Free-boundary equilibrium transport simulations of ITER scenarios under control

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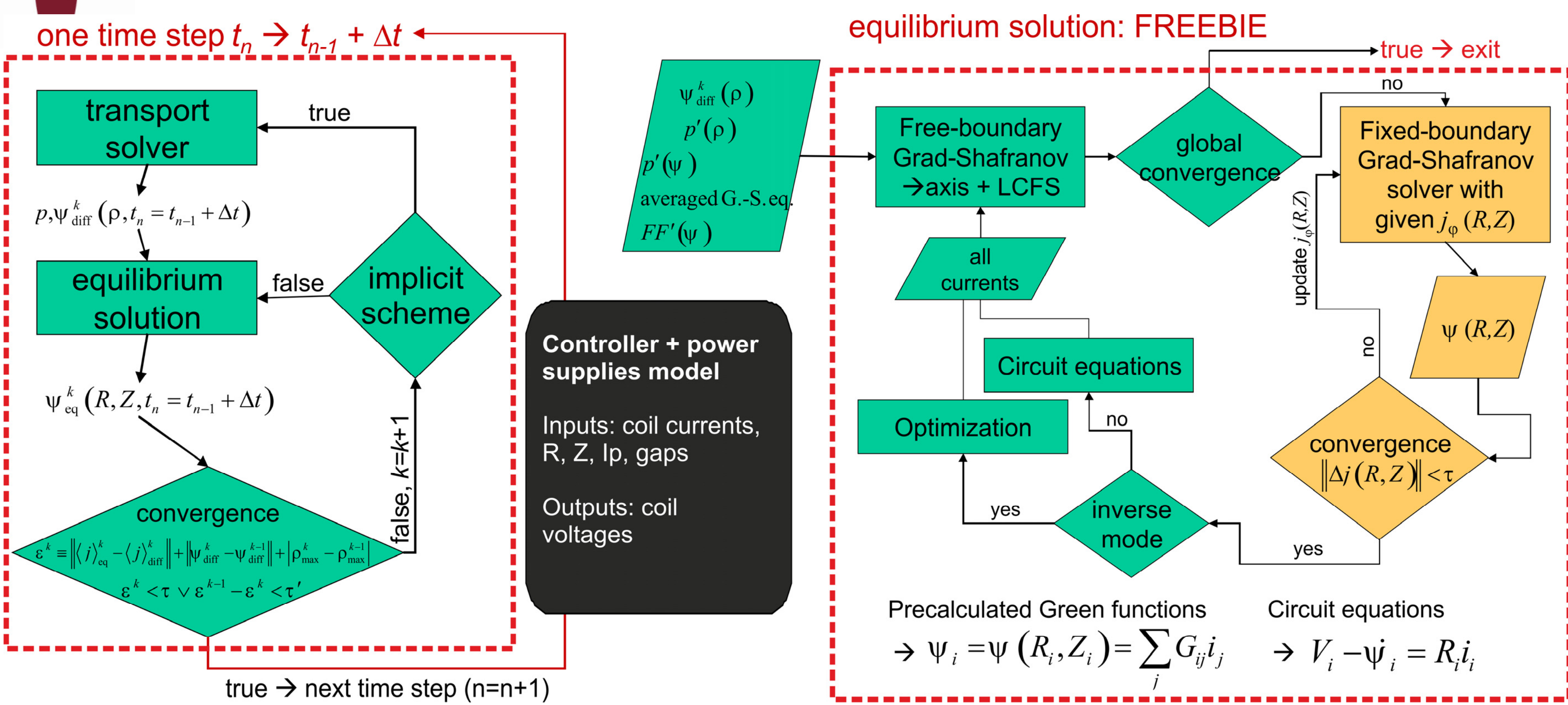
FREEBIE is self-consistently (implicitly) coupled with CRONOS + controllers (CRPP)

- Consistency between equilibrium and transport is enforced.
- External controller (DINA-CH framework) controls position, current, shape (gaps).



Boundary conditions are crucial – two possibilities implemented

Predictor-corrector boundary conditions

$$\psi_a - \psi_b = L_p I_p$$

$$\Delta\psi = \psi_b^{diff} - \psi_b^{equil}$$

$$I_p^* = I_p\left(1 + \frac{\Delta\psi}{\psi_a - \psi_b}\right)$$

L_p contains contribution from plasma and coils (equilibrium coil currents ~ I_p).

Use I_p^* as next time step boundary condition for the current diffusion equation.

Robin type boundary condition – more physical

$$\psi_a = \psi_a^{ext} + \psi_a^{pl}$$

$$I_p = -C\psi', \quad \psi' = \left.\frac{\partial\psi}{\partial\rho}\right|_{\rho=\rho_{max}}$$

Separate the flux at the axis into plasma and external part (straightforward in FREEBIE).

Discrete time derivative finally yields a Robin boundary condition for ψ_b.

