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Simulation of burn control for DEMO using ASTRA coupled with Simulink

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Abstract

DEMO is a proposed demonstration fusion power plant which is under design. Fusion power, P_{fus}, has to be controlled to stay above a minimum level to produce sufficient net electricity. However, this has an impact on the power through separatrix, P_{sep}, and thus can produce excessive heat flux to the divertor which can lead to damage. Due to neutron radiation, the materials are even more susceptible to damage for a given heat flux than in non-reactor devices. One way to protect the divertor is seeding plasma impurities to radiate the energy in the scrape-off-layer and in the divertor region before it hits the divertor target plates. This gives a limit for allowable P_{sep}.

The aim of this work is to develop a framework which will give a possibility to design and to test controllers with simulation of DEMO plasma transport. Therefore, we coupled the ASTRA transport modelling code for fusion devices with the Simulink simulation framework. ASTRA is equipped with equilibrium, transport, fuelling, heating and current drive modules. Simulink is a powerful tool to model and to simulate different dynamic systems. It allows fast and simple development of controllers using its built-in blocks. Therefore, coupling of ASTRA with Simulink gives the advantage of fast development of controllers for the power plant modelled with sophisticated physics based on the transport codes.

This coupling was used to run the first basic simulations, where we simulated feedback control of fusion power, power through separatrix and top pedestal Greenwald density fraction, $n_{\mathrm{GW}}^{\mathrm{ped\ top}}$. $n_{\mathrm{GW}}^{\mathrm{ped\ top}}$ is controlled using pellet frequency to keep it below one. Fusion power is controlled with external heating (NBI). To prevent increasing P_{sep} and heat load on the divertor while increasing P_{fus}, xenon gas can be puffed into the vessel. However, P_{sep} has to be kept above a threshold to stay in H-mode. Therefore, feedback control of the xenon gas puff into the separatrix is modelled. These controllers were used to control fusion power, power through separatrix and top pedestal Greenwald density fraction with two different external disturbances. In the first one, we mimicked changes of H-factor and in the second one we mimicked fall of a tungsten flake.

Keywords: tokamak, DEMO, ASTRA, Simulink, burn control

1. Introduction

DEMO [1, 2, 3, 4] is a proposed demonstrative nuclear fusion power station which should produce sufficient and stable net electricity. It is necessary to control fusion power, to provide stable and high enough net electricity output. However, high fusion power can produce high heat flux on the divertor. Therefore, power through separatrix [5] has to be controlled below the melting point of the divertor tiles $\approx 200\,\mathrm{MW}$ (EU DEMO1) but above L-H threshold $> 145\,\mathrm{MW}$ [6].

The controllers have to be well designed and robust otherwise, e.g. badly controlled power through separatrix can lead to severe damage of the divertor and disruptions. Also, it is important to keep the Greenwald fraction of the top pedestal density below 1.0 with some safety margin to avoid density limit disruption.

Presented work is focused on coupling ASTRA code [7], used for modelling transport in DEMO plasma, with Simulink [8] and used for simulation of burn control for DEMO.

Simulink is a wide-spread tool commonly used by control system engineers to model and to simulate dynamic systems. Its built-in blocks and the option to add noise, latencies and disturbances allow fast and simple development of controllers.

ASTRA is a 1.5-D transport code for fusion devices equipped with equilibrium, transport, fuelling, heating and current drive modules. A model of DEMO transport has been developed in ASTRA. Currently, there is no divertor model in ASTRA, no scrape-off-layer (SOL) and shape of plasma is fixed. However, this model will be available in future ASTRA releases. Operation points are set by preprogrammed input values and allow running simulations to study steady state as well as transient evolution. In ASTRA, uncontrolled non-steady state operation can reach computational (physical limits) and leads to sudden stop indicating a loss of control for a real DEMO discharge.

Therefore, control of plasma parameters is necessary. Thus, we can answer questions about DEMO requirements and we can provide feasibility analysis. Simulink con-

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tributes the necessary tools for simulating closed feedback control loops. Coupling of ASTRA and Simulink has already been attempted earlier to control loop voltage with a PID controller [9], however, the coupling method was not described in this work. Therefore, our solution can be different and it will be shortly described in following section.

