# GRT-519
# ITER Plasma Control

# Final Meeting

## Design of a realistic feedback+feedforward control scheme able to manage the whole plasma pulse

Presented by A. Pironti

# Status of the task

| **Task N.** | **Task title** | **Responsible Officer** | **Subtasks** | | | |
|---|---|---|---|---|---|---|
| | | | N. | **Title** | **Principal Investigator** | |
| 3 | Plasma axisymmetric magnetic control | A. Pironti | 3.1 | Design of the feedback controllers for limited and diverted configurations with and without the use of the VS3 inner vessel vertical stabilization coils | A. Pironti (CREATE) | ☑ |
| | | | 3.2 | Analysis of a feedforward action to cope with unforeseen H-L transition | R. Ambrosino (CREATE) | ☑ |
| | | | 3.3 | Design of a realistic feedback+feedforward control scheme able to manage the whole plasma pulse | M. Ariola (CREATE) | ☑ |

- Subtask 3.1: after an initial phase we focused on design based on the use of the VS3 (results of PM2)
- Subtask 3.2: Results are in this presentation
- Subtask 3.2: The scheme has been discussed in PM3, but we have made some modification (discussed here). The scheme has been validated on nonlinear simulations (see presentation from Roberto)

# The controlled variables

- The current flowing in the PF & CS coils
- The plasma current
- The centroid vertical velocity
- The current in the VS3 circuit (auxiliary variable needed for vertical stabilization instead of the centroid vertical position)
- Plasma shape descriptors (which change during the scenario phases)

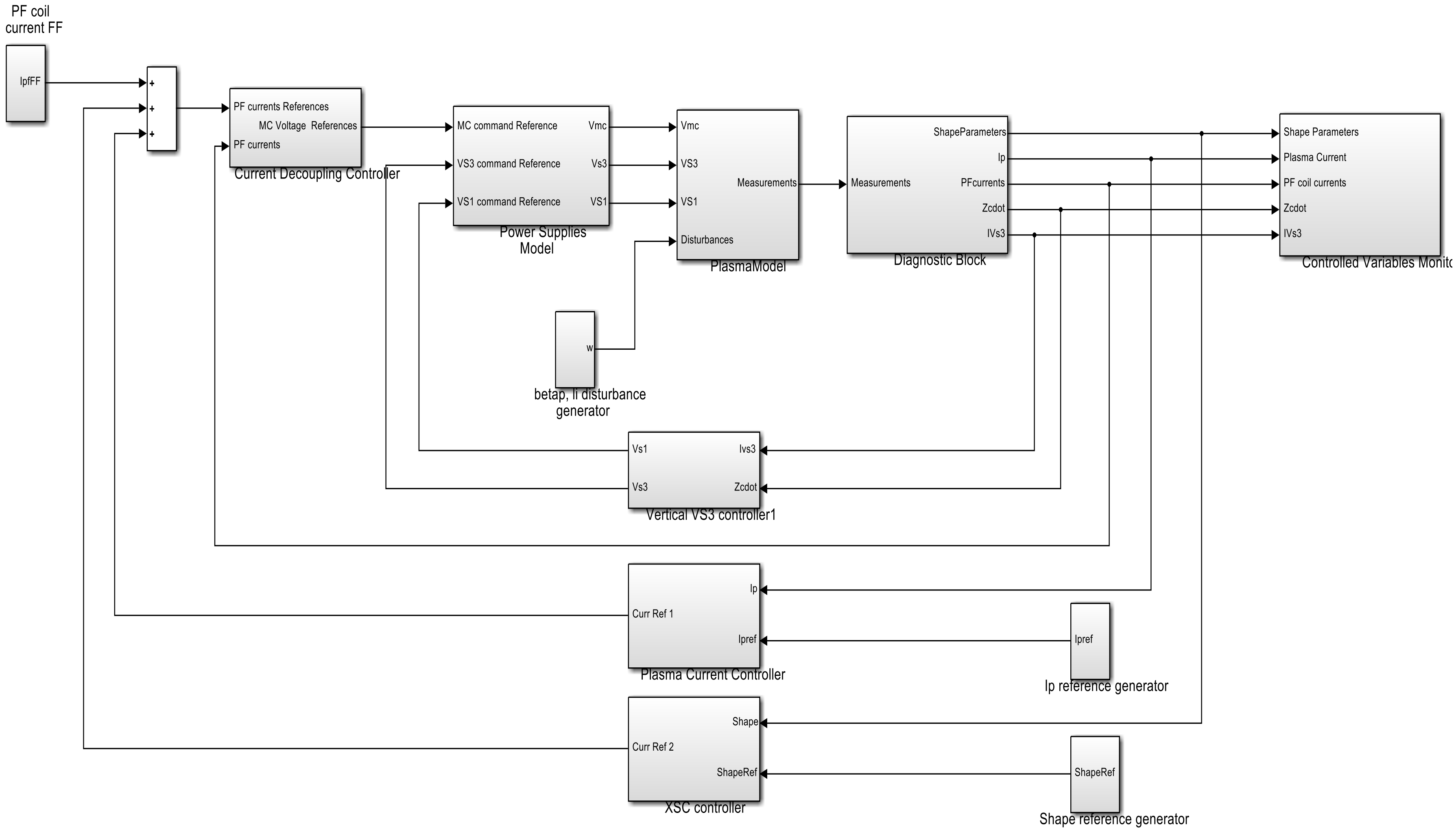
# Plasma shape descriptors

- We considered the following scenario
  - Initial phase (just after the initiation phase): the controlled variables are the vertical position of the current centroid and a radial flux difference;
  - Limiter phase: The controlled variables are the position of the limiter point, and a set of flux differences (isoflux control)
  - Limiter to divertor transition phase: The controlled variables are the position of the X-point (not necessarily active), and a set of flux differences (isoflux control)
  - Diverted phase: The controlled variables are the plasma current and a set of gaps describing the plasma shape (gap control)
  - Divertor to limiter Transition phase: The controlled variables are the plasma current, the position of the X-point (not necessarily active), and a set of flux differences (isoflux control)
  - Limiter phase: The controlled variables are the position of the limiter point, and a set of flux differences (isoflux control)
- Note that we have not carried out an analysis of the initial phase and of the divertor to limiter phase

# Actuator used

- Main converters of the CS & PF coils to control the current flowing in them
- VS3 power supply for plasma vertical stabilization
- VS1 power supply to reduce the current in the VS3 coil

# The general scheme



# The control system structure

- The control system consists of 4 independent controllers
  - The current decoupling controller
  - The vertical stabilization controller
  - The plasma current controller
  - The shape controller
- In principle the parameters of each controller can change on the base of events generated by an external supervisor (the simplest one being a clock)
- The plasma current controller and the shape controller generates references for the current decoupling controller

# The current decoupling controller (CDC)

- The current decoupling receive in input the CS & PF coil currents and their references, and generate in output the voltage references for the main converter
- In the general scheme the CS & PF coil current references are generated as a sum of three terms coming from
  - a scenario supervisor which provides the nominal currents needed to track the desired scenario
  - the plasma current controller which generates the current deviations (with respect to the nominal ones) needed to compensate errors in the tracking of the plasma current
  - the plasma shape controller which generates the current deviations (with respect to the nominal ones) needed to compensate errors in the tracking of the plasma shape

# Structure and design of the CDC

- The CDC equations are

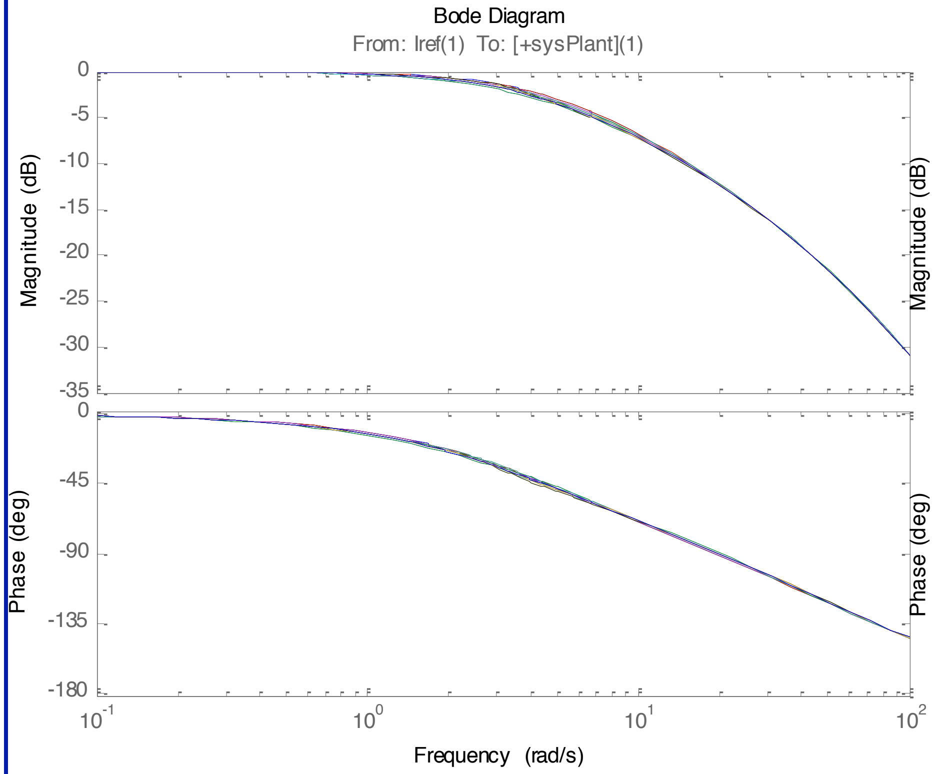
$$V_{PF} = K_c\left(I_{PF,ref} - I_{PF}\right) + R_{PF} I_{PF}$$

- the second positive feedback term is needed to compensate the residual resistance (due for example to the bus bar) of the CS & PF coils (this term is not present in our simulation, where $R_{PF}=0$).
- The choice of compensating the residual resistance allows to obtain a zero steady state error in the tracking of constant current references and a finite steady state error in the tracking of ramp current references
- The feedback matrix $K_c$ is designed in such a way to assign the desired closed loop bandwidth to the system

