ICRF Experiments on the Stellarator W7-AS

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INTRODUCTION

The first successful ICRF plasma heating experiments in the W-7AS stellarator [1] have demonstrated effective plasma heating and plasma sustainment, for 2nd harmonic and two-ion hybrid heating regimes without significant increase of impurity radiation. The results presented in this paper establish ICRH as an attractive method to heat and sustain the plasma in stellarators under steady-state conditions.

TECHNICAL SETUP

The RF system of W7-AS consists of two RF generators with a nominal power of 1.5 MW that are connected to two antennas. For the experiments to be described the RF power was launched with a broad four-port antenna exciting a narrow $k_{||}$-spectrum around $k_{||} = 6\mathrm{m}^{-1}$ for $\pi-$phasing [2,3] After a faster arc protection system (full power switch-off within $20\mu s$ of an arc) and a section of lossy transmission line to avoid generator self-oscillations [4] had been installed more effective conditioning of the antenna became possible. Thus RF pulse lengths longer than one second with voltages in the transmission lines up to 70 kV were reached.

EXPERIMENTAL RESULTS

Plasma heating, sustainment and startup from a seed discharge were investigated for the two-ion hybrid heating scenario for hydrogen minority in a deuterium and ^{4}helium plasma. Good absorption of the RF power radiated from the antenna was observed only if the hydrogen concentration was less or about 10%. Such low hydrogen concentrations were obtained after boronization of the vessel interior with B_2D_6 or after helium glow discharges with about 5% deuterium. The hydrogen concentration was infered from comparison of the intensity of the H_α and D_α lines and comparison of the CX hydrogen and deuterium fluxes. This ratio was uncontrolled and only determined by wall recycling. Good wall conditions (obtainable only after many hundreds of plasma discharges) were imperative for keeping the hydrogen concentration sufficiently low during the ICRF experiments.

ECRH generated deuterium and helium plasmas (P_{ECRH}=500 kW, $n_e(0) = 3. \times 10^{19}\mathrm{m}^{-3}$, $T_e(0)$=2.5 keV, $T_D(0)$=450eV, ι=0.34, W_{diam}=5 kJ, central heating) were used as targets. Antenna loading approximately doubled with plasma compared to vacuum loading. Thus half of the generator power was radiated into the plasma, the remainder was ohmically dissipated in the antenna.

Fig. 1 shows the temporal evolution of an ICRF-heated ECRH plasma. During the ICRF pulse an increase of about 25% of the diamagnetic energy was observed. The dominant part of this increase is due to an increase in deuterium temperature. Fig. 2a shows the deuterium temperature profiles with and without ICRF. An overall increase from 400 eV to 550eV is observed. Fig. 2b shows the electron temperature profiles with and without ICRF. The strongest increase in electron temperature was observed off-axis at the approximate location of the two-ion hybrid resonance and was mainly due to direct electron heating.

Fig. 3 shows the radial profile of the RF power density absorbed by the electrons. This was evaluated from the change in slope of the ECE electron temperature and the Thomson electron density profile at the turn-on time of the RF power. The total RF power absorbed by the electrons was around 30 kW for this case.

The transient drop of the central electron temperature within the first $50\mu s$ is not understood. It cannot be attributed to a central density increase or an increase in impurity radiation.

For RF powers up to about 400 kW the increase in diamagnetic energy followed the stellarator confinement time scaling [5]. From this one can conclude that most of the radiated power is absorbed in the plasma. For higher RF powers the diamagnetic energy increased less than expected as can be seen in Fig.4 . There the increase in diamagnetic energy is shown for different ICRF powers radiated from the antenna. The solid line is the prediction based on the confinement time scaling for W7 -AS [5]. For RF powers larger than 400kW, which corresponds to $P_{ICRF}/P_{ECRH} \approx 0.6$, a saturation in the relative increase of the diamagnetic energy is observed. Data at higher ICRF power that should be available now are necessary to clarify this point.

Bulk hydrogen temperature up to 1.2 keV was measured at the plasma center with active CX whereas the deuterium temperature was about 400 eV. Hydrogen fluxes with energies up to 45 keV were observed at an angle of about 45° to the magnetic field lines. At RF powers less than about 400 kW an increase of the tail temperature with RF power was observed. However, the tail temperature saturated at about 7 keV for RF powers greater than 400 kW.

It was possible to sustain the plasma solely with ICRF. Pulse lengths up to 1 sec (>50 energy confinement times) at RF powers of 500 kW were achieved. Fig. 5 shows the time evolution of such an ICRF plasma. The achieved plasma parameters were: $W_{diam} \leq 4.2$ kJ, $T_e(0) \leq 800$ eV, $T_D(0) \leq 500$ eV, $n_e(0) \leq 4.5 \times 10^{19}$ m^{-3}, $P_{RF} \leq$ 700 kW. Good wall conditions facilitated density control over the length of the discharge. After some slightly transient behavior steady-state was reached where all measured plasma parameters were constant. In particular, no increase of impurity radiation was observed.

