PLASMA HEATING AND SUSTAINMENT IN THE ION CYCLOTRON RANGE OF FREQUENCIES ON THE STELLARATOR W7-AS

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Abstract

On the stellarator W7-AS resonant and non-resonant ICRF heating scenarios were successful both in increasing the ion and electron temperature of ECRH or NBI target plasmas and in sustaining the plasmas under steady-state conditions. The investigated scenarios were: D(H), ^{4}He(H) minority heating (minority species in brackets), D/H mode conversion heating and second harmonic H heating. In all cases density control was possible and no significant increase in impurities was observed. The heating efficiencies were comparable to tokamaks.

1. INTRODUCTION

Electromagnetic waves in the ion cyclotron range of frequencies (ICRF) have become a successful and reliable means for plasma heating in tokomaks with the advance of larger devices and better wall conditioning. In stellarators ICRF heating is still in the process of being established. It is hampered by the comparative smallness of the devices and - for some heating schemes - by the large aspect ratio, but is desirable in order to achieve ion heating without particle refueling.

Here we report that on the stellarator W7-AS resonant and non-resonant ICRF heating scenarios were successful both in increasing the ion and electron temperature of ECRH or NBI target plasmas and in sustaining the plasmas under steady-state conditions. The investigated scenarios were: D(H), ^{4}He(H) minority heating (minority species in brackets), D,H mode conversion heating and second harmonic H heating. In all heating schemes there was no significant rise of impurities and the plasma density was controllable for $n_e(0) > 4 \times 10^{19}\mathrm{m}^{-3}$ depending on the condition of the torus walls.

The used ICRF antenna is located on the high field side where the plasma has a prolate cross-section and a tokamak-like magnetic profile with effective radius of $R_{\mathrm{eff}} = 1\mathrm{m}$. The plasma major and minor axis are 0.3 m and 0.11 m, respectively. The antenna [1] has four ports. One RF generator is connected to two ports, the other two ports are resonantly short circuited. In π-phasing the antenna excites a narrow $k_{||}$-spectrum centered around $k_{||} = 6\mathrm{m}^{-1}$. The antenna was operated at 34 and 38 MHz with voltages in the unmatched part of the transmission line reaching 40 $\mathrm{kV_{eff}}$ for up to one second, corresponding to RF generator powers of 1 MW. The antenna loading resistance typically doubled with plasma. Thus it was estimated that the RF power radiated from the antenna was about half of the applied generator power.

The sensitivity of the minority and mode conversion schemes to the hydrogen concentration required preceeding wall conditioning with glow discharges in B_2D_6 or subtle changes to hydrogen sources (e.g. the position of graphite limiters and the presence of diagnostic hydrogen beams), respectively. The relative hydrogen concentration n_H/n_e was estimated from active charge exchange measurements and - at times - spectroscopically from the ratio of H_α/D_α. Both measurements agreed within the absolute errors of ± 0.15.

The stellarator W7-AS is a five-fold modular advanced stellarator with a toroidally averaged major radius R=2.04 m. The volume averaged radius of the last closed flux surface is $r_{\mathrm{eff}} = 18$ cm. The rotational transform in the experiments described was $\iota = 0.34$. Since plasmas are predominantly heated with ECRH at 70 GHz or 140 GHz the magnetic field on axis mostly is 1.25 T or 2.5T.

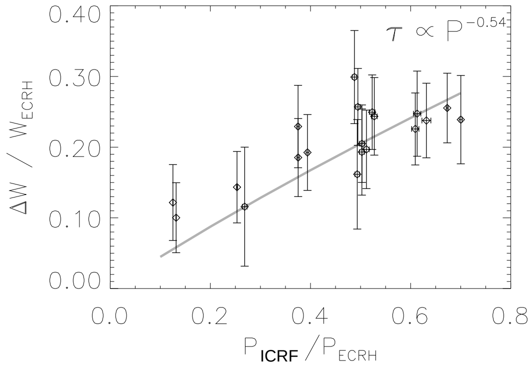

FIG. 1. Relative increase of the diamagnetic energy of an ECRH plasma during the ICRH pulse.

