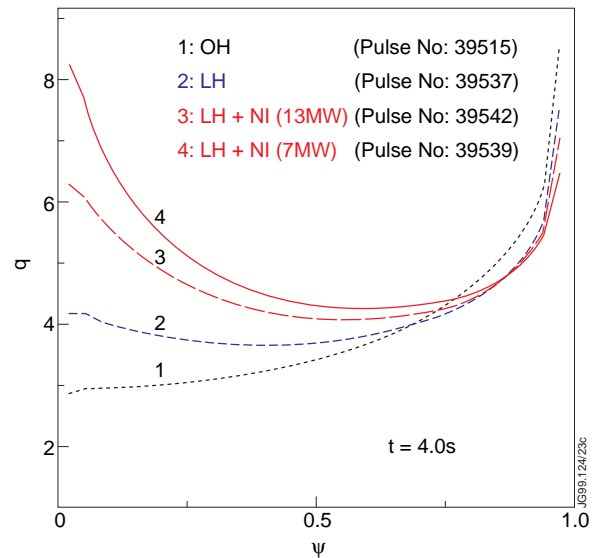Fig.5: Current profile modification with LHCD and NBI during current ramp-up.

Fig.6: q-profiles obtained with long LHCD pulses and NBI during current ramp-up.

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The current profile control with LHCD in high performance Double Barrier plasmas has encountered major problems with maintaining good coupling. The evolution of the average reflection coefficient and the resulting power transmission is shown in Fig. 7 for a long LHCD pulse covering plasma formation, current ramp-up and high power heating phases. While good coupling with low reflection of R≈3% is achieved in the initial low-ß phase, the reflection increases rapidly to R≈20% after the H-mode transition and the coupled power drops. An additional ITB only worsens the situation.
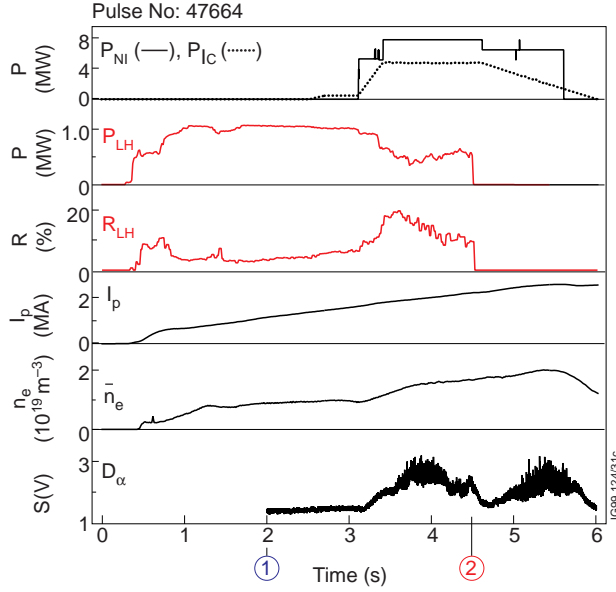

Fig.7: LHCD coupling with low reflection during the low-ß current ramp-up phase and high reflection during high performance.
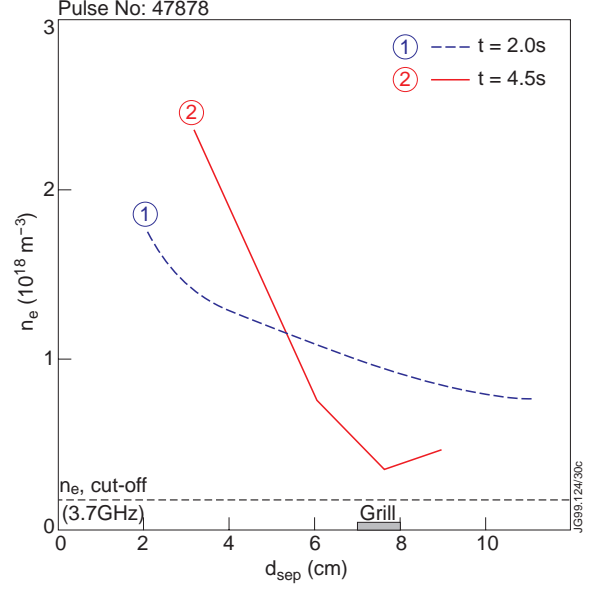
Fig.8: Edge density profiles during low-ß current ramp-up phase and high performance ITB/ELMy H-mode phase.

