Characterization of a Highly Energetic Electron Component
of Electron Bernstein Wave Heated Plasmas in the WEGA Stellarator

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A standard method to heat magnetically confined plasmas is electron cyclotron resonance heating (ECRH). The heating efficiency is strongly dependent on the chosen electron cyclotron harmonic frequency of the launched electromagnetic (EM) wave as well as their polarisation and angle of incidence with respect to the magnetic field vector. At typical plasma temperatures of some keV and densities of 10^{19} m^{-3}, the highest possible frequency with nearly 100% absorption is the second harmonic in extraordinary polarisation launched perpendicular to magnetic field vector. In this case, the achievable electron density is given by the upper X-cut-off-frequency, although the plasma density in stellarators as well as spherical tokamaks is not restricted by a stability limit. However, an upper density limit does not exist for electrostatic electron Bernstein waves (EBW) based on a coherent motion of the gyrating electrons around the magnetic field lines. But, the excitation of EBWs from vacuum is impossible because the plasma acts as propagation medium. Hence, an elliptical ordinary (O) polarized EM-wave launched under a certain oblique angle with respect to the magnetic field vector has to be converted to a slow extraordinary (X) polarized EM-wave and subsequently into EBWs at the upper hybrid resonance layer (UHA) [1]. This so called OXB mode conversion process is shown in Fig.1 as an example of the heating system of the stellarator WEGA. Here Ar- and He-plasmas are fully sustained by OXB heating at a magnetic field of 0.46 T with a 10 kW - 28 GHz heating wave. The confined plasma volume has a major radius of about 70 cm and a minor radius of 9 cm. A necessary condition to reach an OXB-heated plasma is to pass the critical plasma density ($1 \cdot 10^{19}$ m^{-3} for a 28 GHz O-mode wave). Similar to the Brewster angle in optics, the conversion is strongly dependent on the polarisation and the angle of the incident wave. The latter is adjustable through a movable second mirror, whereas the optimal angle is in coincidence with a minimum of 28 GHz stray radiation [2, 3].
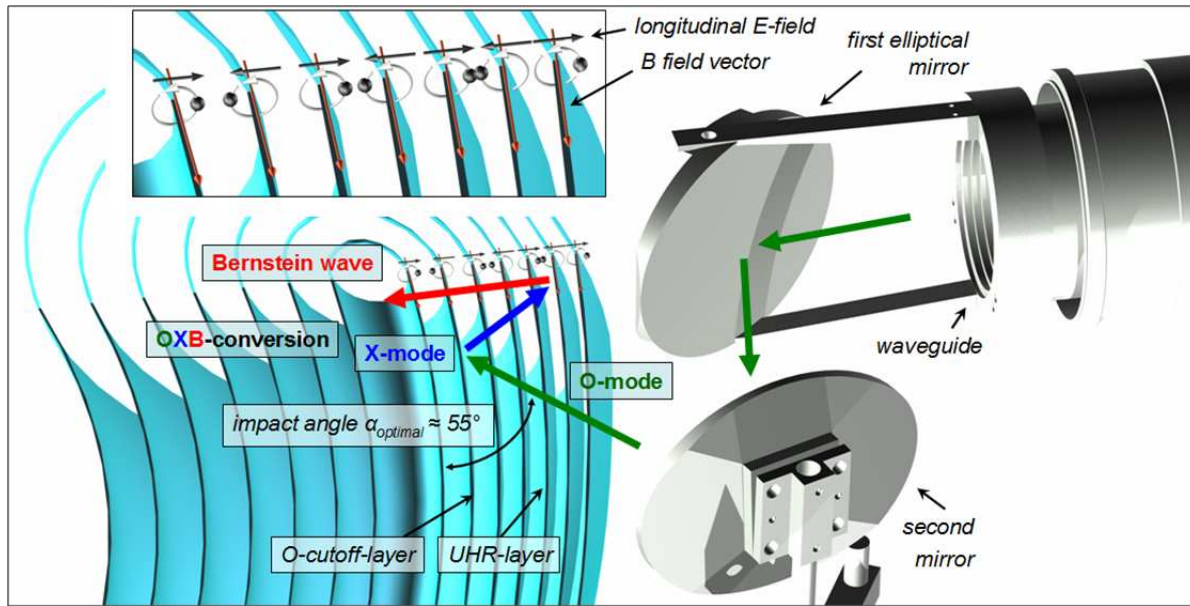
Fig. 1: Quasi-optical 28 GHz-heating system to reach OXB-heating of over-dense plasma at WEGA.

