Rapid radial profiles simulation and scenario preparation on TCV using RAPTOR

C. E. Contré, F. Felici, C. Heiss, A. Merle, S. Van Mulders, O. Sauter and the TCV team

Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

Abstract

- Our goal is to facilitate the **preparation of TCV discharges** by showing that **fast prediction of the current density & kinetic radial profiles** with RAPTOR[1] can help to better validate the pulse schedule and prepare safer scenarios
- We first discuss the feasibility of a predictive-RAPTOR model, by simulating:
  - two ITER baseline ramp-downs with H-L transition in the termination phase, testing the impact of NBI timing
  - an ohmic ramp-up & H-mode flat-top, where we aim to rely on scaling laws & coupling between different transport models to minimize inputs from the experiment
- Then, a **new coupling between RAPTOR and FBT** [2], a free-boundary equilibrium solver is presented, with these questions in mind:

How does the RAPTOR-FBT coupling change the predicted coil currents?

Can we provide realistic self-consistent KEP (Kinetic Equilibrium Prediction) for more complete calculations before a shot?

RAPTOR equations

RAPTOR is a 1D radial transport model which solves the current and kinetic profiles:

Poloidal flux diffusion

$$\sigma_\parallel(T_e)\frac{\partial\psi}{\partial t}\Big|_\rho = \frac{R_0J^2}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\psi}{\partial\rho}\right) - \frac{V'}{2\pi\rho}\left(j_{bs}(n_e,T_{e,i}) + j_{aux}(n_e,T_{e,i})\right)$$

Electron/ion **temperature** diffusion

$$\frac{3}{2}\frac{\partial}{\partial t}\left[n_eT_{e,i}\right]\Big|_\rho + \frac{1}{V'}\frac{\partial}{\partial\rho}\left(q_{e,i}(\psi,n_e,T_{e,i}) + \frac{5}{2}T_{e,i}\Gamma_{e,i}(\psi,n_e,T_{e,i})\right) = V'P_{e,i}$$

Electron **density** diffusion

$$\frac{\partial}{\partial t}\langle n_e\rangle|_\rho + \frac{1}{V'}\frac{\partial}{\partial\rho}\Gamma_{e,i}(\psi,n_e,T_{e,i}) = S_{e,i}$$

Given:

- G_2, J, V' ⇠ an equilibrium code (e.g. FBT, CHEASE [5])
- $q_{e,i}, \Gamma_{e,i}$ ⇠ 1 of the RAPTOR transport models
- j_{bs} ⇠ the boostrap formula
- j_{aux} ⇠ NBICD, ECCD …

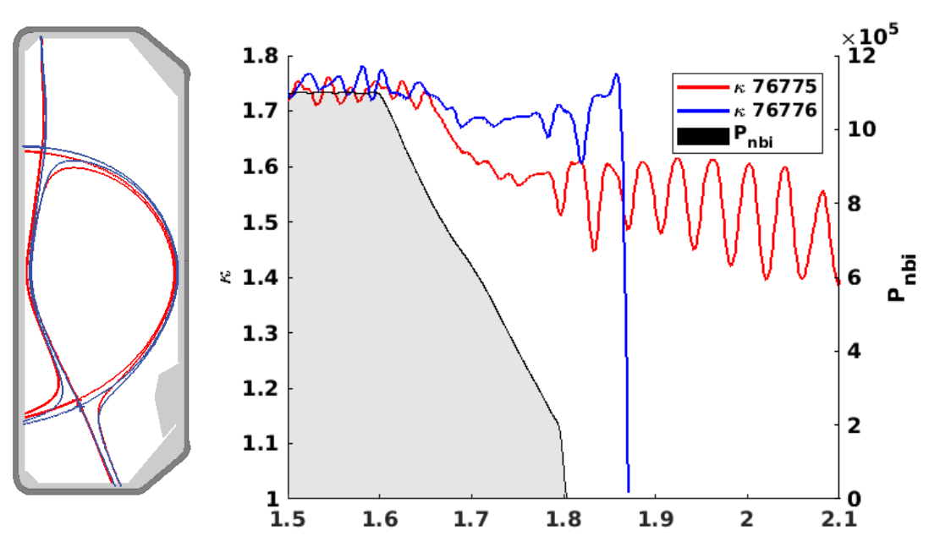
Conclusion

- This work presents the **predictive simulation** of TCV shots using RAPTOR
- Two ramp-downs with NBI heating and different equilibria were successfully reproduced, showing that **a faster NBI ramp can dangerously increase l_i**
- A set of ohmic ramp-ups were also simulated, by using scaling as a preliminary model to estimate the T_i profiles and by minimizing inputs from the experiment
- Finally, a **loose-coupling between RAPTOR and FBT**, an inverse feed-forward equilibrium solver, has enabled us to converge on a consistent solution in 2 iterations, opening the door to better pre-shot **kinetic equilibrium prediction** (KEP) during TCV operations

