SECOND HARMONIC HYDROGEN HEATING ON THE STELLARATOR W7-AS

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1. Introduction

Ion cyclotron resonance heating (ICRH) on the W7-AS stellarator has successfully been demonstrated for a hydrogen minority in a deuterium plasma [1]. This heating scheme, however, imposes severe restrictions on the torus wall condition since the heating efficiency drops drastically for hydrogen concentrations larger than 10%. Thus an alternative heating method is desirable. Second harmonic hydrogen heating is such a means. Using this heating scheme on W7-AS it was possible to sustain plasmas with ICRH alone and to heat NBI target plasmas. The heating efficiency was about 20% worse than that of hydrogen minority heating, but no significant impurity production was observed. Earier attempts to heat ECRH generated hydrogen plasmas were not successful; most likely because the RF power was not sufficiently high to generate a tail in the hydrogen distribution function.

2. ICRH only

Neutral beam (NBI) generated hydrogen start-up plasmas were successfully sustained solely with ICRH for up to 250 msec at the second hydrogen harmonic. About 1.1 MW of radiofrequency (RF) power were applied to one antenna. Pulse duration and maximum power were limited by arcs in the transmission lines. However, the approximate 500 kW power from the antenna, P_{RF}, (estimated from the change in antenna loading resistance with plasma) were sufficient to obtain plasmas with steady-state values of electron density, $n_e(0) = 5 \times 10^{19}\mathrm{m}^{-3}$, electron temperature, $T_e(0) = 300$ eV and hydrogen temperature $T_H(0) = 600$ eV. No increase in the bolometric signal was observed, thus there was no rise in impurity concentrations. The time dependence of the major plasma parameters of a typical shot is shown in Fig. 1. At higher densities steady-state could not be achieved with the maximum available power.

At sufficiently high RF power this heating method does require neither an initial seed nor a constant source of fast hydrogen. This is concluded from investigation of the time evolution of the central hydrogen energy distribution shown in Fig. 2. The distribution is measured with active charge exchange at an angle of 45° to the magnetic field lines. At t=200 msec when NBI is switched-off and ICRH is switched on, the plasma has not yet reached steady-state and the hydrogen energy distribution is determined by the slowing down spectrum of NBI. Within 25 msec the supra-thermal part of the distribution has vanished due to the very short

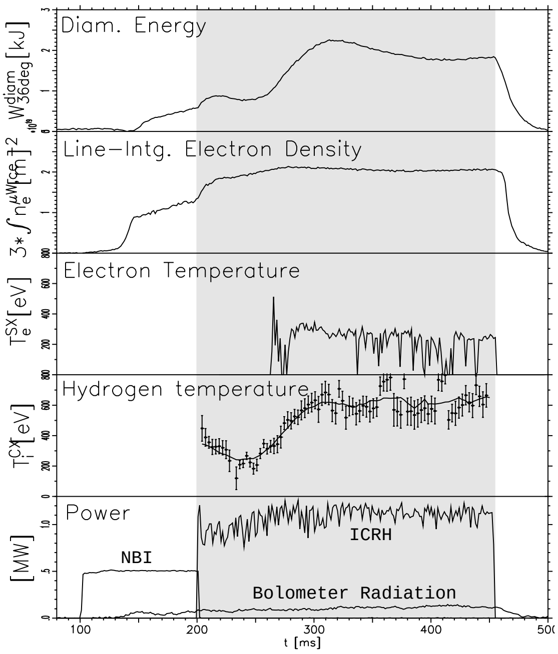

Figure 1. 2nd harmonic hydrogen plasma.

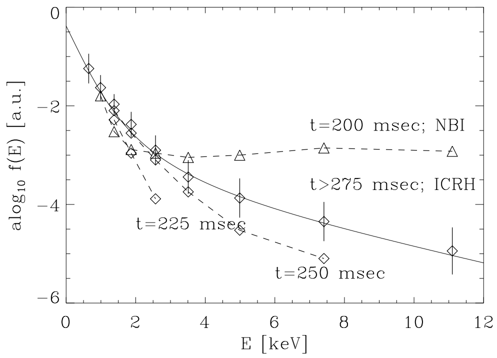

Figure 2. Hydrogen energy distribution function.

equipartition time with the still cold electrons. During the following 50 msec the supra-thermal part slowly increases again following the rise in electron temperature. Eventually at t=275 msec and thereafter the distribution is steady-state.

