Diagnostic Development for Wendelstein 7-X at the WEGA Stellarator

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Introduction WEGA is a classical five period, $l = 2$ stellarator with a major radius of $R = 72\,\mathrm{cm}$, a minor radius of the vessel of $r = 19\,\mathrm{cm}$ and a maximum plasma radius of $a \approx 11\,\mathrm{cm}$ [1]. The magnetic field coil system allows quasi steady state operation at 0.5 T for about 20 s. The plasmas are generated in helium, argon and hydrogen at 0.5 T operation utilizing a 28 GHz ECRH system (10 kW, cw). Additionally, a transformer for Ohmic heating and two 2.45 GHz magnetrons (26 kW in total, cw) are available. Maximum electron densities of $n_e = 1.4 \times 10^{19}\,\mathrm{m}^{-3}$ and bulk electron temperatures of a few ten eV are routinely obtained. However, during Bernstein wave and lower hybrid heating experiments also a supra-thermal electron component with an energy in the keV range and currents of a few hundred A can be detected [2]. Within the last years an increasing set of contact-less diagnostics has been installed at WEGA in preparation for Wendelstein 7-X. In this paper an overview of these diagnostics including selected results is presented.

Microwave Emission Diagnostics A start-up diagnostic of W7-X will be the Electron Cyclotron Emission (ECE) diagnostic to determine the electron temperature. The diagnostic will base on a heterodyne system [3] where the second harmonic extraordinary (X2) cyclotron emission from the plasma is mixed down to an intermediate frequency (IF) of 2 to 40 GHz. For frequency resolved measurements the IF is split into continuous frequency bands by two radiometer banks. One of them in the range of 18-40 GHz is used in combination with a low noise preamplifier as standalone system to detect the cyclotron emission at WEGA [4]. Depending on the discharge scenario the microwave emission spectrum is collected by two different horn antennas. The first one is aligned perpendicular to the magnetic field lines for considering the X2-emission being optically thin for WEGA plasmas. The second horn antenna is used at electron densities greater than $0.97 \times 10^{19}\,\mathrm{m}^{-3}$ i.e. above the corresponding second harmonic ordinary (O2) wave cut-off). At this over-dense plasma operation which is also planned to be realized at

W7-X there is no X2-emission. Therefore, a determination of the electron temperature by the standard ECE diagnostic will be impossible. However, the electrostatic Bernstein wave based on a coherent motion of electrons around the magnetic field lines has no upper density limit and thus is able to propagate. By a two-step conversion process (BXO) at the plasma edge Bernstein waves are converted into a slow X-mode and then into an elliptically polarized O-Mode which can be detected from outside the plasma usable for electron temperature measurements. Such a system is currently under development at WEGA. Since the conversion efficiency depends on the emission angle with respect to magnetic field vector the emission of the resulting O-mode shows a maximum under a certain angle which is 55° in the case of WEGA. For future investigations of the angle dependency of XO-conversion and the determination of the conversion efficiency an optimized quasi-optical mirror system with astigmatic elliptic mirrors was designed.

Supersonic Helium Beam Diagnostic A supersonic helium beam diagnostic was setup allowing the determination of the central electron temperature and density from line ratio measurements. The helium neutrals are excited by collisional interactions with the electrons in the plasma. Due to the different density and temperature dependencies of the excitation and de-excitation rates some line intensity ratios can be utilized for the derivation of the plasma parameters. For the temperature measurement the singlet transition $3^1S \rightarrow 2^1P$ ($\lambda = 728.12$ nm) and the triplet transition $3^3S \rightarrow 2^3P$ ($\lambda = 706.52$ nm) were considered. For the density measurement additionally the mentioned singlet transition and a second singlet transition $3^1D \rightarrow 2^1P$ ($\lambda = 667.82$ nm) were chosen. Two different approaches have been applied to calculate the line intensity ratios using the collisional-radiative model for atomic helium and to determine the electron temperature and density. In the steady-state approach the line intensity ratios are calculated locally for a given set of temperature and density. In the time-dependent approach the movement of the beam through the plasma is additionally taken into account. The helium beam is injected via a solenoid valve (orifice diameter of 0.8 mm) in vertical direction through the center of the plasma with a velocity of $v = 1700$ m/s and a pulse length of 200μs. A skimmer with 2 mm in diameter generates a collimated neutral beam with a on-axis particle density of $n_{He} = 4 \times 10^{18}\,\mathrm{m}^{-3}$. With the help of the diagnostic the intensities of the mentioned lines could be detected in helium plasma applying a X2 heating scenarios with the 28 GHz ECRH. The calculated temperature was about 30 eV at the plasma edge and about 80 eV in the center. The derived plasma density was about $n_e = 10^{18}\,\mathrm{m}^{-3}$. This in satisfying correspondence with results from Langmuir probes and microwave emission measurements.

