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ICRH analysis of high-performance JET hybrid discharges using PION modelling and neutron spectrometry measurements

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**See Appendix of F. Romanelli et al., Proc. 25th IAEA FEC 2014, Saint Petersburg, Russia*

Introduction The hybrid scenario is an operational tokamak plasma regime designed to achieve long pulse operation with a combination of inductive and non-inductive current drive. It has been suggested for ITER to allow operation at a high fusion power over 1000 s at a lower plasma current than for the inductive reference scenario. In the recent 2014 JET experimental campaign with the new ITER-like-wall (ILW) and deuterium as the main gas, high-performance hybrid discharges have been achieved with combined deuterium neutral beam injection (NBI) and ion cyclotron resonance heating (ICRH) [1]. ICRH was tuned to the fundamental cyclotron frequency of minority hydrogen ions which coincides with the second harmonic cyclotron frequency of deuterium ions in the plasma centre ($\omega \approx \omega_{cH} = 2\omega_{cD}$). In the present paper a number of JET high-performance hybrid discharges are analysed using the ICRH modelling code PION which takes into account NBI+ICRH synergy due to beam ions that are resonant with ICRH [2, 3]. Comparisons between the experimental results with modelling are presented, with special emphasis on the ICRH enhancement of the neutron rate measured with the neutron time-of-flight spectrometer TOFOR [4]. Furthermore, we analyse the ICRH power transfer to bulk ions and electrons and we extrapolate the best performing discharges to D-T.

Experimental overview The main parameters for JET hybrid discharges 86614, 87331 and 86871 analysed in the present paper are shown in Fig. 1. Discharges 86614 and 86871 were carried out at a toroidal magnetic field B_T of 2.9 T and a plasma current I_p of 2.5 MA, while a lower B_T of 1.95 T and I_p of 2.1 MA was used for discharge 87331. Up to 22 MW of D NBI was applied with injection energies in the range of 90-115 keV. In discharges 86614 and 86871 up to 5 MW of ICRH power was applied at a frequency of 42.5 MHz while in discharge 87331 up to 2.5 MW of ICRH power was used at 32.4 MHz. The $\omega \approx \omega_{cH} = 2\omega_{cD}$ resonance was located at R_{res}–R_0 of 2.5 cm, -33 cm and 9 cm at the peak performance for discharges 86614, 87331 and 86871, respectively. Here R_{res} and R_0 are the major radii of the resonance and magnetic axis, respectively. The best performing discharge 86614 reached a normalized beta β_N of 2.1 and a confinement factor H98 of 1.1. The duration of the high-power phase was limited by impurity accumulation [1].

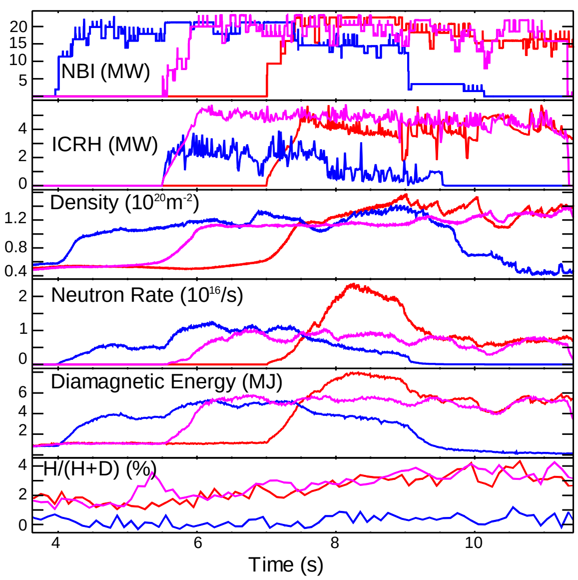

Figure 1 NBI and ICRH power, line-integrated electron density, neutron yield, plasma diamagnetic energy and hydrogen concentration for JET hybrid discharges 86614 (red), 87331 (blue) and 86871 (magenta).

