Validation of the Fenix ASDEX Upgrade flight simulator

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Abstract

Fenix [1, 2] is the ASDEX Upgrade (AUG) flight simulator based on the 1-D transport code ASTRA coupled with the 2-D equilibrium solver [3] SPIDER and Simulink (simulation platform integrated with MATLAB). Fenix is designed to simulate the entire discharge from the ramp up of the Poloidal Field (PF) coils, through the plasma phase, finishing with the ramp down of the PF coils. Currently, controllers for position, shape, fuelling and heating are implemented according to the AUG control system setup. Also, a model of the Poloidal Field (PF) coils and the models of their corresponding power supplies are provided, as well as basic models of heating actuators such as Electron Cyclotron Resonant Heating (ECRH), Neutral Beam Injection (NBI) and fuelling using either pellets or gas.

As a next step, the Fenix simulations have to be validated against an already existing database of the discharges. This article compares the behaviour of Fenix simulations against various AUG discharge measurements. It shows that it succeeds in its goal as a comprehensive tokamak discharge simulator.

Keywords: Fenix, flight simulator, tokamak control, plasma control simulation, ASDEX Upgrade, validation

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1. Introduction

Tokamak operation is becoming more and more challenging, pushing the physics and the experimental devices to their limits. The plasma physics challenging scenarios (with e.g. temperature profile control) require advanced control approaches and good preparation of the pulse schedule to fulfil the experimental target. Moreover, experiments are time and cost demanding, which creates a high necessity for a flight simulator which can model the entire tokamak operation. Such a simulator has to include the precise physics, control, actuator and diagnostic models. There are several different tokamak simulators already developed with different focus on speed, real-time capabilities or precision [4, 5, 6, 7, 8]. However, none of them comprises the entire plasma discharge including actuators and the control system settings and integration into the pulse execution. Therefore, Fenix [1, 2] is being developed to simulate the plasma discharges before their execution. It should help a session leader to prepare the pulse schedule and it has to fulfil two main conditions. First, the flight simulator has to predict the plasma discharge and the control system behaviour with reasonable accuracy according to the pulse schedule to detect possible errors in pulse design. Second, the simulation has to run fast enough to be executed in between discharges (i. e. it should take only a few minutes). Except for these two conditions, Fenix can also be used to prepare the discharges far in advance (with better numerical accuracy). It can be used in developing new and advanced control modes, testing different control strategies, actuators sharing and exception handling. Another possibility is to use Fenix to test different physics models and to compare against measured data from the discharge database. Moreover, it can be used to train session leaders. Currently, one simulation of the entire discharge takes approximately three minutes. This allows us to run in between two discharges (typically 20 to 30 minutes gap).

Fenix is designed as an open-architecture framework where different models of devices, actuators

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and diagnostics can be changed. It is a generic simulator as it can simulate not only the AUG but also other tokamak devices. Currently, Fenix is used to study kinetic control of the European DEMO tokamak [9]. The Fenix simulator is built on the ITER Plasma Control System Simulation Platform (PCSSP) [8, 10] which makes it portable to simulate ITER discharges.

Fenix is built as a Simulink model which contains the AUG control system architecture, a control-oriented model of the actuators and the plasma model (ASTRA/SPIDER) implemented as an S-function. The inputs to the plasma model are the coil voltages, particle fluxes from valves and pellets and heating sources injection geometry and power. The output from ASTRA/SPIDER are ideal diagnostic signals (coil currents, plasma shape, position, density, etc.) which are then used by the control models in Simulink. To make transport-equilibrium cycle numerically fast, the following simplification has been applied: We assumed typical time scale for the plasma movement (given by vacuum vessel 10 ms to 15 ms) to be slower than the simulation time step which 1 ms. In this case one can replace the Picard iterations for the non-linear Grad-Shafranov equation solver with the time stepping. This can be done because the time step is much smaller than the resistive time scale. This makes the simulation much faster. There is a simple switch to switch on or off the Picard iterations. We checked that results of two settings satisfy required precision.

In this article, we are showing that a fast pulse simulator in general, not only can be built up but also can reach a satisfactory level of realism. We are validating it on different types of AUG discharges.

2. Validation

Different types of scenarios need to be selected to validate Fenix properly. Therefore, we chose these discharges: a standard H-mode, a plasma core fuelled with pellets, an R_{aus} scan - a scan of the distance between the position of the outermost separatrix point and the wall at the Low Field Side (LFS) - and a discharge with a sudden loss of heating power.

The key aspect of the validation is that the physics models do not contain discharge dependent free coefficients. That means there is no model parameter which we tune between shots. Moreover, a Fenix simulation runs with the same pulse schedule and control settings [11] as they were configured for the experiments.