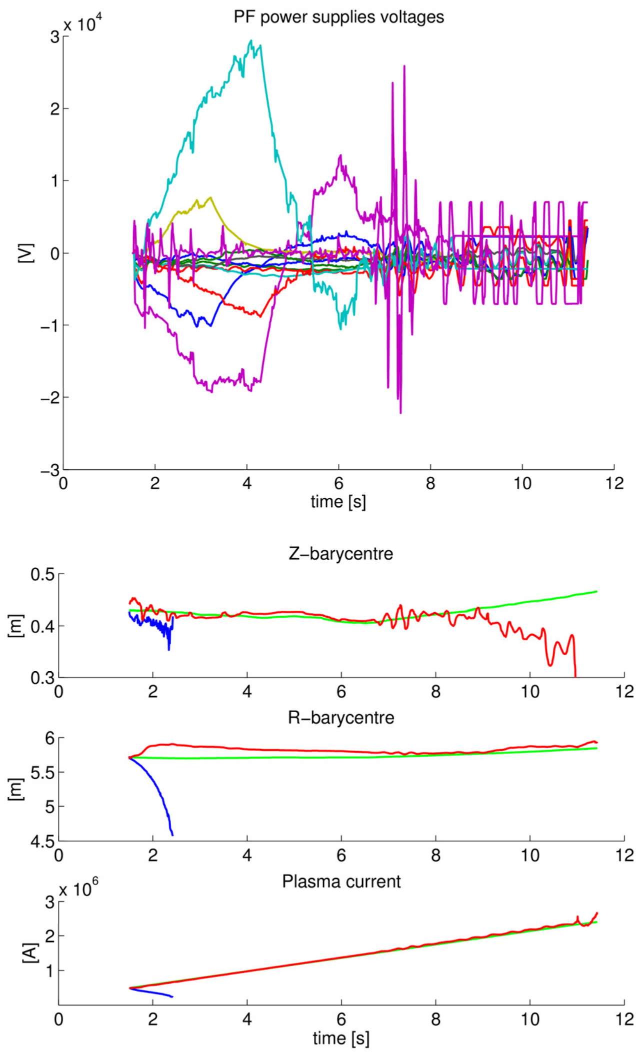
$$\psi_b + CL_{ext}\psi' = \left(\tilde{\psi}_b + \psi_a^{ext} - \tilde{\psi}_a^{ext}\right) - \tilde{L}_{ext}\tilde{I}_p,$$

Tilde is for previous time step values.

$$L_{ext} = \psi_a^{pl}/I_p - L_i \qquad \gamma = L_{ext} / \tilde{L}_{ext}$$

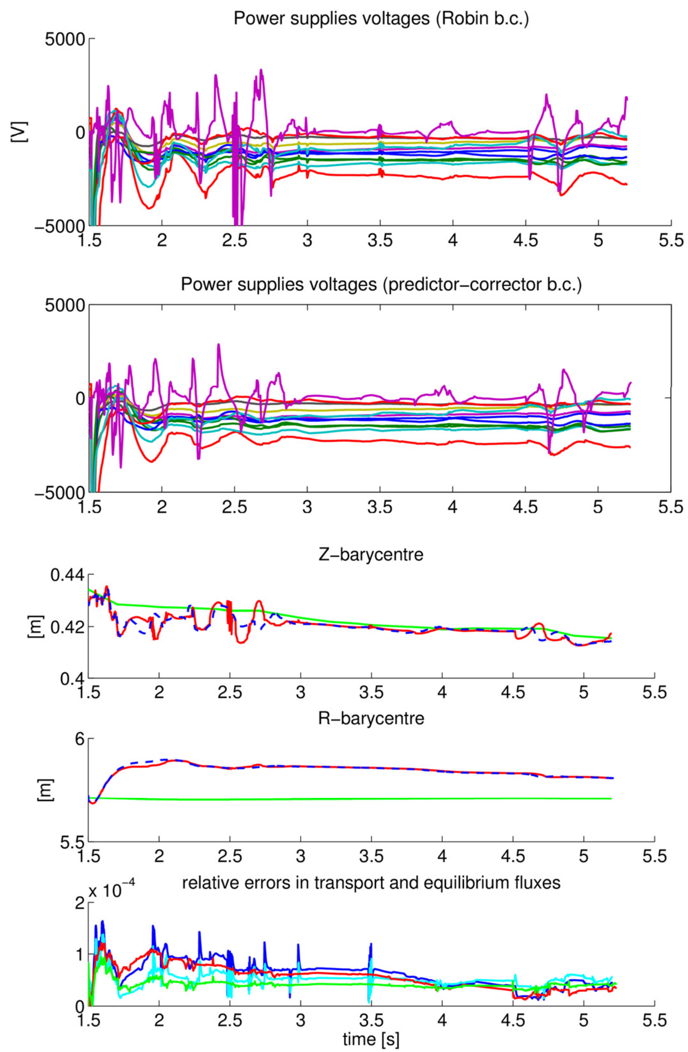
ITER results – not optimized feed-forward

- Feed-forward currents (for the controller) are calculated by the inverse mode of FREEBIE.
- Saturated coils and excessive voltages appear without a suitable regularization term.
- Until 8 s, no voltage limits are applied and the excessive voltages reasonably control the plasma. After 8 s, the controller cannot sustain the reference waveforms because of the voltage limits and coil saturations and the simulation finally stops converging at ~11.5 s.



Optimized feed-forward yields more reasonable results

- By switching on the regularization term, which minimizes I^2_{PF} and ΔI_{PF}, and adjusting the weight, it was possible to create more reasonable waveforms and feed-forward currents.
- Voltage demands are now within the power supplies limits, except for the first ~50 ms, when the shell currents are building up.
- The two boundary conditions yield similar results. Robin b.c. is a bit more noisy.
- Boundary and on-axis fluxes are consistent in transport and equilibrium.

