Current profile tailoring with the upgraded ECRH system at ASDEX Upgrade

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Adjustable current and q-profile shapes are of particular interest for the development of advanced scenarios, e.g. non-inductive tokamak operation [1], and for testing and refining of transport models for predictive capabilities. The current profile is tailored at ASDEX Upgrade using improved heating and current-drive actuators with an upgraded ECRH system with nominally up to 8 MW for 10 s at 105 and 140 GHz [2]. The adjustable, localised current drive capability of this flexible ECRH environment allows dedicated variations of the shape of the q-profile.

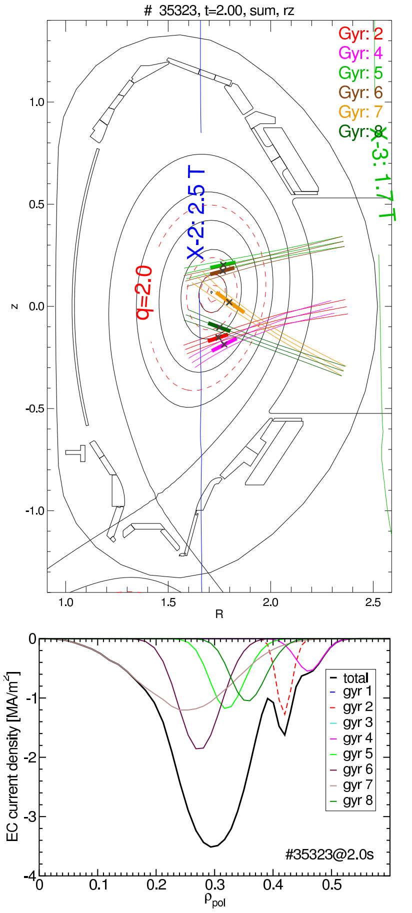

Figure 1: *Poloidal cross section of the EC heating and current drive system with 6 gyrotrons in an off-axis counter ECCD setting.*

To resolve the highly-shaped current distribution an integration of all available measurement and modelling information is necessary. The equilibrium is reconstructed coupling a Grad-Shafranov (GS) solver with the current diffusion (CD) equation employing a physical coupling of neighbouring time points [3]. This coupling improves the estimated equilibrium current profile if neo-classical current diffusion can be assumed. Further ingredients are given by reliable electron and ion temperature and density profiles from an integrated data analysis approach [4, 5], fast-ion pressure and driven current profiles from the RABBIT code [6], the electron-cyclotron driven current from the TORBEAM code [7], bootstrap-current evaluation, all magnetic data of an extended set of poloidal-field and diamagnetic-loop measurements, internal current measurements from imaging MSE [8] and polarimetry [9], and a sawtooth detection algorithm [10].

A recently developed fast reconstruction of the current distribution between plasma discharges allows for an educated and efficient scenario development. The equilibrium code IDE

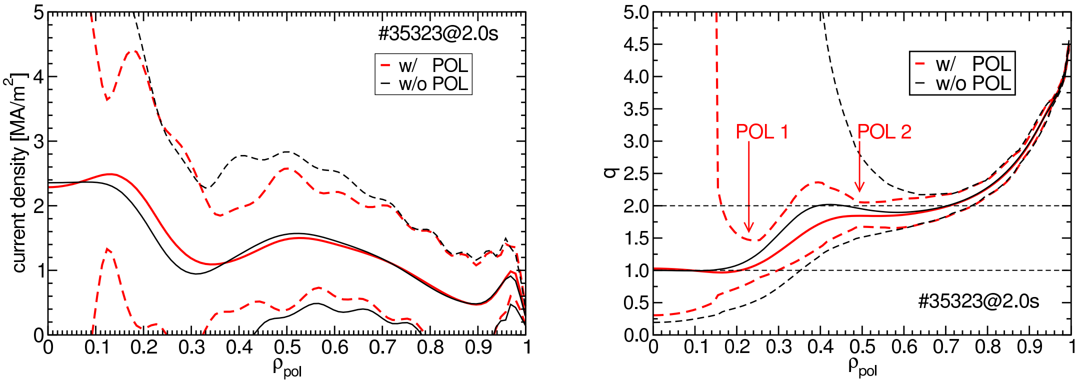

Figure 2: *Current density profile (left) and q-profile (right) with current diffusion modelling only (black line) and additional polarimetry measurements used (red lines).*

