Application of the Fenix flight simulator to TCV

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Introduction

As operational limits and the associated (financial) risks will be much more important for the next generation of tokamaks, the capacity to avoid these limits needs to be improved as well. Tokamak flight simulators, integrating both the plant systems (controllers, observers, and actuators) and the plasma magnetic and kinetic behaviour in a self-consistent way, are prime tools to mitigate these risks by enabling realistic checks of discharge scenarios. Moreover, flight simulators can be used in the design of these discharge scenarios and elements of the plant control system. To gain confidence in such complex simulations, it is important to develop and test them for different existing tokamaks. As such, this contribution presents the extension of the Fenix flight simulator [1, 2] developed for ASDEX Upgrade (AUG) to TCV. The compatibility with existing TCV workflows has been improved by coupling Fenix with the FGE free boundary equilibrium code of the MEQ suite [3] that is routinely used for TCV. An emulator of the TCV "hybrid" magnetic controller [4, 5] has also been added to the Fenix model.

The Fenix flight simulator for TCV

In this section, we give a brief overview of the structure of the Fenix flight simulator, as well as the models and codes used in the TCV version. The core block of Fenix is the ASTRA transport code [8, 9]. In this work, a rather rudimentary transport model is used in ASTRA, see table 1. Regardless of the choice of transport model, ASTRA needs information on the magnetic geometry to solve its transport equations. To this end, the SPIDER [6] and FEQIS [7] codes were already available (both their prescribed boundary and free boundary versions). In this work, we coupled Fenix-ASTRA with the FGE free boundary code. FGE provides ASTRA with the geometric profiles it needs, as well as the poloidal flux of the external conductors on the separatrix ψ_{ext}. The latter allows to use $L_{ext}I_p + \psi_B = \psi_{ext}$, with $I_p \sim (\partial\psi/\partial\rho)_B$ the plasma current, L_{ext} the external inductance, and ψ_B the total poloidal flux on the boundary, as a boundary condition for the flux diffusion equation [10]. The other way around, ASTRA provides

*See the author list of H. Reimerdes et al, 2022 Nucl. Fusion 62, 042018 the current density profile to FGE. Next, the control system provides the voltages for the coils modelled by the free boundary equilibrium code, as well as the fueling, heating, and current drive inputs. In this work, we ported an emulator of the TCV hybrid magnetic controller to the Fenix model. This work was facilitated by an already existing framework coupling this emulator with FGE [5]. Time traces for heating and fueling going into ASTRA are implemented, but these are not yet coming from an emulator of the TCV kinetic controller. Instead, feedforward traces can be specified for the heating, and an ad-hoc controller is implemented to control the plasma particle content with the neutral flux crossing the separatrix.

The Fenix model thus allows self-consistent, predictive simulations of TCV starting from reference input trajectories going to the controller, and calculating as output the evolution of the state of the tokamak (kinetic profiles, coil voltages, controller state) in time. Table 1 summarise the different elements of the Fenix model used here. The next two sections show results of two flattop phases to provide a first benchmark of Fenix for TCV.

Table 1: Summary of the reduced Fenix model used for TCV

transport		ASTRA8 code
	equations solved	n_D, n_C, n_n, T_e, T_i, T_n, ψ
	current transport	neoclassical conductivity, bootstrap, sawtooth
	heat and particle transport	Ad hoc model based on Ref. [11]
	EC and NBI	Ad hoc gaussian deposition
	radiation	Bremsstrahlung, synchrotron, carbon radiation
	Boundary conditions	imposed n_D, n_C, T_e, T_i, T_n, Γ_n
		ψ_{ext} from FGE or imposed I_p
		neutral flux from controller
equilibrium		FGE free-boundary code
		SPIDER prescribed-boundary code
control system	magnetic control	emulation of TCV hybrid controller
	kinetic control	ad hoc density controller
		feedforward heating traces

Kinetic results for an Ohmic, limited TCV plasma

This section considers the limited, Ohmic, L-mode, 210kA TCV discharge 78055. This case is simulated once with the new Fenix-FGE-hybrid controller coupling and once with the existing Fenix-SPIDER prescribed boundary version. For the latter, the plasma current and the separatrix shape have been set to the average value in the experiment. In the former, they are self-consistently solved through the free boundary equilibrium controlled by the hybrid controller using the reference signals which were used in the experiment. A comparisson of the plasma current and the poloidal flux map is shown in figure 1. An interpretative ASTRA-SPIDER prescribed boundary simulation is shown for reference as well. In this simulation only the current density equation is solved, with the other quantities taken from experimental measurements. For the Fenix-FGE case and the Fenix-SPIDER case, the same basic kinetic model is used (see table