The total radiation as determined by bolometry remained comparable to ECRH plasmas. VUV measurements showed a slow increase of iron and chromium radiation that saturated after a few hundred milliseconds in agreement with the long particle confinement times expected at these densities and power levels.

It was also possible to generate the plasma with ICRF starting from a seed plasma given by the afterglow of a discharge. The time evolution of such a discharge is shown in Fig. 6. At the start of the ICRF pulse the density of the seed plasma was less than the cut-off density for the fast wave and the antenna loading was equal to the vacuum loading. Within 100 msec of the start of the RF pulse typical ICRF-plasma parameters were recovered. The stub tuners of the system had to be set to a compromise setting to ensure sufficiently low VSWR during the whole discharge.

CONCLUSIONS

Plasma heating, sustainment and generation from a seed plasma is possible with ICRF for the two-ion hybrid heating scenario in an advanced stellarator. ICRH-sustained plasma parameters were comparable to those achieved with ECRH. The experiments showed, however, that the heating efficiency degraded rapidly if the hydrogen concentration increased beyond 20-30 %. Therefore, control of the minority concentration is of crucial importance for this heating scenario in a large aspect ratio device as the W7-AS stellarator. A viable alternative to hydrogen minority could be ^{3}He, whose concentration can easily be controlled.

REFERENCES

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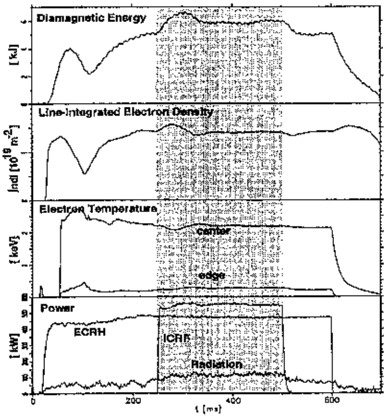

FIGURE 1. Shot 37298. ICRF heating of ECRH plasma.

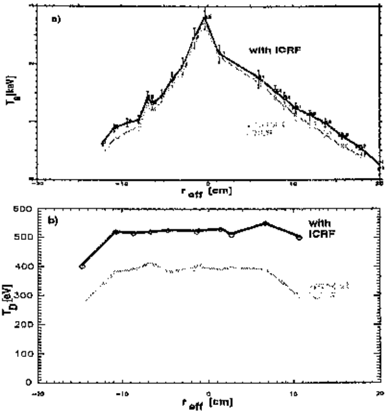

FIGURE 2. Electron and deuterium temperature profile for shot 37298.

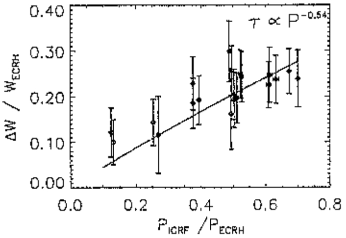

FIGURE 3. Relative increase in diamgnetic energy versus the ratio of ICRF power radiated from the antenna to ECRH power.

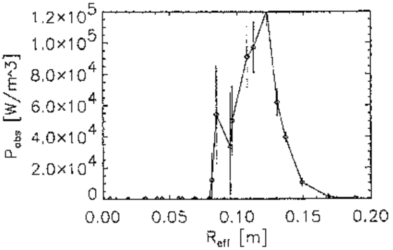

FIGURE 4. Radial profile of RF power density absorbed by electrons.

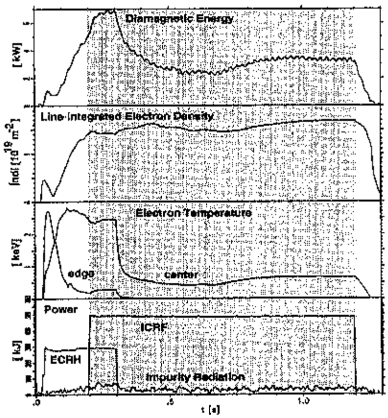

FIGURE 5. Shot 39387. ICRF sustained plasma.

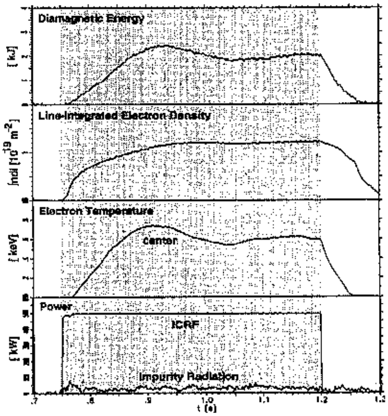

FIGURE 6. Shot 39389. ICRF generated plasma.