FMPCMP Project

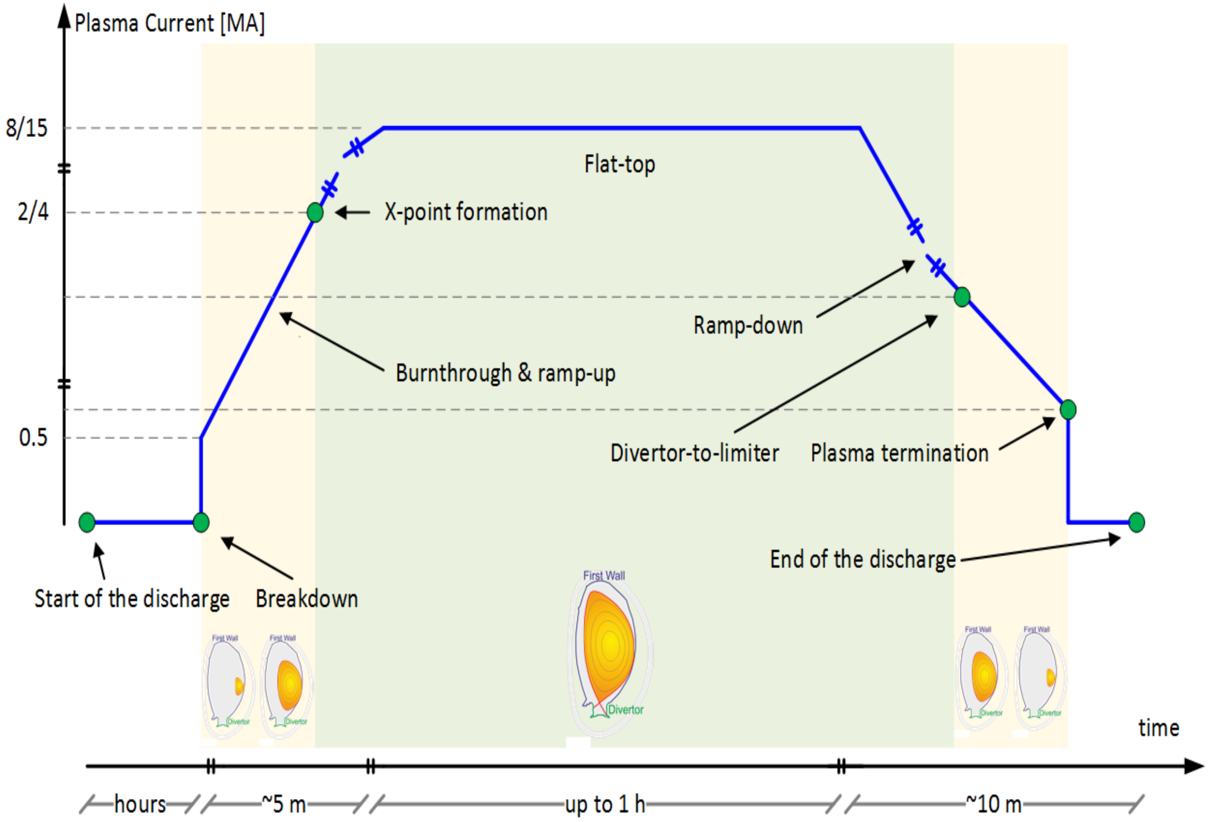
ITER magnetic axisymmetric control system

Presented by A. Pironti on behalf of CREATE team

Outline of the presentation

- A brief description of the ITER baseline scenario
- The magnetic control system
- Actuators
- Diagnostics
- The vertical stabilization controller
- The current decoupling controller
- The shape controller
- The Current Limit Avoidance system

A brief description of the ITER baseline scenario

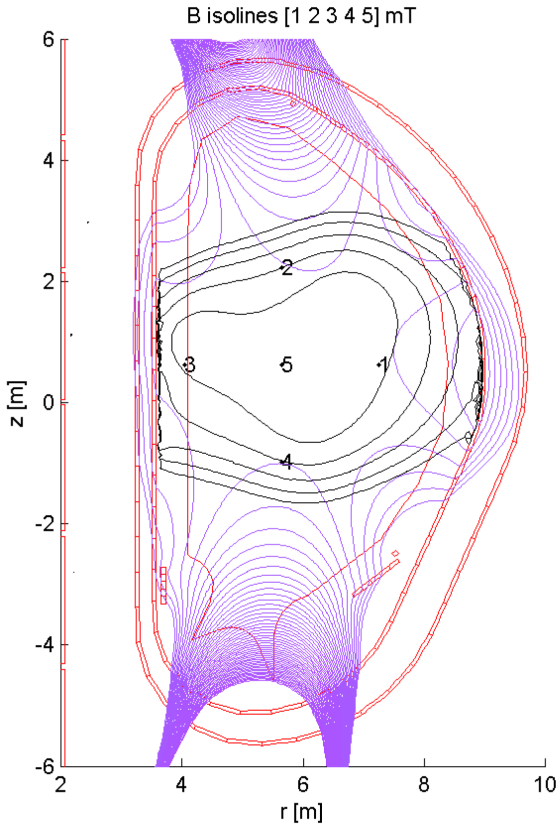


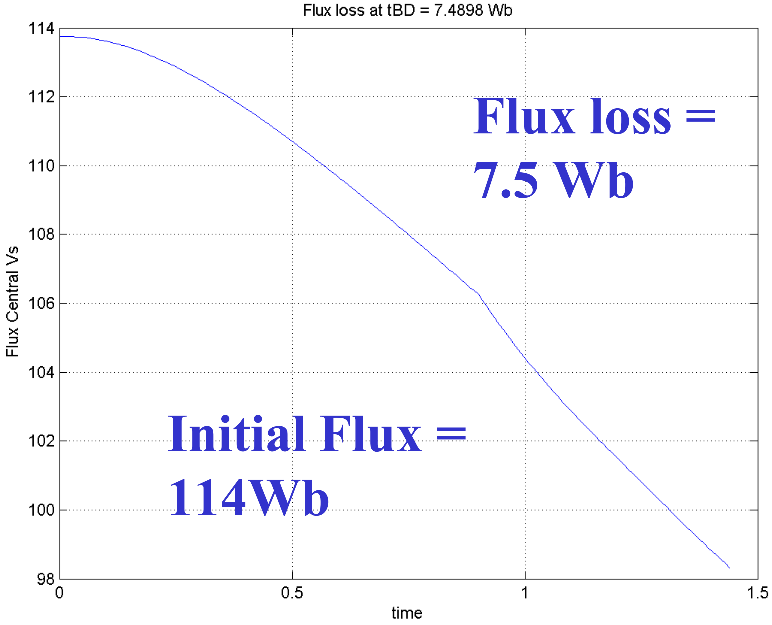
- The main phases for magnetic control purposes are
  - Breakdown
  - Ramp-up
  - Flat-top
  - Ramp-down

Breakdown

- The breakdown phase starts with the poloidal field coils charged at established values of PFC currents (during the pre-magnetization phase)
- Then the PF coils are discharged as fast as possible to produce inside the vacuum chamber the electrical field necessary to start the plasma current
- The main objective are
  - To obtain a sufficiently high electrical field (depends on the time derivative of the PF coil currents)
  - To obtain a sufficiently large region in the vacuum chamber where the magnetic field is sufficiently small at the breakdown time instant (depends on the values assumed by the PC coil currents and eddy currents)
- In this phase the PF coils are driven directly with voltage commands, or with current commands, in this case the current control loop (see later) is used.
- The optimization of the waveforms can be pursued by solving a constrained open loop control problem
- Feedback control can be envisaged in this phase, but it can be a difficult problem due to the actuator and diagnostic limitations

Breakdown



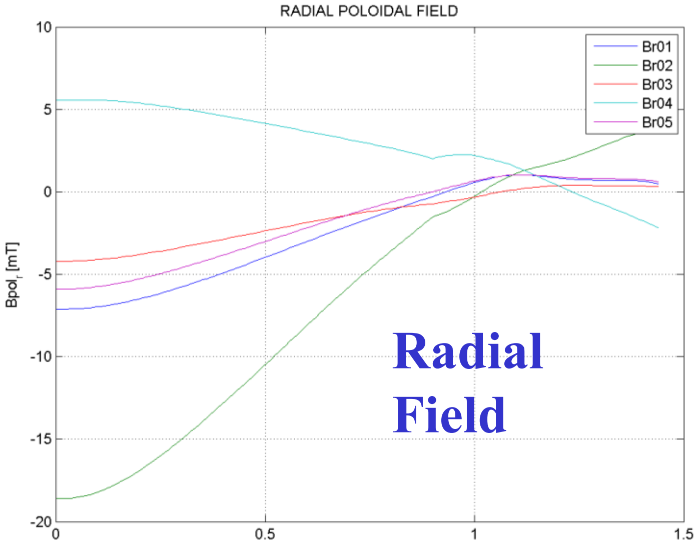


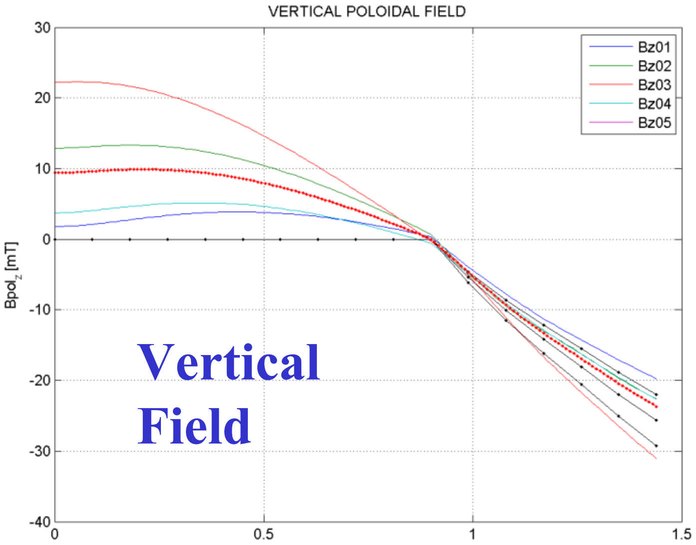
Flux loss = 7.5 Wb

Initial Flux = 114Wb

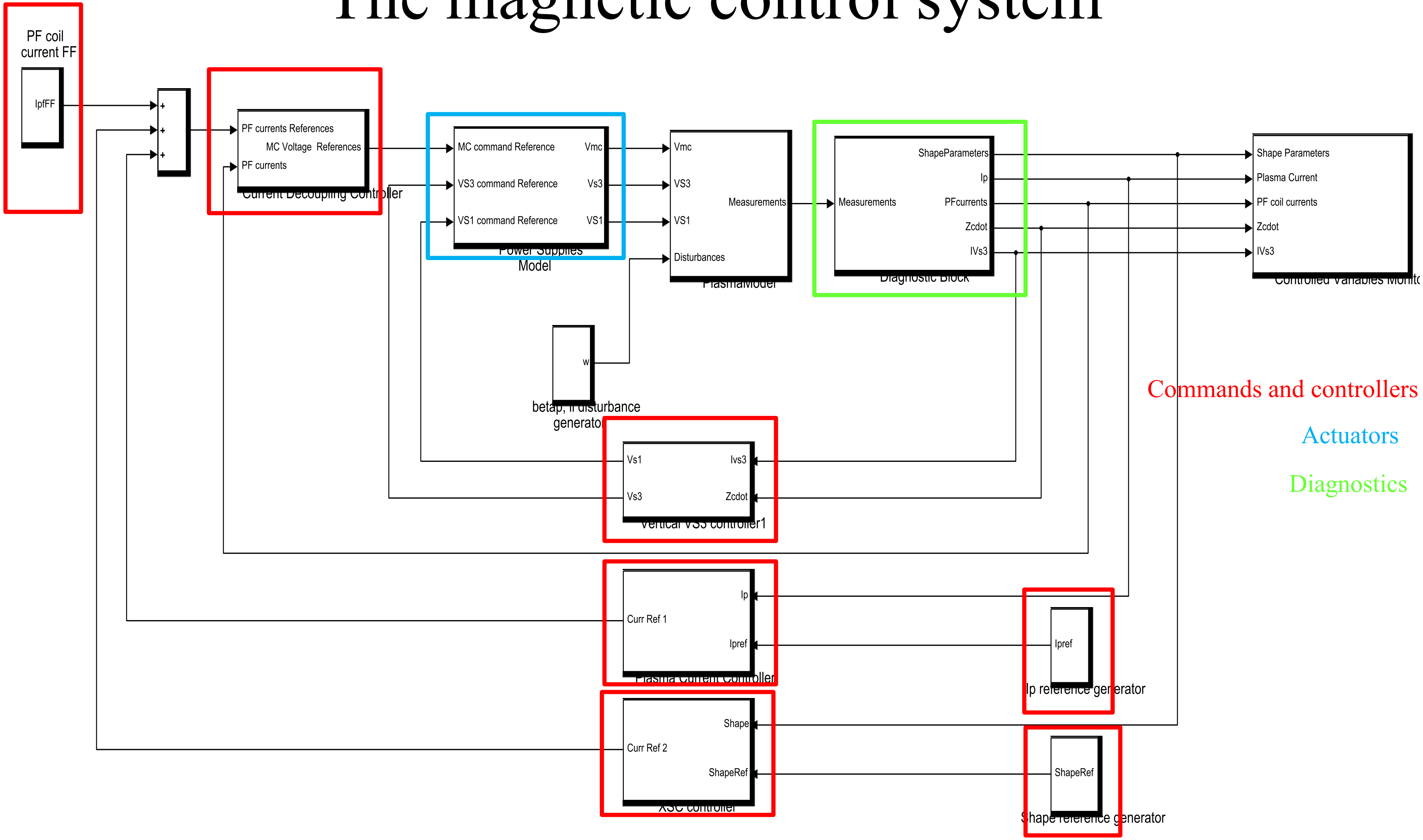
- The time derivative of the flux function provides the electrical field

