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ABSTRACT

Results of the experimental studies of ICRH at the fundamental cyclotron frequency of the majority deuterons in JET plasmas with near-tangential deuteron neutral beam injection (NBI) are presented. 1D, 2D and 3D ICRH modeling indicated that several ITER relevant mechanisms of heating may occur simultaneously in this heating scheme: fundamental ion cyclotron resonance heating of majority and beam D ions, impurity ion heating and electron heating due to Landau damping and TTMP. These mechanisms were studied in JET experiments with a ~90% D, 5% H plasma including traces of Be and Ar. Up to 2MW of ICRH power was applied at 25 MHz to NBI heated plasmas. In most of the discharges the toroidal magnetic field strength was 3.3T, but in one it was equal to 3.6T. The E_+ component of the electric field governs the ion cyclotron heating of not too fast particles. The Doppler shifted RF absorption of the beam deuterons away from the cold resonance at which E_+ is small was exploited to enhance the RF power absorption efficiency. Fundamental ICRH experiments were also carried out in LHD hydrogen plasma with high energy hydrogen NBI. ICRH was performed at 38MHz with injected power <1 MW. The effect of fundamental ICRH was clearly demonstrated in both machines.

INTRODUCTION

Ion heating schemes at the fundamental cyclotron frequency of the majority ions were tested in the past. There were successful experiments in the stellarator-C (1968, PPPL), the Kharkov torsatrons and the US mirror traps. Small tokamaks (TM-1-Vch (1974) [1], TO-2 [2], T-11M [3] and Globus-M [4]) and L-2 stellarator [5] have also shown good heating results at the fundamental harmonic of the majority ions. LHD has recently demonstrated bulk ion heating at the fundamental cyclotron frequency in high density plasmas, with densities close to those of the scenarios foreseen for ITER's activated phase [6]. Bulk ion heating was also demonstrated in experiments with fundamental deuterium ICRH in 20% D + 80% T plasma during DTE1 [7]. Studies of the fundamental ICRH mechanism in ITER-like conditions at JET and LHD are crucial for understanding the perspectives of application of this ICRH scheme in ITER plasmas.

MODELING OF JET FUNDAMENTAL FREQUENCY ICRH

1-, 2- and 3-D TOMCAT [8], CYRANO [9] and PSTELION [10,11] codes were respectively used for modeling the RF power absorption of ions and electrons for experimental conditions typical for JET. The radial distribution of the powers absorbed by thermal and fast deuterons, Be and Ar impurities and electrons were calculated. The TOMCAT code predicts a very low (~5-15% depending on whether fast ions are included in the modeling or not) total double pass power absorption, suggesting that large electric fields are likely to be set up in order to absorb the launched power and hence that interaction with the wall can be expected to be significant; this was observed in the experiment. The calculations made by the PSTELION code not only allow to study the fast wave dynamics but equally the fate of power transferred at ion-ion hybrid layers to mode converted short wavelength branches (IBW and ICW), and this accounting for the actual 3-D geometry. The simulations have confirmed that mode conversion effects are small but fast wave electron damping is significant in the majority D-heating JET scenario. Majority D heating and particularly beam D heating evidently plays a key role (see [11] for CYRANO modeling), but absorption by impurities should not be overlooked either.

RESULTS OF FUNDAMENTAL ICRH OF JET D PLASMA

The following heating mechanisms were experimentally studied on JET: fundamental ICRH of bulk D-plasma (pre-heated to higher than Ohmic temperatures by high energy deuterium neutral beam injection), fundamental ICRH of beam D ions (benefiting from the large Doppler shifts), indirect ICRH of bulk D-plasma through addition of Beryllium and Argon, and direct electron heating. The experiments were carried out in plasmas containing ~90%D, 5%H, as well as main impurities Be (≤1%, with decreasing concentration from shot to shot after vacuum vessel beryllium evaporation prior to the experiments) and Ar (≤0.5% due to gas puff), with $I_p = 2$ MA, $n_e(0) = 2.5\times10^{19}$ m^{-3} (optimized to favor RF heating of the beam ions) and $R_{ax} = 2.97$ m. Two sessions of experiments were carried out. The first was performed with 5MW of low energy (80keV) NBI injected from octant 4 at about ~80^o to the magnetic axis (normal beam) and 1.3 MW, 130 keV beam injected at ~60^o (tangential beam) to magnetic axis. The second experiment adopted 5.9 MW of 130 keV beam, integrally injected from octant 8 at ~60^o to the magnetic axis. The NBI power was limited to avoid going into H-mode. Up to 1.65 and 2 MW of ICRH power were applied at 25MHz during the first and second sessions, respectively. To optimize heating, dipole phasing was imposed, most power being launched with $|k_{||}| = 6.6$ m^{-1}. In most of the discharges the toroidal magnetic field strength was equal to 3.3T (the plasma deuterons resonance layer being at R=3m, that of Be and Ar resonances at ~2.7m). To position the Be/Ar resonance layer more centrally one experiment was done at 3.6T. Evolutions of total neutron yield measured by fission chamber together with NBI and ICRH powers in discharge 68287 are presented in Fig.1. Adding ~20% of (RF) auxiliary heating power results in a ~45% increase of the neutron yield (left figure), 35% of which is interpreted as due to the ICRH benefiting from the NBI and 10% due to the natural evolution of the NBI-only heated discharge to reach stationary state conditions. This effect can be seen on the neutron camera plot (right figure): the number of counts in a 100ms interval when both RF and NBI power are applied exceeds the number resulting from the isolated RF or NBI heating.

