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Identification of a dynamic model of plasma current density profiles

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Introduction

Advanced tokamak scenarios ([1],[2]) can be achieved generating an internal transport barrier (ITB [3]) in the plasma core. One of the main mechanisms which enables the ITB formation is the modification of the current profile using the additional heating and current drive actuators (NBI, LHCD and ICRH). The ITBs formation and sustainment are strongly linked with the safety factor and magnetic shear profiles ([3],[4]), consequently it is necessary to control both the pressure and the current profiles, acting on the additional heating systems with a feedback controller. The design of such a controller relies on the estimation of a suitable model. This paper introduces a dynamic nonlinear model for the plasma current profile. First an overview of the overall model structure will be given. The identification procedure for both the driven and bootstrap current profiles blocks will be shown in the third section. These blocks have been identified using data from several JETTO ([5]) simulations. Eventually a comparison between the model outputs and the JETTO simulations will be carried out.

Model architecture

Model identification can be pursued following different approaches. A common classification (see [6]) is based on whether the model is derived from first principles (*white box* model) or from experimental data (*black box* model). For this work the *grey box* approach has been used, i.e. a combination of the latest two, where both the knowledge from the first principles and from other sources, such as simulations outputs or experimental measurements, can be used to obtain the desired model.

Several assumptions on the physics of the process have been done and the full experimental system has been analyzed in a number of actual blocks. The overall model results from the interconnection of all these blocks. In Figure 1 a block diagram of the proposed model is shown: the red arrows refer to profiles, while the blue ones refer to time traces. The inputs of the model are the additional heating powers, while the output is the plasma current density profile, or, equivalently, the q-profile. The black arrows are used to model auxiliary non manipulable inputs that will affect the output behaviour (for example the electron temperature and density for the LHCD driven current).

Each block will be identified separately using experimental data, when possible, or data from transport code simulations. For example, the identification of the three current sources has been carried out only with data from JETTO simulations (see next sections). In the future the kinetic blocks will be identified using both simulated and experimental data. The final tuning of the overall system will be performed with the experimental data and using the q-profile as output.

All the blocks in Figure 1 are supposed to be nonlinear. It is worth to notice that the models

*See Appendix of J. Pamela et al., Fusion Energy 2004 (Proc. 20*th* Int. Conf. Vilamoura, 2004) IAEA, Vienna (2004)

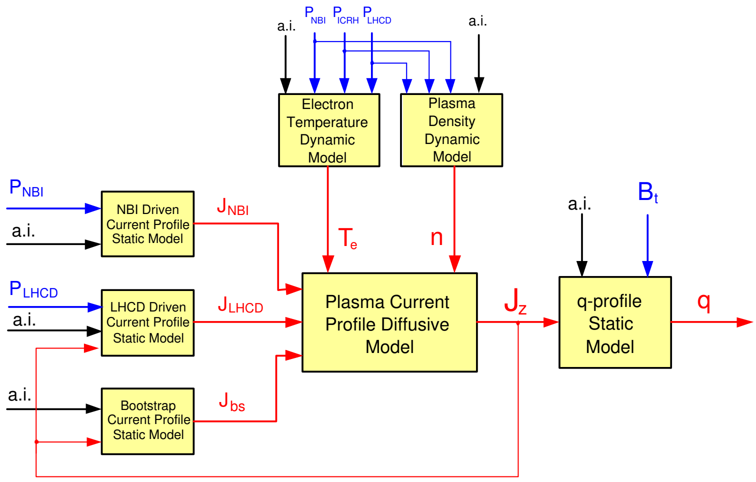

Figure 1: Model block diagram

for the driven and bootstrap currents are assumed to be instantaneous, while the density and temperatures blocks are assumed to be dynamic. Once all the blocks in the scheme of Figure 1 are identified for a given shot, the model can be linearized via numerical computation around a given equilibrium point and, eventually, it could be suitable for the design of a controller.
The modular approach presented in this paper differs from the one recently used at JET to design a real-time profiles controller ([7],[8]), where a single *grey box* linear model has been used to identify the overall system.

