

Analysis of the Influence of Different ICRF Heating Scenarios on the Performance of Optimised Shear Discharges in JET

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INTRODUCTION

Optimised shear discharges, i.e. discharges with an Internal Transport Barrier (ITB), are normally heated by a combination of Neutral Beam Injection (NBI) and Ion Cyclotron Range of Frequency (ICRF) heating in JET. Although the NBI power in general dominates, ICRF power has been found to be important for obtaining good performance. Several ICRF heating scenarios have been tested, including the use of hydrogen and ³He as a minority species, on and off-axis heating and different phasings of the ICRF antennas. Here, we concentrate on analysing the influence of the different phasings of the ICRF antennas on the performance.

In JET the ICRF antennas can be phased to launch toroidally directed waves. In general, the performance of optimised shear discharges has been found to improve when the phase difference between the currents in the JET four strap antennas has been set to +90°, which corresponds to waves propagating along the current, as compared to -90° corresponding to propagation antiparallel to the current. Smaller differences have been observed between +90° and symmetric phasings.

A possible theoretical explanation for these experimental results could be the presence of an ICRF induced spatial pinch of the resonating ions. Theory predicts that the turning points of trapped resonating ions are driven inward/outward when the waves propagate parallel/antiparallel to the plasma current [1,2], and experimental evidence for this has been observed [2]. An important consequence of the ICRF induced pinch is a peaking of the fast ion pressure profile and a concomitant peaking of the collisional heating of the background plasma when the waves propagate along the current and a broadening for antiparallel propagation. The current driven by the fast ions is also modified.

In optimised shear discharges one would intuitively expect the fast ion pressure, and thus the heating of the background plasma, within the ITB to play a significant role. It is therefore important to establish whether the ICRF induced spatial pinch is strong enough to explain the experimental results.

EXPERIMENTAL RESULTS

Here we will show results from two discharges obtained during the MKIIa divertor campaign; similar results have also been obtained with the MKIIGB ("Gas box") divertor. Figure 1 shows an overview of two deuterium optimised shear discharges heated by NBI and ICRF, using the hydrogen minority scheme. One of them has +90° phasing of the ICRF antennas and other has -90°. As can be seen, the performance in terms of neutron production

is significantly better for $+90^\circ$ than for -90° phasing. However, the stored energies in the two discharges are nearly identical, indicating similar global confinement. The difference in neutron production lies in the ion temperature profiles as shown in Fig. 2. Here one can see that the ion temperature profile is more peaked for $+90^\circ$ phasing, with the ion temperature reaching about 27 keV in the plasma centre while for -90° phasing the central ion temperature stays below 20 keV. On the other hand, for -90° phasing the pedestal edge temperature is higher, which is a sign of the presence of an H-mode edge. This is confirmed by the D_α signals displayed in Fig. 3, which show grassy ELMs for -90° phasing whereas the $+90^\circ$ case is ELM free. Similar observations have been made earlier in ICRF only discharges [2], where -90° phasing produced stronger ELM activity.

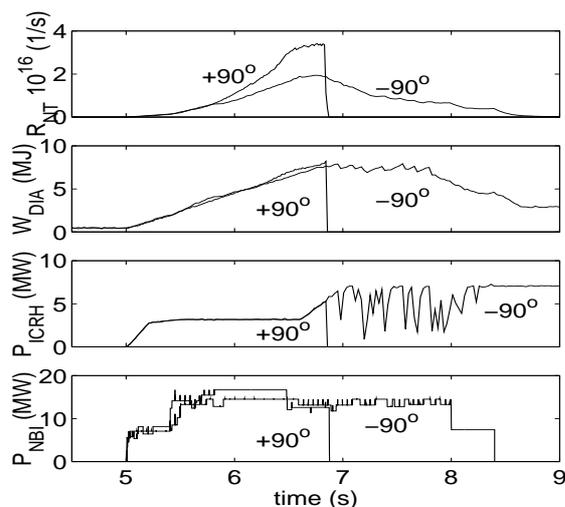


Fig. 1 DD neutron rates, diamagnetic stored energies, ICRF and NBI heating powers for discharges 40066 ($+90^\circ$) and 40068 (-90°).

