Multi-Frequency Microwave Heating and Current Drive in over-dense Plasmas at the WEGA Stellarator

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Introduction: The operation density in stellarators is not restricted by a limit based on stability. Thus operation at densities well beyond 10^{20} m^{-3} is possible. High density maximizes fusion power staying within the optimum fusion reaction range even at higher beta, and minimizes the population of fast particles. In addition, current drive, which shows reduced efficiency at higher densities, is not an issue for stellarators but important for in spherical tokamaks. Moreover, stellarator confinement scales favorably with density. However, rf-heating requires the limit placed by the cut-off density of the launched high frequency waves to be overcome.

WEGA is a classical five period and $l = 2$ stellarator with a major radius of 0.72 m and an aspect ratio of 7. It is equipped with three independent coil systems: The toroidal field coils, the two oppositely energized helical field coils generate the rotational transform and thus the closed magnetic flux surfaces and the vertical field coils. The discharge length at 0.5 T is typically up to 20 s, which allows operating the plasma in a stationary state. Most of the discharges are operated in helium. The heating system of WEGA consists of a 10 kW 28 GHz cw gyrotron with a waveguide transmission line and a quasi-optical steerable antenna system for proper beam launch into the plasma. The 2.45 GHz system consists of 2 magnetrons with 20 kW and 6 kW power, respectively, and two mono-mode TE01 transmission lines. The antennas are circular TE11 waveguides with a specially shaped end horn to get an oblique asymmetric $k_{||}$-vector distribution. WEGA is used for fundamental research on plasma-wave interaction in steady-state conditions. The combination of different RF frequencies generates beneficial synergy effects, which makes it possible to reach otherwise inaccessible plasma conditions. Two scenarios are presented: With the assist of a 2.45 GHz resistive R-(Whistler-) wave heating the density threshold for the resonant 28 GHz electron Bernstein wave (EBW) heating by mode conversion was overcome. Since there is no density limit for EBW propagation, ECRH at over-dense plasma could be established. At lower densities the 28 GHz ECRH with

X-waves generates seed electrons for Landau interaction of the fast electrons with the 2.45 GHz waves. In this scenario plasma current of 100 A/kW and electrons of MeV energy are generated.

28 GHz Bernstein wave heating and current drive with 2.45GHz assist: The generation of 28 GHz EBWs by **O**rdinary-e**X**traordinary-**B**ernstein-mode conversion (OXB) [1] requires to overcome the density threshold (1×10^{19} m^{-3}), which is the O-mode density cut-off and is inaccessible with 28 ECRH only. In the low temperature plasma of several tens eV the 2.45 GHz R-waves are well damped resistively and an additional power of 20 kW rises the density above the threshold. Here, the OXB mode conversion takes place and the EBWs propagate into the over-dense plasma center, where they are well absorbed at the cyclotron resonance. This is well seen by the drop of the 28 GHz stray radiation and the increase of density due to highly improved power absorption in Fig. 1. Once the transition into mode conversion heating happened the 2.45 GHz assist can be switched–off and the plasma is sustained by 28 GHz EBW only. This so called "OXB"-phase is characterized by a centrally localized supra-thermal electron component with mean energies of more than 10 keV, which was detected by X-ray imaging with a pulse height analyzer. This supra-thermal electron component emits also EBWs (EBE) with a radiation temperature of more 10 keV, which could be detected by the inverse OXB-process. The EBWs strongly vary their parallel component ($N_{||}$-value) of the refractive index vector, when propagating through the magnetized plasma. By a proper choice of the launching position the $N_{||}$-value can be even larger than unity at the position where absorption takes place. The EBW driven current bases on the Fish-Boozer mechanism [2]. The total current is with up to 30 A below the prediction by ray-tracing and Fokker-Planck calculation, but can be explained by additional damping due to inelastic collisions of the electrons with the not fully ionized Helium ions. It should be noted that the non-zero $N_{||}$ value reduces the resonant magnetic field by 12% due the Doppler shift. Both the OXB-heating, -current drive and the supra-thermal EBE are modeled with ray-tracing calculations taking into account a non-thermal electron energy