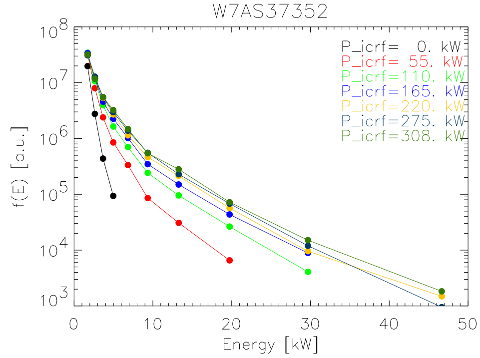

FIG. 2. Measured hydrogen energy distribution for different RF power.

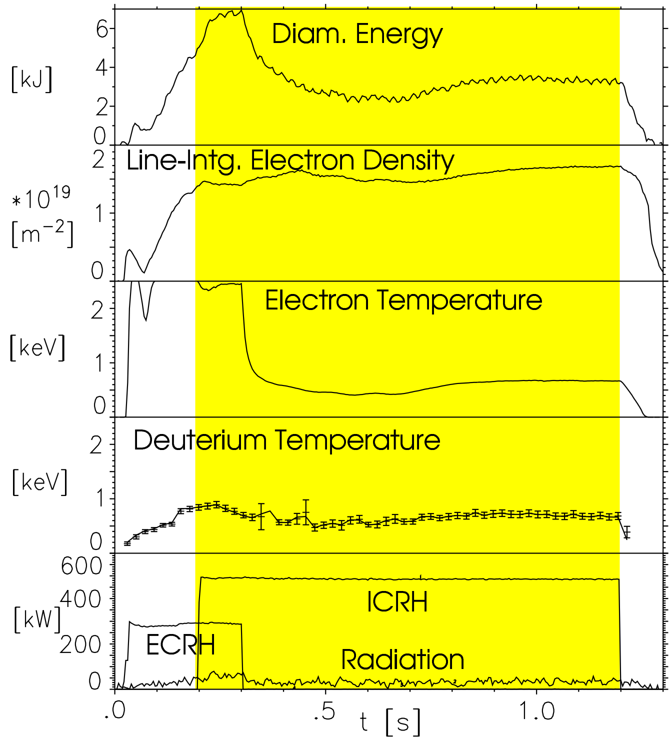

FIG. 3.Sustainment of plasma with D(H) minority heating.

Previous ICRF heating experiments on W7-AS were not successful [2]. In those experiments a conventional double strap antenna with Faraday screen on the low field side was operated. This antenna had a wider $k_{||}$-spectrum than the antenna that was used for the experiments reported here. Applying RF power to the LFS antenna generally resulted in a density increase accompanied by an increase in impurities. In addition during minority heating fast but unconfined hydrogen ions were observed.

2. D(H) MINORITY HEATING

With the hydrogen resonance located at the plasma center, hydrogen minority heating in D and ^{4}He plasmas was successful if the hydrogen concentration was less or about 10%. For higher concentrations the ion-ion hybrid resonance moved outside of the plasma. Heating ECRH discharges with ICRF the diamagnetic energy rose by up to 25%. An increase of the deuterium temperature of about 150 eV over the plasma cross-section was observed. The electron temperature rose off-axis by 150 eV as a possible result of Landau damping close to ion-ion hybrid layer.

The RF power absorbed in the plasma, $P_{\rm RF}$, was estimated by comparing the increase in the diamagnetic energy for different RF power levels radiated from the antenna, $P_{\rm ant}$, with a scaling model for the global energy confinement time, $\tau_E \sim (P_{\rm ECRH}+\alpha P_{\rm ant})^\gamma$. α is the fraction of the RF power radiated from the antenna that is absorbed by the plasma, thus $P_{\rm RF} = \alpha P_{\rm ant}$. For the typical experimental case where the RF power radiated from the antenna, $P_{\rm ant}$, is much smaller than the ECRH power, $P_{\rm ECRH}$, it is not possible to differentiate between α and γ; i.e. one cannot distinguish between a degradation of confinement with increased RF power or an unaccounted loss mechanism for the RF power. Even RF modulation experiments done at different frequencies cannot separate one from the other and lead to an apparent discrepany if the evaluation is not based on the same model for the energy confinement time [3]. For the ECRH and NBI heated discharges of W7-AS the global energy confinement time is proportional to $P^{-0.5}$ where P is the (calculated) absorbed power ($\gamma = 0.5$). Applying the same scaling to discharges with additional ICRF heating one thus finds agreement with the experimental data if the absorbed power, $P_{\rm RF}$, is taken to be about 90% of the power radiated from the antenna. The increase in diamagnetic energy for different ICRF powers is shown in Fig. 1. The line shows the expected increase in diamagnetic energy with $P = 0.9 \times P_{\rm ant}$.

