Current distribution reconstruction for plasma scenario development at ASDEX Upgrade

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Fast and reliable reconstruction of the current distribution is of major interest for experimental on-the-fly plasma scenario development, in particular for the development of advanced scenarios where fine-tuning of the q-profile using heating and current-drive actuators is desired [1]. The goal is to reconstruct the most reliable equilibrium achievable from all available experimental data and modelling constraints before the setting of the next plasma discharge has to be decided. The number of plasma discharges for the typically challenging plasma performance optimisation is often large but required to be as small as possible for budget reasons. The equilibrium reconstruction for performance optimisation between discharges is to be distinguished from real-time equilibrium reconstructions [2] and most sophisticated equilibrium reconstructions converged with all diagnostics data interpretation [3]. Real-time equilibrium reconstruction is based on a reduced set of available real-time diagnostics and does not allow for time consuming forward modelling of, e.g., electron cyclotron emission (ECE) and lithium beam, profile diagnostics. A consistent set of equilibria and profile reconstructions from all available diagnostics with high spatial and temporal resolution is, at the moment, too time consuming for an inter-discharge analysis. At ASDEX Upgrade the goal is to have the most reliable current and q-profiles within 20 min after the previous discharge for plasma parameter tuning for the next discharge. The first 10 min are foreseen for kinetic profile reconstruction employing an integrated data analysis (IDA) [4] approach of all profile diagnostics available shortly after the previous plasma discharge (not necessarily in real-time). The next 10 min are dedicated for equilibrium reconstruction with a temporal resolution of 5 ms for a typical plasma discharge of 8 s. This work shows the state-of-the-art realisation of an inter-discharge equilibrium and profile reconstruction at ASDEX Upgrade.

Equilibrium reconstruction employing pressure constraints, bootstrap current evaluation and current diffusion modelling benefits from profiles of thermal temperature and density for electrons and ions $(T,n)_{\mathrm{e,i}}$, fast-ion density and pressure $(n,p)_{\mathrm{fast}}$, effective charge Z_{eff} and plasma rotation v_{tor}. Table 1 summaries the results (✓) and dependences (d) of the various profile di-

	T_e	n_e	T_i	n_i	v_tor	Z_eff	n_fa	p_fa	j_EC	j_NB	j_BS	j_tor	t_ST	equ
ECE	✓	d												d
LIB	d	✓												d
TS	✓	✓												d
DCN		✓												d
CXRS		d	✓	✓	✓	✓								d
SXR													✓	d
TORBEAM	d	d				d			✓					d
RABBIT	d	d	d	d	d	d	✓	✓		✓				d
BOOTSTRAP	d	d	d	d		d	d				✓			d
ST reconnect.												✓	d	d
CDE	d	d	d	d	d	d	d		d	d	d	✓		d
IDE	d	d	d	d	d	d	d	d	d	d	d	d	d	✓

Table 1: *Results (✓) and dependences (d) of the profile diagnostics (ECE, LIB, TS, DCN, CXRS), the sawtooth diagnostic (SXR), the driven current and fast particle modelling codes (TORBEAM, RABBIT, BOOTSTRAP), the sawtooth (ST) reconnection modelling, the current diffusion modelling (CDE) coupled with the equilibrium solver (IDE).*

agnostics and modelling codes. The $(T,n)_\mathrm{e}$ profiles are provided by analysing a combined set of measurements from ECE, interferometry (DCN), Thomson scattering (TS) and lithium beam (LIB) diagnostics [4]. The forward modelling of the ECE including radiation transport modelling and of the LIB emission profile are one of the most time consuming evaluations of the first 10 min IDA analysis. ECE modelling provides T_e but depends on n_e profiles and the LIB modelling vice versa. The $(T,n)_\mathrm{i}$ and v_tor profiles are provided by various charge exchange recombination spectroscopy diagnostics [5]. These ion profiles are fitted by cubic splines to all available data from the lines-of-sight of the various CXRS diagnostics. Since the available CXRS set depends on the neutral heating beams used, the full set of diagnostics is typically not available. In case of an ohmic plasma T_i is approximated by a simple fitting function of $T_\mathrm{e}/T_\mathrm{i}$ from figure 6d in [6], $T_\mathrm{e}/T_\mathrm{i} = 1 + 0.2/\nu_\mathrm{eff}$, employing the effective collisionality ν_eff [6]. For non-ohmic discharges without neutral beam heating $T_\mathrm{i} = T_\mathrm{e}$ is assumed.

