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Ion Cyclotron Resonance Heating Experiments on the Stellarator W7-AS

G. Cattanei, *D.A. Hartmann, D.A. Rasmussen†, J.F. Lyon†, V. Plyusnin‡,*
ICRH-Team, W7AS-Team
Max-Planck-Institut für Plasmaphysik, Euratom Association, 85478 Garching, Germany
†Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
‡Kharkov Institute of Physics and Technology, Kharkov 310108, Ukraine

Ion cyclotron resonance heating (ICRH) has, for the first time, successfully been demonstrated on the stellarator W7-AS. A novel broad antenna [1,2] designed to excite a narrow spectrum of fast waves was used. Two different heating scenarios were investigated: second harmonic heating of neutral beam heated hydrogen plasmas and hydrogen-minority heating of ECRH deuterium plasmas. Both scenarios showed plasma heating without a significant concurrent increase in plasma density or impurity radiation loss. In addition, it was possible to sustain the plasma with ICRH alone.

The ICRH antenna, shown in Fig. 1, is located on the high field side in the elliptical cross-section of the non-axisymmetric plasma. It has four feeders that allow operation in 0- and π- phasing. Typically it is operated in π-phasing. Then the poloidal current has an almost sinusoidal distribution in the toroidal direction and excites a narrow $k_\parallel \approx 6\text{m}^{-1}$ spectrum of fast waves. During the Spring 1995 opening of the torus vessel the feeders to the antenna, shown in Fig. 2, were closed off against plasma penetration. This eliminated anomalously high loading of the antenna during plasma operation observed previously [3] and increased the maximum rf-voltage at which electrical breakdown (arcing) occurred. Most plasma targets had $\iota \approx 0.33$ and were shaped by inside limiters. In those plasmas the distance from the antenna to the fast-wave cutoff is about 6 cm and the observed antenna plasma loading is only about $0.5\ \Omega$. Voltages of up to 55 kV for 400 msec, corresponding to a maximum power of about 400 kW at the antenna, have been achieved after extensive conditioning. Real time visual observation of the antenna during plasma operation and inspection after the vacuum break confirmed that arcs did not occur in the antenna, but only in the feeders and in the transmission lines.

In the second harmonic hydrogen heating scenario with a neutral beam heated target plasma an increase in the diamagnetic energy of about 10 % (0.6 kJ) was obtained. The central hydrogen temperature was about 800 eV and central electron densities were $6 \times 10^{19}\text{m}^{-3}$. One estimates that about 60 % of the power P radiated from the antenna is found in the plasma, if P is the generator power reduced by the ohmic losses in the antenna and $P^{-0.6}$-scaling of the energy confinement time is invoked. Under good wall conditions, the plasma density could be kept constant during the rf-pulse, even though the H_α-observation indicated enhanced outgassing at the antenna. The impurity radiation inferred from the bolometer did not increase. An increase in the flux of hydrogen atoms with energies between 10 keV and 33 keV was observed; however, no significant increase in the bulk hydrogen temperature was observed. Maximum heating occurred if the location of the second harmonic resonance coincided with the center of the plasma; almost no heating occurred if the resonance was outside of the plasma. The antenna loading was independent of the location of the resonance even though a rf-probe (located half-way around the torus) detected a wave signal only if the resonance was outside of the plasma. Heating at 0-phasing showed similar increases in the diamagnetic energy as in π-phasing and no enhanced impurity radiation. No significant heating was observed in ECRH plasmas of the same density, presumably because the hydrogen temperature of the target plasma was too low (about 350 eV).

In the H-minority heating scenario with an ECRH target deuterium plasma an increase in the diamagnetic energy of about 15 % (1 kJ) was obtained. This corresponds to absorption of about all of the radiated power P. Fig. 3 shows a typical example of a plasma shot. The spectroscopically estimated H/D ratio was about 10%. The line-of-sight averaged deuterium temperature rose from 300 eV to 400 eV; the central electron temperature rose slightly. Energetic hydrogen atoms with energies up to 33 keV were observed. The impurity radiation did not increase.

In this heating scenario it was possible to sustain an ECRH-created plasma with ICRH alone for as long as 500 msec. The duration of the ICRH-only phase of the plasma was solely limited by arcing in the transmission lines. An almost steady state condition could be obtained about 200msec into the ICRH-only phase of the discharge. Typical parameters were diamagnetic energy of 2 kJ, average electron density of $4. \times 10^{19} m^{-3}$, central electron temperature of 300 eV, and central deuterium temperature of 350 eV.