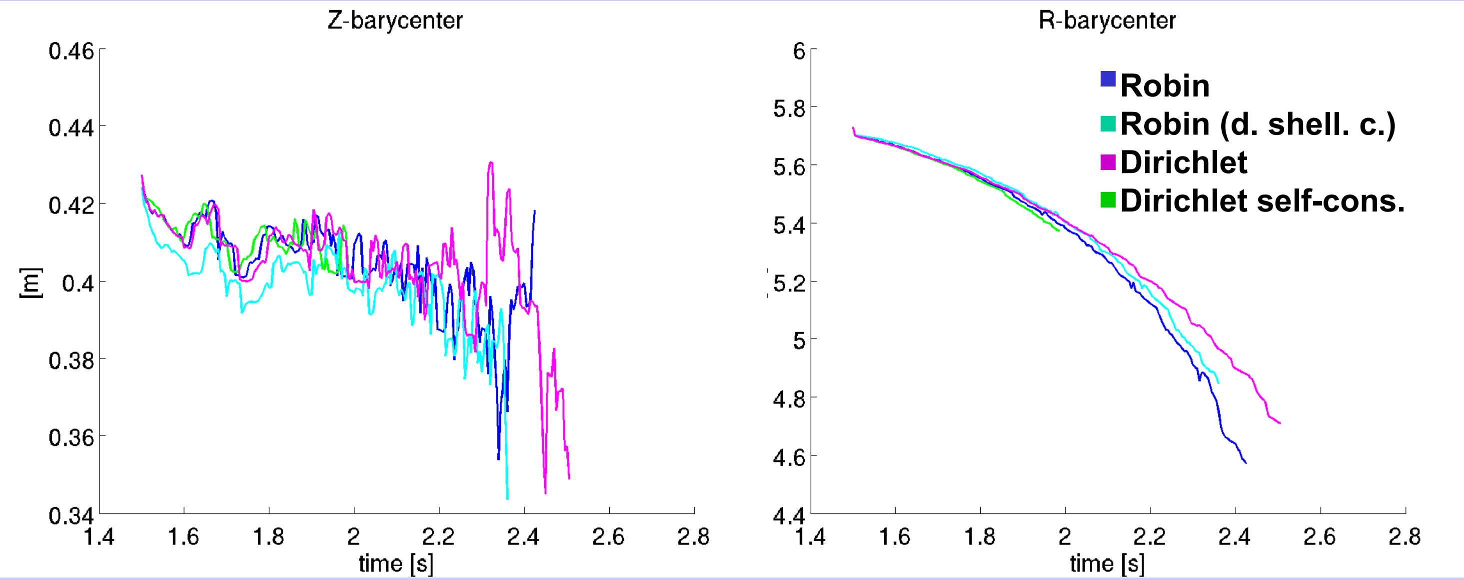


Summary

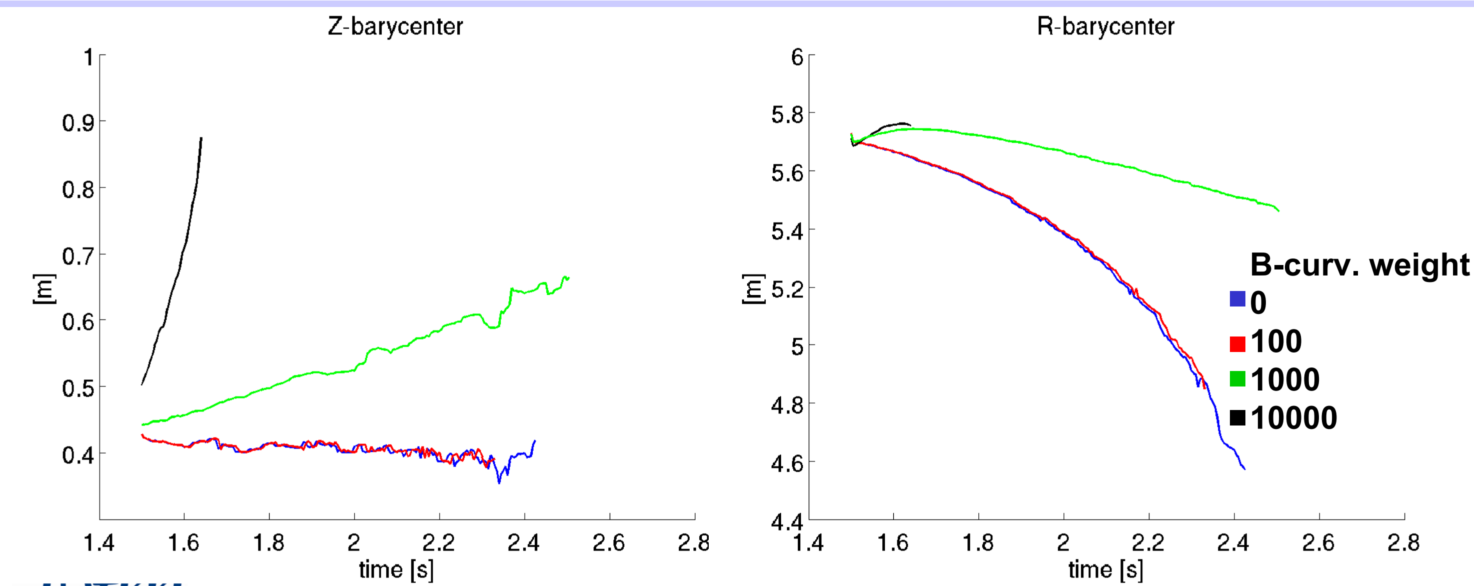
- CRONOS is now fully equipped for free-boundary equilibrium simulations using FREEBIE and an external controller.
- Both explicit and implicit schemes are implemented.
- The capabilities are demonstrated on a limited part of an ITER hybrid scenario:
  - with optimized waveforms it is possible to perform simulations in free-boundary regime with reasonable results
  - equilibrium and transport are simulated consistently.
- Simulation parameters, numerics and performance will be improved to reduce the noise and enable full scale simulation.

