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ORIGINAL PAPER

Overview of recent results from the WEGA stellarator

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Abstract. Repeated magnetic flux surface measurements confirmed the existence of closed and nested flux surfaces, but also revealed the existence of magnetic error fields. The simultaneous application of two radio frequency systems for plasma heating operating at 28 GHz and 2.45 GHz, respectively, allowed to reach otherwise non-accessible plasma regimes in WEGA due to synergetic effects. These regimes are characterized by over-dense plasmas at 0.5 T operation by means of electron Bernstein wave heating and the existence of supra-thermal electrons associated with soft X-ray and γ-rays. The thermal electron diffusion coefficient was determined in the electron Bernstein wave heated plasma regime. Additionally, results from turbulence studies in low density plasmas in the vicinity of magnetic islands are presented.

Key words: magnetic confinement • supra-thermal particles • electron Bernstein waves

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Introduction

WEGA is a classical five-field period and $l = 2$ stellarator with a major radius of $R = 0.72$ m and an aspect ratio of about 7. The magnetic field coil system includes three independent types: 40 toroidal field coils, 2 pair of helices and a pair of vertical field coils allowing a radial plasma shift and a modification of the magnetic shear. Furthermore, it is equipped with an error field compensation coil. Thus, WEGA has a very flexible magnetic configuration space which has been examined in detail with the help of vacuum magnetic flux surface measurements.

Two radio frequency (RF) heating systems operating at a frequency of 2.45 GHz (26 kW, cw) and 28 GHz (10 kW, cw), respectively, and a transformer with a capacity of 440 mVs for Ohmic heating and current drive are available. The plasma discharges generated in WEGA at 0.5 T have a typical length of 10 s and are stationary. The typical plasma densities in argon or helium discharges are of the order of $n_e = 10^{17}$–10^{18} m^{-3} with an electron bulk temperature range of $T_e = 5$–50 eV. A single-channel 80 GHz interferometer and various Langmuir probe systems are used to measure the central plasma density, the radial density profiles and the electron temperature, respectively.

However, the simultaneous application of the two RF systems allows access to two unique plasma regimes characterized by densities up to $n_e = 1.5 \times 10^{19}$ m^{-3} on

