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Electron Bernstein wave heating and current drive in overdense plasmas at the Wendelstein7-AS-Stellarator.

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Abstract

Successful heating with 2nd, 3rd and 4th harmonic 140 GHz EBW's and current drive with 70 GHz EBW's was demonstrated at W7-AS. Further, temperature profiles and heat wave propagation was measured by EBW-emission.

Introduction

Standard 1st and 2nd harmonic ECRH at 70 GHz and 140 GHz fails to support high-density operation $>10^{20}$ m^{-3}, which is necessary to attain detachment at W7-AS island divertor configuration. ECRH is limited by the O1-cutoff (0.6 10^{20} m^{-3}) for 70 GHz and the X2-cutoff (1.2 10^{20} m^{-3}) for 140 GHz respectively at 2.5T. For the propagation of electron Bernstein waves (EBW), however, no upper density limits exist, but they have to be generated by the OXB-mode conversion process from the electromagnetic waves [1]. For this process threshold densities of 0.6 10^{20} m^{-3} (70GHz) and 2.4 10^{20} m^{-3} (140GHz) exist. Efficient OXB-heating with 70 GHz has already been successfully demonstrated at Wendelstein7-AS [2], but the higher harmonic OXB heating with 140 GHz EBW's remained unexplored until improved performance by divertor operation above the critical density of 2.4 10^{20} m^{-3} was shown recently. In a stellarator the highest beta is achieved for a high-density plasma at a low magnetic field. For RF-heating with 140 GHz electron Bernstein waves, this requires an interaction with at the third or higher harmonic. Fortunately, here the cyclotron absorption is high enough for efficient heating.

Heating Experiments

Three 140 GHz Beams with a total power of 1.5 MW were launched into a NBI sustained (up to 4 MW) high-density plasma (up to 3.5 10^{20} m^{-3}). The rotational transform was matched to the island divertor operation parameters. The ECRH launch was optimised in respect to the angular window necessary for efficient EBW generation. Here the optimisation criterion was the increase of plasma energy shown in Fig.1 and the reduction of the non-absorbed ECRH stray radiation. Further a magnetic field scan was performed to achieve central power deposition. Here we could only partially succeed, since the EBW-heat wave analysis with EBE was not available online. In particular for the 4th harmonic heating central power deposition is not possible since for the resonant absoption in the center the next harmonic appears at the edge. For the 2nd harmonic we have got a power deposition at an effective radius of about 4 cm as shown in Fig. 2. During the EBW-heating the central plasma temperature rises from about 270 eV to 310 eV. The temperature profile was also broadened implying a transition from detachment to attachment due to the increase power flow across the separatrix. This explanation is assisted by the divertor measurement. The plasma energy content is increased during EBW-heating by about 40% as shown in Fig.1. It was estimated that about half of this energy increase is due to the profile change at the detached-attached transition. Although with 140 GHz second harmonic EBW heating off-axis power deposition could be achieved only, the EBW heating efficiency was comparable with NBI. Even more, EBW heating becomes more effective with increasing density. In further experiments the EBW heating could successfully substitute NBI-heating with comparable power without degrading the plasma performance. Since the plasma is optically thick for higher harmonic EBW, also third and fourth harmonic heating could be succesfully demonstrated with 140 GHz at 1.5T and 1.1T respectively. The maximum achievable density in a stellarator is only limited by the heating power, which has to balance thermal losses. At low magnetic field this density limit could be significantly increased by additional EBW heating.