DE LA RECHERCHE À L'INDUSTRIE

Circular plasma is vertically stable for a wide range of parameters

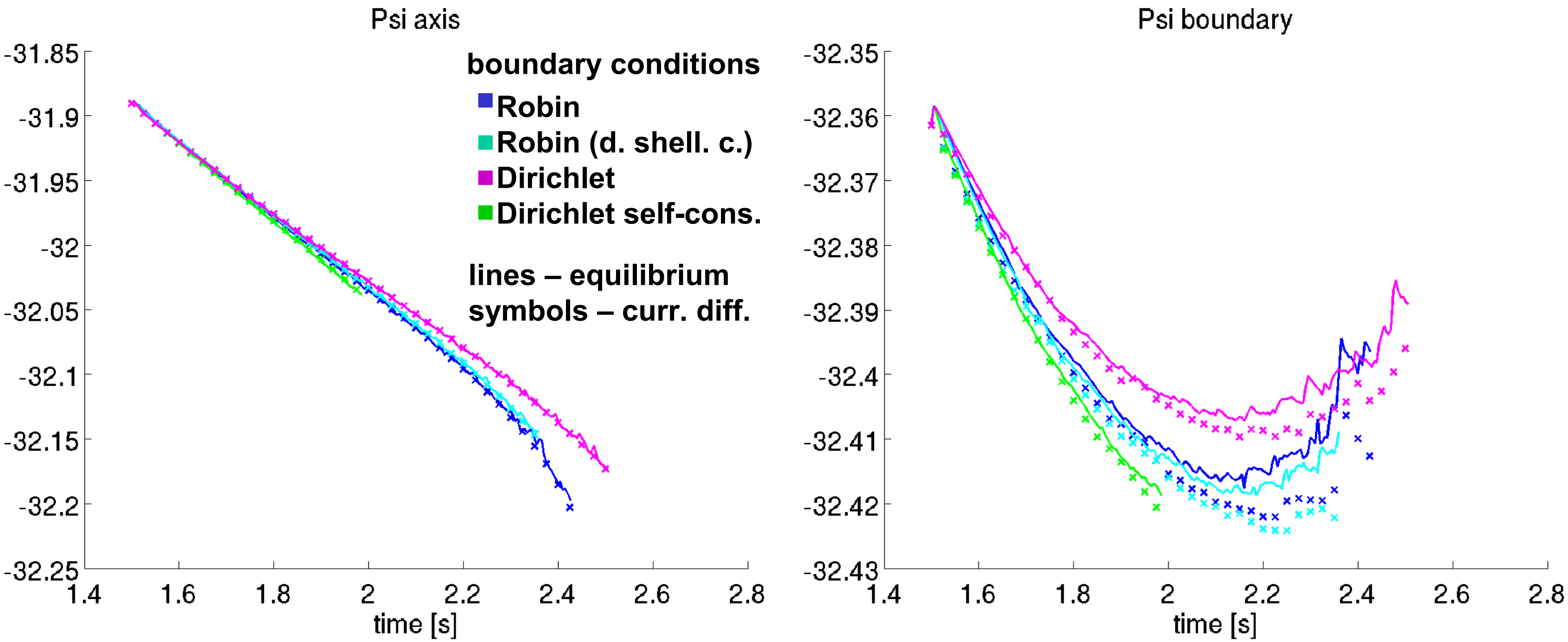


← Almost the same results for different boundary conditions. Self-consistent mode stopped converging sooner.



← B-curvature constraint in the initial inverse mode can lead to vertically unstable plasmas.

Psi is consistent on the axis and the boundary



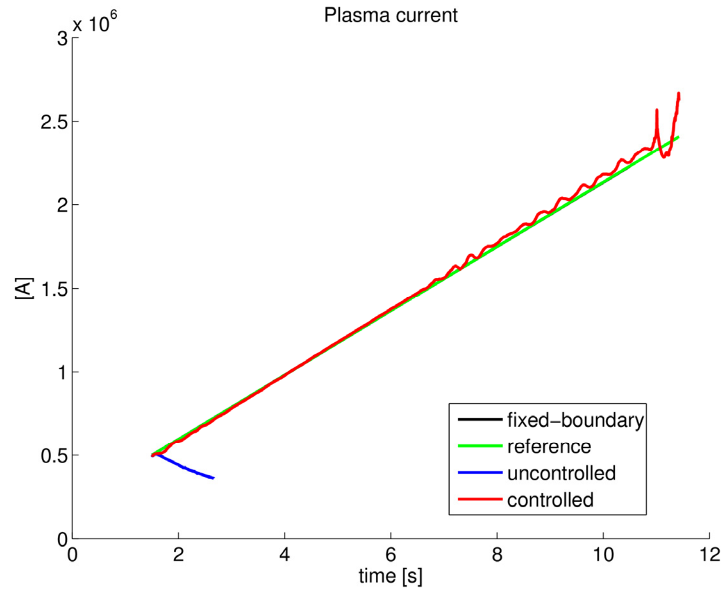
- Psi consistency is not automatic
  - convergence criterion is on $<j>$.
  - normalization by I_p or ψ_a-ψ_b

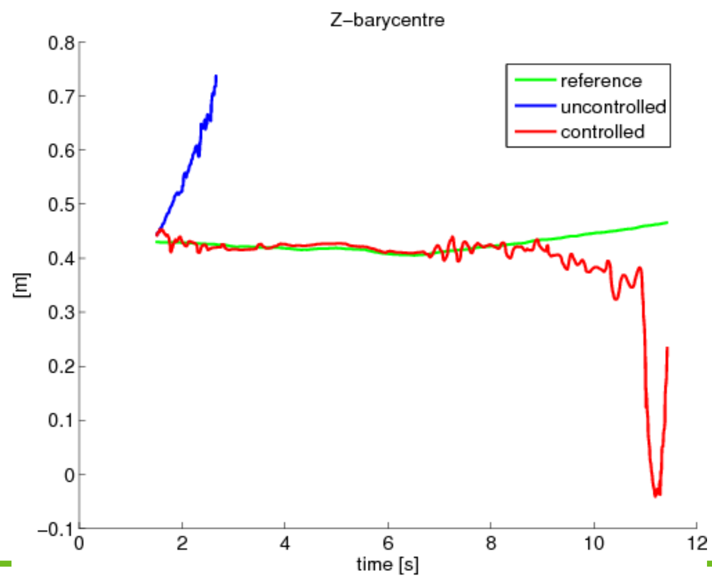
Feed-forward currents (shaping) are calculated by CRONOS/FREEBIE