H minority in ^{4}He yielded similar results.

The antenna was also operated in 0-phasing. The heating efficiency was seemingly slightly worse than the efficiency for $\pi-$phasing. However, since the heating efficiency is sensitively dependent on the hydrogen concentration, such a difference could also be due to an increased concentration. The impurity radiation was the same for 0-phasing and π-phasing.

During ICRF heating of ECRH discharges a tail of fast hydrogen with energies up to 45 keV is observed with active CX at an angle of 40° to the magnetic field lines. The decay time of the high energy fluxes is longer than the energy confinement time. In Fig. 2 the measured hydrogen energy distribution function is shown for different ICRH powers. These measurements were compared with solutions of the Fokker-Planck equation for the self-consistent energy distribution based on assumptions for the absorbed RF pwoer density [6]. Toward high energies the measured distribution decays faster than the predictions. This could be an indication of increased hydrogen orbit loss. This is also corroborated by the observed saturation of the increase in diamagnetic energy. For the next experimental campaign a lost particle analyzer has been installed that might elucidate this observation.

For hydrogen concentrations higher than 10% the mode conversion layer moves to the plasma edge and no efficient plasma heating and sustainment were possible. No fast wave direct electron heating was observed in this case. However, even in this for RF heating unfavorable situation there was only a rise in electron density and H_α-radiation but no rise in impurity radiation.

ECRH startup plasmas were successfully sustained with ICRF as the only heating source under steady-state conditions with electron and ion temperatures of 650 eV and densities of $n_e(0) = 3.\times 10^{19}\mathrm{m}^{-3}$ for one second. The time traces of a typical shot are shown in Fig. 3. In this and Figs. 5 and 7 the electron density is integrated along a vertical chord through the plasma center. The electron temperature is based on the ECE signal from the center of the plasma. The deuterium temperature is based on active CX (passive in Fig. 5) of a sight line through the plasma center. “Radiation” is the volume integrated bolometric signal. The time limit of one second had to be imposed solely to avoid excessive ohmic heating of the not actively cooled antenna straps. During the discharge the impurity radiation stayed constant. Depending on the torus wall condition plasmas with constant central densities as low as $n_e(0) = 2. \times 10^{19}\mathrm{m}^{-3}$ and central electron temperature $T_e(0)$ =800 eV were achieved.

The diamagnetic energy was not always constant during the ICRF heating phase but could deviate by up to 30% from its mean value despite constant density. This behavior was also seen in the electron temperature. No concurrent changes in the impurity radiation were observed. However, transients in the hydrogen concentration were observed due to enhanced recycling and are probably responsible for a decreased power absorption. This interpretation is supported by measurements of a bandpass limited RF pick-up probe located in the diagonally opposed torus side. This probe can an indicator for the absorption of the launched RF-wave: high signal meaning poor absorption and vice versa. The increased RF signal was detected while the diamagnetic energy was decreased.

Due to the low electron temperature and the short slowing down times no or only a weak tail in the hydrogen energy distribution function was observed.

It was not possible to sustain ^{4}He plasmas with H minority heating. This is probably also due to an increased release of hydrogen from the walls in a helium discharge.

The measured confinement times of the ICRH plasmas were compared with the results of the ECRH and NBI confinement time scaling on W7-AS. Under the assumpion that 80% of the power radiated from the antenna are absorbed in the plasma the measured confinement time was still about 30% smaller.

3. D,H MODE CONVERSION HEATING

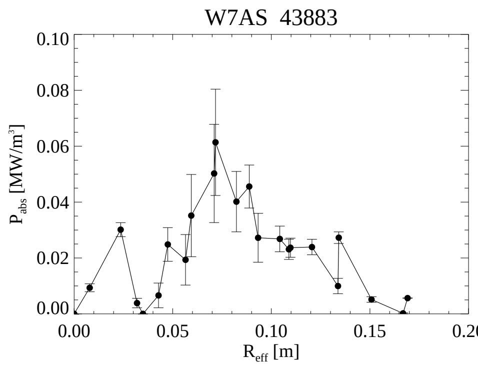

FIG. 4. Power density of the absorbed RF power by the electrons.