Current Drive

EBW's offers also the possibility to drive current. Even more, due to their electrostatic character the parallel component of the refractive index can become of the order of 1 implying a high EBW current drive (EBCD) efficiency [5]. Since the CD efficiency scales like T_e / n_e the experiment were performed with 70 GHz first harmonic EBW-heating at a density of 1.05 10^{20} m^{-3}. An ECRH beam with 0.45 MW power was launched in a current free sustained NBI (0.5 -1MW) sustained target plasma. The magnetic field was adjusted to 2.15 T in order to get central power deposition. Here the large $N_{||}$ component of the EBW's requires a stronger reduction of the resonant magnetic field than for standard ECCD with electromagnetic waves. Since OXB mode conversion needs an optimal launch angle no angular scan is possible to investigate the driven current. However the $N_{||}$ component of the EBW's could be varied by both, the reversal of the magnetic field and the change of the magnetic configuration, which means to have a local minimum or maximum of the magnetic field at the EBW launch position. In the current free discharges all plasma currents are compensated by the inductive current. The loop voltage is then a gauge for the plasma currents. $U_{loop} = R_{Plasma}\left(I_{Bootstrap} + I_{NBI} \pm I_{ECCD}\right)$. For co- and counter-EBCD the contribution to the loop voltage changes its sign, while the other currents remain unchanged. Hence, the difference of the co- and counter-CD is $\Delta U_{loop} R_{plasma} = I_{co-CD} + I_{Counter-CD}$ shown in Fig.3. In the case of EBCD a current of 3 kA ± 0.5 kA (co + counter current) and was estimated. The highest CD efficiency was achieved in the case of co-EBCD (see Fig 4). Here with 450 kW a current of 1.85 (+1,-0.5) kA was driven. In a similar discharge, but with zero loop voltage, the plasma current rises above 1.2 kA during the EBW-heating as shown in Fig.4.

Summary and Conclusions

Successfully heating of extreme high-density plasma, which are achievable now for divertor operation at Wendelstein7-AS, was demonstrated with 140 GHz second, third and fourth harmonic electron Bernstein waves. This ECRH frequency is foreseen for the large Wendelstein7-X experiment, which is in construction now. The reason for the high OXB-mode conversion efficiency is mainly the extremely steep density gradient in the high-density target plasma at Wendelstein7-AS. Further, current drive with the 70 GHz first harmonic Bernstein waves in an overdense plasma was demonstrated for the first time.

References

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Figures

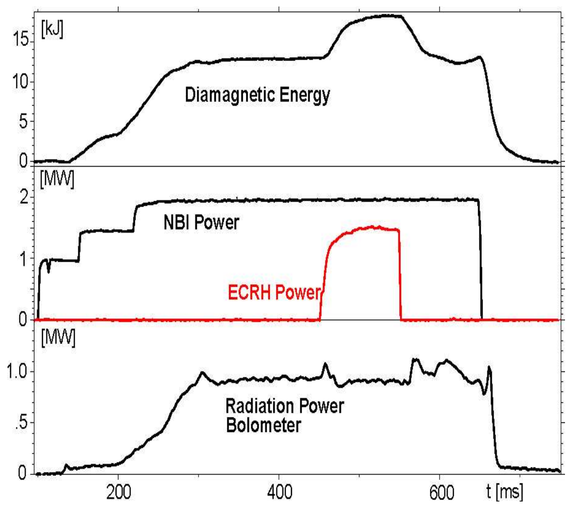

Fig 1 Increase of plasma energy due to second harmonic Bernstein wave heating (B2) with 140 GHz.

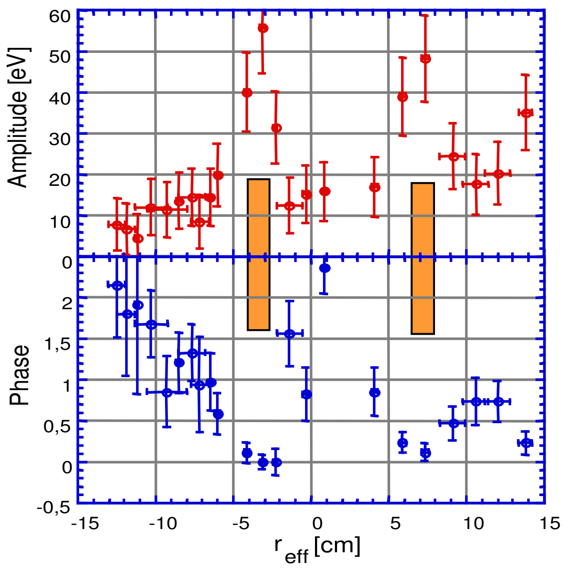

Fig. 2: Heat wave amplitude and phase generated by off-axis 140 GHz B2-heating and reconstructed from first harmonic EBE. The reason for the apparent asymmetry of the power deposition is due the strong Shafranov shift of the plasma, which could no be taken into account completely in the EBE temperature profile reconstruction.

