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Real–Time Simulation of Internal Profiles in the Presence of Sawteeth Using the RAPTOR Code and Applications to ASDEX Upgrade and RFX-Mod

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Real-time simulation of internal profiles in the presence of sawteeth using the RAPTOR code and applications to ASDEX Upgrade and RFX-mod

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The high performance of future thermonuclear fusion reactors will require an integrated model-based approach to estimate and control the plasma state and its evolution in real-time. As an example, if an accurate control of the plasma profiles is well coordinated with the active control of MHD instabilities, disruptions can be detected in time and avoided with preventive actions using multiple actuators.

The supervision and the active control of the plasma state can be achieved in real-time by combining the RApid Transport simulatOR – RAPTOR code [1] with a state observer. In so doing, a rapid yet accurate plasma profile evolution estimate can be obtained every few ms by solving two coupled 1D diffusion equations involving the electron temperature (T_e) and the poloidal magnetic flux.

Recently, RAPTOR has been upgraded to include the Porcelli's sawtooth model [2] to reproduce the effects of the sawtooth instability on the safety factor (q) and the T_e profiles in real-time. The implemented heuristic model predicts a sawtooth crash whenever the magnetic shear on the q=1 surface (s_1) overcomes a critical threshold, being $s_1(\text{crit.})\approx 0.2$ in most plasmas of interest. The localization of the q=1 surface is performed with a linear interpolation on the iota ($\iota=1/q$) profile, that is mapped over a dense spatial grid (1001 points in the present work) for this purpose. If the ι profile is not monotonic, the code takes into account the outer radius where the equality $\iota=1$ is satisfied. Once a sawtooth crash is triggered, the plasma profiles evolve according to either the Kadomtsev's complete magnetic reconnection model [3] or to the incomplete one [2]. Eventually, the new profiles are down sampled back to the spatial grid of the real-time model that is usually 100 times less dense than the sawtooth model's one such that the code execution time is compatible with the time scale of the plasma dynamics.

The RAPTOR-based state observer, originally developed on TCV [1], has also been recently embedded in the ASDEX-Upgrade [4, 5] and RFX-mod real-time [6] control systems.

In ASDEX-Upgrade RAPTOR has also been used in offline simulations to model operational scenarios in sawtoothing plasma, providing a better understanding of sawtooth control and locking experiments, like the one that is reported in Fig.1. This figure shows the time evolution of the NBI power (a), the EC one (b) and its corresponding deposition locations (c), as the color code suggests. In this experiment an EC launcher (red) is pointed well inside the q = 1 surface, while the pulsed power of the remaining ones (blue and green) is deposited just outside this surface with the aim to stabilize and lock sawteeth. In this experiment the sawtooth locking period is increased in consecutive time windows in the range T_{LOCK} = [70, 100, 140]ms, while the duty cycle is fixed at 80%. The last two panels compare the core ECE T_e (e) and the measured sawtooth period (f) (blue) with the RAPTOR predictions (red). The agreement is remarkably good, sawtooth locking almost succeeds only with T_{LOCK}=100ms both in the experiment and in RAPTOR simulation as the near overlap with the green dashed line suggests.

