LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-JRNL-231396

ITER Shape Controller and Transport Simulations

T. A. Casper, W. H. Meyer, L. D. Pearlstein, A. Portone

June 1, 2007

Fusion Engineering and Design

Disclaimer

ITER Shape Controller and Transport Simulations

T.A. Casper[1], W.H. Meyer[1], L.D. Pearlstein[1] and A. Portone[2]

[1]Lawrence Livermore National Laboratory, University of California, Livermore, CA 94550 USA
[2]EFDA0CSU Barcelona, C/Josep Pla 2, B3, 08-10 Barcelona, Spain

ABSTRACT: We currently use the CORSICA integrated modeling code for scenario studies for both the DIII-D and ITER experiments. In these simulations, free- or fixed-boundary equilibria are simultaneously converged with thermal evolution determined from transport models providing temperature and current density profiles. Using a combination of fixed boundary evolution followed by free-boundary calculation to determine the separatrix and coil currents. In the free-boundary calculation, we use the state-space controller representation with transport simulations to provide feedback modeling of shape, vertical stability and profile control. In addition to a tightly coupled calculation with simulator and controller imbedded inside CORSICA, we also use a remote procedure call interface to couple the CORSICA non-linear plasma simulations to the controller environments developed within the Mathworks Matlab/Simulink environment. We present transport simulations using full shape and vertical stability control with evolution of the temperature profiles to provide simulations of the ITER controller and plasma response.

1. Introduction

As we begin construction of the ITER experiment, assessment of its discharge performance becomes critical to meeting the goals of experimental operations. Scenarios are being studied by a variety of groups using several different transport codes [1,2]. Our CORSICA code [3] has been used to study both ITER performance in various reference scenarios and to explore issues of diagnostic suitability [4]. In CORSICA, we use a 2D equilibrium package that runs in either fixed- or free-boundary mode or in combination of the two. These are coupled to 1D transport with a variety of models and sources that are simultaneously converged at each time step in the simulated discharge evolution. This unique suite of capabilities allows us to take a variety of approaches to explore operation of experiments. Benchmarking of the code is obtained through its use to predict [5] and analyze [6,7] operation on DIII-D.

Previously, CORSICA's equilibrium package (TEQ) was used to design the poloidal field (PF) coil system and explore controller operation on ITER during the EDA and CDA design efforts. We have revised and improved this capability and added the necessary modifications to allow ITER-FEAT control simulations with transport to study more realistic discharge operating scenarios. We now provide multiple options for exploring controls scenarios for experiments such as ITER. Our "scenario control evaluation" mode extends the original scenario performance operation running in fixed-boundary mode to include free-boundary evaluation of the control parameters such as, for example, the central solenoid (CS) and PF-coil voltage demands. We have also improved on our original "internal free-boundary controller" mode where the state-space control matrix representation is imported into the internals of the code as we have done for ITER. We have recently developed a new "code-coupled free-boundary controller" mode using a remote procedure call interface to the Matlab/Simulink software environment to extend the use of CORSICA for more flexible and rapid development and testing of prototype controllers.

In this paper, we will define these various CORSICA operational modes and provide examples of their respective execution. We are currently using this suite of tools in our research on the DIII-D National Fusion Facility to design, analyze and benchmark these capabilities as well as apply them to predictions for ITER. A series of ITER-scaled experiments is a recent focus of some experimental activities on DIII-D.

2. Scenario Control Evaluation (SCE) mode

We simulate the time-dependent scenario performance in CORSICA using the fixed-boundary mode with a sequence of prescribed boundary shapes representative of the desired output of a shape controller. We interpolate between shapes over time to achieve the shape evolution of the equilibrium that is then solved with a transport model to evolve the discharge characteristics and evaluate the controller performance in these 1 ½ D transport simulations. The equilibrium and transport (with source evaluation) are converged at each time step. For the "control evaluation", we then solve the free-boundary equilibrium using updated kinetic data (density, temperature, and q profiles) resulting from the transport step to determine the separatrix, flux linkage to the external circuits and coil currents. We use the fixed-boundary shape as a mean-square constraint on the free-boundary separatrix. This avoids the need to use a true controller for shape and, more importantly, does not require control of the vertical position. Thus, we can run simulations with relatively large time steps and maintain robust operation that allows one to efficiently assess performance over the full discharge evolution in a rather short code execution time. We show in figure 1 one such example for a Q=14, P_{fus}=550MW ITER discharge using "scenario2-like" conditions [8].