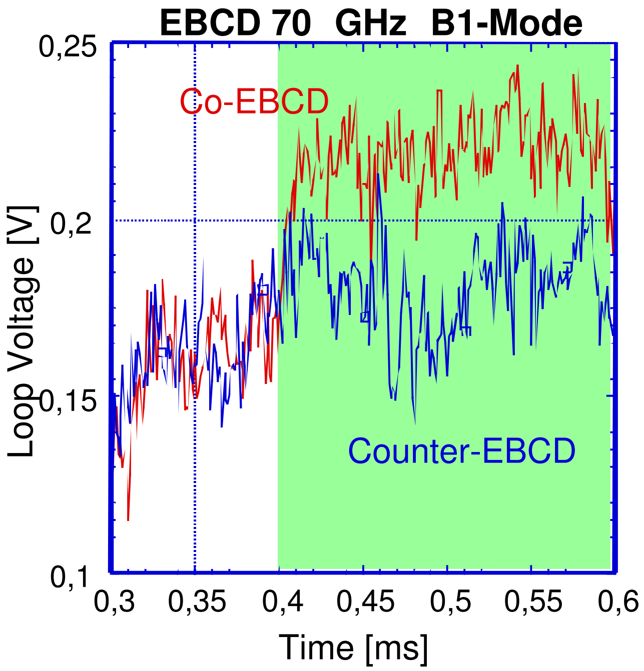

Fig. 3: Loop voltages for co- and counter EBCD . The ECRH was switched on at 0.4 s. Here the temperature was 700 eV and the density was 1.05 10^{20} m^{-3}.

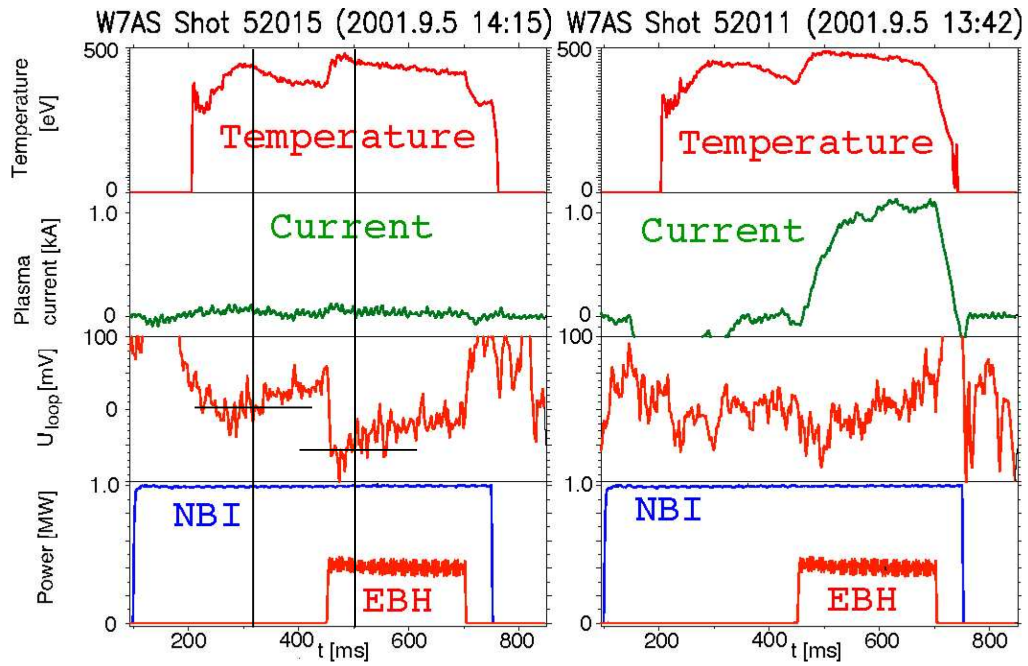

Fig.4 Discharge parameters . Left : A net current free discharge, where the EBCD current is compensated by the loop voltage. Right: A discharge with free running plasma current. For both discharges the plasma density was 1.1 10^{20} m^{-3}.