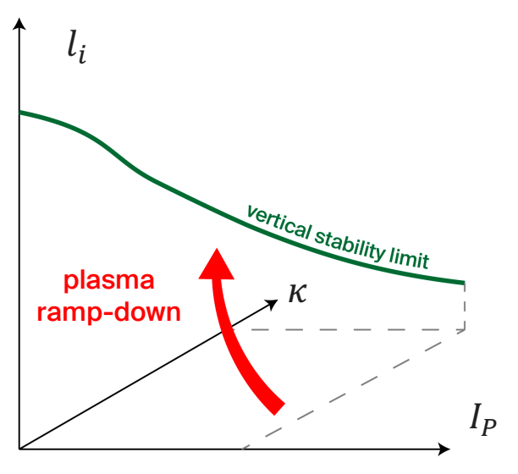
Post-shot RAPTOR analysis on TCV

Validation of RAPTOR models: two ITER baseline ramp-downs with NBI (#76775-6)

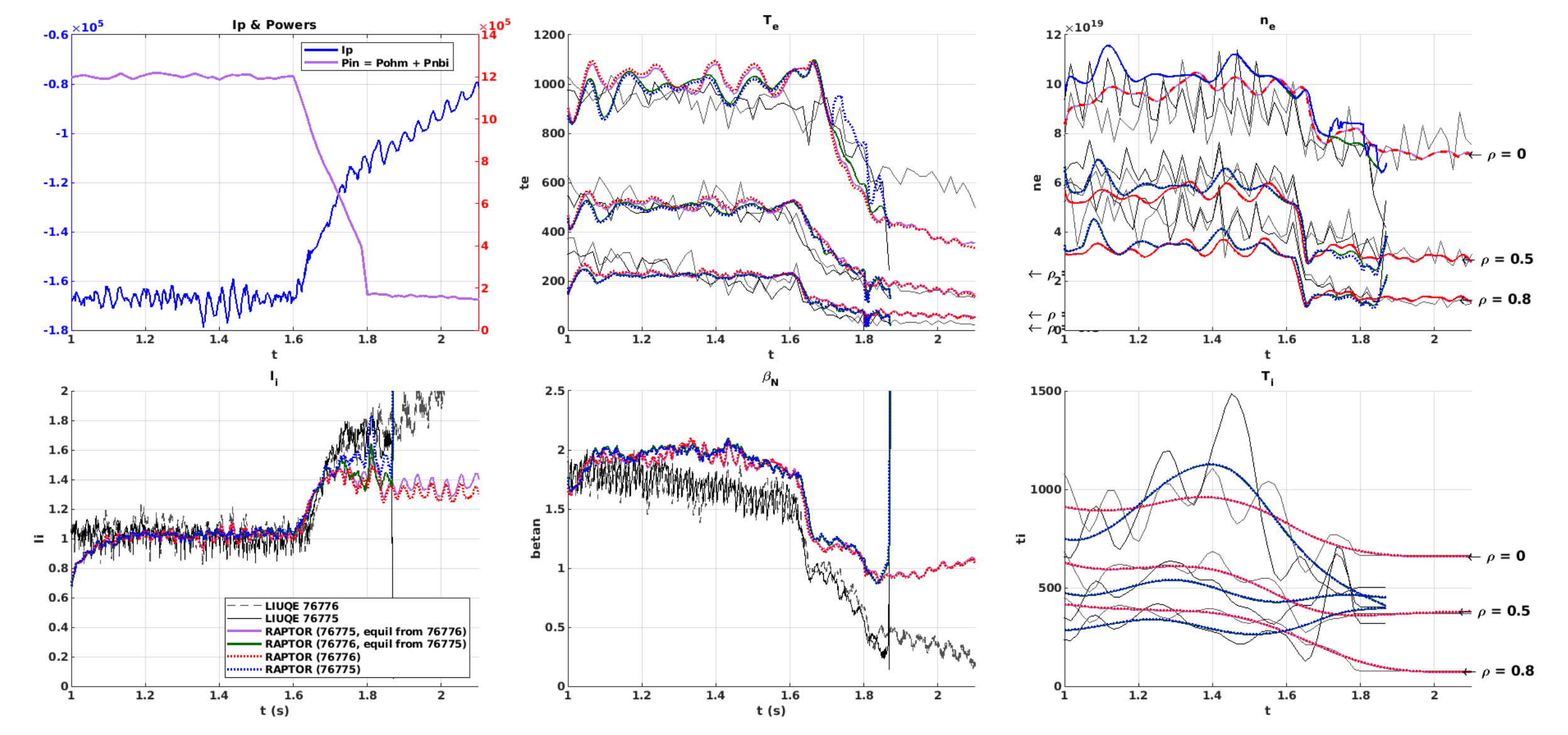
Two ITER baseline (IBL) discharges[6] (#76775-6) were terminated with different elongation κ values.