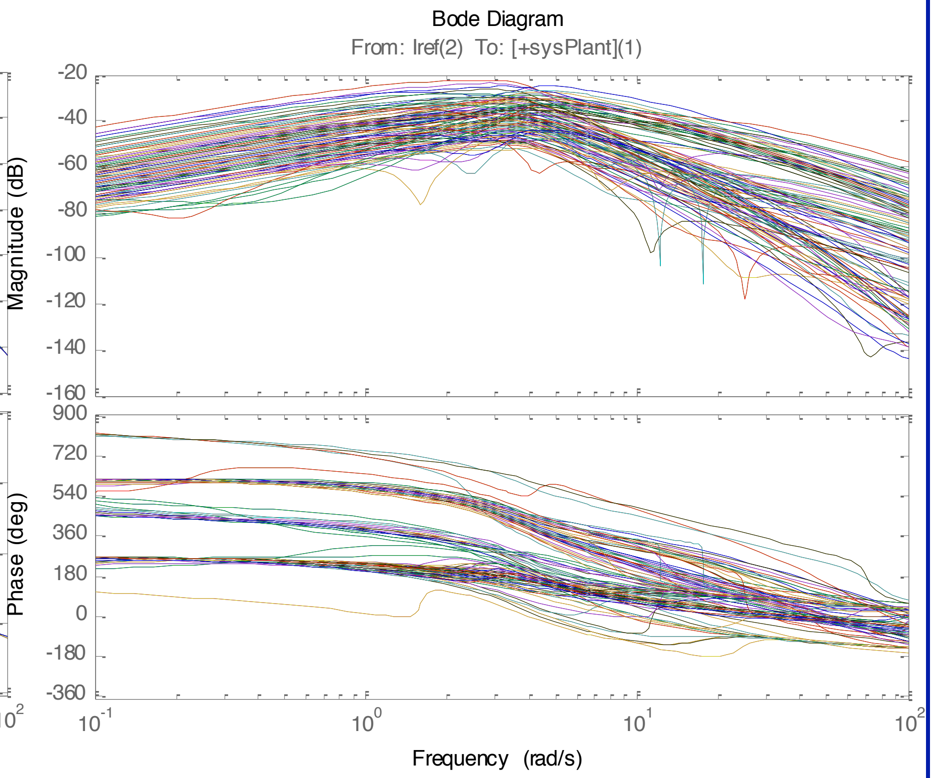
# Structure and design of the CDC

- We made the following design choice
  - The matrix $K_c$ have been designed on the base of the plasmaless model, the passive structures have been only partially take into account
  - To all the diagonal transfer function (main channels) have been assigned the same behavior
- We have selected two values for the matrix $K_c$, one with a higher gain, allowing a faster tracking of the currents, and the other with a low gain. The higher gain matrix has been used during the limite/diverted transition. The lower gain matrix has been used during the flat-top
- Note that, since the CDC is a simple proportional controller it is not needed to include a bumpless mechanism when the matrix $K_c$, is changed
- The bandwidth for the tracking of the CS & PF currents is limited mainly by the power supplies voltage limits and then by the presence of the passive structures.

# Performance of the CDC controller



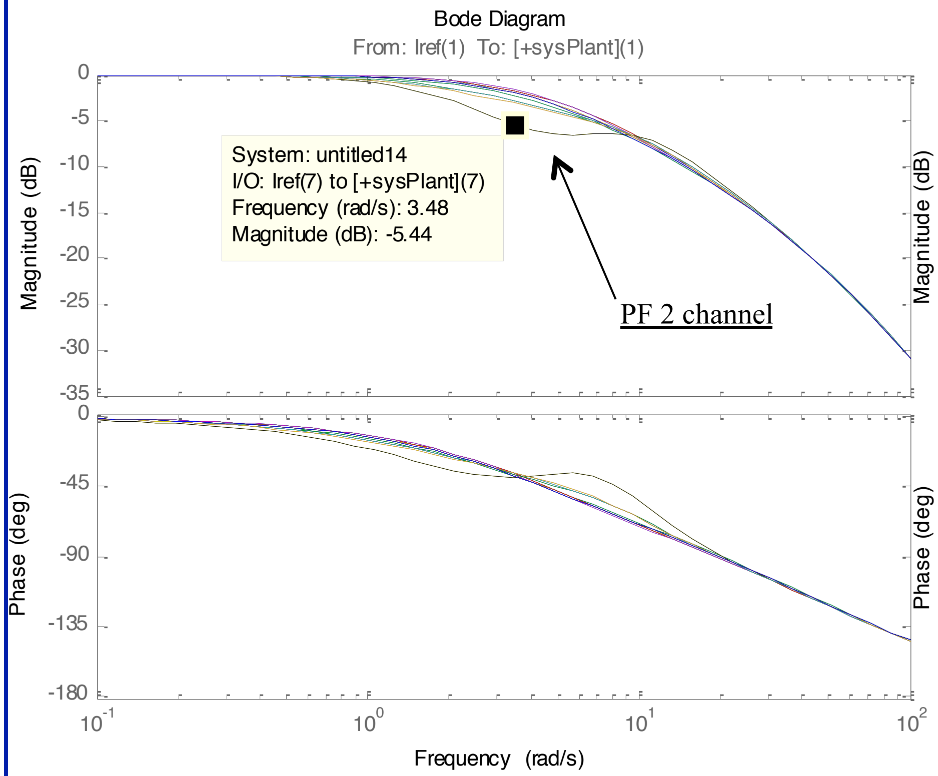
Diagonal transfer function



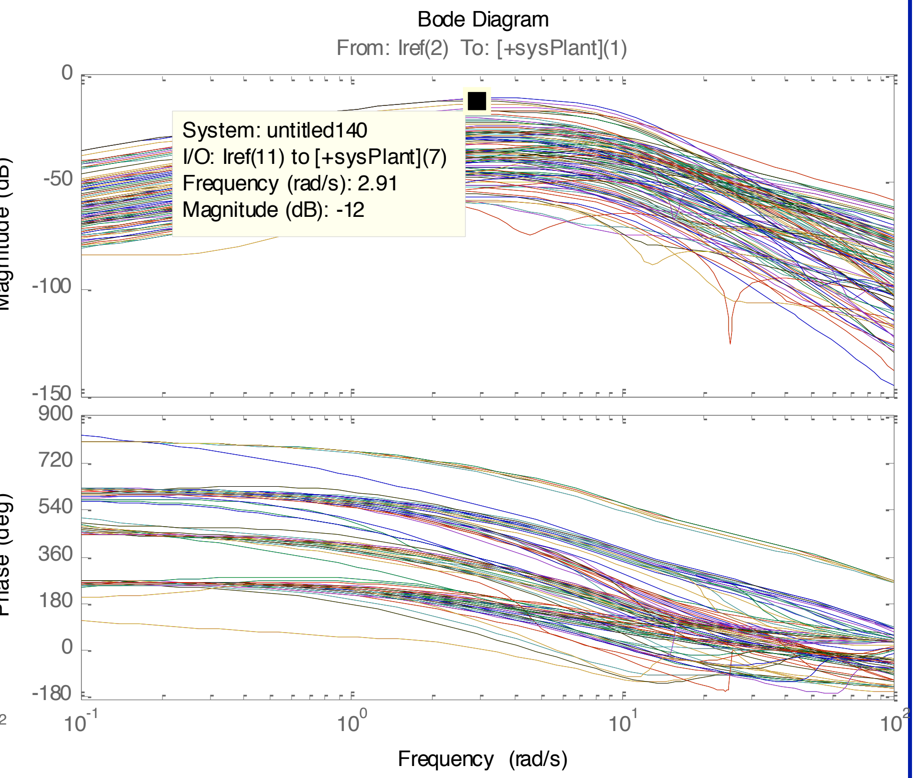
Off-diagonal transfer function

CDC closed loop system without the vertical stabilization loop

# Performance of the CDC controller



Diagonal transfer function



Off-diagonal transfer function

CDC closed loop system with the VS1 loop

# Performance of the CDC controller

- Note that the presence of the VS1 loop (a small gain loop aimed at reducing the current in the VS3 coil) has a detrimental effect on the CDC loop (especially on the PF2 channel)
- However in our simulation we found that this detrimental effect has not a large impact on the overall control system, while it allow to reduce the current and the RMS ohmic power on the VS3 circuit

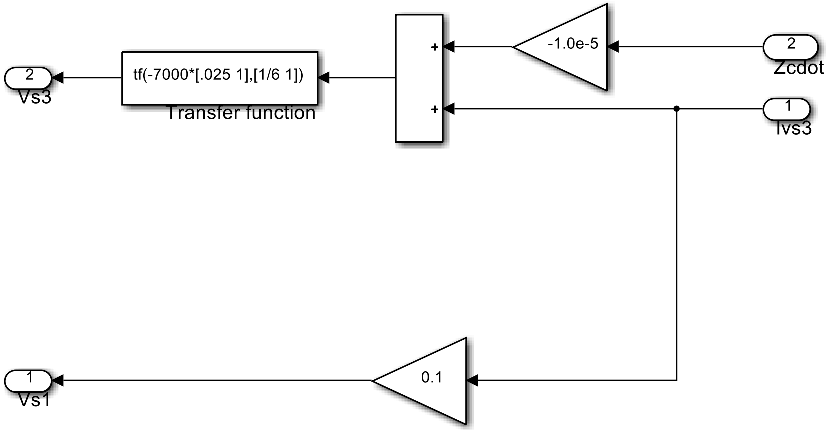
# The vertical stabilization controller

- The vertical stabilization controller has as input the centroid vertical velocity and the current flowing in the VS3 circuit and generate as output the voltage references for the VS3 and VS1 power supplies.
- The VS3 circuit is actually used to stop the movement of the plasma current centroid and hence to stabilize the plasma equilibrium.
- The VS1 circuit is used to reduce the current and the RMS ohmic power in the VS3 circuit
- The equation of the controller are

$$
\begin{aligned}
V_{VS3} &= \mathcal{L}^{-1}[F(s)] * (K_1 \dot{z} + K_2 I_{VS3}) \\
V_{VS1} &= K_3 I_{VS3}
\end{aligned}
$$

- We found that all the parameter of the controller can be kept constant from just after the limited/diverted transition to the entire flat-top, with the exception of $K_1$ which must be scaled with the plasma current.

# The vertical stabilization controller



$I_p = 15\text{MA}$

$$K_1 = 1$$

$$K_2 = -10^{-5}$$

$$K_3 = 0.1$$

$$F(s) = -7000\,\frac{\frac{s}{40}+1}{\frac{s}{6}+1}$$

# The plasma current controller

- The plasma current controller has as input the plasma current and its time-varying reference, and has as output a set of CS & PF coil current deviation (with respect to the nominal values)
- The output current deviation are proportional to a set of current providing (in the absence of eddy currents) a transformer field inside the vacuum vessel, so as to reduce the interaction with the plasma shape controller
- Since it is important for the plasma current to track the reference signal during the ramp-up and ramp-down phases, the controller has been designed to contain a double integral action
- We selected two plasma current controller, one for the ramp-up and ramp-down phases, with a larger gain, and the other for the flat-top phase, with a smaller gain.

