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A full-discharge tokamak flight simulator

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A full-discharge tokamak flight simulator
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Operation of a plasma discharge in a tokamak requires simultaneous integration of actuators and diagnostics for plasma control, and physics insight into the type of plasma scenario that is going to be performed. In view of the initial ITER operation, considering that a pulse has to be operated in the most secure way possible to avoid loosing the discharge (with associated costs) or even worse, ending in a disruption, one needs a tool capable of predicting the full discharge beforehand, only using the pulse schedule plus machine conditions as available information. Such a software could be called "flight simulator"because it would effectively simulate the real system in its entirety, allowing the pulse operator to correct errors or optimize the discharge parameters before running the discharge.
This tool should include sufficiently realistic plasma models typical of the tokamak burning plasma, integrated inside the real control system and its actuators (heating, fueling, magnetic control) with simplified models. Moreover, it must not depend on shot-specific parameters that are only diagnosed after the shot has been performed, or it would loose predictive power.
This tool has been obtained for the first time at ASDEX Upgrade, integrating the 1.5D transport-equilibrium solver ASTRA+SPIDER [1,2], inside the ASDEX Upgrade plasma control system in SimulinkTM [3]. This integrated package is called Fenix [4,5]. In this contribution, Fenix is presented, detailing the physics content and demonstrating the several capabilities. Plasma non-linearities are integrated in a fast simulation framework including control actuators and their realistic behavior. Fenix reads the pulse schedule of ASDEX Upgrade and predicts the full behavior of the plasma-control system. From the plasma physics side, the core plasma inside nested flux surfaces is modeled with 1D transport equations for heat, particles, momentum, and poloidal flux on a 2D quasi-statically evolving magnetic equilibrium. Reduced models for neoclassical, turbulent transport, MHD activity and heating/fueling deposition are employed. For the SOL/divertor open-field lines region, simplified 0.5D models are used which nevertheless contain non-linearities that are observed experimentally (detachment, dependence of neutral fluxes on gas puff, etc). The magnetic equilibrium is computed in a dynamical way using the free-boundary solver SPIDER including vacuum vessel currents, yet SOL currents are not accounted for.
All the pieces of the flight simulator work in concert to reproduce a real plasma with particular focus on the physics interactions among the elements and how these affect the interpretation and prediction of experiments. The most critical aspects of the entire system are the links between the elements outside of the plasma (plasma facing components, gas valves) and the plasma. The problem of heat flux exhaust and of plasma fueling are some of the most complex in tokamak plasma physics and require a combination of physics insight and empirical evidence to obtain a rather complete model applicable to the real plasma.
Moreover, machine conditions can affect the execution of a discharge. It is discussed how this can be taken into consideration in such a flight simulator. Another aspect which has strong impact on the simulation result is the non-linear interaction between plasma confinement and equilibrium evolution. An example is the effect of edge instabilities (ELMs) in determining the average edge current and thus the X-point angle, and the average pedestal height which determines the global plasma pressure and equilibrium displacement (Shafranov shift). Or the core transport, usually dominated by microturbulence, would tailor the profiles peaking which is important for discharge performance optimization (for example in view of a burning plasma). Still elusive is a complete theory of the L-H transition which is included in the model in different ways, starting from a more global criterion (check on power crossing the separatrix), down to a more heuristic local model (comparing the local radial

electric field). The consequences that the choice of the model has on the simulations are discussed.
Finally, it is shown how the simulation comprehensively predicts several types of scenarios and it is compared to discharges not yet performed (discharge forecast). Examples of the application of the flight simulator Fenix to a future reactor prototype (EU-DEMO) are also shown.
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[4] F. Janky et al., Fus. Eng. And Design Volume 146, Part B, September 2019, Pages 1926-1929
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