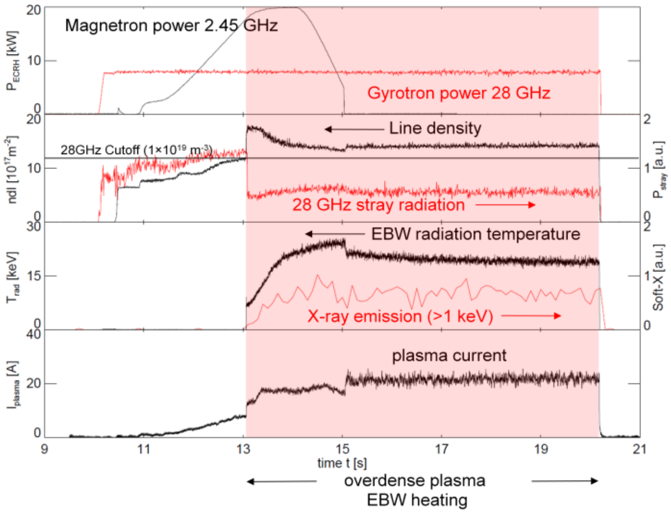

Fig 1 Over-dense plasma heating by OXB-mode conversion. Signals from the top: heating power, density and 28 GHz stray radiation, X-ray emission and EBE-radiation, plasma current.

distribution function. This heating scenario is also foreseen for W7-X at ultra-high densities above 2.5× 10^{20} m^{-3}.

2.45 GHz LH-current drive and MeV electron generation with 28 GHz assist: Below the 28 GHz cut-off density but well above the 2.45 GHz cut-off density at typically 2×10^{18} m^{-3}, the 28 GHz ECRH enables the 2.45 GHz waves to couple with fast electrons and to drive current >100 A/kW with high $N_{\|}$ R-waves in steady state. The 28 GHz produces the plasma start-up und generates the seed electrons for Landau damping with 2.45 GHz. This heating scenario is characterized by the appearance of extremely high-energetic relativistic electrons (>1MeV). Their drift orbits strongly deviate from the magnetic flux surfaces and are located at the low field side concentrated around the equatorial plane. Electrons with the highest energy of >3 MeV were confined at so called stagnation orbits [3] close to the equatorial plane and even extended the plasma edge at the low field side. Those particles which are colliding with the mostly closest in-vessel components are generating hard X-(HX)-ray emission and γ-radiation by bremsstrahlung. The γ-spectrum was measured with a Geiger-Mueller counter (Gamma-Scout) by varying the lead thickness screening from 0 to 25 mm as shown in Fig. 2. Even with the thickest lead thickness γ radiation could still be detected, which is a clear evidence for the relativistic electrons with energies above 1 MeV. The confinement of those highly energetic electrons is completely non-isotropic. Only for counter-propagating electrons stabile orbits exist. Therefore, the driven current could be reversed by the reversal of the magnetic field only and was independent of the antenna k-spectrum as shown in Fig. 3. During the 2.45 GHz heating the ECE-emission was strongly enhanced over all channels (20-40 GHz) with radiation temperatures of up to 1.2 keV.

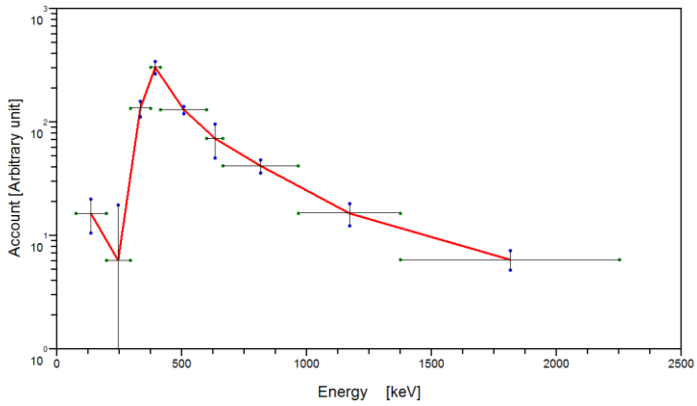

Fig 2 γ-ray spectrum deduced form the lead filter method.

