ASDEX Upgrade flight simulator development

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Abstract

Fenix, the ASDEX Upgrade (AUG) flight simulator under development, is based on the Plasma Control System Simulation Platform (PCSSP) developed for ITER, the ASTRA transport code and the SPIDER equilibrium code. Fenix will give a session leader the possibility to check whether the discharge will meet experimental goals prior to execution. It is also designed to facilitate the development of control system features and the validation of physical models. It reads the AUG discharge program and checks if all the parameters and reference waveforms are reasonable during the discharge simulation.

ASTRA serves as a plant model (physical model of AUG tokamak) which outputs idealised diagnostic signals (temperature, density, etc.). ASTRA calculates these data from the particle and energy transport in the plasma core, plasma edge, Scrape of Layer (SOL) and divertor. It also includes particle balance, L-H transition and sawtooth models, and it is equipped with the 2D equilibrium reconstruction code SPIDER.

The second component of Fenix is a model of the Discharge Control System (DCS) and AUG actuators. The DCS model processes diagnostic signals from ASTRA, computes commands for actuators and sends them back to ASTRA closing the feedback loop. Controllers for coil currents to control plasma current, position and shape are implemented in the model as well as gas puff valves (divertor and midplane) and the pellet injector to control electron density. The DCS model also simulates external heating actuators such as NBI, ECRH and ICRH.

Fenix has methods for reading configuration files and archiving. This article presents modelling of the ASTRA and DCS components, and the first results from the simulations of the flattop phase.

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

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1. Introduction

Operation of the ASDEX Upgrade (AUG) tokamak is complex and requires careful preparation of every single discharge. To prepare a pulse an AUG experiment leader must define waveforms (references) for plasma current, position and shape, electron density, external heating sources and many others in the discharge program. Typically, the session leader reuses parts of scenarios from older experiments, sometimes even from discharges performed years ago, to assemble a new discharge program. This process can be error prone; a wrong configuration can lead to missing the experimental goal or a plasma disruption. The discharge then has to be analysed, refined and re-run. Therefore, a tool (typically called *a flight simulator*) which can simulate a designed and prepared scenario is necessary. This tool needs to read the prepared configuration, simulate it fast with reasonable precision, verify that the experimental goal can be reached, report which actuators are close to their limits and, if necessary, block the execution of the discharge. This way, the loss of experimental time is reduced and investment protection is improved.

Another use of the tool is to design new physics models and validate them in current experiments. Developing and testing new control strategies [1] before their implementation will make use of this tool. This requires an option to run simulations not only fast but also with high precision so that the tool has to be able to contain both options.

Therefore, we are developing a new tool called *Fenix*. The architecture of Fenix is described in [2]. Fenix is based on the ASTRA transport code [3, 4], the equilibrium code SPIDER [5], the Plasma Con-

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trol System Simulation Platform (PCSSP) framework [6] and MATLAB/Simulink. Fenix is designed to allow the fast simulations necessary to run before every discharge to check if all is set-up correctly, as well as to simulate detailed physics to validate models and compare them with real experiments.

This article describes the current state of Fenix development and its first results. In section 2, the implementation of Fenix, its features as well as control modes with their description and switching policies are presented. Section 3 explains how the simulations were performed in order to test the implementation. Section 4 shows the first simulation of a short part of a typical AUG discharge using controllers as they are currently configured for the Discharge Control System (DCS), in particular the simulations of plasma current, plasma shape, β_{pol}, line averaged and core electron density. Section 5 sumarizes the state of development.

2. Implementation

Fenix is based on previous work for DEMO [7]. It is built on the 1-D transport code ASTRAcoupled with the 2-D equilibrium solver SPIDER [5], the PCSSP framework for ITER [8] and Simulink®.

2.1. ASTRA

ASTRA includes the Neoclassical Tearing Mode (NTM) model, the L-H and H-L model with low hysteresis based on power crossing separatrix,P_{sep}, Scrape-off Layer and the divertor (SOL/div) 0-D particle balance model [9] and the SOL/div 1-D exhaust model. A detailed description of the coupling between ASTRA and Simulink® is given in [7].

2.2. SPIDER

In each time step, ASTRA provides the pressure and the current profile to SPIDER. Moreover, Simulink provides SPIDER with the coil voltages produced by the power supplies. From these SPIDER computes both the 2-D magnetic equilibrium using the information from ASTRA and the actual coil currents, and in addition it evolves the coil currents themselves consistently with the plasma motion and the input voltages from Simulink.

A model of the wall and the passive stabilisers allows consistent treatment of resistive Vertical Displacement Event (VDE) physics.