# The plasma current controller

- In our simulation the plasma current controller does not need to be scheduled
- In any case, if necessary a mechanism similar to the one described for the plasma shape controller could be used for bumpless transfer between two different controllers

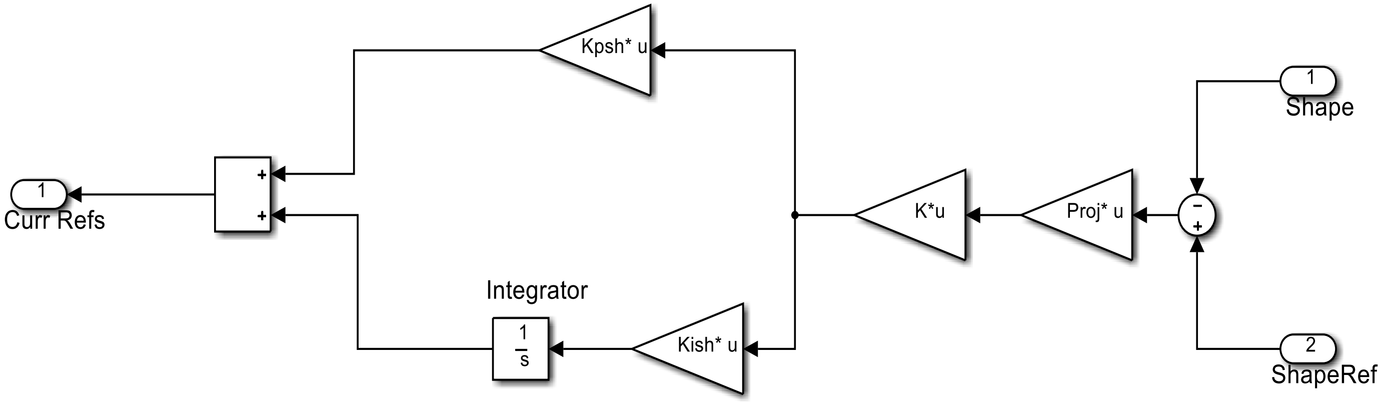
$$\delta I_{PF,1}(s) = \alpha I_{TF} \frac{10s+1}{100s^2}\left(I_{p,ref}(s) - I_p(s)\right) \qquad I_{TF} = \begin{bmatrix} -0.3154 \\ -0.3347 \\ -0.3541 \\ -0.2925 \\ -0.2591 \\ -0.2483 \\ -0.0766 \\ -0.0103 \\ -0.0393 \\ 0.0158 \\ -0.1614 \end{bmatrix} \times 10^{-2}$$

- α=2, for the ramp-up and ramp-down phases
- α=1, for the flat-top phase

# The plasma shape controller

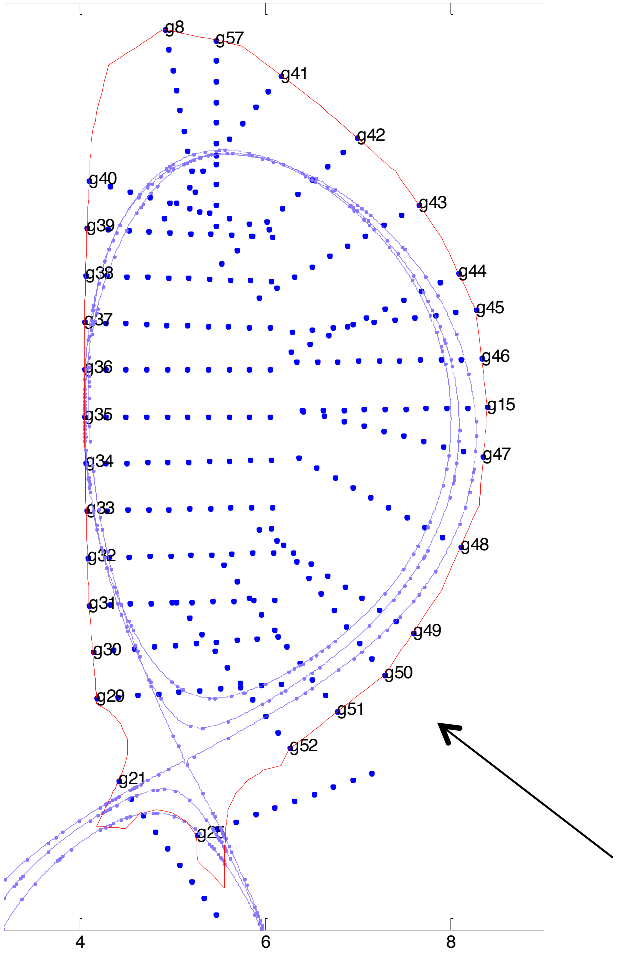
- The plasma shape controller has as input the controlled plasma shape parameters and their references, and has as output a set of CS & PF coil current deviation (with respect to the nominal values)
- The structure of the plasma shape controller is based on the XSC controller.
- This allows to track a number of shape parameters larger than the number of active coils minimizing a weighted steady state quadratic tracking error when the references are constant signal
- The parameter on which the XSC design is based are
  - A set of weight for the shape parameter: these weights allow to reduce the tracking error of some shape parameters with respect to others
  - A set of weight for the CS & PF coil current: these weights balance the values of the steady state CS & PF current deviations, allowing to take into account the proximity of each coil to their limit
  - A parameter which allows to speed-up the dynamics of the control system

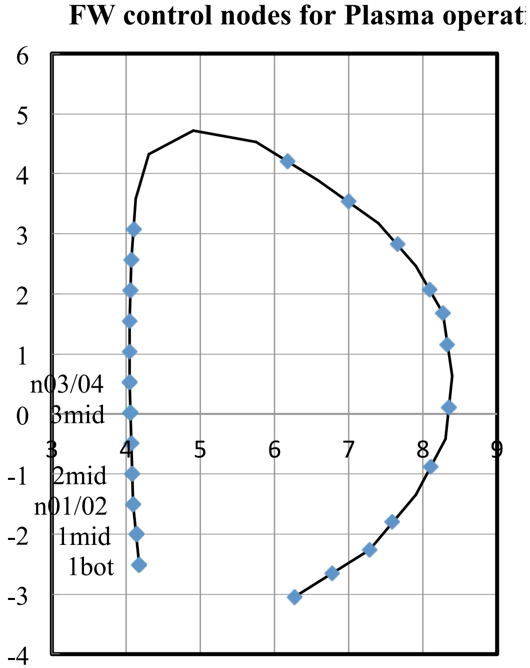
# The plasma shape controller structure



- The structure of the XSC controller is based on two projection matrices and then on a diagonal PID controller (the PID are the same on each diagonal element)
- The integrator at the end of the controller will be used to obtain a smooth transition from one controller to another (bumpless transfer)

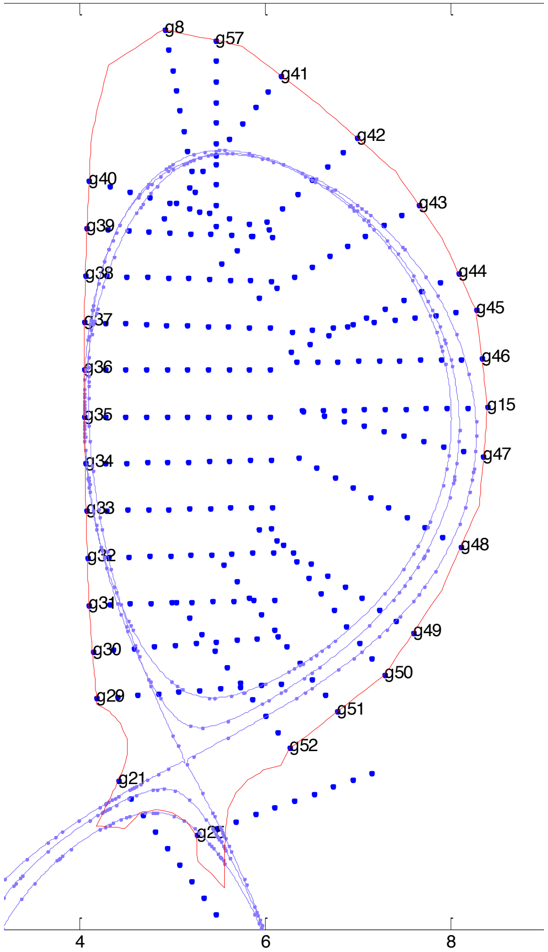
# The plasma shape parameters




FW control nodes for Plasma operat

- Control specifications are given in terms of distances from control nodes. We considered segment perpendicular to the FW, starting from the control node.
- We added three control nodes along the FW, and two control nodes in the strike point channels
- In total we considered 29 control segments

# The plasma shape parameters



- Consider a control segment, and let $g$ be an abscissa along that segment ($g$=0 at the FW), the plasma shape intersect the control segment in the point where it is satisfied the equation

$$\psi(g) = \psi_B$$

- where $\psi_B$ is the flux at the plasma boundary, $g$ define the gap between the separatrix and the FW.
- On each control segment, given a reference abscissa $g_{ref}$, the intersection with the separatrix, can be constrained, either imposing (gap control)

$$g_{ref} - g = 0$$

- or, imposing (isoflux control)

$$\psi(g_{ref}) - \psi_B = 0$$

- Note that

$$\psi(g_{ref}) - \psi_B \cong \frac{\partial\psi}{\partial g}(g_{ref} - g)$$

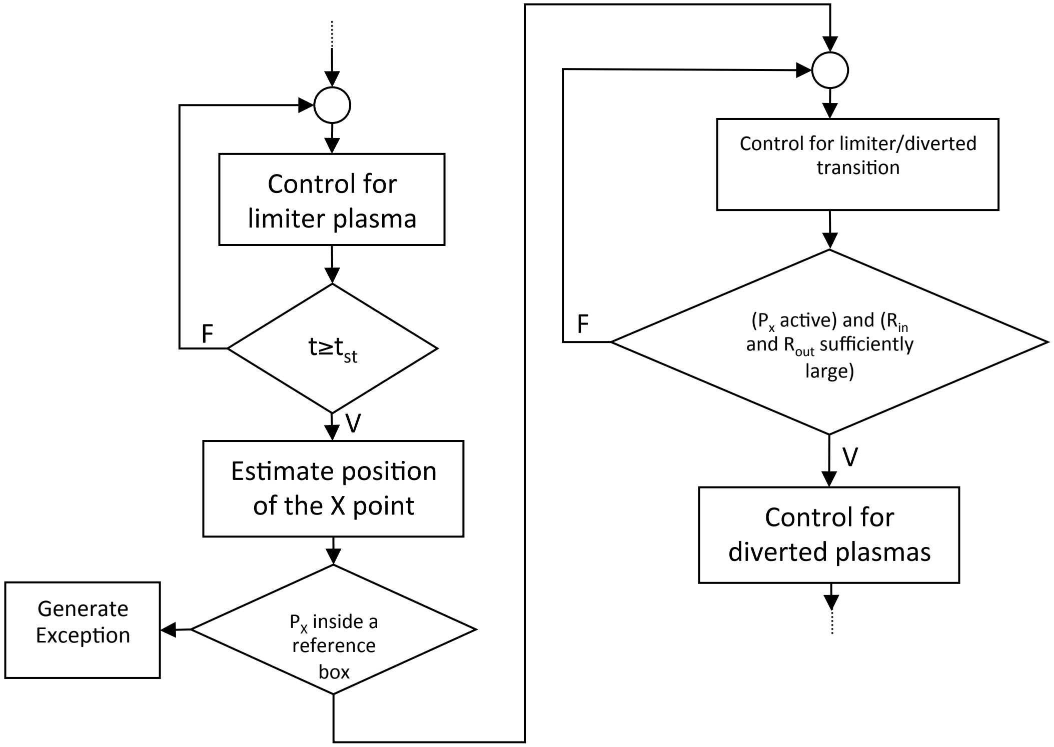
- So as the error signal seen by the controller in the two cases differ for a proportionality factor depending on the magnetic poloidal field