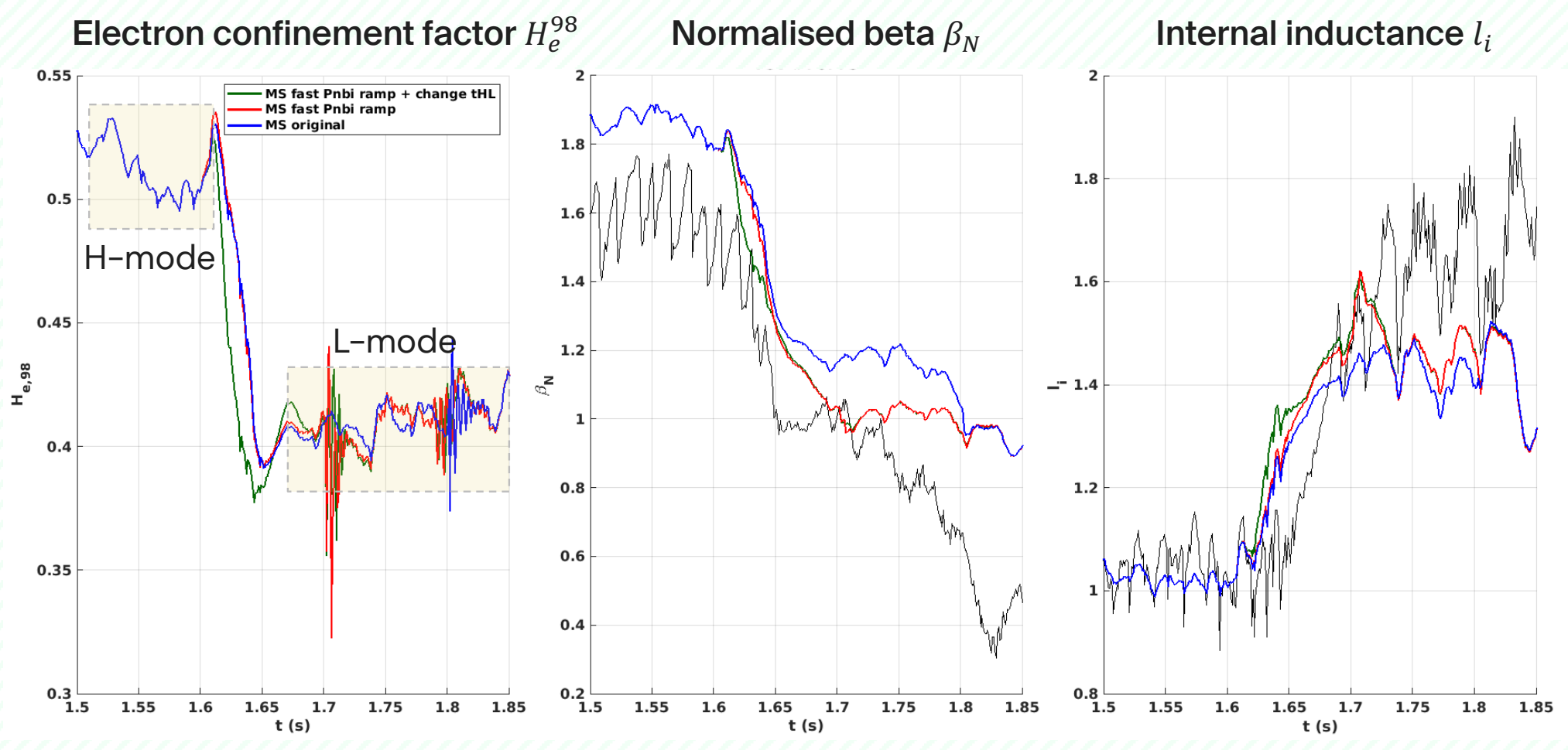
Confirming a well-known strategy in tokamak plasma, **only the ramp-down for which the κ was not decreased (#76776) disrupted**… due to the existence of a combination of (l_i, κ, I_p) above which the plasma becomes uncontrollable. If l_i ($\propto \kappa, I_p, H_e^{98}$ …) raises too fast compared to the decrease of κ and I_p, then there is a risk that it will go straight into the limit.



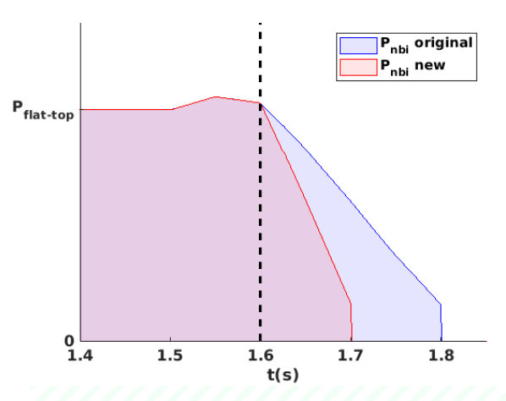
We propose to test the **RAPTOR gradient-based model** on these two IBL ramp-downs with a particular focus on the back **transition from H mode to L mode performed during the ramp-down phase**



Simulation of #76775-6 using the gradient-based (MS) model



We repeat the simulation of #76775 but speed up the NBI ramp by 2…



…and adapt the transition time from H to L mode (t_{HL}) accordingly

We can see from these simulations that speeding up the NBI ramp and switching to L mode earlier has the effect of **increasing the plasma l_i** faster, which is detrimental for stability.