Driven and bootstrap current blocks

This section gives an outline of the identification procedure used to derive the driven and bootstrap currents blocks from the outputs of transport code simulations. These blocks are supposed to be static and nonlinear and they have the generic structure depicted in Figure 2, where the J_x output is the generic current source and the P_{AH} input is the generic additional heating power. One or more non manipulable inputs can be added to the model. Since these models work with profiles, the *principal component analysis* (PCA, [6]) tool has been used to reduce the output space dimensionality, that is the identification is performed only for the most important principal components (PCs) of the outputs. The transformation matrix $T_{J_x}^{-1}$ is used to return to the profile variables space. For example to describe the NBI current profile at 17 different radii with up to 95% of accuracy only 2 PCs are needed, while to model the bootstrap current with the same accuracy 3 or 4 PCs are needed. Modelling the LHCD current at 12 different points with the same accuracy requires much more information: between 7 and 10 PCs are needed. There are no benefits, indeed, in terms of reduction of the output space dimension. In this case a different approach should be employed. It should be remarked that the PCA has been applied also to all the auxiliary inputs which are profiles.
For the generic current profile J_x, a polynomial relationship has been assumed:

$$\begin{bmatrix} \widetilde{J}_{x_1} \\ \widetilde{J}_{x_2} \\ \vdots \\ \widetilde{J}_{x_m} \end{bmatrix} = \begin{bmatrix} c_1^T \\ c_2^T \\ \vdots \\ c_m^T \end{bmatrix} \begin{bmatrix} 1 & P_{AH} & \dots & P_{AH}^n & ai_1 & \dots & ai_1^n & \dots & ai_l & \dots & ai_l^n \end{bmatrix}^T \qquad (1)$$

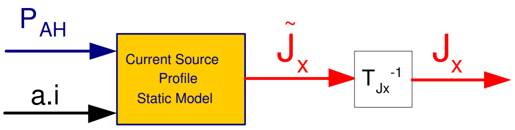

Figure 2: Generic current source block

where m is the number of PCs for the current, n is the polynomial order of the model, ai_j is the j-th auxiliary input and c_i^T is the row vector of the polynomial coefficients for the i-th output. It follows that the current profile vector is given by:

$$J_x = T_{J_x}^{-1} \cdot \widetilde{J}_x \tag{2}$$

The following models have been used to carry out the results showed in the next section:

$$\begin{aligned}
\widetilde{J}_{NBI_j} &= \begin{bmatrix} 1 & P_{NBI} & P_{NBI}^2 & \widetilde{p}_1 & \widetilde{p}_1^2 & \dots & \widetilde{p}_{k_1} & \widetilde{p}_{k_1}^2 & \widetilde{\nabla p}_1 & \widetilde{\nabla p}_1^2 & \dots & \widetilde{\nabla p}_{k_2} & \widetilde{\nabla p}_{k_2}^2 \end{bmatrix} c_j \\
\widetilde{J}_{LHCD_j} &= \begin{bmatrix} 1 & P_{LHCD} & P_{LHCD}^2 & \widetilde{T}_{e_1} & \widetilde{T}_{e_1}^2 & \dots & \widetilde{T}_{e_{k_3}} & \widetilde{T}_{e_{k_3}}^2 & \widetilde{n}_1 & \widetilde{n}_1^2 & \dots & \widetilde{n}_{k_4} & \widetilde{n}_{k_4}^2 & \widetilde{J}_{z_1} & \widetilde{J}_{z_1}^2 & \dots & \widetilde{J}_{z_{k_5}} & \widetilde{J}_{z_{k_5}}^2 \end{bmatrix} c_j \\
\widetilde{J}_{bs_j} &= \begin{bmatrix} 1 & \widetilde{p}_1 & \widetilde{p}_1^2 & \dots & \widetilde{p}_{k_1} & \widetilde{p}_{k_1}^2 & \widetilde{\nabla p}_1 & \widetilde{\nabla p}_1^2 & \dots & \widetilde{\nabla p}_{k_2} & \widetilde{\nabla p}_{k_2}^2 & \widetilde{J}_{z_1} & \widetilde{J}_{z_1}^2 & \dots & \widetilde{J}_{z_{k_5}} & \widetilde{J}_{z_{k_5}}^2 \end{bmatrix} c_j
\end{aligned} \tag{3}$$

where $\widetilde{p}_i$, $\widetilde{\nabla p}_i$, $\widetilde{T}_{e_i}$, $\widetilde{n}_i$ and $\widetilde{J}_{z_i}$ are respectively the k_1, k_2, k_3 k_4 and k_5 PCs of p, ∇p, T_e, n and J_z profiles.

