Development of the Fenix flight simulator for DEMO transients scenarios

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IAEA 8th DEMO WS: 30 August – 2 September 2022

Fenix scope

- Fenix tokamak plasma “flight simulator” [F. Janky et al., FED 2017; E. Fable et al., PPCF 2022]

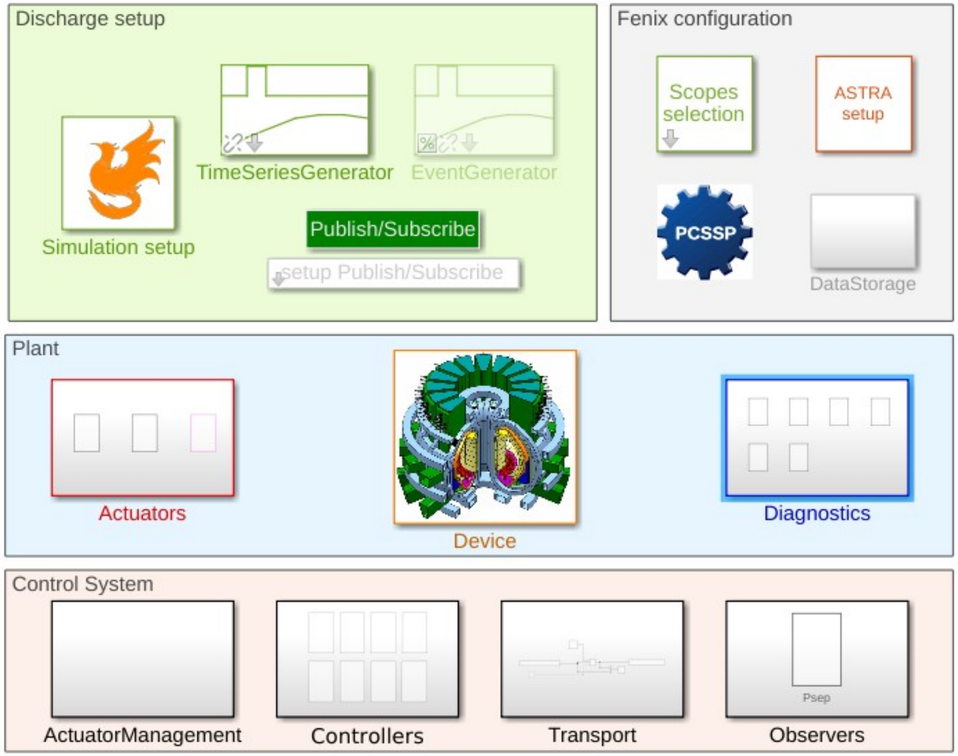
- Complete for ASDEX Upgrade (AUG), magnetic control in progress for the EU-DEMO [G. Federici et al., NF 2019], with kinetic control fully working

- **Goals**:
  - Check Pulse Schedule (PS) trajectories consistency *including* the full plasma response
  - Check if PS satisfies physics goals (H-mode, density, detachment, etc etc) → relies on quality of implemented physics models
  - Develop/improve the plasma control schemes
  - Develop/improve reduced physics models for the plasma dynamics
  - Help in scenario development (as it is being used for the EU-DEMO)

- **Requirements**:
  - be fast (as of now, can do a 10s AUG discharge in 3-5 minutes) → but has flexibility in choice of models complexity if time not an issue
  - be realistic in the plasma model (profile effects, non-linearities)
  - embed plasma into control system and machine response
  - user friendly (e.g. to be used in the control room)
  - modularity but not at all levels (logic of modularity is given by the interfaces)

Fenix structure

- Simulink™ as “hosting software” → PCSSP (ITER platform for the control system) as the embedding framework [M. L. Walker et al., FED 2015]
- Controllers, actuators are modeled in Simulink™ → can be made arbitrarily realistic
- Whatever enters or leaves the plasma → only 1 interface via a single S-function “Device”