To reduce the computational cost to a minimum, the coils and the wall are represented with few filaments, while the free boundary solution region is represented by a grid with the lowest affordable resolution (which still gives accurate results). Moreover, while the circuit equations for the coil currents are solved implicitly, the plasma response and the plasma-coil mutual inductances are computed explicitly in time. This produces a certain loss of accuracy, but it is necessary to keep the code fast. However, it is always possible to cross-check the low fidelity simulation with a high fidelity one in post-processing.

2.3. Control

Controllers implemented in Fenix are based on a generic controller which is a core component of AUG DCS [10]. Each controller is set up with a configuration file. The configuration can define an arbitrary number of control modes. The control mode defines input, reference, feedforward and output signals, control policies and transition methods. Currently, several different control policies are implemented such as: frozen, feedforward, proportional (P) and scaled P, proportional integral (PI) and scaled PI controllers. All are available as scalars, multivariable and discrete controllers. All control algorithms except frozen include a feedforward component. The frozen controller holds the last command from the previous control mode. The control mode for each controller changes according to a mode command signal. Therefore, during the simulation, the different control modes can be used the same way as the DCS system changes them in real operation. When a control mode changes, several transition methods allow to continue the command outputs smoothly or abruptly. Transient methods and anti windup policies are implemented in accordance with the AUG DCS.

Each output command can be limited either by a constant value, a change rate or a scaled signal. A number of limits can be configured at the same time. For the lower limit, the highest value of selected limits is used while for the upper limit, the lowest value of upper limits is used.

3. Simulations

Magnetics: Plasma current, shape and position are controlled separately. Each of them has its own set of control modes specified in the same way as in the DCS. The controllers produce coil current command outputs for the central solenoid Ohmic Heating (OH), eight Poloidal Field (PF) coils and two fast internal control coils. These are used as inputs for modelled power supplies which compute voltages. The models of the power supplies include coil current feedback controllers.

The electron density is controlled in simulations in two different ways. The line averaged density is controlled with a gas puff. Alternatively, the core density can be controlled with the pellet frequency. The pellet launcher actuator realistically represents the AUG injector's pellet sizes and frequencies. A realistic model of the AUG valves is not yet implemented.

β_{pol} control uses normalised power per beam box as it is for DCS. The normalised power from one to eight (corresponding to 1 to 8 Neutral Beam Injection (NBI) boxes) is multiplied by the corresponding power per beam box i.e. 2.5 MW to get the actual power. Pulse Width Modulation (PWM) modulation used at AUG to control NBI is not yet modelled. Instead, a quasi continuous power deposition is assumed in the simulations.

4. Results

To verify the correct implementation of the controllers and the models, several case studies were performed. Simulations of the plasma current control response to a requested step, a step of the vertical position, a change of the shape control mode, feedforward and feedback control of electron density and β_{pol} were performed.

4.1. Plasma current control

During the testing of the plasma current control a step of plasma current from 0.8 MA to 1 MA was requested (see red solid line in top graph of Fig. 1). Plasma current is controlled by the OH circuit which responds with a command to a power supply (green solid line). The simulated change of OH current in the flat-top phase corresponds to the experiments. However, the overshoot in plasma current (blue dashed line) is not typical in real discharges, therefore, this will be further investigated.

4.2. Position control

Vertical and horizontal position control is done using a Multiple Input Multiple Output (MIMO) controller with different inputs e.g. geometrical centre, magnetic axis positions, distance from the outer limiter etc. The effective control quantities can be switched with the control mode. In the simulation a step in vertical position from 0.04 m to 0.045 m was requested for the value *Zsquad* - the vertical coordinate of the plasma current centre. Corresponding commands and coil currents of CoIo and CoIu (i.e. the fast internal control coils) are in good agreement with a real discharge during the flat-top phase, however, during the step request the simulated data have to be validated with real experiments.

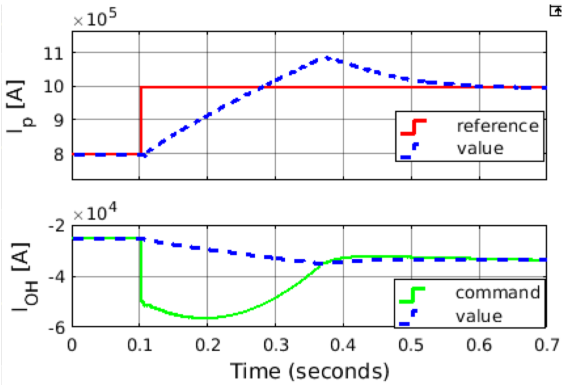

Figure 1: Top: programmed step in plasma current (red solid line) and simulated plasma current value (blue dashed line). Bottom: The response of OH command (green solid line) and simulated OH coil current value (blue dash line).