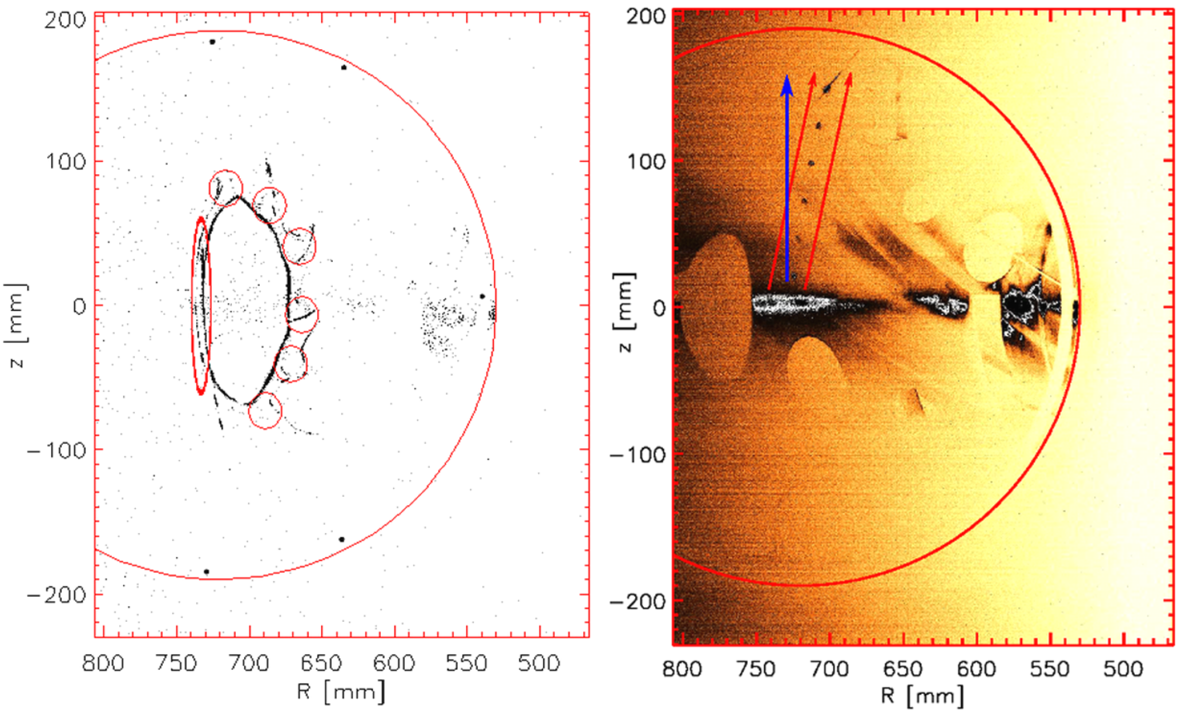

Fig. 1. Left: edge magnetic flux surface with 7 non-natural islands due to an $n = 4$ error field component. Right: drift trajectory of an electron beam (red arrows) in a purely toroidal magnetic field exhibiting the expected vertical (blue arrow) and an additional inward directed drift component.

the one hand and the existence of supra-thermal electron energies in the MeV range on the other hand.

In the following selected results will be presented.

Magnetic flux surface measurements

After 10 years of operation, the magnetic field topology was again carefully investigated by magnetic flux surface measurements. For this purpose, the electron beam technique [2, 3, 6, 7, 19] in combination with a fluorescent detector were utilized. The position and the shape of the closed and nested magnetic flux surfaces for a fixed current ratio in the toroidal and helical field coils are nearly unchanged and the former results could be verified [10, 13]. A closer look at the magnetic flux surfaces revealed also magnetic islands of the order of $n = 4$ where a resonant rotational transform is fulfilled as can be seen in Fig. 1(left).

Additionally, the influence of the magnetic stray field of the Ohmic transformer coils on the magnetic topology was studied, showing a significant shift of the magnetic flux surfaces by a net radial and vertical magnetic field component. Furthermore, drift experiments of an electron beam in a purely toroidal magnetic field revealed an additional radial deviation from the expected vertical drift was found indicating a further magnetic error field component.

RF heating regimes

The simultaneous application of the two RF heating systems operating at different frequencies opens new fields of otherwise not accessible areas which will be discussed in the following.

Over-dense plasma operation by electron Bernstein wave heating

The operation density in stellarators is in contrast to tokamaks not limited by means of stability reasons. For electron cyclotron resonance heating, the maximum reachable density is limited by the associated cut-off density of the heating frequency. However, over-dense operation in stellarators can be achieved by an alternative heating concept, basing on electron Bernstein waves (EBW) [1], which has been successfully established at different experiments [5, 9, 15, 17, 18].

In order to overcome the cut-off density necessary for the propagation of the Bernstein waves, a two-step conversion from the electromagnetic ordinary (O)-mode wave into an extraordinary (X)-mode wave and subsequently into an electrostatic electron Bernstein (OXB) wave is applied at WEGA [15]. At a magnetic field of 0.5 T, stationary operation at high-density in argon and helium plasmas are routinely achieved by combining both available RF heating systems [4, 11, 12, 14]. As shown in Fig. 2 the plasma is ignited by the 28 GHz electron cyclotron resonance heating (ECRH) system at about $t = 10$ s, and starting from $t = 11$ s additional power by resistive R-wave heating of the 2.45 GHz system is provided. As a consequence, a continuous increase of the plasma density can be observed up to $t = 13$ s. At this time, the critical cut-off density of $n_e > 0.97 \times 10^{19}$ m^{-3}, necessary for the OXB-heating at 28 GHz (second harmonic), has been overcome. Reaching the critical cut-off density is associated with a fast increase of the central electron density, obtained from the interferometer data, and a significant reduction of about 50% of the 28 GHz microwave stray radiation level, indicating a central absorption of the heating wave. The typical time-scale for the transi-

