Investigations on kinetic edge profiles and their gradients of magnetically perturbed ASDEX Upgrade plasmas

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Introduction

The intended operation scenario for ITER, the High-confinement mode (H-mode), is accompanied by type-I Edge Localized Modes (ELMs). The power flux along the open field lines in the scrape-off layer during these ELMs may likely exceed the critical limit of the divertor plates. At ASDEX Upgrade, non-axisymmetric Magnetic Perturbation (MP) of the plasma edge by external coils has been proven to enable ELM mitigation and, therefore, effectively reduce the peak power load on the target [1]. To improve the understanding of the underlying mechanism in order to assess the possibility of ELM mitigation with MP at ITER, detailed analysis about its effect on plasmas under diverse conditions is necessary.

Since ELMs are supposed to be related to high edge pressure gradients according to peeling-ballooning theory, the influence of MP on the electron edge kinetics might be essential for ELM mitigation. A suitable tool to study these is provided by Integrated Data Analysis (IDA) of different diagnostics for simultaneous analysis of the electron density and temperature [2] and, therefore, also the pressure. However, previous investigations of perturbed edge profiles concentrated on the electron density [3] because IDA was lacking a reliable interpretation of the Electron Cyclotron Emission (ECE) data for the electron temperature reconstruction in the edge gradient region. Recently, IDA has been enhanced by a sophisticated model for ECE which delivers reliable edge electron temperature profiles with high spatial resolution [4]. Based on these results, a thorough investigation on the kinetic edge profiles and their gradients — with emphasis on electron temperature and pressure — of discharges with perturbed magnetic field has been started. In this contribution we present first results which demonstrate slightly lower edge electron kinetic gradients in the presence of MP.

Integrated data analysis

IDA combines the data of different complementary diagnostics for joint analysis of the electron density and temperature, applying Bayesian probability theory [2]. The edge electron density, thereby, is mainly determined by LIthium Beam emission spectroscopy (LIB). For the electron temperature reconstruction IDA employs ECE data. Unlike previous ‘classical’ ECE analysis which — applying the optically thick plasma approach — had identified the electron temperature with the radiation temperature at the cold resonance position of the measured frequency [5], we made use of the newly developed Electron Cyclotron Forward Modelling (ECFM). With this method we achieved reliable electron temperature profiles also in regions of optically thin plasma or steep gradients like the plasma edge by calculating the broadened electron cyclotron emission and absorption profiles for each measured frequency and solving the radiation transport equation through the entire plasma as specified in [4].

Discharge description

The behaviour of the edge kinetics with or without MP and with or without ELM mitigation was studied in discharge #26078 with two MP phases. In the first phase the ELM frequency and size decreased constantly down to complete ELM mitigation. During the second phase the ELMs were mitigated almost immediately. Both MP phases exhibited the same coil setting with $n = 2$ and odd up-down parity. The different ELM mitigation behaviour was related to the lower edge density in the first phase [1]. Apart from the applied MP it was a typical H-mode discharge with plasma current $I_P = 0.8\,\mathrm{MA}$, toroidal magnetic field $B_t = -2.5\,\mathrm{T}$, central electron density $n_{e,0} = 7.7 \times 10^{19}\,\mathrm{m}^{-3}$ and total heating power $P = 9.1\,\mathrm{MW}$.

