

Magnetic equilibrium reconstruction using geometric information from temperature measurements at ASDEX Upgrade

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Tokamak magnetic equilibria are routinely calculated by a Grad-Shafranov solver using external constraints from magnetic measurements and, if available, internal constraints from motional Stark effect (MSE) measurements. The reconstruction of the magnetic equilibrium is ill-posed using external measurements only and the internal MSE measurements are cumbersome to be calibrated. Therefore, additional internal constraints would be helpful to restrict and validate the ill-posed inversion problem by providing complementary and redundant information. One type of internal constraint can be provided by pressure profiles. Edge pressure constraints were successfully applied, e.g., to reconstruct the edge current distribution for plasma stability studies [1, 2]. Core pressure profiles are usually not applied because the pressure of fast particles is laborious to be estimated. Alternatively, the current distribution and, hence, the magnetic equilibrium can, in principle, be determined completely from pure geometric information about the shape of the magnetic surfaces [3]. As the temperature is considered to be constant on a closed flux surface, redundant measurements on the same flux surface can provide sufficient information to determine their position and shape as long as temperature gradients allow to label flux surfaces with temperature values. Multiple electron temperature (T_e) measurements on the same flux surface are provided by electron cyclotron emission (ECE) measurements in the core plasma of ASDEX Upgrade. Therefore, the ECE data allow to provide geometric constraints for the Grad-Shafranov solver consisting of pairs of coordinates, each pair being on

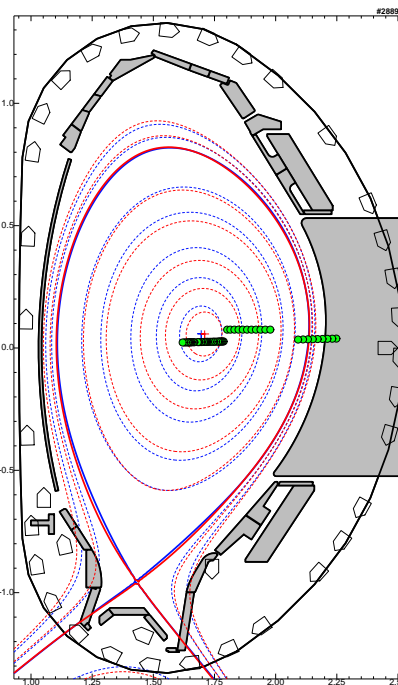


Figure 1: *Equilibrium using magnetic measurements only (blue) and a combination of magnetic, pressure and iso-flux data (red), and the ECE resonance positions (green).*

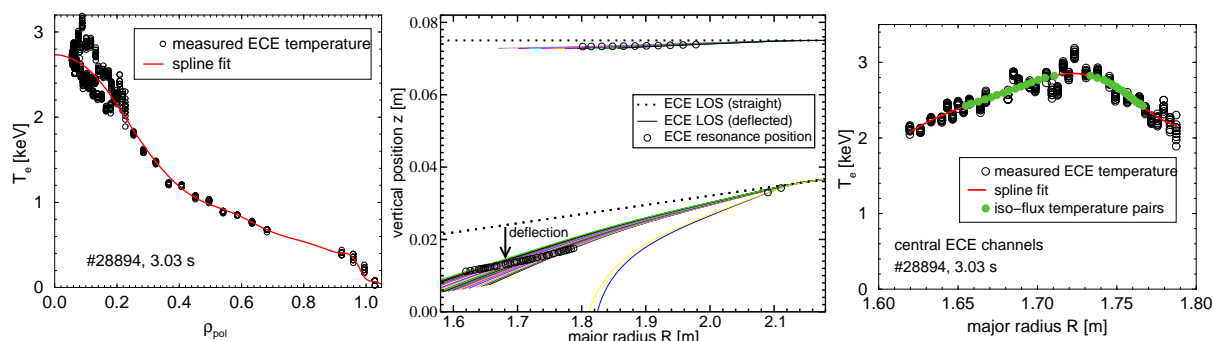


Figure 2: *Left: Temperature profile using the standard equilibrium. Middle: Radial position of ECE LOS and resonance position from a beam tracing code. Right: Iso-flux positions from a spline fit to $T_e(R)$.*

the same contour of a flux surface.