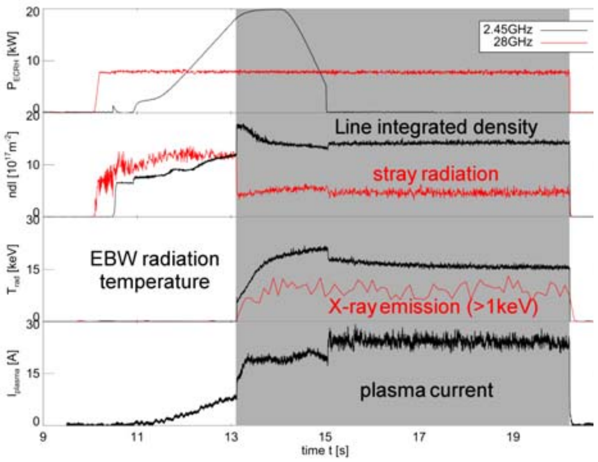

Fig. 2. Transition into an OXB phase of a 28 GHz ECR heated plasma by using an additional resistive 2.45 GHz heating (grey shaded area). From above: injected ECRH power P_{ECRH}, line integrated density n·dl, non-absorbed 28 GHz stray radiation P_{stray}, radiation temperature T_{rad}, soft X-ray emission and plasma current I_{plasma}.

tion into the over-dense regime, where the EBW can propagate inside the plasma, was determined by a fast Si-photodiode (AXUV) bolometer camera and is of the order of 0.5 ms. The central density, determined with the help of a fast reciprocating single Langmuir probe during repeated experiments, is of the order of $n_{e,0}$ = 1.3 × 10^{19} m^{-3} thus well above the cut-off. Once the cut-off threshold has been overcome, the additional 2.45 GHz heating system is ramped down and finally turned off at t = 15 s. The discharge is fully sustained by the 28 GHz electron Bernstein waves (EBW) heating up to the end of the discharge at t = 20 s.

During the OXB-regime, indicated as the red-shaded region in Fig. 2, the plasmas are characterized by a bulk electron temperature of a few 10 eV measured with Langmuir probes and an additional fraction of supra-thermal electrons in the plasma center with energies up to 20 keV accompanied by small toroidal net-current of a few 10 A. These supra-thermal electrons are the source of soft X-ray emission. Their spatial distribution has been determined by different soft X-ray detectors. The localization and the energy range of the soft X-rays near to the center of the plasma is in agreement with measurements from the AXUV bolometer camera and an electron Bernstein wave emission (EBE) diagnostic.

The OXB-heating, -current drive and the supra-thermal EBE are modeled by ray-tracing calculations taking into account the non-thermal electron energy distribution function and the radial density profile, similarly to previous experiments with 2.45 GHz [16]. However, in this case, the modeling does not explain the experimental results satisfactorily.

Generation of highly energetic electrons

A second synergetic effect associated with the simultaneous use of the 2.45 GHz and 28 GHz RF heating systems is the generation of a toroidal net-current and the existence of relativistic electrons in the MeV range. In this scenario a target plasma is generated by the 28 GHz heating system. The typical density of n_e > 2 × 10^{18} m^{-3} is above the 2.45 GHz, but below the 28 GHz cut-off density. Via Landau type damping, increasing mainly the parallel momentum of the electrons, currents of > 100 A/kW cw could be maintained in the plasma. A synchrotron-like broad electron cyclotron emission (ECE) radiation spectrum, measured by a microwave radiometer, is generated by the high-energy electron component. Their energy distribution is determined by γ-ray detectors with varying lead thickness covering the detector. Even with a lead screening of 28 mm, which absorbs γ-energies up to 1 MeV, a significant count rate well above the background rate could be observed, as shown in Fig. 3a. At energies above 200 keV, the electron confinement in WEGA becomes highly asymmetric for toroidally co- and counter propagating electrons as shown in Fig. 3b. Thus, the RF driven current does no longer depend on the $N_{//}$ spectrum of the emitting antenna. Instead, the toroidal net-current is maintained by the electrons propagating in the direction with stable trajectories, while particles propagating in the opposite direction are immediately lost [20].