In these simulations, an H-mode-like analytic profile is used to model the density. It is adjusted to be narrow during ramp up and broadened for H-mode conditions at high auxiliary power input. The temperature profiles are determined from the assumed transport model, typically used is GLF23 [9] without rotation over most of the profile and the edge (where GLF23 is known not to be valid) by a scaled L-mode [10] model. The overall minimum thermal conductivity is set to neoclassical values. Note that we do not set the pedestal temperature but rather determine it from details of the transport model used. Considerable research is on-going to provide a self-consistent pedestal transport model along with improved models for core transport (e.g. TGLF[11]). These can be added when made available to the fusion community. In the latter sections of this paper, we will use these same scenario simulations with the state-space controllers.

Since we include all the external circuits in this mode of operation, with the calculation of the external flux linkage we can "back out" the controller currents that are consistent with maintaining shape in this discharge. The current demand for the PF- and CS-coil control for this simulation is shown in figure 2. As we show, during the current ramp up and flattop the predicted coil currents are consistent with the reference scenario values shown. There is no specification as to the ramp down and we use our own parameter variation to bring the simulated ITER discharge from full power at 15MA to 5MA with no auxiliary power input where we stopped the simulation. In figure 3, we show the free-boundary-determined shape evolution for this simulation during plasma current ramp up, flattop and ramp down. We note that in this simulation we are not constraining the divertor strike point so we have some difficulty in achieving the desired X-point location during portions of the simulated evolution. This is dependent on the transport characteristics being used. In previous simulations with prescribed beta and internal inductance (l_i) profiles, we did not observe the small variations in the X-point and divertor strike point locations. If we choose to constrain the strike point, we obtain better flux-mapping into the divertor at the expense of small errors in the plasma shape. In controller simulations where we control the strike point we do not see these variations. We are still studying these issues and note they are more pronounced with highly peaked edge bootstrap current and the resolution in the free-boundary solution. In figure 4, we show plasma parameters representative of the discharge evolution and note in passing that the l_i variation is not consistent with the scenario2 variations particularly during ramp up. Exploration of these physics issues is beyond the scope of this paper.

3. Controlled Operation Modes

In figure 5 we show a block-diagram representation of a recent version of the ITER-FEAT shape controller (Joint Central Team February, 2001) that we have installed in CORICA using two methods. In the “closely coupled” version of the code, the state-space matricies and the feedback control loops are all coded inside the CORSICA environment. The primary advantages of the internal implementation are code development and debugging and simulation performance. We have all the advantages of our scripting-language environment and graphics to facilitates code development both to implement and to use the controller. The disadvantage of this approach is that each unique controller (different controllers for ITER or controllers for different experiments) requires code development and implementation of any experimental details. A distinct operational advantage is we can run the simulations with implicit, time-centered advancement of the transport that allows for much larger time increments when evolving the discharge. This leads to shorter execution times when studying controller performance over long times.

We have also developed a code-coupling package for our CORSICA simulator to connect it to remote processes running under the Matlab/Simulink commercial software used by several groups for controller development [12]. This has an advantage of clearly separating the controller environment from the non-linear plasma transport simulation. It provides a potentially more flexible method for development and testing of controllers. It offers the opportunity for pushing most details of a particular experiment out to the controls environment, e.g. the details of the power supply configuration and characteristics are handled by the controls developers rather than by the plasma modelers. This is particularly true with the development of a generic interface between controllers and simulations [13]. Our code-coupling package uses remote procedure calls between the simulation and controller processes that need not be running within the same computers or even at the same site. As indicated in the diagram in figure 6, this allows computationally expensive non-linear plasma simulations to run in parallel compute clusters while the controller can run it its own environment. A potential disadvantage of this method, however, is that we currently must run transport explicitly since the simulink-based controller is determining the time advancement. Optimization of this coupling will be the focus of future work. One step in this direction is the ability to run with the internal implementation maintaining vertical stability control while using the code-coupled version to study shape control over long time scales.