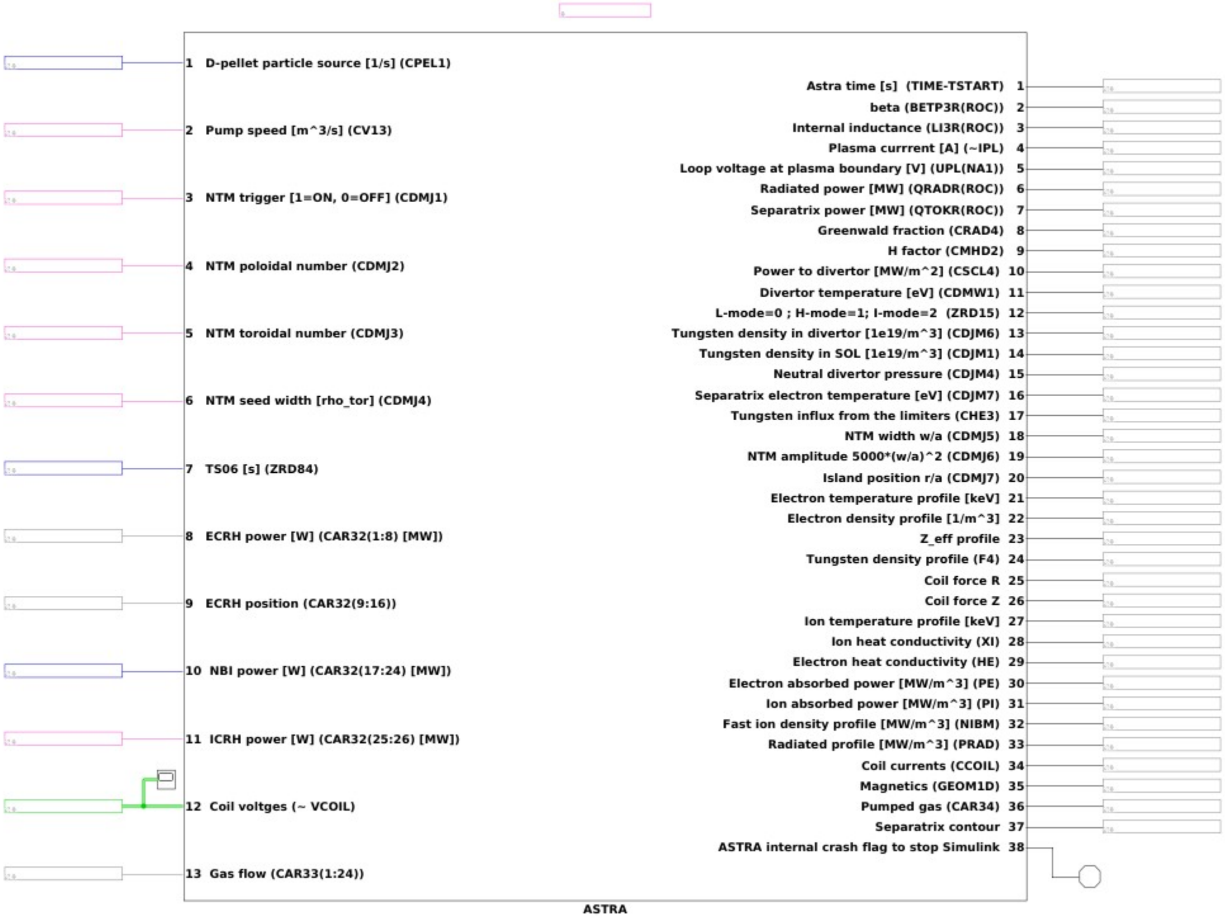
I/O between control sys and plasma

- The S-function is an C interface to the ASTRA transport code

- ASTRA computes the dynamics of the plasma (Grad-Shafr. + circ. Eqs. + transport eqs)

- Inputs: actuator signals

- Outputs: synthetic diagnostics



EU-DEMO setup

- EU-DEMO considered has the following parameters:

- $R = 8.94$ m, $a = 2.94$ m, $B_T = 4.89$ T, $I_p = 19.07$ MA, $\langle n_e \rangle_V \sim 8.5\ 10^{19}\ \mathrm{m}^{-3}$
- $P_{fus} \sim 2$ GW, $P_{rad} \sim 250$ MW, $P_{aux} \sim 0\text{-}50$ MW, $H_{98(y,2)} \sim 1$ (standard H-mode)

- Kinetic control (quantity → actuator):
  - (electron) Density of the pedestal top (e.g. $x \sim 0.95$) → pellet injector
  - Density at the separatrix → DT gas puff from mid-plane valve
  - Power crossing separatrix → Xe puff from mid-plane valve
  - Divertor cooling (to be specified) → Ar puff from the divertor valve
  - Fusion power output → central heating or density level
  - MHD events (sawteeth/NTMs) → dedicated ECCD launcher(s)
  - others → to be discussed

- All these control modes are implemented via PID SISO controllers.

- Magnetic control (of plasma equilibrium and coil currents) is done independently

- For now diagnostics are considered “at will” and “ideal”

Critical aspects of DEMO control

- Optimization of the diagnostics coverage (being studied inside WPDC) – limited due to several reasons (port access, neutron flux, ...)

- High fusion output scenario works close to some limits (density limit, L-H transition power, detachment regime, peeling-ballooning limit, ...)

