*27th EPS Conference on Contr. Fusion and Plasma Phys. Budapest, 12-16 June 2000 ECA Vol.* **24B** *(2000) 5 -8*

# Recent Progress with ICRF Heating on the Stellarator W7-AS

D.A. Hartmann, G. Cattanei, W7-AS Team, ICRH Group

*Max-Planck Institut für Plasmaphysik, EURATOM Ass.,*
*85748 Garching, Germany*

## 1. Introduction

Plasma heating using radio frequency waves in the ion cyclotron range of frequencies (ICRF) is particularly attractive for superconducting fusion devices, such as the forthcoming stellarator W7-X, with their potential for steady-state operation since cw capable generators of at least 0.5 MW power are already commercially available. In helical confinement device, ICRF has only rather recently become successful [1,2]. In particular, on the medium size stellarator W7-AS (major radius R=2 m, average minor radius a=0.18 m, maximum magnetic field on axis B=2.5 T) the first ICRF plasma heating and plasma sustainment results were obtained using an antenna of novel design, called broad antenna. This antenna was designed for a reduced RF electric near field in order to minimize deleterious power absorption in the plasma edge. For the last experimental campaign the broad antenna was replaced with a conventional double strap antenna in order to evaluate the importance of the RF electric near field. The plasma properties of similar magnetic configuration and densities were being compared.

## 2. Antenna coupling and heating efficiency

The broad antenna and the double strap antenna were both mounted on the high field side in a region where the plasma has elliptical cross-section and a tokamak-like magnetic field profile. Both antennas had a Faraday screen. The broad antenna (described in detail in [3]) consisted of an assembly of 58 straight poloidal conductors whose vertical inclination changed with position such that they stayed tangential to the last closed flux surface (LCFS) of a standard plasma configuration with an average distance of 0.08 m. The double strap antenna consisted of two straps of such a shape that it matched the three-dimensional form of the plasma so that the distance of the current strap and the LCFS was constant at 0.05 m. Fig. 1 shows the calculated, normalized $k_{||}$-spectrum of the measured RF magnetic vacuum field, $B_{||}$, in the direction of the confining magnetic field if the two straps are fed with a phase difference of 180°, called $\pi$-phasing. Obviously only the double strap antenna has high $k_{||}$ components. These components couple weakly to the plasma since the cutoff density for fast wave propagation rises with $k_{||}^2$ and since the radial decay of the $B_z$-field is proportional to $e^{-k_{||}\delta r}$, where $\delta r$ is the radial distance from the antenna. They do, however, contribute to the electric near-field of the antenna and could thereby increase the recycling or impurity production.

For similar plasmas the antenna loading resistance, $R_{plas}$, was about 8 Ω for the double strap antenna and about 1.5 Ω for the broad antenna. Both antennas had approximately the same antenna vacuum resistance, $R_{vac}$, of 0.8 Ω since it was predominantly given by the stainless steel vacuum feed through. Both antennas showed the same dependence of the loading resistance on the distance between the current strap and the fast wave cutoff density (calculated from the edge density profile measured with Lithium beam). This difference cannot exclusively be explained by the closer fit of the double strap antenna to the plasma contour. One possible explanation is that in the broad antenna a larger than evaluated fraction of the antenna current flew toroidally and thus did not contribute to the coupling. Taking the dissipation of RF power in the feeders into account the fraction of RF power that is radiated into the plasma, $P_{ant}$ ,is calculated from the generator power, $P_{gen}$, according to:

$$P_{ant} = \frac{R_{plas} - R_{vac}}{R_{plas}} P_{gen}$$

Because of the good voltage standoff of the broad antenna system and the high antenna loading of the double strap antenna system the power was limited by the maximum generator power of 1.1 MW in both cases. However, because of the large difference in antenna loading only a maximum of 500 kW of power could be launched into the plasma with the broad antenna, compared to 900 kW with the double strap antenna. The heating efficiency, $\eta$, is experimentally determined by heating a target plasma with ICRF and calculating the ratio of power that can account for the observed increase in diamagnetic energy, $\Delta W$, based on the established power scaling of the energy confinement time and the launched ICRF power, $P_{ant}$. For W7-AS this is approximately given by:

$$\eta \approx \frac{P_o}{P_{ant}}[(\frac{W_0 + \Delta W}{W_0})^{2.2} - 1],$$

where $P_0$, $W_0$ are power and energy of the target plasma.