2. Implementation

Data exchange between ASTRA and Simulink is accomplished via shared memory. At the beginning of each simulation, Simulink starts ASTRA. Then ASTRA, as well

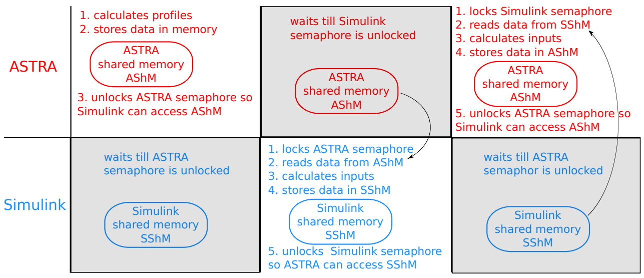

Figure 1: Synchronisation and data exchange between Simulink and ASTRA. Grey fields illustrate a waiting process. Column two and three are continuously repeating. The first column sketches initialisation.

as Simulink each creates semaphores and shared memory regions for synchronisation and data exchange (see Fig. 1). During initialisation semaphores are locked. First, ASTRA computes profiles and stores them in the ASTRA shared memory - AShM. Then ASTRA unlocks ASTRA semaphore (created by ASTRA). Till this moment Simulink is waiting for ASTRA semaphore. Then Simulink locks ASTRA semaphore, reads the ASTRA outputs from AShM, computes control responses and stores them to Simulink shared memory (SShM). Subsequently, it unlocks the Simulink semaphore which allows ASTRA to read new system inputs. The sequence of reading, calculating, writing and unlocking is repeated for each simulation step. This way time is running the same way for Simulink and for ASTRA, therefore, they are synchronised. Semaphores prevent reading old data or partially written data.

In all these simulations we used a simulation step of 0.01 s. Comparing runtime of the standalone ASTRA simulations of the ASTRA-Simulink coupling we obtained following results. A simulation of 100 s DEMO plasma discharge, in combination ASTRA coupled with Simulink, takes $\approx$ 70 s. of computer time. Standalone ASTRA simulation with plotting profiles on the screen takes approximately the same time. However, standalone ASTRA simulation running in the background (without plotting) takes $\approx$ 30 s. Coupled ASTRA with Simulink running ASTRA on the background, with commented Simulink scopes and without saving data also takes $\approx$ 30 s. So the coupling of ASTRA with Simulink did not significantly increase simulation time.

3. Simulations and results

In this work we simulated two different cases; change of a transport coefficient (energy diffusivity) and injection of a tungsten impurity. In both cases we compared ASTRA running in open loop without external controllers with ASTRA parameters controlled by PI (Proportional-Integral) regulators in Simulink.

In open loop mode, 20 MW of external power from neutral beam injection (NBI) is injected, together with a constant xenon puff of 0.57×10^{19} particles /second and with a pellet injection frequency of $f = 2.2$ Hz. These settings give the fusion power, $P_{\rm fus} \approx 2$ GW, power through the separatrix, $P_{\rm sep} \approx 162$ MW and the Greenwald density fraction at the top of the pedestal, $n_{\rm GW}^{\rm ped\ top} \approx 0.95$. The pellet ratio between deuterium and tritium was set to 1:1 in all simulations. However, when the transport coefficient changes or the tungsten impurity is injected in order to simulate a perturbation, then controllers will adjust NBI heating power, xenon gas puff and pellet injection frequency to compensate the resulting changes of $P_{\rm fus}$, $P_{\rm sep}$ and $n_{\rm GW}^{\rm ped\ top}$.

In these simulations we used three simple PI controllers. One controls the fusion power, commanding neutral beam injection (NBI). The second one changes the flow of the xenon gas to control the power through separatrix. The third one controls the density Greenwald fraction at the top of the pedestal with changing of the pellets frequency. The three controllers are set to control $P_{\rm fus} = 2$ GW, $P_{\rm sep} = 180$ MW and $n_{\rm GW}^{\rm ped\ top} = 0.95$. As it can be seen, the reference values are the same values as are set for open loop simulation.

3.1. Change of the transport coefficient

One application is to mimic increasing neoclassical tearing modes (NTM) activity leading to a decrease of the of H-factor [10, 11] and finally fusion power. When NTMs are suppressed then H-factor rises back to the value before NTM [12, 13]. However, there is no NTM model implemented in ASTRA. Therefore, the transport coefficient c

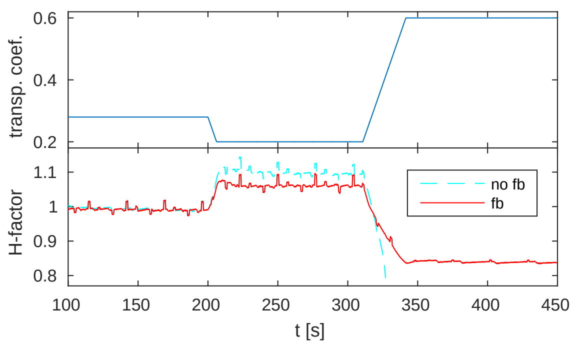

Figure 2: Top: transport coefficient (energy diffusivity) changed by Simulink. Bottom: H-factor response according to the changes in transport coefficient.

in the plasma core ($\rho = 0 \to 0.96$) from Eq. 1 was changing (see top Fig 2) that at the beginning H-factor was between

