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Real–Time Plasma Profile State Reconstruction on ASDEX–Upgrade

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Integrated control and the need for centralized state reconstruction

The focus of tokamak control is slowly shifting from support of physics experiments to increasingly integrated operation of the tokamak to increase performance and reliability in view of large tokamaks such as ITER. Consequently, increasingly sophisticated plasma monitoring and supervision systems are being developed for plasma control systems worldwide. This evolution also calls for a centralized approach to estimating the state of the plasma in real-time: one algorithm where all the available real-time diagnostic data is collected, analyzed, and merged into a consistent estimate of the plasma state [1].

Existing approaches such as equilibrium reconstruction, spline fitting of profiles, learning-based regime identification approaches are essentially static methods which do not take the dynamics of the process into account. In previous contributions [2] we have proposed to use a dynamic state observer, more specifically an Extended Kalman Filter (or EKF, an established tool in the signal processing/control engineering community), to approach this *data fusion* problem for tokamak fusion reactors. This method has the great advantage that physics model knowledge is combined in real-time with diagnostic measurements, which hence can be checked and validated in real-time.

This work describes new results and analysis from the implementation of an EKF for plasma profile reconstruction on ASDEX-Upgrade (AUG), undertaken as part of the MST1 2014 experimental campaign. The EKF algorithm is first described and it is shown how the RAPTOR real-time 1D plasma transport code is included. Then, some technical details of the implementation on the ASDEX-Upgrade Discharge Control System are discussed. Finally we show a comparison to off-line analysis using TRANSP for a shot with NBCD, as well as a shot illustrating the identification of unexpected diagnostic signals in real-time.

Extended Kalman Filter for estimating plasma state and disturbances

The Extended Kalman Filter (EKF) is a recursive algorithm to compute an estimate $\hat{x}_k$ of the state x_k of a system based on a time series of diagnostic measurements y_k for all time indices k. It employs a (nonlinear) dynamic model of the system and measurements which is represented in discrete-time form as $x_{k+1} = f(x_k, u_k)$, $y_k = h(x_k)$. The state estimation is done in two steps: first, the physics model of the system is used to predict the next state of the system based on the previous state estimate $\hat{x}_{k|k-1} = f(\hat{x}_{k-1}, u_{k-1})$. Then, the predicted diagnostic measurements for this new state are computed using a forward model of the diagnostics $\hat{y}_k = h(\hat{x}_{k|k-1})$. The model-based state estimate is then corrected using the difference between measured and predicted diagnostic signals: $\hat{x}_{k|k} = \hat{x}_{k|k-1} + K(y_k - \hat{y}_k)$. The observer gain matrix K can be recursively computed using the knowledge of the model functions f, h and statistical properties of the noise acting on the system, which is assumed to be Gaussian. Details of the algorithm can be found in [3] and its application to plasma profile estimation is discussed in [4]. To handle systematic differences between the true plasma evolution and the diagnostic measurements, the model is extended by assuming that a constant disturbance d_k acts on the system: $x_{k+1} = f(x_k, u_k) + d_k$. By defining an augmented state vector $z_k = [x_k^T,\ d_k^T]^T$, the EKF can easily be reformulated to estimate the state and disturbance simultaneously [4]. Effectively, the disturbance absorbs any systematic discrepancy between the modeled and measured plasma response. Its signature can be used to classify the nature of the discrepancy.

Real-time profile evolution model RAPTOR and its implementation on ASDEX-Upgrade

The key component of the EKF is the forward model f. This model should accurately represent the dynamic evolution of the plasma profiles and be sufficiently fast to run in real-time. For the purpose of estimating the plasma profiles, the 1D profile evolution equations for magnetic flux and electron temperature are used [5], which are simulated with the the RAPTOR code [6], [7].

Details of the implementation of the EKF state observer on ASDEX-Upgrade and the RAPTOR code were presented earlier [2] and will be briefly mentioned here. The state observer takes several AUG real-time diagnostic signals, checks their validity using the provided status flags, and feeds these to the RAPTOR profile state observer. Some quantities, such as plasma current, density profile, and actuator power, are directly used as inputs to the simulator. Others, in particular the ECE and boundary flux, are used as measurement inputs to the EKF. The system runs routinely in real-time every 10ms. Note that no real-time internal measurements of the current density profile are used, hence the reconstruction of the q profile relies entirely on the physics model.

