

Radial electric fields from passive He II emission in the edge transport barrier of ASDEX Upgrade

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Introduction

The preferred operating regime in ITER is intended to be the H-mode [1]. An important feature is a region of strongly reduced transport at the plasma edge, called the pedestal, which leads to a major improvement of plasma confinement. A commonly accepted theory explains this by the development of strong shear in the radial electric field at the edge which tears apart the turbulent eddies and thus reduces turbulent transport [2]. Great effort is put into characterizing the edge of H-mode plasmas at ASDEX Upgrade and profiles with high spatial and temporal resolution could be measured. [3] The method presented in this paper adds highly resolved radial electric field measurements to the set of edge profiles at ASDEX Upgrade and thus helps to improve the understanding of the H-mode pedestal. It is a spectroscopic method using passive emission of He⁺ that is located in a narrow region near the plasma boundary. Using a forward model within a fully probabilistic frame work, estimations of He⁺ density and temperature profiles are also possible.

Description of the method

Integrated data analysis is used to determine the radial electric field from passive He II emission. 18 lines of sight, probing the plasma almost poloidally, are used to get radially resolved profiles. The line integrated measurements are unfolded by optimizing the parameters Θ of a forward model within a fully probabilistic framework. A likelihood probability distribution function (PDF) $P(d | \Theta, \sigma, I)$ is used to characterize the agreement of the measured line spectra d with the modeled ones, with respect to the used model and the uncertainties σ . Another PDF is used to include prior knowledge I (e.g. the measured electron density) in the model and is referred to as prior PDF $P(\Theta | I)$. A Marcov chain Monte Carlo (MCMC) method is used to explore the posterior PDF $P(\Theta | d, \sigma, I)$, which is given by Bayes law

$$P(\Theta | d, \sigma, I) = \frac{P(d | \Theta, \sigma, I) \cdot P(\Theta | I)}{P(d | I)}, \quad (1)$$

and to estimate the parameters Θ and their uncertainties.

Local line spectra are calculated using three parameterized profiles: the radial electric field, the He⁺ temperature and the He⁺ density. The toroidal main ion velocity, the electron density profile, and the photon emission coefficients (PEC) are provided. The line integration of the local spectra is done by summing up these local spectra along the LOS:

$$F(\lambda) = \int \left[n_e \cdot n_{\text{He}^+} \cdot \text{PEC}(n_e, T_e) \cdot f(\lambda, T_{\text{He}^+}, v_{\text{He}^+}) \right]_{\rho_{\text{pol}} := \rho_{\text{pol}}(l)} dl. \quad (2)$$

f represents a Voigt function that takes into account the Doppler broadening and the spectrometer function. $F(\lambda)$ is compared with the measured spectra. The central wavelength of the calculated line spectrum is dominated by the velocity profile. Contributions to this profile are the projection of the toroidal velocity to the LOS, the diamagnetic velocity, and the ExB velocity which is the dominating term as the pressure profile for He⁺ is rather flat. Therefore, this method is very accurate concerning the determination of the radial electric field. Additionally, the He⁺ temperature at the plasma boundary can be estimated from the width of the line spectra, because the whole profiles are modeled and not only the central position. The He⁺ density profile is determined from the intensities of the line spectra.

Sensitivity study

The electron density and temperature profiles are determined routinely at ASDEX Upgrade by integrated data analysis [3] of the Li-Beam, the interferometer and the electron cyclotron emission (ECE) diagnostics. Because the positions of n_e and T_e profiles, with respect to the equilibrium, as well as with respect to each other, is only accurate within 5 mm ($0.01 \rho_{\text{pol}}$), a study of the influence of relative positions was carried out. Figure 1 shows the results obtained with different positions of the n_e and T_e profile with respect to each other (see figure 1 a, b for color and line style coding), while all other input parameters were kept constant. Small shifts ($\pm 0.01 \rho_{\text{pol}}$) of the radial position of both profiles (dashed and dashed dotted lines) do not affect the radial electric field (figure 1 d). The reason for this is the unchanged shape of the emission profile (figure 1e) for all shifts. This conservation of shape is only possible by varying the He⁺ density profile. Therefore the He⁺ density should be very sensitive to changes in n_e and T_e , this can be seen in figure 1 c. Outwards shifts (green) can be

completely compensated by the He^+ density whereas inward shifts (red) also have a small effect on the emission profile. A reason for this is the kink in the n_e and T_e profiles at the pedestal top: outwards shifts barely change the density and temperature inside the separatrix, but inward shifts drastically reduce them.

