Simulation of the Spectrally-resolved Plasma Radiation in the WEGA Stellarator and Comparison with Bolometer Measurements

D. Zhang, R. Burhenn, M. Glaubitz, R. König, H.P. Laqua, S. Marsen, T. Stange, M. Otte,
and the WEGA-Team

Max-Planck-Institut für Plasmaphysik, EURATOM Ass., D-17491 Greifswald, Germany

1. Introduction

At the WEGA stellarator [1], a 12-channel gold-foil bolometer [2] has been installed to monitor the plasma radiation features. The gold foil absorber has high sensitivities in the UV and soft X-ray range but is less sensitive to low energetic photons (λ > 400 nm) due to high reflectance. Because the WEGA plasma, obtained through an OXB-heating process by a 28 GHz gyrotron of 10 kW heating power [3], has typical electron temperature about 20 eV, even at the center, the knowledge about the spectral distribution of the plasma emissivity (in particular the fraction in the low energy and less sensitive window of the bolometer) is essential for determining the radiation power with high accuracy. Due to a lack of sufficient spectroscopic information, a numerical estimation based on a diffusion model has been carried out. The plasma studied is a pure helium-one and "impurities" are not taken into account as there are no spectroscopic indications in WEGA so far. The radiated power density, i.e. the emissivity, originates from He^0, He^{1+} and He^{2+} only and can be written as $P_{rad} = \sum_{z=0}^{Z_0} n_e n^z f(z, T_e)$ where $Z_0 = 2$, n_e and n_z being the electron and particle density, and T_e denoting the electron temperature, respectively. The radiative power loss coefficient $f(z, T_e)$ for particles in ionization stage z is a function of T_e predominantly and has less dependence on n_e. It consists of contributions from different atomic processes and is related to line emission, bremsstrahlung and radiation due to electron-ion recombination. For z = 0 and z = Z_0, i.e. He^0 and He^{2+}, contributions from bremsstrahlung and from line radiation are absent individually. The coefficients are obtained from ADAS [3]. The n_e-, T_e-profile is measured by a Langmuir probe. Further parameters needed for performing the simulations are the particle densities, which are derived by solving the particle balance equation. Emissivity profile and radiation spectra are accordingly calculated. A comparison of the simulated results with those measured by the bolometer is demonstrated.

2. Simulations

The studied plasma is divided into a confined region within the last closed magnetic flux surface (LCFS) with an effective radius *a*, and an edge region outside the LCFS. The region inside the LCFS is further divided into discrete ring-shaped zones ('onion skin model'), defined by the cross section of the closed magnetic flux surfaces. Each of them has a circle-equivalent area and an effective radius r_{eff}. Each zone has a width of $\Delta r = a/n_r$, being adjustable by the total zone number n_r. The lines of sight of the bolometer and the cross section of the closed magnetic flux surfaces are illustrated in Fig. 1 (left). The plasma parameters are assumed to be uniform in each zone with T_e/n_e-pairs obtained by interpolating the measured data set (see Fig. 2, right). The edge region is also divided into zones ($n_{r,sol}$) by extending the LCFS outwards until it reaches the plasma vessel, since it is necessary for performing the simulation of the edge plasma radiation.