In addition to the coupling between CORSICA and simulink, we also use the MDSplus data system (a US standard for data acquisition and archival [14]) for storing results of simulations, the modeling analog of MDSplus-based data acquisition from experiments. MDSplus is also used for executing some analysis tasks. We use the Java Scope Display package provided with MDSplus to display simulation output during the simulated discharge evolution or when post-processing data stored in MDSplus.

4. Simulation Results

As shown in figure 5, the CORSICA simulator indicated by the simulation block in the feedback diagram accepts control voltage demands determined from the controller, whether from simulink or internally. This input is used for solving a free-boundary equilibrium at each time step along with the transport model determining the electron and ion temperature profiles and alpha-particle density given a prescribed electron density profile. Once converged, CORSICA provides flux data (controller gaps) output from the equilibrium solution back to the controller. We have done simulations using this ITER-FEAT controller for the flattop phase of the discharge for both the internal and code-coupled versions of CORSICA. The scenario modeled is similar to that shown in section 2 for the SCE-mode of running the code.

We show in figure 7 results of a flattop simulation from 100s to 400s using the internal feedback controller mode for conditions similar to the ITER discharge scenario simulation presented in Section 2. This simulation uses both thermal transport and heating source simulation with the ITER controller maintaining vertical position and shape. We run the controller during the interval when auxiliary heating power is increased to achieve burn conditions and then termination of the heating before current ramp down. In figure 8, we show results obtained with the transport code coupled to simulink that similarly demonstrates plasma shape control for evolution from 100s to 150s. We are just beginning to study the small differences between these simulations that relate to time-stepping differences between the internal implicit code operation and the explicit time stepping used by the simulink model. In both cases, the ITER controller maintains good control over the discharge burn phase as can be observed by the shapes shown in figures 7 and 8. The gap control locations outside the divertor region provide good control with minimal shape variations. The two gap control points inside the divertor maintain good control of flux mapping into the divertor region. Shape variations away from the gap control points are influenced by the edge bootstrap current peak coming from the H-mode density profile and the pedestal temperature.

6. Summary

We have developed the capability for evaluating controllers in combination with scenario modeling for ITER. Multiple techniques are available to study controller performance. The most robust mode of simulation is the SEC where fixed-boundary evolution is used for scenario studies and free-boundary calculation allows us to evaluate the controller parameters, e.g. coil currents and volt-second demands for a given scenario. Full free-boundary evolution with transport and sources allows us to demonstrate and evaluate controller performance. The internal code implementation now available for ITER studies provides the most efficient means to study controller performance over long time-scales where both vertical stability and shape are controlled. The code-coupled version provides a flexible means for rapidly prototyping controllers under development without the need to import the specifics of the experiment or details of the external systems into the code.

Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No.W-7405-Eng-48.

References

[1] See http://www.pppl.gov/snowmass_2002/snowmass02_report.html

[2] A.R. Polevoi, et al., Plasma Phys. Control. Fusion 48, A449-A455 (May 2006).

[3] J.A. Crotinger, et al., LLNL Report UCRL-ID-126284, 1997 available from NTIS #PB2005-102154

[4] T. A. Casper, *et al.*, Rev. Sci. Instrum. **75**, 4193 (2004).

[5] T. A. Casper, *et al.*, Plasma Phys. Control. Fusion **45** (July 2003) 1193-1208.

[6] T. A. Casper, *et al.*, Plasma Phys. Control. Fusion, **48** (May 2006) A35-A43

[7] T. A. Casper, *et al.*, IAEA-CN-149/EX/P6-4, Proc. of 21st IAEA Fusion Energy Conference, Chengdu, China, 2006, to be published in Nuclear Fusion

[8] Y. Gribov, private communication

[9] R, Waltz, *et al.*, Phys. of Plasmas 6 (1995) 2408.

[10] S.C. Jardin, *et al.*, Nucl. Fusion 33 p371 (1993).

[11] G.M. Staebler, *et al.*, Phys. Plasmas 12, 102508 (2005).

[12] M.L. Walker, *et al.*, IEEE Control System Magazine 26, p35 (2006).