Breakdown


RADIAL POLOIDAL FIELD
Br01
Br02
Br03
Br04
Br05
Bpol$_r$ [mT]
10
5
0
-5
-10
-15
-20
0
0.5
1
1.5
Radial
Field


VERTICAL POLOIDAL FIELD
Bz01
Bz02
Bz03
Bz04
Bz05
Bpol$_z$ [mT]
30
20
10
0
-10
-20
-30
-40
0
0.5
1
1.5
Vertical
Field

The magnetic control system



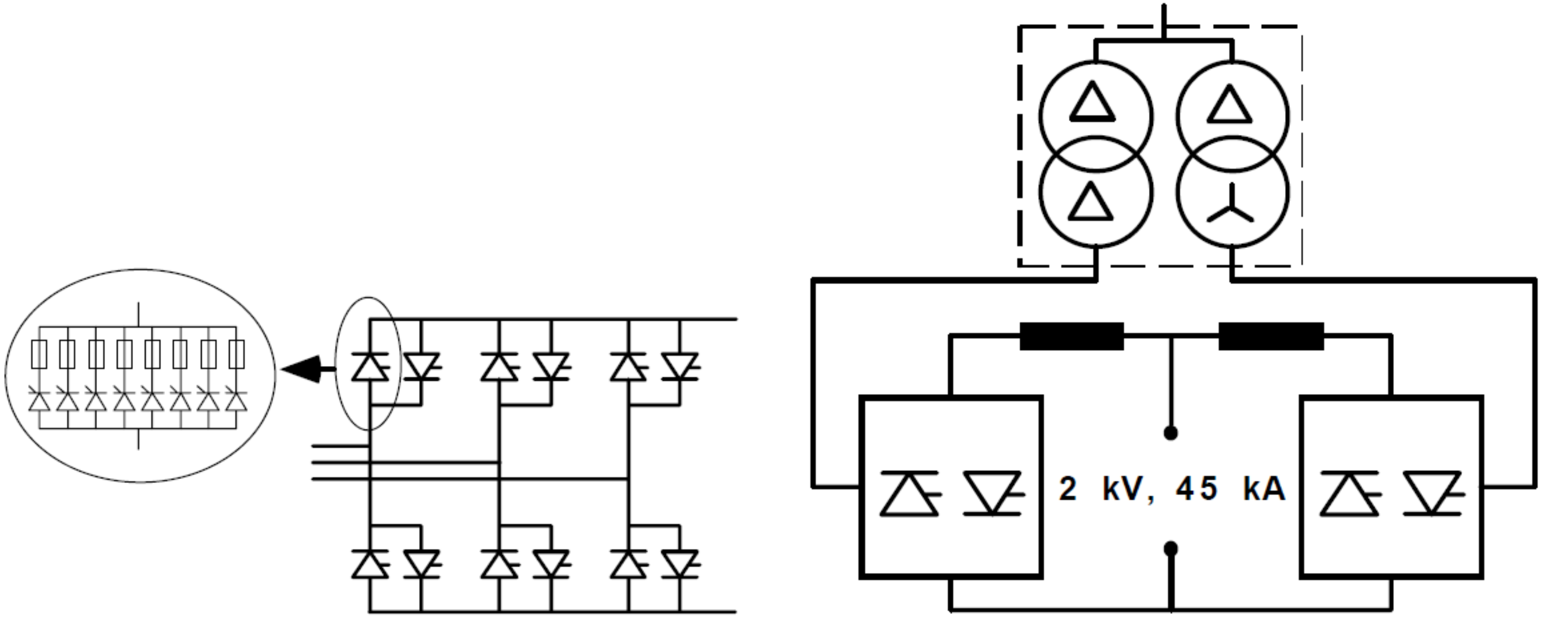
The general scheme

Commands and controllers

- Preprogrammed waveforms for the PF coil currents (designed in such a way to achieve the nominal scenario)
- Preprogrammed waveforms for the plasma current and the shape parameters
- Vertical stabilization controller
- Current decoupling controller
- Plasma current controller
- Shape controller
- It is worth to notice that also different schemes have been proposed (e.g. preprogrammed voltages, integrated controllers, etc.). Each one has its strong point and its weakness

Actuators

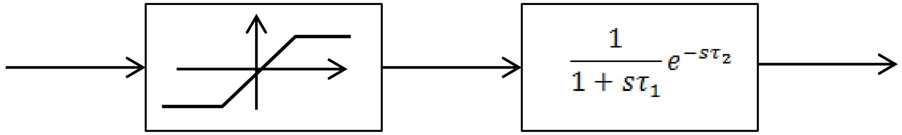
- The actuators of the magnetic control system are the PF coil power supplies.



12-pulse 4-quadrant 90MVA PF main converters

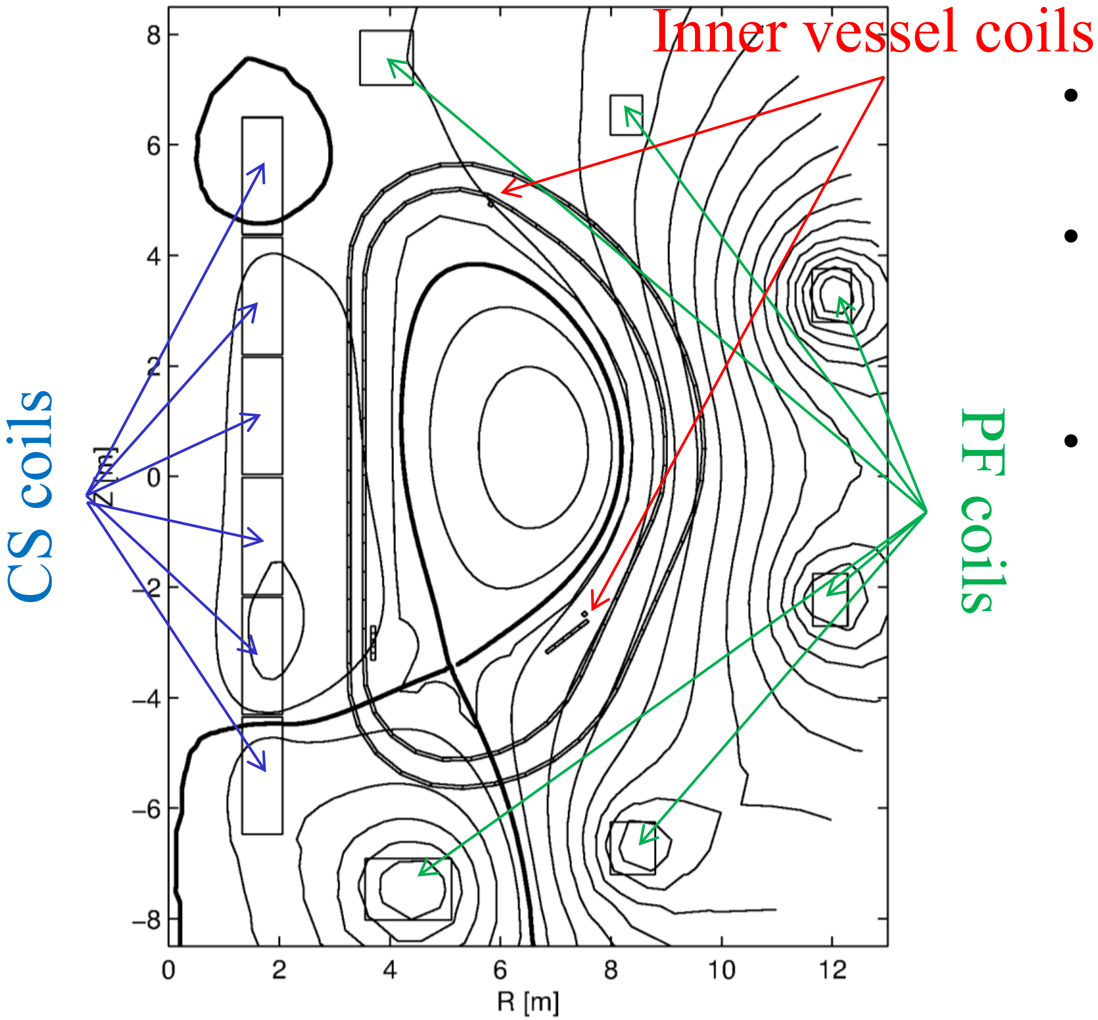
Actuators

- From a control point of view they are modeled by a simple Hammerstein model

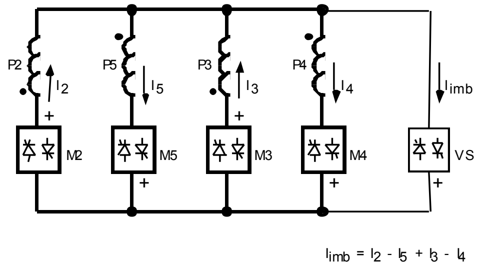


- Voltage limits are directly included in the simulation scheme, whereas current, power, and power derivative limits are checked after the simulation

Actuators



- Main converter (MC): drives the CS and PF coils
- VS3: drive the inner vessel coils (connected in anti-series)
- VS1: drive the PF2-PF3-PF4-PF5 coils connected in such a way to produce a radial field (vertical stabilization)



$I_{imb} = I_2 - I_5 + I_3 - I_4$

Diagnostics

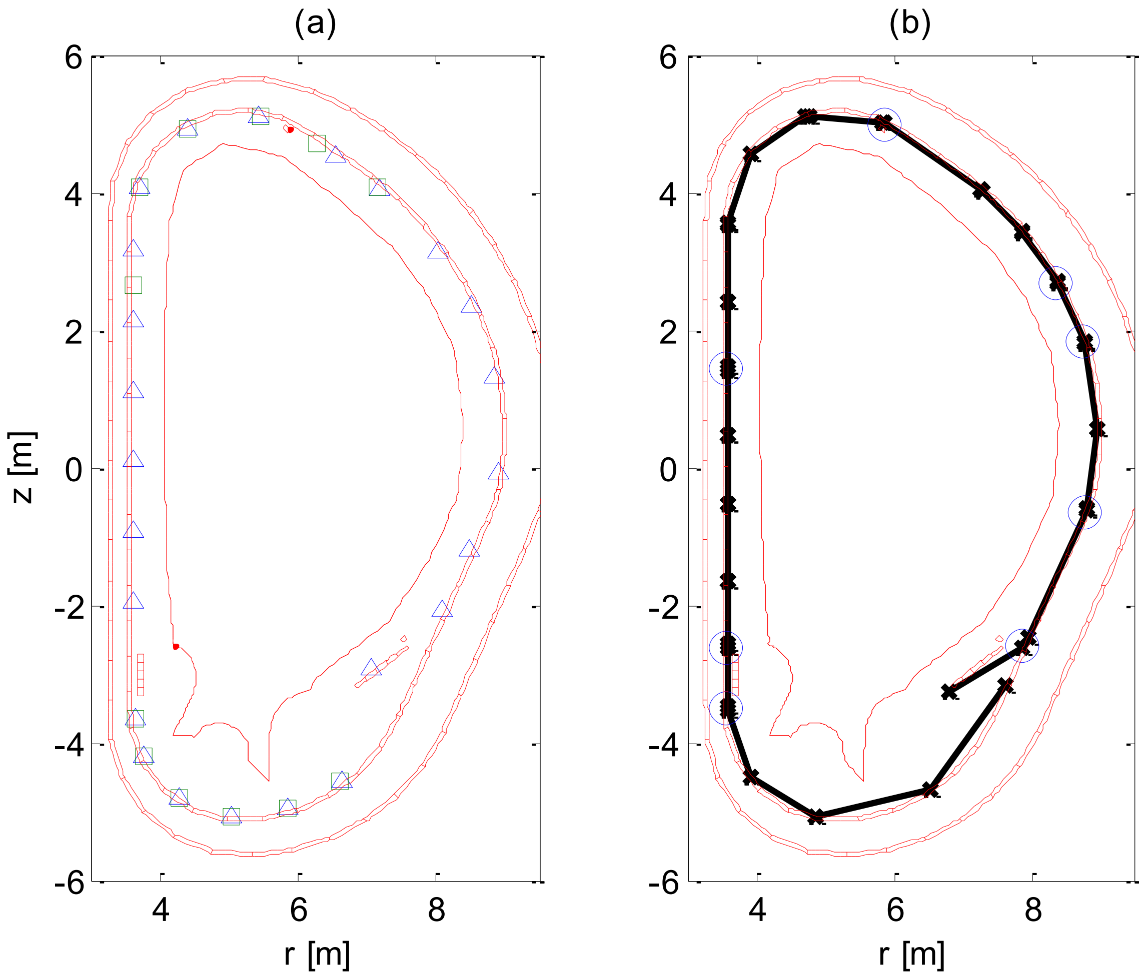
- Diagnostics provide an estimates of the plasma parameters to be controlled
- Note that this parameters are not directly measurable, and have to be reconstructed by means of the available magnetic measurements and suitable algorithms. For example

$$I_p \cong \sum_i w_{t_i} B_{t_i}$$

$$z_p I_p \cong \sum_i v_{t_i} B_{t_i} + \sum_i v_{n_i} B_{n_i}$$

$$r_p^2 I_p \cong \sum_i h_{t_i} B_{t_i} + \sum_i h_{n_i} B_{n_i}$$

- Problems related to
  - Accuracy of the estimation algorithm (systematic error)
  - Effect of the eddy currents
  - Offset integration error (sensors based on the Lenz law measures field and flux time derivatives)
  - Accuracy of the sensors