Detailed analysis is ongoing about the nature of this augmentation. Since various neutron diagnostics observe an overall growth of the signal when RF heating is applied, one may suspect that it is the *number* of particles mainly contributing to the neutron yield that is increased in the NBI+RF heating phase. Aside from that, modeling efforts suggest that – for the available RF power at 25MHz – a very small subpopulation of the D particles may reach energies of ~200keV, an effect becoming more pronounced when increasing the RF power [11]. The fundamental ICRH caused the ion and electron temperature increases up to ΔT_i=1keV and ΔT_e=0.4keV near the plasma center when ~1.5MW of RF power was added. Both electron and ion temperatures decrease in the outer plasma region during ICRH start-up, an effect attributed to the strong impurity influx from the wall into the plasma as a consequence of the rather poor RF power absorption. After t~0.5s, this effect fades out but both the electron and ion temperature profiles remain somewhat peaked during most of the RF phase. To compare experimentally the relative efficiency of on- versus off-axis majority D heating as well as impurity absorption in JET, pulse 68734 was done at a different magnetic field, 3.6T. Compared to the on-axis heating pulses (e.g. 68733), a broadening of both the ion and the electron temperature profiles was observed during ICRH at 3.6T.

FUNDAMENTAL ICRH STUDIES OF LHD H PLASMA

Experiments were performed in LHD discharges 63804 and 63808 in 90%H + 5%He plasma with parameters: B=2.82T, R_{ax}=3.5m, $n_e = 0.5 – 1.1 \times 10^{19}$ m^{-3}, T_e at resonance = 2.1 keV. The energies of the hydrogen NBIs were in the range 154-172 keV with total power of 11.1 MW. Injected powers of ICRH at 38MHz were equal to 0.67 MW (63804) & 0.94 MW (63808). Since the majority heating tests were done in conjunction with another experiment, ICRH was not optimized: as the axis was at 3.5m and the antenna outward shifted, the power was far from maximum. In spite of such non optimal conditions, the effects of plasma and beam proton heating by fundamental ICRH were demonstrated by an increase of plasma stored energy from 220 to 290kJ (32% by adding ~ 8% of power (63804)) and by the enhancement of the fast perpendicular ion population and its T_{eff}. Through direct or indirect RF heating, a growth of the H central ion temperature from 1 to 1.2keV was observed. The central electron temperature also increased from 2.8 to 3.0 keV.

CONCLUSIONS AND FUTURE PROSPECTS

The majority heating scheme traditionally suffers from adverse polarization near the cold resonance. JET and LHD experiments demonstrated that Doppler shifting the resonance layer away from the cold resonance is beneficial and makes this scheme more attractive. This effect was exploited by adopting neutral beam injection. As any population having a non-negligible fraction of its particles at higher energies will suffer less from the adverse polarization, the higher temperatures and densities on ITER would allow to benefit from this effect even without explicitly requiring a beam. Because fundamental RF heating affects the whole distribution rather than a small subfraction, it is capable of affecting the fusion yield significantly. Further exploring this heating scheme seems worthwhile but more RF power would be needed to make the results more ITER-relevant. Also the balanced H-^{3}He majority fundamental RF heating scenarios could be studied in future ITER-like JET and LHD ICRF experiments not only to model basic D-T ITER scenario but equally to contribute to the study of scenarios that will be used in the non-activated ITER phase. Such experiments can help build confidence that majority heating schemes can be optimized to heat ITER.