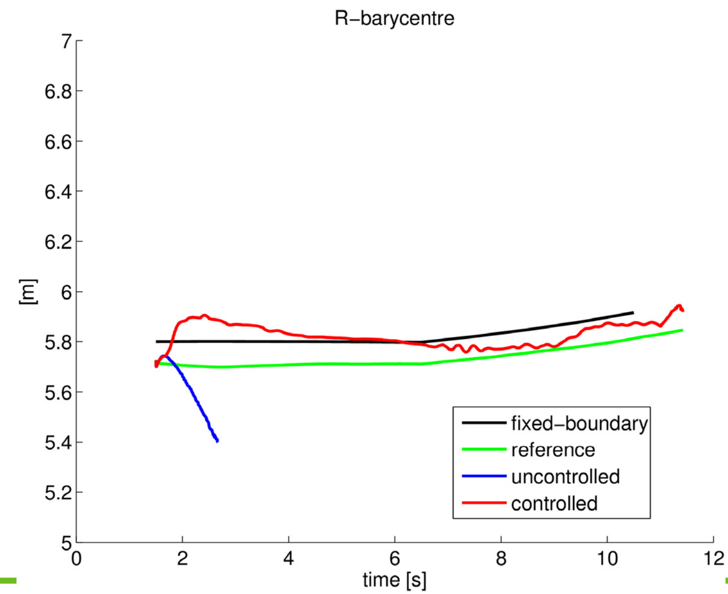
- During the initial phase of the discharge, only the position and I_p is controlled ➔ feed-forward currents are needed for plasma shaping.
  - These currents can be calculated by FREEBIE in inverse or Poynting mode.
  - Later on, gaps control is turned on (too slow for the ramp-up).
- Some coils are saturated for the test case.
  - Need to change the scenario?

Example – initial phase of the ITER hybrid scenario under control

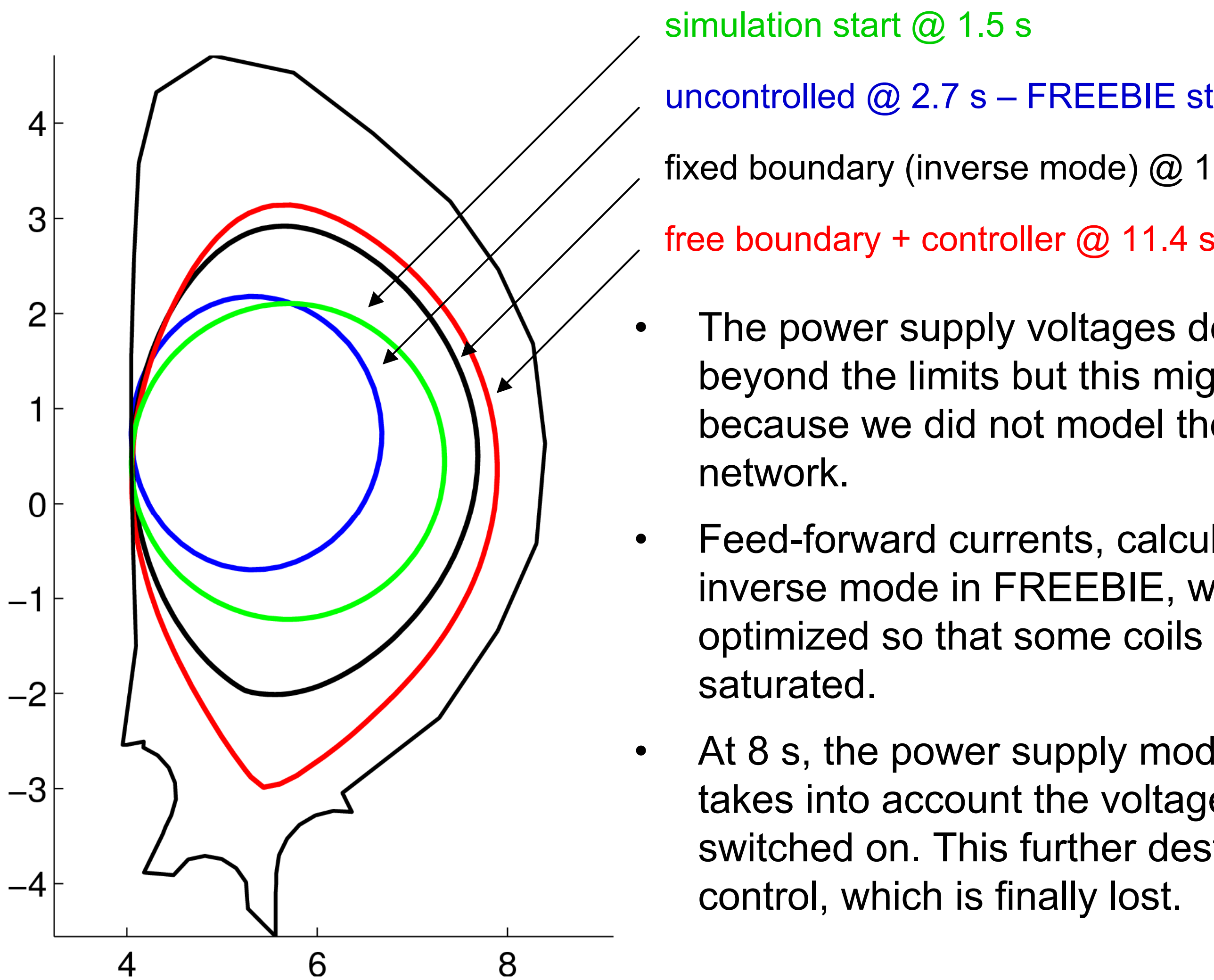
- The coupling became operational only recently.
- Plasma follows reasonably the waveforms.
- Optimizations of the initial equilibrium stability and target waveforms are ongoing.
  - Saturated coil currents from the inverse mode.