Simulation of #76775 with a fast NBI ramp

FF	MS	QLKNN
Simplified model [1]	Gradient-based model [3]	QLKNN-hyper-10D [4]

Simplified model [1]

- $q_{e,i}$ and $\Gamma_{e,i}$ expressed via transport coefficients $\{\chi_n^\alpha, \chi_T^\alpha\}$ evaluated through simple **analytical formulation** based on **experimental observations**:

$$\chi_e = \underbrace{\chi_{neo}}_{\text{neoclassical}} + \underbrace{c_{ano}\rho q T_e^{C_T}}_{\text{anomalous}} + \underbrace{\chi_{central}e^{-\rho^2/\delta_0^2}}_{\text{local flattening at the center}}$$

Gradient-based model [3]

- Based on the observation that radial transport is stiff in most of the plasma volume
- $\{T_{e,i}, n_{e,i}\}$ modelled by **constant gradients** in 3 radial regions:

$$\begin{cases} \text{a flat region in } \rho \in [0, \rho_{inv,x}] \\ \lambda_X = -\frac{1}{X}\frac{\partial X}{\partial\hat\rho} = \text{cste in } \rho \in [\rho_{inv,x}, \rho_{ped,x}] \rightarrow \text{stiff} \\ \mu_X = -\frac{\partial X}{\partial\hat\rho} = \text{cste in } \rho \in [\rho_{ped,x}, 1] \rightarrow \text{non-stiff} \end{cases}$$

- $\lambda_{ne,Te}$ is given (independant of I_p & P_{tot})
- μ_{Te} & μ_{ne} are controlled to match H_e^{98} & n_{el}

QLKNN-hyper-10D [4]

- Neural−network surrogate of the quasilinear gyrokinetic transport model **QuaLiKiz**
- Estimates $q_{e,i}$ and $\Gamma_{e,i}$ according to local parameters
- $100-1000$ times faster that QualiKiz for only $1-10\%$ loss of accuracy
- Limited by the parameter space chosen for training

Can RAPTOR be fully predictive? From ohmic ramp-up to NBI flat-top (#56653)

RAPTOR proposes 3 different reduced transport models, each of them needing different inputs. A first step toward a predictive model is therefore to examine what we have to give.

	MS	FF	QLKNN
ψ, T_e	SOLVED	SOLVED	SOLVED
T_i	SCALING		SOLVED
n_e	SOLVED	MS	

Stategies employed to minimize the dependance on experimental data, by models

		MS	FF	QLKNN
ψ	sep	■	■	■
T_e	sep	■		
	ped		■	■
T_i	sep	□		
	ped		□	■
n_e	sep	■		
			□	□

Required BC at the separatrix & pedestal by models

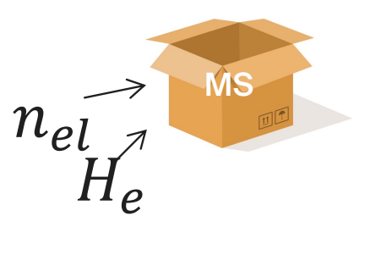
■ *used here* □ *not used here (quantity is given)*

We propose to simulate an **ohmic ramp-up with NBI from $t > 0,6s$** using minimal inputs from the experiment

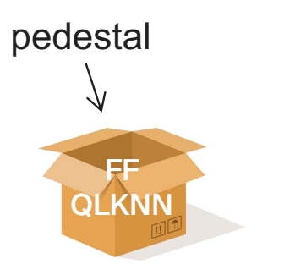
To this end, some of these models were used with a **simple scaling law for ion temperature**, based on ohmic and EC heated simulations:

$$\frac{T_I}{T_e} = 0{,}14.\frac{Z_C-1}{Z_C-Z_{eff}}.n_{el}[10^{19}m^{-3}]^{0.8}q_{95}^{0,6}$$

