Expanding the operating space of ICRF on JET with a view to ITER

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The size and capability of the Joint European Torus (JET) to confine very energetic particles, together with its versatile ion cyclotron resonance frequency (ICRF) system, provide a unique environment to develop ICRF techniques relevant to the Next Step. During the JET experimental campaigns of 2003 and early 2004, in addition to further development of ICRF as a tool for the experimental programme, several heating and current drive scenarios have been investigated, contributing to the physics understanding and operational expertise required for successful use of ICRF on ITER. The first part of the paper focuses on these advances. The second part presents the technical enhancements planned on the JET ICRF system, themselves likewise strongly driven by the preparation for ITER.

In the start-up phase of ITER, activation will at first be minimized by operating in hydrogen plasmas, and the reference ICRF scenarios rely on a minority species such as ^{3}He or D. In the past very few experiments have been dedicated to these scenarios. The heating of ^{3}He in H has now been explored in a sequence of discharges in which 5MW was reliably coupled to the plasma and the ^{3}He concentration was varied from below 1% up to 10%. The minority heating regime was observed at low concentrations (up to ~2%), with formation of energetic tails in the ^{3}He distribution with effective temperatures ~100keV and bulk electron temperatures up to 6keV. At around 2%, a sudden transition was reproducibly observed to the mode conversion regime, in which the ICRF fast wave couples to a short wavelength mode, leading

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[*] *See annex of J. Pamela et al., this Conference, Paper OV/1-X.*

to efficient direct electron heating and bulk electron temperatures up to 8keV. Attempts were made to locally drive current with these mode-converted waves. Opposite directive phasings of the ICRF antennas were compared, in conditions where the short waves are damped on the q=1 surface. The preliminary results show stabilization of the sawteeth from heating effects, but no significant difference between the two phasings, suggesting that the directivity is not inherited from the launched fast wave. All these experiments systematically used power modulation techniques to assess the radial profiles of direct wave absorption by the electrons. They strongly benefited from the expertise developed at JET to control the ^{3}He concentration in real time, and levels as low as 1.8% were successfully controlled for the first time. In contrast, the use of D as a minority in H proved much more difficult since the C^{6+} impurity, which has the same cyclotron layer as D, influences wave propagation like a much higher equivalent D concentration and directly leads into the mode conversion regime.

Plasmas with low tritium concentration will occur when ITER starts to use T. On JET, minority heating of tritium at concentrations up to ~1%, introduced in the discharge either by gas puffs or by neutral beam injection, showed energetic T tails of 80 to 120 keV, close to the maximum of the D-T reaction rate. This attractive scenario, not included in the present range of frequencies of the ITER RF system because of its transition to mode conversion at higher concentrations, would be relevant to a fusion material irradiation test facility. In low T concentration JET discharges, second harmonic heating of T was shown better suited to the higher concentrations of ITER or of a full JET D-T campaign. Heating of tritium at its second cyclotron harmonic is indeed the main ICRF scenario intended to bring the ITER plasma to thermonuclear temperatures, as it allows a continuous increase of the T concentration without reducing the ICRF heating efficiency. (At low concentration the wave damping will be increased by addition of ^{3}He.)

Wave absorption at the second ion cyclotron harmonic depends on the ratio of the particle Larmor radius to the wavelength. Theory predicts a maximum absorption when this ratio increases to ~ 0.5, followed by a decrease to much smaller levels at higher ratios. Using second harmonic hydrogen heating in a density scan (i.e. varying the wavelength), the measured proton energy distribution clearly exhibits the expected dependence. This type of experiment requires confining protons in the MeV range and can thus only be performed on JET.

A range of parameters has been identified on JET for efficient direct electron heating with the fast wave. With dipole ($0\pi0\pi$) phasing of the present four-strap A2 antenna arrays, the heating efficiency is similar to that of hydrogen minority heating. With directive antenna phasing, the heating and current drive efficiencies are reduced by a parasitic absorption mechanism, as a significant fraction of the power cannot be accounted for by radiation from the plasma or from divertor thermocouple measurements. The lost fraction decreases with increasing single pass wave absorption, and is therefore expected to be negligible on ITER, where direct electron heating will be much stronger.

Additional experimental evidence has been gathered on the heating efficiency of the JET A2 ICRF antennas. As is well known, the heating efficiency is maximum in dipole phasing, but only half as much in monopole (0000) phasing despite the much higher antenna loading. It has now been shown that powering only one or two adjacent straps of each array in phase (00) doubles the heating efficiency with respect to the full monopole. These observations support previous interpretations based on RF sheath dissipation phenomena, and provide important information for the detailed design of the ITER antenna.

Beside widening the physics operating space of ICRF on JET, progress has also been made in extending the range of experimental conditions in which ICRF can operate. ELM-resolved RF measurements provide forefront data to estimate the performance of future launchers. An ELM-tolerant antenna matching scheme based on the same principle as the one proposed for ITER, but using an external matching circuit, was successfully tested on half an A2 antenna. This scheme could thus enable reliable generator operation on ELMy plasmas.

A major enhancement is under way with the scheduled installation of an additional ITER-like antenna in 2005 (nominal power ~7.2MW), which will be a key test of the ITER concept. This is accompanied by the addition of 3dB hybrid couplers in the transmission systems of two of the four existing antennas. Both measures will also provide additional power for a wide range of JET plasma conditions, in particular at low frequency (minority heating of ^{3}He, second harmonic heating of T, relevant to a future D-T campaign), and in presence of ELMs, further expanding the relevance of the JET ICRF system for ITER.

Acknowledgments

This work was conducted under the European Fusion Development Agreement. It is a pleasure to thank the staff who operated the JET tokamak, its heating systems and diagnostics. The work carried out by the UKAEA personnel was jointly funded by the United Kingdom Engineering and Physical Sciences Research Council and by EURATOM. The work of E.L. is supported by the EU under a EURATOM Intra-European Fellowship.