- Time scales and coupling between actuators and plasma introduce strong latencies and non-linear response (mostly due to the plasma size and the dominance of the α-power over the auxiliary power)

- Possible failures could lead to catastrophic plasma termination → address each one of them and define a “SCRAM” scenario that minimizes damage to internal components

- In general, it is desirable to plan a scenario where the probability of having to use the “SCRAM” scenario, or that leads to a potential disruption, be minimal → balance between enough fusion output and safe scenario → control the plasma to stay on the “safe” trajectory, with consideration or “shaded area” around the nominal trajectory

Focus of this work

- Evidence the main sources of perturbations during the normal operation, in the plasma flat-top phase

- Describe the way this plasma is controlled

- Show examples when major perturbations happen

- Simulations of ramp-up scenarios

- Considerations on ramp-down modeling

Main sources of perturbation during normal flat-top operation

- 1 Intrinsic transport fluctuations (estimated at +- 5% of the local transport coefficients, appears effectively as noise on the profiles during the simulation)

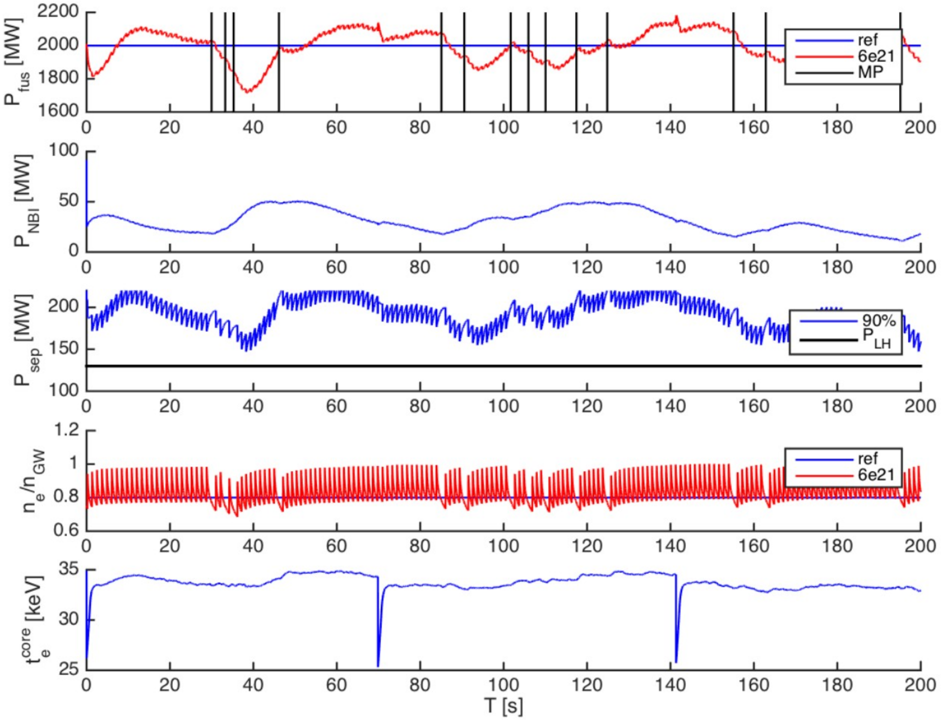
- 2 Periodic MHD activity (sawteeth) → should disappear in DEMO (consideration of hybrid scenario)

- 3 Pellet injection: ideally periodic, but in practice non-periodic as pellet failure rate is > 0% (~ 10% realistically)

- 4 Fluctuations in delivered gas puff (not yet included)

- 5 ELMs (Edge Localized Modes) → dangerous for the divertor, should be avoided

→ For the design of the pellet injection scheme in DEMO, the point 3 has been thoroughly investigated



[from F. Janky]

Major perturbations

- Ab-normal events that have been considered:

