Integration of a multi-rate electron density profile observer in the plasma control system of TCV

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Introduction

In high-power magnetic confinement fusion devices, a combination of codes and diagnostics will be used for reliable plasma state estimation during a discharge. Due to limited diagnostic data availability [1] for such devices, the adoption of observers is an attractive approach to integrate information provided by various diagnostics and predictive models to ensure robust state estimation while rejecting faults and errors. The reconstruction process occurs inside the plasma control system (PCS) and the estimated signals are fed to controllers supervised by actuator managers and plasma monitors. In this work, we present the integration of RAPDENS [2], a multi-rate electron density observer, into Système de Contrôle Distribué (SCD) [3], the plasma control system of the TCV tokamak. RAPDENS provides real-time density profile estimation at 1kHz, enabling plasma density limit monitoring for disruption avoidance and proximity control [4], estimation of ECRH wave propagation, and NTM suppression [5]. Detailed real-time spatial and temporal information on the electron density profile is also required in the framework of operating in advanced scenarios, such as the development of reactor-relevant steady-state regimes with high beta and elevated q-profile, by leveraging external heat and current drive sources ECRH-CD and NBI [6]. An improved version of RAPDENS, in both spatial and temporal reconstruction of the density profile, integrates a multi-rate observer for density profile estimation in TCV [7]. Diagnostics with different sampling times, specifically Far Infrared interferometer (FIR) (f_{FIR} = 10kHz) and Thomson scattering (TS) data (f_{TS} = 60Hz) are combined in an Extended Kalman Filter (EKF) algorithm.

Here, we present further improvements and the set-up ready to be used in real time in TCV. We show an overview of the architecture of the PCS that hosts the codes and algorithms adopted to reconstruct the electron density profile in the EKF step, as well as a procedure to estimate and adapt in real time unknown transport coefficients leveraging TS diagnostic data. Finally, the results of an offline reconstruction of the electron density profile are reported for a non-inductive H-mode discharge, showing the capabilities of the code to successfully represent spatial and temporal features of the density profile in L- and H-mode, in the presence of fast ELMs.

SCD integration of the electron density observer

A graphical representation of the electron density observer implementation in SCD is shown in Fig. 1. Plasma diagnostics signals are collected and pre-processed in the RT-diagnostics module on a dedicated computational node. These signals, along with reconstructed plasma, controllers, and actuator states, are labeled with Quality and Production state tags for handling in different discharge phases. Strategies have been put in place to handle missing or corrupted signals. FIR signals are further pre-processed in a digital filter module to filter real-time fringe jumps [8] over the 14 FIR chords on TCV. Interferometer data is acquired at 200kHz and analyzed at 10kHz, selecting the best data for each packet of 20 data per chord by analyzing the phase and magnitude of the signal. Magnetic measurements are routed to RT-LIUQE [9] to reconstruct the plasma magnetic equilibrium and provide geometrical quantities for RAPDENS.

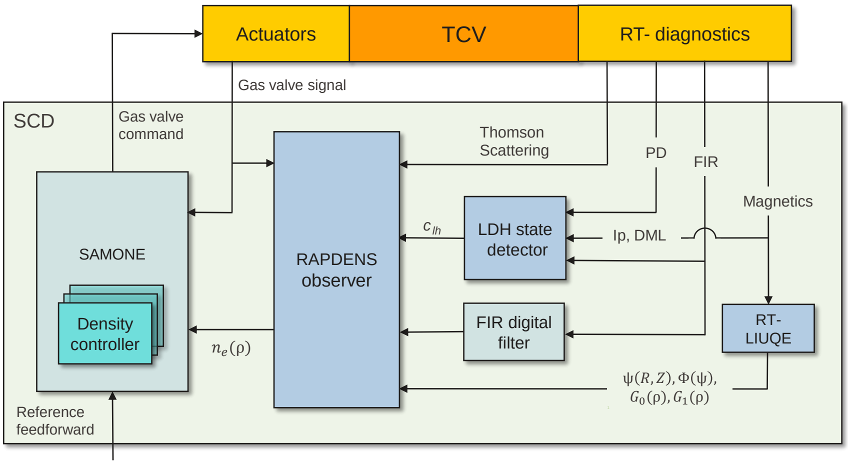


Figure 1: Schematic of the implementation of electron density observer inside the plasma control system of TCV.

The poloidal and toroidal magnetic flux, along with knowledge of the LCFS, enable mapping between the poloidal plane and normalized toroidal coordinates. Confinement state estimation of the plasma is achieved through the LDH state detector module [10]. This signal is employed to switch transport coefficients and parameters tuned for L-mode and H-mode phases of the discharge in the predictive step of RAPDENS. The reconstructed density profile is used in a feedback density controller to regulate gas valve flow rate to yield zero error between a reference target of the plasma density profile (e.g. core, averaged, or edge density) and the estimated profile. The gas valve command is provided by SAMONE [11], determining the controller references for available actuators in different discharge phases. The flow rate sensor signal is also provided to RAPDENS as an estimate for the fueling flux entering the machine.

