Introduction to RAPTOR

Kinetic Equilibrium Prediction & pulse design for TCV

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What is RAPTOR?

RApid **P**lasma **T**ransport simulat**OR**[1,2]

- **Rapid** transport solver of 1D tokamak plasma profiles

  Why? → Turbulent transport is obtained via reduced models or NN regressions

- Designed for **real-time control**…

  Why? → Written in Matlab, easily transferable to Simulink
  → Feedback controllers can be used for any actuator
  → Any diagnostics can be included as additional information into RT simulation

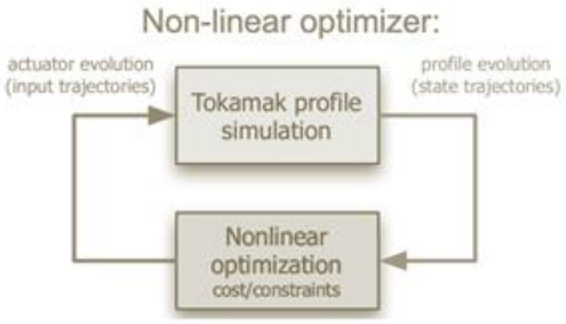
- … and inter-discharge **optimization**

  Why? → Knowledge of the analytical Jacobians $\frac{\partial \tilde{f}}{\partial x}, \frac{\partial \tilde{f}}{\partial u}$

DISCLAMER

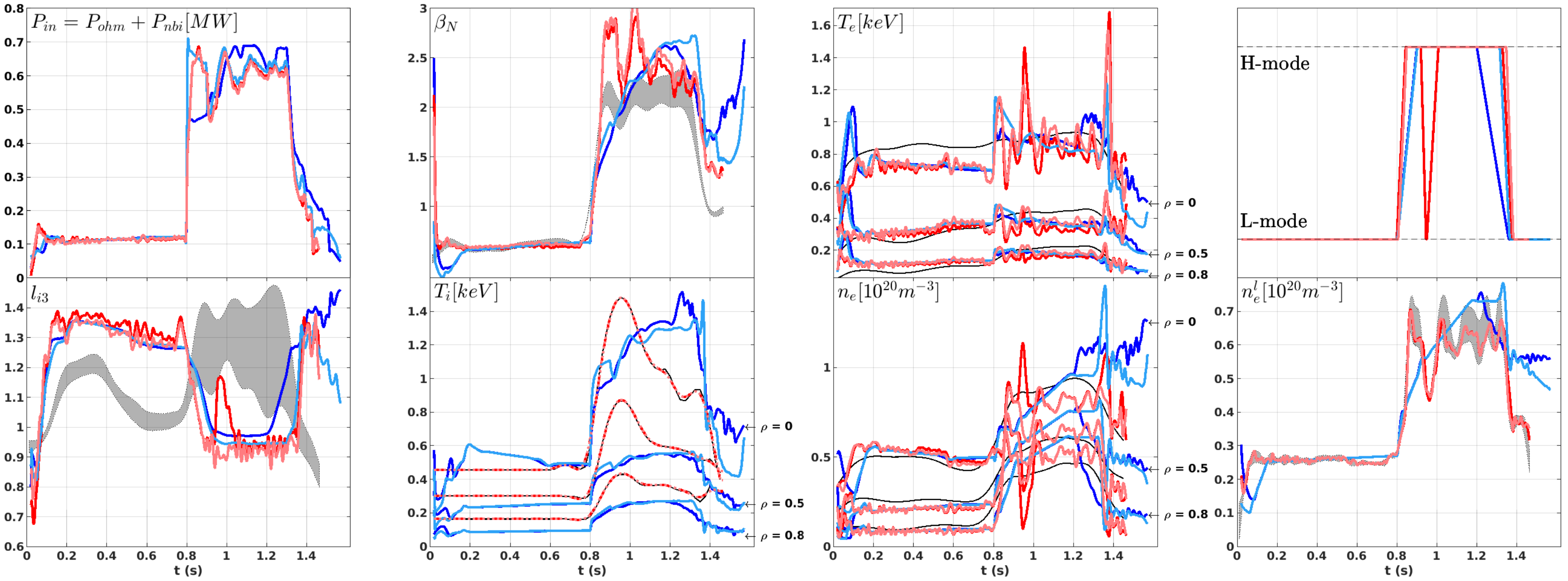
Not made for:

