Third harmonic ICRF heating of deuterium beam ions on ASDEX Upgrade

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Introduction We report on recent experiments on the ASDEX Upgrade (AUG) tokamak (major radius R ≈ 1.65 m, minor radius a ≈ 0.5 m) with third harmonic ICRF heating of deuterium beam ions. Prior to this work, the scheme has been developed and applied on the JET tokamak, the largest currently operating tokamak (R ≈ 3 m, a ≈ 1 m), for fusion product studies and for testing alpha particle diagnostics in preparation of ITER [1]. The experiments reported here demonstrate that this scheme can also be used in medium size tokamaks such as AUG despite their reduced fast ion confinement.

Experimental set-up The experiments were carried out in H mode AUG plasmas with 2.5-5 MW of deuterium NBI with a maximum injection energy of 59-93 keV. A total of four discharges (cf. Table 1) were performed with ICRF power tuned to the central D resonance with an ICRF frequency of 41.8 MHz and the 0π phasing of the ICRF antennas.

Experimental results and comparison with modelling The main plasma parameters of discharge 32331 are compared in Fig. 1 with those of discharge 32330 which was prepared in the same way but without ICRF power. The comparison of these discharges shows a clear increase in the neutron rate R_{NT} with ICRF power, which was observed with two independent neutron detectors, i.e. an epithermal neutron detector [2] and a LaBr3 detector [3]. Both discharges were terminated by a disruption due to impurity accumulation, with an earlier disruption at t = 2.68 s in discharge 32331.

Table 1 Main parameters for AUG discharges with third harmonic ICRF heating of deuterium beam ions

Parameter\Discharge	32331	32573	32604	32605
Magnetic field (T)	1.8	1.85	1.85	1.85
Plasma current (MA)	1.0	0.8	0.8	0.8
NBI power (MW)	2.6	5.1	5.0	5.0
NBI inj. energy (keV)	59	59 and 93	59	59
ICRF power (MW)	2.0	1.8	3.6	3.8

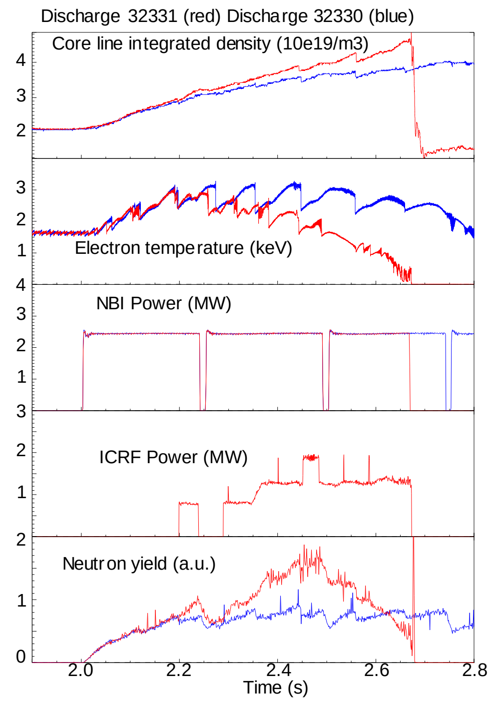

Figure 1 Main plasma parameters for AUG 1MA/ 1.8T discharge 32331 and reference discharge 32330 without ICRF power.

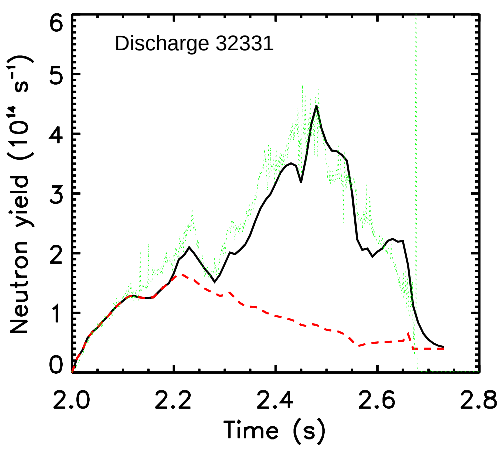

Figure 2 Measured (green) and simulated (black) R_{NT} as given by PION for discharge 32331. The measured R_{NT} has been scaled to match the simulated R_{NT} at t = 2.25 s. Also shown is R_{NT} as calculated by PION assuming zero ICRF power (red dashed line).