In the beginning, the pulse schedule is parsed by Fenix. It contains feedforward coil currents, requested trajectories of different signals (e.g. referenced plasma current, line averaged density, etc.) and the control modes [11] (e.g. control mode for plasma shaping). Then, according to the pulse schedule, the pre-magnetisation phase and gas prefilling starts (without plasma). Because there is no breakdown model in Fenix, plasma starts when $\frac{dI_{OH}}{dt} < -100\,\mathrm{kA/s}$ which is consistent with the actual central solenoid slope observed in real discharges. The initial plasma is circular with the plasma current $I_{\mathrm{pl}} = 100\,\mathrm{kA}$, line averaged density $n_{\mathrm{e}}^{\mathrm{avg}} = 0.2 \times 10^{19}\,\mathrm{m}^{-3}$, minor radius $a = 0.32\,\mathrm{m}$, geometrical centre of the plasma boundary $R_{\mathrm{geo}} = 1.42\,\mathrm{m}$, elongation $\kappa = 1$, and $T_{\mathrm{e}} \propto I_{\mathrm{pl}} \cdot (1 - x^2)$ and $n_{\mathrm{e}} \propto 4I_{\mathrm{pl}} \cdot (1 - x^2)$, where x is normalised toroidal flux coordinate. These initial settings are the same for every simulated discharge.

After the initialisation of Fenix with the prescribed plasma, the simulation continues according to the definition in the pulse schedule.

3. Results

A comparison of simulated and experimental plasma current and current in ohmic heating circuit is in Figure 1. Three different discharges are shown here: #35241 hydrogen discharge with nitrogen seeding and with L-H transitions, #36496 deuterium H-mode discharge and #36470 high density H-mode discharge. The plasma current (top graph)

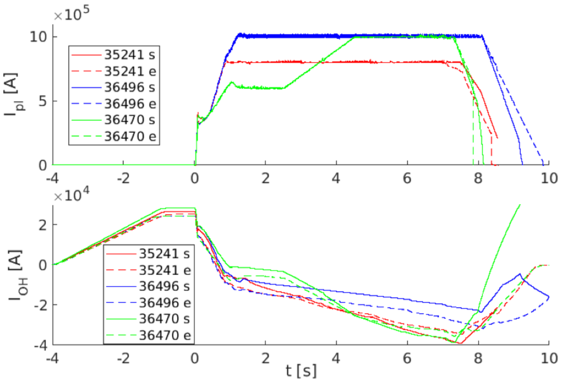

Figure 1: A comparison of simulated (labelled as "s") and experimental ("e") plasma current (top) and ohmic heating current (bottom) for three different discharges.

from simulations are in good agreement and differs only at the end of the discharge. The reason behind is that the plasma current ramp-down in the simulation is executed according to the pulse schedule. However, during the AUG experiment, there is a special function implemented which changes the ramp-down segment according to the current plasma state. This function is not implemented currently. The OH current in simulation (bottom graph) differs from the experiment due to different amount of impurities (Z-effective) and to lower edge electron temperature in the simulation than in the experiment. Notice also that the value of Z-effective can change on shot to shot basis depending on the wall condition and it is hard to predict, so we use a typical value.

3.1. Start-up phase

A comparison of the start-up and ramp-up phases will be discussed for the standard H-mode discharge #36440 because they are common to all discharge types. Therefore, it is crucial to match the coil currents in the simulation.

To validate the models of the magnetic control system, the power supply actuators and the plasma equilibrium, the experimental pulse schedule with the feedforward PF coil currents, requested plasma current, shape and position is read. Up to breakdown, $t = 0\,\mathrm{s}$, the simulated (and also in a discharge) PF currents are in feedforward. After the plasma breakdown, the feedback controllers for plasma current, shape and position computes the desired PF currents using the actual plasma state modelled by SPIDER. In the simulation, the PF currents are fed to the power supplies model. The power supplies model computes the voltages which are given as an input to the SPIDER equilibrium/circuit solver. SPIDER computes the currents in the coils, plasma current, position and shape and sends them back to Simulink. Fig. 2 shows the temporal evolution of PF coil currents for driving the plasma current and plasma shape. There is some difference in the absolute values for coils used in plasma position feedback V1u, V2o and V2u even though the general trend agrees. The disagreement starts when the X-point is formed. The reason lies in the relation between the X-point angle and the edge plasma current density: this has an influence on the strike point positions and thus on the coil currents devoted to the strike point control. The edge current density is determined mostly by the bootstrap current, whose time-averaged value during the H-mode is not known a priori (depends on the Edge Localised Mode (ELM) frequency and amplitude). The currents in these coils are computed signals corresponding to the response of the controllers (during the operation and simulation as well) to the desired plasma current, shape and position request.

