

## Advanced High Power ECRH Launch Scenarios at the W7-AS Stellarator

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### Abstract

At the W7-AS stellarator 140 GHz ECRH-Beams with up to 0.8 MW power in the second harmonic X-mode (X2) polarisation have been launched from the low field side, which couples to the thermal electrons, and from the high field side with preferred coupling to high energetic electrons. A strong increase of the suprathermal electron population was observed as compared to the standard low field launch scenario. The influence of the different electron distribution functions on the confinement was investigated for different magnetic configurations.

### Introduction

Sophisticated ECRH-systems are not only useful for local heating in the real space, but also give access to the electron phase space. The distortion of the electron distribution function causes enhanced electron drifts in the specific stellarator magnetic field, which can lead to a net electron flux in the real space. If the flux is toroidally directed, EC-driven currents are generated[1]. If the flux is radially directed, electric fields are generated, which can change the neo-classical and turbulent transport [2].

Advanced heating was investigated at the Wendelstein7-AS (W7-AS) stellarator to get a deeper insight into ECRH phase space physics at high power densities around  $50 \text{ MW/m}^3$ . In addition, the results should establish a basis for improved ECRH launch at the successor experiment Wendelstein7-X.

### Experimental set-up and results

At the W7-AS stellarator two independent 140 GHz ECRH-beams with up to 0.4 MW power each were used for both the high field launch (HFL) and low field launch (LFL) experiments. Since the plasma is not accessible from the high field side via a port, the beams were launched from the low field side with second harmonic ordinary polarisation (O2). For perpendicular O2-waves the absorption is very low (<1%) at the W7-AS plasma parameters and the beams penetrate through the plasma and hit an inner wall graphite reflector. Corrugated graphite tiles rotate the polarisation of the reflected wave by 90 degrees from ordinary to extraordinary .

With the help of ray-tracing calculations and carefully adjusting of both the low field side movable launch mirrors and polarisers it was ensured that the reflected beam was absorbed in the plasma centre. The polarisation of the LFL beams was checked by a transmission diagnostic (microwave probe array incorporated in the reflector). Since at the corrugated graphite about 8% of the power is absorbed and the polarisation efficiency is about 98%, we assume that for the high field launch the plasma is heated by only 90% of injected the power in comparison with the low field launch. In addition after the reflection the beams are less focused than in the LFL case and thus their deposition profile is broader.

The absorption profile in the real space is measured for the different scenarios by modulation techniques. The input power was modulated by 10-30 % in a wide range of frequencies (5-5000 Hz) and for each gyrotron individually. The perturbed electron temperature was measured by coherent detection of ECE. The measured deposition profile of each gyrotron was compared with ray tracing calculations. The absorption profile in the phase space was measured by vertical ECE at the ECRH launch position. In the vertical observation geometry the line of sight is approximately along the mod B surface, therefore the spatial resolution is lost, but due to the relativistic mass dependence of ECE-radiation, information of the electron energy distribution is available. The interpretation of the vertical ECE spectrum is, however, difficult, because a broadening of the spectrum is seen due to a slight variation of mod B along the line of sight and due to the finite optical resolution (width of the line of sight). Moreover, the thermal radiation at the central resonant ECE-frequency is partially reabsorbed by cold plasma at the plasma edge. For lower radiation frequencies of the fast electrons however, the plasma is optically thin. In