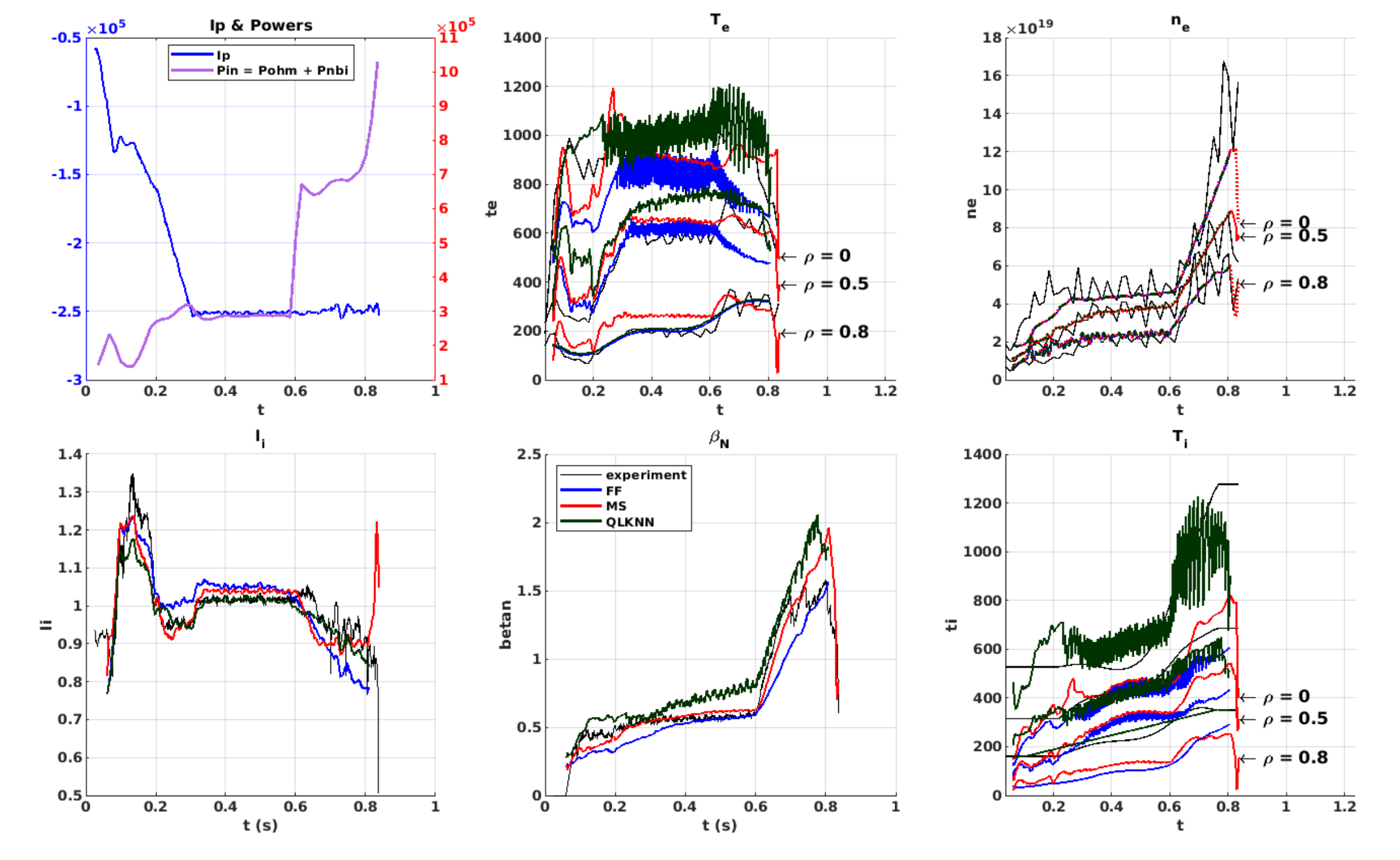
The advantage of the MS model is that it only requires the line-averaged density and confinement quality for the diffusivity controller



This means that we provide pre-estimation of the confinement quality… But also that we don't need to provide any information on the pedestal



But for all of these models, an estimation of the effective charge Z_{eff} and of the heating/current deposition profiles is needed



Simulation of #56653 using the 3 models

FBT-RAPTOR coupling for Kinetic Equilibrium Prediction (KEP)

FBT is a **static free-boundary equilibrium code** that searches for the active coil currents needed to maintain a certain plasma shape given a set of constraints.

By default, FBT uses very simple internal profiles without solving for transport. The goal of this coupling is **to provide RAPTOR p' and TT' profiles to FBT** and to perform a convergence loop to improve the prediction of the required Poloidal Field Coil (PFC). currents and to obtain a self-consistent kinetic equilibrium before the experiment