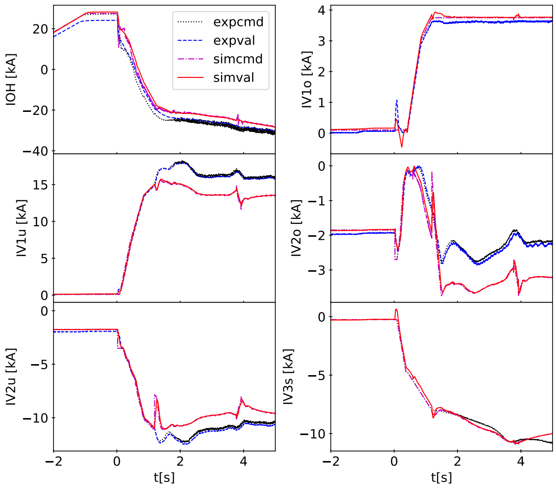

Figure 2: #36440: A comparison of different poloidal field coil commands in experiment (expcmd) and simulation (simcmd) and comparison of the corresponding measured (expval) and simulated currents (simval).

3.2. R_{aus} scan

To verify the quality of the simulated equilibrium during plasma movements a discharge, #33173, with a scan of the outermost plasma major radius point was modelled. This horizontal plasma movement has also an impact on the tungsten influx due to the proximity of the plasma to the first wall limiter. The input signal is R_{aus} and the validated signals are the coil current (CoIu), tungsten influx and the radiated power. The results are shown in Fig. 3. The top graph shows the plasma movement towards the outer limiter and back repeated three times. The signal R_{aus} from the simulation is computed by the equilibrium solver SPIDER and R_{aus} from the experiment is computed by functional parametrisation (FP) used in real-time [12]. The second graph shows good agreement between simulated data and measured signal for one of the coils (CoIu) responsible for the plasma movement. The small discrepancy can be caused by the difference in the equilibrium solution between SPIDER and FP. Moreover, the effect of the plasma movement on the

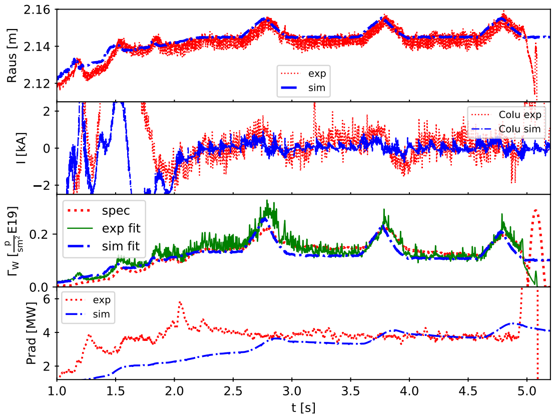

Figure 3: #33173: Top: comparison of experimental and simulated R_{aus} signal. Second: Comparison of experimental and simulated poloidal coil current during the plasma movement. Third: a comparison of experimentally obtain tungsten influx from spectroscopy (red dash); a fit to the experimental data (green); tungsten simulated influx (blue). Bottom: Radiation calculated during the experiment (red) and simulation (blue).

plasma current profiles may not be realistic enough in the model. The third graph shows tungsten influx measured by a spectrometer, calculated influx from experimental measurements (plasma position and electron temperature) and simulated tungsten influx using the modelled plasma position and electron temperature. On the bottom graph, there is a comparison between simulated and calculated radiated power in the experiment. One can see a difference for $t < 3$ s. This is due to the main simulated source of tungsten is at the plasma outer limiter. However, during the plasma ramp-up phase there are other tungsten sources (inner limiter or the divertor) which are not currently numerically implemented. When the plasma moves towards the limiter in the simulation the radiation increases immediately, however, in the experiment there is a delay between plasma movement and increased radiation. The reason is, that in Fenix, tungsten from the outer wall is sputtering into the Scrape-off Layer (SOL) a thus directly into the plasma (SOL model is 0-D). This way tungsten is considered in next time step as a source at the separatrix. Radiated power also increases in the experiment but the effect is smaller and 3-D transport between SOL and separatrix.

3.3. β_{pol} modelling

The sudden loss of a heating source has a big impact on β_{pol} and can lead to an inward shift of plasma and to a disruption. We selected discharge #31899 where sudden loss of Neutral Beam Injection (NBI) heating source caused a drop of β_{pol} and the discharge disrupted (see Fig. 4). As the sudden trip or loss of a heating source is happening only in the experiment, the heating sources in the simulation were adapted according to what happened during the experiment (top graph). The middle graph shows good agreement between the Fenix simulation and the experiment for β_{pol} and R_{aus}. At time ≈ 5.6 s the NBI heating sources are switched off (in the simulation to mimic the NBI loss), that causes fast drop of β_{pol} and thus the plasma moves towards High Field Side (HFS). The reaction of the control system moves the plasma towards the LFS. However, the plasma becomes vertical unstable at ≈ 5.75 s and disrupts. In the simulation, sudden loss of NBI heating leads to fast decrease of β followed by Vertical Displacement Event (VDE) (same as in the experiment) [13, 14]. At the time when the plasma disrupts, the Fenix simulation stops due to the equilibrium solver switching from the resistive branch to the Alfvénic branch. That appears in the code as a sequence of non-converging solutions. At each time step the solution is further away from the previous solution with unphysical speed causing an unphysical solution.