Fig. 1 the vertical ECE spectra of a HFL heated and LFL heated plasma are compared. By HFL ECRH the population of suprathermal electrons in the plasma core is strongly increased. The spectrum shows a large deviation from a thermal spectrum, which was calculated with the experimental temperature and density profiles. Note, that in the standard configuration of the W7-AS the central magnetic field at the line of sight of the vertical ECE antenna is slightly increased with an according EC resonance frequency of 144 GHz. The enhanced interaction with suprathermal electrons is seen more clearly by fast modulation of the ECRH power. Here we even get some spatial resolution for the vertical ECE observation. At modulation frequencies above 1 kHz the radial heat perturbations are strongly damped. Therefore only emission from the plasma centre is detected, where the modulated ECRH power is absorbed. Fig. 2 shows that for the same power modulation amplitude, by HFL ECRH the modulation of the high energy electron radiation was increased by a factor of four compared to LFL. For the simulated spectrum it was assumed that the thermal emission originates only from the ECRH deposition zone (effective radius  $<3$  cm). The amplitude of the spectrum was matched to the LFL spectrum. The influence of the different electron distribution functions on the confinement was investigated for different magnetic configurations [3]. In a stellarator the confinement of trapped particles in the long mean free path regime is poor. The neo-classical heat diffusivity scales with  $T^{7/2}$ . But the diffusivity is strongly reduced by an ambipolar radial electric field [4]. ECRH with x-mode polarisation with perpendicular launch increases the perpendicular momentum of electrons with low parallel momentum (trapped particles). With high power ECRH from the low field side a radial electron flux, which generates a positive electric field in the plasma centre, can be established [2]. The resulting extremely high central electron temperature gradient could only be explained if a reduction of the neo-classical heat diffusivity by a radial electric field was assumed. This positive electric field could be measured by CX-spectroscopy [2]. Assuming that the EC-driven (suprathermal electron flux) positive radial electric field exceeds the neoclassically driven (thermal ambipolar flux), HFL ECRH should generate a higher positive electric field and a better neo-classical confinement since it generates more suprathermal electrons, which are less confined. The temperature profiles of a HFL and LFL heated plasma are compared in Fig. 3. The central magnetic field in the HFL experiments was 20 mT higher to compensate for the power is deposition at a slightly higher resonant field. It was also taken care, that the density profiles measured by Thomson scattering were the same with a central density of  $2 \cdot 10^{19} \text{ m}^{-3}$ . The magnetic configuration in these experiments was the so-called standard configuration with a field minimum at the ECRH launch position. Therefore EC-heated particles are trapped and should perform a radial drift. For both launch scenarios an improved central confinement, an electron root like regime, could be established, but for the HFL the central electron temperature gradients are even more pronounced. Since all other plasma parameters were the same, only a higher central radial electric field could explain the steeper temperature gradients. The results are compared to a magnetic configuration with a maximum B at the ECRH launch position. There, the EC-interaction with trapped particles is reduced and an electric field is much more difficult to establish. With no radial electric field the HFL is less advantageous and as shown in Fig. 4 with LFL heating slightly higher electron temperatures are achievable.

The radial electric field was measured by CX-spectroscopy in a Helium discharge. With LFL ECRH the improved central confinement could not be achieved, while for the HFL it could easily be established even with 10% less power and a broader deposition profile. First indication of a positive radial electric field of  $600 \pm 100 \text{ V/cm}$  was found at the effective radius  $6.3 \pm 1 \text{ cm}$ , which supports the interpretation of EC-driven electric fields. Only few data points are available, and this measurement will be continued.

### Summary and conclusions

ECRH from the high field side couples preferably to the high energy electrons and generates a strongly increased population of suprathermal electrons compared to low field side launch. In magnetic configurations where a minimum of the magnetic field is located at the ECRH launch position (i.e. preferable heating of trapped particles), a radial flux of suprathermal electrons can be established, which generates a positive radial electric field. The radial electric field reduces the neo-classical heat diffusivity. With HFL confinement improvement could be achieved in the standard configuration compared to the LFL. In a maximum B configuration with less trapped

particles in the ECRH launch position the confinement is only slightly affected by the ECRH launch scenario, which gives further evidence that confinement improvement is related with ECRH interaction with fast trapped particles. Also first electric field measurement by CX-spectroscopy indicated, that the radial electric field is established more efficiently by suprathreshold electrons generated by ECRH launched from the high field side.