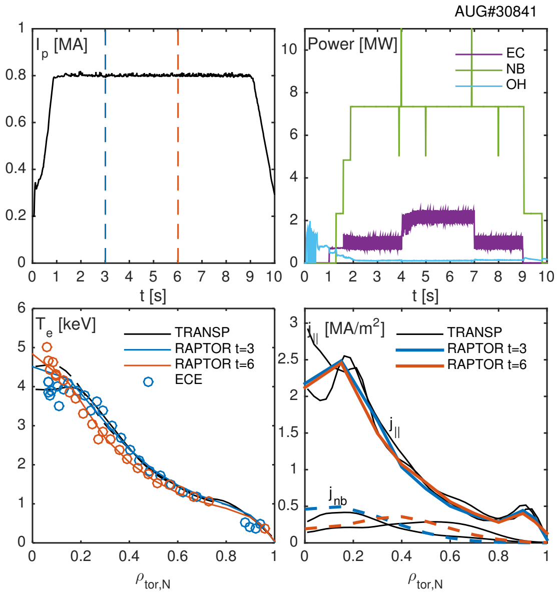

Figure 1: Comparison of RAPTOR- and TRANSP-reconstructed T_e, j_{nb} (– –) and $j_{||}$ (-) profiles for a shot with Neutral beam current drive.

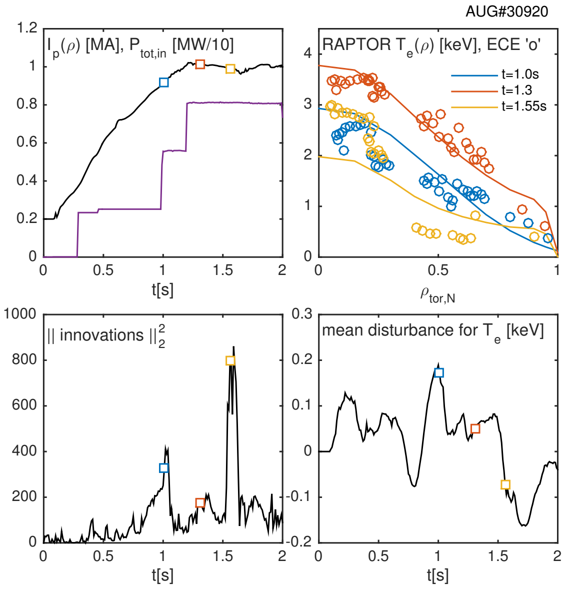

Figure 2: Plasma parameters, norm of innovation sequence and mean T_e disturbance for a shot with a large MHD mode at $t = 1.5$s.

Comparison to off-line profile reconstruction using TRANSP

To validate the results from the RAPTOR state observer, the reconstructed profiles are compared, in Figure 1, to more detailed TRANSP interpretative simulation analyses for a particular shot featuring on and off-axis neutral beam current drive (NBCD) [8]. The temperature profiles are similar, with the differences explained by the fact that RAPTOR uses the ECE diagnostic while for the TRANSP run several diagnostics are used and the Grad-Shafranov equilibrium is re-computed as part of the data fitting process. As a result the total parallel current is also very similar, since this is mostly composed of ohmic and bootstrap current, which are calculated using the same equations in RAPTOR and TRANSP. The neutral beam driven current in TRANSP is computed using the Monte-Carlo code NUBEAM to simulate the beam-driven fast ions. The neutral beam current density profiles in RAPTOR are approximated using Gaussian profiles, which were scaled to match TRANSP predictions for similar representative plasmas.

Indeed, the RAPTOR-based state observer is expected at best to approach more sophisticated physics modelling codes to an accuracy sufficient for real-time control purposes. Analyses using more complete physics-based codes remain essential to compute quantities that are difficult or impossible to measure or calculate in real-time and for detailed physics studies. Parametrizations of results from more complete codes continue to play a key role to obtain models that are tractable in real-time.

Real-time detection of unexpected events

Finally, we present an example of using the innovation sequence $(\hat{y}_k - y_k)$ and disturbance estimate d_k to detect and diagnose unexpected events in the plasma (Figure 2). The norm of the innovation sequence, a scalar measure for the discrepancy between measured and predicted diagnostic signals, is shown. The two spikes in this signal are caused by sudden discrepancies between the modelled and measured plasma behaviour. In the first case, the plasma has transitioned into H-mode, as is visible on the ECE (blue, edge channels), while RAPTOR-EKF has not. As soon as the model transitions into H-mode the discrepancy disappears. The second spike is caused by an MHD mode: its appearance around $t = 1.5$s causes a strongly degraded confinement and inconsistent ECE measurements, caused by cutoff (yellow). The disturbance estimate (bottom right) shows how the disturbance term adapts to the model-measurement mismatch and gives information about the nature of the discrepancy: the H-mode case shows that a positive correction in the temperature is needed to match the measurements, while the confinement-degrading MHD mode leads to a negative temperature correction as expected. At the time shown in red, the model and measurements can be combined with good agreement.

Conclusions and outlook

Diagnostic measurements and physics model predictions are ‘fused’ using the EKF algorithm to estimate key plasma profiles in real-time on ASDEX-Upgrade. The quality of the reconstruction can approach that of more complex post-shot analysis, though manual tuning of some parameters based on more complete physics code is sometimes required. Estimates of an additive model disturbance can be used to diagnose mismatch between model and measurements. Future work will focus on extending this classification to be able to provide information to a higher-level plasma supervision system. The reconstructed plasma profiles will also be fed to the real-time Grad-Shafranov code to yield more accurate real-time equilibria.

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