[13] D. Humphreys, *et al.*, this meeting

[14] see www.mdsplus.org

Figures

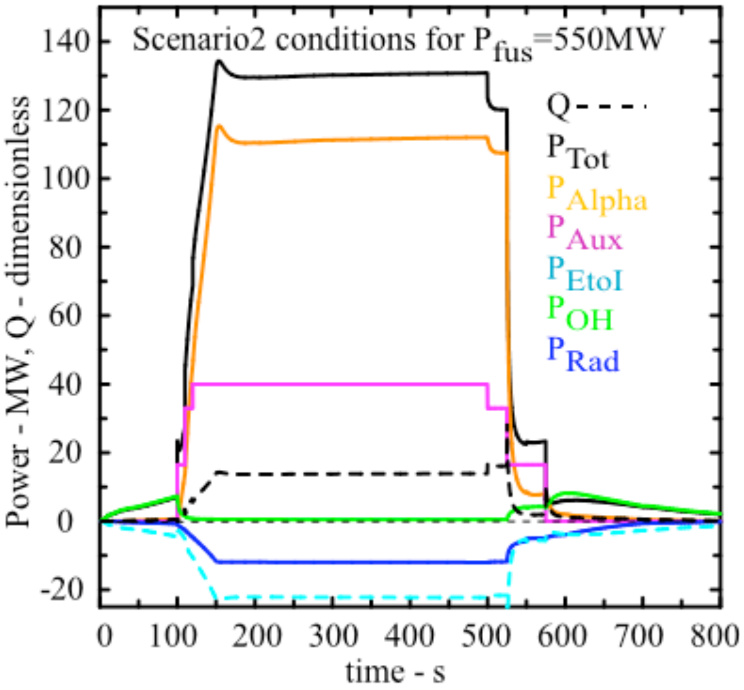

Figure 1 ITER simulation used for studying controllers based on Scenario2 parameters: Q=14 at P_{Fusion}=550MW with performance determined by edge transport pedestal conditions.

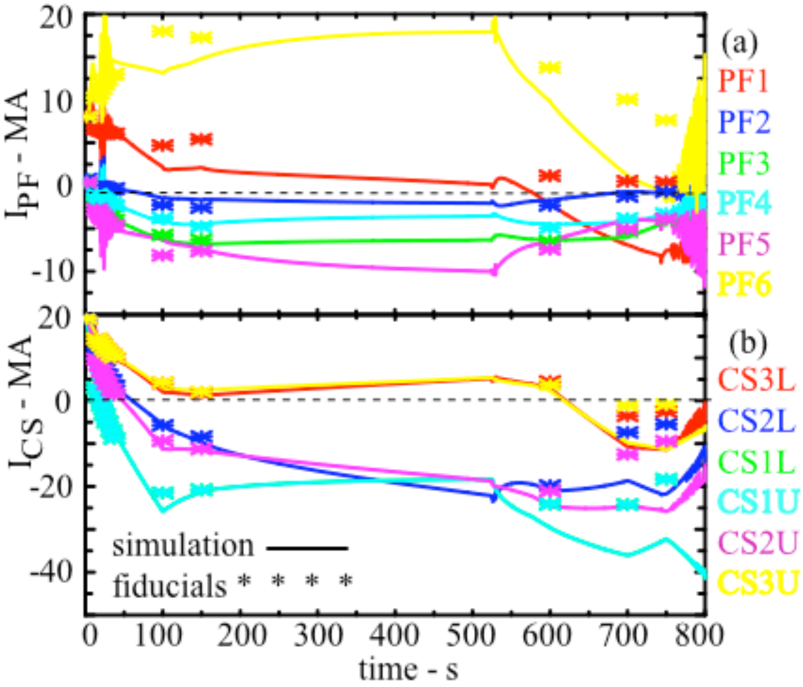

Figure 2 (a) PF coil currents and (b) CS coil currents obtained with the "scenario control evaluation" mode of running to evaluate the controller demands. There is generally good agreement between the simulated evolution and the reference currents used to generate the fiducial shapes.