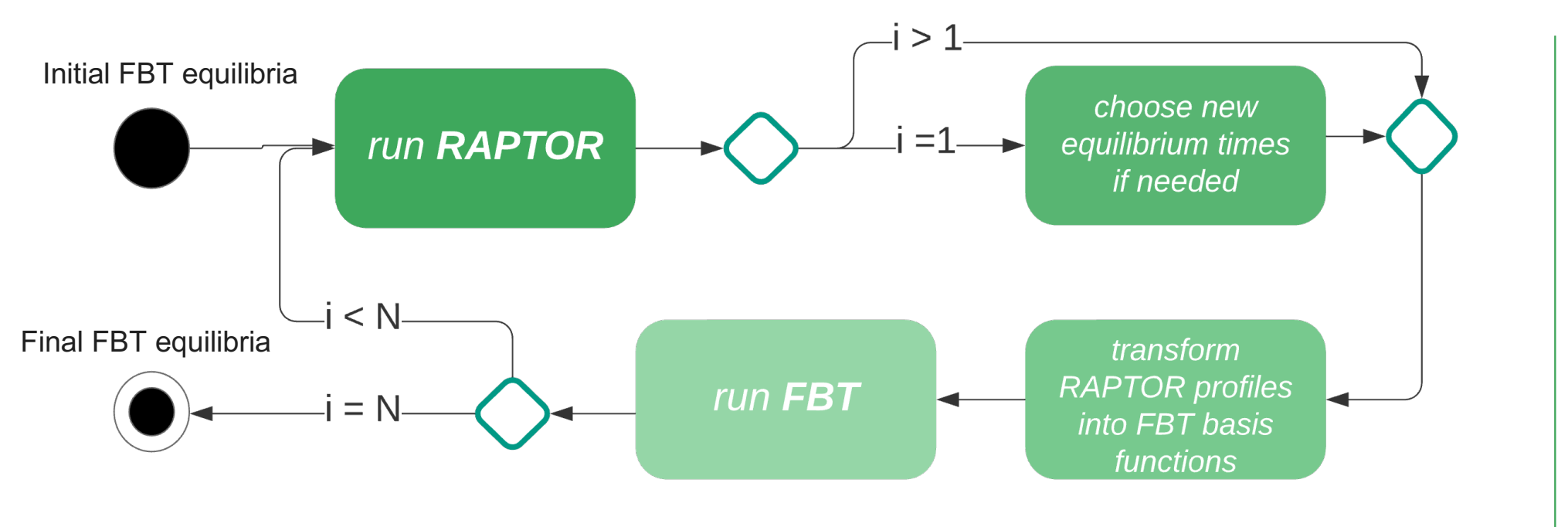


Illustration of the iterative coupling process between RAPTOR and FBT

Typically used in shot preparation, FBT:

- ❑ solves the **Grad-Shafranov / Poisson equation:**

$$\Delta^*\psi = -2\pi R\mu_0 j_\varphi(p', TT', \psi)$$

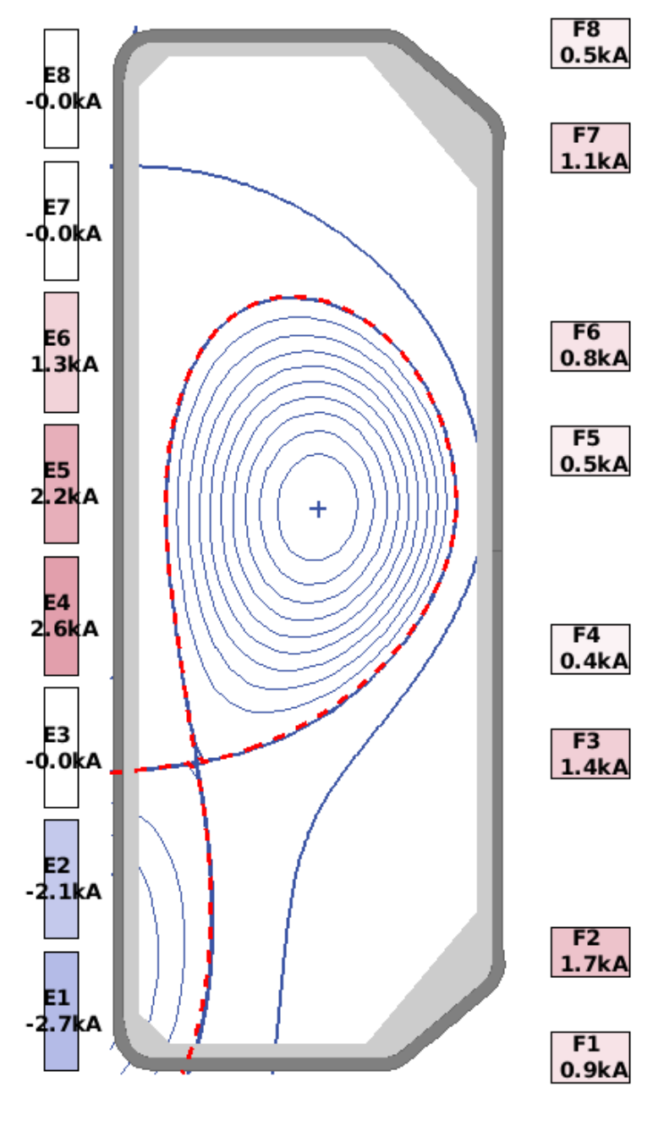
- ❑ updates the PFC currents by solving **the least-square problem**:

$$\min_{I_a^{[n]},\psi_C}\left\|\psi\left(R_C, Z_C, I_a^{[n]}, j_\varphi^{[n-1]}\right) - \psi_C\right\|$$

