AIP Proceedings

Effect of collisional heat transfer in ICRF power modulation experiment on ASDEX Upgrade

N. Tsujii, R. D'Inca, J.-M. Noterdaeme, R. Bilato, Vl. V. Bobkov, M. Brambilla, D. Van Eester, R. W. Harvey, E. F. Jaeger, E. A. Lerche, P. Schneider, and ASDEX Upgrade Team

Citation: AIP Conference Proceedings **1580**, 239 (2014); doi: 10.1063/1.4864532

View online: http://dx.doi.org/10.1063/1.4864532

View Table of Contents: http://scitation.aip.org/content/aip/proceeding/aipcp/1580?ver=pdfcov

Published by the AIP Publishing

Effect of Collisional Heat Transfer in ICRF Power Modulation Experiment on ASDEX Upgrade

N. Tsujii[*,†], R. D'Inca[*], J.-M. Noterdaeme[*,**], R. Bilato[*], Vl.V. Bobkov[*], M. Brambilla[*], D. Van Eester[‡,§], R.W. Harvey[¶], E.F. Jaeger[‖], E.A. Lerche[‡,§], P. Schneider[*] and the ASDEX Upgrade Team[*]

[*] *Max-Planck-Institut für Plasmaphysik, Garching, Germany*
[†] *The University of Tokyo, Kashiwa, Japan*
[**] *Universiteit Gent, Gent, Belgium*
[‡] *JET-EFDA Culham Science Center, Abingdon, UK*
[§] *LPP-ERM/KMS, Association "EURATOM - Belgian State", Brussels, Belgium*
[¶] *CompX, Del Mar, USA*
[‖] *XCEL Engineering, Oak Ridge, USA*

Abstract. ICRF (ion cyclotron range of frequencies) heating experiments were performed in D-H plasmas at various H concentrations on ASDEX Upgrade. The rf power was modulated to measure the electron power deposition profile from electron temperature modulation. To minimize the contribution from indirect collisional heating and the effect of radial transport, the rf power was modulated at 50 Hz. However, peaking of electron temperature modulation was still observed around the hydrogen cyclotron resonance indicating collisional heating contribution. Time dependent simulation of the hydrogen distribution function was performed for the discharges, using the full-wave code AORSA (E.F. Jaeger, et al., Phys. Plasmas, Vol. 8, page 1573 (2001)) coupled to the Fokker-Planck code CQL3D (R.W. Harvey, et al., Proc. IAEA (1992)). In the present experimental conditions, it was found that modulation of the collisional heating was comparable to that of direct wave damping. Impact of radial transport was also analyzed and found to appreciably smear out the modulation profile and reduce the phase delay.

INTRODUCTION

Waves in the ion cyclotron range of frequencies (ICRF) are widely used to heat fusion plasmas. Usually, fast waves are launched and absorbed by a small concentration of seed ion species (minority heating). The absorbed energy is subsequently transferred dominantly to electrons through collisions. At higher H concentrations ($>15\%$), absorption becomes weak, but it is an interesting regime to study since mode conversion heating starts to play a role. At the two-ion hybrid resonance that exists between the ion cyclotron resonances, the launched fast waves may convert to slow waves such as ion Bernstein waves and ion cyclotron waves. These slow waves are absorbed relatively strongly by electrons, resulting in localized electron heating around the two-ion hybrid resonance (mode conversion heating).

Numerical simulations are essential to analyze ICRF heating in a realistic tokamak geometry, especially, in the presence of both mode conversion and minority heating. In this work, the two-dimensional full-wave code AORSA [1] was used to simulate the ICRF waves. AORSA is a full-spectral solver, and the model is valid for arbitrary $k_\perp \rho_L$ (ρ_L is the Larmor radius) and arbitrary number of cyclotron harmonics. The code is coupled to the bounce-averaged Fokker-Planck solver CQL3D [2] to simulate self-consistent distribution functions and wave fields [3].

In this work, ICRF power was modulated at 50 Hz to estimate the electron power deposition profile from the resulting electron temperature modulation. The fast electron temperature measurement was performed by electron cyclotron emission (ECE) radiometer. Analysis of the measurements was performed taking into account the collisional heating contribution and radial transport effects.