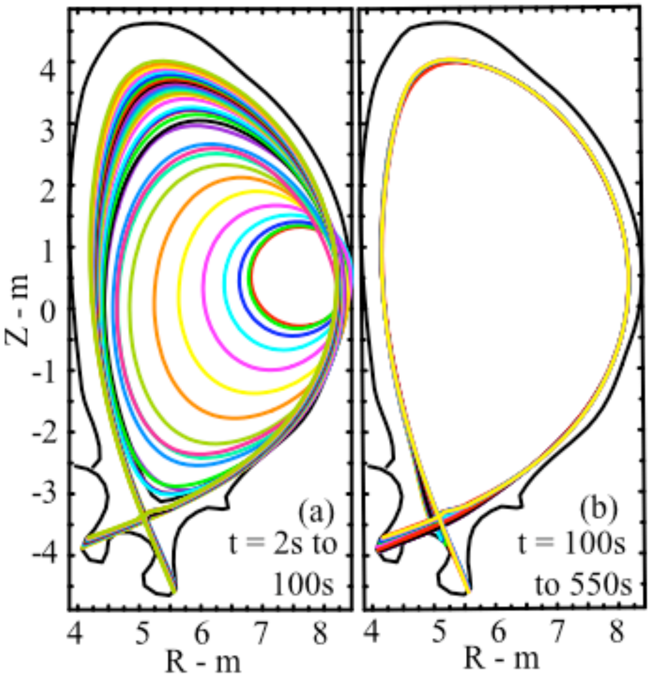

Figure 3 Shape evolution during plasma current ramp up (a) and flattop (b) using fiducial design shapes.

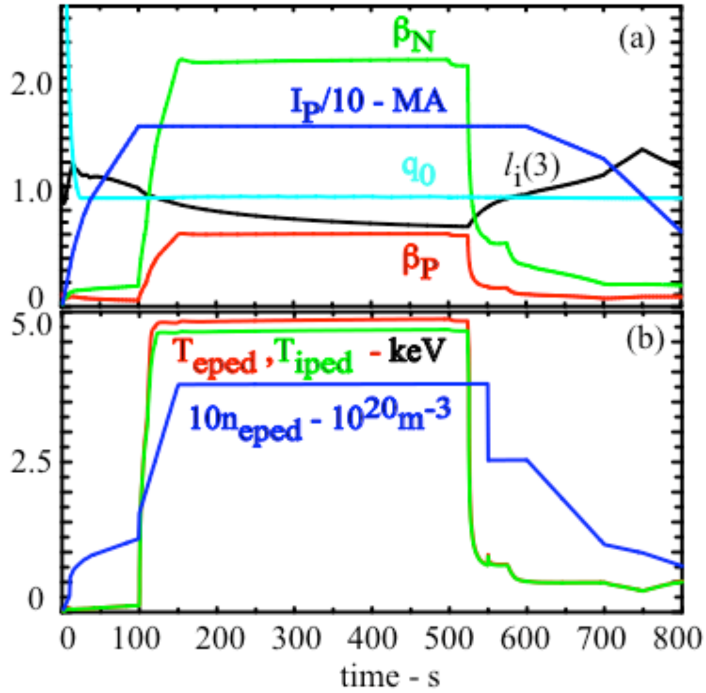

Figure 4 ITER performance parameters for the reference simulation of Scenario2 conditions where I_p is the plasma current, q_0 the safety factor at the magnetic axis, $l_i(3)$ the internal inductance, β_P and β_N are the plasma and normalized betas, T_{eped} and T_{iped} are the pedestal temperatures in keV and n_{eped} is the pedestal density in m^{-3}.