The ITER inner vessel sensors : (a) tangential (triangle) and normal pick-up coils (square); (b) partial (line segments) and full (circle) flux loops

Main choices for the magnetic control system

- Current decoupling controller to track desired currents in the CS&PF coils. The desired currents are both pre-programmed scenario currents and current variations dictated by other loops (e.g. shape control, plasma current control, etc.)
- VS3 circuit to control the vertical position (in a first phase) and then to vertically stabilize the plasma
- VS1 circuit (in certain phases) to decrease the current flowing in the inner coils
- Plasma current control achieved by a double integrator controller generating a suitable transformer field in the plasma region
- Plasma shape control based on a isoflux + XSC approach

The controlled variables

- The current flowing in the PF & CS coils
- The plasma current
- The centroid vertical speed
- 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

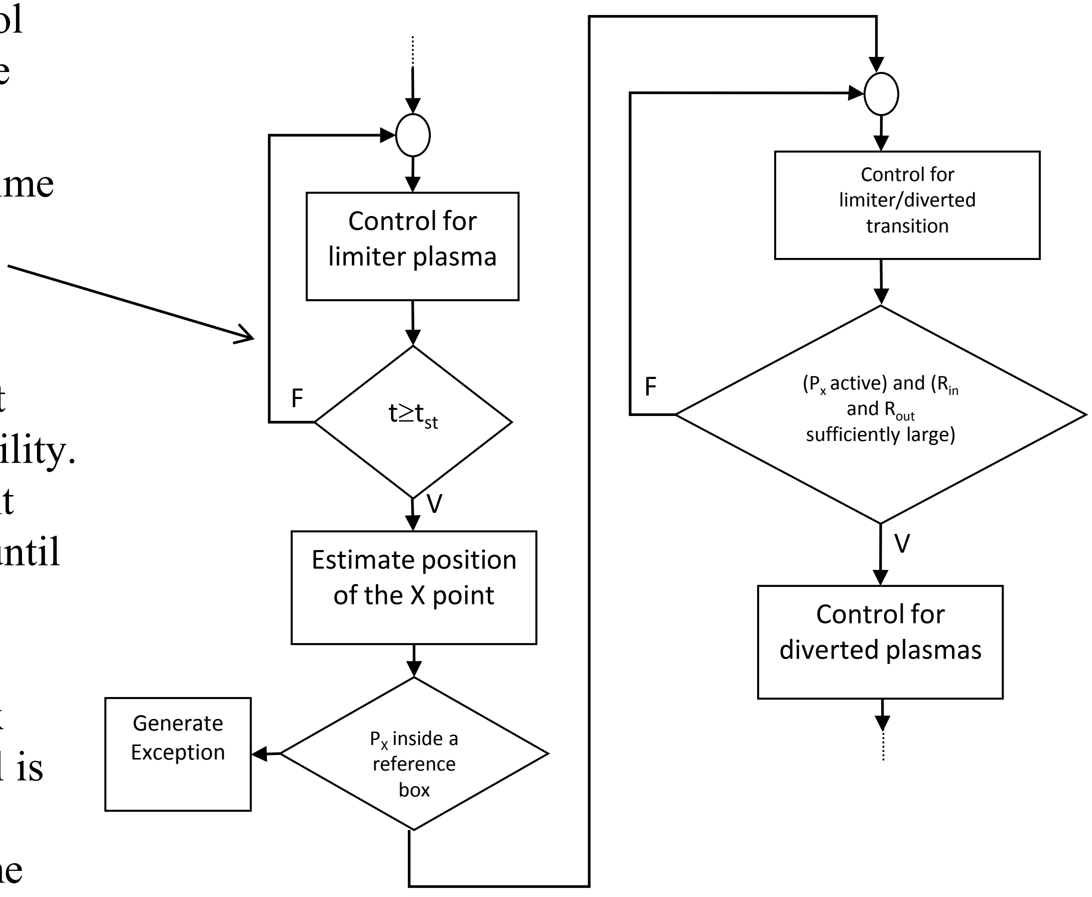
- We considered the following scenario
  - Initial phase (just after the initiation phase): the controlled variables are the vertical and radial position of the current centroid;
  - Limiter phase: The controlled variables are the position of the limiter point, and a set of flux differences (isoflux 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)

Scheduling of the controllers (only the initial phase is shown)

Phase	Controller variables	Comments
t_{start}=1.5s, $I_p \cong$500kA	Controlled Variables: r_p, z_p, I_{VS3}, I_{CS}, I_{PF}, Actuators: V_{CS}, V_{PF},V_{VS3}, V_{VS1}	Vertical control with VS3; VS1 to reduce current in the inner coils Plasma current not controlled controlled in feedforward
t_{start}=5s, $I_p \cong$1.7MA	Controlled Variables: a set of flux differences, zdot, I_{VS3}, I_{CS}, I_{PF}, I_{CS}, I_p Actuators: V_{CS}, V_{PF},V_{VS3}	Vertical control with VS3; Isoflux control for limiter configurations
t_{start}=9s, $I_p \cong$2.6MA	Controlled Variables: a set of flux differences, R_X, Z_x, Zdot, I_{VS3}, I_{CS}, I_{PF}, I_{CS}, I_p Actuators: V_{CS}, V_{PF},V_{VS3}	Vertical control with VS3; Isoflux control for limiter/diverted configurations. Control of the X-point position starts before it becomes active
t_{start}=11s, $I_p \cong$3.2MA	As before, just a reference change	
t_{start}=??		Switch to gap control

Remarks

- The switching between several control phases has been smoothed by suitable bumpless transfer algorithms
- The scheduling of the controllers is time driven, it should become event/time driven (managed from the pulse scheduler).
- In any case, the time scheduling must consider the diagnostic system capability. For example the control of the current centroid position should be delayed until a sufficiently accurate estimation of position is available
- During the ramp-up phase the isoflux control approach is used. Gap control is planned to come in when the requirements on shape control become tighter (at a certain point after the X-point formation)



Example of time/event driven scheduling

The current decoupling controller (CDC)

- The current decoupling receive in input the CS & PF coil current measurements and their references, and generate in output the voltage references for the main converter
- In general the CS & PF coil current references are generated as a sum of several terms coming for example from
  - the 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

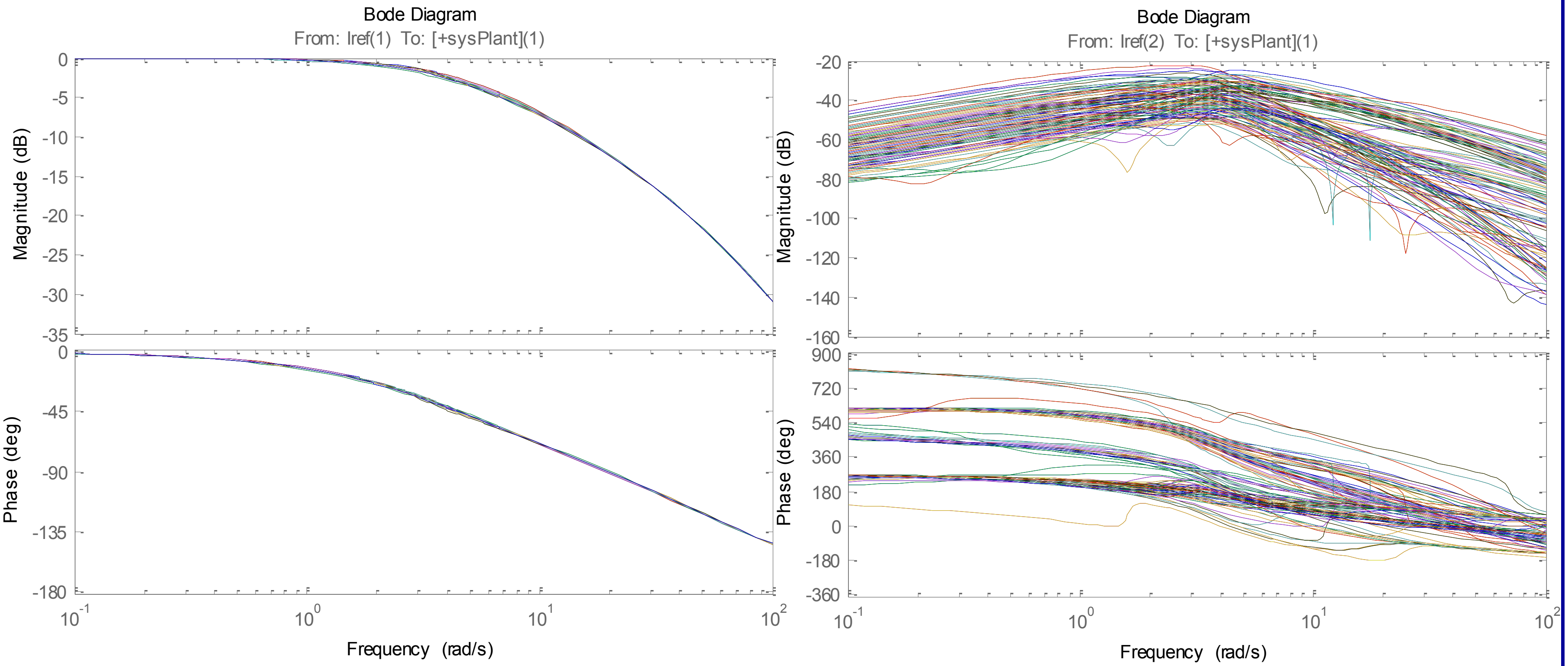
$$V_{PF} = K_c\left(I_{PF,ref} - I_{PF}\right) + R_{PF} I_{PF}$$

- 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). Note that the resistances due to the switching networks are not compensated.
- 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 in the initial phase where it is desired that the CDC does not counteract the effects of the switching networks.
- 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 (if a larger bandwidth is desired it is not possible to neglect the eddy currents).

Performance of the CDC controller



Diagonal transfer function

Off-diagonal transfer function

CDC closed loop system on a plasmaless model

The vertical stabilization controller

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 power supply.
- The VS3 circuit is used to stop the movement of the plasma current centroid and hence to stabilize the plasma equilibrium.
- The vertical stabilization controller parameters, with the exception of the gain on the vertical speed, which is proportional to the plasma current, have been kept fixed for the whole phase.

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 power supply.
- The VS3 circuit is used to stop the movement of the plasma current centroid and hence to stabilize the plasma equilibrium.
- The equation of the controller are

$$V_{VS3} = \mathcal{L}^{-1}[F(s)] * \left[K_1 \dot{z} + K_2\left(I_{VS3} - I_{VS3,ref}\right)\right]$$

- The reference on the I_{VS3} is added to avoid large jump on the VS3 voltage when the vertical stabilization controller is inserted (the I_{VS3} current at this time instant is different from zero, because of the induced currents and of the fact that in the previous time window VS3 is used to control the vertical position).
- The vertical stabilization controller parameters, with the exception of the gain K_1, which is proportional to the plasma current, have been kept fixed for the whole phase.

The vertical stabilization controller Parameters

$$V_{VS3} = \mathcal{L}^{-1}[F(s)] * \left[K_1 \dot{z} + K_2\left(I_{VS3} - I_{VS3,ref}\right)\right]$$

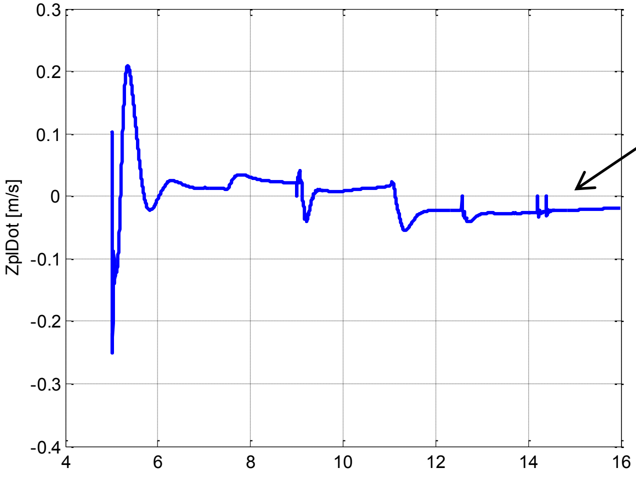
$$F(s) = -12075 \frac{\frac{s}{40} + 1}{\frac{s}{6} + 1}$$

$$K_1 = \frac{I_p}{15e6}$$

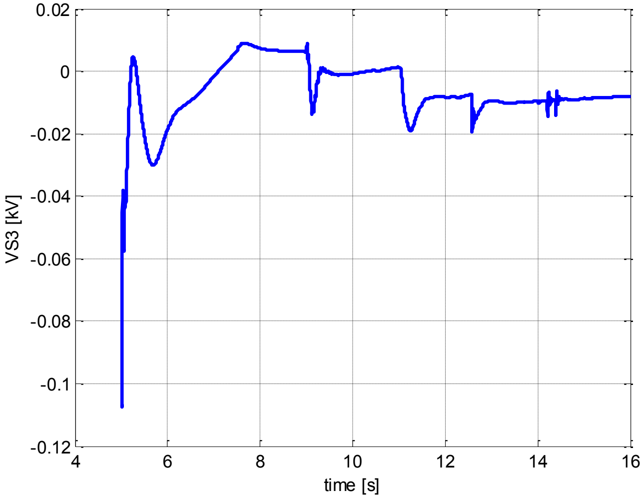
$$K_2 = -1.2^{-5}$$

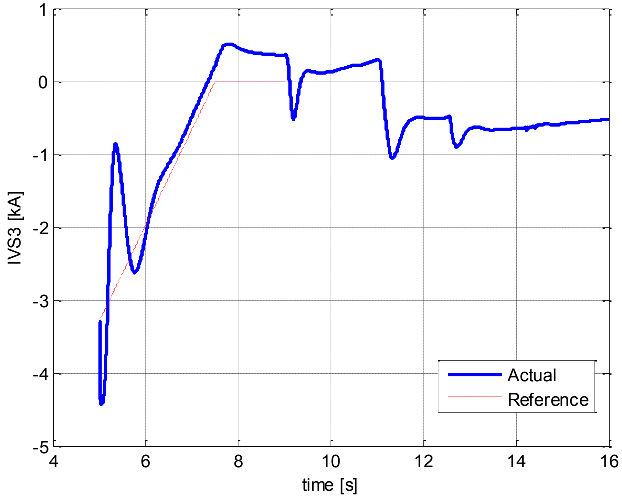
Parameters tuned on the base of Nichols plot (classical design) to maximize the phase margins

Behavior of the vertical controller variable



The vertical position of the plasma is changing due to the shape controller action





The current centroid position controller

- The current centroid position controller is used in the first phase of the discharge (low plasma current, low elongation), it is composed by two independent loops:
  - The vertical position controller: this is a proportional controller feeding back the tracking error on the current centroid vertical position. The main actuator is the VS3 circuit, while the VS1 circuit is used to decrease the current flowing in the inner coils.
  - The radial position controller: this is a proportional-derivative controller feeding back the tracking error on the current centroid radial position. The output of the controller is a current pattern on the PF3 and PF4 coils. This current pattern is chosen in a such a way to provide a vertical field.