An example of an ICRH sustained plasma is shown in Fig. 4 starting at 400 msec. The generator frequency and the approximate H/D-ratio were such that both, the H-resonance and the ion-ion-resonance were located inside of the plasma volume, as shown in Fig. 2. The average electron density first rose by increased outgassing of the antenna but returned towards the initial value near the end of the ICRH plasma. The central electron temperature dropped rapidly within an energy confinement time and then stayed constant throughout the ICRH phase. The total radiation measured with bolometers stayed constant, even though an accumulation of iron and chromium could be inferred from VUV observation; yet soft X-ray measurements indicated that $Z_{\rm eff}$ did not increase. We can therefore conclude that, at least in the range of parameters investigated, the ICRH sustained plasma is not hampered either by uncontrolled density increase or by enhanced impurity production.

The plasma density profile, measured with Lithium beam diagnostic, Langmuir probes, microwave reflectometry and Thomson scattering, was narrower and had steeper edges during the ICRH sustained plasma than during comparable ECRH heated plasmas. The transition between these two profiles occured within approximately one energy confinement time. Further narrowing of the plasma was observed on a longer time-scale. The resulting increase of the distance from the antenna to the fast wave cutoff could explain the decrease of the antenna plasma loading and therefore the decrease in diamagnetic energy. A radial electric field of about -1.5 kV/m built up at the beginning of the ICRH phase of the discharge, presumably due to increased high-energy hydrogen losses as indicated by CX measurements.

References:

[1] G.Cattanei et al., Stellarator News, Issue 25, January 1993, p.3.

[2] G. Cattanei and the W7-AS Team. Topical Conference on Radiofrequency Heating and Current Drive of Fusion devices. (Brussels 1992) p. 121.

[3] M. Ballico et al., IAEA Technical Committee Meeting on Stellarators and Other Helical Confinement Systems, Garching (1993), p. 413.

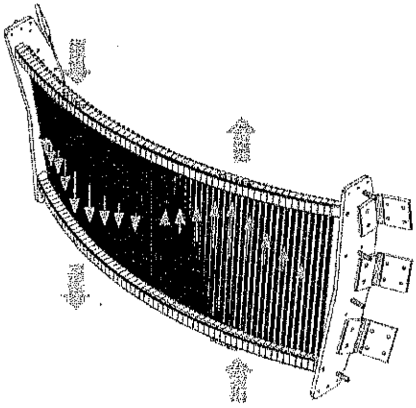

Figure 1. ICRH antenna shown without Faraday screen.

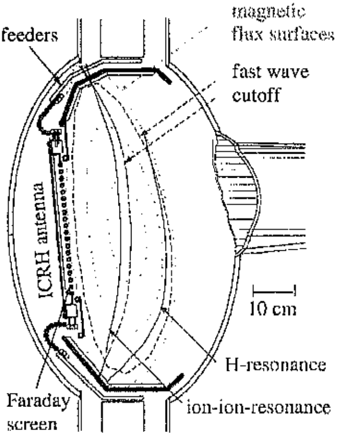

Figure 2. Poloidal cross-section through the ICRH antenna. Resonances and cutoffs shown for the ICRH plasma in Fig.3.

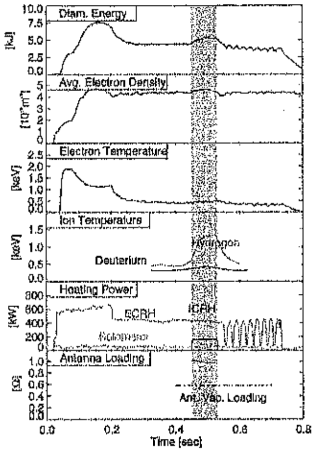

Figure 3. Time trace of shot 33882. Ion temperatures infered from unweighted line-of-sight average of CX fluxes. $B_T = 2.5$T, ι=0.34.

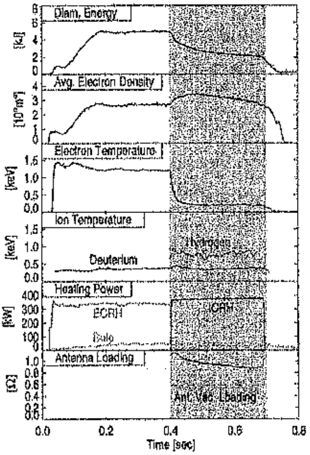

Figure 4. Time trace of shot 33634. Ion temperatures infered from unweighted line-of-sight average of CX fluxes. $B_T = 2.5$T, ι=0.34.