Particle density modeling for real-time density profile reconstruction and fringe jump detection on TCV and ASDEX Upgrade

T.C. Blanken[1], F. Felici[1], C.J. Rapson[2], the TCV team[3] and the ASDEX-Upgrade Team[2]

[1] *Eindhoven University of Technology, Eindhoven, the Netherlands. Contact: t.c.blanken@tue.nl*

[2] *Max-Planck-Institut für Plasmaphysik, Garching, Germany*

[3] *École Polytechnique Fédérale de Lausanne, SPC-EPFL, Lausanne, Switzerland*

Plasma particle density monitoring and control in a tokamak reactor is important because the density determines the fusion power, radiation, transport, non-inductive current density profiles, proximity to disruptions, diagnostics validity (e.g. ECE cut-off) and EC beam propagation. Real-time density profile estimation is essential for ITER, but is often not performed on present-day tokamaks. Inversion of interferometry measurements to an electron density profile is often ill-conditioned. Moreover, many individual density diagnostics have inherent drawbacks for density estimation and control, such as diagnostic faults (e.g. fringe jumps on the 184.3µm interferometers at TCV and (pellet-induced) fringe jumps on the 195µm interferometers at AUG [1]), severe noise and electromagnetic interference with ICRH (most notable on the 10.64µm interferometer at AUG) and the dependence of Z_{eff} on Bremsstrahlung.

Main contribution

We have implemented a real-time density profile estimation algorithm [2, 3] on both AUG and TCV. It employs an interpretative transport model for the density in a dynamic state estimator, integrating the predicted density evolution with multiple diagnostics signals. This approach ensures estimation quality and robustness against diagnostics faults by leveraging the combined strength of many diagnostics, and is similar to work on real-time estimation of temperature and current density profiles [4, 5]. Our model is physics-based yet control-oriented, capable of simulating in real-time the evolution of the electron density profile. A fringe jump detector is used that checks the difference between predicted and measured interferometry signals, allowing real-time correction. Additionally, the dynamic state estimator selects usable diagnostics channels among all available for estimation.

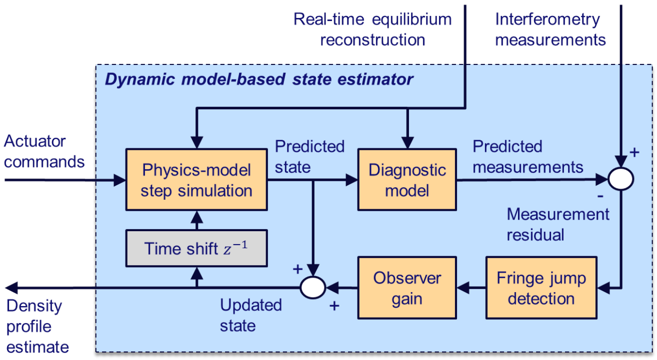

Figure 1: *Block scheme of the dynamic state observer.*

We present results of real-time density profile estimation on TCV and AUG. The results show good accuracy of the estimated profiles and quality of fringe jump detection.

Physics-based control-oriented model

The model is based on a 1D PDE for radial electron density transport in the plasma [6] and two ODEs for the particle inventories of the wall and the vacuum (similar to [7])

$$\frac{\partial}{\partial t}(n_e V') = \frac{\partial}{\partial \rho}\left(V'\left(D\frac{\partial n_e}{\partial \rho} + v n_e\right)\right)$$
$$+V'\left(S_{\text{ion\&rec}} + S_{\text{NBI\&pellets}} - S_{\text{SOL}\to\text{wall}}\right)$$
$$\frac{dN_w}{dt} = \Gamma_{\text{SOL}\to\text{wall}} - \Gamma_{\text{recycl}}$$
$$\frac{dN_v}{dt} = \Gamma_{\text{valve}} + \Gamma_{\text{recycl}} - \Gamma_{\text{ion\&rec}} - \Gamma_{\text{pump}}$$

where ρ denotes the normalized toroidal magnetic flux (a measure for radial distance) and $V' = \frac{\partial V}{\partial \rho}$ is the derivative of enclosed volume to ρ. We favor an empirical transport model for the plasma and set the diffusion and pinch coefficients D and v as simple functions of ρ. We also choose simple models and approximations for the particle flows in the tokamak. The model takes as input the plasma current, edge temperature (acquired from the real-time RAPTOR-based observer [5] in TCV and AUG), gas valve and neutral beam mass flow, reconstructed equilibrium, magnetic configuration (limited or diverted plasma) and confinement mode