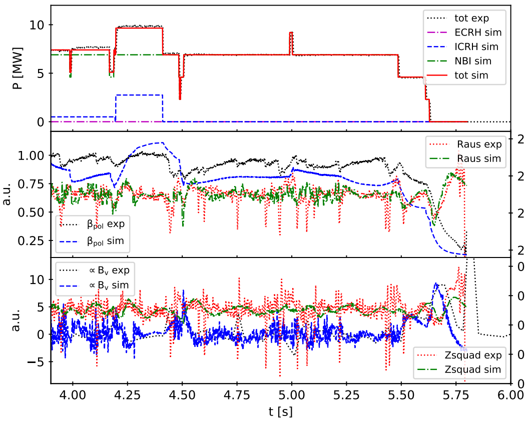

Figure 4: #31899: Top: Total heating power from experiment (tot exp) and simulations (tot sim) and individual simulated heating sources. Middle: Experimental (black) and simulated (blue dashed) β_{pol} at left y-axis. Outermost plasma major radius point (right y-axis) experimental (red) and simulated (green) values. Bottom: A sum of poloidal field coils creating vertical magnetic field (experiment - black, simulation blue) at left y-axis. Experimental (red) and simulated (green) vertical position at right y-axis.

3.4. *Density controlled by pellets*

Fuelling the plasma core is important for future fusion devices like ITER and DEMO. However, fuelling by gas valves is predicted to be inefficient. Therefore, plasma core can be fuelled by pellets. With pellet fuelling, the density in the core can reach values above the Greenwald fraction. Such experiments have been performed at AUG (e.g. #34182) and provide an interesting test for the simulation of core density profile modelling and the control of the core density in Fenix (see Fig. 5). We calibrated the pellet size to match the experiment according to the density increase per pellet. In future, the transport model will be improved such that the real pellet size will be used in the simulation. Currently, the simulated pellet size is roughly three times smaller compared to the experimental one. The top graph shows the reference value, the core density calculated by observer [15], the line averaged density which suffers from fringe jumps, the Thomson scattering core density and the simulated density. There is a good agreement between the simulated and the measured densities.

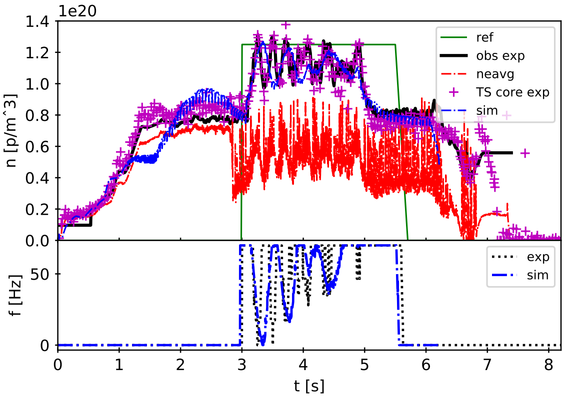

Figure 5: #34182: Top: requested electron density (ref) in green; electron density obtained by the density observer in black, measured density by the interferometer (red), Thomson scattering measurement (magenta) and simulated value in blue. Bottom: pellet frequency request in experiment (black) and simulated request (blue).

In our simulation, we used realistic pellet launcher behaviour with 90% of the pellets delivered and a total of 96 pellets. Therefore, in the experiment and the simulation, there is a sudden decrease in density, even though there is high pellet frequency requested (bottom graph). There is a similar pattern of the requested pellet frequency in the experiment and the simulation. Differences can come also from randomising pellet delivery success.

4. Conclusions

This validation shows that Fenix is a simulation framework which provides capabilities for pulse discharge design and validation, control system development and also some dedicated physics studies. Every single case runs with the same model parameters. The modularity on the Simulink side and in the plasma model (different transport and physics models) allows for efficient validation and development of control and the physics models. In the examples shown here, there is an overall good agreement between the coil currents and the electron density of the simulation and the experiment. With respect to the discrepancies that were observed, this tool allows us to efficiently investigate the physics or the numerical reasons. As an example the influence of the bootstrap current on the X-point angle can be tuned with a proper averaged ELM model.

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