0.97 to 1. After that c was changed so the H-factor stays 1.1 for 90 s and then H-factor decreases to 0.85 (see bottom Fig. 2).

$$\chi_i = c\frac{T_\mathrm{e}^{3/2}}{B^2}q^2\frac{\mathrm{d}p}{\mathrm{d}\rho}\frac{a}{p}. \tag{1}$$

T_e is the electron temperature, B is the magnetic field, q is the safety factor, p is the plasma pressure, a is the minor radius and $\rho = \sqrt{\frac{\Phi}{\pi B_0}}$, where Φ is toroidal flux and B_0 is vacuum field. For L-H transition ($\rho = 0.96 \rightarrow 1$) we used Eq. 2:

$$\chi_i = \frac{c_1\frac{R}{L_{T_\mathrm{i}}}}{1+c_2\gamma_\mathrm{E}^2} + c_3\left(\frac{\beta_\mathrm{ped}}{c_4}\right)^4 + \chi_\mathrm{neo}, \tag{2}$$

where $c_{1,2,3,4}$ are fixed constants scaling pedestal (with top pedestal temperature $T = 6\,\mathrm{keV}$), R is major radius, L_{T_i} is logarithmic temperature gradient, γ_E is $E \times B$ shear, β_ped is pedestal pressure normalised to magnetic pressure and χ_neo is neoclassical transport.

The changes of the H-factor directly affect P_fus. Increasing of H-factor increases P_fus and vice versa.

The reason is, that while in the feedback controlled simulation P_fus is controlled by NBI (see Fig. 3), in the non

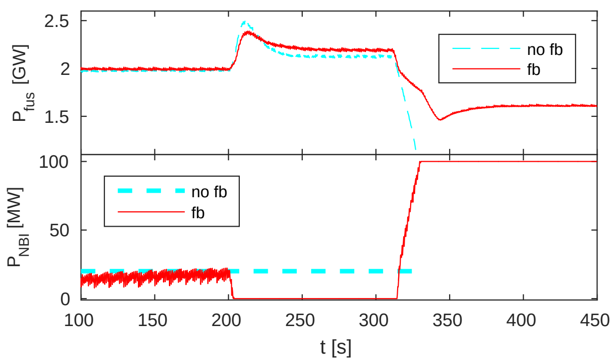

Figure 3: Top: Fusion power feedback controlled and non controlled. Bottom: NBI power for feedback controlled and non controlled ASTRA simulation

controlled simulation NBI has the constant power 20 MW. Therefore, P_fus changes in the open loop simulation more than when feedback controlled. However, full compensation of P_fus is not possible with the simple PI controller using only NBI as an actuator because the controller's command output is limited by the assumed maximal installed NBI power $P_\mathrm{NBI} = 100\,\mathrm{MW}$).

When P_fus changes it also influences P_sep. There are two critical limits for P_sep. The first one is the bottom limit, when P_sep has to be bigger than $P_\mathrm{L-H} \approx 145$ MW and the second one has to be below the critical value for divertor damage $P_\mathrm{sep} < \approx 200\,\mathrm{MW}$. This is ensured injecting xenon gas into the separatrix. When xenon gas puff is constant, P_sep reaches values higher than 250 MW but also 0 MW. With feedback control P_sep is between 160 MW to 205 MW. The open loop simulation is unstable because fusion power drops very fast (Fig. 3) as well as power through separatrix (see Fig. 3). When P_sep is below

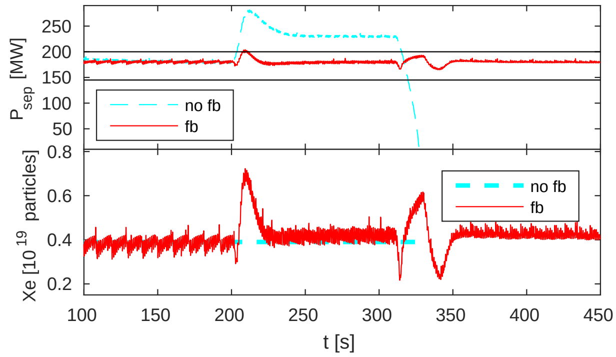

Figure 4: Top: Power through separatrix controlled by feedback and non controlled. Bottom: Xenon gas puff for feedback controlled and non controlled ASTRA simulation

$P_\mathrm{L-H}$ threshold, confinement is lost and decrease is even faster. $P_\mathrm{L-H}$ in the model is approximately 150 MW.