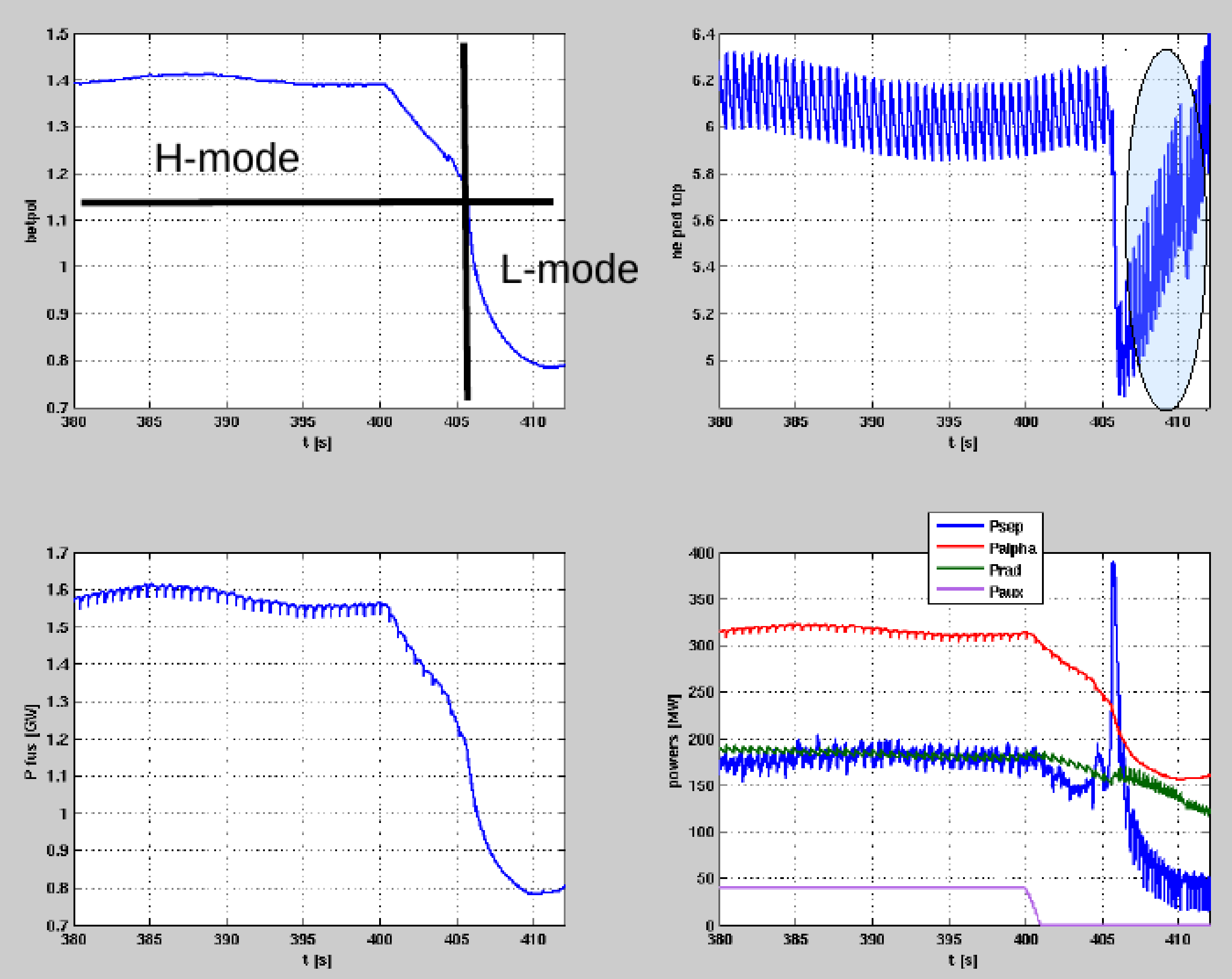
1) Failure of an auxiliary heating system leading to $P_{sep} < P_{LH}$

2) W flake enters the plasma (4, 8, 12 mg)