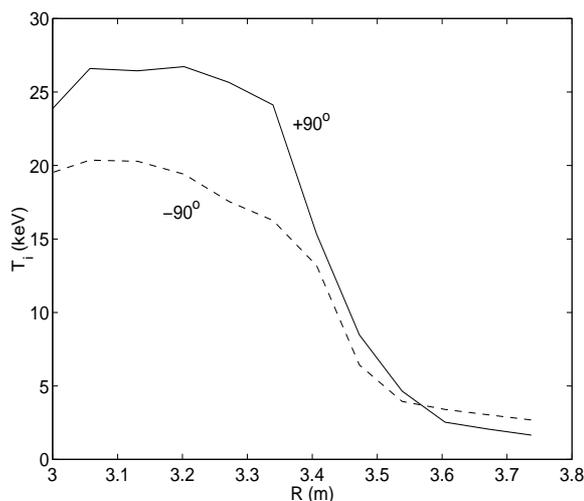


Fig. 2 Ion temperature profiles versus major radius measured by charge exchange for the two discharges in Fig. 1 at $t=6.5$ s.

In addition to the differences in the neutron rates and ion temperature profiles, there are differences in the time it takes to trigger an ITB. Analysis of the ion temperature measurements shows that for $+90^\circ$ phasing an ITB is triggered around $t = 5.6$ s whereas for -90° phasing ITB formation is delayed until $t = 6$ s. Since a high pressure in the centre is thought to be beneficial for the formation of an ITB, a possible explanation for this is that the pressure in the centre of the plasma is lower in the discharge with -90° phasing.

THEORETICAL CONSIDERATIONS

The ICRF induced spatial particle pinch arises owing to a fundamental relationship between the change in energy E and toroidal angular momentum $P_\phi = mRv_\phi + Ze\psi$ of a particle, where ψ is the poloidal flux. One can show that during interaction with a wave having a toroidal mode number N the change in toroidal angular momentum is given by $\Delta P_\phi = (N/\omega)\Delta E$ [1]. As a consequence, ions interacting with waves having an asymmetric toroidal mode number spectrum experience on average a drift in their toroidal angular momentum, with the sign depending on whether the waves have predominantly positive or negative toroidal mode numbers. The effect of the changing toroidal angular momentum is most obvious for trapped ions. Since at the turning point of a trapped ion $P_\phi = Ze\psi$ and ψ is a flux surface label, we can see that the drift in toroidal angular momentum corresponds to

a drift of the turning points of the interacting trapped ions. One can show that for waves propagating along the current the drift is inwards and for antiparallel propagation it is outwards.

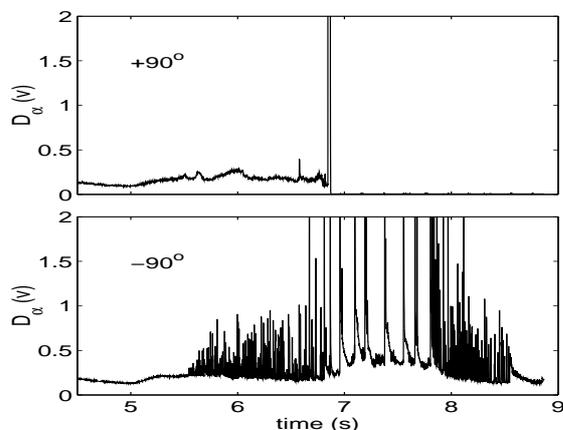


Fig.3 D_{α} signals for the two discharges in Fig. 1.

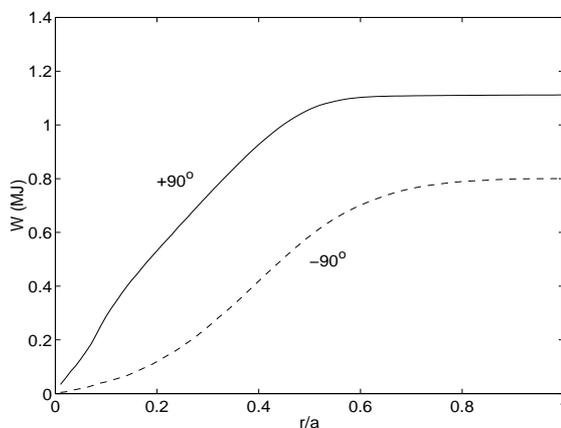


Fig. 4 Volume integrated fast ion energy densities as given by the FIDO code for the discharges in Fig. 1.

In order to assess the importance of the ICRF induced pinch for the optimised shear discharges reported here, we use the ICRF code FIDO [3]. This code solves the 3D orbit averaged Fokker Planck equation, $\partial f / \partial t = \langle C(f) \rangle + \langle Q(f) \rangle$ [4], with a Monte Carlo method, where the distribution function, f , is a function of three invariants of the unperturbed particle motion and $\langle \dots \rangle$ denotes orbit averaging.