The existence of such stable orbits – the so-called stagnation orbits – for highly energetic particles has been predicted theoretically [21]. For WEGA calcu-

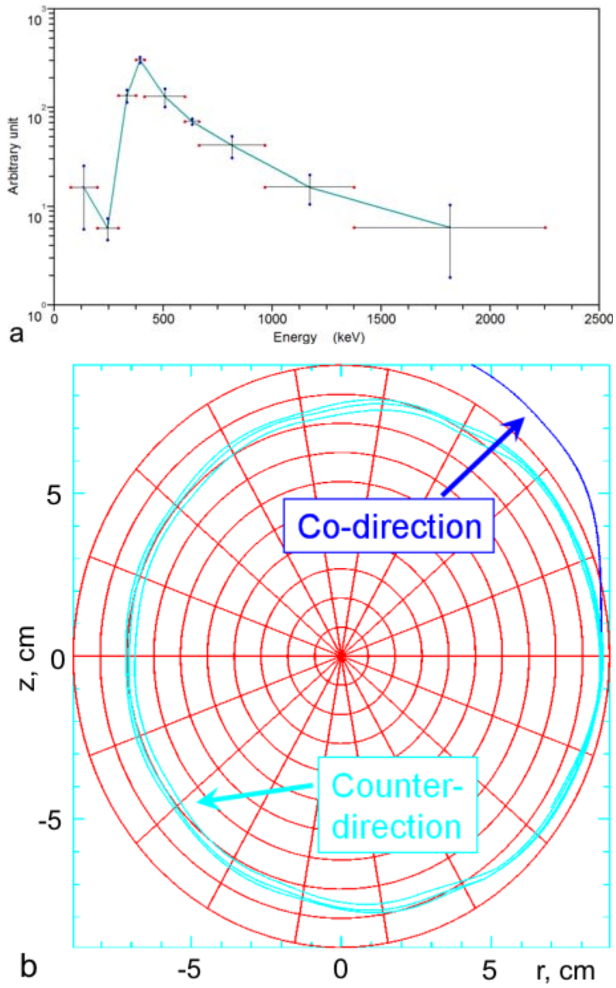

Fig. 3. (a): γ-Spectrum originated by supra-thermal electrons derived from measurements with a Geiger-Müller counter behind a lead shield with varying thickness between 0 and 25 mm. (b): Poloidal plot of the trajectory of a supra-thermal electron in co- and counter-direction with respect to the magnetic field.

lations with a field line tracing code result in particle trajectories that are located in the horizontal plane on the low field side. With increasing energy the particle orbits begin to deviate significantly from the magnetic flux surfaces and do not encircle the magnetic axis anymore. Finally, the particles collide with the RF antennas in the plasma vessel. At these positions, the highest count rates of the γ-ray detectors have been determined experimentally, proofing the simulations.