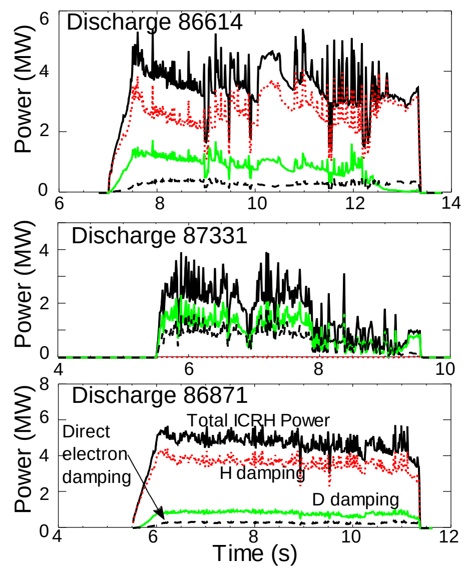

Figure 2 Total ICRF power (solid black line), hydrogen damping (red), deuterium damping (green) and direct electron damping (dashed black line) as given by PION for discharges 86614, 87331 and 86871.

For the $\omega \approx \omega_{cH} = 2\omega_{cD}$ scenario, the ICRF power partitioning between the resonant hydrogen minority and deuterium ions depends on the hydrogen concentration $n_H/(n_H+n_D)$ [3]. The hydrogen concentration, deduced from the ratio of the D_α and H_α light collected along lines of sight through the plasma, was 2-3% in discharges 86614 and 86871 and below 0.5% in discharge 87331. Penning gauge spectroscopy in the divertor gave somewhat higher $n_H/(n_H+n_D)$ values of 2-4%, 3-5% and 1-2% for 86614, 86871 and 87331, respectively.

Results from ICRF modelling and comparisons with experimental results Figure 2 shows the ICRF power partition as given by PION for the three discharges. In discharges 86614 and 86871, up to ≈20%, 70-75% and 5-10% of the ICRH power is absorbed, respectively, by D ions, hydrogen minority ions and by direct electron damping by electron Landau damping and transit time magnetic pumping. In discharge 87331 damping by hydrogen minority ions is reduced due to a lower $n_H/(n_H+n_D)$. The best agreement with the measured data is obtained assuming a very low $n_H/(n_H+n_D)$ of < 0.1%. As result, the H damping is negligible, while direct electron and D damping take 45 and 55% of the ICRH power, respectively. The ICRH power transferred to the bulk ions was about 2, 2.5 and 1 MW for 86614, 86871 and 87331, respectively, the rest being transferred to the plasma electrons. The ICRH power was deposited centrally inside r/a < 0.5, where r/a is the normalised plasma minor radius.

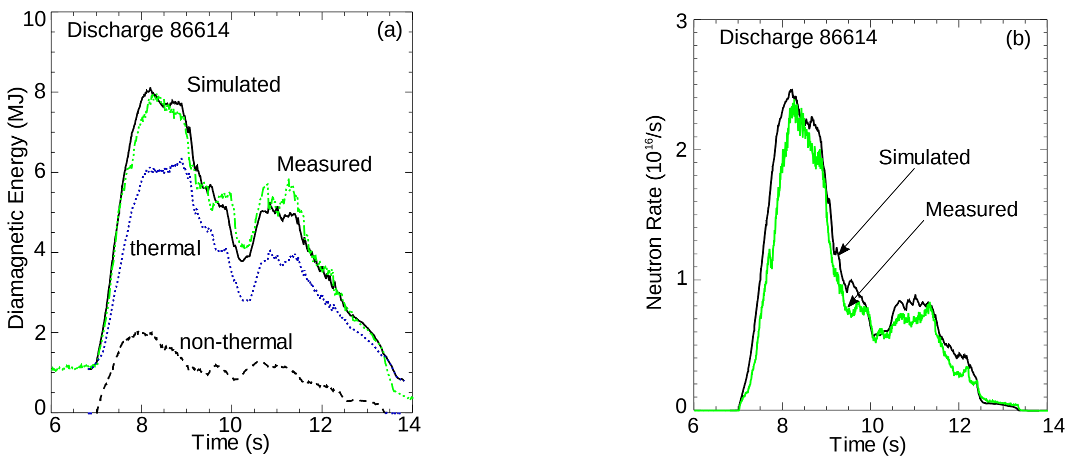

Figure 3 (a) Measured (green) and simulated (solid black) total plasma diamagnetic energy content as given by PION and (b) measured (green) and simulated (black) total neutron rate as given by PION for discharge 86614. In (a) the measured thermal (dotted blue) and simulated nonthermal (black dashed) contributions are also shown.