A detailed analysis of discharge 32331 with the TRANSP and PION codes shows that the measured R_{NT} is up to a factor of 4-5 times larger than R_{NT} due to beam-thermal and thermal fusion reactions. PION [4, 5] provides time-dependent modelling of combined ICRF and NBI heating, taking into account the absorption of ICRF power on the resonant D beam ions. It uses the measured plasma parameters and the NBI deposition as calculated by TRANSP as input. According to PION, the observed increase in R_{NT} during ICRF heating is consistent with the acceleration of D beam ions with ICRF waves above the maximum injection energy. As we can see in Fig. 2, PION reproduces both the time behaviour and the observed relative increase in R_{NT}. As the fast deuterium tail develops in the deuterium distribution function as ICRF power is absorbed by D, the single pass D damping more than doubles from about 20% at t = 2.2 s to 45% at t = 2.55 s for the toroidal mode number N = 12. According to PION, about 85%, 10%, and 5% of the ICRF power is absorbed by deuterons, direct electron damping and parasitic edge damping, respectively, at t = 2.55 s. The parasitic edge damping was included in the PION modelling in the same way is for earlier JET discharges [6, 7].

Further confirmation for the acceleration of fast deuterons above the injection energy was obtained with passive and active neutral particle analysers (NPAs) [8]. Significant deuterium fluxes above the maximum NBI injection energy were observed by the NPAs up to the maximum energy of 200 keV of the measurements (Fig. 3). No fast protons were detected, which is consistent with the applied scenario. The D ion distribution function as simulated by PION and SELFO [9] are broadly consistent with the measured NPA fluxes. According to both codes, the calculated D distribution function extended to the 1 MeV range and the fast ion losses remained small. The high-energy cut-off of ICRF induced velocity space diffusion due to finite Larmor radius effects [10,11] was about 1.2-1.5 MeV and roughly equal to the maximum energy of trapped deuterons that were confined in these plasmas.

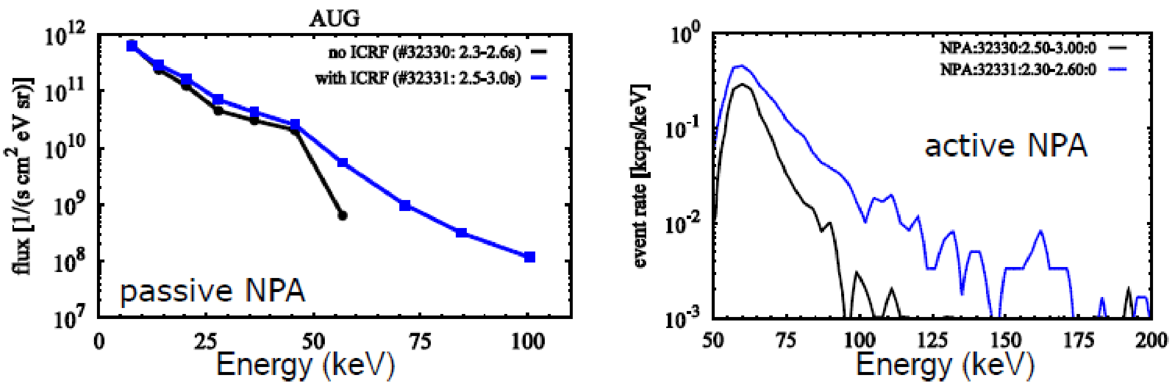

Figure 3 Deuterium flux as measured with the passive NPA and the event rate measured by the active NPA for AUG discharge 32330 with NBI only and discharge 32331 with third harmonic heating of deuterium beam ions.