# The plasma shape parameters

- We made the following choices
  - During the limiter phase, the controlled shape parameters are the position of the limiter point and a set of differences between the flux at the reference point on each control segment and the flux at the limiter point.
  - During the limiter/diverted transition the controlled shape parameters are the position of the X-point (not necessarily active), and the differences between the flux at the reference point on each control segment and the flux at the X-point
  - During the diverted phase the controlled variables are the gaps evaluated along the 29 control segments

# Switching between the phases

- The switching between the three control mode can be achieved by following the algorithm presented in figure



Control for limiter plasma

$t \geq t_{st}$

F

V

Estimate position of the X point

$P_X$ inside a reference box

Generate Exception

Control for limiter/diverted transition

($P_x$ active) and ($R_{in}$ and $R_{out}$ sufficiently large)

F

V

Control for diverted plasmas

# Switching between controllers

- Switching between different controllers happens at the start of each phase, but this switch can occur also during a single phase (controller scheduling to optimize the performance).
- Assume you want to change the controller at time $t^*$, and assume that with the new controller you want to track a new reference configuration, reaching it after a transition time $t_{trans}$.
- Let $p(t^*)$ the value of the new controlled variables at the time $t^*$, and $p_{ref}$ the desired value for $p$.
- To have a smooth transition between the old and new controllers, the following steps can be taken
  1. At $t^*$ charge the integrator, at the output of the XSC controller, with the last output of the previous controller.
  2. Generate for the new controller a reference signal so as to go smoothly from $p(t^*)$ to $p_{ref}$ in the time interval $(t^*, t^*+t_{trans})$
- Since the new controller sees an initial error which is zero, the output of the controller corresponds with the initial state of the output integrators, and hence the signal at the output of the control system remain continuous

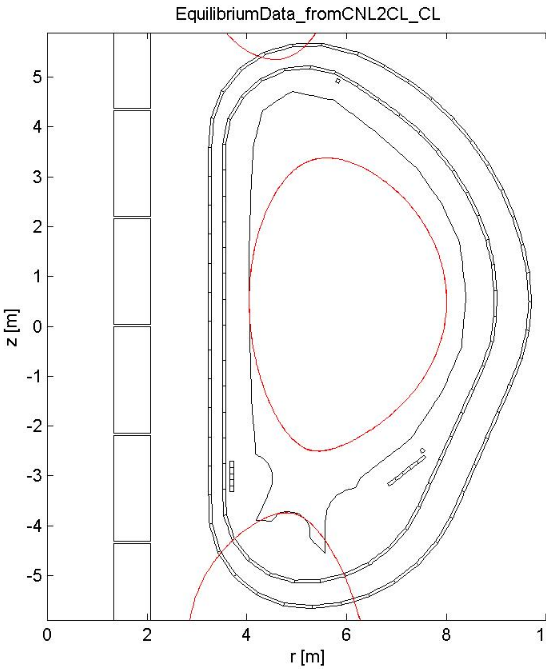
# Simulation results

- The following simulation results will be presented
  - Limited to diverted transition
  - Rejection of disturbance during the flat-top phase
  - Nonlinear simulation of the ramp-up (grt-255, 001 case)
  - Nonlinear simulation of the L-H transition (grt-255, 001 case)

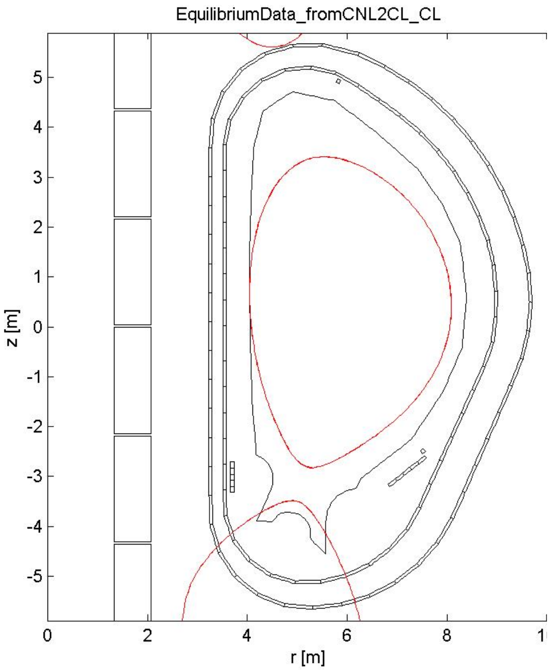
- Other simulations will be included in the final report

# Simulation of the limited to diverted transition

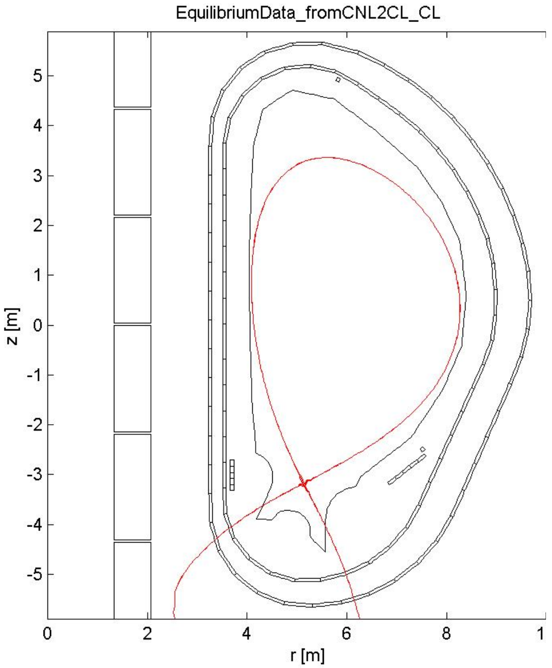
# Limited/diverted transition



t=9.9s
Ip=3.66MA
Betap=0.05
li=0.96



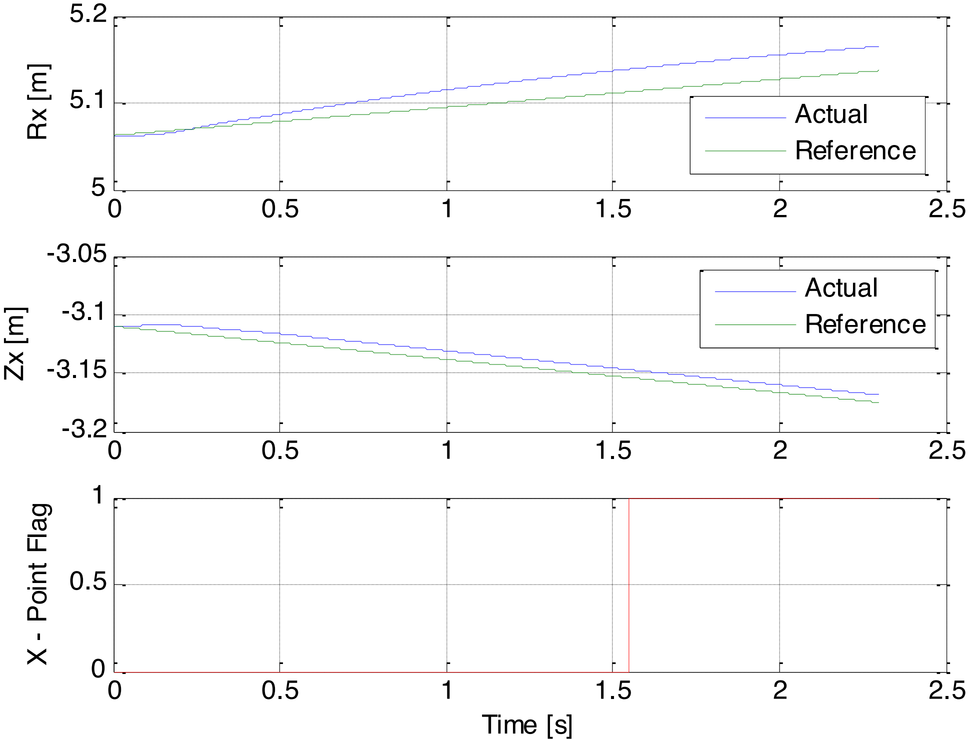
t=10.9s
Ip=3.84MA
Betap=0.05
li=0.94

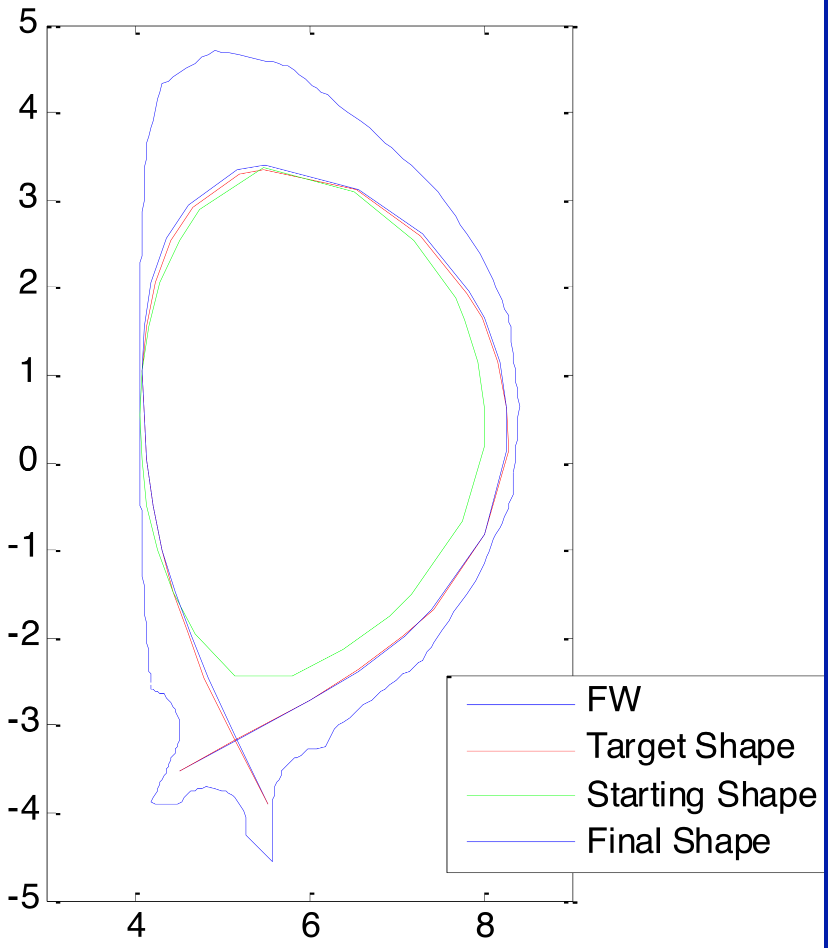


t=11.9s
Ip=4.021MA
Betap=0.05
li=0.98

The limited/diverted transition occur in a time-interval of 2s (we do not specify an exact time instant)