The analysis of all diagnostics depends on a magnetic equilibrium providing a common coordinate system. The first IDA evaluations are performed with a function parameterised equilibrium (FPP) [7] available shortly after the discharge. FPP equilibria are known to be less precise than a Grad-Shafranov (GS) solution but provide a good starting point for a first iteration. IDA Te and ne profiles are obtained in about 2 min per time point allowing for 1500 sets of profiles in 10 min on a linux cluster employing 300 parallel jobs. This corresponds to 5 ms temporal resolution for a discharge with typically 8 s duration. Since profile reconstruction for different time points are treated independently, the temporal resolution directly scales with the cluster size.

The equilibrium reconstruction is based on the coupling of an *interpretive* GS solver with the integration of the *predictive* current diffusion equation (CDE) employing a physical coupling of equilibria of neighboring time points. The source current profiles for the CDE are given by j_{EC}, j_{NB} and j_{BS}: The electron-cyclotron driven current j_{EC} is evaluated with a recently upgraded TORBEAM code [8]. The profiles of $(n,p)_{\mathrm{fast}}$ and of the neutral-beam driven current j_{NB} are provided from the recently developed RABBIT code [9]. The bootstrap current profile j_{BS} is calculated with a recent extension of the Sauter formula [10]. Whenever a ST crash appears the current diffusion is replaced with a current redistribution scheme according to a Kadomtsev reconnection model or a $q = 1$ surface conserving variant. t_{ST} are determined with an automized sawtooth detection algorithm using soft X-ray (SXR) diagnostics [11]. The toroidal current profile resulting from the CDE or the ST current redistribution is provided as a constraint (with uncertainties) additional to all magnetic data of an extended set of poloidal-field and diamagnetic-loop measurements, pressure constraints and internal current measurements from (imaging)MSE and polarimetry, if available.

The temporal constraints of the equilibrium reconstruction are met with the equilibrium code IDE, employing a fast Grad-Shafranov solver [12], and a parallelisation strategy based on the Message-Passing Interface (MPI) and OpenMP threads, as detailed in [13]. In addition to the MPI-parallel computation of the GS-solver response matrix, MPI is used to operate the TORBEAM code [8] in parallel for of up to 8 EC-beams for the CD-integration. The RABBIT code [9] is executed in parallel for up to 8 NI-beams using OpenMP. A standard, server-class machine (Intel Xeon E5-2680v3 with 24 cores at 2.50GHz) is sufficient to run the entire calculation with 1600 time steps within about 9 minutes (AUG #33134 with 4 EC beams, 6 NI beams, employing a spatial grid of 65x129 points, 28 basis functions, and a temporal resolution of 5 ms). Even after thorough parallelisation and optimisation of the GS-solver response matrix computation, and by taking advantage of some significant optimisations we have contributed to the TORBEAM code on top of the version described in [8], these two components remain by far the most significant, individual time consumers, using about 20% (response matrix) and 30% (TORBEAM) of the total runtime, respectively. Thanks to the rather flexible parallelisation scheme [13] we can easily compensate larger numbers of EC beams, NI beams, or basis functions by parallel scaling up to about 40 cores of a server with latest-generation processor technology which is about to be deployed at AUG.

Summarising, the set of profile diagnostics, the modelling codes of the driven current and fast particles profiles, and the coupling of an equilibrium solver with the current diffusion provides the basis for fast and reliable reconstruction of the current distribution for on-the-fly plasma scenario development. The method will be applied for the first time in the 2018/2019 ASDEX Upgrade campaign.

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