Optimising the use of ICRF waves in JET hybrid plasmas for high fusion yield

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Introduction In the recent experimental campaigns on the JET tokamak, good progress was made in the development of high-performance plasma scenarios compatible with the ITER-like wall (ILW). The record JET ILW fusion yield, averaged over 100 ms, was increased from 2.3×10^{16} neutrons/s to 2.9×10^{16} neutrons/s with respect to the previous 2014 JET ILW fusion record. This paper reports on the optimisation of the use of ion cyclotron resonance frequency (ICRF) waves for high fusion yield in the hybrid scenario. The hybrid scenario is an operational plasma regime designed to achieve long pulse operation with a combination of inductive and non-inductive current drive. It has been proposed for ITER to allow operation at a high fusion power over 1000 s at a lower plasma current than for the inductive reference scenario.

Experimental set-up High-performance hybrid discharges were achieved with combined deuterium neutral beam injection (NBI) and ICRF heating. ICRF waves were tuned to the fundamental cyclotron frequency of minority hydrogen ions which coincides with the second harmonic cyclotron frequency of deuterium ions ($\omega \approx \omega_{cH} = 2\omega_{cD}$). Impurity control with

ICRF waves was found to be one of the key means for extending the duration of the high-performance phase. This is illustrated in Figure 1a which shows plasma parameters for two 1.5 MA/ 2.1 T hybrid discharges 90348 and 90350. They were prepared in the same way apart from the external heating power. While discharge 90350 with NBI heating only suffers impurity accumulation which leads to a deterioration of the fusion performance, the performance is maintained throughout the heating phase in discharge 90348 with ICRF heating at 32 MHz tuned to a central H minority resonance. The reason for this difference is believed to be the central heating provided by ICRF waves. It resulted in a more peaked temperature profile and a flatter density profile (cf. Fig. 1b) in the plasma core, which were favourable for the avoidance of impurity accumulation. In subsequent discharges where we varied the ICRF resonance location, we found that a central resonance with $|R_{res}-R_0|<15$cm is required in order to prevent impurity accumulation and deleterious MHD modes. Our results are in line with previous results on ICRF heating for core impurity control in JET-ILW [1, 2], extending them to high-performance hybrid plasmas of long duration.

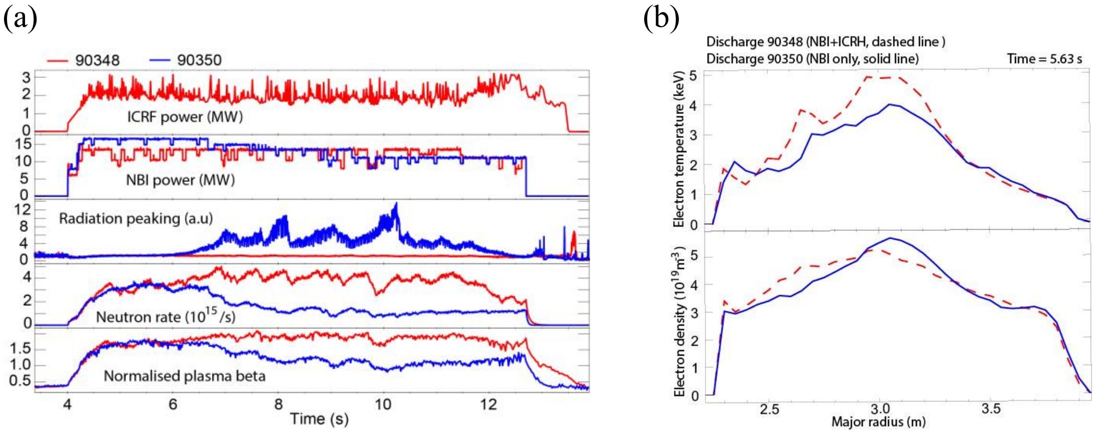

Figure 1 (a) ICRF power, NBI power, radiation peaking factor, neutron rate and normalised plasma beta for 1.5 MA/2.1T JET hybrid discharges 90348 (red) and 90350 (blue). The radiation peaking factor is the ratio of three most central bolometer channels to three channels off-axis and is an indication of the impurity content in the plasma center. The hydrogen concentation was 1%. (b) Electron temperature and density profiles at t = 5.63 s in the two discharges. The magnetic axis and the ICRF resonance are located at a major radius of 3.05 and 2.95 m, respectively.