Fig. 1 shows poloidal magnetic flux surfaces reconstructed with magnetic data only (standard equilibrium, blue lines, #28894, 3.03 s, shortly before the next sawtooth crash). The green dots depict the cold resonance position of 60 ECE channels. The central ECE channels are located close to the magnetic axis which enables to infer shape information about the geometry of the magnetic surfaces in the plasma core from multiple T_e -measurements on the same flux surface. Mapping the resonance position of the ECE channels to the corresponding magnetic coordinate (normalised poloidal flux ρ_{pol} of standard equilibrium) results in an unphysical T_e -loop close to the magnetic axis (Fig. 2 left). A possible source of this T_e -loop is given by microwave deflection which results in distorted lines-of-sight (LOS) and, hence, in shifted ECE resonance positions. But, considering the deflection of the LOS via a beam tracing code (TORBEAM) [4] shifts the loop on the ρ_{pol} axis but cannot resolve the loop. For the present discharge with a moderately peaked electron density profile (Fig. 3 left) the deflection of the ECE channels is $\lesssim 1$ cm (Fig. 2 middle).

Another reason for the T_e -loop might be given by the magnetic equilibrium used for coordinate mapping of the ECE resonance positions. It is well known that the equilibrium in the plasma core is insufficiently determined using external magnetic data only. The internal T_e -values can

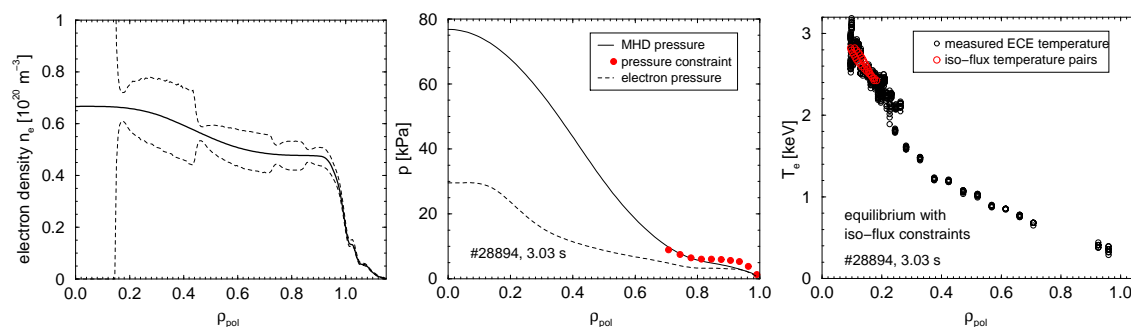


Figure 3: *Left: Electron density profile. Middle: Electron (dashed) and MHD pressure (solid) profile and pressure constraints (red dots). Right: Electron temperature and iso-flux pairs for improved equilibrium.*

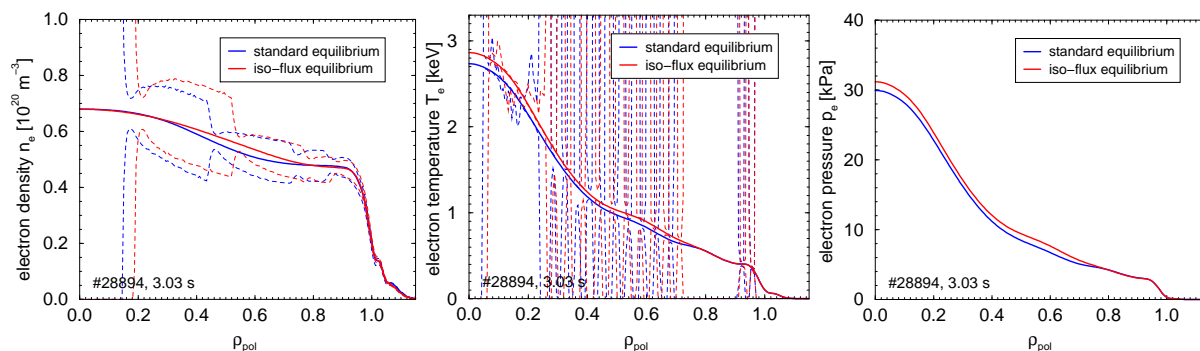


Figure 4: *Electron density, temperature and pressure profiles with equilibria using magnetic data only (blue) and magnetic, pressure and iso-flux data (red).*