- The current centroid position controller is composed by two independent loops:
  - The vertical position controller

$$V_{VS3} = K_z\left(z_{c,ref} - z_c\right) \qquad K_z = \frac{5000}{3.7e6} I_p$$

$$V_{VS1} = K_{IVS3} I_{VS3} \qquad K_{IVS3} = 0.1$$

  - The radial position controller

$$\delta I_{PF} = I_{rad}[K_p\left(r_{c,ref} - r_c\right) + K_d \dot{r}_c$$

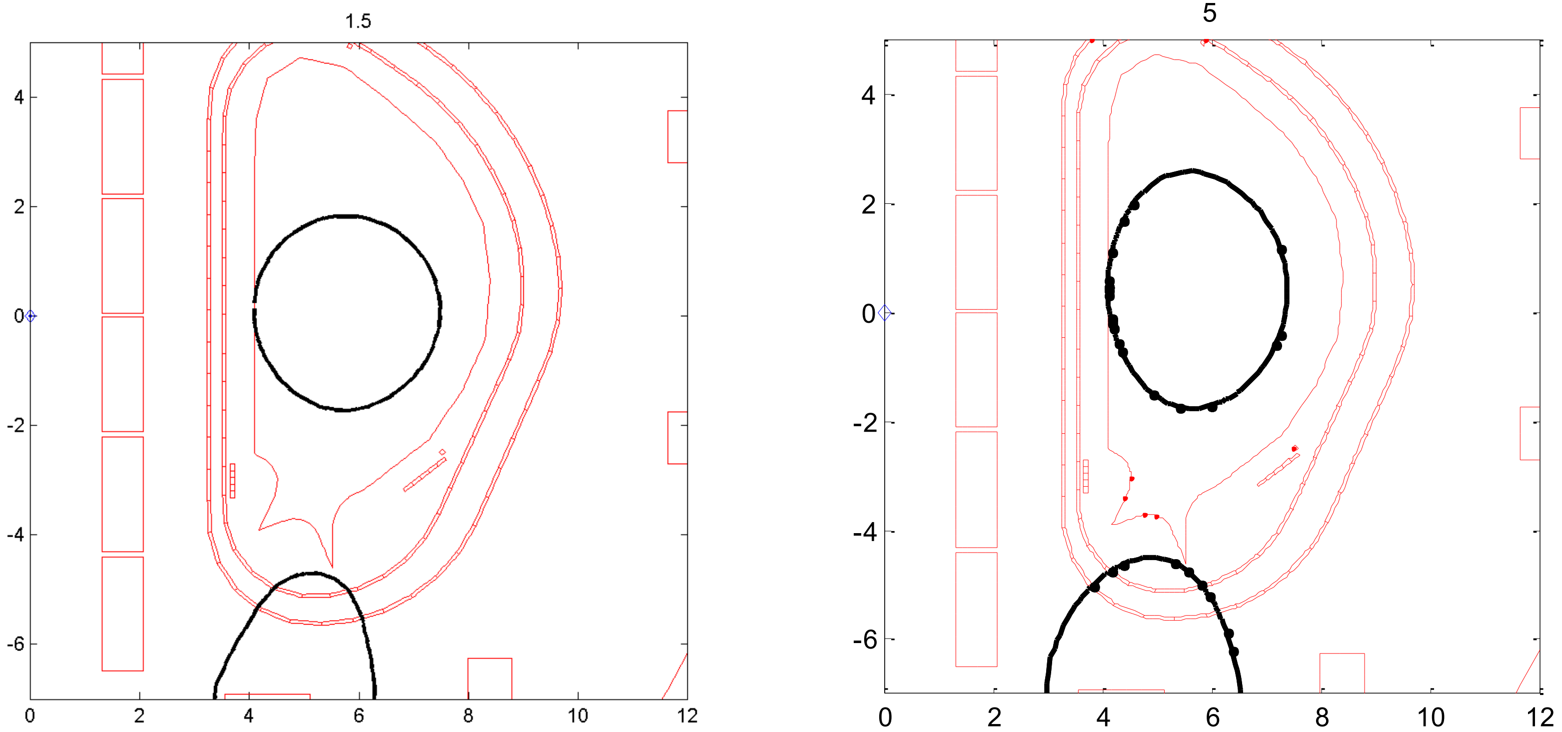
$$K_p = 0.8, \qquad K_d = 0.5$$

$$I_{rad} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 2.74 \\ 1.75 \\ 0 \\ 0 \end{bmatrix} \times 10^3 \times \frac{I_p}{5e5}$$

PF3 and PF4

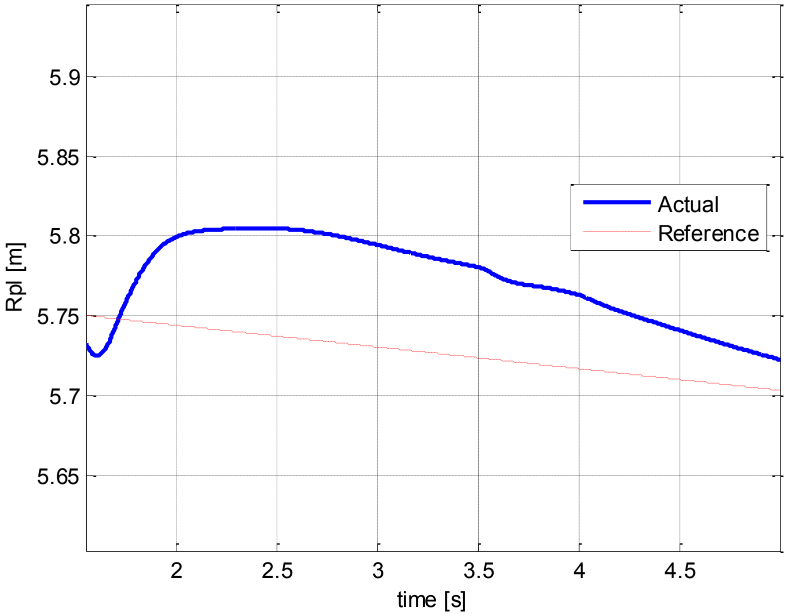
CREATE

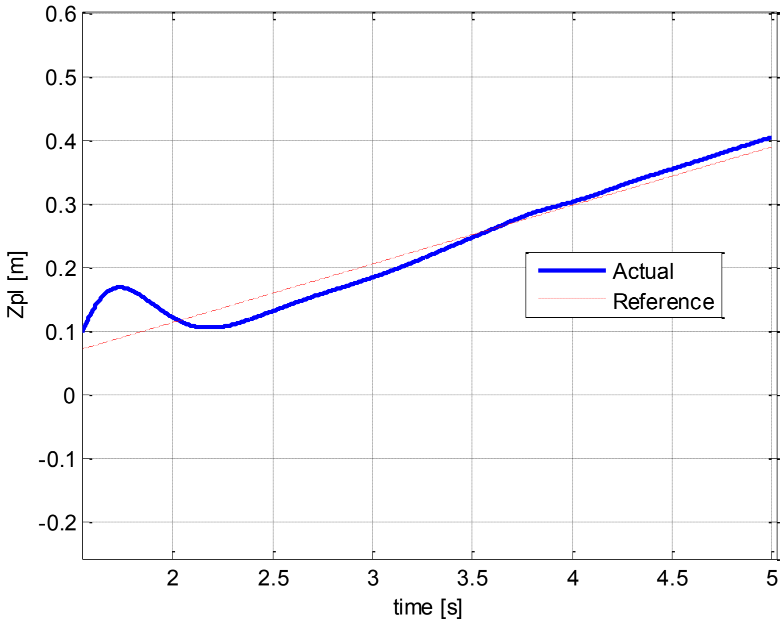
Initial and final plasma configurations



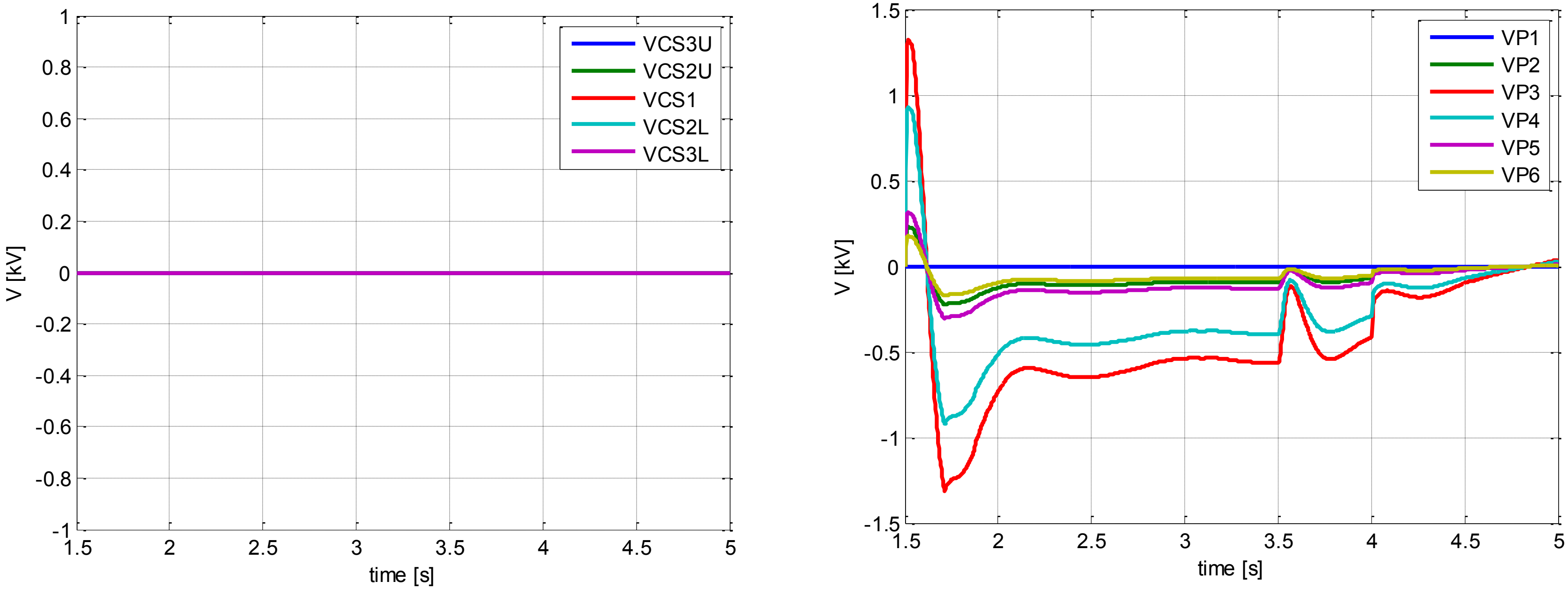
tstart=1.5s, tfinal=5s

Behavior of the controlled variables (1)