Antenna design

Dedicated to lower-hybrid (LH) current drive experiments during the low density discharges with MeV-electrons, new antennas for the 2.45 GHz RF heating system have been designed. So far the best coupling was found with an open double cut circular antenna with a symmetric k-spectrum. In order to test the current drive mechanism, a front bended tube was used which emits circular polarized waves only in one direction. An antenna rotation of 180° did not change the current direction as expected from the high-energy particle orbit. Recently, a new LH-type grill antenna of circular cross-section with variable $N_{//}$ values between 2 and 4 was designed and built. In addition, the flexible waveguide of the antenna allows a coupling optimization by varying the antenna-plasma distance. Due to imperfections of the manufacturing process, the measured phase shift in the 5 adjacent waveguides was not optimal but could be significantly improved by including additional teflon and stainless steel inserts in the waveguides. A theoretical model predicted a good coupling of the waves with the plasma once a minimum distance between the antenna and the plasma edge has been reached. However, the new antenna installed at WEGA showed only a weak coupling with the plasma; although, the distance between the antenna and the plasma as well as the density of the plasma was varied in a wide range. This unexpected behavior will be studied in the future.

Turbulence studies at magnetic islands

The moderate plasma parameters in WEGA give the possibility to access the whole plasma cross-section with Langmuir probes. Two probe arrays and a single probe are installed in WEGA to perform toroidally and poloidally resolved fluctuation measurements. A recent topic is the study of turbulence in the vicinity of magnetic island. In low density discharges zonal flow like structures were found in potential fluctuations [8]. These are poloidally and toroidally symmetric fluctuations in the frequency range of about 5 kHz. A characteristic feature of these fluctuations is a long range correlation along distances comparable to the system size. In magnetic configurations showing low order islands at the edge these structures were observed at minor radii smaller than the island position, i.e. about 1 cm apart from the islands. However, inside the island these long range correlations were not observed. Potential fluctuations inside the island appeared more to be large scale structures with a finite poloidal and toroidal wave number. The poloidal correlation length was gradually decreased with increasing island width which was realized by additional error field compensation coils. It could be shown that this goes together with an increased turbulent transport across the island's X-point.

Electron thermal diffusivity in OXB heated plasmas

The thermal diffusivity of the electrons in helium plasmas was studied by power modulation experiments. For this purpose, the emitted power of the 28 GHz gyrotron was modulated periodically with frequencies from 37 Hz up to 376 Hz during the OXB discharges. The electron Bernstein waves are absorbed in the plasma center at $B = 0.5$ T where the resonance condition is fulfilled, leading to a highly localized power deposition. A modulation mainly of the electron temperature T_e is obtained by optimizing the modulated amplitude, the duty-cycle and the modulation frequency. The heat wave propagation was monitored by a fast 16-channel Si-diode bolometer system covering the whole plasma cross-section. A fast Fourier transform (FFT) analysis of the temporal behavior of the signals shows clear coherence of the line-integrated signals among the different channels and a monotonic radial increment of the phase delays of the fundamental components in the central channel signals. This allows the determination of the electron thermal diffusivity coefficient D. Assuming a purely diffusive heat transport, Monte-Carlo based simulations yield a typical value of $D = 1.9$ m^2/s. Within the error bars the local power balance calculation based on a 12-channel gold-foil bolometer yields a similar diffusivity value.

Summary and conclusions

After 10 years of operation the repeated magnetic flux surface measurements have shown no significant changes in contrast to the initial measurements. However, the studies revealed further details of the magnetic structure of the magnetic field system of WEGA.

The simultaneous application of two different RF heating systems has opened access to new operational regimes. Thus, it is possible to generate steady state over-dense plasmas via pure electrostatic electron Bernstein wave heating. In another plasma scenario the simultaneous use of both RF heating systems is connected with the generation of supra-thermal electrons in the MeV range. Simulations have shown that these highly energetic electrons can propagate in WEGA in one toroidal direction with stable trajectories, while those electrons propagating in the opposite direction are immediately lost resulting into a significant toroidal net-current. Using a fast diode array the thermal diffusion coefficient of the electrons in a helium plasma heated by electron Bernstein waves was studied by power modulation experiments.

With the help of Langmuir probes, fluctuation studies in the vicinity of magnetic islands have been performed. Long range correlation structures in the potential fluctuations were found for distances comparable to the system size. Such structures were also studied in magnetic configurations where magnetic edge islands are present.

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