The main goal for the subsequent discharges was to establish more stable plasmas while maintaining efficient acceleration of D ions by ICRF waves. This was achieved in discharge 32573 with the changes to the discharge parameters as indicated in Table 1. Furthermore, the plasma electron density was increased to $5x10^{19}$ m^{-3} and three pulses of ICRF power were programmed while maintaining constant NBI, each long enough to reach steady-state plasma conditions. As we can see in Fig. 4, the neutron rate R_{NT} clearly responded to the application of ICRF power. This result was confirmed with all three available independent neutron detectors, i.e. the epithermal neutron detector, the LaBr3 detector and a neutron spectrometer [12]. They showed an increase of a factor of 1.7-2.1 in R_{NT} with respect to its level without ICRF power. However, the observed ICRF enhancement was found to be smaller than the factor of about 2.5 predicted by PION. The reasons for this difference are under investigation and may be related to interaction of fast ions with MHD modes such as the m = 2 / n =1 locked mode that persisted throughout the discharge. In the two remaining discharges 32604 and 32605, the ICRF power was increased while the maximum beam injection energy was reduced back to 59 keV as in discharge 32331. The latter change allowed better diagnosis of the fast D tail with the NPAs. The measured NPA deuterium fluxes were observed to increase with ICRF power, as expected from theory. At the highest coupled ICRF powers in discharge 32605, however, the observed ICRF enhancement of R_{NT} was found to be smaller than that predicted by PION as for discharge 32573 above. Unfortunately, like discharge 32331 above, discharges 32604 and 32605 suffered from radiation events and impurity accumulation. Their comparison with discharge 32575 suggests that increasing the NBI energy, which leads to improved D single pass damping, is beneficial for the applied scheme on AUG. Finally, we note that according to PION, the deuterium energy content increased approximately by 30-50% with the application of ICRF power in these AUG discharges.

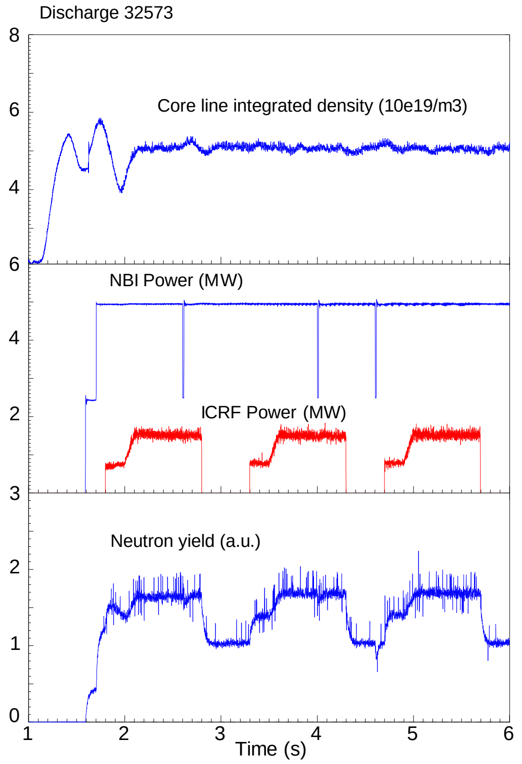

Figure 4 Overview of discharge 32573. The neutron yield is as measured by an epithermal neutron detector.

Conclusions Third harmonic ICRF heating of deuterium beam ions has been demonstrated on AUG for the first time. The acceleration of fast deuterons above the beam injection energy was confirmed by three independent neutron diagnostics and direct measurements with passive and active NPAs. The magnitude of the observed deuteron acceleration is consistent with modelling. The scheme provides a new tool for fast ion physics studies and diagnostic development on AUG.

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