The distribution functions of the resonating hydrogen ions in the two discharges with different phasings have been simulated with the FIDO code using experimental data (density, temperature profiles etc.) taken at $t = 6$ s as input. In Fig. 4 the volume integrated energy densities of the resonating ions are shown as a function of the normalised minor radius r/a . As can be seen, the energy content of the resonating ions is higher and much more concentrated in the centre of the plasma for $+90^\circ$ than for -90° phasing. This is also reflected in the simulated electron heating profiles. The volume integrated collisional power densities from the resonating ions to the electrons are shown in Fig. 5. Inside the barrier, i.e. within $r/a \approx 0.4$, almost twice as much power is deposited to the electrons for the $+90^\circ$ case as for the -90° case. Thus, the ICRF induced pinch has a significant effect on the RF-power absorbed within the barrier. This indicates that a central power deposition is important for the performance of an optimised shear discharge cf. [5].

The current driven by the resonating ions is also affected by the phasing of the antennas [6]. Figure 6 shows the current densities as simulated by the FIDO code (note: the electron back current has not been included, which gives a reduction of about a factor two). The current densities approach values of the order of magnitude of the total current density only close to the centre of the plasma, with the total driven current being less than 0.1MA for $+90^\circ$ phasing as compared to the plasma current of 3MA. Thus, the central q could be somewhat affected, but the influence on the total current profile should be modest. The signs of the currents are such that for $+90^\circ$ phasing the driven current would tend to reduce the central q value, whereas it would increase it for -90° phasing. Furthermore, simulations with the ACCOME code [7] indicate that the other current components (ohmic, beam driven and bootstrap currents) provide less current in the plasma centre and/or more current at the edge for -90° phasing (e.g. the higher edge pressure for -90° phasing will drive more bootstrap

current at the edge). Thus, the simulations do not indicate that the poorer performance for the -90° discharge was caused by a higher positive shear than in the $+90^\circ$ discharge.

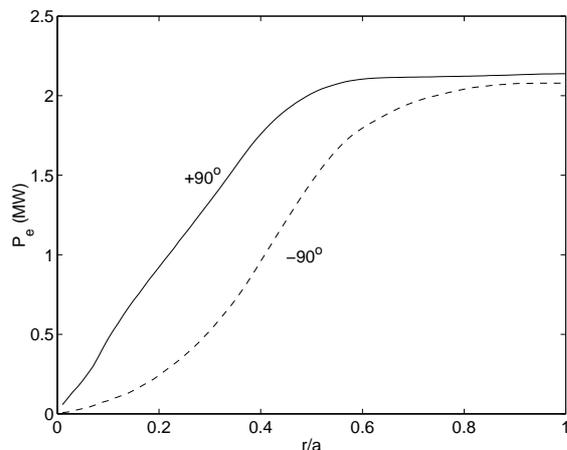


Fig.5 Volume integrated collisional power densities to the electrons as given by the FIDO code.

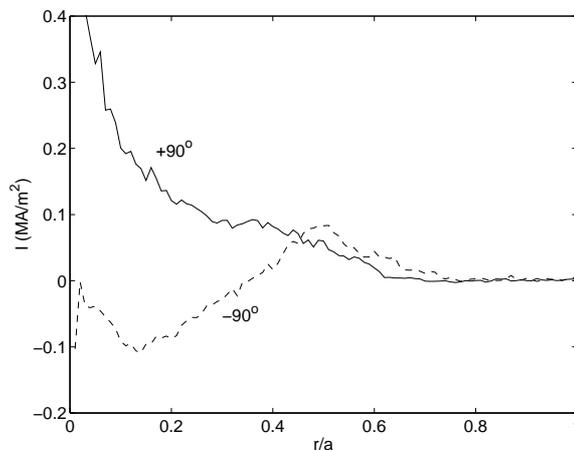


Fig. 6 Current densities driven by the resonating ions according to FIDO simulations.

CONCLUSIONS

The experimentally observed differences between optimised shear discharges using different phasings of the JET ICRF antennas are consistent with an ICRF induced spatial particle pinch. This particle pinch has been shown to be strong enough to significantly affect the power deposited within the internal barrier. In addition, the current driven by the resonating ions is also influenced by the phasing. However, the total current driven by the resonating ions should have been too small to have had a substantial effect on the total current profile, but the sensitivity of the performance to central q reported in [8] should be noted. Nevertheless, a high pressure of the resonating ions in the centre and a power deposition to the background plasma concentrated within the barrier appears to be essential for obtaining good performance.

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