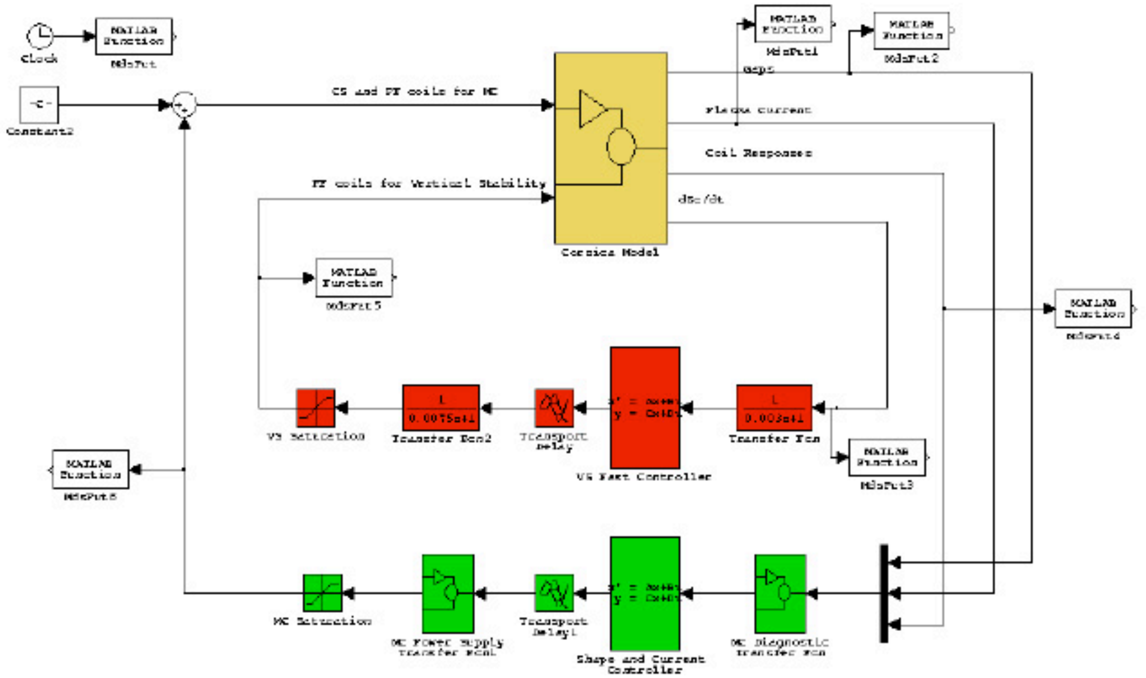

Figure 5 Block diagram of ITER controller used in the code-coupled mode connecting to the Simulink environment. The feedback loops and matricies were also implemented inside CORSICA to provide the internal controller capability.

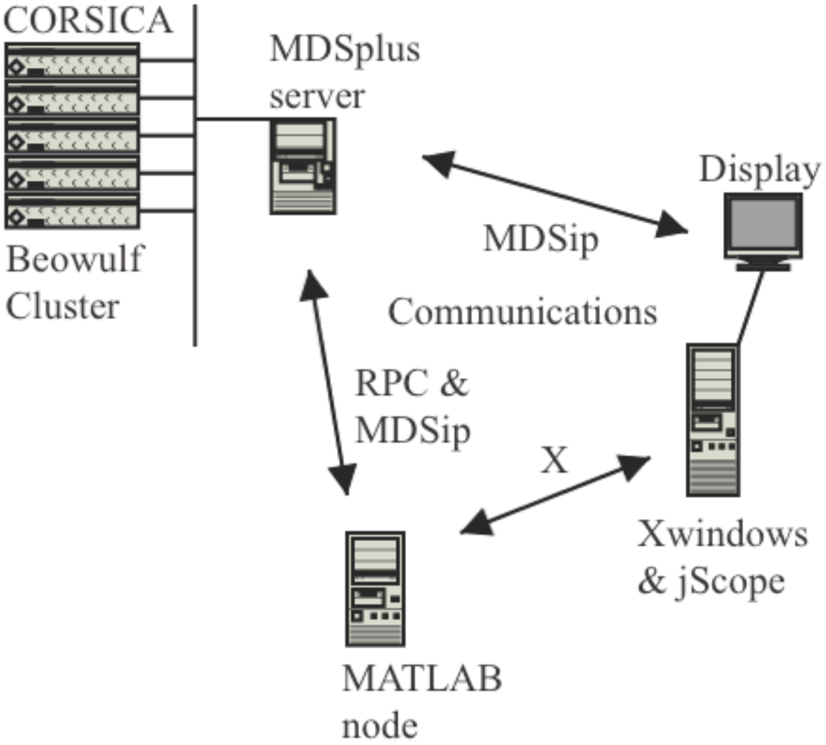

Figure 6 Code-coupling environment for connecting CORSICA to Simulink.