be used to constrain the magnetic equilibrium in the core. The T_e -measurements as a function of major radius R of the ECE resonance positions on the deflected beams (Fig. 2 right, black circles) allow to determine pairs of coordinates $(R, z)_{1/2}$ with the same T_e belonging to the same flux surface. The red line shows a 5-pivot spline fit to ECE data from the central channels within an interval of 1 ms around 3.03 s. The green circles depict pairs of T_e -values on the high- and low-field-side, respectively, belonging to the same flux surface (iso-flux pairs). The information of coordinate pairs lying on the same flux surface was included as an additional constraint in a newly developed Grad-Shafranov solver IDE (Integrated Data analysis Equilibrium) based on the concept of CLISTE [5]. The values of the magnetic flux are irrelevant as well as the values of T_e . Only the relative calibration of the T_e -measurement has to be reliable to be able to resolve the geometry of the flux surfaces. Since the relative T_e -calibration for ECE channels belonging to the same local oscillator (LO) is considered to be sufficiently reliable, we use the central channels only.

The red lines in Fig. 1 show the equilibrium using magnetic, pressure (Fig. 3 middle, red circles) and iso-flux data (Fig. 3 right, red). The resulting flux surfaces are radially shifted and compressed. The magnetic axis is shifted outward by about 15 mm. The T_e -loop is much reduced (Fig. 3 right, black). Please note that no geometric constraints about the vertical position of flux surfaces could be provided as the LOS of the central ECE channels are nearly horizontal.

The ECE T_e -data allow to improve the equilibrium in the core, but the revised equilibrium also affects the profiles estimated from various diagnostics in an integrated data analysis (IDA) approach [6]. Fig. 4 depicts electron density, temperature and pressure profiles evaluated with equilibria using magnetic data only (blue) and magnetic, pressure and iso-flux data (red). The profiles coincide at the plasma edge but differ at the core. The different positions of the 5 interferometry LOS for the two different equilibria can clearly be seen in the location of the dips in the density uncertainties.

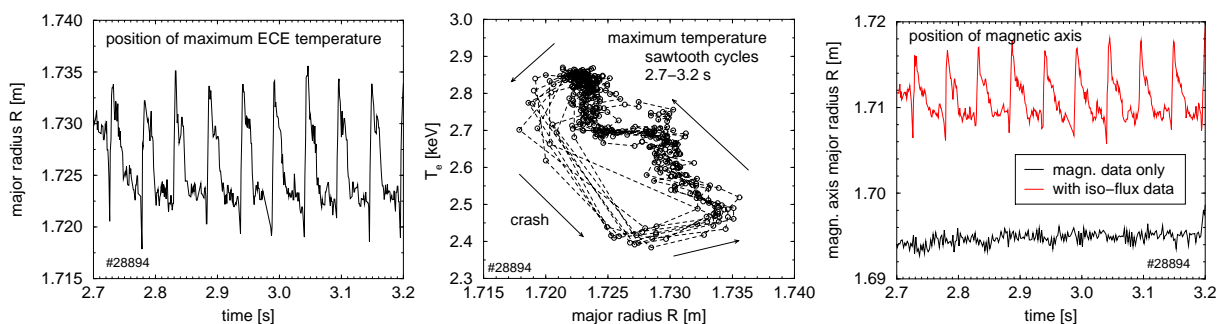


Figure 5: Sawtooth cycles: $R(t)$ of $T_{e,\max}$ (left) and $T_{e,\max}(R)$ (middle), and major radius $R(t)$ of magnetic axis (right) using magnetic data, pressure and iso-flux data (red) and magnetic data only (black).

The evolution of the position of the maximum $T_{e,\max}(t)$ and $T_{e,\max}(R)$ during a sawtoothing period of the plasma is shown in Fig. 5 (left and middle). The sawtooth cycles of the iso-flux data have their counterpart in the radial position of the magnetic axis (right, red), whereas the axis of the equilibrium using magnetic data only stays nearly constant about 15–20 mm at smaller radius (right, black).

In conclusion, the magnetic equilibrium in the plasma core is estimated more reliably by providing geometric information about the shape of the magnetic surfaces using T_e -measurements of the central ECE channels at ASDEX Upgrade. The data are not sufficient to constrain the equilibrium completely, as e.g. the amount of available ECE channels is limited and vertical information is not provided. A thorough sensitivity study with respect to the equilibrium parameters and uncertainties of input quantities, e.g. the toroidal field and the density profile is in progress.

References

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