Edge kinetic profiles

Figure 1 shows the edge kinetic profiles at two different time points. The profiles on the left-hand side ($t = 2.94\,\mathrm{s}$) belong to a phase with MP and mitigated ELMs, while the right plots illustrate the unperturbed profiles at $t = 3.35\,\mathrm{s}$. The red lines in (a) and (e) depict the edge electron temperature obtained with ECFM analysis along the major radius R. Additionally, the measured (black dots) and modelled (red dots) radiation temperatures are plotted against their positions of cold resonance R_{cr}. The reliability of the results is indicated by the residuals (cf. (b) and (f)) with values predominantly between ± 1, stating that ECFM was able to reconstruct most ECE data — belonging to the modelled time frame — within their uncertainties. The electron densities are plotted in (c) and (g). Their original profile position given by the LIB data is shown in grey. Within ECFM analysis the density was shifted relative to the ECE by -16 (black line in c) and $-7\,\mathrm{mm}$ (black line in g) to fulfil the condition $\rho([\mathrm{d}^2 n_e/\mathrm{d}R^2]_{max}) = \rho(T_e = 100\,\mathrm{eV})$ described in [4]. Within the diagnostics radial resolutions and uncertainties in the equilibrium reconstruction these shifts were supposed to be reasonable. As expected, the misalignment between ECE and LIB was larger at $t = 2.94\,\mathrm{s}$ because the local disturbances of the field lines due to non-axisymmetric MP were stronger at the position of the LIB than of the ECE diagnostic. The electron pressure profiles obtained with the shifted density profiles are presented in (d) and (h). The dashed lines in the plots on the right-hand side each correspond to the profiles at $t = 2.94\,\mathrm{s}$ — the shifted one in case of the density — to facilitate the comparison of the perturbed with the non-perturbed case.

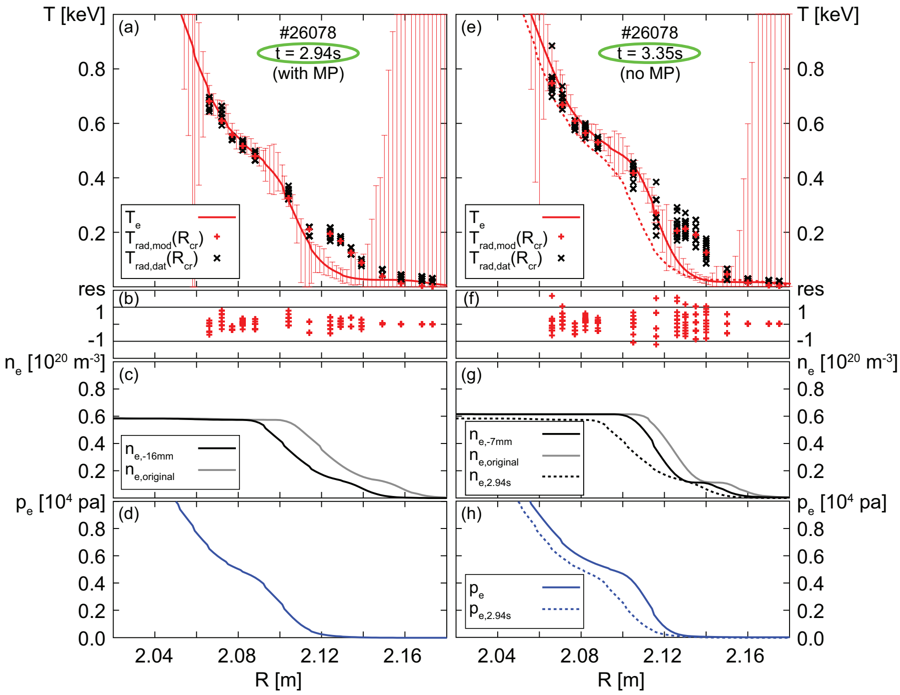

Figure 1: (a,e) Edge T_e profiles (red lines) together with the modelled (red pluses) and measured (black crosses) T_{rad} values at the positions of their cold resonance and (b,f) the corresponding T_{rad} residual values, (c,g) shifted (black) and original (grey) n_e profiles and (d,h) p_e profiles of discharge #26078 at $t = 2.94\,\mathrm{s}$ (left) and $t = 3.35\,\mathrm{s}$ (right); the dashed lines on the right replicate the profiles at $t = 2.94\,\mathrm{s}$

The perturbed electron temperature profile (dashed line in (e)) exhibited a less pronounced knee at $R \approx 2.1\,\mathrm{m}$ compared to the non-perturbed case (solid line at $R \approx 2.11\,\mathrm{m}$), which caused a slightly flatter edge gradient (cf. time points in Fig. 2(a) marked by green circles). Comparing the density profiles revealed a slightly lower pedestal top density and a significantly flatter gradient in the presence of MP (black dashed line in (g)). Consequently, also the gradient of the edge electron pressure (h) was reduced in the ELM-mitigated phase.