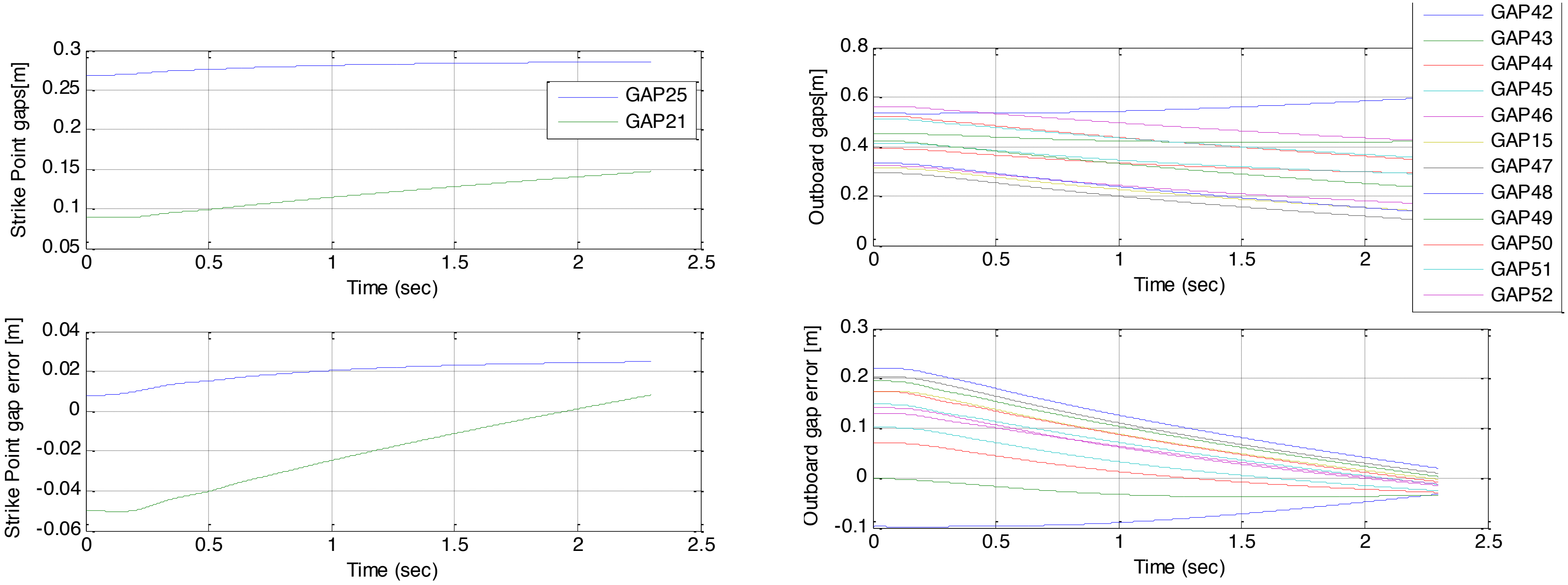
# Limited/diverted transition



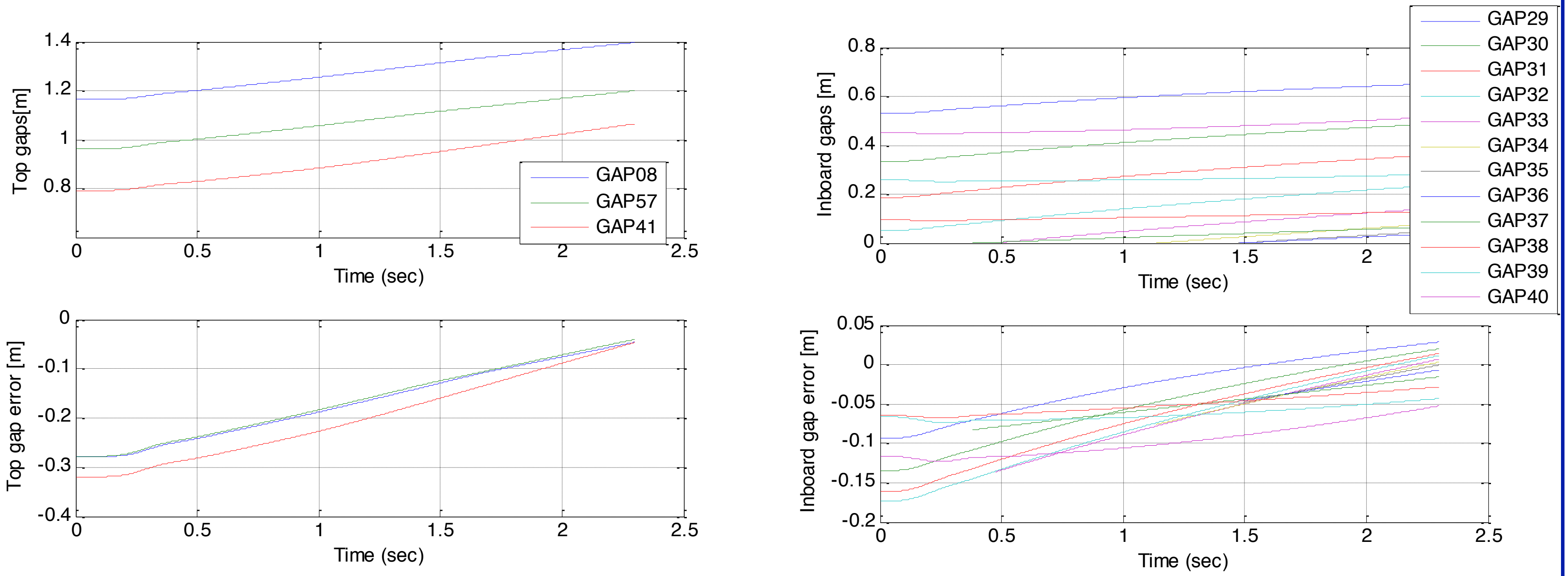


The limited/diverted transition happens at about 1.6s

# Limited/diverted transition

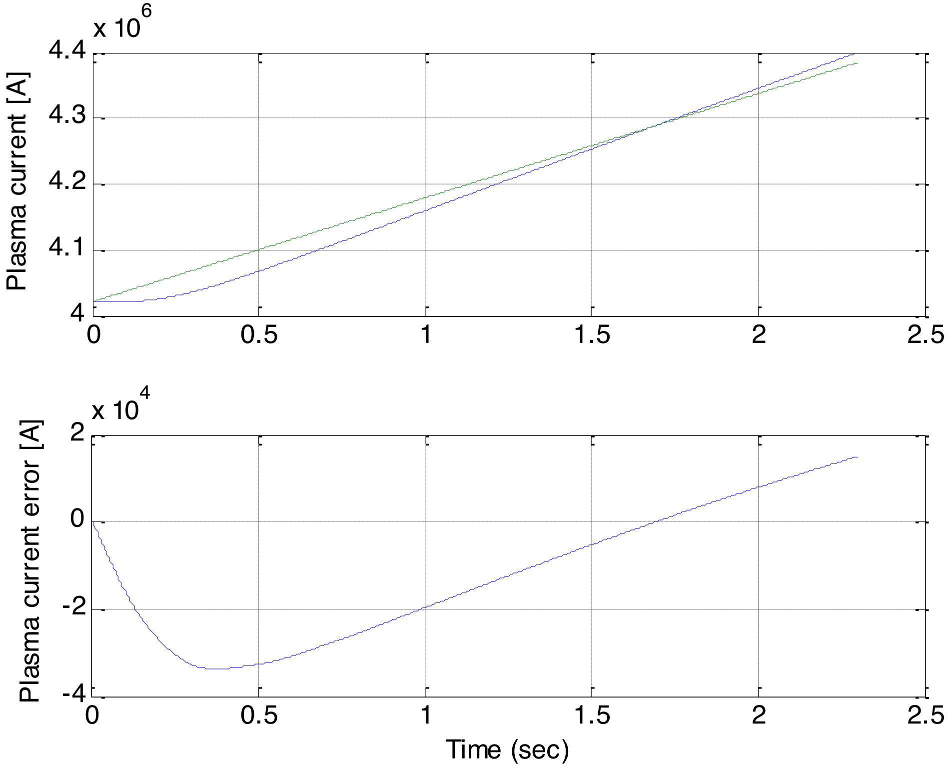


# Limited/diverted transition



The maximum absolute gap error is about 5cm

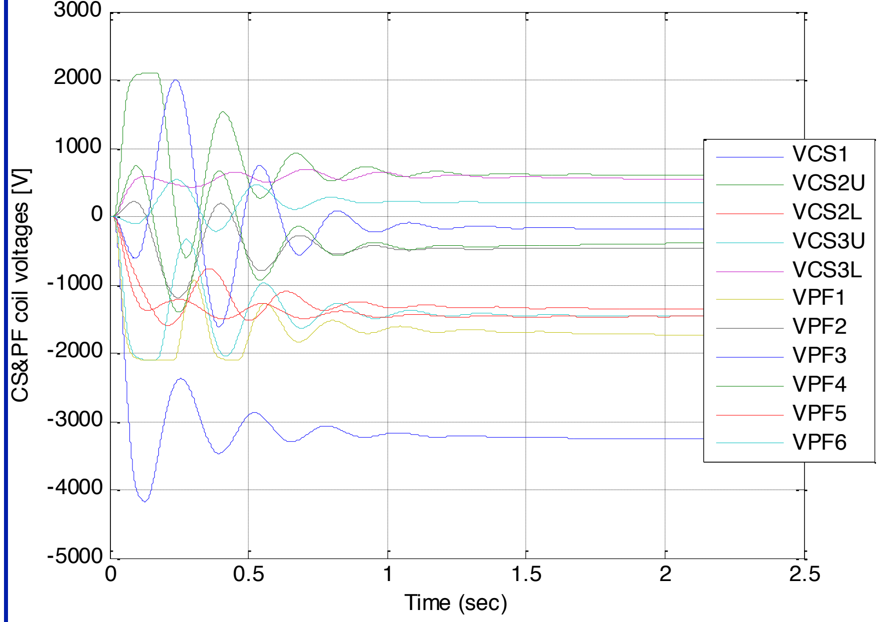
# Limited/diverted transition

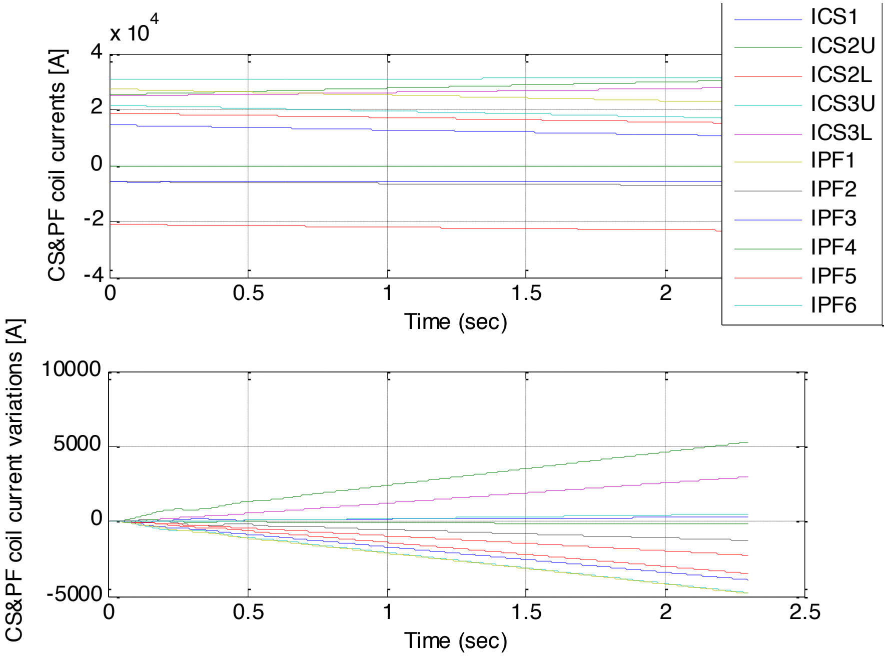


## Note that

- The initial transient is due to the fact that the simulation starts from an equilibrium (i.e. Ipdot(0)=0), actually in the real discharge the current would be already ramping
- The pre-programmed currents are designed to compensate for voltage drop on the plasma (due to the plasma resistivity). In the linear simulation the voltage drop has been reduced
- The controller will compensate the error on a time scale of about 20s