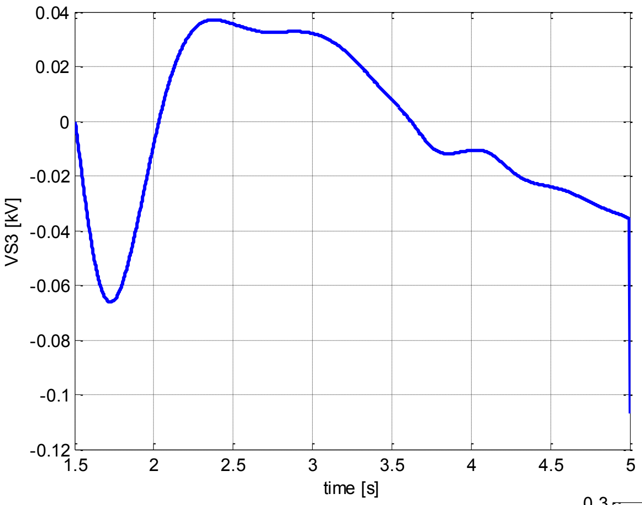


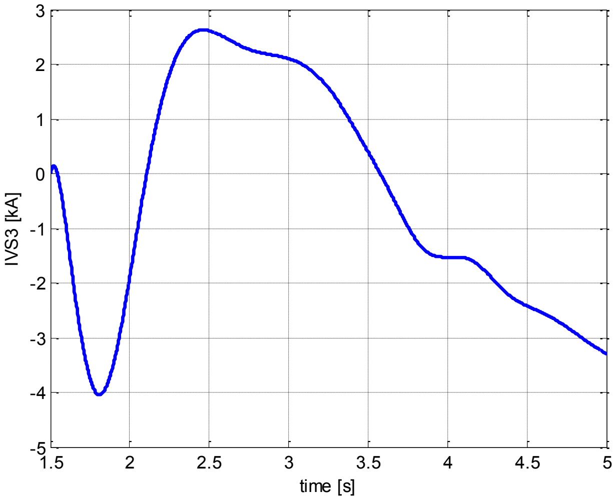
Behavior of the actuator variables (3)

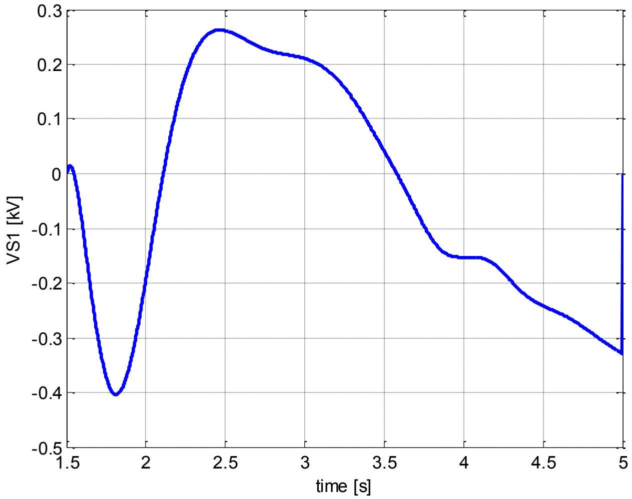


Voltages due only to the current centroid position controller

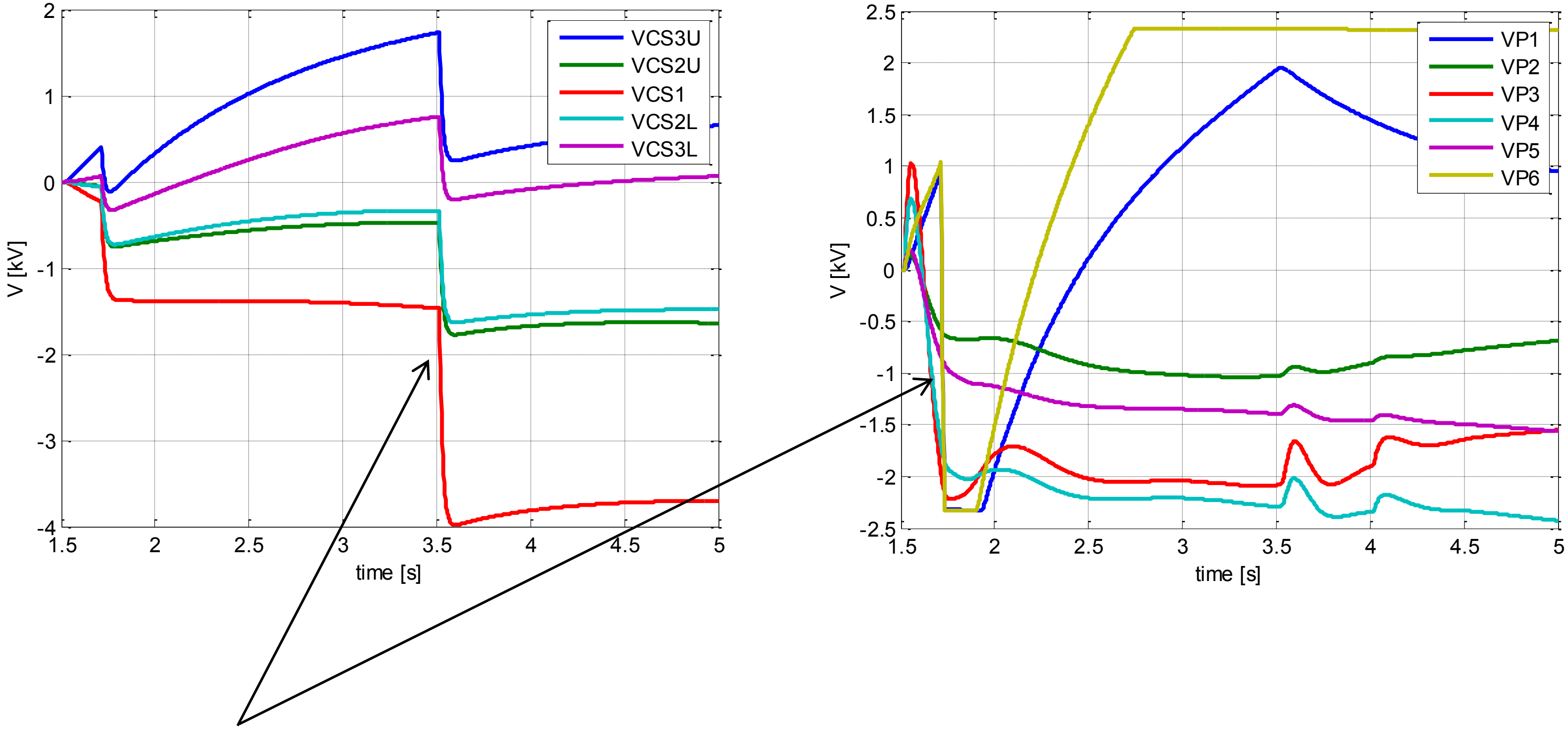
Behavior of the actuator variables (2)





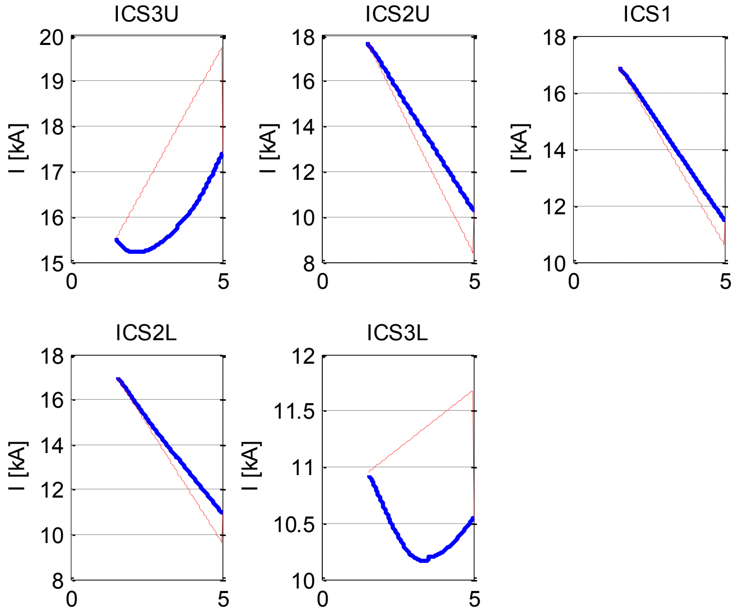


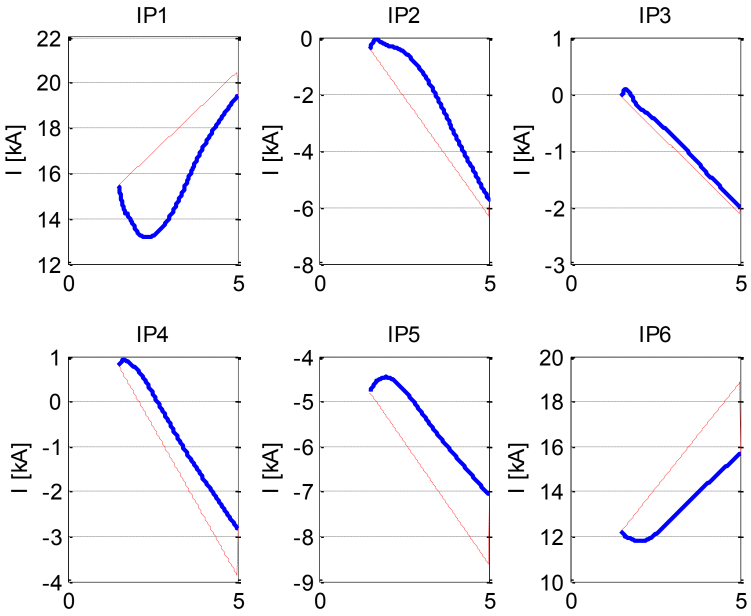
Behavior of the actuator variables (4)



Voltage jump to guarantee a smooth behavior when the switching network are turned off

Behavior of the actuator variables (5)





Pre-programmed and actual CS&PF currents. The differences are due to

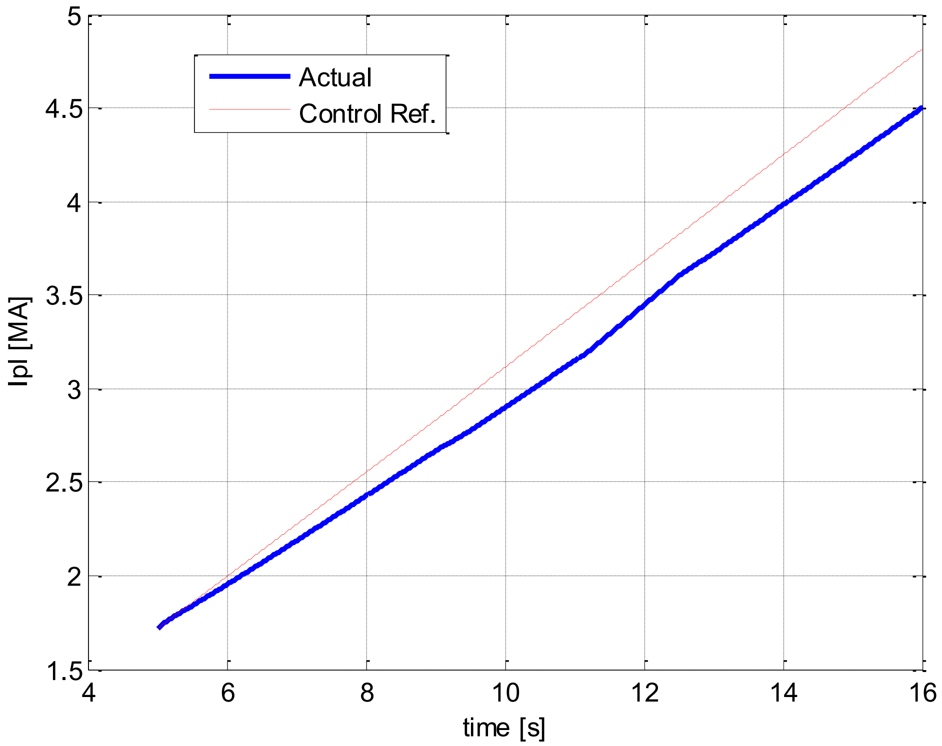
- The feedback action of the current centroid position controller (which changes the current references)
- The presence of the switching network

The plasma current controller

The plasma current controller

- The plasma current controller has as input the measued plasma current and its reference waveform, and has as output a pattern of CS & PF coil current deviation (with respect to the nominal values)
- The output current deviation are proportional to a pattern 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
- For the whole ramp-up phase, starting from t=5s, the plasma current controller has fixed parameters.