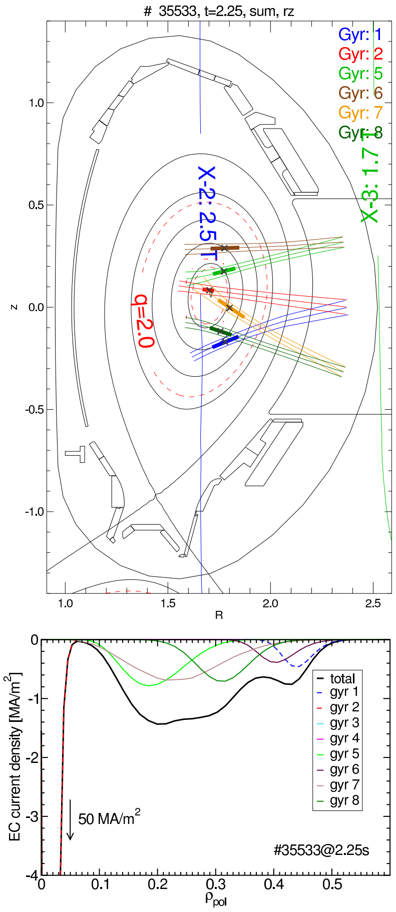

Figure 3: *Similar to Fig. 1 but with gyrotron 2 shifted to obtain on-axis current drive.*

is parallelized using an *OpenMP* scheme within the Grad-Shafranov solver, within the RABBIT code of up to 8 NI-beams and within the TORBEAM code. On top of this, an MPI (Message Passing Interface)-based approach is applied for parallel calculations of the GS-solver response matrix and for parallel TORBEAM evaluations of up to 8 EC-beams for the CD-integration [11].

Figure 1 shows a plasma (#35323, 2.0 s, 1.0 MA, -2.5 T) with 6 gyrotrons in an off-axis counter-ECCD setting. The scheduled on-axis ECCD could not be achieved in #35323 because an unexpected reduction of the plasma energy resulted in a smaller than expected Shafranov shift. For such cases a real-time (RT) current-drive control system would be beneficial. The resulting current density profile (Fig. 2 left) shows a decrease at about $\rho_{\text{pol}} = 0.3$ corresponding to the counter-ECCD location (Fig. 1 bottom). The respective q-profile (Fig. 2 right) shows an on-axis $q_0 = 1$ with a pedestal at around $\rho_{\text{pol}} = 0.3$. The black lines in Fig. 2 show the current density and q-profiles reconstructed without internal measurements where the current density is only constraint by current-diffusion modelling. The red lines are reconstructed using polarimetry measurements of two core lines-of-sight (LOS) additional to current-diffusion modelling. Since both results agree within their uncertainties, the assumption about neo-classical current diffusion appears to be consistent with the measurements. Shifting one of the 5 gyrotrons (gyr 2) to obtain

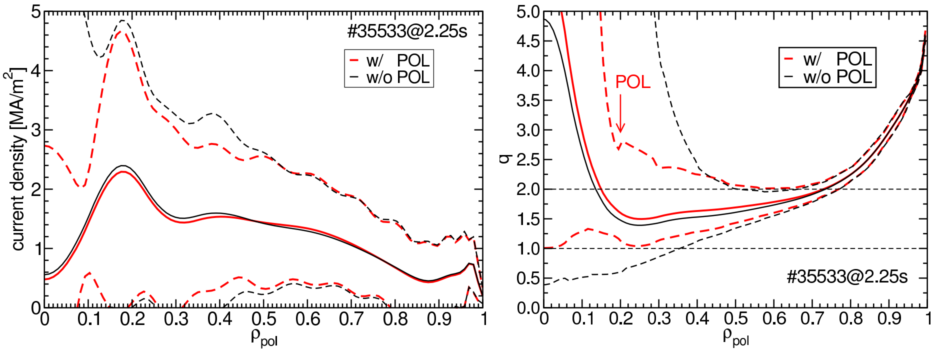

Figure 4: *Current density profile (left) and q-profile (right) with current diffusion modelling only (black line) and additional polarimetry measurements used (red lines).*