This "bootstrapping" of the hydrogen energy distribution is confirmed by measurements with a bandpass limited RF pickup probe. This probe is located toroidally opposite to the antenna. It is an indicator for the absorption of the launched RF-wave: high signal meaning poor absorption and vice versa. For second harmonic heating the absorption should increase with the fraction of tail particles. It is found that the probe signal is inversely correlated to the measured hydrogen flux at 2 keV.

The central hydrogen energy distribution agrees well with the steady-state solution of the quasilinear equation [2]. That solution is shown as a solid line in Fig. 2. The calculation is based on an RF-power density of 0.6 W/cm^3. This corresponds to a distribution of the 500 kW radiated power over a volume about half of the plasma volume of 1.6 m^3.

3. ICRH combined with NBI

ICRH at the second harmonic hydrogen frequency was applied to NBI target plasmas. With typical plasma parameters of $n_e(0) = 5 \times 10^{19} m^{-3}$, $T_e(0) \approx T_H(0) = 450$ eV and 400 kW NBI, both electron and ion temperature rose by about 200 eV when 500 kW of radiated RF power were applied for 300 msec. The hydrogen tail temperature rose from 7 keV to 9 keV with the In those experiments a small increase in bolometric signal of about 50 kW was observed and could predominantly be attributed to an increase in carbon radiation. The antenna was operated in 0 and in $\pi-$phasing. No substantial difference was found either in the antenna coupling resistance or in the bolometric signal.

By comparison of the increase in diamagnetic energy, W_{dia}, with established W7-AS confinement time scaling it was found that about 70% of the ICRH power radiated from the antenna were absorbed in the plasma. Fig. 3 shows the increase in diamagnetic energy as a function of radiated RF-power at different densities. The solid lines are calculated for the power dependence of the W7-AS confinement time scaling equating the absorbed RF power, P_{ICRH}, to 70% of the radiated RF power.

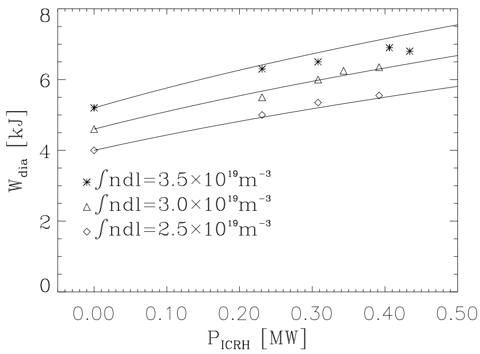

Figure 3. Diamagnetic energy for different power levels and densities.

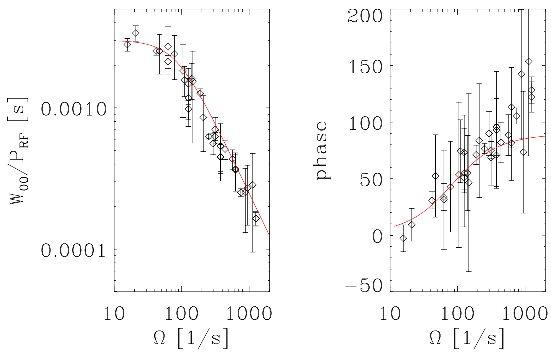

Figure 4. ICRH power modulation.

In a series of modulation experiments the RF power was square-wave modulated with frequencies between 2.5 and 200 Hz. A global confinement time model (dW/dt=-W/τ+αP_{RF}) was fitted to the measured amplitudes of Fourier components of the diamagnetic energy and to the phase shift between RF power and diamagnetic energy. α is the absorbed fraction of the radiated power and τ is the incremental confinement time. The experimental results are shown in Fig. 4. The solid lines are the fit to the data with α=0.5 and τ =12 msec. The discrepancy of the absorbed power from scaling and modulation measurements was also found for hydrogen in deuterium minority heating experiments. It is not yet understood.

The radial electric field in the outer region of the NBI plasma is negative with values up to -15 kV/m (measured passively on Bor). With ICRF it increases at fixed radial positions up to -23kV. DKES [3] calculations, however, show a weak dependence of the radial electric field on the radial ion flux. Therefore it is not possible to decide if fast ion losses in the relatively large local mirror of W7-AS account for the missing RF power.

4. Discussion

Second harmonic hydrogen heating is a reliable means for heating of NBI plasmas and for sustaining plasmas at medium densities for the W7-AS stellarator. Earlier attempts to heat ECRH generated hydrogen plasmas were not successful. The available RF power at that time was only about 40% of the power of these recent experiments. This power was probably too low to generate and sustain a fast hydrogen tail. If so an increase in the heating efficiency at higher power could be expected especially in the successor experiment W7-X which should have better fast ion confinement.

Acknowledgements

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References

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