Behavior of the controlled variable



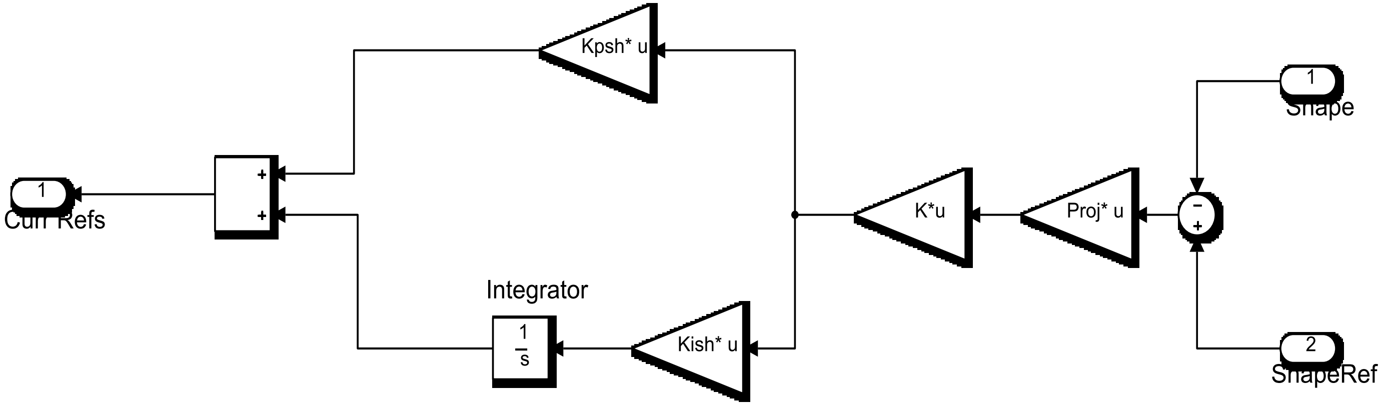
The tracking error could be reduced by increasing the gain of the plasma current controller

The plasma shape controller

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

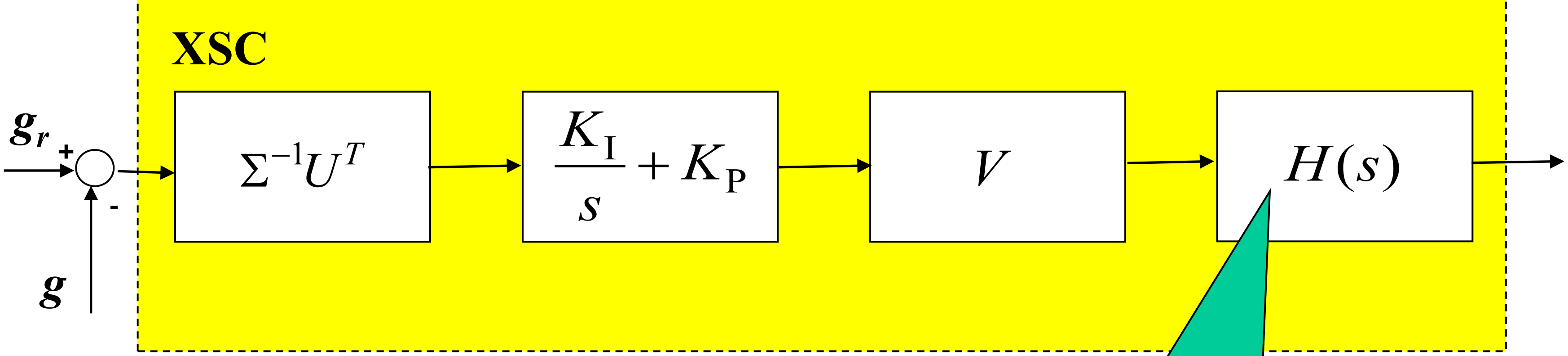
The plasma shape controller structure



- 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)

XSC structure

With 8 control variables, using an integral action we can drive to zero 8 linear combinations of the error. The eight linear combinations chosen by using the SVD matrices, guarantee the minimization of the steady state quadratic error



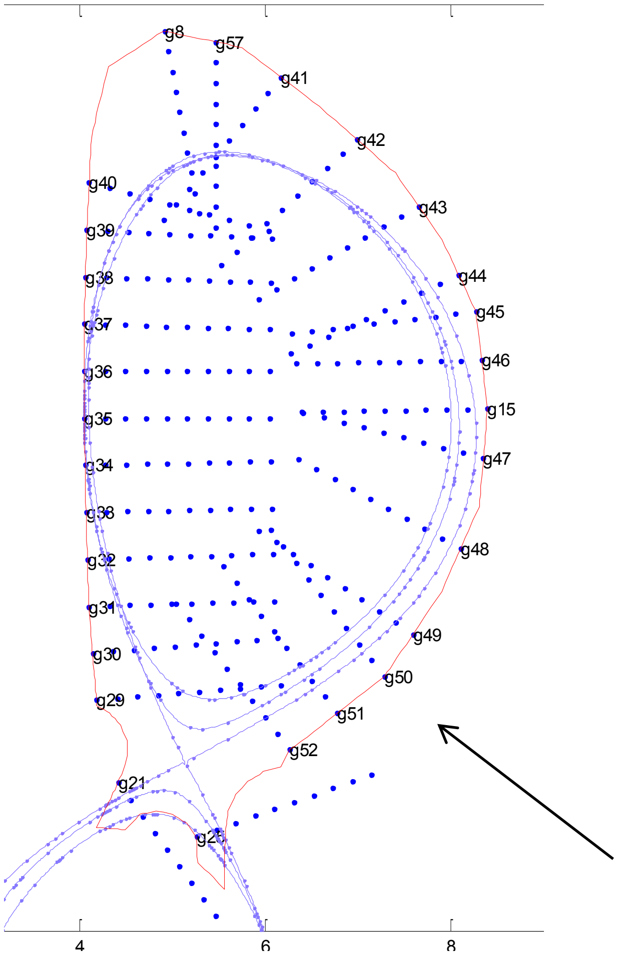
Assuming stability of the closed loop system, the structure of the controller guarantees the minimization of the following performance index

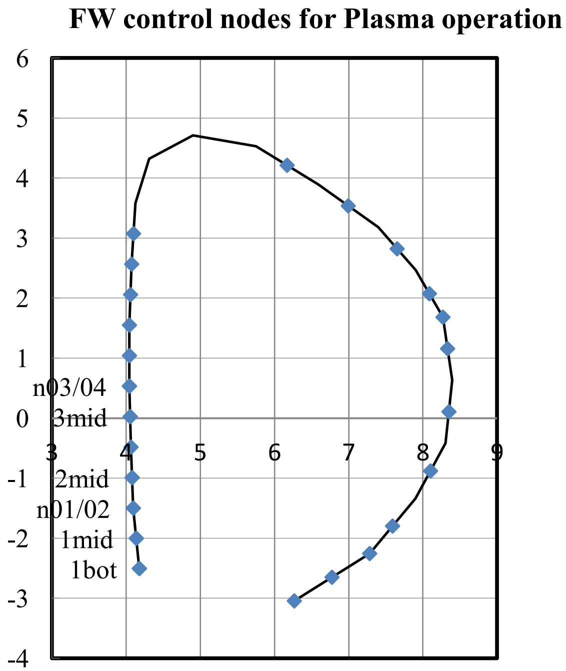
$$\lim_{t\to\infty} (\bar{g}_r - g)^{\mathrm{T}} (\bar{g}_r - g)$$

Equalizing filter

$$H(s) = \begin{bmatrix} \frac{1+s\tau_1}{1+s\tau} & 0 & \cdots & 0 \\ 0 & \frac{1+s\tau_2}{1+s\tau} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \frac{1+s\tau_8}{1+s\tau} \end{bmatrix}$$

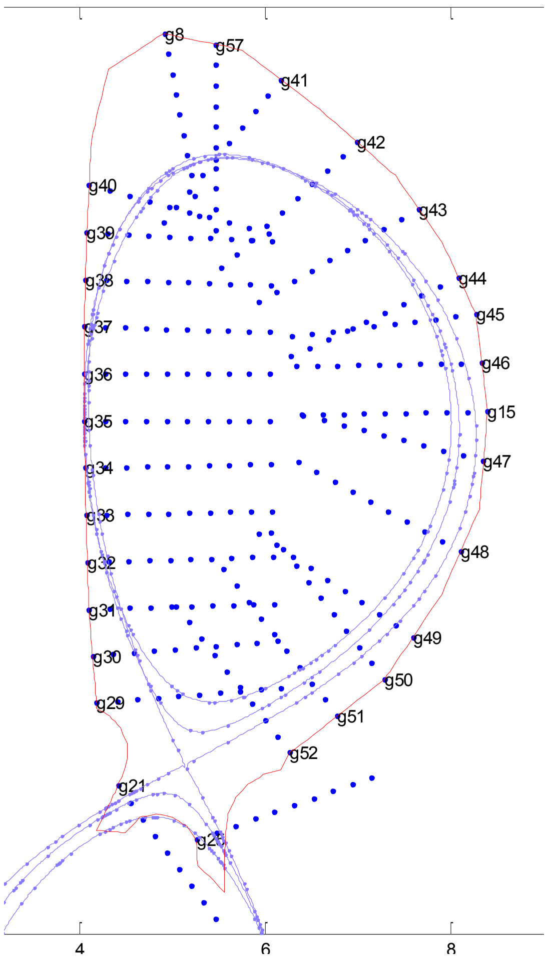
The plasma shape parameters





- 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 ψ_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

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

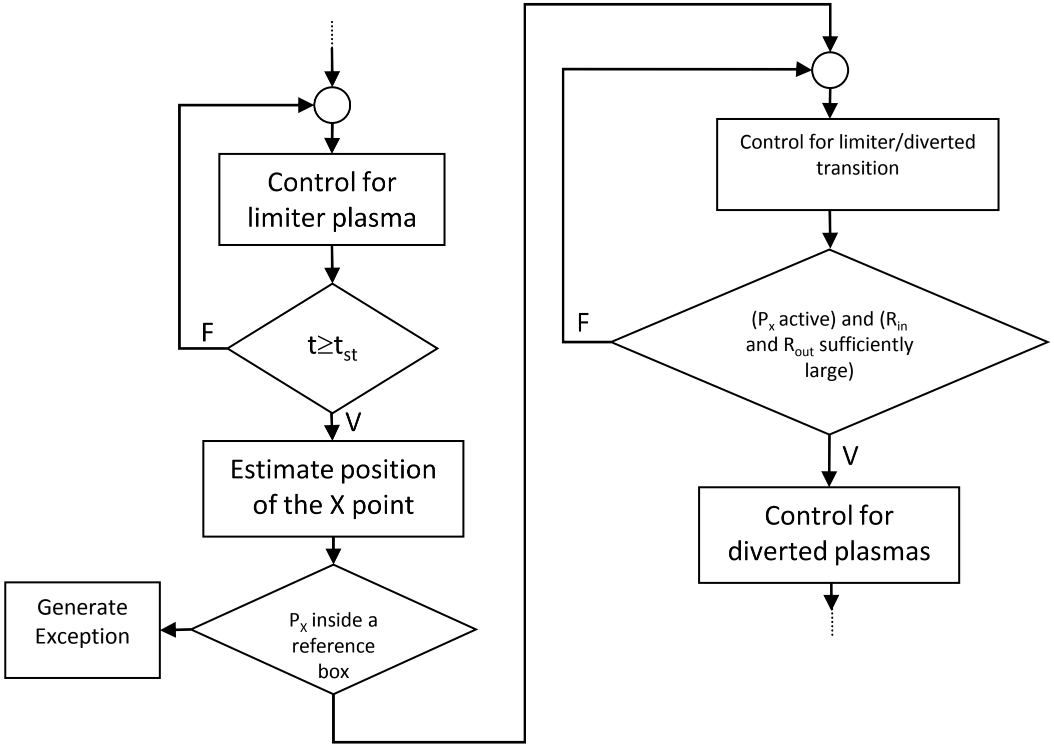
- So as the error signal seen by the controller in the two cases differ for a proportionality factor depending on the magnetic poloidal field

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



Switching between controllers

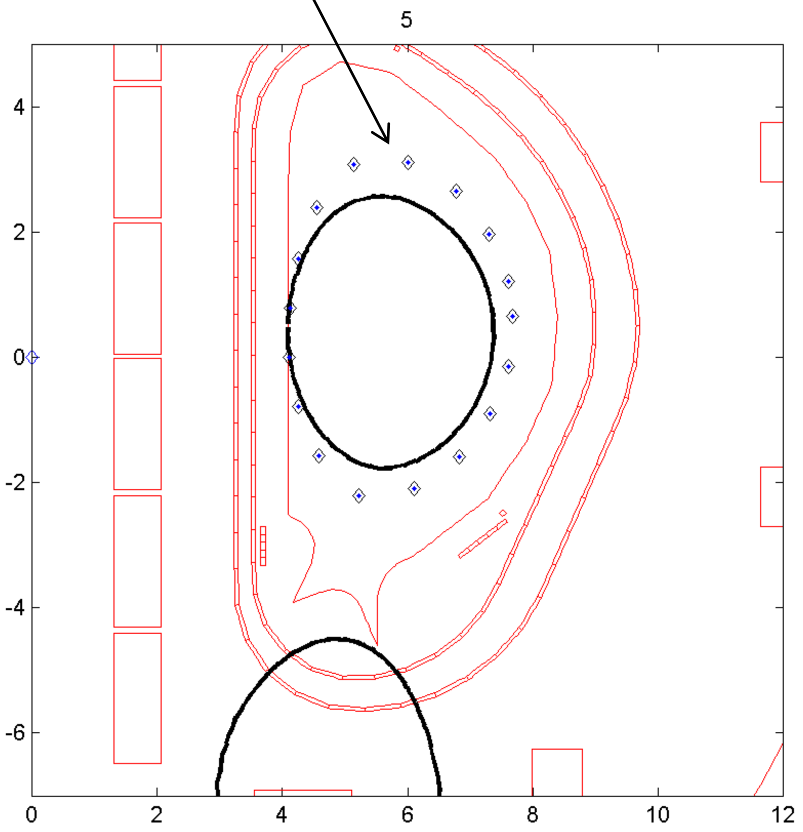
- Switching between different controllers happens at the start of each phase, but this switch can occur also during a single phase (controller scheduling to optimize the performance).
- Assume you want to change the controller at time t^*, and assume that with the new controller you want to track a new 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

The plasma shape isoflux controller

- During the initial ramp-up phase the plasma shape controller has two different configurations in the following time windows
  - t∈[5s, 9s]: in this time window the plasma is in limiter configuration; the plasma shape is driven to a configuration for which the transition to diverted configurations can begin. During this time window, as specified later, the controlled variables are 17 flux differences evaluated between target shape points and the target limiter point.
  - t∈[9s, 15s]: in this time window the plasma becomes diverted; During this time window, as specified later, the controlled variables are the radial and vertical position of the X-point (which initially is not active) and 29 flux differences evaluated between the target shape points and the moving X-point.
    In this time window at t=11s a change of reference shape is also introduced, i.e. the control towards the final plasma shape is accomplished in two steps.
- After this time-windows it is foreseen to switch to gap control (but this will be investigated in detail in TO-2)

The plasma shape controlled variables for lim2lim phases

17 control points specify the target shape



- The isoflux controlled parameters for lim2lim transitions are 17 flux differences evaluated along the desired target shape.