3) Unwanted H → L transition

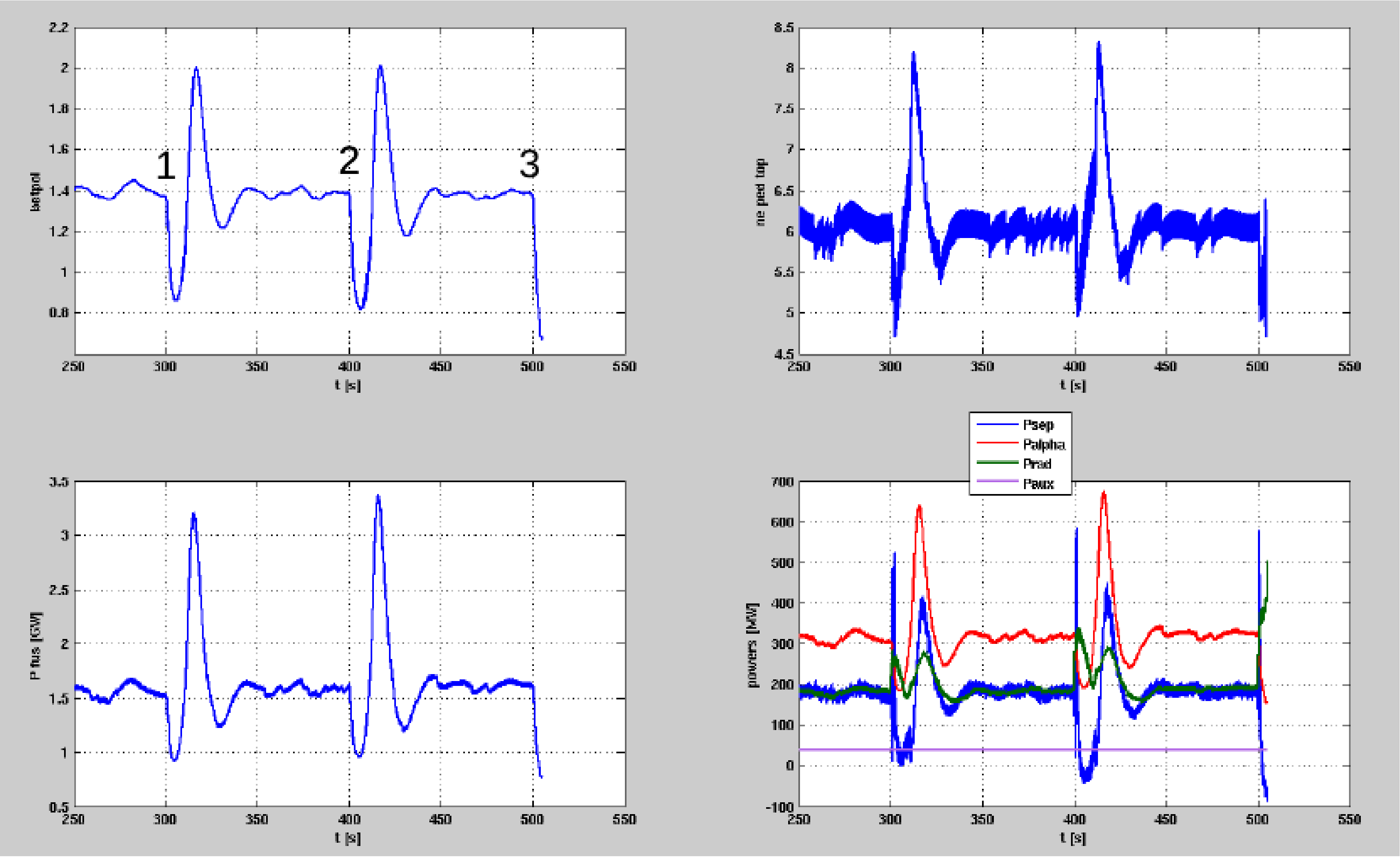
Major perturbations

1) Failure of an auxiliary heating system leading to $P_{sep} < P_{LH}$ + 3) Unwanted H → L transition



Major perturbations

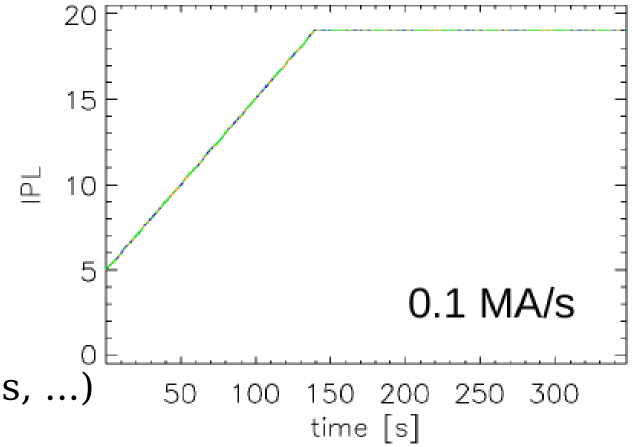
2) W flake enters the plasma (4, 8, 12 mg)



Ramp-up scenarios

- The plasma ramp-up serves as both the plasma scenario “roadmap” and also as a mean to optimize some parameters along the operational phase (previous work performed for DEMO by P. Vincenzi and T. Bolzonella)

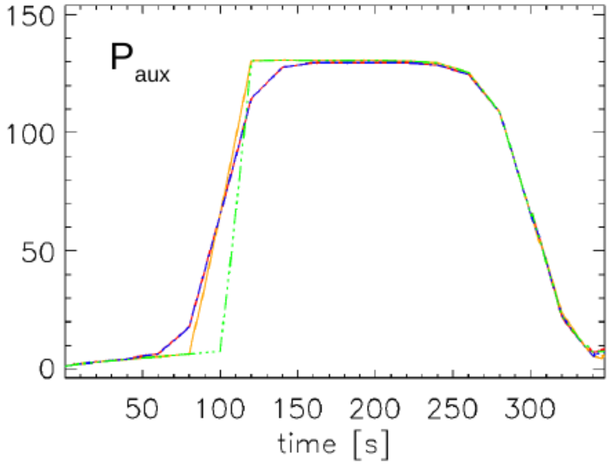
- In particular: smooth out eventual overshoots (as in P_{sep} or edge density)

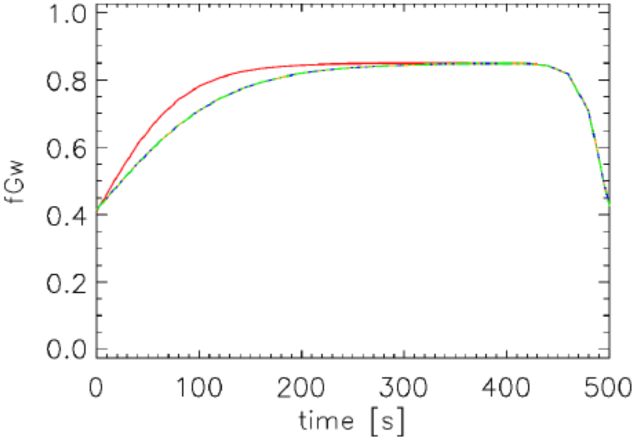


- The plasma shapes have been provided by the CREATE group

- Optimize trajectories of P_{aux} and fueling (auxiliary power cap at 130 MW)