Inputs:		Outputs:
Desired boundary shape Internal p', TT' profiles	**FBT**	Required PF coil currents I_a equilibrium flux mapping

where:

- j_φ is the toroidal plasma current density
- $p' = \frac{dp}{d\psi}$, $TT' = T\frac{dT}{d\psi}$, with $T = RB_\varphi$
- R_C, Z_C, ψ_C are the cylindrical coordinates & poloidal flux at the LCFS

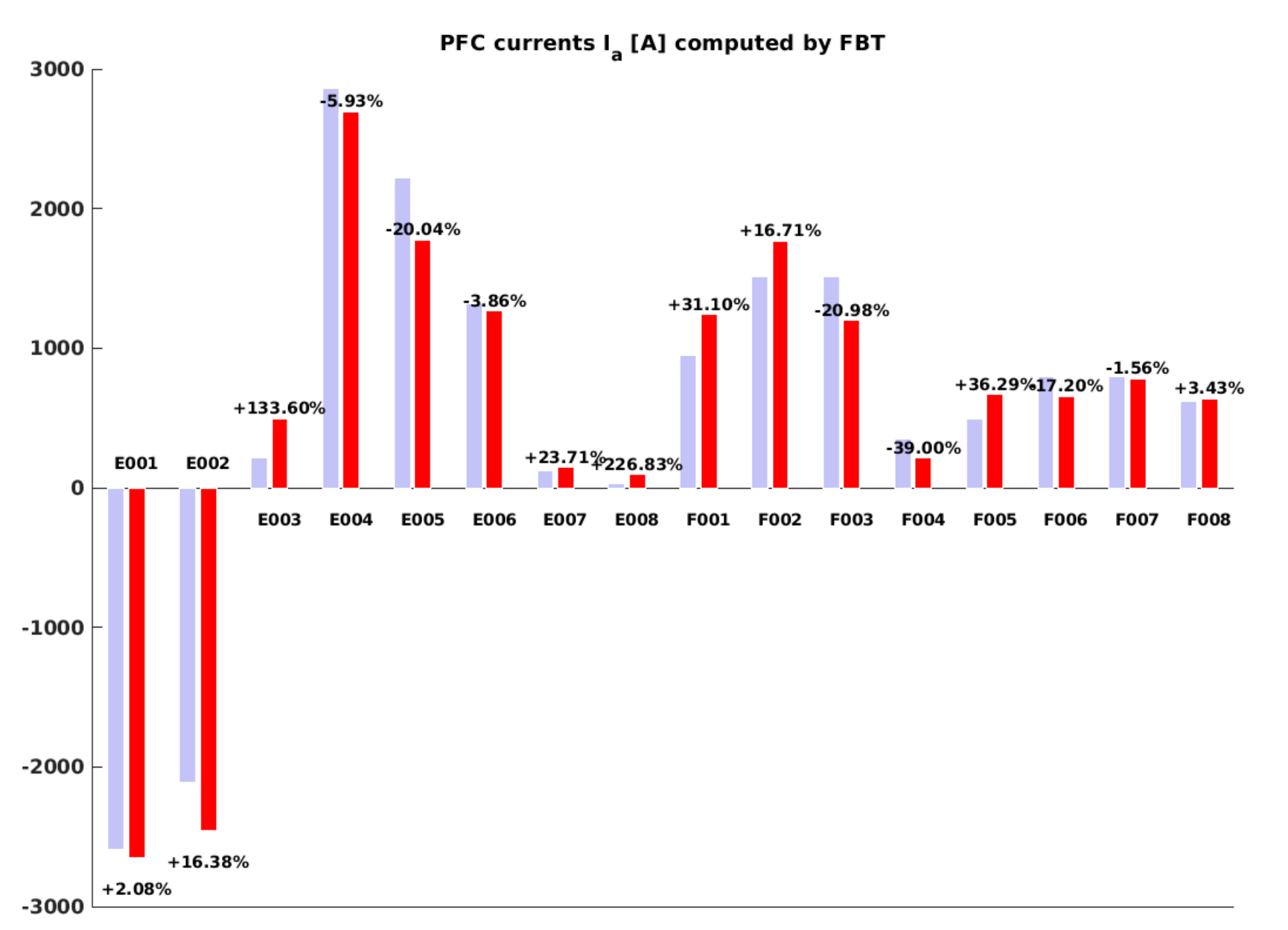


Poloidal view of the TCV vessel showing the location & currents of the PFCs, as well as the plasma flux contour at time $t = 0{,}71s$.