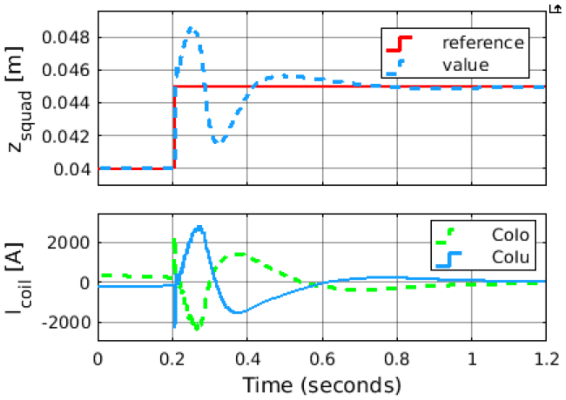

Figure 2: Simulation of a response to a requested vertical position step. Top: requested value (solid line) and simulated response (dashed). Bottom: Command output for the coils controlling vertical and horizontal position.

4.3. Electron density control

The simulation of core density control using pellets with a realistic pellet launcher is illustrated in Fig. 3. The feedback control is switched on at 0.9 s. The frequency is calculated by a pellet controller

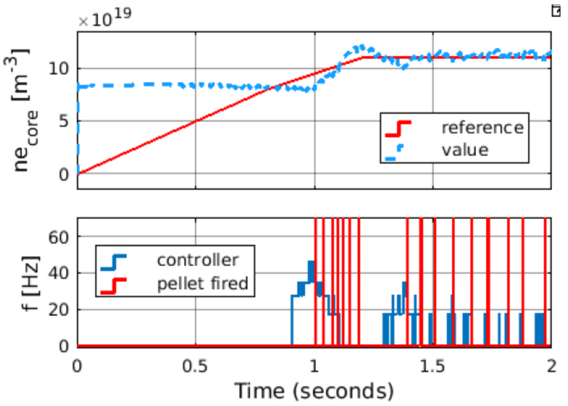

Figure 3: Core density control using pellets. Top: ne_{core} reference (red solid line) and the simulated value (blue dashed line). Bottom: frequency requested from the pellet controller (blue line). The vertical red lines show the time when the pellets were fired. The feedback control starts at 0.9 s.

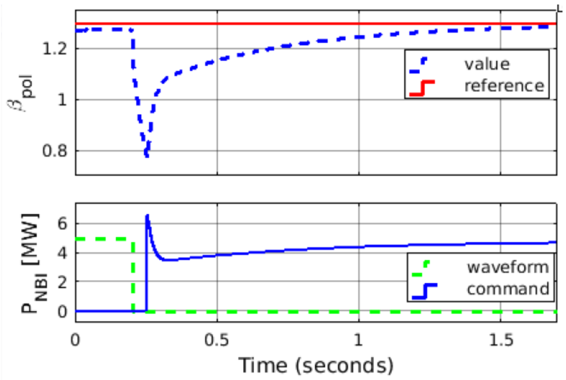

Figure 4: Top: β_{pol} control simulated value (blue dashed line) and the requested value 1.3 (red solid line). Bottom: programmed waveform of NBI is switched off at 0.2 s (green dashed line). The controller starts at 0.25 s requesting NBI power (blue solid line).

(bottom panel blue line). There are visible discrete controller output values because the pellet launcher fires the pellets only in distinct frequencies corresponding to the centrifuge turns. The centrifuge speed is 140 Hz and thus pellets are able to be fired every second, third, etc. turn. The red vertical lines show the time when each pellet was fired. The delay is realistic and is 100 ms, therefore, the first pellets come 100 ms after the first request. Moreover, there are pellets appearing also after the controller requests 0 Hz. This is easy to imagine that there are fired pellets already in the tube "flying" to plasma. To be able to show this simulation we used a 6 times smaller pellet size (6×10^{19} perticles/pellet) than the real one. The response of the core density is not in a good agreement with the real experiments because the absolute values of time scales for density relaxation depend on details of the SOL transport coefficient and geometry which now are put ad-hoc. Later on they will be fit on a database of discharges.

4.4. β_{pol} control

In the simulation for β_{pol} control, the feedforward command for the external heating source was switched off on purpose at 0.2 s (see Fig. 4 green dashed line) to test the behaviour of the controller.Due to the missing heating source, the β_{pol} drops to a value below 0.8 (top Fig. 4 blue dashed line). The β_{pol} control mode was activated at time 0.25 s with request to reach β_{pol} at 1.3. The controller requests NBI power and β_{pol} is brought to the desired value with NBI power 5 MW which is in good agreement with a real experiment.

5. Conclusions

The design and the results show that Fenix can be used as an AUG flight simulator as well as a basic tool to validate physical models or to develop new control modes and strategies. We found good agreement between the behaviour of the simulated heating and coils actuators together with the physical models and the real experiment during the flattop phase. We still have to tune the models for fuelling and check that the coils respond realistically in the cases of the requested steps on the plasma position, current, etc. Moreover, validation over an entire discharge (from breakdown to ramp-down) is necessary, as well over a database of disparate cases.

Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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