- Additional boundary conditions: external components (turbines, …)





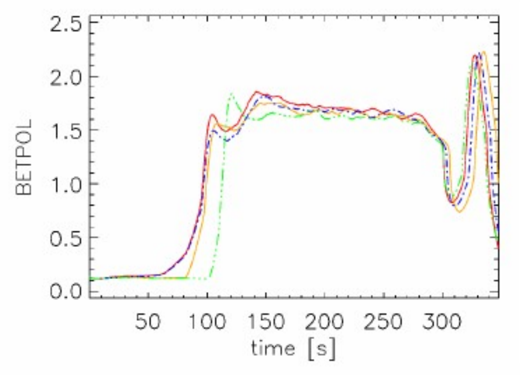
[from F. Palermo]

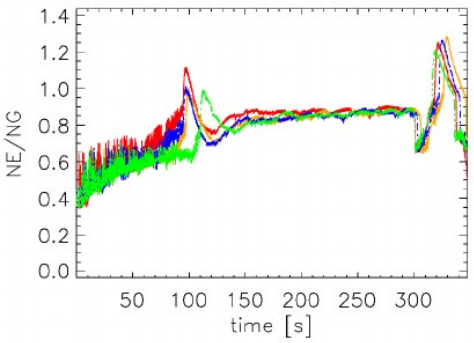
Ramp-up scenarios

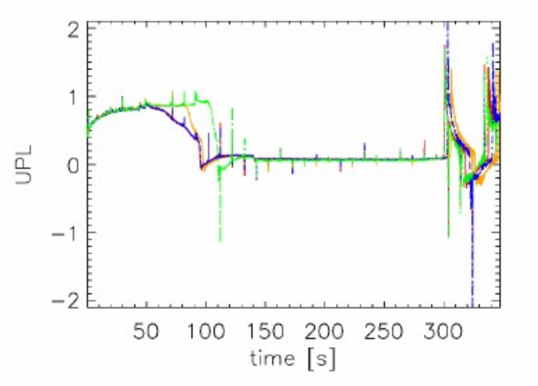
- The “orange” and “blue” trajectories are the best ones in terms of leading to the smallest excursions

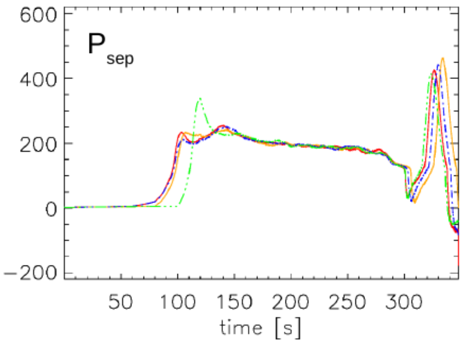
- The “blue” trajectory has a decrease in loop voltage (UPL) at earlier times → best flux consumption

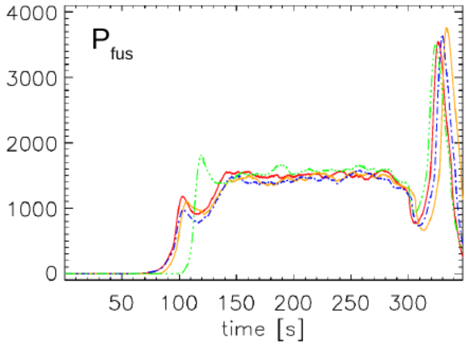
- Notice that the D feeding valve and the pellet injector control independently $n_{ped,top}$ and n_{sep}