### References

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### Figures

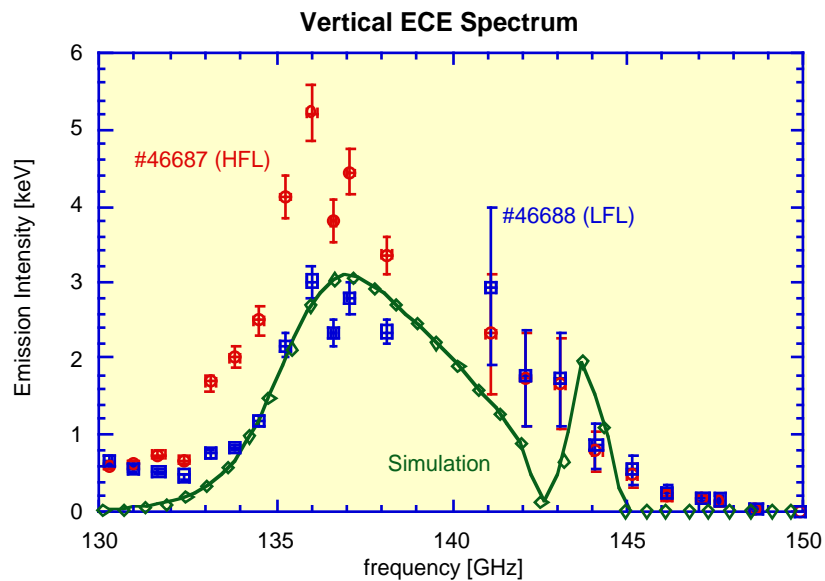


Fig. 1: Vertical ECE spectrum. Note, that here the frequency is not related with the radial position but with the electron energy. HFL (circles) is compared with the LFL (rectangles). The solid line is a simulation for thermal emission with a central Temperature of 3.5 keV. The dip around 142 GHz is explained by to reabsorption at the plasma edge.

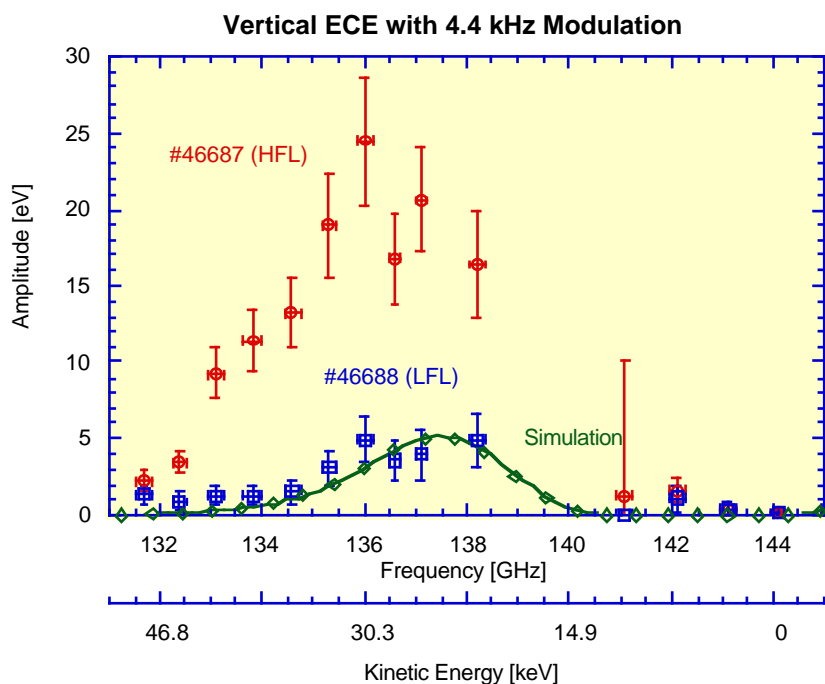


Fig. 2 : Spectrum of modulated vertical ECE with coherent detection. Here the HFL (circles) is compared with the LFL (rectangles). In addition a simulated spectrum (solid line) is plotted. In this simulation it was assumed that the thermal emission origins only from the ECRH deposition zone (effective radius <3 cm). The amplitude of the spectrum was matched to the LFL spectrum.