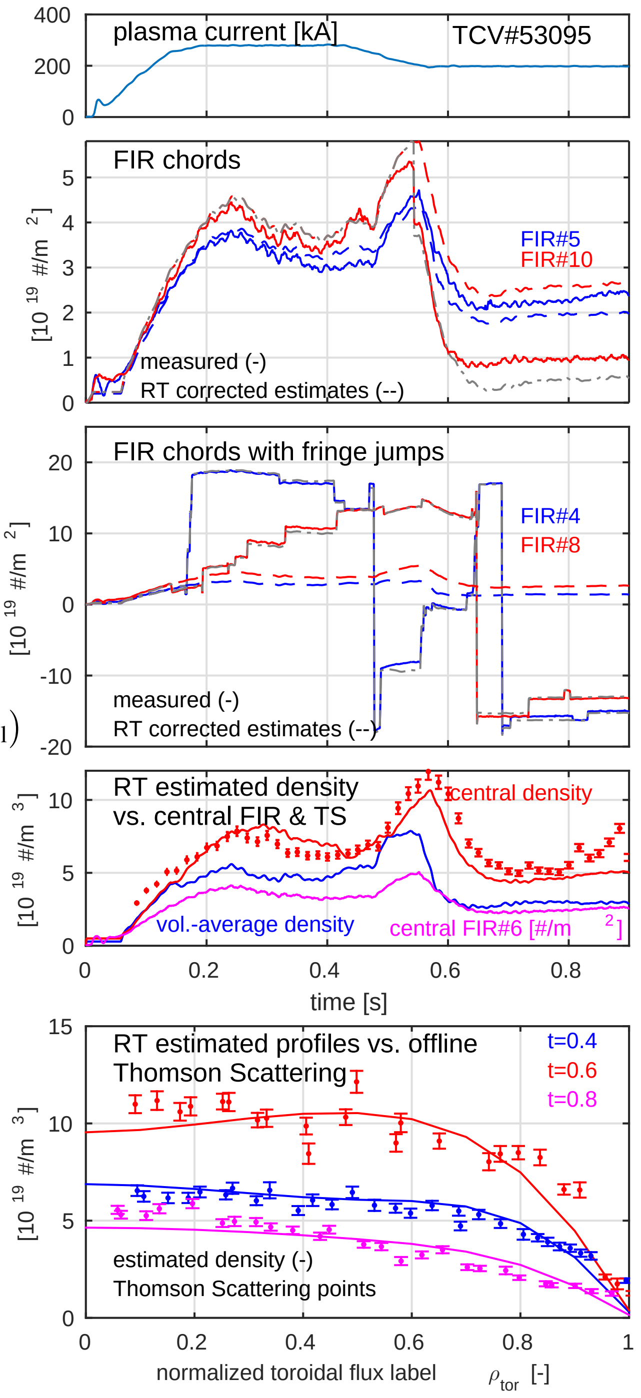

Figure 2: *Reconstruction results of the observer during TCV shot #53095. Plasma current in (a), measured and estimated line-integrals of FIR chords #5, #10 in (b), and #4 and #8 in (c), estimated density traces, central FIR chord #6 and central Thomson Scattering density in (d), estimated density profiles versus offline Thomson Scattering density profiles in (d). Many fringe jumps occur on chords #4 and #8, which are all detected and corrected in the profile estimation. Otherwise the jumps would render the signals unusable.*

(ohmic, L or H mode plasma).

The model includes their influence on plasma transport, SOL particle loss, wall particle saturation and recycling, ionization and recombination. The wall retention and recycling model accounts for effects during one discharge, not for the history of retention in the machine.

Dynamic state observer for real-time density profile estimation

We use a dynamic state observer (or Kalman filter), a common tool in the systems and control community for multi-sensor data fusion. The observer estimates the density iteratively by solving one-sample ahead model-based predictions from the previous estimate and updating the predictions using the measurement residuals (see Figure 1). The observer can be used to detect known fault modes of density diagnostics. Here, we detect fringe jumps as jumps between two moving average filters in sequence, receiving the interferometry measurement residual as input. Inevitable model versus reality mismatches are handled by using feedback from the measurement residual to update the model-based state estimate evolution (see Figure 1), and estimating systematic measurement versus model deviations as a particle source disturbance. Usable diagnostic signals and channels are selected among all avail-