The best heating scenario for comparing the two antennas is second harmonic hydrogen heating since the carbon tiles of the inner limiters constitute large reservoirs of hydrogen which make it difficult to obtain conditions of low hydrogen concentration, e.g. for hydrogen in deuterium minority heating. Fig.2 shows the measured heating efficiency of both, the broad antenna and the double strap antenna versus launched ICRF power for second harmonic heating at a generator frequency of 38 MHz and a magnetic field on axis of 1.25 T. Obviously within the launched power range that was accessible for both antennas they had the same heating efficiency of about 70%. Only at the highest powers with the double strap antenna a degradation is noticeable. Since second harmonic hydrogen heating increases the perpendicular energy of hydrogen it is likely that this decrease in efficiency is due to loss of fast hydrogen with energies above 30 keV. The increase of bolometric radiation, which in the given temperature range is a measure of the impurity accumulation, shows the same increase with launched power, i.e. for the given conditions, particularly of a boronized machine, the different near fields of the antenna do not affect the heating efficiency. However, there is a difference in RF induced recycling. The increase in $H_{\cdot}$–radiation and the ensuing increase in plasma density was much larger with the double strap antenna than with the broad antenna. So ICRF sustained plasmas were terminated by a radiation collapse caused by the constant increase of density. The rate of density increase was larger if the hydrogen resonance was moved from on-axis to off-axis heating. This is in qualitative agreement with a concurrent decrease in the estimated single pass absorption from 25% to 15%. The situation was even worse for a generator frequency of 74 MHz and a magnetic field of $B_0$=2.5 T which was only done with the double strap antenna. Heating was always accompanied by an even stronger density increase in concordance with an estimated single pass absorption of 8% only.

For plasmas consisting of a mixture of hydrogen and deuterium we term minority heating, D(H), the situation where both the hydrogen resonance and the two ion hybrid resonance are inside of the plasma (for hydrogen concentrations less than 10%) and we term mode conversion, D/H, the situation where only the two ion hybrid resonance is inside of the plasma (for hydrogen concentrations between 20 and 40% and for a generator frequency of 34 MHz). The heating efficiencies of both scenarios, shown in Fig. 2, are comparable for both the broad antenna and the double strap. Similarly there is no significant difference in the increase of the bolometric radiation with RF power. For launched RF powers above about 500 kW there is a marked decrease in heating efficiency in the minority heating scenario. Simultaneously saturation of the measured hydrogen tail temperature and a sharply increased signal of lost ions is observed [4]. Thus it can again be concluded that the decrease in heating efficiency is due to orbit loss effects. For the mode conversion scenario, on the other hand, where the launched fast wave converts to an ion-Bernstein wave near the two ion hybrid resonance which then is damped by electrons propagating parallel to the confining magnetic field, only a weak degradation was observed within the range of launched RF power. Using minority or mode conversion heating it was possible with either antenna to sustain the plasma under steady-state conditions with ICRF alone.

## 3. Magnetic beach heating

In W7-AS the possibility to independently feed different sets of field coils allows the realization of a magnetic field configuration where the field decreases toroidally away from the antenna. Fig. 3 shows the horizontal cross-section of the vacuum mod B contour lines in a half module of the W7-AS field for such a magnetic mirror configuration together with the location of the hydrogen resonance, mode conversion layer and associated cutoff calculated for a hydrogen concentration of 30% and a generator frequency of 34 MHz. When the launched fast wave propagates towards the mode conversion zone the group velocity perpendicular to the mode conversion layer approaches zero such that the fast wave can propagate toroidally towards decreasing magnetic field. Approaching the hydrogen resonance it is converted into a slow wave (shear Alfvèn wave). The slow wave finally is strongly damped on hydrogen via cyclotron damping [5]. In the original experiments on magnetic beach heating no mode conversion zone was necessary and the slow wave could be excited at the plasma periphery because of the low density and the radially constant magnetic field [6]. For the W7-AS situation substantial heating of an ECRH target plasma and plasma sustainment with ICRF alone are possible. For an ECRH target plasma the increase in the hydrogen temperature is larger than the increase in the electron temperature which is an indication of direct hydrogen heating. In the ICRF stand alone plasma the hydrogen temperature is higher than both the electron temperature and deuterium temperature.  No heating is observed if the hydrogen concentration is too high so that the mode conversion layer is no longer in the core plasma. No fast hydrogen is observed if the magnetic mirror is reduced and the hydrogen resonance is no longer inside of the plasma.

For the magnetic mirror configuration one expects some competition between mode conversion heating and direct hydrogen heating. We define the mirror ratio to be the ratio of the minimum magnetic field in front of the antenna, $B_{36}$, to the maximum magnetic field at the end of one module, $B_0$, (comp. Fig. 3). In Fig.4 the ratio of the measured electron to hydrogen temperature is plotted versus mirror ratio (abscissa) and distance of the mode conversion layer from the plasma center (ordinate). Lowering the hydrogen concentration, i.e. shifting the mode conversion layer towards the plasma center, favors electron heating; lowering the mirror ratio, i.e. shifting the cyclotron layer in the maximum B region towards the center, favors hydrogen heating.