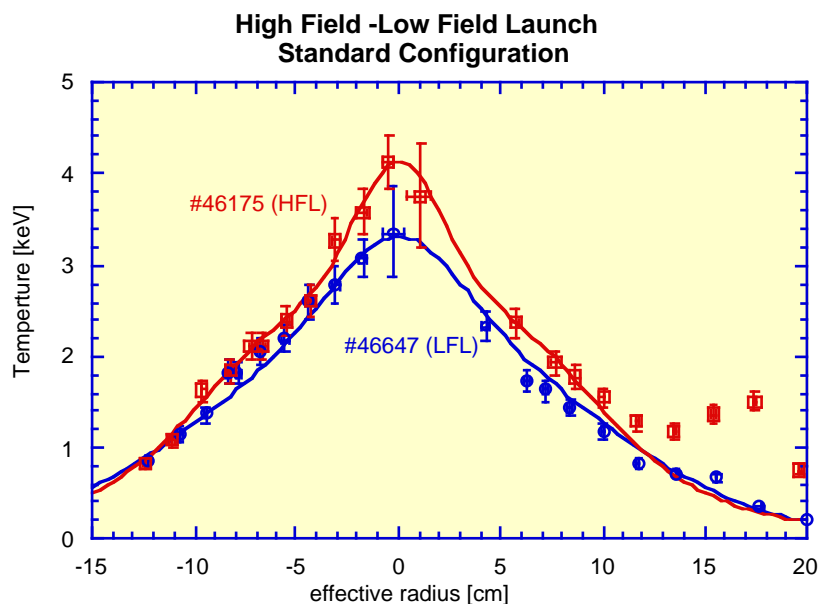


Fig. 3 : Electron temperature profiles of a low field launch (LFL) and high field launch (HFL) heated ECRH plasma in the standard configuration with trapped particles at the ECRH power deposition zone. The second peak at the right plasma edge is due to the suprathermal emission from the plasma centre and does not represent the edge temperature.

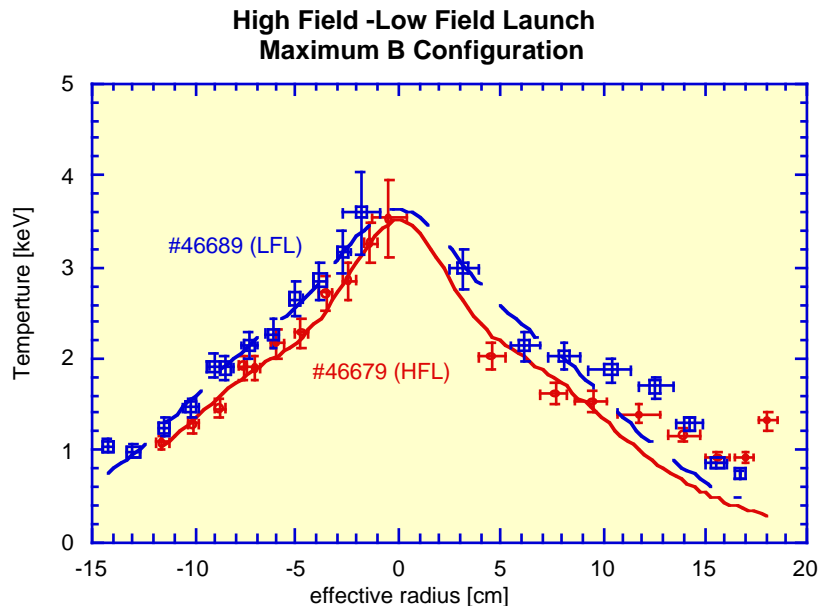


Fig. 4 : Electron temperature profiles of a low field launch (LFL) and high field launch (HFL) heated ECRH plasma in the maximum B configuration with less trapped particles at the ECRH power deposition zone.