Estimation of electron pinch velocity with TS data

One limitation of RAPDENS predictive model lies in the adoption of heuristically tuned transport coefficients, resulting in a limited accuracy in the computation of the density profile. This problem has been addressed in [12] by adopting gyro-bohm transport coefficients, using T_e profile provided by RAPTOR [13] in AUG discharges. We show here an alternative approach, leveraging the information provided by the TS data in the estimation of electron pinch velocity $\nu = \nu(\rho)$ transport coefficient. The estimated coefficient is computed and updated as a new TS point is available, retaining the spatial resolution of the density profile provided by the TS diagnostic. This procedure notably improves the reconstruction of the electron density at the edge.

Starting with the steady-state 1D flux-surface averaged electron density equation (see [2] for details):

$$-\frac{\partial}{\partial \rho}\left[V'\left(G_1 D \frac{\partial n_e}{\partial \rho} + G_0 \nu n_e\right)\right] = SV', \qquad B.C.: \frac{\partial n_e}{\partial \rho}(0,t) = 0, \quad n_e(\rho_e,t) = 0 \tag{1}$$

Integrating over ρ both sides, applying B.C.s and isolating ν leads to:

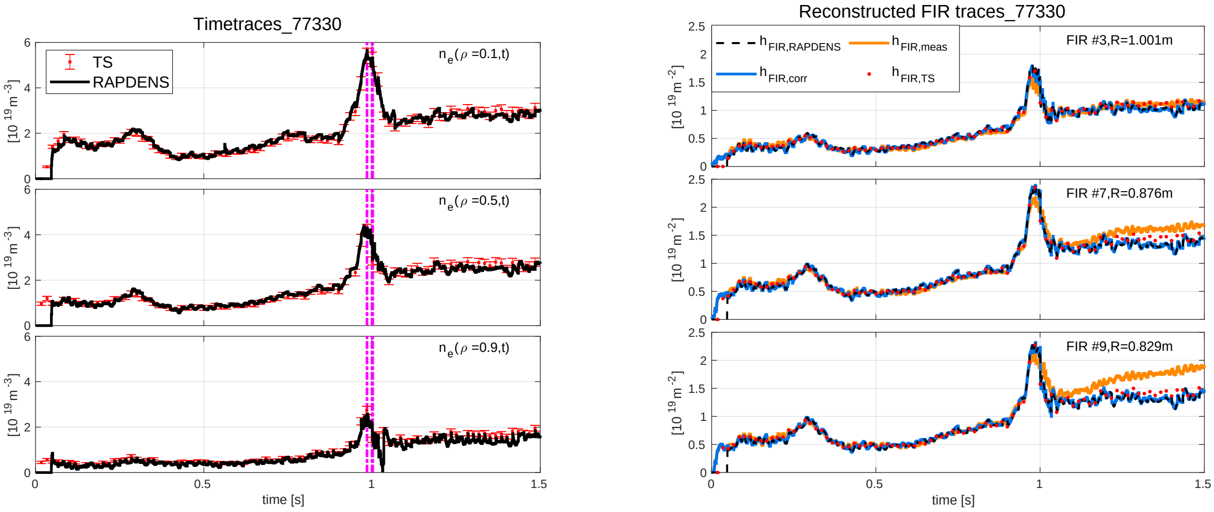
$$\nu = -D\frac{G_1}{G_0}\frac{1}{n_e}\frac{\partial n_e}{\partial \rho} - \frac{\hat{S}}{G_0 n_e}, \quad \hat{S} = \frac{1}{V'}\int_0^{\rho} SV' d\rho \tag{2}$$

In this work, the source term $\hat{S}$ of Eq.2 has been neglected for simplicity since the determination of the spatial distribution of the source term for gas is not accurate enough and NBI fueling deposition profile is not available in real time. The impact of the gas fueling term is small but measurable at the edge, as the main ionization source term is spatially localized inside the region

$\rho \geq 0.60$. Evaluation of NBI fueling rate, mainly localized in the core, has also to be assessed and included in the model.

Results: steady-state scenario on TCV, shot #77330

Steady-state scenarios on TCV are highly sensitive to n_e profile, being constrained on one side by the minimum density required to sustain the plasma in H-mode and on the other by the cutoff density of the X2 EC waves. The reconstruction of the electron density profile for TCV discharge #77330 is presented, using the scheme of Figure 1, executed offline for validation purposes. The discharge features a transient H-mode plasma with strong off-axis ECCD. H-mode in a non-inductive scenario has been achieved at t=0.95s, coupling 1.12MW of NBI power with 2.45MW of X2-ECH. At t=1.03s the plasma experiences a back transition to L-mode, with a consequent lowering of β_p [14]. The numerical result obtained by RAPDENS reconstruction is compared with the FIR and TS signals.



(a) Time traces of the density profile compared with TS data for different radial positions. Dashed lines in magenta represent the different time slices of Fig.3.

(b) Time traces of FIR raw (orange), corrected (cyan) and reconstructed (dashed black), compared with TS data expressed as line-integrated data (red dots).

Figure 2: Density time traces for TCV discharge #77330 reconstructed with RAPDENS.

Figure 3: Different time slices of the density profile using v_{TS} and an heuristically tuned v_0. The two pinch velocity profiles are compared in the first subplot. Predicted and corrected profiles are shown in solid and dashed lines. The decomposition of the profile in the different splines used in the numerical PDE solving scheme is shown in the last subplot in magenta. TS data for comparison: t=0.9843s for first two subplots, t=1.0003s for last two.

Time traces over different radial coordinates and FIR signals of three different chords are presented in Fig. 2a and Fig. 2b. The dynamical evolution of the reconstructed density profile