Edge kinetic gradients

To investigate the behaviour of the gradients in the presence of MP in more detail, we analyzed the temporal evolution of the maximal gradients of the electron temperature (Fig. 2(a)), density (b) and pressure (c). To recognize useful ECFM results automatically we set up two criteria for the modelling output: We considered only time points with at least one residual value between ± 1 in every edge channel and with separatrix temperatures smaller than $150\,\mathrm{eV}$. Due to a failure of the LIB diagnostic there was no density information about the edge gradient region after $t = 3.5\,\mathrm{s}$ and, therefore, also the electron temperature was poorly determined because

ECFM analysis relies on accurate density profiles.

Despite the large scatter in the data — resulting from fluctuations in the measurements as well as some remaining outliers of ECFM analysis — we were able to observe some tendencies in the maximal electron temperature, density and pressure gradients related to the presence of MP (Fig. 2(e)) and the ELM frequency (d). All the kinetic gradients followed the same behaviour — with strongest characteristic in the density, and least in the temperature. Between 1.5 – 1.9 s the maximal edge gradients and also the ELM frequency exhibited some changes, but slightly before the MP onset (I) they seemed to reach a constant level, which also extends into the ramp-up phase of the MP coils. From $t \approx 2.1$ s on the MP gave rise to a constantly reduced ELM frequency (IIa) accompanied by a flattening of the maximal electron kinetic gradients. With (almost) complete ELM mitigation (IIb), the maximal gradients stayed at a constant level. After switching off the MP coils (III) the ELMs came back and the maximal gradients increased again.

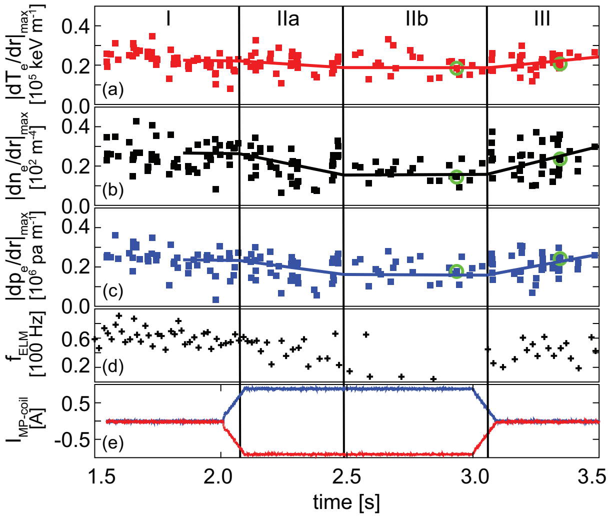

Figure 2: Time traces of the maximal edge gradients of (a) T_e, (b) n_e and (c) p_e together with (d) the ELM frequency and (e) the current of an upper (blue line) and corresponding lower (red line) MP coil of discharge #26078; time points of profiles in Fig. 1 marked by green circles

Conclusion

We demonstrated that ECFM analysis is able to resolve effects that could not be seen with ‘classical’ ECE analysis and, therefore, delivers a valuable tool for detailed investigations on changes in the kinetic edge profiles caused by perturbations of the axisymmetric magnetic field. First results indicate that perturbed edge plasmas exhibit slightly reduced edge kinetic gradients compared to non-perturbed phases. This might be one criterion for ELM mitigation by stabilizing the ballooning mode. This hypothesis still needs to be tested for different plasma scenarios and MP coil configurations and the large scatter in the gradients demands for a validation of the observed trends.

References

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