Magnetic Diagnostics With respect to investigations of plasma energy and plasma currents a set of magnetic diagnostic was build up at WEGA. In order to measure the plasma current both an internal and external Rogowski coil were put into operation. An absolute calibration has been performed by means of a conductor carrying a current with known amplitude inside the torus. The plasma energy can be determined by a system consisting of a compensation coil and a diamagnetic coil installed at a poloidal plane inside the torus. Furthermore, a two loop system, comprised of two additional diamagnetic loops of different diameter, was developed and integrated in the torus. Here, the diamagnetic effect can be determined from a change in the ratio of both signals. Thus, it was possible to verify plasma energy measurements by using two different and independent diagnostics. To perform the temporal integration of the signals the digital integrator designed for W7-X, was used. The integrator bases on a chopped input stage and a digital integration [5]. Due to the polarity change of the input signal the drift of the following electric components averages out when the signal is reconstructed. Thus, it does not contribute to the integral signal anymore. The system allows precise measurements on a multi-minute time scale. In WEGA it was possible to measure plasma currents with a resolution of 1 A for discharges of several seconds and plasma energies below 1 J.

Bolometry A 12-channel bolometer and a fast 16-channel Absolute Extreme Ultra Violet (AXUV) diode array with a resolution of below 30 μs are routinely used. The lines of sight are covering the whole poloidal plasma cross-section, hence the diagnostic is used to determine the temporal development of radiation profiles and the total emitted power. Especially the AXUV system is a useful tool for the investigation of transient events and transport parameter. With the help of this diagnostic the plasma startup, the propagation of heat waves or the detection of power deposition zone are investigated. However, it was found that the AXUV diodes showed a strong decrease in the sensitivity in UV range below 400 nm hence the determination of the absolute emitted power is an issue. The system was hardened against microwave stray radiation and shows now an improved electromagnetic compatibility.

Soft and Hard X-Ray Diagnostics Although the bulk temperature of the electrons in WEGA discharges is of the order of a few 10 eV a small component of supra-thermal electrons in the keV-range could be detected at 0.5 T operation during OXB-mode conversion experiments with the 28 GHz ECRH and lower hybrid heating scenarios with the additional non-resonant 2.45 GHz heating system. For the detection of the supra-thermal electron component two new Silicon Drift Detectors (SDD), manufactured by PNSensor at the semiconductor laboratory of the Max-Planck-Institutes, were successfully applied. The first sensor SDD1 has a thickness of 450μm and a on-chip collimator of 3.2 mm in diameter. It has a 8μm beryllium and 30 nm aluminum layer on top to avoid visible light detection. The sensor is sensitive in the range between 0.8 keV and 30 keV with a detector resolution of 139 eV at an energy of 5.9 keV (Mn K_α). As mentioned before, during the OXB heating scenarios in the helium plasma, a soft X-ray spectrum in the range of $1.5 - 15$ keV could be detected. For the analysis the detector response was taken into consideration. The detector response as a function of energy was obtained using the detector efficiency as well as the filters used in front. The continuum bremsstrahlung emission model, folded with the above detector response function, is fitted to the observed spectra by excluding the region of line emissions. The lines were fitted separately with single Gaussians on top of the continuum. The temperature of about 10.8 keV is derived from the slope of the continuum. This value is good agreement from the Bernstein emission experiments where also a radiation temperature in the keV-range during OXB heated plasma was detected. Out of the 5 peaks 3 could be identified as K_α lines form argon, chromium and iron, respectively. While argon is a residual gas from previous experiments, iron and chromium are plasma impurities from the plasma vessel and the ECRH antenna system. Furthermore, a second sensor SDD3 with an anti reflection coating for visible light, coupled to a CsI(Tl) scintillator crystal was used for hard X- and gamma ray detection. This detector is sensitive up to energies of a few 100 keV. During lower hybrid heating scenarios in helium plasma discharges an energy of up to 250 keV was detected. The energy spectrum below 100 keV showed a strong decrease of the intensity caused by the thickness of the stainless steel plasma vessel of 3 cm.

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