# Limited/diverted transition





The total power (including VS3 and VS1 circuits) peak is about 85MW

# Additional linear simulation results

- In PM 3 we presented linear results on the rejection of disturbance during the flat-top phase.
- We completed the analysis considering the following list of disturbance

| Disturbance | Models | Simulation |
|---|---|---|
| Uncontrolled ELMs (H-mode Case 1 Scenario) | SOB equilibrium (Equil_PCSSP_Scenario01_t090_CL.mat) | simA1 |
| Minor disruptions (L-mode Case 1 Scenario) | SOB equilibrium (Equil_PCSSP_Scenario01_t090_CL.mat) | simA2 |
| Fast H-L transition (Case 1 Scenario) | SOB equilibrium (Equil_PCSSP_Scenario01_t090_CL.mat) | simA3 |
| L-H transition (Case 1 Scenario) | SOF equilibrium (Equil_PCSSP_Scenario01_t080_CL.mat) | simA4 |
| Fast H-L transition (Case 1 Scenario) | EOB equilibrium (Equil_PCSSP_Scenario01_t520_CL.mat) | simA5 |

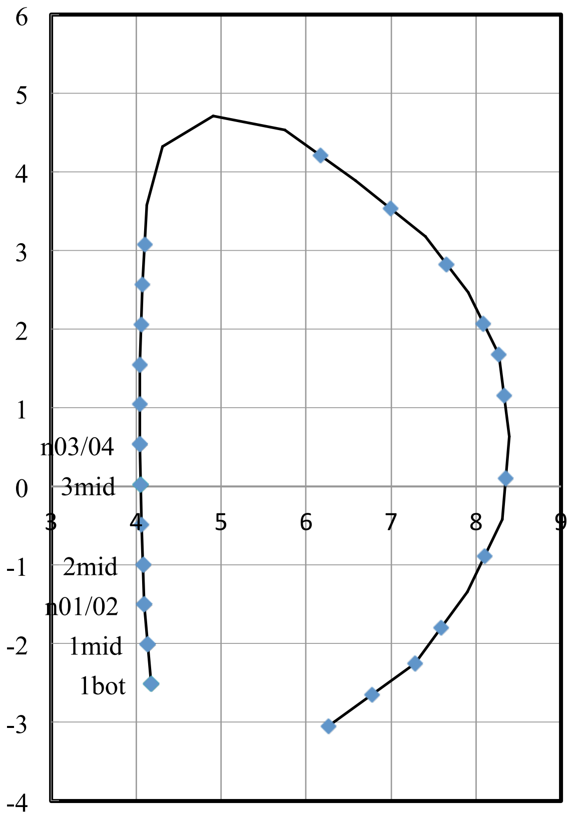
# Additional linear simulation results

- The simulation results show that the proposed controllers have the expected performance. In particular the range of variation of all the gaps describing the plasma shape guarantees that the plasma does not touch the wall in all considered cases
- But ...

| Short Name | Clearance Req. (mm) | Clearance obtained (mm) **simA1** | Clearance obtained (mm) **simA2** | Clearance obtained (mm). **simA3** | Clearance obtained (mm). **simA4** | Clearance obtained (mm). **simA5** |
|---|---|---|---|---|---|---|
| 1bot | 250 | 655 | 568 | 584 | 613 | 582 |
| 1mid | 250 | 553 | 465 | 464 | 504 | 470 |
| n01/02 | 250 | 455 | 371 | 353 | 422 | 369 |
| 2mid | 150 | 340 | 261 | 231 | 330 | 250 |
| n02/03 | 150 | 252 | 176 | 137 | 261 | 154 |
| 3mid | 70 | 187 | 113 | 70 | 209 | 82 |
| n03/04 | 70 | 150 | 75 | 34 | 180 | 43 |
| 4mid | 70 | 129 | 53 | 18 | 160 | 24 |
| n04/05 | 70 | 137 | 53 | 32 | 159 | 36 |
| 5mid | 70 | 161 | 81 | 68 | 174 | 67 |
| n05/06 | 150 | 226 | 148 | 149 | 219 | 143 |
| 6mid | 150 | 327 | 257 | 268 | 288 | 260 |
| 10mid | 110 | 431 | 401 | 430 | 151 | 380 |
| 11mid | 50 | 250 | 256 | 251 | 40 | 210 |
| 12mid | 110 | 231 | 239 | 236 | 48 | 211 |
| 13mid | 110 | 224 | 237 | 230 | 65 | 209 |
| n13/14 | 110 | 257 | 272 | 264 | 103 | 244 |
| 14mid | 50 | 184 | 204 | 191 | 41 | 176 |
| 15mid | 50 | 158 | 183 | 164 | 23 | 167 |
| 16mid | 50 | 164 | 185 | 170 | 18 | 191 |
| 17mid | 50 | 200 | 212 | 205 | 20 | 232 |
| n17/19 | 90 | 287 | 294 | 291 | 85 | 311 |
| 18mid | 90 | 262 | 258 | 263 | 43 | 270 |
| 18bot | 90 | 293 | 269 | 293 | 83 | 279 |
| **Clearance failure time length (s)** | | - | 2.91 | 4.00 | 2.37 | 2.00 |

Clearance specified in the Yuri Excel file

**FW control nodes for Plasma operation**



- **This table lists the smallest gap to a certain list of control nodes of the wall.**
- **LCFS excursions outside this domain shall be on a time scale << 1 second in order to avoid loss of tile or critical heat flux in the cooling channels.**

- Due to the different type of disturbances that can occur, the requirements on the CS&PF power supplies, it is difficult to satisfy with a single plasma shape controller all the constraints specified in the Yuri Table.
- Indeed the shape controller for the flat-top case has been designed on the base of a resonable trade-off between the various constraints
- We solved this problem with a so-called “emergency controller”

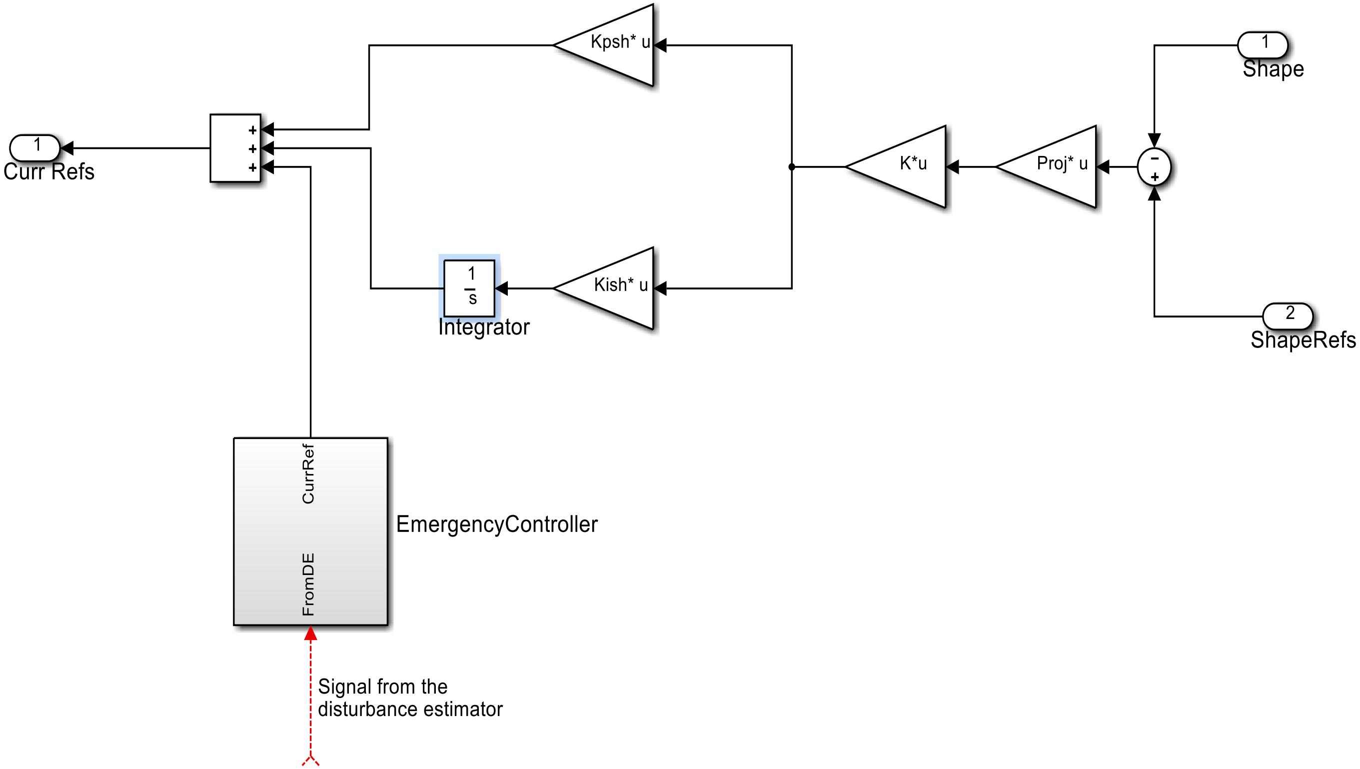
# The emergency controller

- The emergency controller is assumed to be switched on when a certain disturbances occurs.
- As a consequence this controller assumes the availability of a "disturbance estimator" (outside the scope of this grant) able to identify, in a limited time interval, the occurrence of a disturbance belonging to a specified class of "severe" disturbances (for example an unexpected H-L transition, minor disruption, etc.).