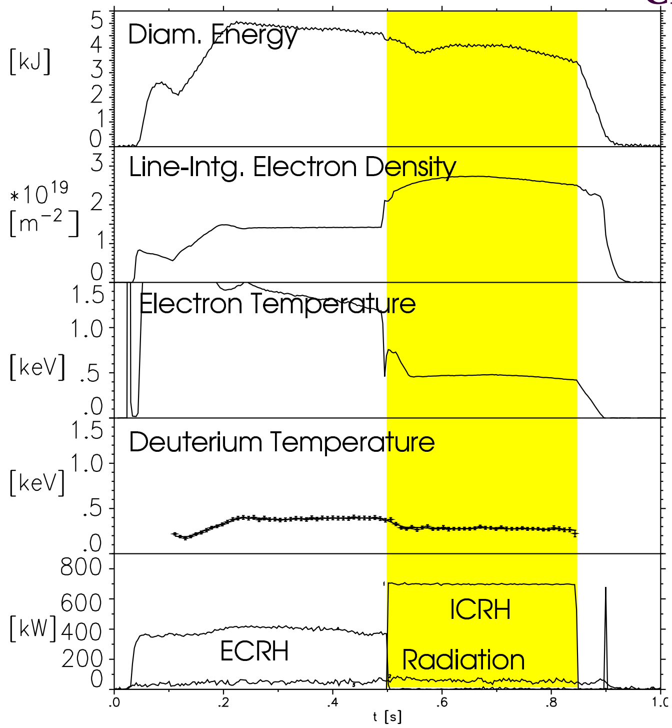

FIG. 5. Sustainment of plasma with D,H mode conversion heating.

With the hydrogen resonance outside of the plasma on the LFS mode conversion heating of a deuterium/hydrogen plasma is possible if the two-ion-hybrid resonance is located inside of the plasma. For the lowest generator frequency available of 34 MHz and the magnetic field on axis of $B = 2.5$ T the ion-ion hybrid resonance is located inside of the plasma for hydrogen concentrations between 15 and 40%. Since the plasma composition is predominantly determined by wall recycling subtle changes had to be made to the hydrogen diagnostic injector and the position of graphite limiters in order to obtain the desired hydrogen concentration.

Heating ECRH plasmas with ICRF the diamagnetic energy rose by about 15%. The electron temperature rose by about 100 eV over the plasma cross-section, in some cases localized heating near the plasma edge occured. No increase in the fast hydrogen flux was observed. The density could be kept constant and there was no increase in the impurity radiation.

Fig. 4 shows the measured power density of the electrons that was derived from a break-of-slope analysis of the measured electron temperature. The peak of the power deposition is off-axis. This is in agreement with the location of the ion-ion-hybrid resonance based on cold-plasma theory for the measured $n_H/n_e \approx 0.2$. The total integrated power, however, was much smaller than the power radiated from the antenna and the power deposition was less localized than expected. For these measurements the slope was determined with straight-line-fits to the measured electron temperature during a time interval about a third of the energy confinement time. This interval might still be too long.

Plasmas could be sustained solely with ICRF for up to 400 msec under steady-state conditions with electron and ion temperatures of 400 eV and densities of $n_e(0) = 6.\ \mathrm{x}\ 10^{19}\ \mathrm{m}^{-3}$. There was an initial density increase but no rise in the impurities. Thus density control can be expected for better wall conditions. The heating efficiency was comparable to the heating efficiency for sustaining D(H) plasmas. The plasma duration was limited by arcs in the RF system. A typical discharge is shown in Fig. 5. The central electron temperature is higher than the deuterium temperature.

4. SECOND HARMONIC HYDROGEN

RF power at the second harmonic hydrogen frequency was applied to NBI target plasmas [4].

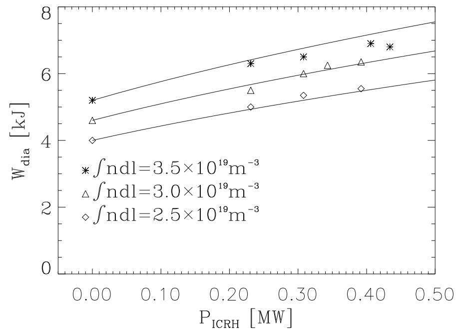

FIG. 6. Increase of the diamagnetic energy of an NBI plasma during the ICRH pulse.