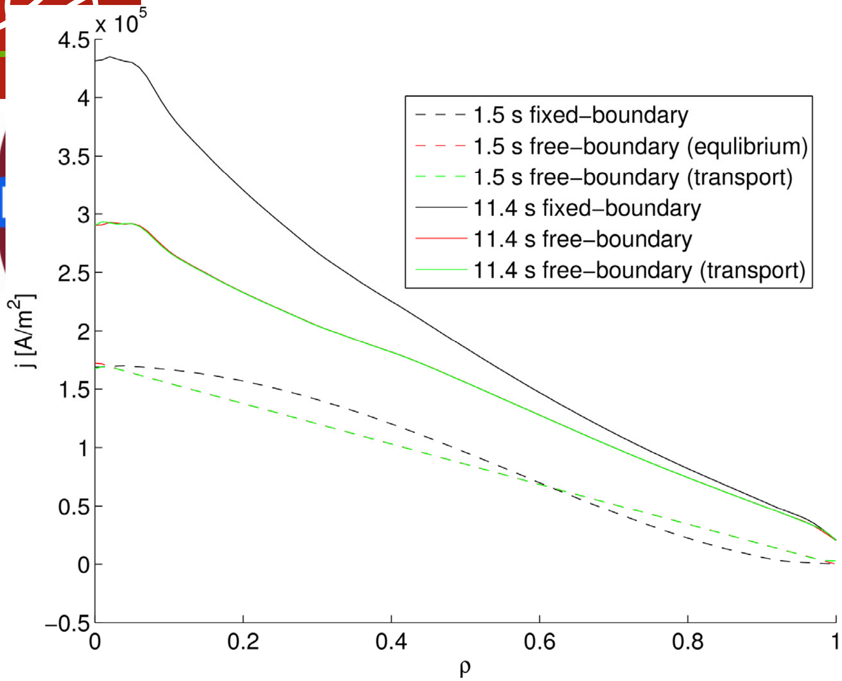


Plasma shaping working but not ideal

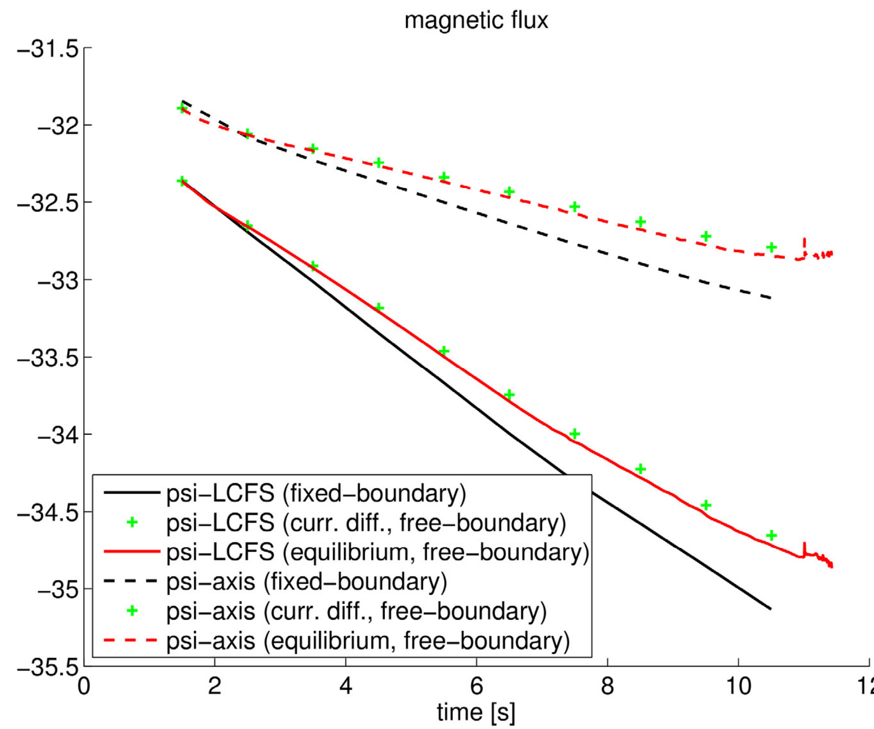


- The power supply voltages demands are beyond the limits but this might be because we did not model the switching network.
- Feed-forward currents, calculated by the inverse mode in FREEBIE, were not optimized so that some coils are saturated.
- At 8 s, the power supply model, which takes into account the voltage limits, is switched on. This further destabilizes the control, which is finally lost.

Magnetic fluxes and current densities are consistent with current diffusion

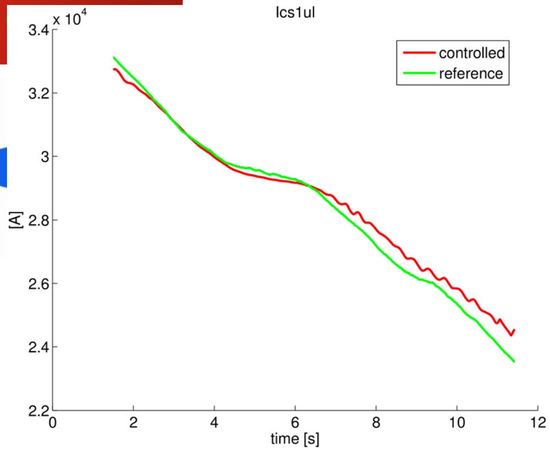


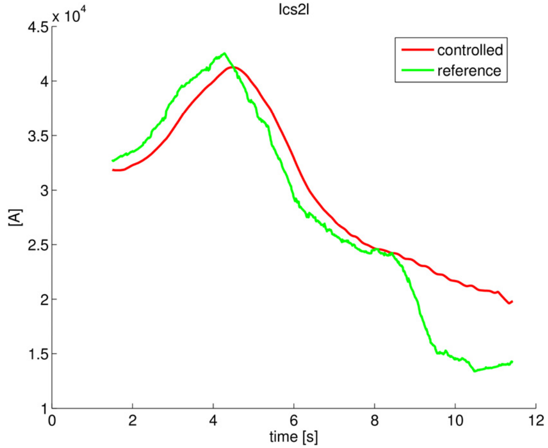
Averaged plasma current density comparison at 1.5 s and at 11.4 s. The difference between fixed and free-boundary solution is mainly caused by the very different plasma size.
Note that the equilibrium and current diffusion profiles are perfectly consistent (red and green superimposed in the figure).