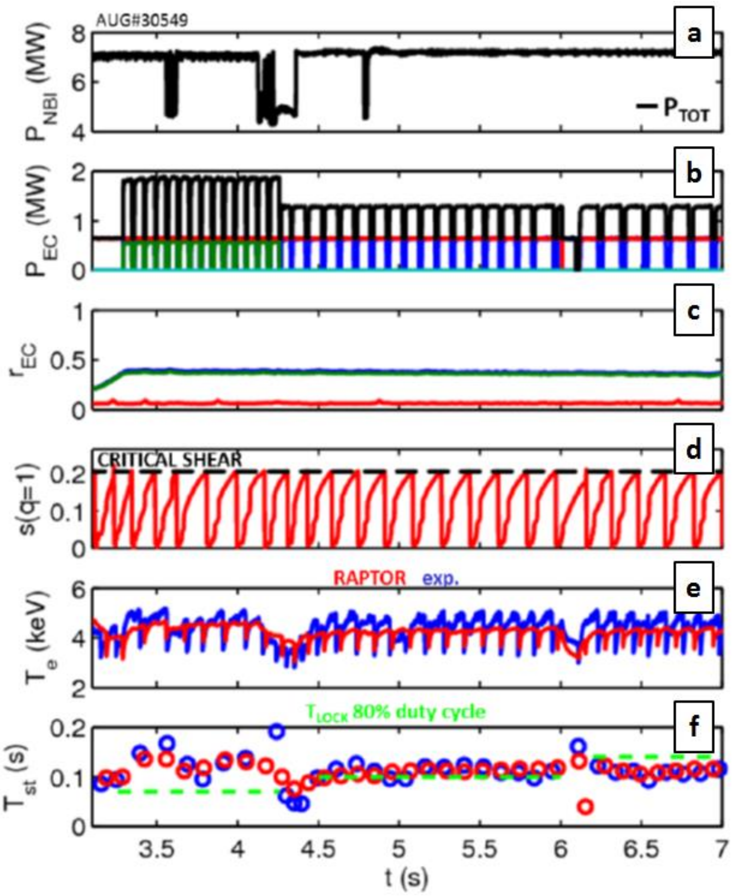

Fig.1 *RAPTOR validation in an ASDEX-Upgrade sawtooth locking experiment. a) Neutral beam injected power, b) Electron Cyclotron - EC injected power, c) radial deposition of the EC power (colour code corresponds to panel b)), d) magnetic shear on the q=1 surface predicted by RAPTOR (red) and critical threshold (dashed black line), e) measured (blue) and RAPTOR (red) core electron temperature, f) measured (blue) and RAPTOR (red) sawtooth period, expected period from locking power injection (dashed green line).*

Offline RAPTOR simulations with different pre-programmed EC square waveforms and power deposition profiles suggest that sawtooth locking is very sensitive to the deposition radius for a given locking period and duty cycle, thus this code is a valuable to optimize the design of such experiments before their execution.

In RFX-mod a RAPTOR-based state observer has been embedded for the first time in the real-time MARTe framework and it has been used to model low-q edge sawtoothing tokamak plasmas. The final aim is a proof of concept experiment where a plasma disruption will be predicted on the basis of the sawtooth period rather than from direct magnetic measurements, that have not been included in this code yet. Sawteeth disappear very reproducibly in RFX-mod q(a)<2 plasmas as a current driven m=2, n=1 Resistive Wall Mode grows in amplitude prior a plasma disruption, as it can be seen in Fig.2 (on the left), but the same evidence is documented also in q(a)>2 plasmas that are terminated by a locked m=2, n=1 Tearing Mode (TM) (on the right). RAPTOR, that is unaware of this MHD dynamics, would predict stationary sawteeth thus the real-time comparison of the measured sawtooth period with the RAPTOR one will possibly predict the occurrence of a disruption a few tens ms early in both these operational regimes. A preparatory experiment for this task is reported in Fig.3. In this experiment, that validates RAPTOR in real-time in a circular tokamak plasma at q(a)=1.7, the pre-programmed gas puffing injection is switched off at t=0.6s to slowly ramp down the electron density (b) and as a result the sawtooth period shortens (d). The core electron temperature and sawtooth period predicted in real-time by RAPTOR (c), d) in red) follow the experimental trend (blue), though they bear the discretization due to the finite cycling time of the code. The latter was fixed to 2ms in these experiments to resolve changes in the sawtooth

