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

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Particle density control is important in a tokamak reactor because the density determines the fusion power, radiation, transport and non-inductive current density profiles. At present, often the line-integrated density of only one interferometry chord is used as input to density feedback control (see e.g. [1]). However, real-time knowledge of the particle density profile allows for real-time monitoring of the fusion power, radiation, proximity to disruptions, diagnostics validity (e.g. ECE cut-off) and accurate ray tracing. Inversion of interferometry measurements to an electron density profile is often ill-conditioned. Moreover, many density diagnostics have inherent drawbacks for density estimation, such as diagnostic faults (e.g. fringe jumps on the 184.3 μm interferometers at TCV and pellet-induced fringe jumps on the 195 μm interferometers at AUG [2]), severe noise and electromagnetic interference with ICRH (specific to the 10.64 μm interferometer at AUG) and the dependence of Z_{eff} on Bremsstrahlung. We propose to integrate multiple diagnostics with a prediction of the density profile evolution, ensuring the profile smoothness and robustness against diagnostics faults by leveraging the combined strength of all diagnostics.

Main contribution

We have tested and implemented a density profile estimation algorithm [3, 4] on both AUG and TCV. It employs an interpretative transport model for the particle density [3, 4] in a dynamic state estimator, merging the predicted density evolution with various diagnostics signals. The approach is similar to work on real-time reconstruction of temperature and current density profiles [5]. Our model is physics-based yet control-oriented, capable of simulating in real-time the evolution of the electron density profile.

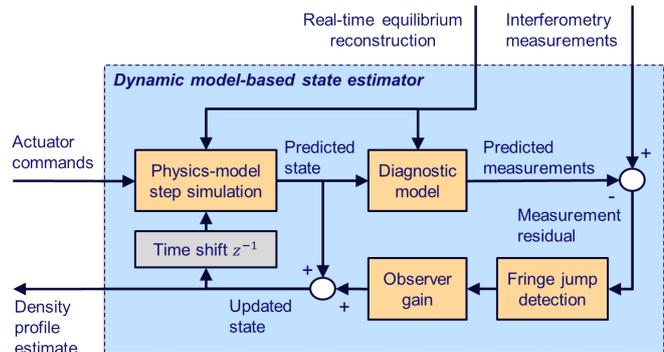


Figure 1: Block scheme of the dynamic state observer.

A fringe jump detector is used that checks the difference between modeled and measured interferometry signals for jump allowing real-time correction of fringe jumps. Furthermore, the dynamic state estimator selects usable diagnostics channels among all available to estimate the plasma density. 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 [1])

$$\frac{\partial}{\partial t}(n_e V') = \frac{\partial}{\partial \rho} \left(V' \left(D \frac{\partial n_e}{\partial \rho} + v n_e \right) \right) + V' S$$

$$S = S_{\text{ion\&rec}} + S_{\text{NBI\&pellets}} - S_{\text{SOL} \rightarrow \text{wall}}$$

$$\frac{dN_w}{dt} = \Gamma_{\text{SOL} \rightarrow \text{wall}} - \Gamma_{\text{recycl}}$$

$$\frac{dN_v}{dt} = \Gamma_{\text{valve}} + \Gamma_{\text{recycl}} - \Gamma_{\text{ion\&rec}} - \Gamma_{\text{pump}}$$

where ρ denotes ρ_{tor} and $V' = \frac{\partial V}{\partial \rho}$. 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 wall retention and recycling model only accounts for effects during one discharge, not for the history of retention in the machine.