# The emergency controller

- The emergency controller will act (in parallel with the XSC), for each type of disturbances, on the current references of a limited number of CS&PF coils, so as to push the plasma far from the first wall in the region where the clearance is expected to be violated. This action is exerted for a specified time interval, and then it is switched off.
- The scheme of the emergency controller proposed in this study will operate in open loop: the current reference step on the selected coils and the time duration of the action are fixed a priori

# The emergency controller scheme



# The emergency controller simulations

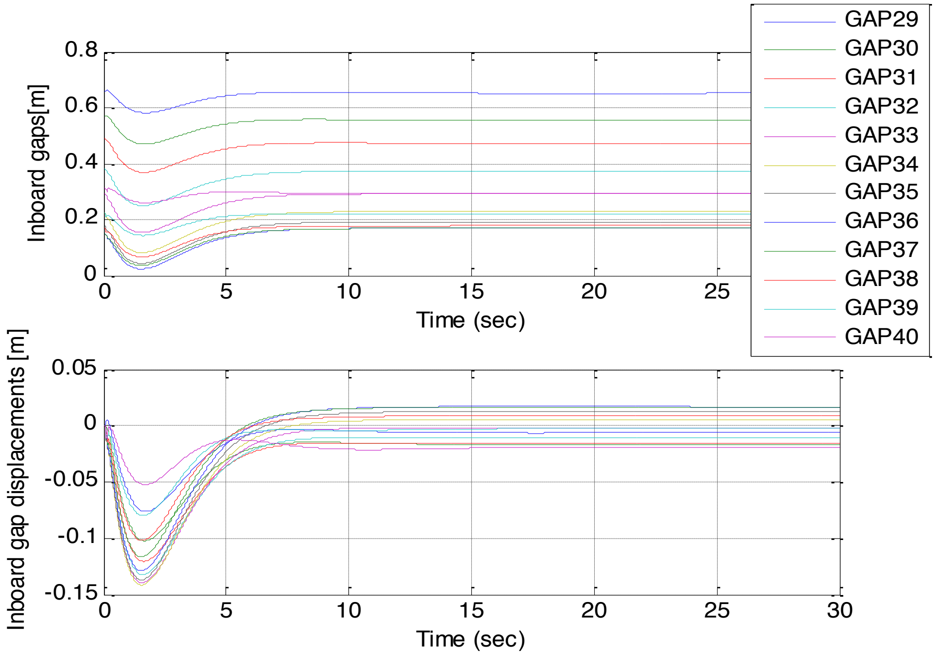
- Simulation simA2 (Minor disruption at SOB) and simA5 (H-L transition at EOB) have been repeated considering the presence of the emergency controller.
- The Emergency controller has been switched on after 0.4s from the occurrence of the minor disruption and 0.3s after the occurrence of the H-L transition (therefore in this cases we require a disturbance estimator and not a  disturbance predictor)
- The emergency controller acts for a time duration of 1.5s

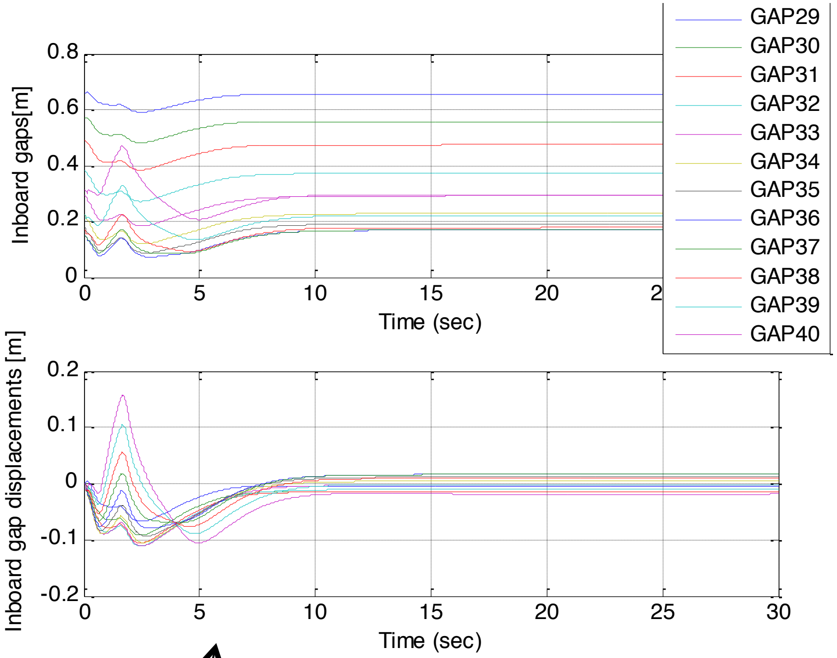
# The emergency controller simulations

| Coil | Reference for the Minor Disruption (A) | Reference for L-H transition (A) |
|---|---:|---:|
| ICS1 | -2800 | -2800 |
| ICS2U | 0 | 0 |
| ICS2L | 0 | 0 |
| ICS3U | 0 | 0 |
| ICS3L | 0 | 0 |
| IPF1 | 2800 | 2800 |
| IPF2 | 2800 | 2800 |
| IPF3 | 0 | 0 |
| IPF4 | 0 | 0 |
| IPF5 | 0 | 0 |
| IPF6 | 0 | 0 |

