Fusion Engineering and Design 126 (2018) 87–103

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Control-oriented modeling of the plasma particle density in tokamaks and application to real-time density profile reconstruction

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ARTICLE INFO

Keywords:
Control-oriented modeling
Density profile evolution modeling
Density profile estimation
Real-time profile estimation
Dynamic state observer

ABSTRACT

A model-based approach to real-time reconstruction of the particle density profile in tokamak plasmas is presented, based on a dynamic state estimator. Traditionally, the density profile is reconstructed in real-time by solving an ill-conditioned inversion problem using a measurement at a single point in time. This approach is sensitive to diagnostics errors and failure. The inclusion of a dynamic model in a real-time estimation algorithm allows for reliable reconstruction despite diagnostic errors. Predictive simulations show that the model can reproduce the density evolution of discharges on TCV and ASDEX-Upgrade after tuning of a few parameters. Offline reconstructions using experimental data from TCV show accurate estimation of the density profile and show examples of fault detection of interferometry signals.

1. Introduction

A key challenge in tokamak operations is maintaining stable plasma conditions, remaining within safety limits and accurate control of the plasma state [1]. Plasma control has expanded in recent years from control of bulk plasma quantities (such as total plasma current, average particle density and average temperature) to control of the spatial distributions of these quantities, e.g. the profiles of temperature, safety factor and rotation [2–6].

Since the density profile affects the plasma pressure and fusion power [7], drives radiation, influences the non-inductive current distribution, determines diagnostics validity (e.g. ECE cut-off), and can trigger detrimental plasma instabilities [8,9], real-time monitoring and control of the particle density profile is of great importance for safe, reliable and high-performance operation of large tokamaks such as ITER [10–13].

An important challenge can be identified as to enable density control, namely the reliable real-time reconstruction of the density profile from diagnostic measurements. Most tokamaks have diagnostics for the plasma particle density that can be used for monitoring and real-time control. Often an interferometry system is used, which measures the line-integrated electron density along one or more laser chords intersecting the plasma [14,15], but other possibilities include Thomson scattering [14,16] and reflectometry [14,17].

In control and monitoring of the density, the line-averaged density is often considered, which is conveniently derived from an interferometry signal if the chord intersection length is known. Moreover, there exist data fitting methods for reconstruction of the density profile for analysis or control that minimize a least-squares criterium or fit splines on multiple interferometry channels [18–24] or Thomson scattering [25,26] at one point in time.

However, the estimates obtained by these static data fitting methods are sensitive to diagnostic faults [18,27], notably drifts. For example fringe jumps occur in an interferometry system if the density fluctuates rapidly, often when a pellet is injected. This may result in a loss of control performance or even a loss of density control.

Despite ongoing research on detection and correction of fringe jumps [19,27,28], no reliable solution is being used on TCV and ASDEX-Upgrade. Moreover, data fitting methods can suffer from ill-conditioning, leading to unrealistic profiles with spatial oscillations [18].

The inclusion of a dynamic model of the density profile evolution in the profile reconstruction may solve these issues by promoting proximity of the measured quantities to solutions that are feasible with

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[1] See Appendix of S. Coda et al., Proc. 26th IAEA Fusion Energy Conf. 2016, Kyoto, Japan.

https://doi.org/10.1016/j.fusengdes.2017.11.006
Received 27 January 2017; Received in revised form 15 September 2017; Accepted 7 November 2017
0920-3796/ © 2017 Published by Elsevier B.V.

respect to our knowledge of the modeled process. Thereby it can suppress unrealistic spatial oscillations in the profile estimate, reject measurement noise and anticipate for the effects of actuation, such as fuelling, on the density evolution.

For this purpose, we present a control-oriented model of the plasma particle density evolution. We prefer a white-box model-based approach over identifying models from data since nonlinear behaviour and physical couplings that evolve in time complicate identification of processes from measurement data. On the other hand, full first-principle physics modeling is challenging since

1. transport inside a tokamak plasma LCFS is modeled by the combination of a set of 1D PDEs for radial transport and a 2D elliptical PDE for the magnetic equilibrium (see [29,30]) which is difficult and time-consuming to solve in combination with calculation of the particle fluxes, and
2. transport outside the tokamak plasma LCFS consists of complex processes such as wall retention and recycling, neutral particle dynamics, and atomic and molecular processes (see [7,31]) which are all complex to model in themselves, let alone in their interaction.

Because of these complications, heuristic models are better suited for real-time applications in this case. We present a control-oriented and real-time nonlinear model for radial (1D) plasma density transport with additional particle inventories (0D) of the wall and vacuum. Compared to existing multi inventory (0D) models for density control [26,32–37], we replace the plasma particle inventory by the spatial distribution of the plasma density. Moreover, we include the influence of plasma equilibrium, temperature, current and operational modes (limited or diverted plasma, low or high confinement [7]) on the transport processes and diagnostics.