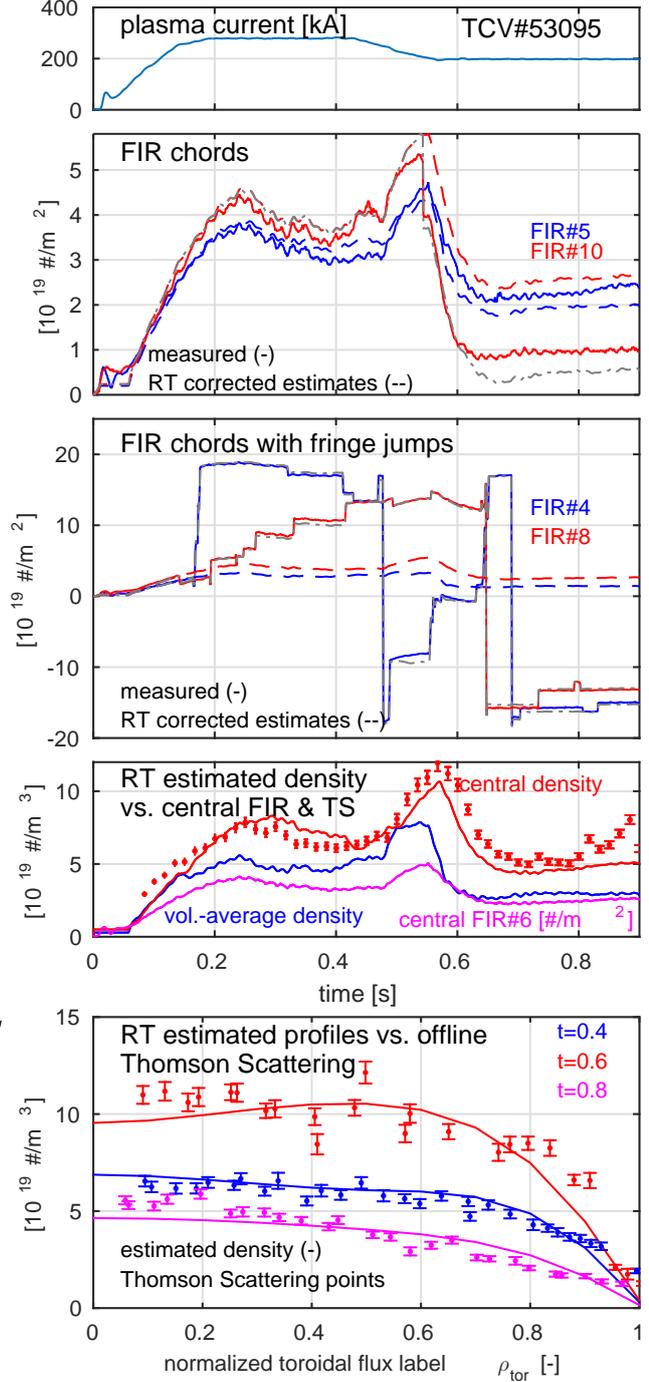


Figure 2: Reconstruction results of the observer during TCV shot #53095. Plasma current in (a), measured and estimated line-integrals of FIR chords #5, #10 in (b), and #4 and #8 in (c), estimated density traces, central FIR chord #6 and central Thomson Scattering density in (d), estimated density profiles versus offline Thomson Scattering density profiles in (e). 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.

The model takes as input the plasma current, edge temperature, gas valve and neutral beam mass flow, reconstructed equilibrium, magnetic configuration (limited or diverted plasma) and confinement mode (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.

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 available in real-time. The selection crite-

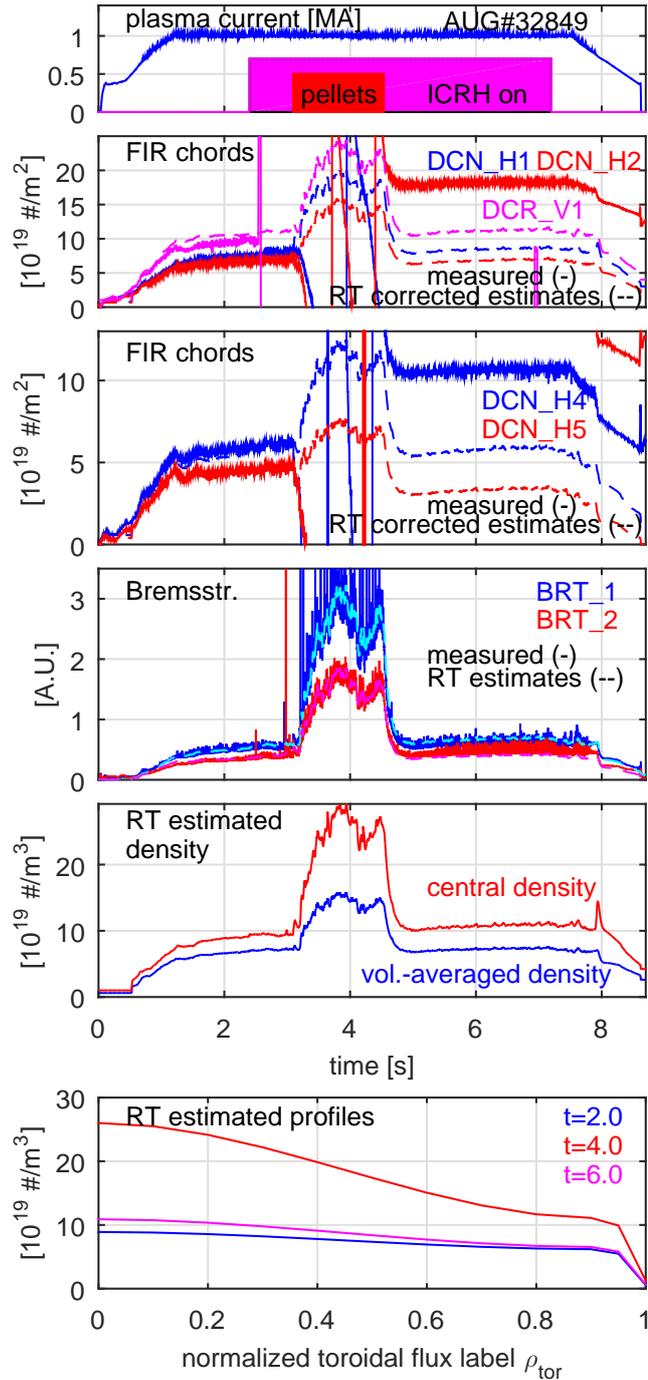


Figure 3: Reconstruction results of the observer of AUG shot #32849. Plasma current, pellet injection and ICRH activation period in (a), measured and estimated line-integrals of FIR chords H1, H2, H4, H5 (195 μm) and V1 (10.64 μm) in (b) and (c), measured and estimated Bremsstrahlung chords #1 and #2 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.

ria comprise checks on sanity of signal values, checks on diagnostic line-of-sight intersecting with the plasma, checks on interference from ICRH to the 10.64 μm interferometer at AUG and checks on fringe jumps caused by pellets. The dynamic state observer [4, 3] is implemented on TCV on a new multi-core node of the SCD distributed real-time control system [7] and on ASDEX-Upgrade as a DCS AP [8]. On AUG, the four 195 μm interferometers, one 10.64 μm interferometer, two Brehmsstrahlung chords and two neutral density gauges are used. On TCV, the 14 vertical 184.3 μm 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 195 μm interferometers and the ICRH induces failure in fringe counting on the 10.64 μm 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 estimation of temperature and current density using RAPTOR. Extending the algorithm to future machines is simplified by the code, which can be adapted to different tokamaks, diagnostics and actuators.

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