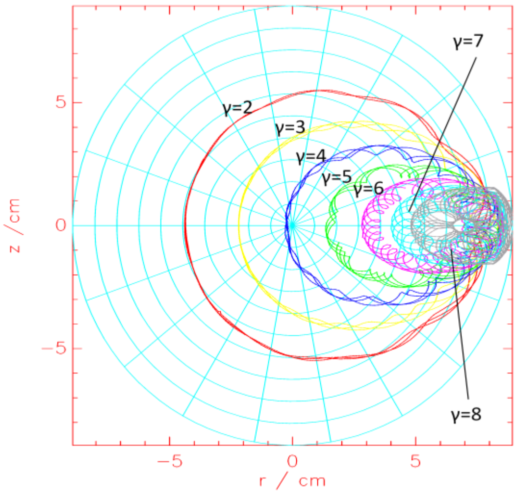

Fig. 3. Poloidal projection of the electron trajectories with initial zero pitch angle for different relativistic γ–values

With additional but un-calibrated ECE channels microwave emission at a frequency of 130 GHz, which was more than nine times the cyclotron resonance frequency of 14 GHz, could be detected. We have identified this radiation as synchrotron radiation, since the polarization was mainly in π-direction (parallel major plasma radius). The localization of the relativistic electrons was measured by a reciprocating Langmuir probe, which was inserted from the low field side into the plasma. When the probe intersected the separatrix, the plasma current, the HX-radiation and the microwave emission started to decay and vanished within the next 3 cm inward motion. In addition a drop of the diamagnetic energy of typically 1.75J was observed. In that case the plasma current was 290 A. With the assumption, that the current is driven by the relativistic electrons only, the total number of those electrons could be estimated to 6×10^{12}, which is about 10^{-4} of the total number of electrons. The average energy of the electrons would be of the order of 1.8 MeV. The directivity of the relativistic electrons could be detected by the directivity of the γ-emission. With a tangentially viewing γ-detector the γ-spectrum showed a reduction of the intensity by a factor of 9 when the plasma current is reversed.

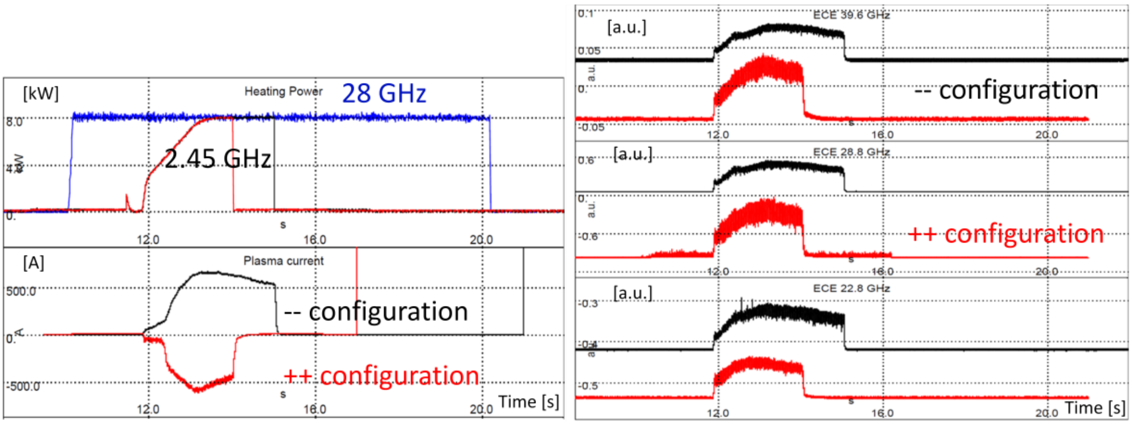

Fig. 4. Time traces two the LH-current drive scenarios with field reversal. Left: heating power and plasma current. Right: ECE-signals in arbitrary units.

Summary and conclusion: The beneficial combination of two frequency heating was demonstrated for the high density 28 GHz OXB-heating scenario and the 2.45 GHz LH-current drive scenario. Both scenarios are steady state and unique at WEGA. The self-sustained EBW-heated over-dense plasma is characterized by a supra-thermal electron population on axis. The 2.45 GHz current drive generates relativistic electrons in the MeV range, which propagate on stagnation orbits emitting HX-bremsstrahlung and synchrotron radiation.

References

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