70 GHz ECRH EXPERIMENTS ON THE W VII-A STELLARATOR

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1. Introduction

In continuation of ECRH experiments at 28 GHz /1/ a new 70 GHz/200 kW/100 ms RF system was put into operation on the Garching W VII-A stellarator. According to the increased frequency this new system has given access to remarkably improved plasma parameters: The plasma density regime could be extended to values well above $10^{19}m^{-3}$ now allowing combined ECRH and NBI operation. Simultaneously electron temperatures above 2 keV were achieved due to the enhanced plasma confinement at the larger magnetic field (B_{res} = 2.5 Tesla). As before the stellarator plasma could be built up from a neutral gas background of deuterium or helium.

In the following paragraphs the heating results for various kinds of EC wave irradiation (unpolarized and linearly polarized O-mode irradiation at the fundamental frequency and X-mode irradiation at the second harmonic frequency) will be reported. Specific problems like impurity release, fast particle generation, and RF related current drive will be discussed, too.

2. Plasma heating for various kinds of EC-wave irradiation

In a first step of the 70 GHz experiments the gyrotron radiation (mainly TE_{02} mode) was launched into the equatorial plane of the torus from the low-field side. The incident wave with $\bar{k}\perp\bar{B}$ corresponds to a 50%/50% O/X-mode mixture, where the X-mode content is reflected at the X-mode cutoff layer at the outer plasma edge.

In a second step the RF power was transformed into the almost linearly polarized HE_{11} mode with the help of specific mode converters. Mode purity was conserved by using optimized overmoded RF components /2/. The resulting low aperture wave was irradiated in O-mode orientation ($\bar{E} \parallel \bar{B}$, $\bar{k} \perp \bar{B}$) for fundamental, and in X-mode orientation ($\bar{E} \perp \bar{B}$, $\bar{k} \perp \bar{B}$) for harmonic ($\omega_{RF} = 2 \cdot \omega_{ce}$) heating. Again the plasma was irradiated from the low-field side. A tiltable mirror (± 10°) was mounted to the opposite inner torus wall allowing current drive experiments by oblique reflection of the non-absorbed power fraction. The incident power and thus the beam absorption could be analysed by five RF pickup antennas installed in the mirror.

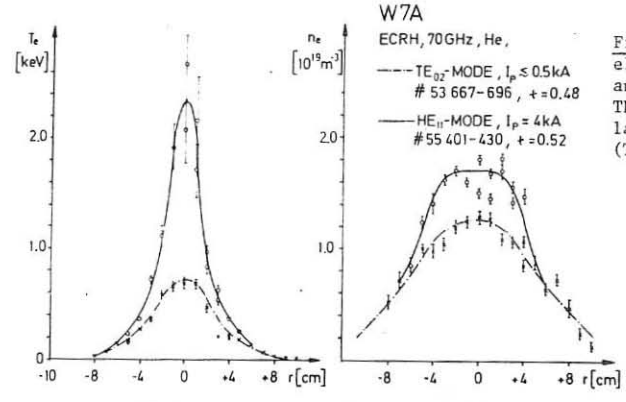


Fig. 1: Profiles of electron temperature and density for TE_{02}- and HE_{11}-mode launching. (Thomson scattering).

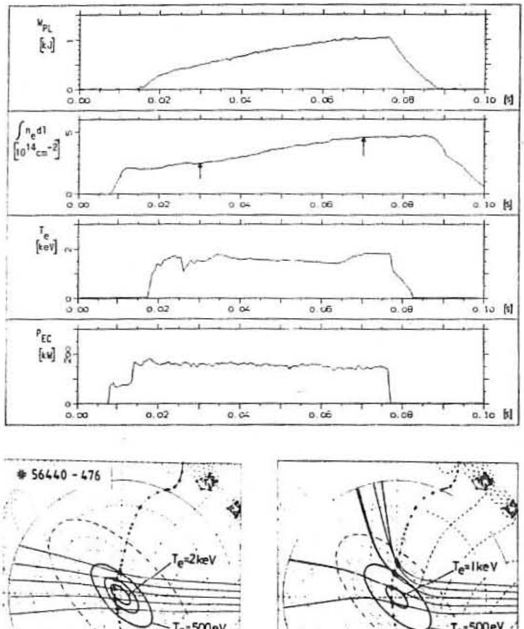
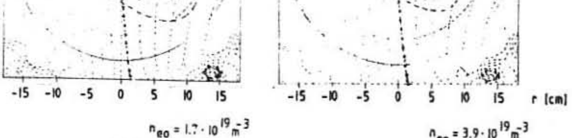


Fig. 2: Temporal development of the plasma energy content W_{PL}, line integrated density $n_e dl$, electron temperature (soft-X) T_e and incident RF-power P_{EC}



$n_{eo} = 1.7 \cdot 10^{19} m^{-3}$
(a)

$n_{eo} = 3.9 \cdot 10^{19} m^{-3}$
(b)

Fig. 3: Calculated ray traces (ordinary mode) for the low (a) and high density case (b), indicated by arrows in Fig. 2.

