Development of the RAPTOR suite of codes towards real-time reconstruction of JET discharges

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The RAPTOR suite of codes combines real-time model-based predictions of the plasma state with the available diagnostic measurements. Following the work on TCV and ASDEX-Upgrade, this paper presents the implementation of the RAPTOR suite for JET. This suite embeds: the upgraded equilibrium reconstruction EQUINOX code, the new FLUXMAP algorithm, which maps the diagnostic measurements from geometric to normalized magnetic flux coordinates; the RABBIT code for the NBI reconstruction and eventually RAPTOR state observer, which combines the output from all these codes with the predictions of 1D control-oriented transport code. The suite is both implemented in MATLAB/Simulink® and it is being integrated in the C++ real-time MARTe2 framework. Thanks to its user-friendly interfaces, which are based on the MDSplus I/O and visualization tools, the RAPTOR suite can be used both offline, for a fast reconstruction of the plasma state, and in integrated control algorithms once it will be deployed in the JET real-time data network.

Keywords: tokamak, JET, real-time integrated control, RAPTOR, MARTe2

1. Introduction

A well-coordinated control of plasma profiles and key integrated quantities allows to access a desired plasma scenario and to maintain its stationarity. This feature is crucial for the future fusion reactors, but also for present experiments whose pulse budget is constrained by hard operational limits, like the neutron production or the Tritium inventory. A promising strategy to tackle this challenge is to combine a suite of control-oriented integrated modeling codes with the available diagnostic measurements. Work in this direction has been undertaken in the past using the RAPTOR code coupled to various other codes on TCV [1] and ASDEX-Upgrade [2] tokamaks, opening a wide range of possible applications, among these the kinetic equilibrium reconstruction [3], the fast modelling of turbulent transport [4] or the real-time actuator management for multi-task integrated control [5]. This paper presents the implementation of the RAPTOR suite of codes for the JET tokamak.

2. The RAPTOR suite

The RAPTOR suite on JET, which is sketched in Fig. 1, integrates the following real-time codes: an upgraded version of the equilibrium reconstruction EQUINOX code [6, 7], the new FLUXMAP re-mapping algorithm, the NBI deposition reconstruction RABBIT code [8-10] and RAPTOR state observer [1], which combines the output from all these codes with a 1D control-oriented transport model [15] and the available diagnostic data. In this work the integration with the MARTe2 [11] and MDSplus [12] framework are also presented. A concise overview of all these codes will be provided in the following.

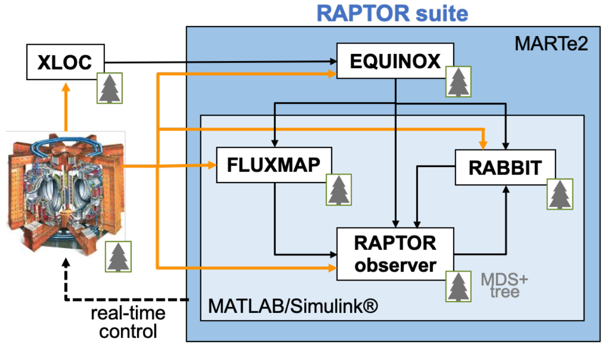

Fig. 1. Schematic of the RAPTOR suite of codes on JET with diagnostic (orange line) and modelled (black line) data flow.

2.1 EQUINOX

The equilibrium reconstruction EQUINOX code [6] is capable of estimating the major plasma magnetic parameters by identifying the source term of the non-linear Grad-Shafranov equation, through a least-square

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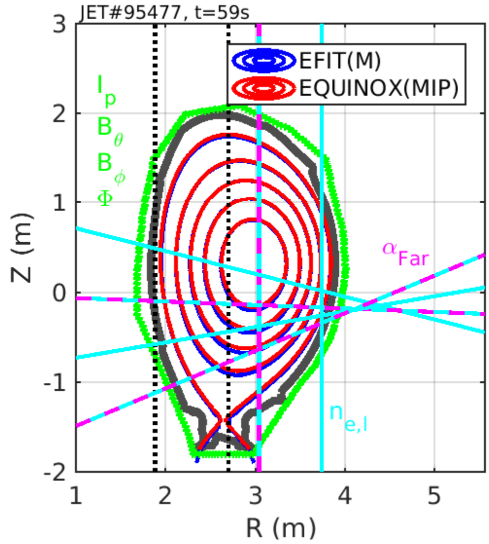