Simulation results

The estimation of the polynomial coefficients c_i has been carried out using data from JETTO simulations of actual JET ITB experiments. For each pulse a set of slightly different JETTO runs have been performed in order to evaluate the effect of all the inputs on the output current profile. Once the models have been identified, they have been validated with the outputs of a JETTO run that uses the experimental values for the additional heating powers. All the JETTO simulations have been performed in fully predictive mode. Figure 3 shows a comparison between the JETTO simulations and the proposed models outputs for JET pulses 58474, 62160 and 62527. Both time traces (3(a), 3(b) and 3(c)) at different radii (ρ is the normalized toroidal flux), and current profiles (3(d)) at different time samples are shown.

Conclusion

In this paper a grey-box approach has been used to identify a nonlinear model for the plasma current diffusion. Both the model structure and the preliminary results for the current sources blocks have been shown.

The knowledge from the first principles has been used to analyze the model structure into several blocks, while the identification of each single block will be performed with data either from experiments or from transport code simulations.

A polynomial model has been assumed for all the currents sources, which is easily linearizable, and the identification has been performed only with data from JETTO simulations.

Further developments are needed to obtain a reliable model that can be used for the design of a current profile controller. First the identification of both the kinetic and the plasma current diffusive models has to be done. The validation of the whole model should be performed using experimental data.

Acknowledgements

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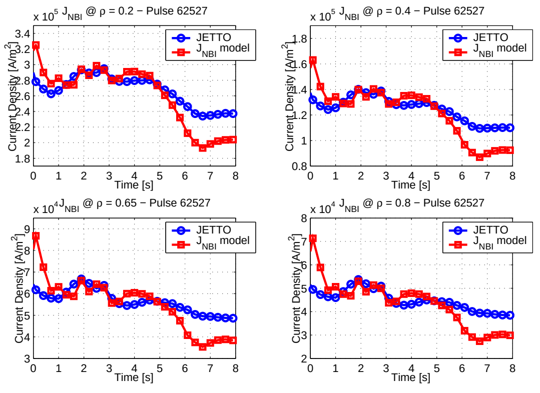
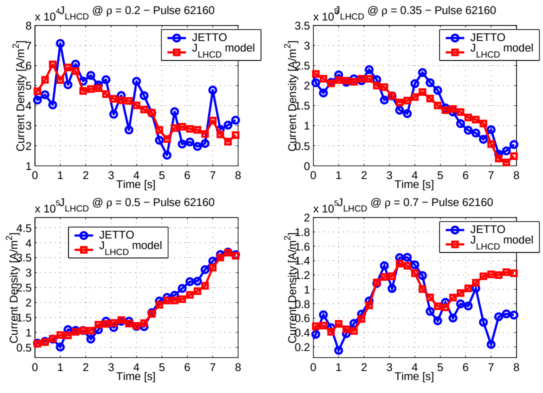
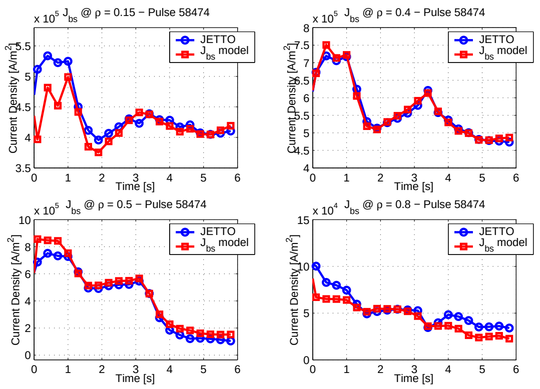


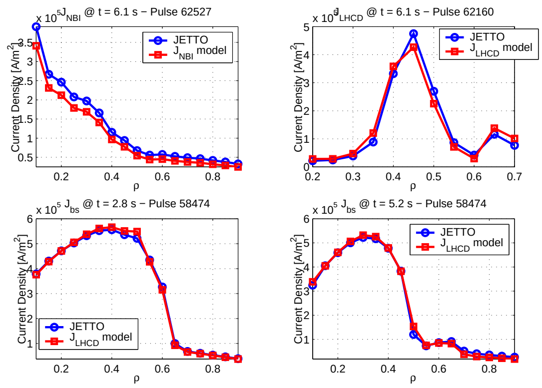
(a) NBI current drive at $\rho = 0.2, 0.4, 0.65, 0.8$ for pulse 62527



(b) LHCD current drive at $\rho = 0.2, 0.35, 0.5, 0.7$ for pulse 62160



(c) Bootstrap current at $\rho = 0.15, 0.4, 0.5, 0.8$ for pulse 58474



(d) Current profiles at different time samples

Figure 3: Simulations results

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