In addition to the over-dense plasma regime with an electron density of up to $1.4 \cdot 10^{19}$ m^{-3} and a bulk electron temperature of maximum 15 eV, a highly energetic electron component is produced with averaged energies of about 18 keV accompanied by a net-current of 30 A. Furthermore, X-rays with an energy up to 70 keV are detectable by a pulse height analyzer (PHA), whereas the spectrum in Fig. 2 is an average over 11 discharges with 4 s integration time, respectively. When inserting a fast reciprocating (< 0.4 s) Langmuir probe with 0.9 mm diameter, the current and the soft X-ray emission is reduced to less than 10 %, indicating that the current is driven by the fast electron component which has a long mean free path and thus is collected by the probe. The change of the line integrated density during the disturbance is less than 5%.
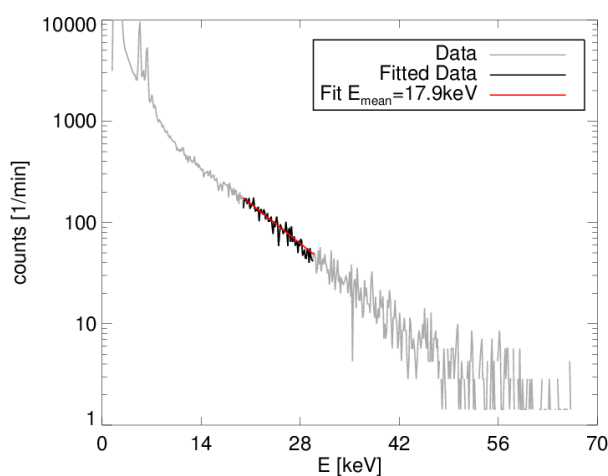

Fig 2: X-ray spectrum by pulse height analyzer

The over-dense OXB-heating regime is also accompanied by an extreme increase of the radiation temperature up to several keV in the frequency range of 27 to 29 GHz. The horn antenna of the observing microwave radiometer is in line with the optimal angle of O-mode emission which is determined by electron Bernstein waves from the plasma converted by the inverse OXB-conversion process (BXO). Parasitic resonances of the gyrotron can be excluded

as source for the suprathermal microwave emission. Ray-tracing calculations indicate that local distribution of the suprathermal electrons is important for the clarification of the heating as well as the emission process. A pure central distribution would not allow electron Bernstein wave emission (EBE) with radiation temperatures of keV because of reabsorption by cold electrons in the plasma edge. On the other hand, a suprathermal electron component located near to the edge of the over-dense area is able to produce radiation temperatures up to 50% of the mean energy assuming a maxwellian distribution of the suprathermal component.

To realize spatially resolved soft X-ray measurements, the PHA was modified by a movable pinhole varying the sight area of the liquid nitrogen cooled detector. Because of the limitations due to the port dimensions, the maximal resolvable effective radius is only 60 mm. By removing the 5 μm Be-filter, the spatial calibration of the pinhole position can be performed by 2 reference LEDs, as shown in Fig. 3.
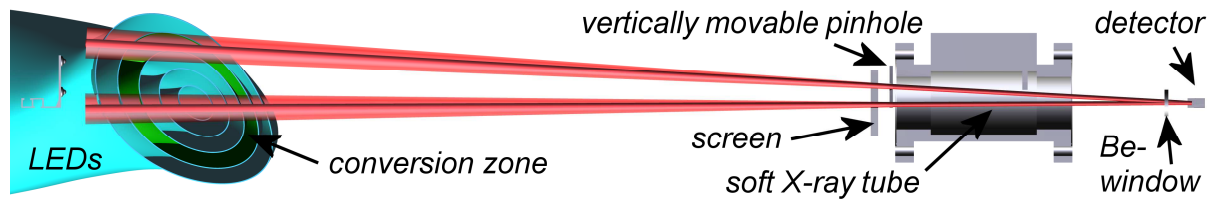
Fig. 3: PHA-detector sight areas produced by pinhole in bottom- and top-position