In this paper, we use for the first time a model-based dynamic state observer for density profile reconstruction. The observer, comprising of an Extended Kalman filter [38], provides both estimates of the density profile as well as reality vs. model deviations that persist over multiple confinement times from multiple diagnostics signals. Here we build upon earlier work in [39,40], where physics-model-based dynamic state observers have been applied for real-time estimation of the current and temperature profiles. In the observer, we employ a threshold method to detect fringe jumps [27], from the discrepancy between the measured interferometry signals and the model-based predictions of these measurements.

The proposed dynamic state observer algorithm can be implemented on control systems of existing tokamaks, and used for e.g. real-time density feedback control and/or deriving whether ECE channels are in cut-off in real-time. For future tokamaks as ITER, this model-based design procedure can be performed today with models extrapolated from existing tokamaks and iterated using the same methodology as density transport parameters become better known in the course of ITER operation. We want to emphasize that the purpose of this paper is not to make statements on the physics of density evolution in tokamaks. Instead, the objective is to demonstrate that a control-oriented model can be used to enhance real-time reconstruction of the density profile.

The remainder of this paper is structured as follows. The control-oriented model of the density transport and synthetic interferometer model is introduced in Section 2, along with simulations of a TCV and an ASDEX-Upgrade discharge. The design of the observer, the detection of fringe jumps and the offline estimation results on experimental data are discussed in Section 3. Extensions and future work that is in line with the proposed solutions are discussed in Section 4. Finally, concluding remarks are given in Section 5.

2. Control-oriented 0 + 1D model of the particle transport

In this section, a 0D + 1D diffusion/drift transport model is presented for control purposes, with the flexibility to adapt for multiple devices, multiple diagnostics and multiple actuators. Particle transport in the plasma, particle flows and sources in the tokamak are modeled in a heuristic fashion, rather than using complex first-principle transport models.

Existing physics models of plasma particle transport (e.g. [41,42]) and models used in offline profile reconstruction algorithms (e.g. ASTRA [30], CRONOS [43]) are not directly suitable for the task of real-time density reconstruction, since their execution time generally exceeds the discharge duration. It has been shown in [2–5,39,40] that low-complexity 1D models can be used for reconstruction and control of the temperature and safety factor profiles.

Our model consists of a 1D drift-diffusion PDE for radial particle transport and two 0D ODEs for the time evolution of the inventory of the wall and the neutral vacuum, all based on particle conservation laws. This approach is similar to multi inventory (0D) models for controller design on TCV [34], JET [35], TEXT [33] and KSTAR [36], but here the radial particle transport in the plasma is also modeled. Since transport on flux surfaces is several orders of magnitude faster than radial transport (perpendicular to flux surfaces), we may consider radial plasma transport only [29]. The ionization, recombination and recycling terms are approximated, and the NBI and pellet injection deposition locations are postulated. See Fig. 1 for a schematic representation of the modeled transport flows considered in this model.

The particle transport processes change in time due to a variety of physical factors. The LCFS electron temperature $T_{\mathrm{e,b}} = T_{\mathrm{e}}|_{\rho=1}$, electrical current I_{p}, plasma geometry through 2D equilibrium $\psi(R, Z)$ and distinct operational regimes (limited or diverted plasma $c_{\mathrm{D}} \in \{0, 1\}$, low or high confinement mode $c_{\mathrm{H}} \in \{0, 1\}$) are included in the model as a time-varying external input parameter. It is assumed that estimates of these parameter values are available through real-time 2D equilibrium reconstruction and other diagnostics.

The PDE is discretized in space and the resulting set of ODEs is then discretized in time. The relation between plasma density and measured quantities is included using diagnostics models.

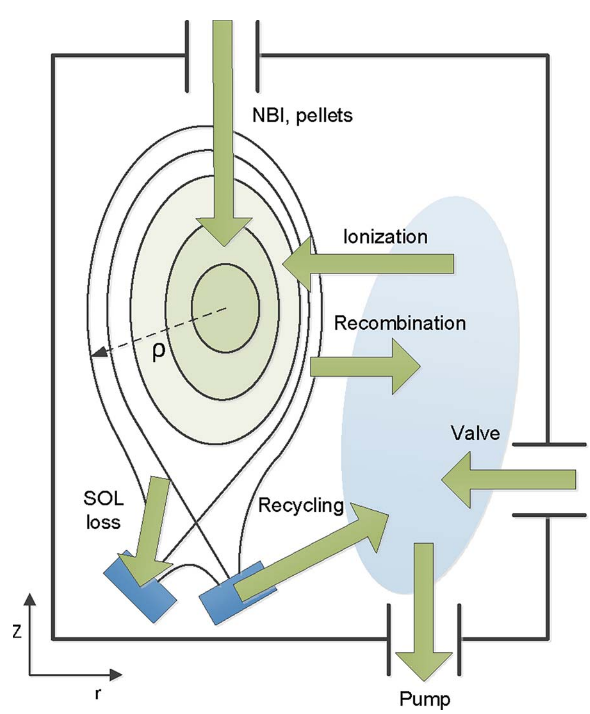

Fig. 1. Schematic representation of the tokamak cross-section in the *R-Z* plane. Depicted are the plasma, the wall components, the neutral vacuum and the modeled particle flows.

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