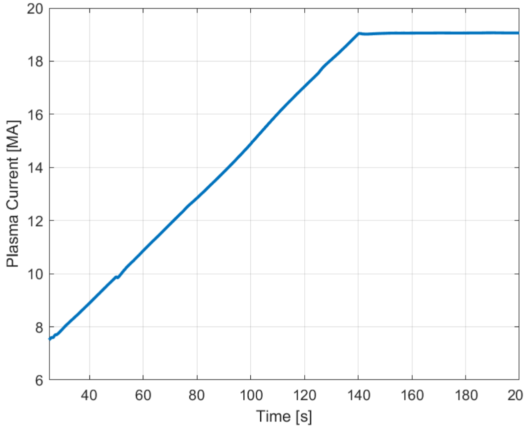


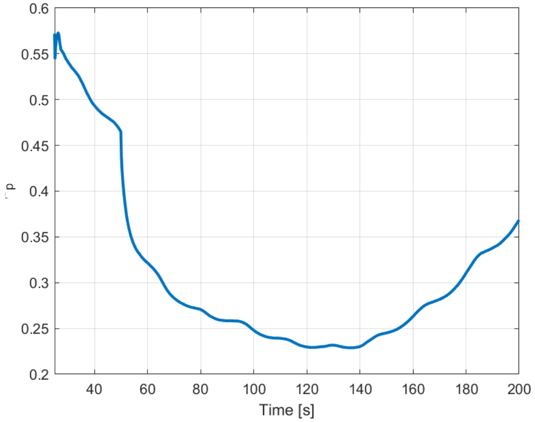


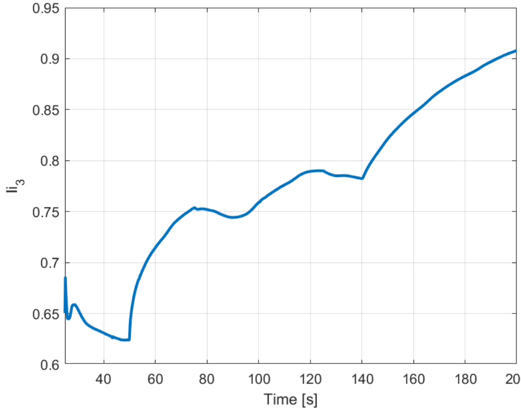


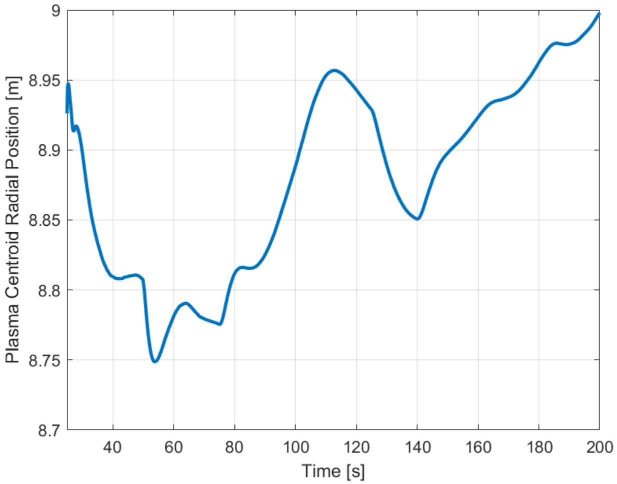
Preliminary ramp-up with magnetic control

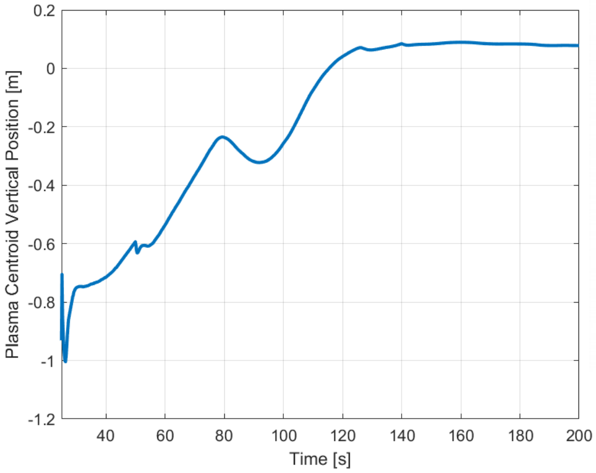
- Added magnetic controllers [work in collaboration with M. Mattei and L. Di Grazia, CREATE Group]