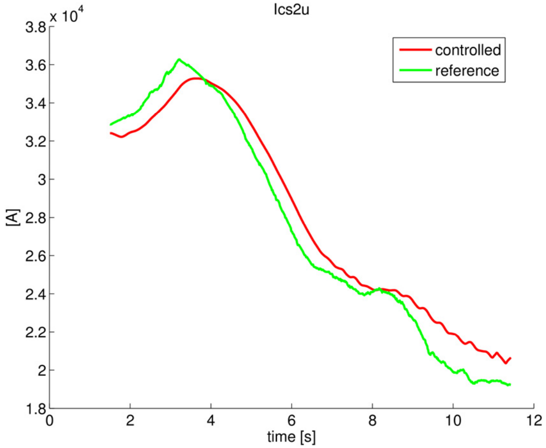


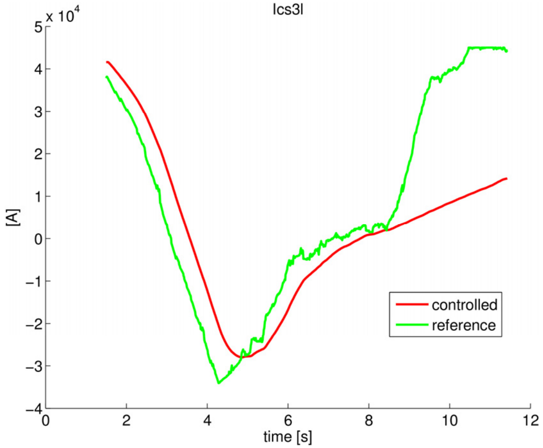
Magnetic flux evolution at the magnetic axis and at the plasma boundary. Comparison with the current diffusion (transport) values.

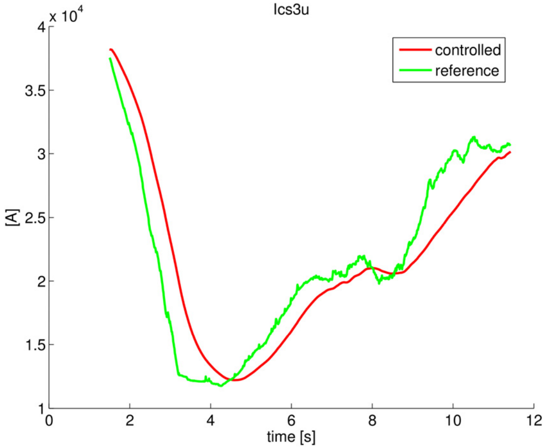
CS currents follow the references unless voltage limits are exceeded after 8 s