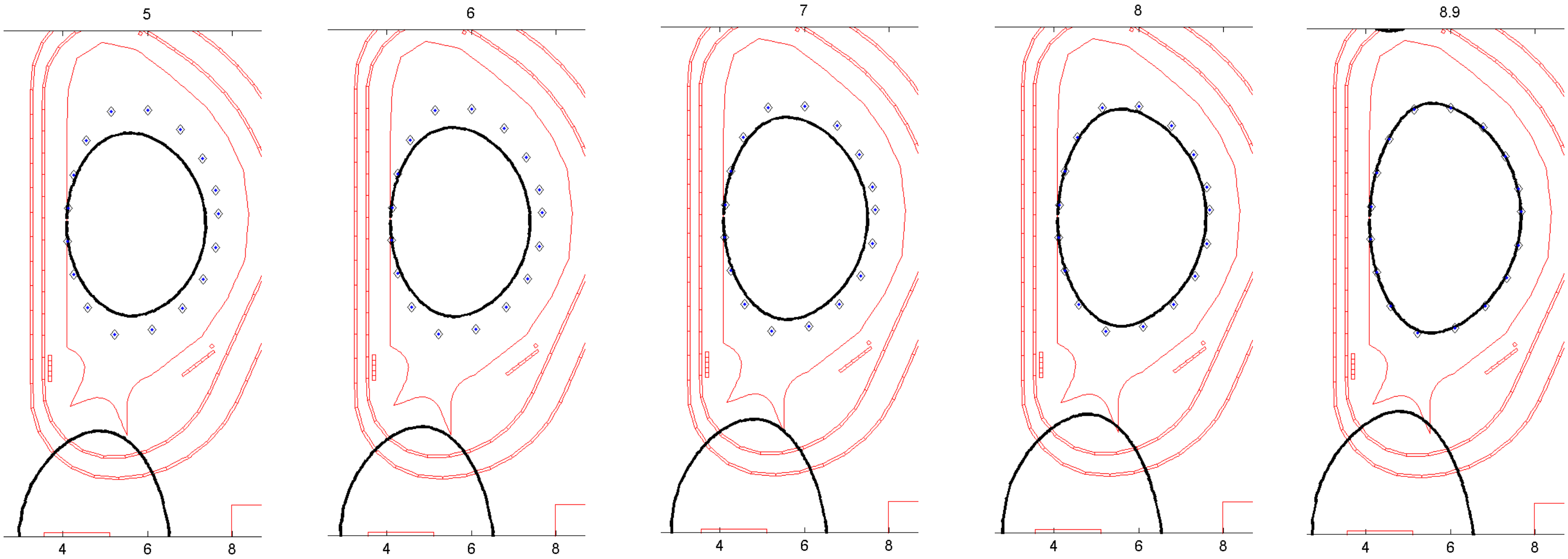
$$\Delta\psi_i = \psi\left(P_{i,ref}\right) - \psi\left(P_{lim,ref}\right)$$

Flux in the i-th control point

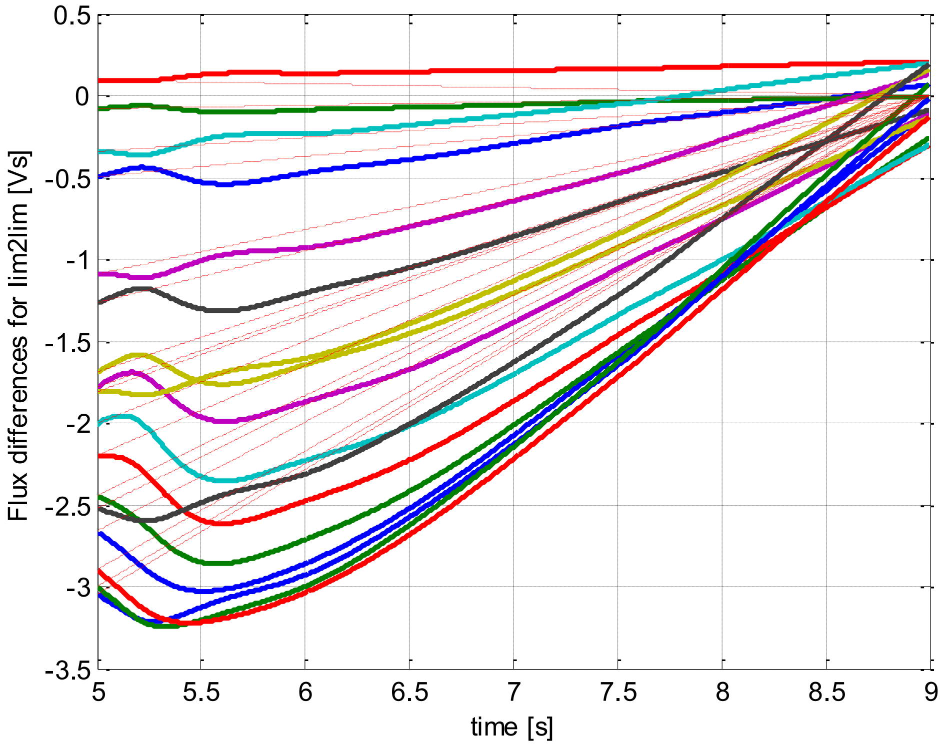
Flux in the target limiter point

- The reference signals for the 17 controlled flux differences are ramp starting from the initial values and going to zero in the desired transition time.

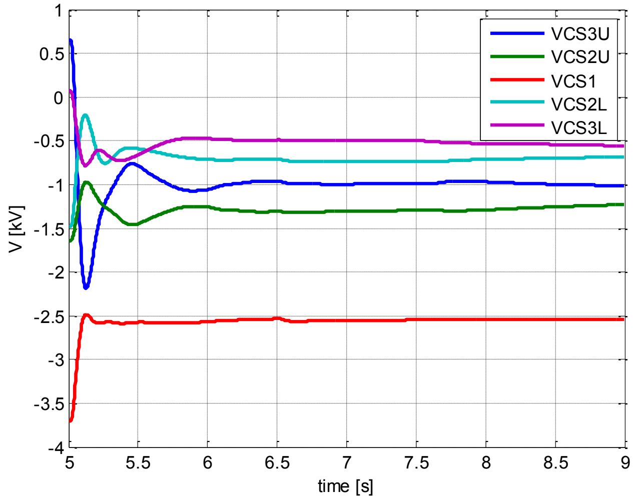
Isoflux lim2lim controller performance

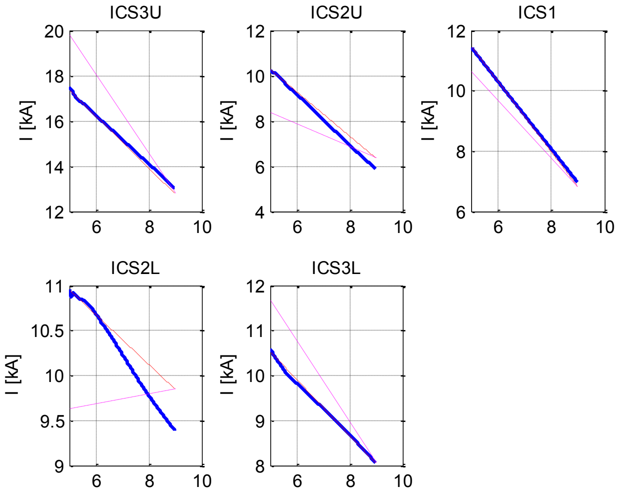


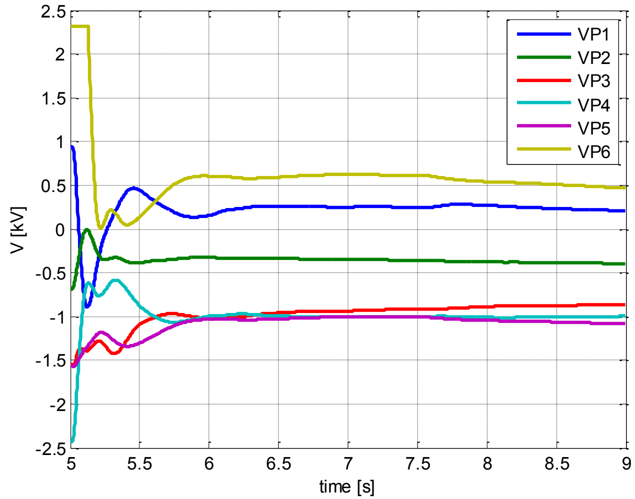
Isoflux lim2lim controller performance

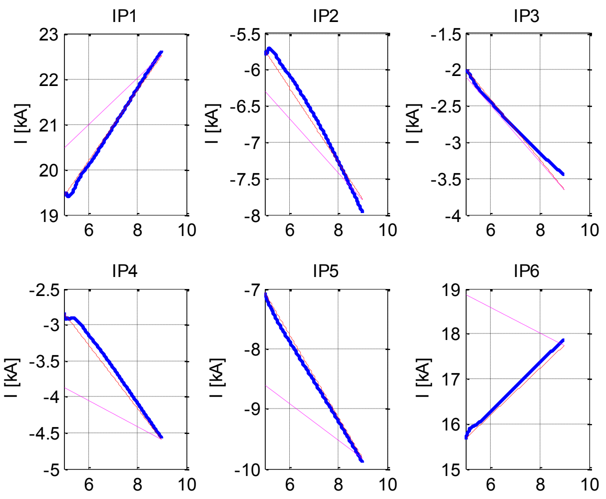


Isoflux lim2lim controller performance



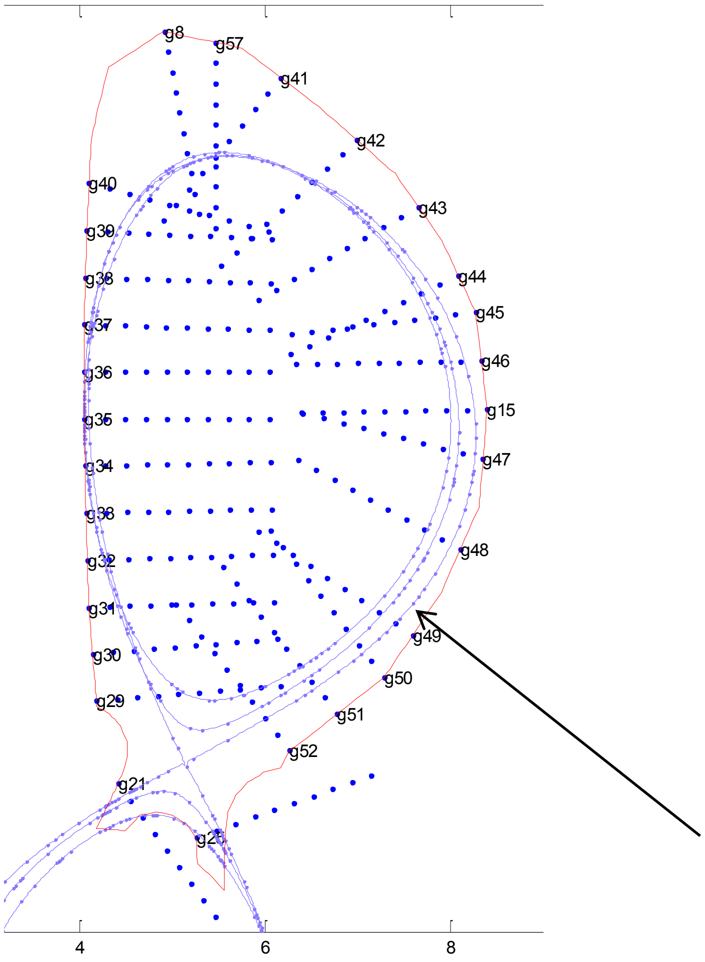


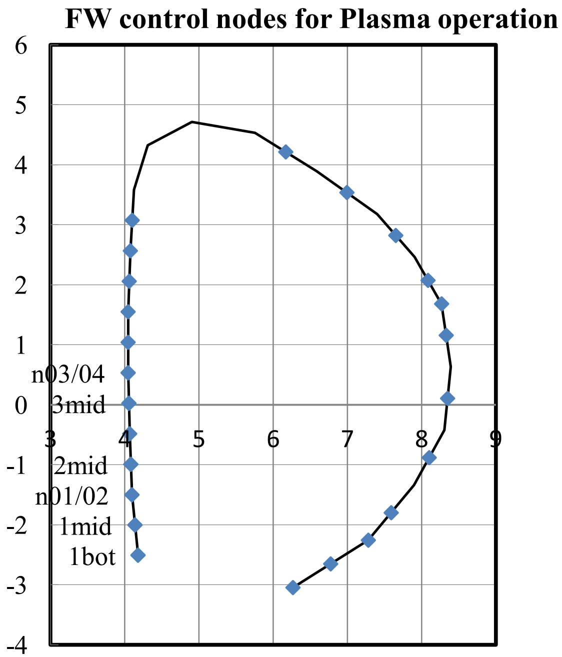




- CS&PF Voltages and currents take into account all the contributions in the time window 5-9s:
  - Pre-programmed current tracking
  - Plasma current control
  - Shape Control
- Note that at the t=9s the CS and PF currents are close to the pre-programmed ones (control actions give only small variations)