RESULTS OF POWER MODULATION EXPERIMENT IN D-H PLASMAS

The ICRF system of ASDEX Upgrade consists of four antennas powered by four 2 MW generators [4]. The frequency is tunable from 30-120 MHz. Usually, 30 or 36.5 MHz is used for hydrogen minority heating at 2-2.4 T. The

Radiofrequency Power in Plasmas
AIP Conf. Proc. 1580, 239-242 (2014); doi: 10.1063/1.4864532

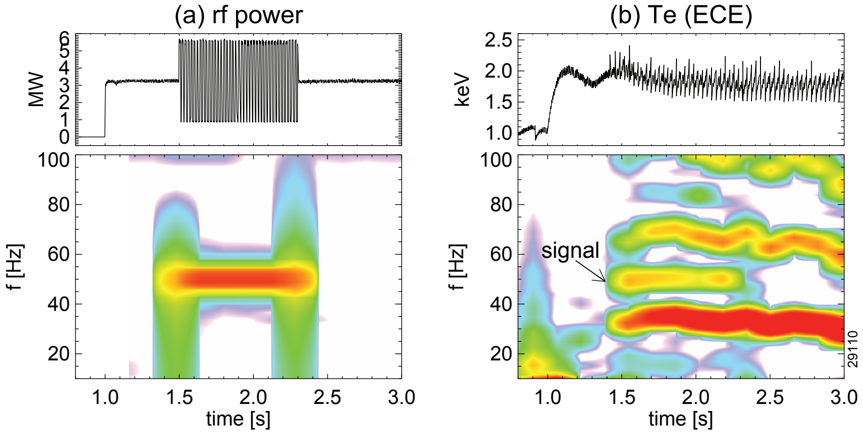

FIGURE 1. The time trace (top) and the spectrogram (bottom) of (a) rf power and (b) electron temperature.

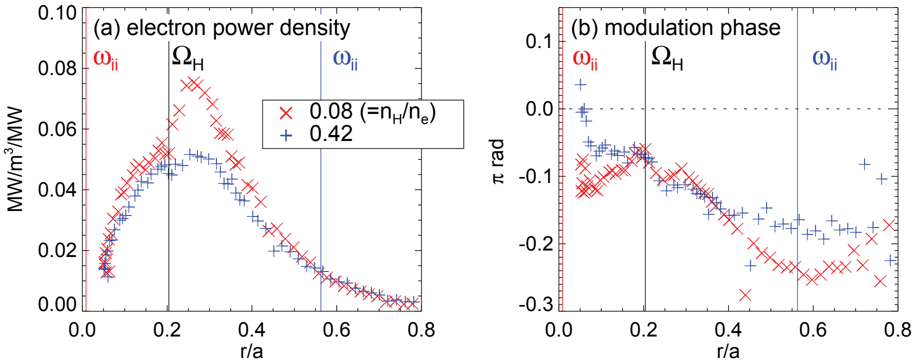

FIGURE 2. The measured power modulation (a) amplitude and (b) phase at two different H concentrations.

electron temperature was measured using a 60-channel second-Harmonic X-mode ECE heterodyne radiometer [5]. The hydrogen concentration was estimated from the ratio of hydrogen and deuterium flux measured by a neutral particle analyzer (NPA).

ICRF heating was investigated in D-H plasmas with various H concentrations by puffing extra H in a D plasma. Typical time traces of the rf power and electron temperature are shown in Fig. 1. Although sawtooth is present, signal due to modulation in the rf power density can be distinguished by setting long enough time window for the FFT (fast Fourier transform) analysis. The reconstructed electron heating power density profiles ($\delta P_{\text{exp}} = -i\omega(3/2)n_{e0}\delta T_e$) are shown in Fig. 2. Little change is seen in the power density profiles at two different H concentrations. The peak stayed close to the H cyclotron resonance, instead of moving around with the two-ion hybrid resonance which was expected to shift during the concentration scan. In the absence of radial transport, the modulation phase is 0 for direct heating and -π/2 for slow indirect heating. The measured phase is around -0.1π, which indicates that multiple effects are in play.