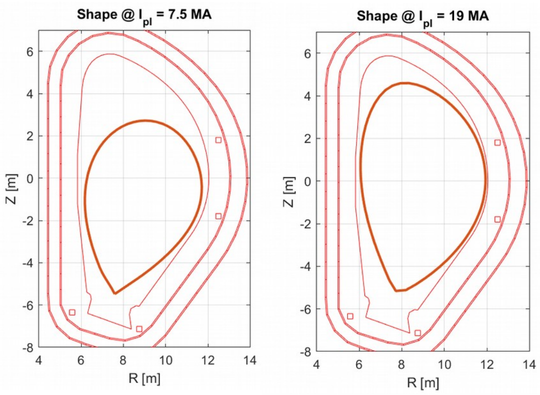










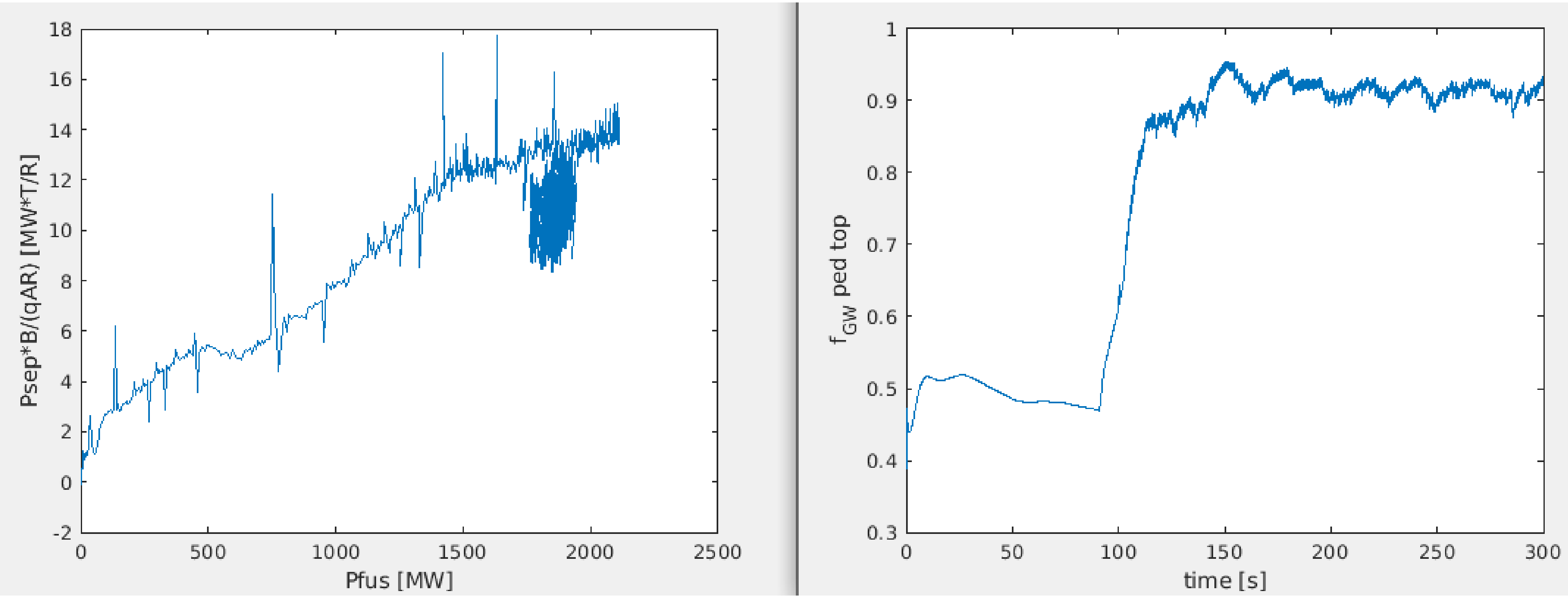


[courtesy of L. Di Grazia]

Power flux during ramp-up

- Before "ignition" (that is, ramping-up of the alpha power) → power flux to divertor expected to be in the order of ~ 1 MW*T/R, but separatrix density limited to 0.5*Greenwald

- During ignition, separatrix power rises fast, and density as well (but only at pedestal top) → separatrix density fixed. Needs to find a good recipe for SOL



Considerations on the ramp-up

- It is still unknown how much W will actually enter and stay in the plasma during the ramp-up, but it is estimated that at concentrations > 1.e-5, it will be required to add auxiliary central ECH to avoid radiation collapse of the plasma core, due to the higher central electron temperature present in DEMO with respect to present machines (expected concentrations varying between 1.e-5 to 5.e-5)

- The evolution of the safety factor q can be crucial for the confinement properties during the flat-top phase. In particular, a “freezing” of the evolution of the q-profile due to the use of ECH in the ramp-up, could lead to non-optimal q-profile shape in the flat-top

- The ramp duration vs heating and fueling scheme needs to be optimized to enter into flat-top, e.g. the burning plasma phase, with a satisfactory core confinement

- The role of the impurities for divertor protection during the ramp-up become critical at the L-H transition. Is it possible to perform the DEMO ramp-up in detached L-mode?

- Compatibility with external elements boundaries of operation (e.g. turbines characteristics, cooling system, inertia of elements, etc)

Considerations on the ramp-down

- Similar arguments apply to the ramp-down:

  - exit from the burning phase and the interplay with the impurities needs to be studied in a dedicated fashion

  - optimization of the ramp to avoid too much excursion of the internal inductance (plasma equilibrium stability issue)

  - SCRAM scenario (fast ramp-down to avoid disruptive situation) → needs design

  - compatibility with constraints on external elements limits (e.g. ramp rate)

Conclusions and outlook

- The Fenix flight simulator, coupling the plasma dynamics to the external control system, allows to predict the evolution of the DEMO scenario including the feedback of the plasma on the actuators and viceversa

- Its applications so far have been in determining requirements for the control system, including some elements of realism in the actuators
  → for diagnostics, a study has been carried out on the Prad sensitivity

- Application to transient scenarios are becoming increasingly complex and realistic, towards the full definition of a self-consistent DEMO scenario

THANK YOU