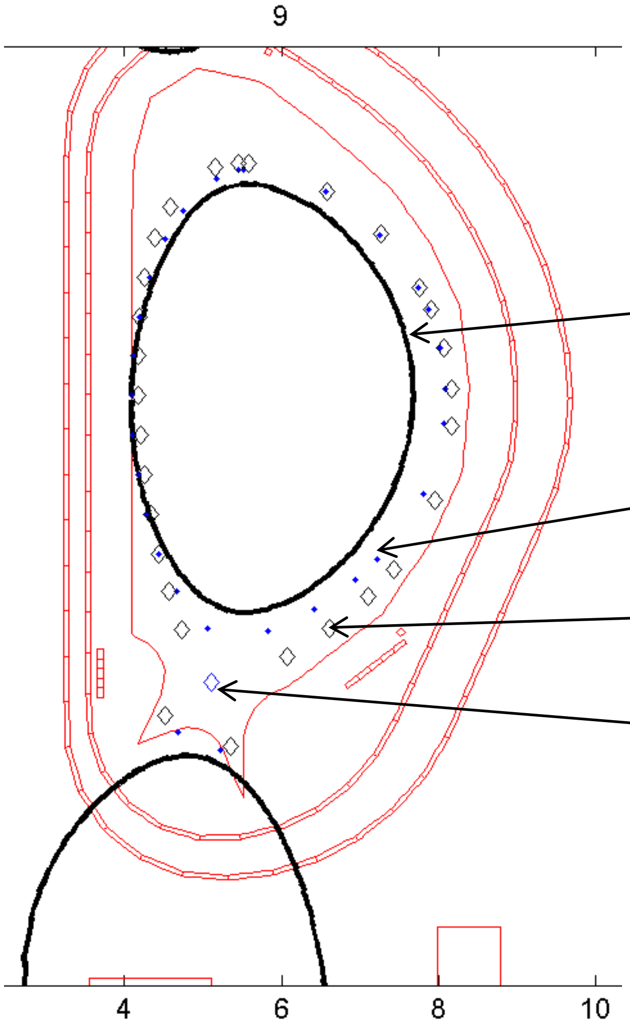
The plasma shape controlled variables for lim2div transition




FW control nodes for Plasma operation

- 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
- Target point are at the intersection of the desired plasma shape with the 29 control segments

The plasma shape controlled variables for lim2div transition



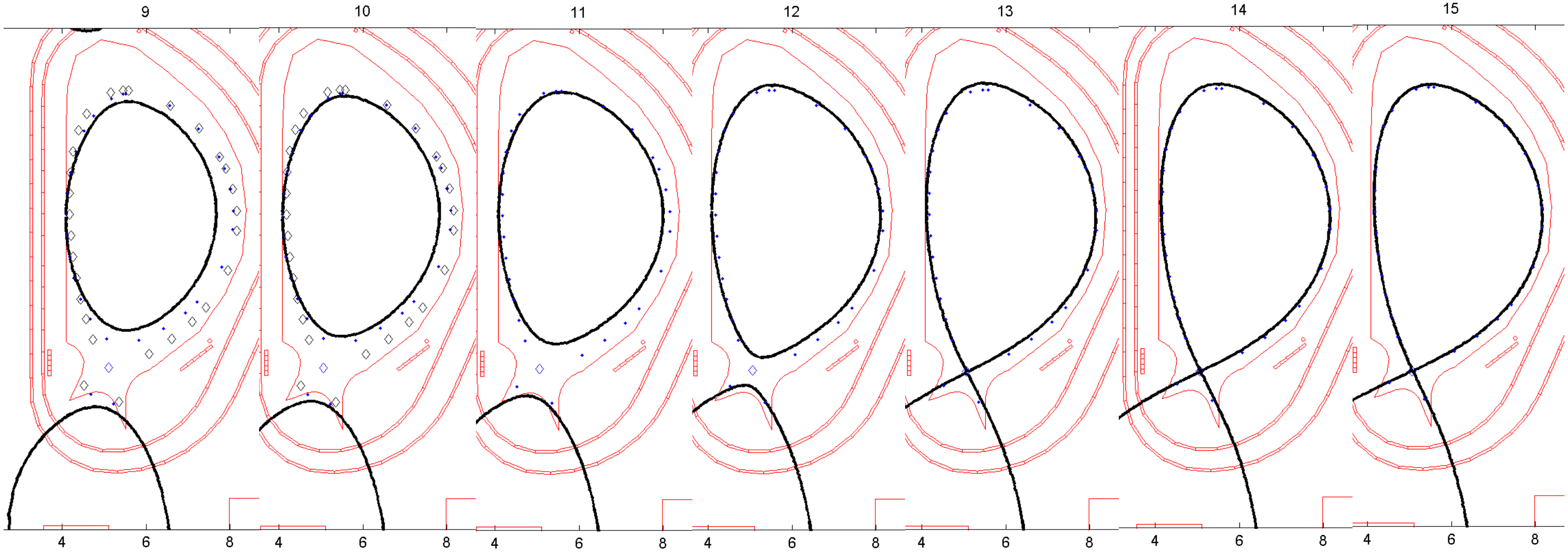
Plasma Shape at t=9s (black line)

Target points, t∈[9s, 11s] (blu dot)

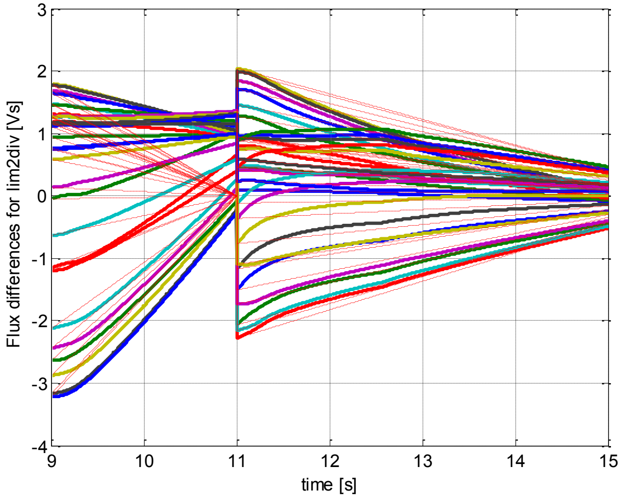
Target points, t∈[11s, 15s] (diamond)

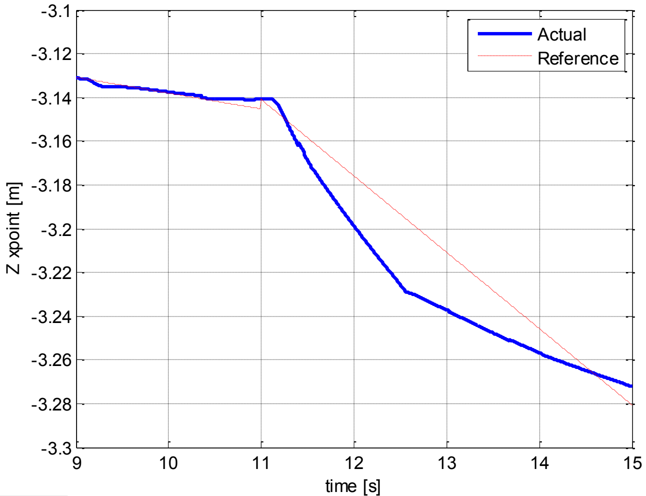
Target X-point at t=9s

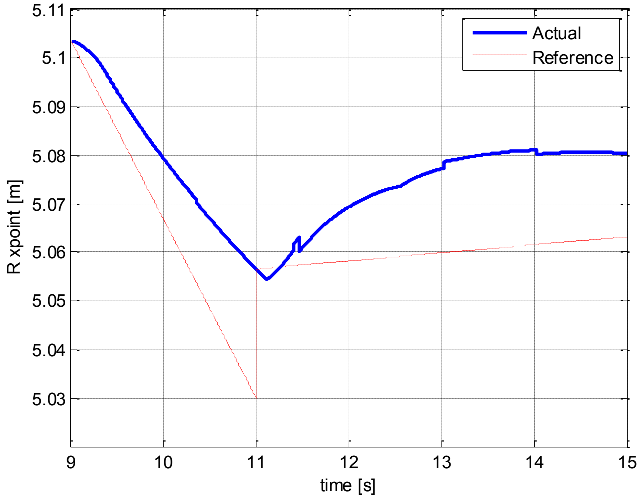
Isoflux lim2div controller performance



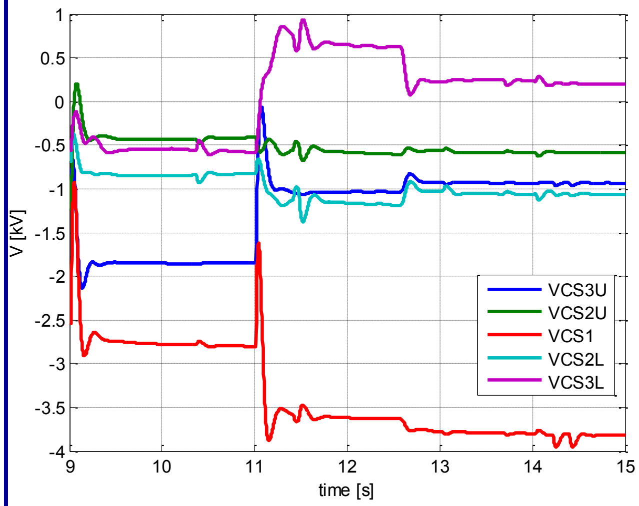
Isoflux lim2div controller performance

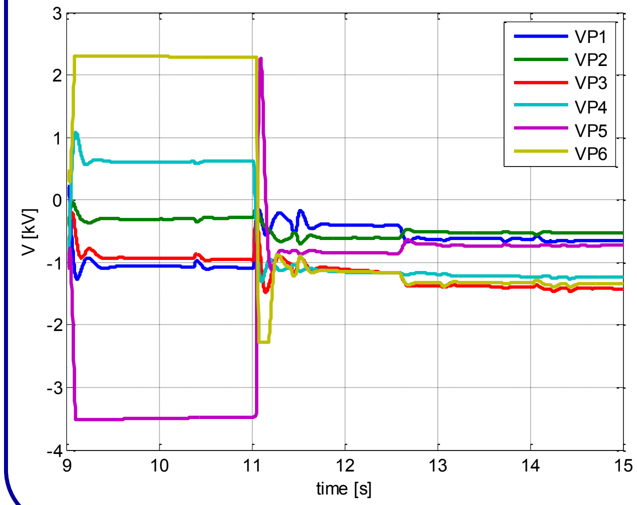


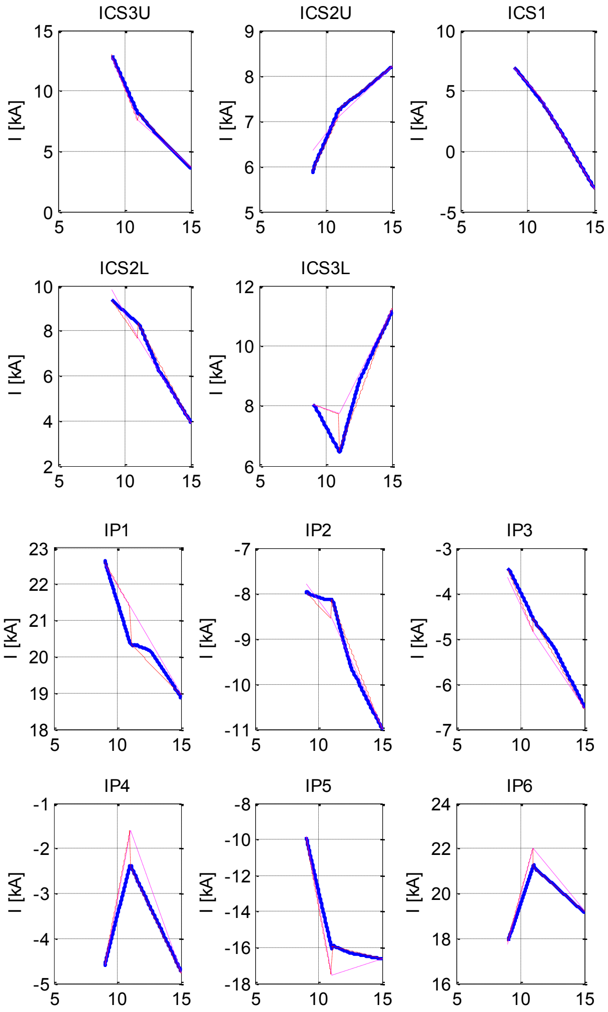




Isoflux lim2div controller performance







- CS&PF Voltages and currents take into account all the contributions in the time window 9-15s:
  - Pre-programmed current tracking
  - Plasma current control
  - Shape Control
- Note that at the t=15s the CS and PF currents are close to the pre-programmed ones (control actions give only small variations)

The Current Limit Avoidance system

- The Current Limit Avoidance System (CLA) has been recently designed and implemented in the JET tokamak to avoid current saturations in the PF coils when the XSC is used to control the plasma shape.
- In ITER such a system would be very useful, especially at the end of the flat-top phase when the PF currents are very close to their limits

The Current Limit Avoidance system

- The CLA uses the redundancy of the PF coils system to automatically obtain almost the same plasma shape with a different combination of currents in the PF coils.
- In the presence of disturbances (e.g., variations of the internal inductance li and of the poloidal beta p), it tries to avoid the current saturations by relaxing the plasma shape constraints
- The main difficulties in implementing the CLA scheme in ITER is in the fact that the PF coils are also responsible for the control of the plasma current (in JET plasma current is controlled by a dedicated coil), and that the plasma current control loop is not integrated inside the XSC controller
- Work is in progress to overcome these difficulties.