Automated comparison of profile reconstruction from measurements with integrated models

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I. Introduction

As tokamak experiments produce large quantities of data (50 Gbytes of data per second is expected for an ITER pulse), one requires an automated processing to systematically analyze these data. Physicists are usually interested in computing a number of plasma physical quantities from the experimental data and this is done by a so called chain of codes for plasma reconstruction. What is done quite rarely is a systematic comparison of the results obtained from experimental data to the ones produced by physics models verified for other shots (and possibly tokamaks).

Such comparison may validate our models in case of good agreement or may help to find discrepancies between experiment and models and indicate the source of discrepancies: whether it is a "data validation" problem, i.e. models do not describe correctly the physics (possibly because of interesting new phenomena), or it is a reconstruction problem, i.e. the experimental data is inconsistent (uncalibrated, falsie, etc.).

To implement these functionalities, we developed an expert system carrying out in an integrated way:

1. The Plasma Reconstruction from the measurements, using Bayesian methods
2. The prediction of the reconstructed quantities, according to validated expectations / models
3. An intelligent comparison of the first two steps providing an automated analysis and reporting on events of physical interest during the pulse

The novelty of the overall method lies in the development of relevant comparison criteria between predicted and reconstructed quantities, allowing the automation of the physical analysis. Although the method has been primarily designed for experimental data analysis and validation, it can also reciprocally be used for model validation.

We present here application of the developed expert system to three different use cases.

- **validation of density profile peaking models**

The first use case consists in reconstructing the electron density profile from measurements and in comparing it to models predicting its peaking factor. The analysis was performed for 20 Tore Supra and 14 JET L-mode shots for one time slice per shot. Two different empirical models for predicting the density profile peaking have been evaluated.

- **temperature profile reconstruction and validation of heat transport models**

The second use case extends the first one to electron temperature profile reconstruction and validation of a heat transport model. 21 Tore Supra and 14 JET shots were analysed, but this time a time dependent transport analysis is carried out after automated reconstruction of temperature profiles on several time slices. Both are compared in order to determine the domain of validity of the heat transport model used.

- **quantification of uncertainty on current diffusion**

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* *See the Appendix of F. Romanelli et al., Proceedings of the 24th IAEA Fusion Energy Conference 2012, San Diego, USA*

The third use case is the quantification of how the uncertainties on the electron and ion temperatures and densities reconstruction impact predictions of current diffusion. The analysis is carried out systematically for the whole pulse. The profiles corresponding respectively to the mean and highest probability density interval profiles obtained using Bayesian methods are used as input to an integrated simulation code to calculate current diffusion. The application was demonstrated for one Tore Supra and one JET pulse.

In the next chapter we will shortly present the code we were using for the prediction of plasma profiles and calculation of current diffusion. In the chapter III we shall present the results and in the chapter IV derive some conclusions.

II. The METIS code

Integrated Modelling is a powerful tool for prediction and model validation and has the advantage of enforcing the consistency of the simulated parameters, a common point with Bayesian analysis. Moreover it allows estimating quantities that are difficult to measure directly, while they may be input to some models, e.g. the safety factor. Therefore we use METIS (Artaud, METIS User's Guide, 2008), a fast integrated modeling transport code. The speed and robustness of this simplified integrated modeling tool are key advantages in view of automated analysis of a large amount of data.
In this work, METIS was used in the following conditions: i) current diffusion is predicted ii) electron and ion temperatures are predicted from the heat transport equations, using a simple diffusion coefficient model with fixed radial shape and renormalized to an L-mode scaling iii) the electron density is calculated as follows.

III. Results

a. Validation of density profile peaking models

In this first application our aim was to validate two density peaking models. The first model assumes a dependence of the peaking factor on ratio between saturation density over average density (Becker, 1990) (Wagner & al., 1993). The second model assumes a linear dependence of the peaking factor on internal self-inductance (Weisen & al., 2005). Comparison criteria have been defined to allow, when a deviation with respect to the model prediction occurs, to discriminate between problems in the experimental data and limits of validity of the models. The method provides here essentially a way to do systematic model validation on an experimental dataset. The first model was giving very good results on the Tore Supra dataset (93% of success), while was less successful on the JET dataset (33% of success). The second model shows marginal agreements on both datasets (7% and 43% of success for Tore Supra and JET respectively). The summary of the analysis for JET and Tore Supra data is presented in the Table 1.