The comparisons of the simulated and measured plasma diamagnetic energy content W_{DIA} and total neutron rate R_{NT} are shown in Fig. 3 for discharge 86614. The agreement between modelling and experimental results is remarkably good. Similar agreement is found for discharges 86871 and 87331. The thermal contribution to W_{DIA} is about 75% while the non-thermal component is about 25%. Furthermore, according to PION, 5-20% of R_{NT} is due to the second harmonic D acceleration (Fig. 4). The predicted ICRH enhancement of R_{NT} has been compared with the results of the time-of-flight neutron spectrometer TOFOR [4]. TOFOR consists of two sets of plastic scintillator detectors that view the plasma vertically through the plasma centre. The energy of the impinging neutrons is deduced from the time of flight between these two sets of detectors. A measured TOFOR spectrum is separated into components due to thermonuclear (TH), beam-thermal (NBI), ICRH induced fusion reactions and scattered neutrons (Fig. 5). The spectral shape of the ICRH component is calculated from the D distributions given by PION while the NBI component is calculated from the slowing down distributions obtained with the NUBEAM code [5], which is part of the TRANSP package, and the TH component is a Gaussian with a width determined by the plasma temperature. An estimate of the ICRH enhancement is obtained from the fitted component intensities as $I_{ICRH}/(I_{TH} + I_{NBI})$. The ICRH enhancement estimated in this way is in good agreement with the PION simulations, as shown in Fig. 4.

Conclusions and extrapolation to DT plasmas Recent JET high-performance hybrid discharges with combined NBI and ICRH have been successfully modelled with the PION code. Good agreement between modeling and measured data was obtained, lending confidence in the simulations. The modeling shows that both central electron and ion heating is increased significantly with the application of ICRH. The extrapolation of discharges 87331 and 86614 to a 50%-50% D-T mixture yields a fusion power of about 4 and 7 MW, with an ICRH enhancement of the fusion yield of ≈5-10% and 15%, respectively. The goal for the JET hybrid scenario development in 2015-2016 is to more than double these values, i.e. to reach predicted fusion power of 15 MW with a pulse duration of at least 5s, in preparation of the JET deuterium-tritium campaign DTE2.

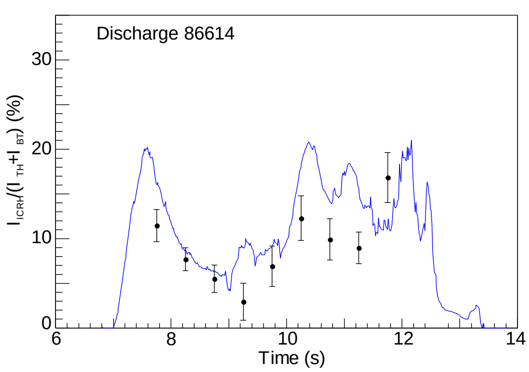

Figure 4 Enhancement of the neutron rate due to second harmonic D damping according to PION (blue line) and TOFOR (points with error bards) for discharge 86614.

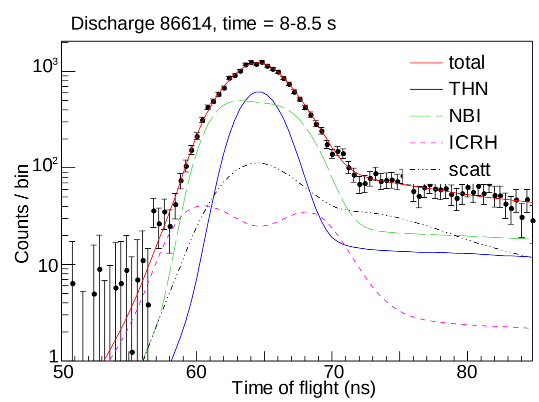

Figure 5 TOFOR data points with error bars for discharge 86614 integrated over a time interval of t = 8-8.5 s. Also fitted components describing thermonuclear (TH), NBI, ICRH and scattered neutrons are shown.

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