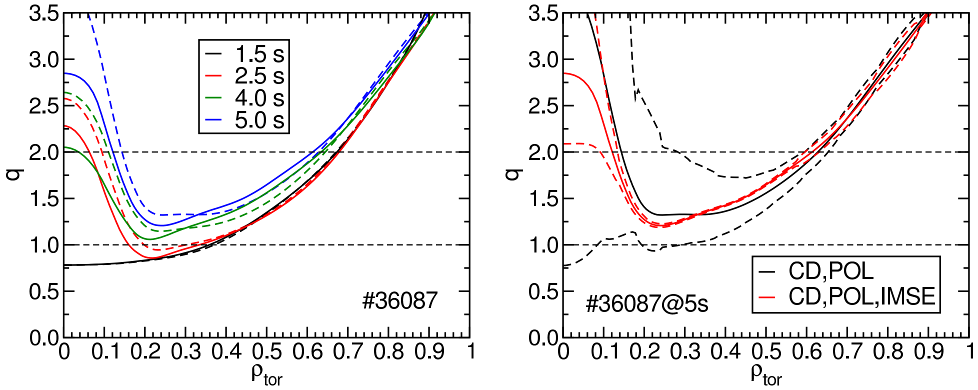

Figure 5: *q-profiles at various time points (left) with counter-ECCD shifting current from the core to the edge estimated with CD-modelling and one polarimetry LOS (dashed lines) and including IMSE measurements (solid lines), and q-profile uncertainties (right).*

on-axis ECCD (Fig. 3) reduces the core current density (Fig. 4 left) and increases the central q-values (Fig. 4 right). Again, the polarimetry confirms the results obtained with current-diffusion modelling only.

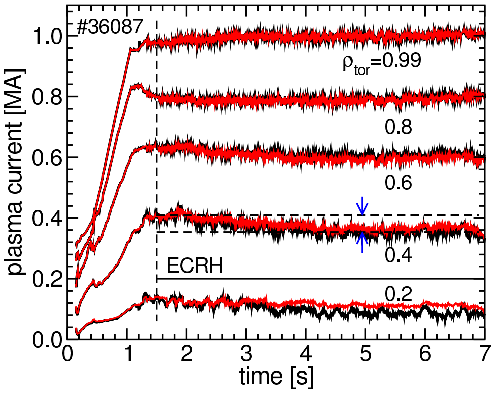

Figure 6: *Plasma current within ρ_{tor} = 0.2, 0.4, 0.6, 0.8, and 0.99 evaluated with current diffusion and one polarimetry LOS (black lines) and additional IMSE measurements (red lines).*

One of the goals for obtaining advanced discharges is to tailor the current profile starting from a stationary plasma, which means independent of the current ramp-up phase. Figure 5 shows the q-profiles of a plasma (#36087, 1.0 MA, -2.45 T) with 7 gyrotrons in a counter-ECCD setting at various time points. Note that there is an additional broad neutral-beam current drive in the co-current direction. At 1.5 s the current and q-profile is stationary with a peaked current profile ($q_0 < 1$). The counter-ECCD, starting at 1.5 s and distributed from the core to mid-radius, results in an increase of the q-profiles with time due to current shifted from the core to the edge. The dashed lines are evaluated with current-diffusion modelling and one LOS of the polarimetry whereas the solid lines are estimated including IMSE measurements. Only IMSE measurements 7 cm above the magnetic axis are used to avoid interpretation difficulties with two interfering neutral heating beams below the axis. Therefore, no IMSE data are provided close to the magnetic axis. The corresponding uncertainties of the q-profiles are shown in the right panel of Fig. 5. The uncertainties of profiles estimated with IMSE measurements consider statistical measurement errors only. Therefore, they are rather small due to the high-spatial resolution of the IMSE diagnostic. Systematic uncertainties due to an offset estimation of the IMSE angles at the beginning of the measurement at 2.2 s is not included. Figure 6 shows the current within the ρ_{tor} surfaces 0.2, 0.4, 0.6, 0.8, and 0.99 evaluated with current-diffusion modelling and one LOS of the polarimetry (black lines) and including IMSE measurements (red lines). The enclosed currents agree within their statistical scatter with the exception of the current within $\rho_{\text{tor}} = 0.2$ where the current has larger uncertainties. The decrease of current in the plasma core can clearly be seen in both reconstructions.

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