Fig. 2. Poloidal magnetic flux surfaces from EQUINOX (in red) using magnetic (in green), interferometry (in cyan) and polarimetry (in magenta) data compared to the EFIT reconstruction (in blue) using magnetic data only.

minimization of the difference between diagnostic measurements and the simulated ones. In this work, the EQUINOX equilibrium reconstruction is constrained with magnetic, interferometric and polarimetric measurements. These are sketched in Figure 2 in green, cyan and magenta, respectively. The magnetic data are pre-processed by the real-time XLOC boundary code [13], which provides the total plasma current, the poloidal and toroidal magnetic field and flux values on the first wall of the vacuum vessel. Compared to the version described in [7], the accuracy of the magnetic boundary reconstruction has been here improved by increasing the boundary points from 67 to 216. The equilibrium is further constrained with the measurements of the line integrated density ($n_{e,l}$), from 6 chords of the interferometer, and of the Faraday angle (α_{Far}), from 3 chords of the polarimeter. The chord that intersects the plasma private flux region and the inner most one (black dotted lines) have been discarded due to the low accuracy of the measurement and the marginal intersection with the plasma separatrix, respectively. The interferometric measurements are also inverted in real-time to provide an estimate of the plasma density profile. Additionally, new surface and volume integrated quantities, which are required by the other codes of the suite, are now evaluated and can be deployed in real-time. Figure 2 compares the poloidal magnetic flux surface reconstruction from EQUINOX (in red) and from EFIT (in blue, using magnetic data only) in a lower single null JET plasma at $I_p = 1.85$ MA, $B_\Phi = 2.15$ T, Greenwald density fraction $f_{GW} = 0.75$ and heated with 7.5 MW of NBI power. All the figures of this work refer to this pulse.

2.2 FLUXMAP

This new algorithm has been developed to map the diagnostic measurements from the geometrical to both poloidal (ρ_θ) and toroidal (ρ_Φ) normalized magnetic flux coordinates, on the basis of the real-time EQUINOX equilibrium reconstruction. This tool is also capable of mapping in real-time the Electron Cyclotron Emission (ECE) cold resonance locations from the (R, Z) to the flux coordinates. In the offline version of the suite that is presented in this work, FLUXMAP is used to re-map the electron temperature (T_e) and density (n_e) profiles from the High Resolution Thomson Scattering (HRTS) and the LIght Detection And Ranging (LIDAR) diagnostics. The latter has been included as an additional diagnostic for code validation. Figure 3 shows the re-mapped diagnostic profiles (blue empty symbols) together with data from RAPTOR suite (red squares) and TRANSP [14] (green line) simulations.

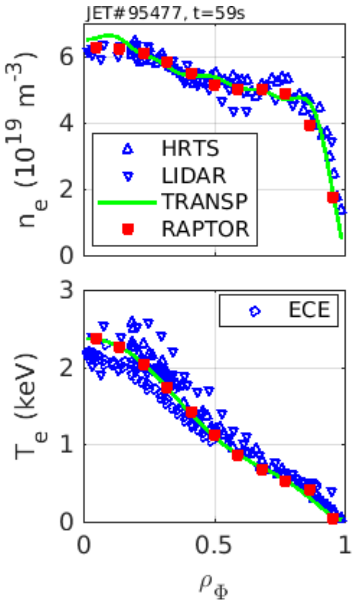

Fig. 3. Electron density and temperature profiles from the HRTS, LIDAR and ECE diagnostics (blue symbols) compared with TRANSP (green) and RAPTOR suite (red squares) data.