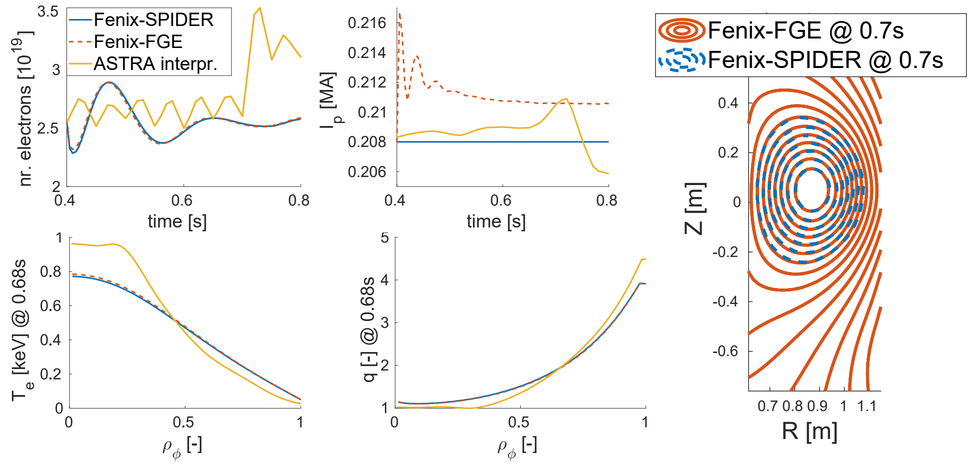

Figure 1: *Plasma particle content, plasma current, electron temperature, safety factor, and poloidal flux distribution for Fenix-SPIDER, Fenix-FGE-hybrid controller, and interpretative ASTRA simulation for TCV discharge 78055.*

1). For these cases, the the Spitzer conductivity has been used, while the neoclassical contribution [12] was on in the interpretative ASTRA simulation. The three remaining plots in figure 1 show that the kinetics quantities are almost identical for both cases, verifying the FGE coupling presented here. There is room for improvement for the match with the experimental data from the interpretative ASTRA simulation. The goal here was to benchmark the ASTRA-FGE coupling in an experimentally relevant parameter range though, not to achieve a perfect match with the experiment. With more (discharge-specific) fine-tuning, the differences could presumably be much reduced.

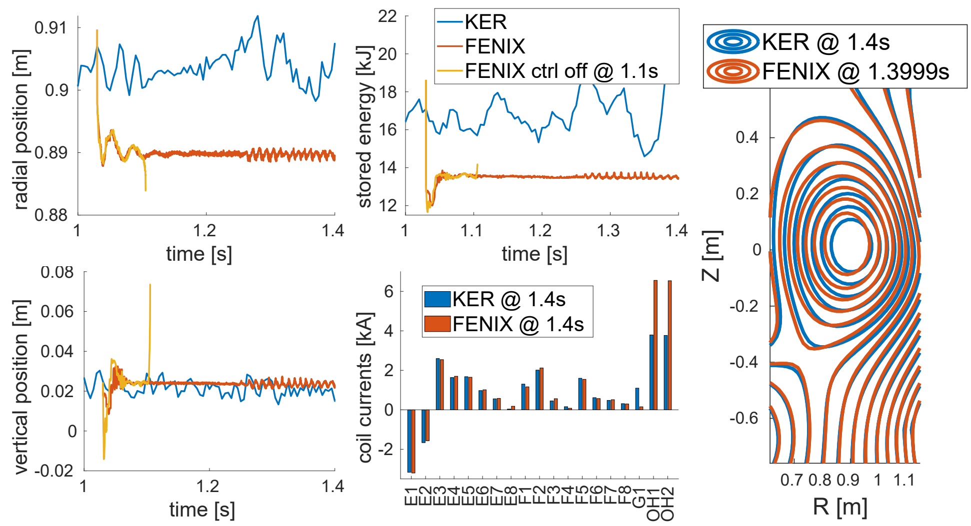

Figure 2: *Magnetic axis R and Z position, stored energy, coil currents, and poloidal flux distribution for kinetic equilibrium reconstruction and Fenix-FGE-hybrid controller for TCV discharge 73927.*

Magnetic results for a diverted, NBI-heated TCV plasma

This section considers the diverted, NBI-heated, H-mode, 220kA TCV discharge 73927. The same Fenix-FGE-hybrid controller set-up is now compared to the kinetic equilibrium reconstruction (KER) [3]. Figure 2 shows that Fenix manages to get a relatively good match of the experimental results. Again, the match is not perfect, which is presumably mostly due to inaccuracies in the kinetic modelling. In particular, the plasma stored energy is underestimated in Fenix, which leads to the equilibrium being shifted inward by about 1cm w.r.t. the KER. Secondly, while most of the coil currents are rather close between Fenix and KER, the OH-coil currents are off. This is due to the effective charge being overestimated and the Bootstrap current not being included included in this simulation. As a small test, the same Fenix-FGE case was run, in which the controller is artificially turned off at 1.1s, which quickly leads to a disruption in the simulation as expected.

Conclusions and outlook

This contribution showed the successful coupling of the Fenix flight simulator with the FGE free boundary code and the TCV hybrid magnetic controller. Benchmark cases comparing to the existing Fenix-SPIDER set-up and kinetic equilibrium reconstruction of a TCV discharge were shown. Limited effort has been devoted to the kinetic modelling though, which largely explains the remaining gap between simulation and experiment. Next to improving the profiles of neoclassical transport coefficients, we plan to run Fenix with more complex modules, e.g. TGLF, Toray, Rabbit. We also envisage using the transport model used for AUG. Furthermore, we aim to implement the TCV kinetic and the magnetic shape controllers. Finally, Fenix will be applied to an extended set of TCV discharges to further improve and develop this simulator.

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