## 4. Conclusions

Both antennas show about the same heating efficiency for all the known ICRF heating schemes available on W7AS. The only substantial difference is the wall recycling which is increased when the double strap antenna is used for second harmonic heating. For hydrogen, deuterium plasmas the location of the mode conversion layer is of crucial importance for the heating performance of both antennas. For two component plasmas no heating is observed if the mode conversion layer is not inside the plasma. It seems likely, that earlier experiments with a low field side double strap antenna were not successful also because the mode conversion was outside the plasma and the weak absorption allowed for increased RF induced wall-sputtering. The ICRF antennas of W7-X are foreseen for the low field side. For this device second harmonic hydrogen heating is a promising scenario since density control will pose less of a problem in W7-X and, in addition, increased plasma size and plasma beta as well as wave focussing will increase the absorption. Whether mode conversion and magnetic mirror heating, particularly attractive since the standard magnetic field has already a mirror configuration, will be equally successive has to be tested.

## References

[1] D.A. Hartmann et al., Proc. 17th Conf. Fusion Energy, Yokohama, 1998, p.565.
[2] T. Mutoh et al., submitted to Phys. Rev. Lett., 2000.
[3] G. Cattanei et al., EPS Top. Conf. On Radiof. Heating and Current Drive, Brussels, 1992.
[3] A. Werner, this proceedings.
[4] V. Vdovin, Kurchatov Institute, Moscow, 1995.
[5] T.H. Stix, Proc. 2nd UN Intern. Conf. Peaceful Uses Atomic Energy, Geneva, 1958.

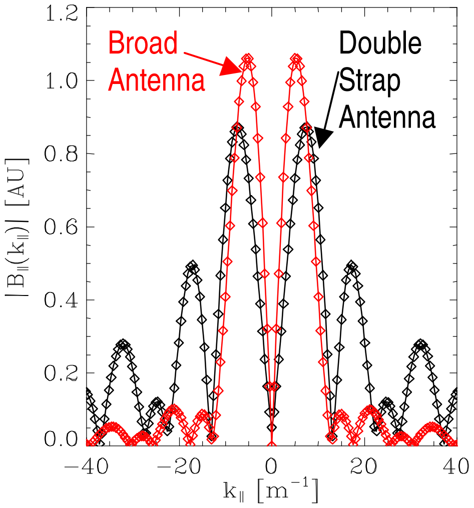

Fig. 1. *k||-spectrum of the vacuum $B_{||}$ field of the broad antenna and the double strap antenna.*

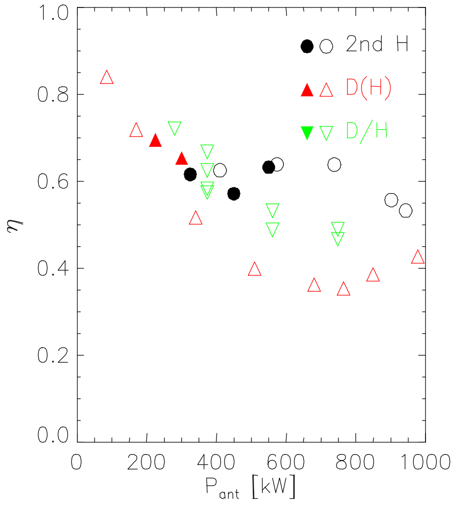

Fig. 2. *Heating efficiency of broad antenna (solid) and double strap antenna (open).*

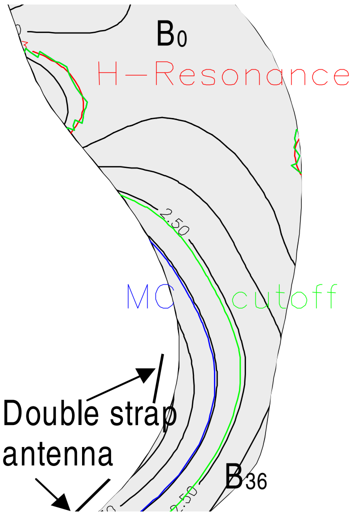

*Fig. 3. Horizontal cross-section of one half-module of W7-AS with magnetic mirror configuration.*

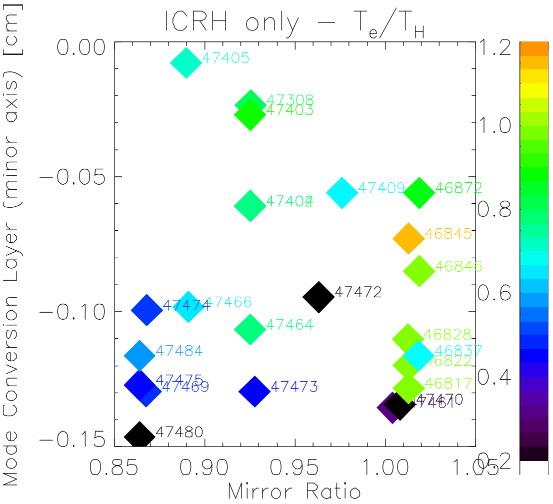

*Fig. 4. Ratio of electron to hydrogen temperature for ICRF plasma in mirror configuration.*