2.3 RABBIT

The RABBIT code evaluates the Neutral Beam (NB) heating, current drive, Fast Ion (FI) distribution [8] and the neutron emission [9]. Despite of being real-time compliant, it has been successfully benchmarked against NUBEAM on ASDEX-Upgrade, where it has also been installed in the Discharge Control System (DCS) [10]. The integration on the real-time Distributed Control System (SCD) of TCV is also on-going. In this work, the code has been embedded in the RAPTOR suite to model the two JET banks of 8 Positive Ion Neutral beam Injectors (PINIs). The NB injection is modelled on the basis of the magnetic equilibrium and the plasma profiles that are provided by EQUINOX and RAPTOR state observer (see Section 2.4), respectively. Figure 4 shows the comparison between TRANSP using NUBEAM (in green) and RAPTOR suite using RABBIT (in red) of (from the top) the NB heating deposition on ions and thermal FIs, on electrons, the NB current fraction, the FI density and the neutron rate emission.

2.4 RAPTOR observer

The RApid Plasma Transport simulatOR (RAPTOR) state observer code [1] is a real-time control-oriented

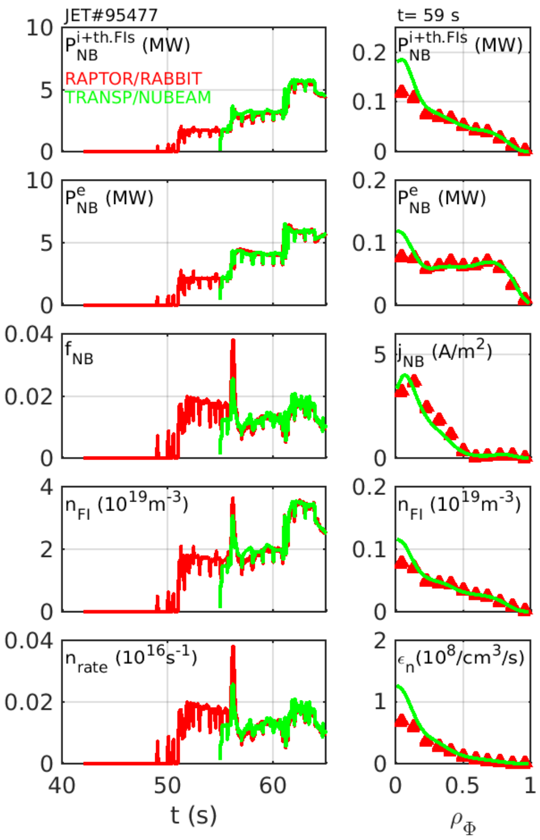

Fig. 4. Comparison of the NBI reconstruction from RAPTOR suite using RABBIT (in red) and TRANSP using NUBEAM. Time evolution and the corresponding profiles at t= 59s of (from the top) the NBI heating power deposited on ions and thermal FIs, the one deposited on electrons, the NB current fraction, the FI density and the neutron rate.

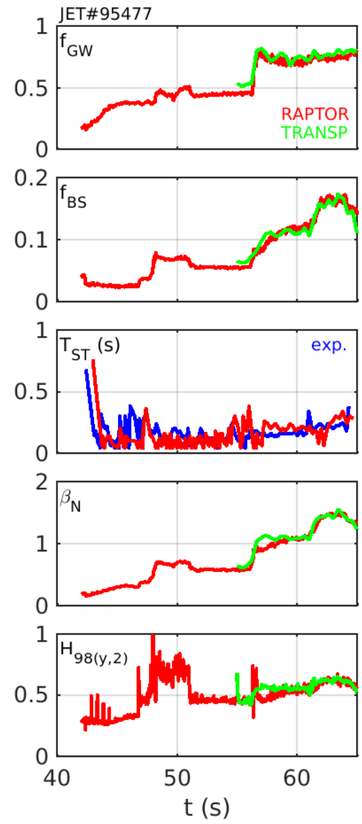

Fig. 5. Time evolution of (from top) the Greenwald density fraction, the Bootstrap current fraction, the sawtooth period, the normalized beta and the confinement factor H98(y,2) from the RAPTOR suite (in red), compared to TRANSP (in green) and experimental data (in blue).