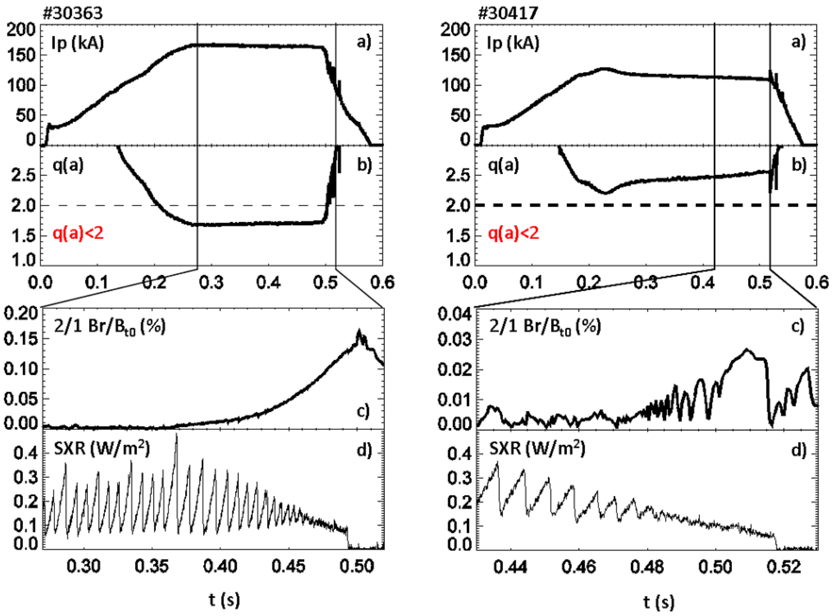

Fig.2 *RWM (on the left) and TM (on the right) mitigating effect on sawtreeth in RFX-mod. Time history of a) the plasma current, b) the edge safety factor and c) the m = 2, n = 1 amplitude of the radial magnetic field normalized to the equilibrium field.*

period in the order of tens ms. The spatial grid was reduced accordingly to 6 points, in order the execution time to be safely shorter than the cycling time. With this configuration the sawtooth model takes around 1.5ms to execute at every crash (e). Since a 25% margin in the execution time is still left, an optimization of the code will likely allow increasing the time resolution in future experiments, improving the accuracy of the real-time predictions.

The disruption avoidance technique that will be tested in RFX-mod will be a demonstrative example of a possible integrated control application with RAPTOR. The real-time comparison of the experimental dynamics with the modelled one can be exploited to contribute to the development of robust disruption avoidance schemes in larger tokamaks, like ASDEX Upgrade or JET, where other instabilities, like locked TMs or radiative ones, can trigger plasma disruptions.

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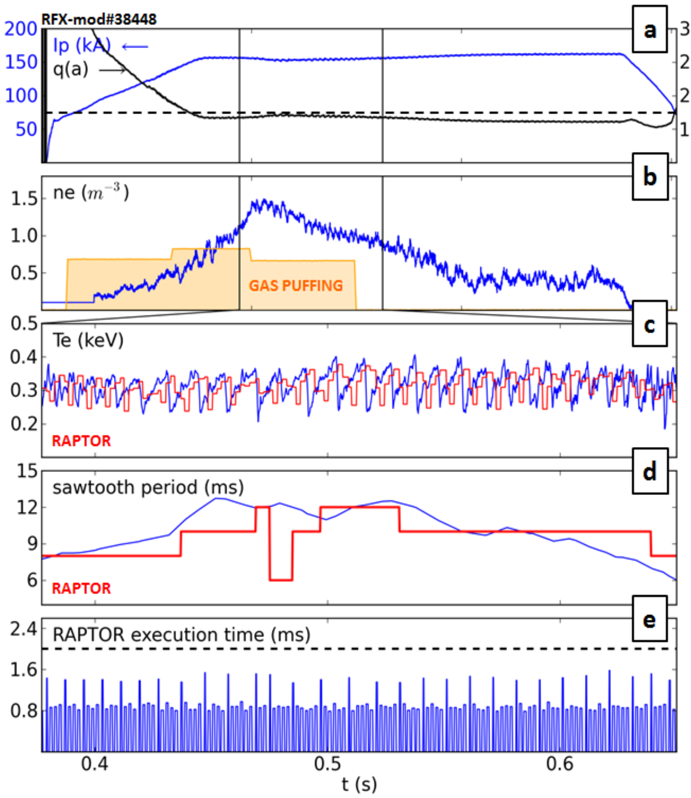

Fig.3 *RAPTOR validation in a RFX-mod low-q sawtoothing plasma. a) Plasma current (blue), edge safety factor (black) and q(a)=2 stability limit (black dashed line), b) electron density (blue) and the pre-programmed gas puffing injection (orange), c) measured (blue) and real-time RAPTOR predicted (red) core electron temperature, d) measured (blue) and real-time RAPTOR predicted (red) sawtooth period, e) RAPTOR execution time in MARTe (blue) and RAPTOR cycling time (black dashed line).*