The current references applied by the emergency controller

# simA5 simulation

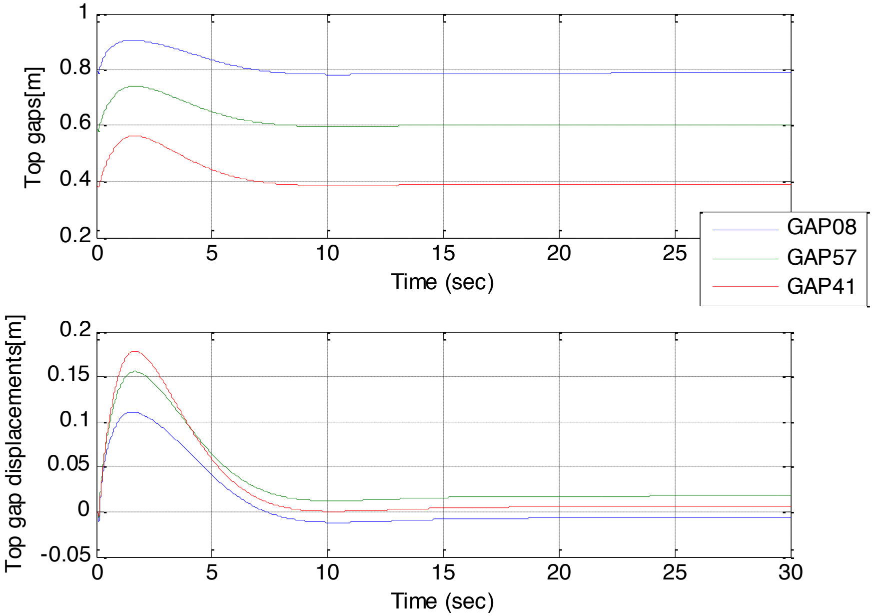


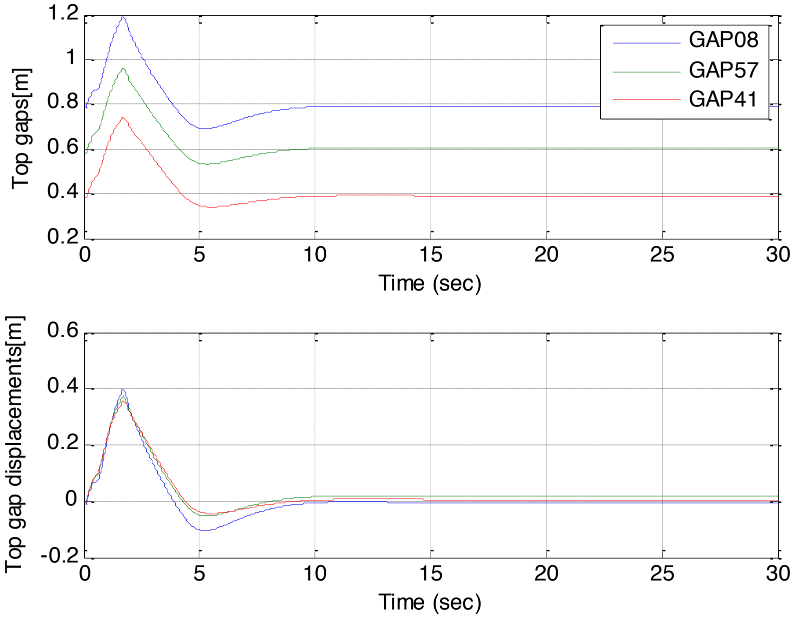


Without emergency controller

With emergency controller

# simA5 simulation

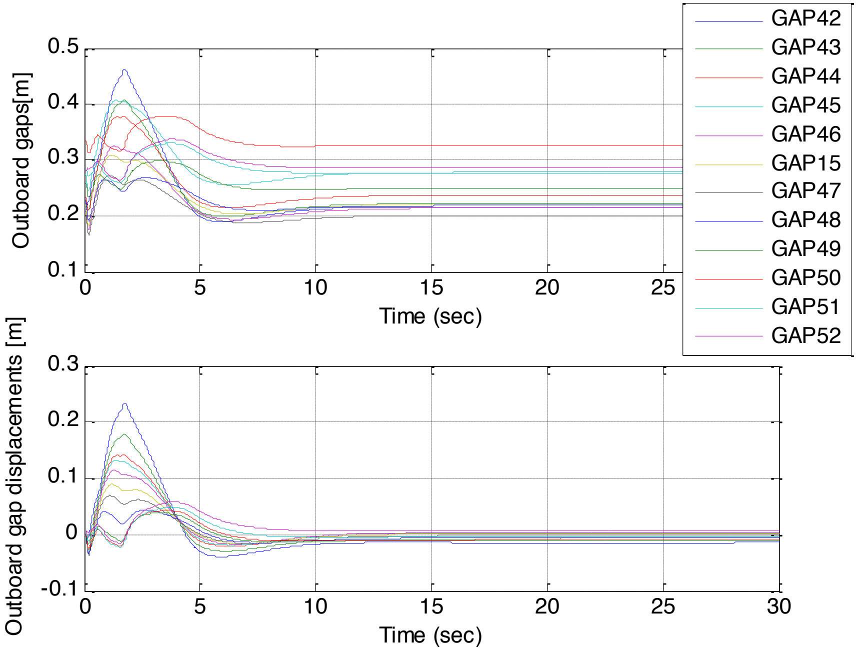




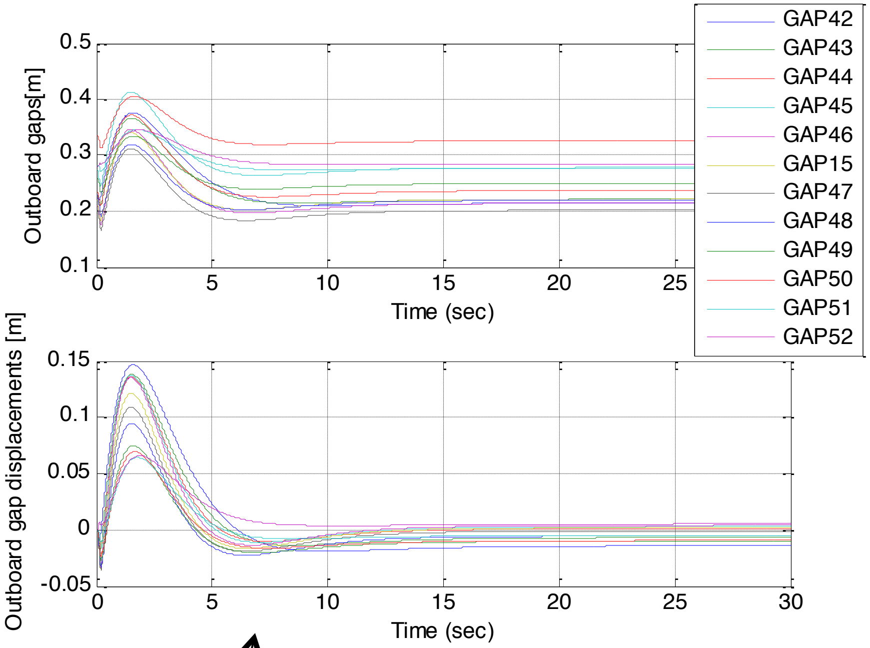
Without emergency controller

With emergency controller

# simA5 simulation

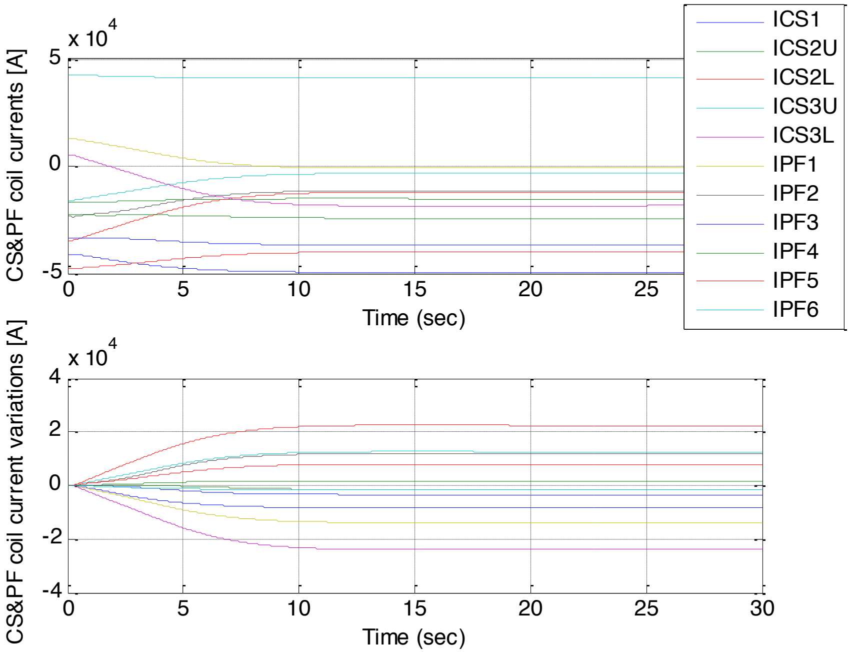


Without emergency controller

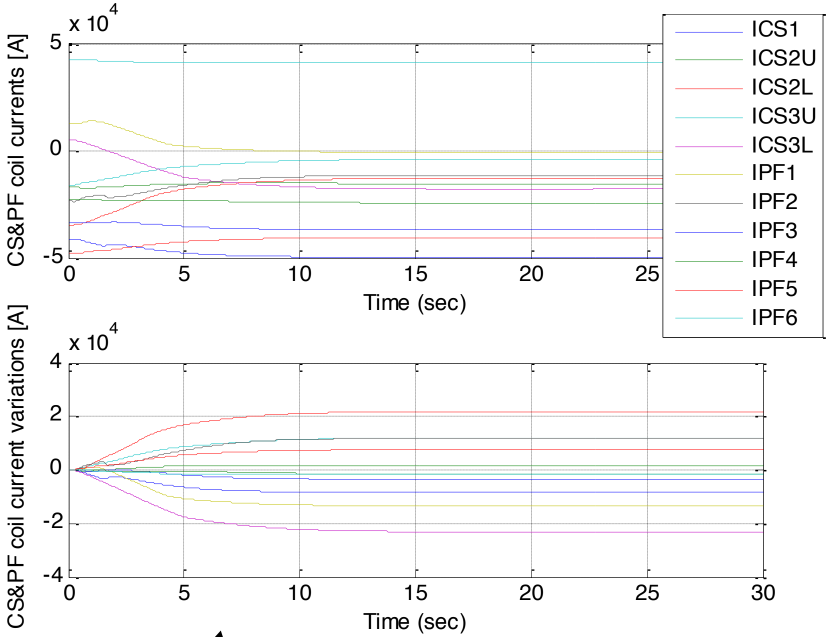


With emergency controller

# simA5 simulation

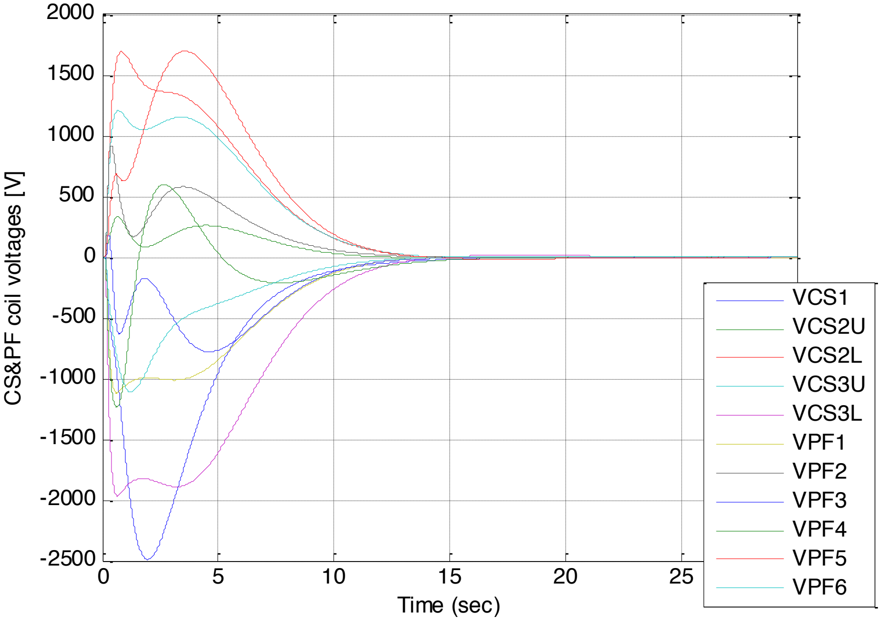


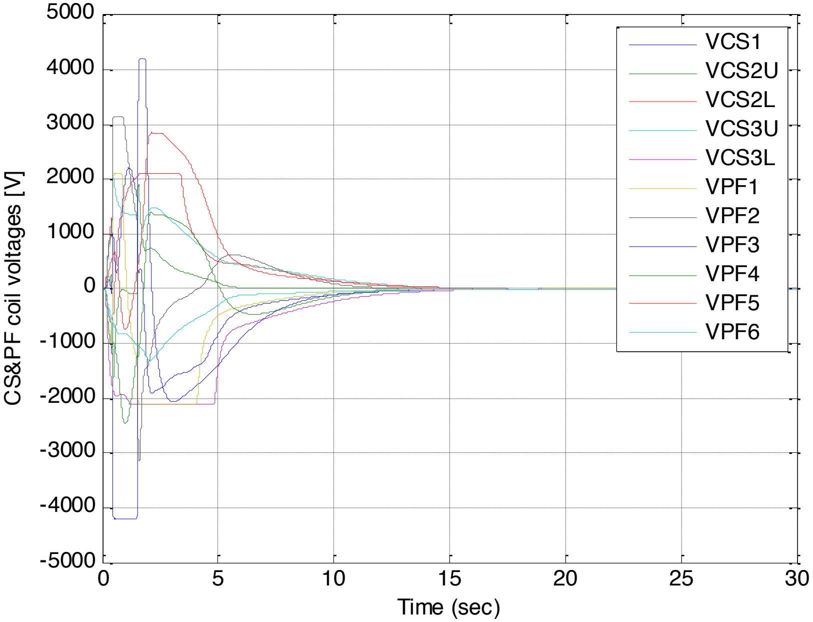
Without emergency controller



With emergency controller

# simA5 simulation





Without emergency controller

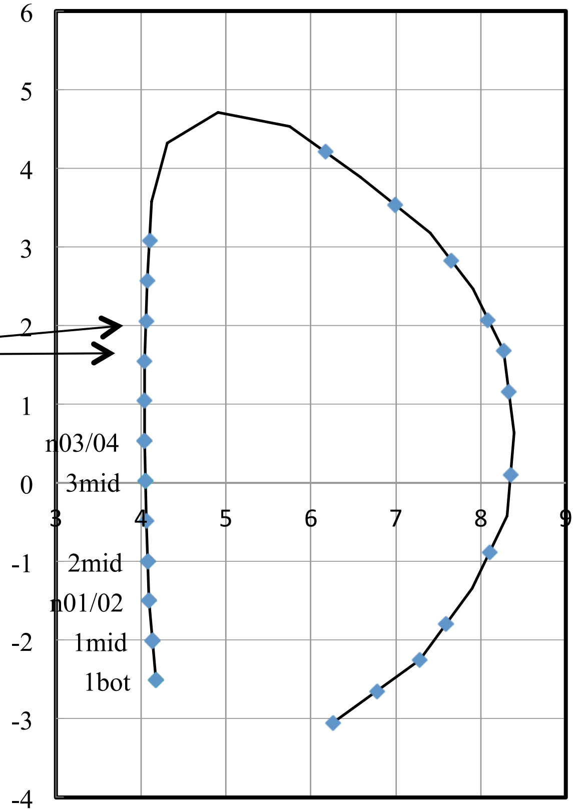
With emergency controller

CREATE

# simA5 simulation

| Short Name | Clearance Requirement (mm) | Clearance guaranteed by the shape controller (mm). **simA2** | Clearance guaranteed by the shape controller (mm). **simA5** |
|---|---|---|---|
| 1bot | 250 | 644 | 591 |
| 1mid | 250 | 539 | 481 |
| n01/02 | 250 | 440 | 384 |
| 2mid | 150 | 327 | 272 |
| n02/03 | 150 | 239 | 183 |
| 3mid | 70 | 172 | 119 |
| n03/04 | 70 | 132 | 87 |
| 4mid | 70 | 106 | 73 |
| n04/05 | 70 | 106 | 84 |
| 5mid | 70 | 122 | 92 |
| n05/06 | 150 | 175 | 134 |
| 6mid | 150 | 266 | 207 |
| 10mid | 110 | 390 | 341 |
| 11mid | 50 | 231 | 190 |
| 12mid | 110 | 225 | 199 |
| 13mid | 110 | 219 | 209 |
| n13/14 | 110 | 245 | 244 |
| 14mid | 50 | 158 | 176 |
| 15mid | 50 | 110 | 167 |
| 16mid | 50 | 91 | 191 |
| 17mid | 50 | 114 | 232 |
| n17/19 | 90 | 200 | 311 |
| 18mid | 90 | 182 | 260 |
| 18bot | 90 | 222 | 265 |
| **Clearance failure time length (s)** | | - | 1.67 |

**FW control nodes for Plasma operation**



# Conclusions

- The emergency controller is almost able to achieve the specified clearance specifications
- Moreover, the remaining problems can be overcome with a fine tuning of its parameters
- However some critical aspects remain
  - It needs a disturbance estimator
  - The timing of the emergency controller action is very dependent from the disturbance occuring
- A closed loop emergency controller, based on the minimum distance of the plasma shape from the wall could solve this criticality

# Possible future work

- Closed loop emergency controller
- Management of the current limits (we shown in PM 2 that this is a required block)
    - Note that since in ITER the control of the plasma current is a task performed by all the CS&PF coils, differently from what happen in our implementation at JET, the current management system should also consider this quantity between its decision variables.