With the transition from unpolarized to advanced, polarized O-mode irradiation a substantial improvement of the resulting plasma parameters has been achieved. This is illustrated in Fig. 1 with temperature and density profiles for both kinds of irradiation. In this example of low density operation ($n_{eo} \approx 0.3\ n_{e,crit}$) the central electron temperature could be doubled by using the polarized beam. Increasing the plasma density towards the cutoff value ($n_{e,crit} = 6.25 \times 10^{19} m^{-3}$) generation of a hot plasma failed for the unpolarized irradiation, whereas T_e remained above 1 keV (e.g. at $n_{eo} = 4 \cdot 10^{19} m^{-3}$) in the case of polarized wave launching. Fig. 2 gives an example of the temporal development of density ramp-up (by gas puffing), plasma energy, electron temperature (soft x-ray signal), and the RF pulse. At two moments, specified in the figure, a cross sectional view of the plasma together with the calculated patterns of rays is given in Figs. 3a and b. From these figures one recognizes that refractional effects and, therefore, access to the central plasma core become critical for the high density operation ($n_{eo} \approx 0.7 \cdot n_{e,crit}$, Fig. 3b). The measured attenuation of the rays (signals of the diagnostic antennas) agreed in all cases quite well with the calculated relativistic absorption according to linear theory.

Further data for the cases of wave heating at the fundamental frequency are summarized in Table I:

Mode	T_{eo} [keV]	n_{eo} [$10^{19} m^{-3}$]	W_p [kJ]	τ_E [ms]	P_{inc} [kW]	Mode content O/X	η [%]
TE_{02}	1.1	0.8	0.2	4.0	170	50:50	30±10
HE_{11}	2.3	1.8	0.5	4.3	175	90:10	65±10
	1.1	4.0	1.1	9.7	175	90:10	65±10

Tab. I: Heating results for two different kinds of wave launching ($\omega_{RF} = \omega_{ce}$)

According to Table I the heating efficiency $\eta = P_{abs}/P_{inc}$ – as determined by power modulation techniques /1/ – is strongly improved in the case of polarized HE_{11} wave irradiation. The relatively large X-mode content of about 10% in the HE_{11} beam can be attributed to a meanwhile identified asymmetric mode content of the 70 GHz gyrotron emission. The missing power fraction in absorption of 35%, even with the advanced HE_{11}-irradiation, is consistent with the small size of the hot and "dark" plasma core in combination with the ray refraction. A further important conclusion is that the power fraction which is not absorbed as O-mode in the first pass, essentially does not contribute to bulk plasma heating. This is explained by a loss of direction and polarization of the primary wave due to multiple wall reflections and subsequent effective surface absorption via oblique X- or R-waves. As a consequence high quality of the incident beam (divergence, polarization) and good absorption (electron temperature, plasma size) are goals for O-mode fundamental heating.

In the first experiments with X-mode irradiation at the cyclotron harmonic frequency ($\omega_{RF} = 2 \cdot \omega_{ce}$ with $B_{res} = 1.25$ Tesla) immediate breakdown and plasma build-up was achieved, too. The resulting temperature and density profiles (with $T_{eo} \approx 0.8$ keV and $n_{eo} \approx 2.5 \cdot 10^{19} m^{-3}$) were rather broad according to the enlarged absorptivity at $\omega = 2\omega_{ce}$. The heating efficiency was determined to $\eta = (80 \pm 10)\%$.

3. Impurity radiation, fast particle production and current drive

The typical radiation losses for the 70 GHz heated stellarator plasmas were around 40 kW. According to the spatially resolved bolometric radiation measurements the major fraction of radiation is emitted from the outer region (i.e. $r > 2/3$ a) and is attributed to atomic processes in this zone. In the inner part of the plasma the radiated power remains at about 30 mW/cm³. A few discharges with additional OH-current showed an increase of Z_{eff} by up to 25% during the ECRH pulse.

The RF generated fast electron population was analyzed by ECE measurements in perpendicularly and parallel oriented observation direction to the major radius. In the low density regime ($n_{eo} \approx 1$ to $2 \cdot 10^{19} m^{-3}$) a small fraction $n_e/n_{eo} = 10^{-3}$ with an energy of 10 keV was found. Operation at higher densities ($n_{eo} \approx 3\text{–}4 \cdot 10^{19} m^{-3}$) showed no suprathermal electrons.

Toroidal plasma currents in the range of 0.5 to 1 kA were observed for all kinds of wave irradiation. The following mechanisms were identified to contribute to the measured current: Co- and counterstreaming fast electrons of different confinement as a main mechanism for current generation at low densities /1/ and as a mechanism of minor importance at higher densities ($n_e \geq 10^{19} m^{-3}$). Because of the increased pressure gradients in the present experiments the pressure driven (bootstrap) current obviously gives the major contribution to the toroidal current. In addition the radial shift of the plasma in the helical field due to finite β contributes to the total current. A directly driven RF-current could be generated by reflection of the non-absorbed incident wave fraction at an oblique angle from the high-field side. By choosing different oblique angles the non RF driven currents could be compensated or even overcompensated.

4. Conclusions

Build-up and heating of a stellarator plasma to reasonable parameters was achieved by polarized and well focussed EC wave irradiation (170 kW, 100 ms) for both cases: first harmonic ordinary mode irradiation (T_{eo}=2.3 keV, $n_{eo}=1.8 \cdot 10^{19} m^{-3}$) and second harmonic extraordinary mode irradiation (T_{eo}=0.8 keV, $n_{eo}=2.5 \cdot 10^{19} m^{-3}$). The impurity radiation remained at low level and the relative fraction of suprathermal electrons was found to be negligible ($\leq 10^{-3}$). Besides direct RF-current drive at slightly oblique angles, plasma induced currents were observed and mainly attributed to the pressure gradient (bootstrap current) or to the toroidal plasma shift.

References

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