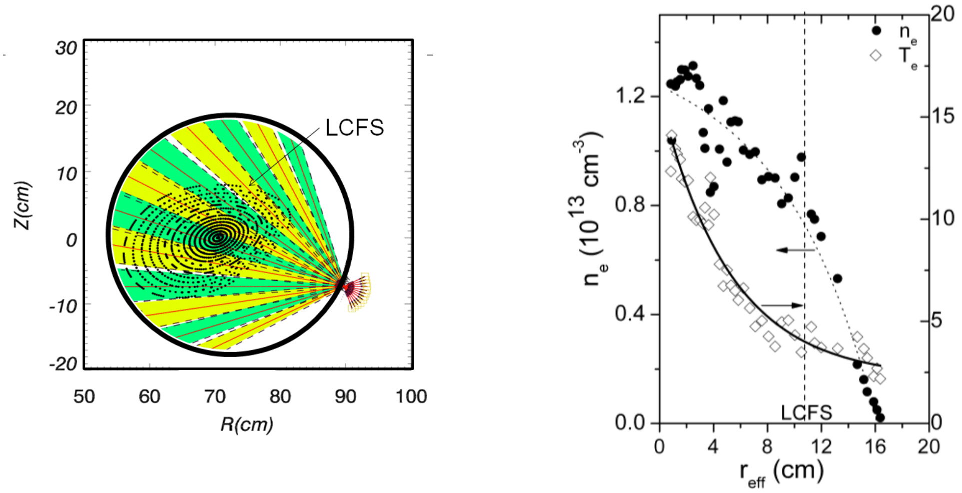

Fig.1. Lines of sight of the 12-channel bolometer (left) and the n_e-, T_e-profile of the He-plasma (right).

Neutral particle distribution n^0 The neutral gas pressure measured during the experiment is $p_0 = 1.0\times10^{-4}$ mbar. The He^0 density at the plasma periphery is accordingly set to n^0 (I) = 1.8×10^{18} m^{-3} with $I = n_r + n_{r,sol}$ being the number of the outmost zone. We assume that an exponential decay of $n^0(r)$ into the plasma, with the decay length being equal to the mean free path of the He-atoms, i.e. $n_I^0 = n_{I+1}^0 \cdot e^{-\Delta r/\lambda(I)}$, where $I = 1, \ldots, n_r + n_{r,sol}$ are the indices of the zones. The mean free path, expressed as $\lambda(I) = v_o/n_{e,I}S_I^0$, depends on the thermal velocity and the local ionization time of the atoms (the denominator). The former is taken as 784 m/s. The latter is proportional to $n_{e,I}$ and associated with the ionization rate coefficient S_I^0 of He^0, depending on $T_{e,I}$ and obtained from ADAS. The obtained $n^0(r)$ is required for the calculation of the ion densities.

Ion density distributions A transport model including the ions, He^{1+} and He^{2+}, is established assuming that the radial transport is governed by a purely-diffusive process. The 1D diffusion equation for stationary state in cylindrical coordinates is given by

$$\frac{1}{r}\frac{d}{dr}\left(r\left(\nu\cdot n^z - D\cdot\frac{dn^z}{dr}\right)\right) = S0 - S1\cdot n^z \qquad (z = 1, 2),$$

where $S0 = (S^{z-1}n^{z-1}+R^{z+1}n^{z+1})n_e$ and $S1 = (S^z+R^z)n_e$ are the source and sink term, respectively. S0 is associated with ionization and recombination processes coupled with lower and higher ionization stages; S1with the corresponding stage only. The rate coefficients, S^z and R^z, are again taken from ADAS. Assuming particle convection $\nu = 0$, the coupled $n^1(r)$ and $n^2(r)$ are determined numerically by setting the diffusivity D to a radially constant value. For D = 3.5 m^2/s and assuming charge neutrality the measured n_e profile could be reproduced with an accuracy of 25%, as can be seen in Fig. 2 (left). This demonstrates that in the core region of the plasma the fractional abundance of He^{1+} dominates, while He^0 and He^{2+} contribute less than 15% each, and towards plasma edge the weighting factor of He^0 increases while He^{2+} becomes negligible. Hence, the plasma radiation from the core is predominantly from He^{1+} while at the edge also the He^0-atoms contribute.