plasma profile simulator, which combines the model-based predictions of the 1D transport code RAPTOR [15] with the available real-time diagnostic measurements, through an extended Kalman-filter algorithm [16]. This code is installed in the real-time SCD on TCV, on the DCS in ASDEX-Upgrade [3] and in MARTe on RFX-mod [17]. The version of the RAPTOR state observer presented in this work solves the coupled non-linear partial differential equations describing the diffusion of the poloidal magnetic flux and the electron energy transport, using time varying boundary conditions. The predicted T_e profile is the "observed" quantity that the Kalman filter corrects on the basis of the ECE (in real-time simulations) and HRTS diagnostic measurements. The code inputs are the real-time EQUINOX equilibria, the RABBIT NBI reconstruction, the Ion Cyclotron Resonance Heating (ICRH) power waveforms, whose deposition is approximated with a simple gaussian model, and the re-mapped T_e and n_e diagnostic profiles. The electron transport is predicted by RAPTOR using the Bohm-GyroBohm model. In the simulation shown in this work we assumed $T_e = T_i$, in presence of ICRH T_i can be rescaled appropriately. Both the timing of the L/H-mode transition and the T_e pedestal gradient are prescribed. The latter is inferred from a heuristic scaling of the plasma current. The plasma conductivity and the bootstrap current are calculated using analytical formulas from neoclassical calculations [18]. The sawtooth instability is modelled using the Porcelli's crash criterion and the Kadomtsev's full reconnection model [17]- Impurity transport is not modelled but its effect on the electron transport is indirectly taken into account by the filter correction of the predicted T_e profile. The plasma state is modelled on a ρ_Φ grid of 11 points, which is the optimal compromise between accuracy and real-time performance. The time resolution of the RAPTOR suite simulations that are shown in this work is 20 ms. Figure 5 compares the time evolution of (from the top) the Greenwald's density fraction, the Bootstrap current fraction, the sawtooth period, the normalized beta and the confinement $H_{98(y,2)}$ factor from the RAPTOR suite (in red), with TRANSP (in green) and experimental data (from the core ECE, in blue).

3 The integration in the MARTe2 framework

The RAPTOR suite is implemented in Matlab/Simulink®. Besides offering an user-friendly computing environment for fast offline simulations, the Simulink Coder™ toolbox allows the automatic generation of the C/C++ code optimized for the real-time execution. The integration in the real-time MARTe2 framework is being carried out in collaboration with the whole developer community of this framework. Quality-compliant wrapper GAMs (Generic Application Modules) [11] are being developed to introspect the generated code and to automatically interface the data I/O within the real-time framework.

3.1 The MDSplus tools

The data storage and visualization in both real-time and offline simulations of the RAPTOR suite are handled using the MDSplus software [12]. A self-consistent set of I/O parameters and signals for each code of the suite is stored in linked MDSplus trees. Metadata are available for each tree entry, these include a tag, i.e. a short univocal textual identifier, a concise description of the parameter or signal, physical units and a time-dependent flag signal that quantifies the quality (“bad”, “unknown”, “good”) of the data output. Furthermore, Python scripts have been developed for the automatic generation of the tree models and the configuration files of the MDSplus visualization tool jScope from user-defined .cvs or MARTe2 configuration files. When the suite is executed in the MARTe2 framework, online data streaming and visualization (using jScope or a browser) are available for all the output signals, including those to monitor the real-time execution performance.

4 Conclusions

The RAPTOR suite has been developed for JET to combine real-time model-based reconstructions of the plasma state with the available diagnostic measurements. The suite includes the following codes: an upgraded version of the equilibrium reconstruction EQUINOX code, the new FLUXMAP re-mapping algorithm, the NBI reconstruction code RABBIT and RAPTOR state observer, which combines them with the 1D transport code RAPTOR and the diagnostic data. A satisfactory agreement both with experimental data and TRANSP simulations is achieved in NBI heated plasmas. The suite is both implemented in MATLAB/Simulink® and it is being integrated in the C++ real-time MARTe2 framework. The MDSplus software has been adopted for I/O and fast data visualization. On JET this tool can be used both offline, for a fast reconstruction of the plasma state or the optimization of the plasma trajectory [15], and in the future also in real-time, coupled to new model-based control metrics [19] or to the NBI and ICRH systems through integrated control algorithms [5].