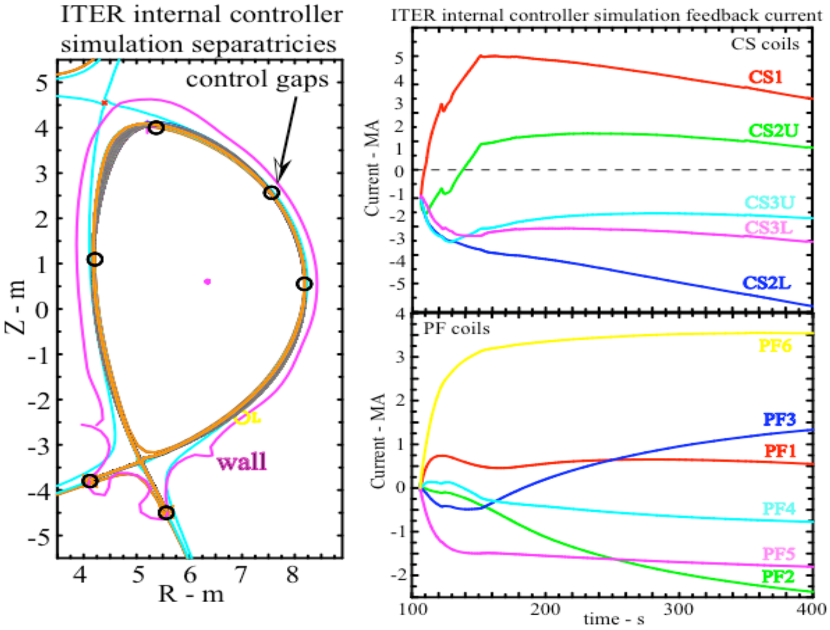

Figure 7 Plasma shape evolution with PF and CS coil currents for the Scenario2 simulation with the internal controller. The shape and divertor flux mapping is well controlled by the ITER controller.

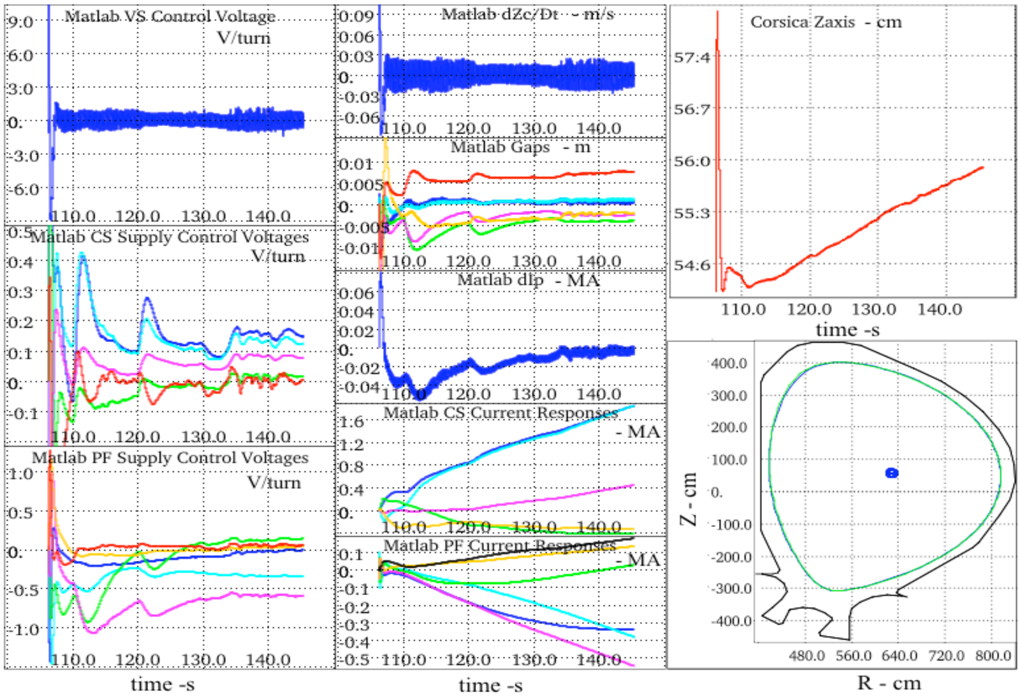

Figure 8 jScope display for code-coupled free-boundary evolution. The CS, PF and gap measurements respond to the increased auxiliary heating power: increase of 16.5MW at 110s and 7MW AT 120S resulting in the burn phase of ITER scenraio2. Good shape control is maintained by the ITER controller during auxiliary and alpha particle heating during the plasma burn.