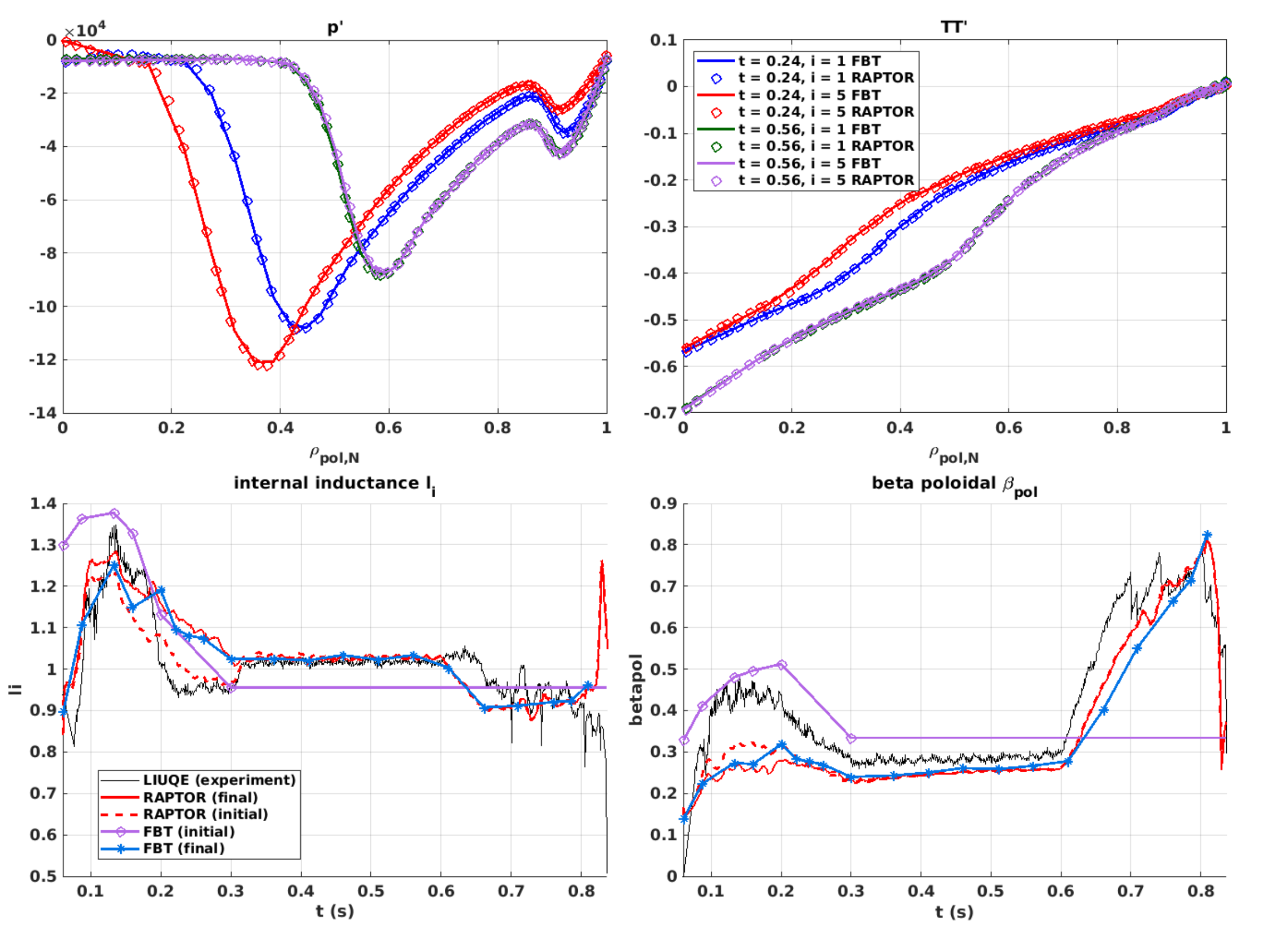
The plasma shape contained in the new FBT equilibrium (in red) is kept the same as in the initial target (in blue).

Result

- After 2 iterations, FBT and RAPTOR converge towards the same p', TT' and q profiles
- Compared to the initial FBT equilibria, the final one **better catch the increase of β_{pol} after the onset of the NBI** (at $t > 0{,}6s$)
- A new sequence of PFC currents I_a is obtained, showing some small corrections w.r.t. the initial estimate



PFC currents found by FBT to maintain the required plasma shape, before and after the coupling for $t = 0{,}71s$



Result of the FBT-RAPTOR coupling for 5 iterations (converged in 2)

References

[1] F. Felici *Nucl. Fusion* **58**(9) 096006, 2018

[2] F. Hofmann. *Computer Physics Communications*, **48**(2), 1988.

[3] A. Teplukhina. *Plasma Phys. Control.* Fusion, **59** 12400, 2017

[4] K. L. van de Plassche. *Phys. Plasma*, **27**(022310), 2020.

[5] H. Lütjens et al. *Computer Physics Communications*, **97**(3), 1996

[6] B. Labit et al, *49th EPS Conference on Plasma Physics*, 2023

Swiss
Plasma
Center

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.