The strong deterioration of coupling is caused by a steepening of the edge density gradient as shown in Fig. 8. The density has been measured with a reciprocating probe outside the launcher protection limiter frame. In the vicinity of the front end of the grill antenna the density is even much lower than shown by the probe measurements. The improved particle confinement with the resulting short density decay length during the Double Barrier phase reduces the density in front of the launcher close to the cut-off density. The distance between launcher and separatrix can not be further reduced without provoking enhanced plasma-launcher interaction. Gas injection through a dedicated feeding line near the launcher which has previously helped to maintain good coupling [8] can also not be increased to the required level without deleterious effects on the ITB quality. LHCD current profile control as required for performance optimization and steady-state operation can therefore only be used efficiently if an independent method of local density control in front of the launcher is developed.

FUSION PERFORMANCE MODELING

Transport code calculations combined with MHD stability optimization studies have shown that current profile control is the principal route to performance enhancement in advanced tokamak scenarios by maximizing the extent of the improved core confinement region and providing MHD stability at high pressure [6,7]. The slowing down of the current diffusion and complete freezing of the q-profile in its shape at peak plasma performance is shown in Fig. 9 for various levels of LHCD power. Further broadening of the current profile allows an expansion of the ITB and the build-up of higher pressure. High performance values of $\beta^* \approx 6\%$, $\beta_N \approx 3.5$ and a bootstrap current fraction of $f_{bs} \approx 0.65$ can then be achieved simultaneously. Predictions of transport code calculations for the fusion power produced on JET with enhanced current drive and heating facilities are shown in Fig. 10. Conditio sine qua non, however, is an efficient off-axis current profile control.
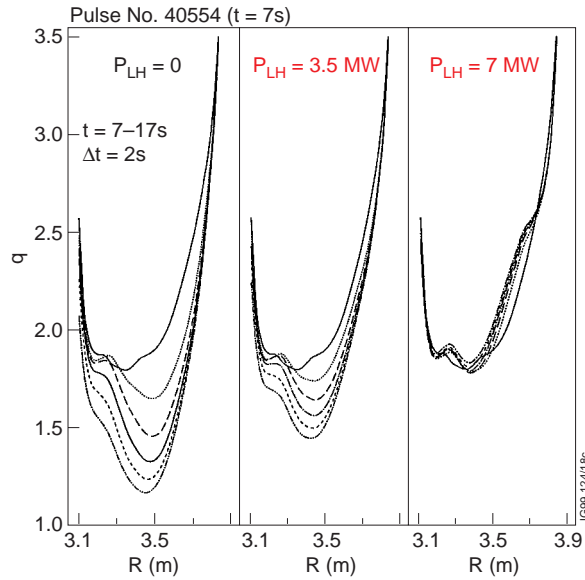
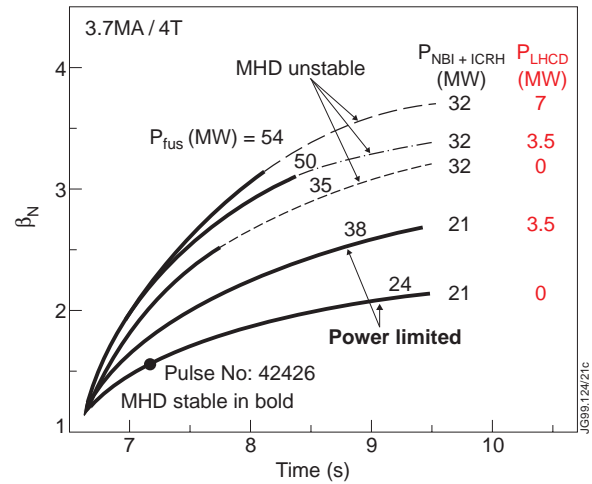Fig.9: Freezing of the q-profile with LHCD in transport code modeling.

Fig.10: Modeling predictions of fusion power production with LHCD profile control and enhanced NBI+ICRF heating on JET.

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