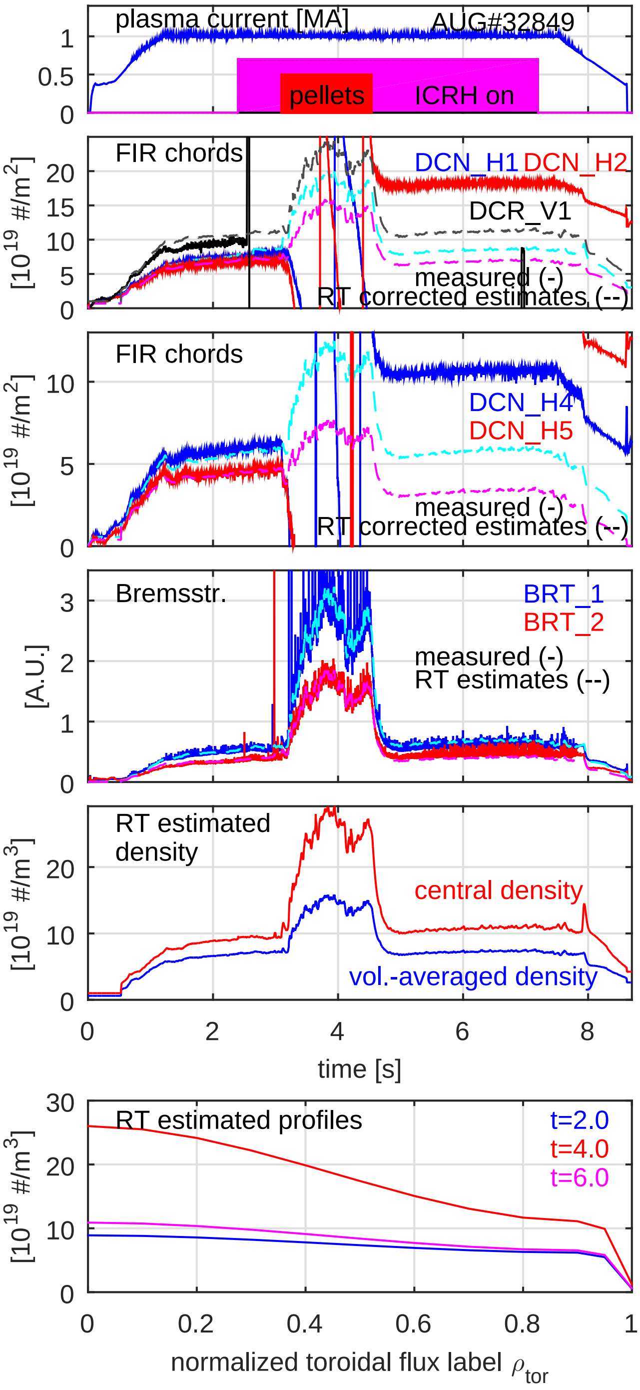

Figure 3: *Reconstruction results of the observer of AUG shot #32849. Plasma current, pellet injection and ICRH activation period in (a), measured and estimated line-integrals of FIR chords H1, H2, H4, H5 (*195 µm*) and V1 (*10.64 µm*) in (b) and (c), measured and estimated Bremsstrahlung chords #1 and #2 in (d), estimated density traces in (e) and estimated density profiles in (f). ICRH and pellet injections render the* 10.64 µm *interferometer useless and cause all* 195 µm *interferometers to fail without showing clear jumps. At these events, the observer ignores the interferometers and relies on the two Bremsstrahlung chords to estimate the density.*

able in real-time. The selection criteria comprise checks on sanity of signal values, checks on diagnostic line-of-sight intersecting with the plasma, checks on interference from ICRH to the 10.64μm interferometer at AUG and checks on fringe jumps caused by pellets. The dynamic state observer [3, 2] is implemented on TCV on a new multi-core node of the SCD distributed real-time control system [8] and on ASDEX-Upgrade as a DCS AP [9]. On AUG, the four 195μm interferometers, one 10.64μm interferometer, two Brehmsstrahlung chords and two neutral density gauges are used. On TCV, the 14 vertical 184.3μm interferometers are used.

Real-time profile reconstruction on TCV and ASDEX-Upgrade

Density estimation during TCV shot #53095 containing fringe jumps is shown in Figure 2, showing good agreement with offline Thomson Scattering profiles. All fringe jumps were detected, keeping all interferometers in use for density estimation. Density estimation of AUG shot #32849 is shown in Figure 3. Pellet injections cause fringe jumps in the 195μm interferometers and the ICRH induces failure in fringe counting on the 10.64μm interferometer, forcing the observer to ignore the interferometers and rely on Bremsstrahlung to estimate the density.

Conclusions and outlook

Real-time model-based density profile estimation algorithm has been implemented on both AUG and TCV. Good reconstruction quality of the density profile is achieved by correcting for fringe jumps and robustness is provided by using multiple diagnostics, selecting healthy signals and correcting for known fault modes. The observer is being used on TCV as an input for control and for estimation of temperature and current density using RAPTOR. Extending the algorithm to future machines is simplified by the machine-independent modeling, which can be adapted to different tokamaks, diagnostics and actuators.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] A. Mlynek *et al*, Rev. Sci. Instrum., 85 (2014).
[2] T.C. Blanken, F. Felici, C.J. Rapson, M. de Baar and W.P.M.H. Heemels, (to be submitted to PPCF).
[3] T.C. Blanken *et al*, 54th IEEE Conference on Decision and Control, Osaka, Japan (2015).
[4] F. Felici *et al*, American Control Conference, Portland, USA (2014).
[5] F. Felici *et al*, 43rd EPS Conference on Plasma Physics, Leuven, Belgium (2016).
[6] F. Hinton and R. Hazeltine, Rev. Mod. Phys. (1976).
[7] W. Vijvers *et al*, 39th EPS Conference on Plasma Physics, (2012).
[8] H.B. Le *et al*, Fusion Eng. Des. 89 (2014).
[9] W. Treutterer *et al*, Fusion Eng. and Des. 89 (2014).