SIMULATION OF COLLISIONAL HEATING MODULATION

The peaking of temperature modulation at the H cyclotron resonance, and its insensitivity to the concentration scan indicates that the contribution of collisional heating from energetic H ions is appreciable. In order to quantify this contribution, time evolution of the H distribution function was simulated with AORSA and CQL3D. The self-consistent

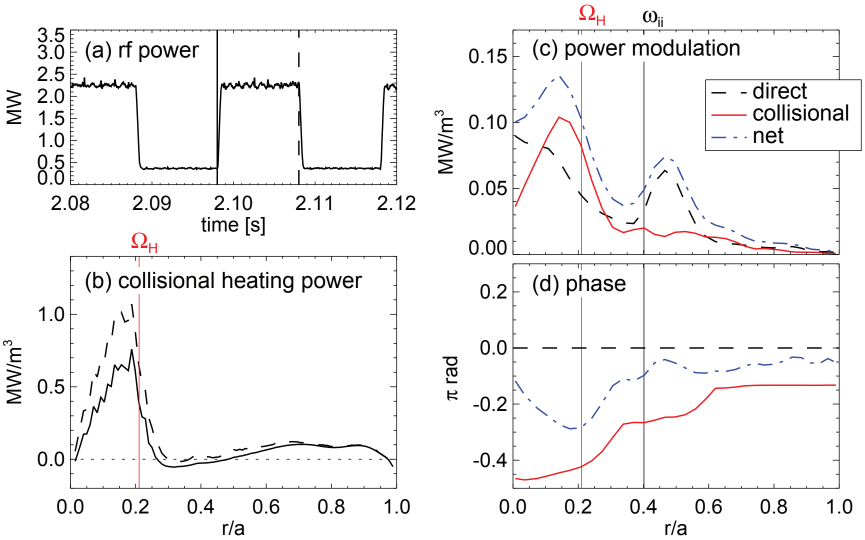

FIGURE 3. The time dependent simulation of electron heating by AORSA-CQL3D. (a) Rf power trace. (b) Maximum (dashed, end of the high power phase) and minimum (solid, end of the low power phase) collisional heating power. (c) Heating power modulation amplitude. (d) Heating power modulation phase relative to the input power modulation.

distribution functions and wave fields were first simulated at the average rf power. Assuming that the perturbation of the wave fields due to modulation of the distribution function is not too large, the wave fields were scaled with the actual modulated rf power, and the H distribution function was evolved under this time-dependent rf quasi-linear diffusion.

The result for the $n_{\mathrm{H}}/n_e = 0.3$ discharge is shown in Fig. 3. For the given rf power modulation (a), the maximum (dashed) and the minimum (solid) simulated collisional heating power is shown (b). The corresponding power modulation amplitude and phase is shown in (c) and (d), respectively. The contribution from collisional heating (solid) is indeed substantial and comparable to direct fast wave and mode conversion heating (dashed).

EVALUATION OF RADIAL TRANSPORT EFFECT

The measured profiles (Fig. 2) are smoother and the phase is advanced compared to the simulated power density (Fig. 3). The transport code ASTRA [6] was used to quantify the impact of radial transport.

The electron energy diffusion coefficient was determined from the experimentally measured profiles, and the simulated average electron heating power density (Fig. 4(a)). The electron temperature was evolved assuming the diffusion coefficient to be fixed at this steady-state value (Fig. 4(b,c), dash-dotted). In reality, the heat transport is non-linear, and the perturbed diffusion coefficient is not the same as the steady-state diffusion coefficient. The result of simulation with diffusion coefficient determined as

$$\chi_e = \chi_{e,\mathrm{exp}} + c\left(\frac{\partial T_e}{\partial \rho} - \frac{\partial T_{e,\mathrm{ave}}}{\partial \rho}\right), \tag{1}$$

is also shown in Fig. 4(b,c) (solid curves). The constant c was tuned to match the measured phase at the modulation peak. The modulation in χ_e at this matched c was $\sim$4% of the average value. The measurement around the modulation peak ($r/a\sim0.2$) is consistent with direct fast wave damping and collisional heating. Note that sawtooth is neglected in the model, and there is no outward convection. Considering also the uncertainty in the H concentration estimate, it is not hard to imagine that the two peaks would actually merge. On the other hand, the phase delay around the hybrid resonance is rather large. That is, mode conversion heating appears to be weaker than collisional heating in the actual experiment more than what is predicted. However, this prediction relies on various numerical simulations, and simplified modeling. In order to make a definitive statement, experiments need to be performed at parameters where mode conversion heating is well-separated from minority heating.