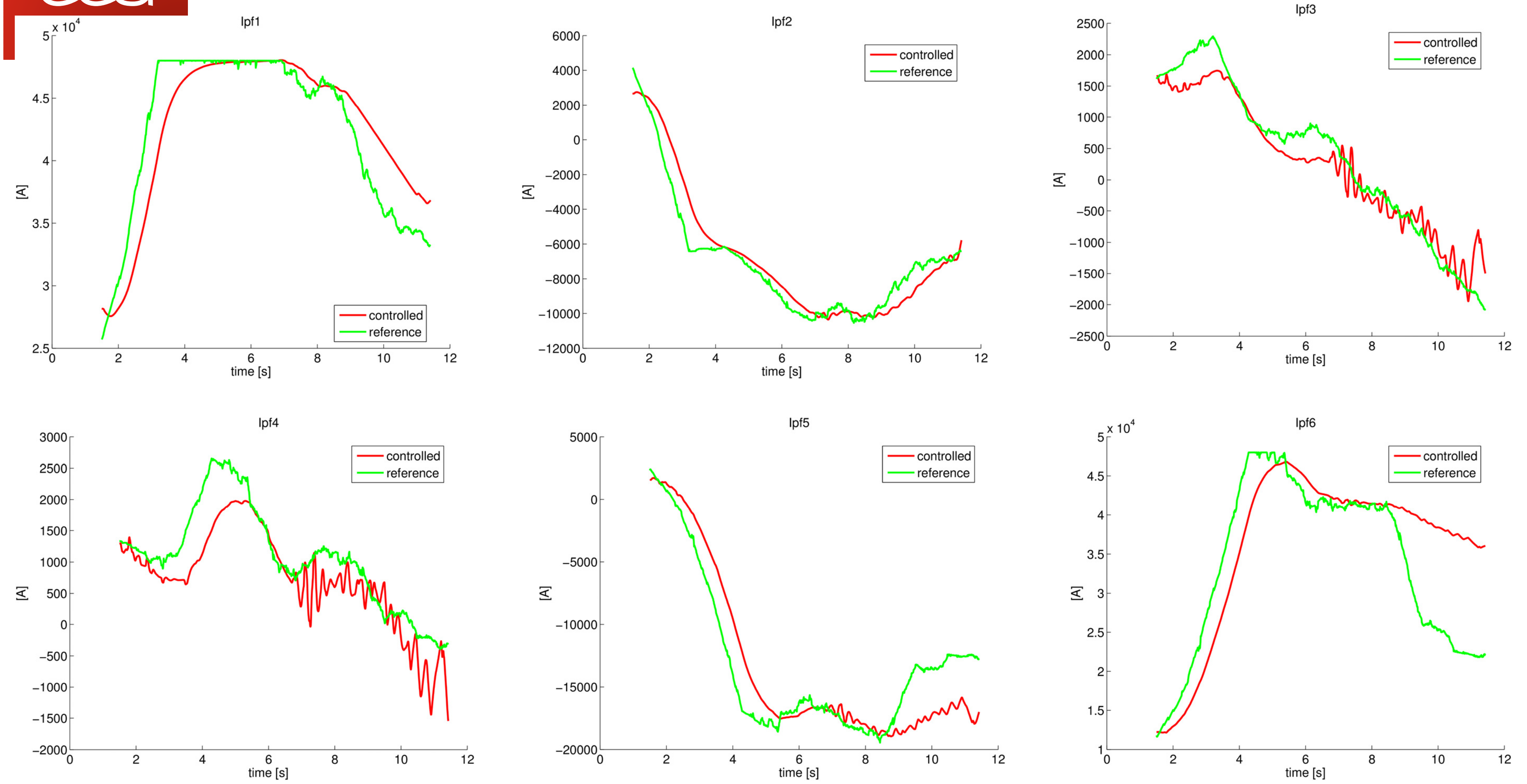




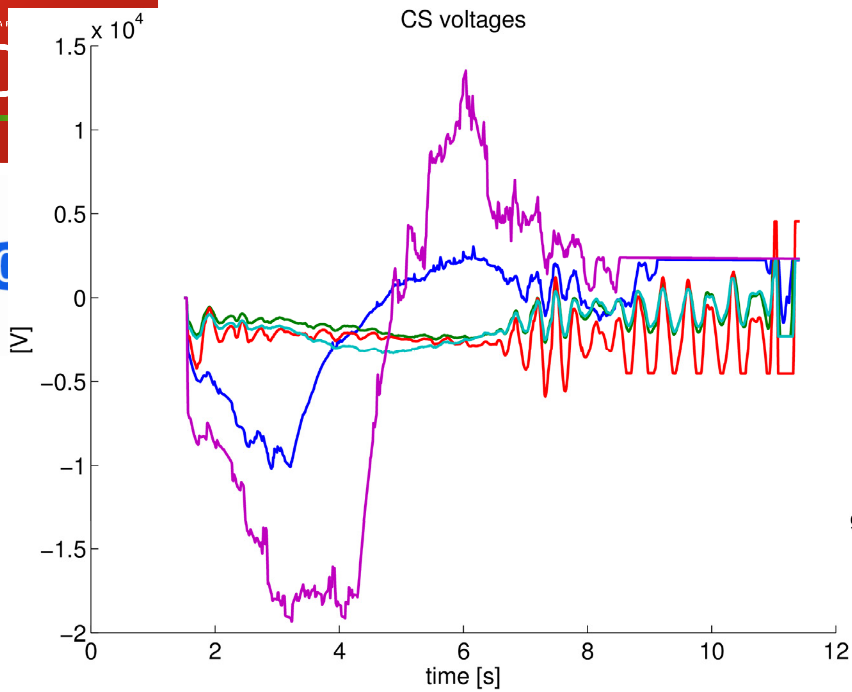




Some PF coils are saturated in inverse mode



PF supplies voltages exceed the limits



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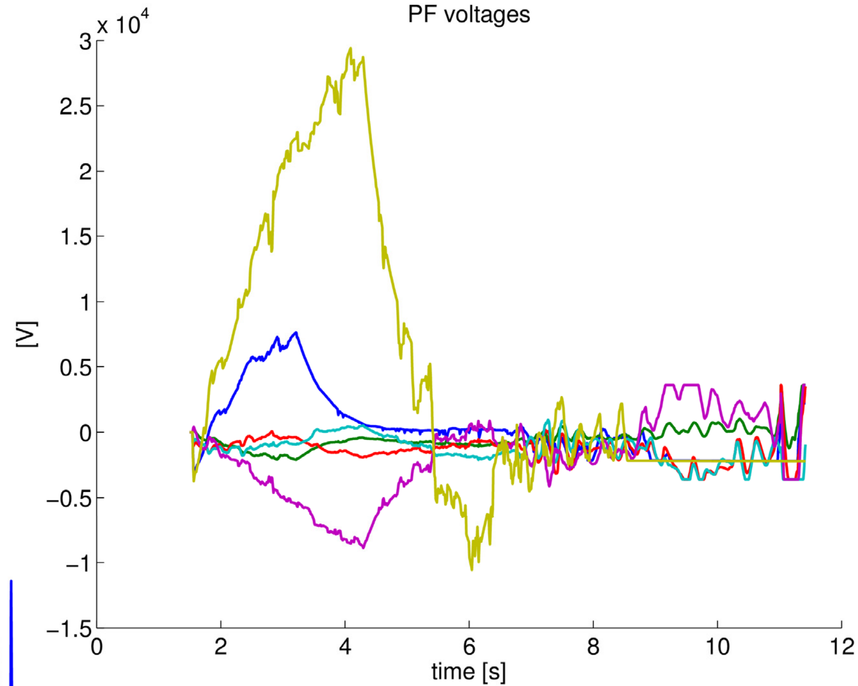

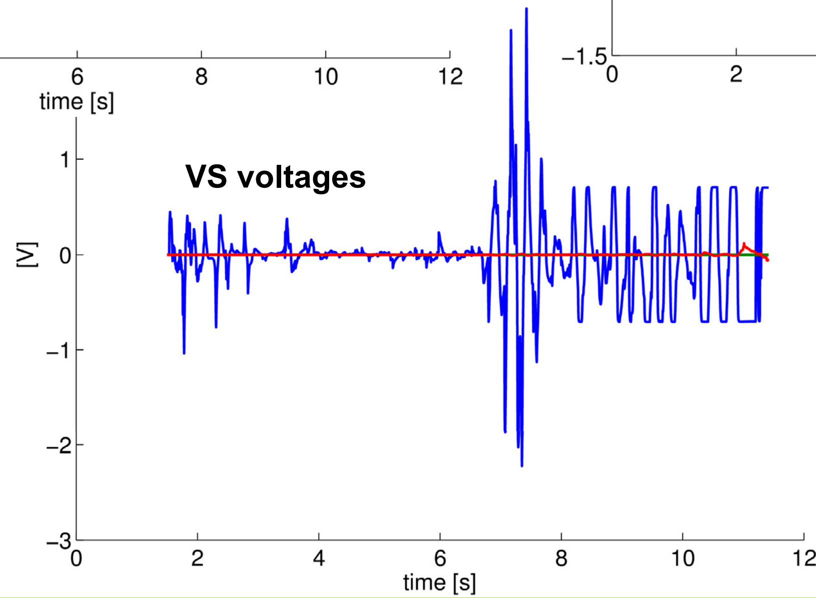

Current issues

- Initial plasma stability
- Induced currents evolution
  - Huge currents growth in the cryostat – had to be switched off
  - Convergence problems when shell currents are neglected
- Mesh resolution for flat-top, fully shaped plasma
  - Deformed boundary in inverse mode
- Target optimization (feed-forward)
  - shape, current ramp, coil currents

What to focus on in future?

- Constraints from PF power supplies (voltage + currents) and PF coils geometry
- Optimizations
  - shape (currents demands, stability)
  - current ramp up/down
  - the right figure of merit?
- What are the major effects of equilibrium on transport and stability?