In the energy range up to 30 keV, the detected soft X-ray emission is localized around the horizontal plane, which is much narrower than the thermal electron component (Fig. 4). The 60 % - width of the distribution is in agreement with the expected deposition zone by ray-tracing calculation. For the spatially resolved measurement of energies above 30 keV, a highly sensitive silicon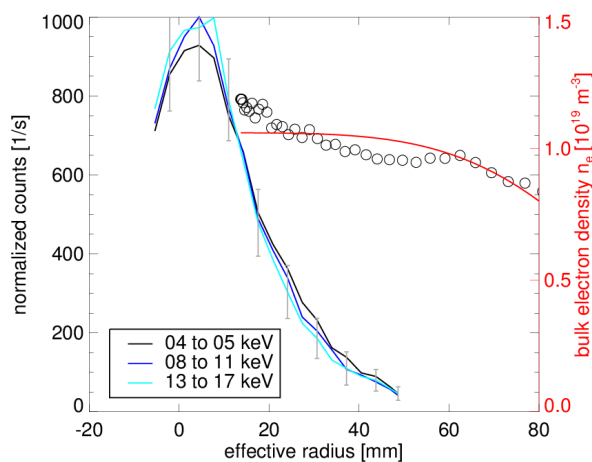 drift detector (SDD) with 77 cells was tested at WEGA. In combination with a conical lead-pinhole of minimal 0.7 mm diameter, 2D-imaging of hard X-ray detection up to energies of 300 keV is possible. Fig. 5 shows the projection of the 60 % intensity contour of both systems on the Poincaré-plot of the magnetic field configuration. The intersection area has a vertical width of about 24 mm as well as a radial shift with respect to the magnetic axis. The latter one is in coincidence with the time dependent
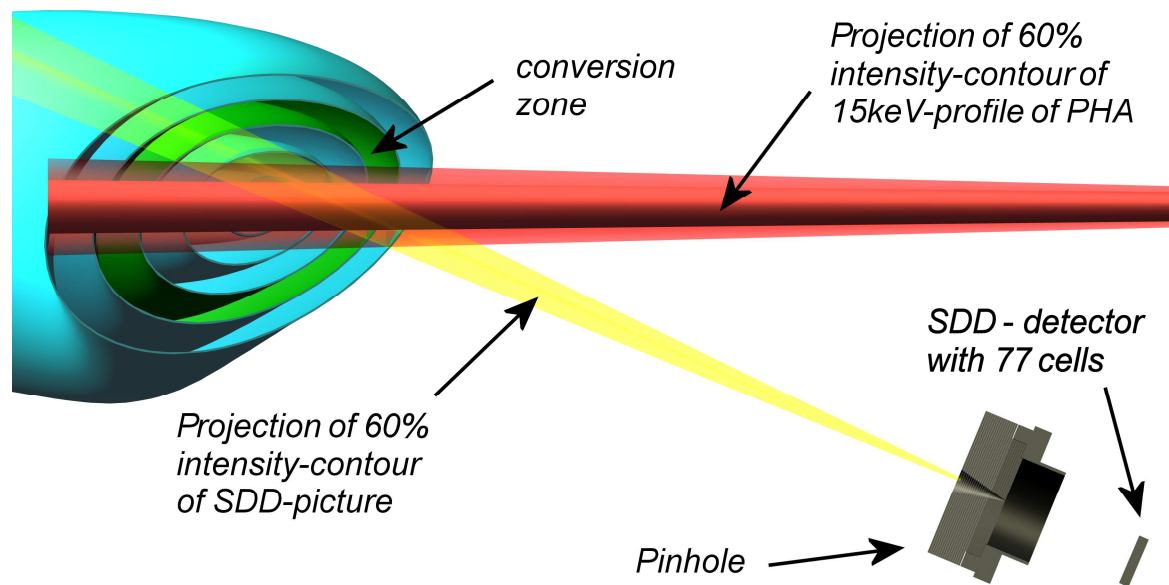
Fig. 4: Comparison of soft X-ray profile of different energy ranges with electron bulk density

Fig. 5: Comparison of X-ray measurements of single detector and 2D-imaging SDD

disturbance of the flux surface by the mentioned Langmuir probe, but has to be clarified with PHA-measurements at same viewing angle and energy range. Regarding the diamagnetic energy of the fast particles determined by modulation experiments, the measurements result in a fast electron density of about 1 % of the bulk electrons. It has to be clarified by high harmonic electron cyclotron emission, if the soft X-ray spectrum comprises the energetic distribution of the fast particle component or only the bremsstrahlung of a basically monoenergetic electron beam. The latter one can produce instabilities that have to be excluded in the comparison of the detected emission with the modelling. A final proof will give the measurement of the angle dependant EBE by a highly optimized quasi-optical antenna system.

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