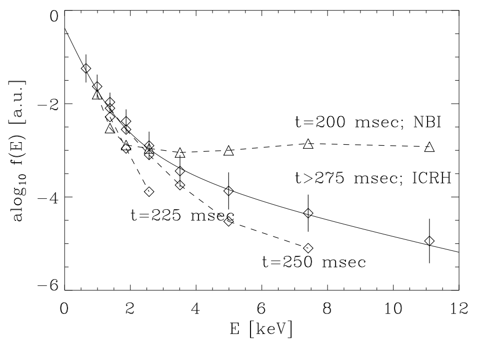

FIG. 8. Measured hydrogen flux at different times of the shot shown in Fig. 7.

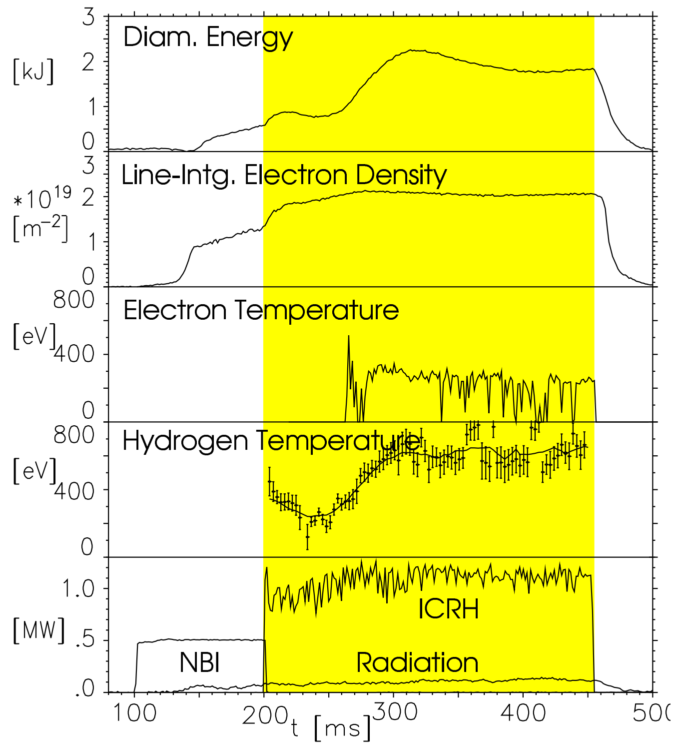

FIG. 7.Sustainment of plasma with second harmonic hydrogen heating.

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 hydrogen 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 the application of the RF power. 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. 6 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, $P_{\rm ICRH}$, to 70% of the radiated RF power.

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 [5] 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.

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 radio-frequency (RF) power were applied to the 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}, were sufficient to obtain plasmas with steady-state values of electron density, $n_e(0) = 5 \times 10^{19}$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. 7. 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 infered from an investigation of the time evolution of the central hydrogen energy distribution shown in Fig. 8. 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 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 the RF pickup probe. This probe is located toroidally opposite to the antenna. 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.

5. CONCLUSION

On the stellarator W7-AS standard ICRF heating scenarios that are established on tokamaks were shown to be equally successful. Within the limited range of available magnetic fields and RF generator frequencies these heating scenarios were minority and mode conversion heating of hydrogen in deuterium and second harmonic hydrogen heating. The heating efficiencies were comparable to the heating efficiencies found in tokamaks. The scenarios were not hampered by impurity radiation. Density controll was given for moderate densities and could be improved with better wall conditions after glow discharges. Fast wave heating at lower magnetic fields with the expected higher absorption efficiency will be attempted in the coming experimental period.

6. ACKNOWLEDGEMENTS

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REFERENCES

[1] CATTANEI, G. et al. *EPS Topical Conference on Radiofrequency Heating and Current Drive*, Brussels 1992, p. 121.

[2] BALLICO, M. et al. *Radio Frequency Power in Plasmas*, (Charleston, SC 1991), AIP Conference Proceedings **244**, p. 150.

[3] HARTMANN, D.A. et al. *Radio Frequency Power in Plasmas*, (Savannah, GA 1997), AIP Conference Proceedings **403**, p. 49.

[4] HARTMANN, D.A. et al. *ICCP & EPS Conf. on Controlled Fusion and Plasma Physics*, (Prague 1998).

[5] BALDZUHN, J. *private communication*

[6] BRAMBILLA, M. *Kinetic Theory of Plasma Waves*, Oxford University Press, Oxford, 1998.