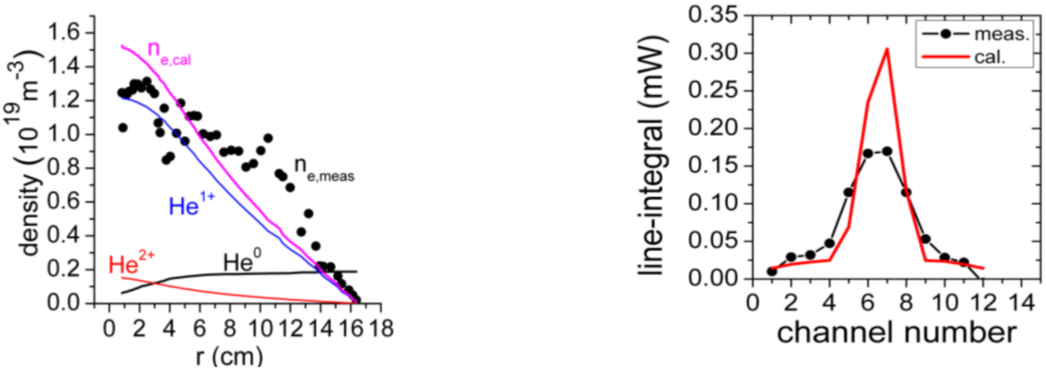

Fig. 2. The density profiles of He^0, He^{1+} and He^{2+} derived from the simulation of the n_e-profile (left) and a comparison of the calculated bolometer line-integrals with the ones measured (right).

Emissivity profile The local emissivity of the He-plasma therefore is given by $P_{rad} = \sum_0^2 n_e n^z f(z, T_e)$. Further analysis of the composition of the radiated power associated with different atomic processes indicates that the line emission from He^{1+} is dominant, while the bremsstrahlung from He^{2+} and the radiation due to recombination of He^{2+} and He^{1+} are negligible. The simulated emissivity profile is highly peaked, being similar with that documented by Abel-inversion based on the bolometer line-integrals [5]. The contribution of each zone to the channel line-integral is expressed as $S_J = k_{IJ} P_{rad,I}$ with k_{IJ} being the geometric matrix of channel *J* associated with zone *I*. The calculated line-integrated signals according to the actual geometry of the bolometer are also compared with the measured ones (see Fig. 2, right). The calculated total radiated power is around 9 kW, being consistent with the one derived from the bolometer measurement (7 kW) within the error bars (20%).

Spectral distribution The radiation spectra are then obtained from the calculated density profiles together with the photon emissivity coefficients (*pec*) from ADAS according to $\varepsilon_\nu = pec(z, h\nu, T_e) h\nu n_e n_z$. They are shown in Fig. 3. It indicates that most of the power is radiated in the UV range, predominantly by line-radiation from He^{1+} ions in the core and with contribution from He^0 close to the LCFS. The low-energetic radiation in the visible range originates mainly from the plasma edge and takes only 5% of the spectrally-integrated radiated power, being completely negligible for the core plasma.

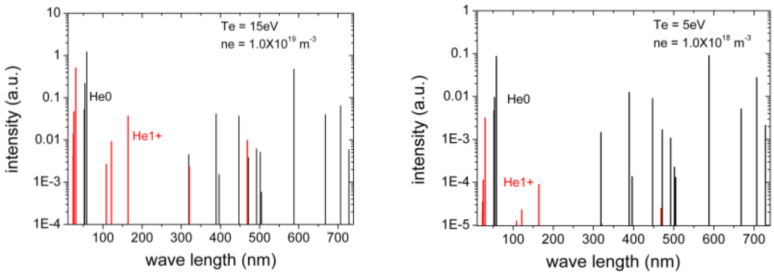

Fig. 3. The spectra of He^0 and He^{1+} from the core (left) and the edge plasma (right).

3. Conclusion

The radiation of the He-plasma at WEGA originates predominately from He^{1+} line radiation in UV-range. The visible light (>400nm) contributes only around 5% to the bolometer edge channels. These results justify the suitability of the gold foil bolometer for measuring the total plasma radiation at WEGA without the need for additional correction due to a reduced sensitivity for low energy radiation. In addition, the total radiation power and the emissivity profile can be directly calculated from the model. Reasonable agreement is found between the calculated results and the ones measured by the bolometer.

Reference

1. M. Otte et al., Plasma and Fusion Research, Vol. 5, S2011-4 (2010)
2. K.F. Mast et al., Review of Scientific Instruments **62**, 744 (1991).
3. H.P. Laqua et al., Phys. Rev. Lett. **78**, 3467 (1997)
4. H.P. Summers: *Atomic Data and Analysis Structure*, JET Joint Undertaking. Report JET-IR(94)06 (1994).
5. D. Zhang et al., to be published.