It is well known that the H concentration plays a key role for the physics of H minority heating, see e.g. [3]. It determines the ICRF power partitioning between the H minority ions and deuterium ions and, thereby, affects the bulk plasma heating and the ICRF enhancement of R_{NT} due to ICRF-accelerated deuterons. To clarify its role in high-performance hybrid plasmas on JET, three 2.8T/2.4MA hybrid discharges were carried out with 5 MW of ICRF power and 20 MW of NBI power but different H gas puffing (c.f. Fig. 2a.) The ICRF frequency was 42 MHz. As we can see, R_{NT} is about 10-25% lower in discharge 92323 with highest H puffing, resulting in a H concentration of about 3%, as compared with other two discharges with lower H puffing and concentration (1.5 and 2%). The observed differences are consistent with the measured stronger ICRF-accelerated fast deuterium tails in discharges with low H concentration and is well reproduced by the PION [4] modelling taking into account NBI+ICRF synergy [5]. The radial profiles of the H and D damping power density as given by PION for the three discharges are shown in Fig. 2(b). The ratio of H to D damping scales roughly as $p_H/p_D \propto n_H$ as expected. We conclude that ICRF heating with a low H concentration is advantageous for maximising the D-D fusion yield through ICRF-acceleration of D ions while preventing central impurity accumulation.

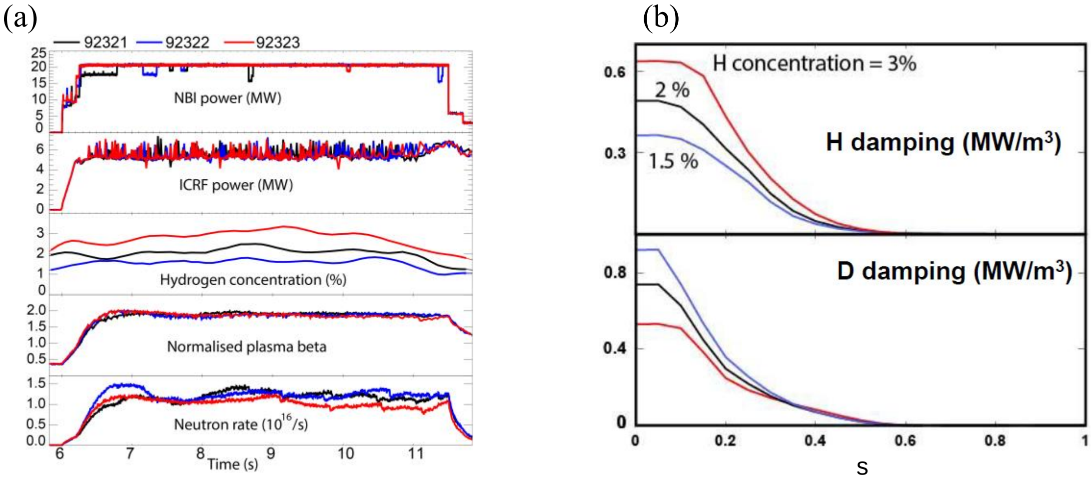

Figure 2 (a) NBI power, ICRF power, H concentration, normalised plasma beta and neutron rate for 2.8T/2.4MA JET hybrid discharges 92321 (black), 92322 (blue) and 92323 (red). (b) Radial profiles of the H and D damping as given by PION for the three discharges in (a). Here s is the square root of the normalised poloidal flux.