3.2. Injecting tungsten impurity

In the second simulation, we tried to mimic a tungsten flake falling into the plasma. Presently, there is no scrape-off-layer (SOL) model available in ASTRA. Therefore, the tungsten flake in total amount of 3 mg was mimicked as a gas, puffed into the separatrix during 100 ms at time 200 s (vertical dashed line in Fig. 5). The total flux of tungsten

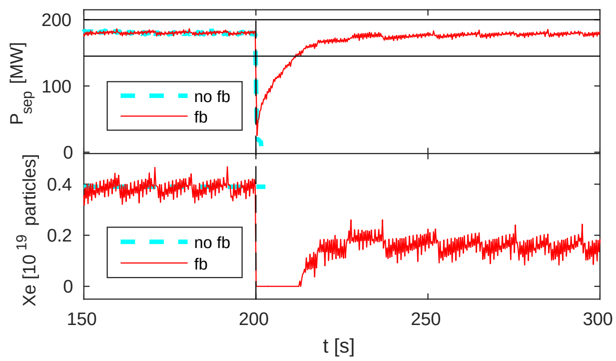

Figure 5: Top: Power through separatrix controlled by feedback and with constant inputs. Bottom: Xenon gas puff for feedback controlled and non controlled ASTRA simulation

is 20 times bigger than the averaged xenon impurity puffed to the separatrix. When the tungsten is injected, P_sep will immediately drop below the $P_\mathrm{L-H}$ threshold. If simulation is without feedback, P_sep drops below $P_\mathrm{L-H}$ threshold). As a consequence P_fus drops below 1.75 GW, the high confinement is lost and P_sep drops to 0 MW. The plasma reaches unreasonable values and simulation is stopped.

With the feedback controlled gas puff, the xenon puff immediately drops to zero to compensate cooling of the separatrix caused by the tungsten radiation (bottom graph of Fig. 5). P_sep reaches its reference value again after 11.5 s. Decrease of P_fus is compensated with increase of the NBI power for a couple of seconds.

From these two simulations, one can see, how strongly P_fus and P_sep are coupled. Decreasing the power through

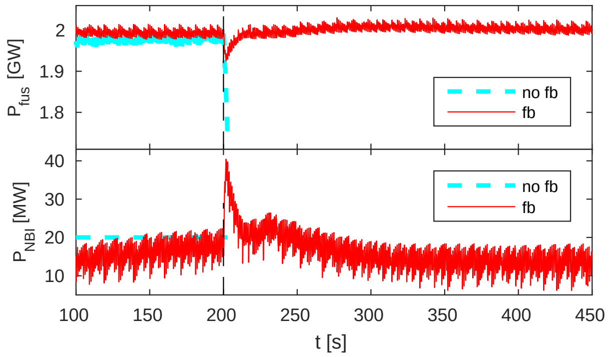

Figure 6: Top: Fusion power feedback controlled and non controlled. Bottom: NBI power for feedback controlled and non controlled ASTRA simulation

separatrix decreases also the fusion power and vice versa. Therefore, to provide good, stable and reliable fusion power plant, a new multiple input - multiple output controller needs to be designed, where few actuators have to act simultaneously to keep all parameters at the requested values and with safety margins. This is foreseen for the next step of the design.

4. Conclusion

In this article the coupling of ASTRA with Simulink was presented. The combination provides the opportunity to control the ASTRA DEMO model using feedback controllers. The coupling was implemented via shared memory where semaphores are blocking and allowing access to the shared memory and thus proper synchronisation is ensured.

Using this system, control of the fusion power and the power through the separatrix was investigated by simulations. In the first simulation, the transport coefficient (energy diffusivity) was changed so H-factor was changing accordingly. Uncontrolled P_{fus} and P_{sep} exceeded the allowed limits. However, the controlled simulation stabilises P_{sep} and reduced changes of P_{fus}. For this reason, a new controller, when P_{fus} and P_{sep} will be controlled together with different actuators (NBI, pellet frequency and xenon gas puff), has to be developed. These simulations already are indications that 100 MW of NBI will not be sufficient to compensate fusion power drops when H-factor decreases significantly. Either more NBI power has to be injected or electron cyclotron resonance heating (ECRH) has to be added. Also ECRH should be included in the MIMO controller, which is delicate, because ECRH is supposed to be used also for NTM control, where we will implement a local model of NTM and its dynamics.

Second simulation shows, that even a small amount of the tungsten flake can have a big impact on the plasma and that the reaction of the xenon gas puff has to be fast. Also it might be necessary to immediately increase the fusion power by ECRH, NBI or increasing the pellet frequency. Otherwise, the transition H-L can occur and the fusion power will be insufficient.

Controlling the top pedestal density Greenwald fraction using the pellet frequency was not necessary because of sufficient margin to the limits. None of the limits was hit in any of the simulations. However, when MIMO controller is used, then limits will have to be considered and applied also in the controller.

Both these experiments will be repeated with the new SOL model implemented in ASTRA. Also, this coupling ASTRA with Simulink will be used for implementing a MIMO controller, ramping from the L to H transition and implementing more realistic actuators and diagnostics with latencies and disturbances.

5. Acknowledgement

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