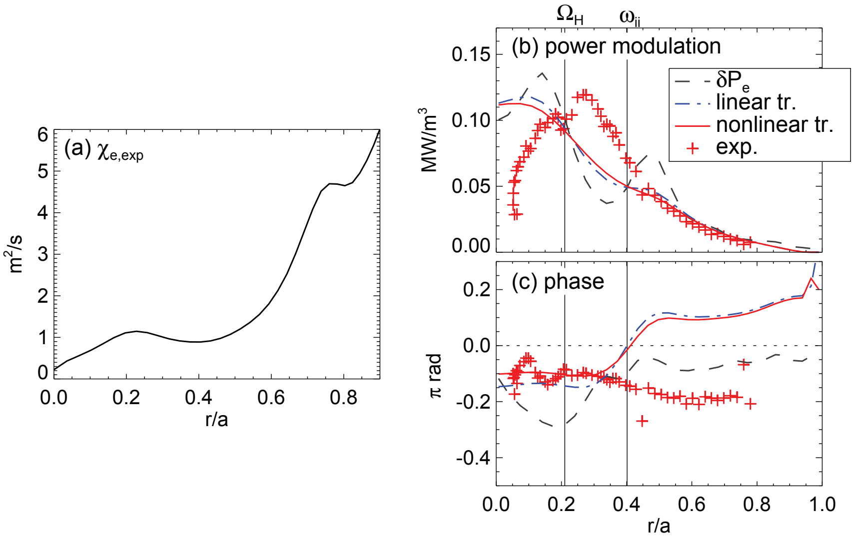

FIGURE 4. (a) The experimentally determined electron energy diffusivity χ_e. (b) The temperature modulation amplitude and (c) phase. The temperature modulation amplitude is multiplied by $(3/2)n_{e0}$ to be converted to power modulation.

SUMMARY

ICRF heating experiments were performed at various H concentrations to study minority and mode conversion heating in D-H plasmas. Rf power was modulated and electron temperature modulation was measured to infer the electron power deposition profile. The power modulation was found to have substantial contribution from collisional heating at 50 Hz modulation frequency. The effect of radial transport was also found to be appreciable under the present experimental conditions. Because of the proximity of the cyclotron resonance and the two-ion hybrid resonance, and rather substantial smearing of the profile due to radial transport, it was difficult to identify mode conversion electron heating. In the future, experiments will be performed with the two-ion hybrid resonance placed close to the center and the cyclotron resonance in the edge to have cleaner measurement of direct electron heating.

ACKNOWLEDGMENTS

The authors thank the ASDEX Upgrade operation and ICRF technical support group. The authors also thank Dr. Tardini and Dr. Fable for their help with the ASTRA transport code.

REFERENCES

1. E. F. Jaeger, L. A. Berry, E. D'Azevedo, D. B. Batchelor, and M. D. Carter, *Physics of Plasmas* **8**, 1573–1583 (2001).
2. R. W. Harvey, and M. G. McCoy, "CQL3D Fokker-Planck code," in *Proceedings of the IAEA Technical Committee Meeting on Simulation and Modeling of Thermonuclear Plasmas, Montreal, Canada, 1992 (USDOC NTIS Document No. DE93002962)*, 1992, p. 40, eDB/700350;.
3. E. Jaeger, R. Harvey, L. Berry, J. Myra, R. Dumont, C. Phillips, D. Smithe, R. Barrett, D. Batchelor, P. Bonoli, M. Carter, E. D'azevedo, D. D'ippolito, R. Moore, and J. Wright, *Nuclear Fusion* **46**, S397 (2006).
4. V. Bobkov, R. Bilato, F. Braun, R. Dux, J.-M. Noterdaeme, the ICRF team, and the ASDEX Upgrade team, *Nuclear Fusion* **46**, S469 (2006).
5. H. J. Hartfuss, T. Geist, and M. Hirsch, *Plasma Physics and Controlled Fusion* **39**, 1693 (1997).
6. G. V. Pereverzev, and P. N. Yushmanov, ASTRA Automated System for TRansport Analysis, Tech. Rep. IPP 5/98, Max-Planck Institute für Plasmaphysik (2002).