Record fusion performance Figure 3a shows the main plasma parameters for one of the hybrid discharges with highest fusion yields in the 2015-2016 experimental campaign. It was carried out at a plasma current of 2.2 MA and a magnetic field of 2.8 T using 27 MW of NBI heating and 4.5 MW of ICRF heating at 42 MHz. The ICRF H minority resonance was in the plasma center and the H concentration was 1-2%. The neutron rate and normalised plasma beta steadily increased to their steady-state values of 2.7×10^{16} s^{-1} and 2.7, respectively, when stationary high-performance plasma was obtained. The dominant impurities were mid-Z impurities Ni, Fe, Cu and Mo. At t = 8.8 s, the discharge was terminated by the machine protection system that detected a main chamber hot spot. The reason for the hot spot is still under investigation. In subsequent shots, the hot spot was mitigated with local gas puffing close to the limiter but it was not possible to progress further due to limited experimental time at the end of the campaign. Figure 3b shows the measured and modelled neutron rate. The modelling has been performed with the PION code and shows excellent agreement not only with the measured total neutron rate but also with the ICRF enhancement of the neutron rate [5]. For this plasma, the ICRF enhancement of the neutron rate was found to be about 15% in the stationary plasma phase. For an equivalent D-T plasma, PION predicts about 7 MW of D-T fusion power with ICRF neutron enhancement of ~5%.

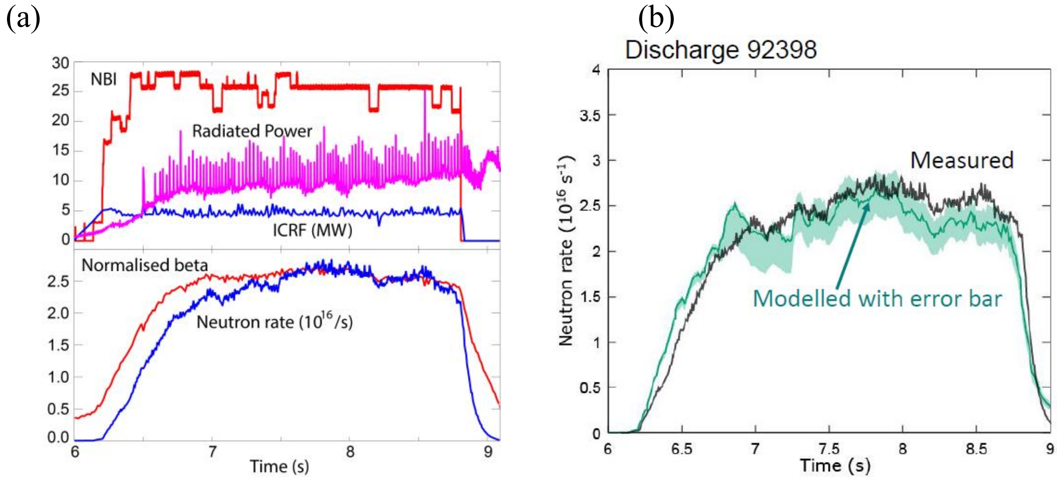

Figure 3 (a) Main plasma parameters for high-performance 2.2 MA/ 2.8 T JET hybrid discharge 92398. (b) Time-evolution of the measured and simulated neutron rate as given by PION. The error bar of the simulated neutron rate accounts for the uncertainties in the H concentration and ion temperature. The error bar was obtained by varying these two key parameters within their measurement uncertainties.

Conclusion and future outlook The record JET ILW fusion yield, averaged over 100 ms, was increased from 2.3x10^{16} neutrons/s to 2.9x10^{16} neutrons/s with respect to the previous 2014 JET ILW fusion record. Impurity control with ICRF waves was one of the key means for extending the duration of the high-performance phase. The best fusion performance was obtained with a central ICRF resonance and with a low H concentration. Future plans include making use of a higher total ICRF+NBI power of ~40 MW and avoiding high limiter heat loads to extend the duration of the steady high-performance phase. The plans for further ICRF optimization include the use of different ICRF antenna phasings to vary $k_{||}$ spectrum, ^{3}He minority heating to vary the fast ion population and ion-to-electron heating ratio and second harmonic tritium heating both in T and D-T plasmas.

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