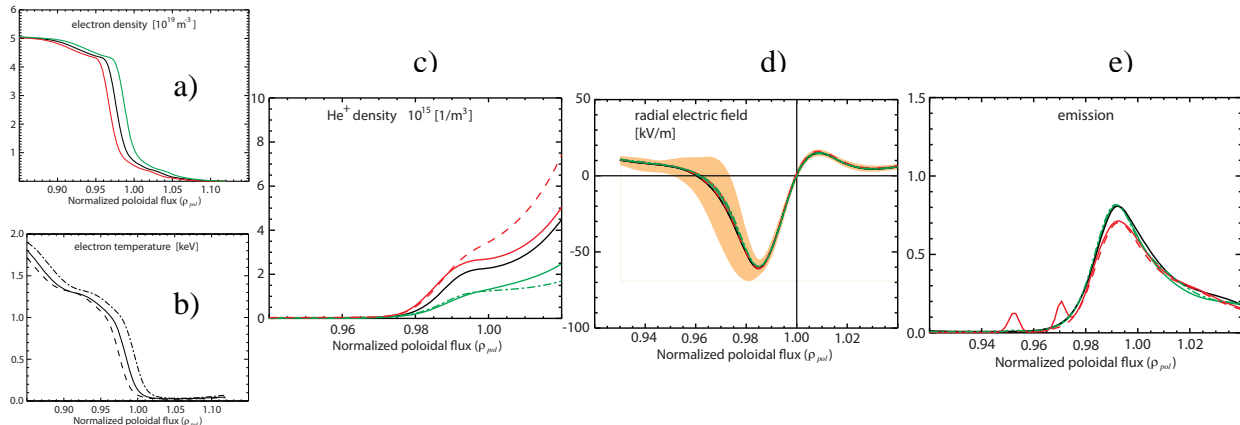


Figure 1: Sensitivity study of the radial electric field varying electron density and temperature

Results

When analyzing the transport barrier at the plasma boundary in H-mode one has to consider edge localized modes (ELM). If an ELM occurs, the gradients of the edge pedestal in electron temperature and density flatten rapidly, followed by a slow recovery phase [5]. In discharges with ELM frequencies lower than the 4ms integration time of the cameras, ELM synchronized evaluation of radial electric fields could be done. Although the ELM crash is much shorter than the integration time measurements of the ELM E_r profile could be made, because during an ELM the plasma is shifted outwards. Due to the increased wall temperature more He ions are emitted into the plasma and this causes a rapid increase in He^+ emission. The measured signal is therefore dominated by a short period just after the ELM crash. In figure 2 two E_r profiles are shown, one using data collected during an ELM crash (blue), and one in between two ELMs (red). The profiles are shifted radially to match the separatrix at the zero crossing due to uncertainties in the equilibrium reconstruction and the mapping to flux surfaces. The E_r profile during an ELM is much flatter than the one in between two ELMs. In the scrape off layer no difference could be observed.

Using this ELM synchronization method one can analyze the influence of different NBI heating power on the radial electric field. In Figure 3, a discharge with three steps of NBI heating power was selected. The steps are 5 MW for the first time point (brown), 7.5 MW for the second time point (red) and 10 MW for the third time point (purple). These profiles are

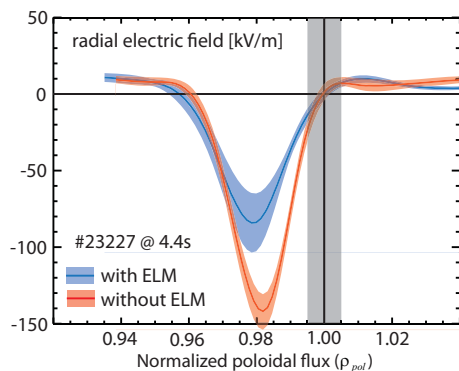


Figure 2: ELM synchronized radial electric fields

MW

also radially shifted to match the separatrix at the zero crossing. One can see that with increased heating power the radial electric field becomes deeper.

The radial electric fields of three discharges with three different levels of D₂ gas fuelling rate were also evaluated and are shown in figure 4. With an increased fuelling rate the radial electric field gets flatter. This is in agreement with the assumption that E_r is proportional to $\nabla p/n$.

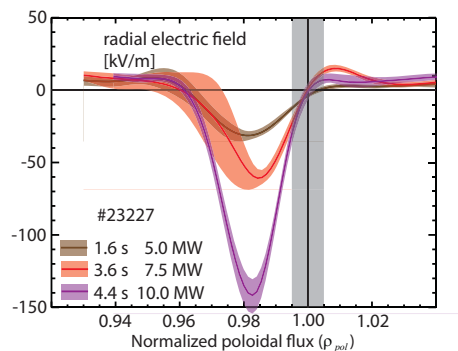
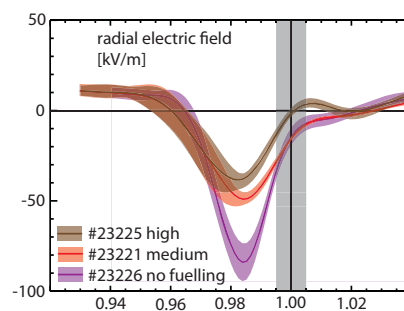
Figure 3: E_r with 3 steps in NBI heating power: 5 MW, 7.5 MW and 10

Figure 4: gas fuelling scan

Summary

In summary, it could be shown that the evaluation of the radial electric field as well as the He⁺ temperature estimation is independent of small changes in the position of the electron temperature and density profiles, they are only relevant for the helium density calculation. Furthermore a breakdown of the radial electric field E_r during an ELM, the increase of depth of the E_r by increased NBI heating power, and a flattening of E_r due to high D₂ fuelling rates was demonstrated. The range of the measured radial electric field lies within 20 kV/m to 150 kV/m.

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