REFERENCES

[1]. V.L.Vdovin et. al., "ICRH at fundamental frequency on TM-1-Vch tokamak" at IAEA Plasma Phys. And Contr. Fusion Conference 1974 (Tokyo)

[2]. V.N.Amosov, L.I.Artemenkov, I.A.Kovan,et.al., Sov.J. Plasma Physics, v.14 (5), p.363 (1988)

[3]. N.B.Rodionov, E.A Azizov , A.V. Krasilnikov et.al., Sov. J. Plasma Physics, v.32 (2), p.1-11 (2006)

[4]. V.K.Gusev, et.al., "ICRF experiments on the spherical tokamak Globus-M" in Proceedings of 20-IAEA Fusion Energy Conference (2004)

[5]. V.A. Batyuk, et al. Sov. J. Plasma Phys. Vol. 13, n.3, p.143-148 (1987)

[6]. T.Mutoh, R.Kumazawa, T.Seki, et.al., Nucl.Fusion 43, 738-743 (2003)

[7]. D.F.H.Start et.al., Nuclear Fusion,v.39, No.3, p.321 (1999)

[8]. D.Van Eester and R. Koch, Plasma Phys. Contr. Fusion 40, 1949-1975 (1998)

[9]. P.U.Lamalle,"Nonlocal theoretical generalisation and tridimensional numerical study of the coupling of an ICRH antenna to a tokamak plasma", PhD thesis, Université de Mons, 1994 and LPP-ERM/KMS Report nr. 101

[10].V.L. Vdovin "ICRF benchmarking modelling of ITER scenario #2", 7th Steady State Operation ITPA Topical Group meeting, Como, Italy, May 4-6 (2005)

[11]. E. Lerche et al., "D majority heating in JET plasmas: ICRH modelling & analysis of RF power dep. profiles", this conference.

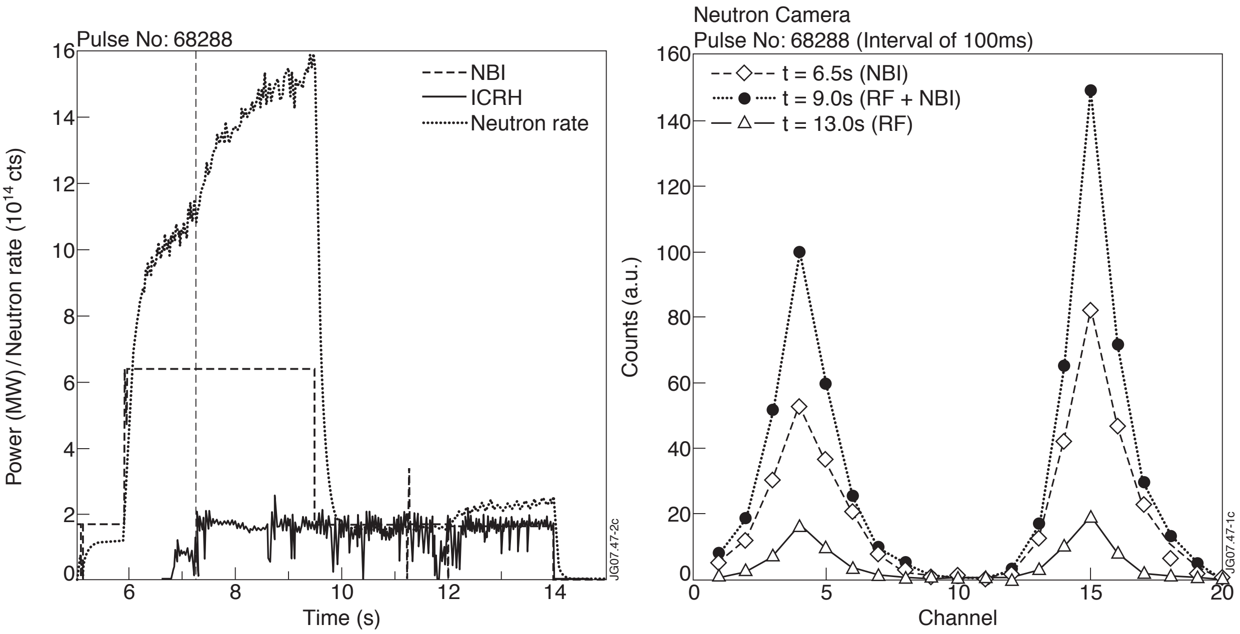

FIGURE 1. Evolutions of neutron rate together with NBI and ICRH powers in pulse 68287 (left). Neutron counts detected by horizontal (channels 1-10 from top to bottom) and vertical (11-19 from inward to outward) neutron cameras during pulse 68288: 6.3 MW NBI only (squares), same NBI together with 1.65 MW ICRH (circles) and 1.65 MW ICRH with only 1.3 MW tangential (charge exchange diagnostic beam power; triangles) (right).