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References

[1] F. Felici et al., Real-time physics-model-based simulation of the current density profile in tokamak plasmas, Nuclear Fusion 51-8 (2011) 083052.

[2] F. Felici et al., Real-time model-based plasma state estimation, monitoring and integrated control in TCV, ASDEX-Upgrade and ITER, 26th IAEA Fusion Energy Conference, Kyoto, Japan, 17-22/10/2016, EX/P8–33

[3] F. Carpanese et al., First demonstration of real-time kinetic equilibrium reconstruction on TCV by coupling LIUQE and RAPTOR, Nuclear Fusion 60-6 (2020) 066020

[4] K. L. van de Plassche et al., Fast modeling of turbulent transport in fusion plasmas using neural networks, Physics of Plasmas 27 (2020) 022310

[5] N. M. Trang Vu et al., Tokamak-agnostic actuator management for multi-task integrated control with application to TCV and ITER, Fusion Engineering and Desing 147 (2019) 111260.

[6] J. Blum, C. Boulbe, B. Faugeras, Reconstruction of the equilibrium of the plasma in a Tokamak and identification of the current density profile in real time, Journal of Computational Physics 231-3 (2012) 960-980.

[7] D. Mazon et al., EQUINOX: a real-time equilibrium code and its validation at JET, World Scientific Series on Nonlinear Science Series B, From Physics to Control Through an Emergent View (2010) 327-332.

[8] M. Weiland et al., RABBIT: Real-time simulation of the NBI fast-ion distribution, Nuclear Fusion 58-8 (2018) 082032.

[9] M. Weiland et al., Simulation of neutron emission in neutral beam injection heated plasmas with the real-time code RABBIT, Nuclear Fusion 59 (2019) 086002

[10] M. Weiland et al., Implementation of the real-time NBI code RABBIT in the discharge control system of ASDEX Upgrade, 61st Annual Meeting of the APS Division of Plasma Physics. Fort Lauderdale, 21-25-10-2019.

[11] https://vcis.f4e.europa.eu/marte2-docs/master/html/index.html

[12] J. Stillerman, T. W. Fredian, The MDSplus data acquisition system, current status and future directions, Fusion Engineering and Design 43 3-4 (1999) 301-308.

[13] F. Sartori, A. Cenedese, F. Milani, JET real-time object-oriented code for plasma boundary reconstruction, Fusion Engineering and Design 66-68 (2003) 735-739.

[14] R.J. Hawryluk, "An Empirical Approach to Tokamak Transport", in Physics of Plasmas Close to Thermonuclear Conditions, ed. by B. Coppi, et al., (CEC, Brussels, 1980), Vol. 1, p. 19.

[15] F. Felici et al., Non-linear model-based optimization of actuator trajectories for tokamak plasma profile control, Plasma Physics and Controlled Fusion 54-2 (2012) 025002.

[16] Felici F., De Baar M. and Steinbuch M., A dynamic state observer for real-time reconstruction of the tokamak plasma profile state and disturbances, Proc. American Control Conf. (Portland, OR, USA, 4–6 June 2014) 4816–23.

[17] C. Piron et al., Integration of the state observer RAPTOR in the real-time MARTe framework at RFX-mod, Fusion Engineering and Design 123 (2017) 616-619.

[18] O. Sauter and C. Angioni, Neoclassical conductivity and bootstrap current formulas for general axisymmetric equilibria and arbitrary collisionality regime, Physics Of Plasmas, 6 7 (1999) 2834.

[19] L. Piron et al., Progress in preparing real-time control schemes for Deuterium-Tritium operation in JET, submitted to Fusion Engineering and Design.