	Model 1 $\boldsymbol{\nu_n(t) = 0.5 \cdot \frac{n_{sat}}{\bar{n}}}$	Model 2 $\boldsymbol{\nu_n(t) = \frac{4}{3} \cdot l_i - \frac{3}{4}}$
Tore Supra		
Number of shots	20	20
Reconstruction issues	*5*	*5*
Simulation issues	*1*	*14*
Acceptable fit	*14*	*1*
Model 1 is appropriate for Tore Supra database (93% success) Model 2 is not appropriate (7% success)		

JET		
Number of shots	14	14
Reconstruction issues	*2*	*2*
Simulation issues	*8*	*7*
Acceptable fit	*4*	*5*
Both models show marginal agreement (33% and 42% success respectively)		

Table 1: Summary of the validation of two density peaking models.

b. Temperature profile reconstruction and validation of heat transport models

The heat transport model in METIS consists of two main parts (Artaud, METIS User's Guide, 2008). The first one is solving a simple 0D equation for the plasma thermal energy content while the second part is solving a 1D time independent transport equation for the electron and ion temperature profiles. There are three options for diffusion coefficients (which are included in the second part) depending on the shape scale factor K_E. If K_E equals 3 then ITER-like dependence is used (ITER), if it equals 0, then Bohm-gyro-Bohm model like dependence on plasma parameters for the diffusion coefficient is used, and in case of K_E =-1.5, the diffusion coefficient is proportional to the safety factor in the power of $|K_E|$. We derived comparison criteria to classify the agreement between reconstructed profiles and the METIS model predictions. The summary of the analysis for three possible K_E choices for JET and Tore Supra data is presented in the Table 2.

Tokamak	**Agreement**	**K_E**		
		3	**0**	**-1.5**
Tore Supra	Acceptable	4	1	0
	Not acceptable	17	20	21
Total		***21***	***21***	***21***
JET	Acceptable	2	1	1
	Not acceptable	12	13	13
Total		***14***	***14***	***14***

Table 2: Summary table on results of the automated comparison for Tore Supra and JET databases with three METIS runs: with K_E equals to 3, 0, and -1.5.

c. Quantification of uncertainty on current diffusion

The current diffusion model is the same as was implemented in CRONOS 1.5D code (Artaud & al., The CRONOS suite of codes for integrated tokamak modelling, 2010) (Hinton & al., 1976). It solves an equation for the poloidal flux Ψ on a uniform toroidal flux coordinate ρ grid. We used the to the mean and highest probability density interval profiles as input to the METIS model to calculate poloidal flux. The comparison of the obtained results to the experimental results for one Tore Supra and one JET shot is shown on Figure 1.

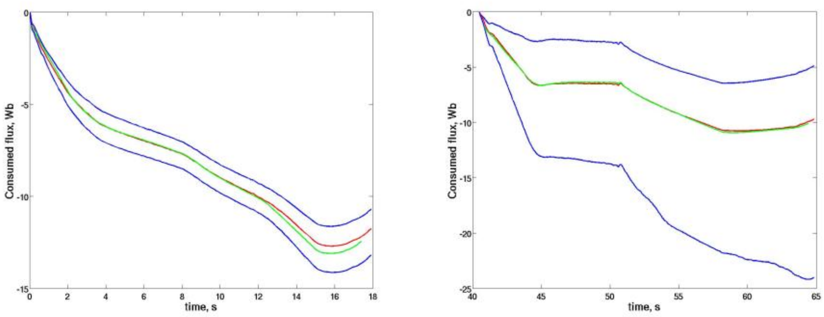

Figure 1: Consumed poloidal flux comparison for the Tore Supra shot #47658 (left) and JET shot #75225 (right). *The flux in W is plotted against the time in seconds. The blue lines shows the results of the METIS run with HPD interval profiles as an input; the red line is the result of the METIS run with the mean profiles as an input. The greed line is the experimental measurements. Note that the offset poloidal flux consumption is unknown thus it was determined as the difference between the mean METIS run and experimental trend in the middle of the shot*

IV. Conclusions

The present work was devoted to developing an expert system discussed in the Introduction. Three applications of the developed system were shown. Such system provides simultaneous validation of experimental data and model validation, with a qualification and quantification of the agreement between a model and the reconstructed profiles from measurements. It provides also statistics of the agreement quality, thus contributing to establish the domain of validity of a given model. The first application of the method was carried out for two density peaking factor models in the METIS simulation code. The analysis showed that the first model that assumes dependence of peaking factor on the ration between saturation density and average density works quite well for Tore Supra data (93 % of acceptable agreement) while for JET data both models show marginal agreement (below 50 % of acceptable agreement). No dependence of peaking factor on internal self-inductance was observed for Tore Supra data and the second model (internal inductance dependence) is clearly not adequate for this dataset. The second application was devoted to the validation of heat transport models. It showed that all the models show marginal agreement for both Tore Supra and JET. The third application concerned quantification of uncertainty in current diffusion and showed an excellent agreement of consumed poloidal flux calculated using the reconstructed profiles to the experiment. The implementation of the methods is tokamak-generic as was performed using the ITM-TF Framework.
In the future we would like to extend the automated comparison method, which is quite generic, to other applications. From a technical and operational point of view, a systematic application of the method to the full duration of a pulse requires parallelization of the analysis over many time slices and needs to be implemented in the future.

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