- predicting the performance of a scenario from scratch
- giving high fidelity predictions



[1] F. Felici et al 2011 Nucl. Fusion 51 083052
[2] F. Felici et al 2018 Nucl. Fusion 58 096006

RAPTOR


$P_{in} = P_{ohm} + P_{nbi} [MW]$
β_N
$T_e [keV]$
H-mode
L-mode
l_{i3}
$T_i [keV]$
$n_e [10^{20} m^{-3}]$
$n_e^l [10^{20} m^{-3}]$
ρ = 0
ρ = 0.5
ρ = 0.8
t (s)

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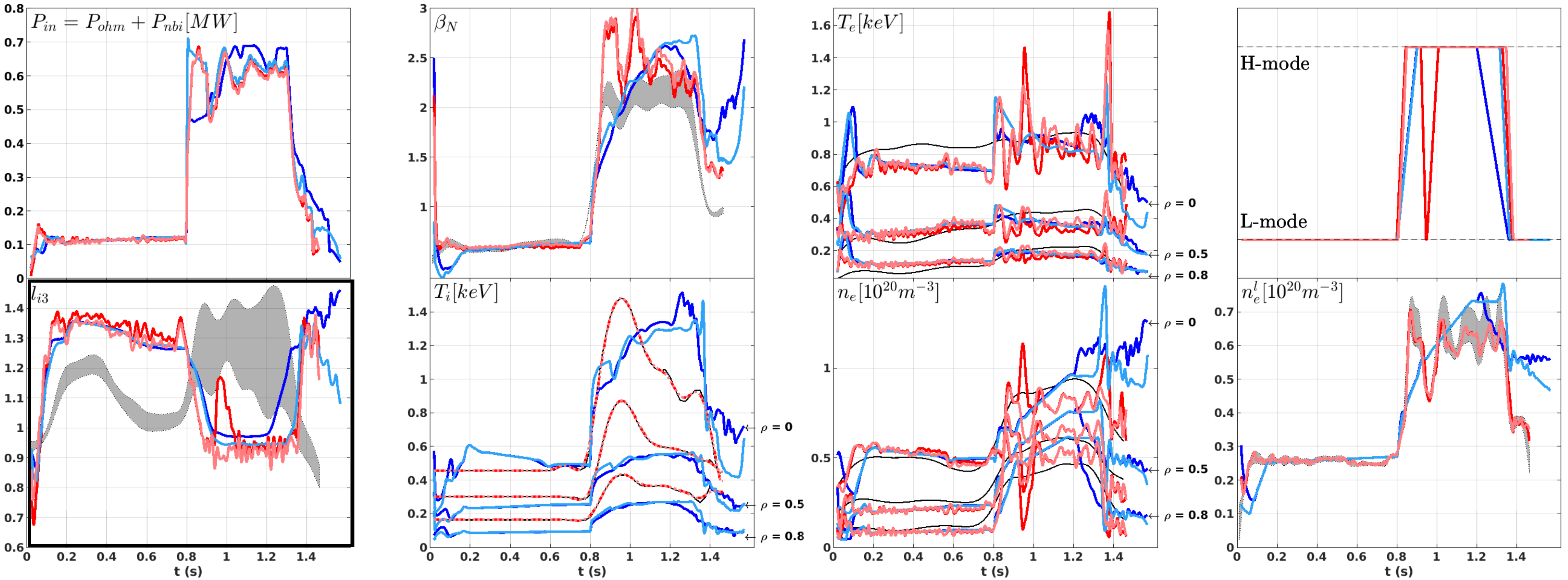
RAPTOR solves for ψ

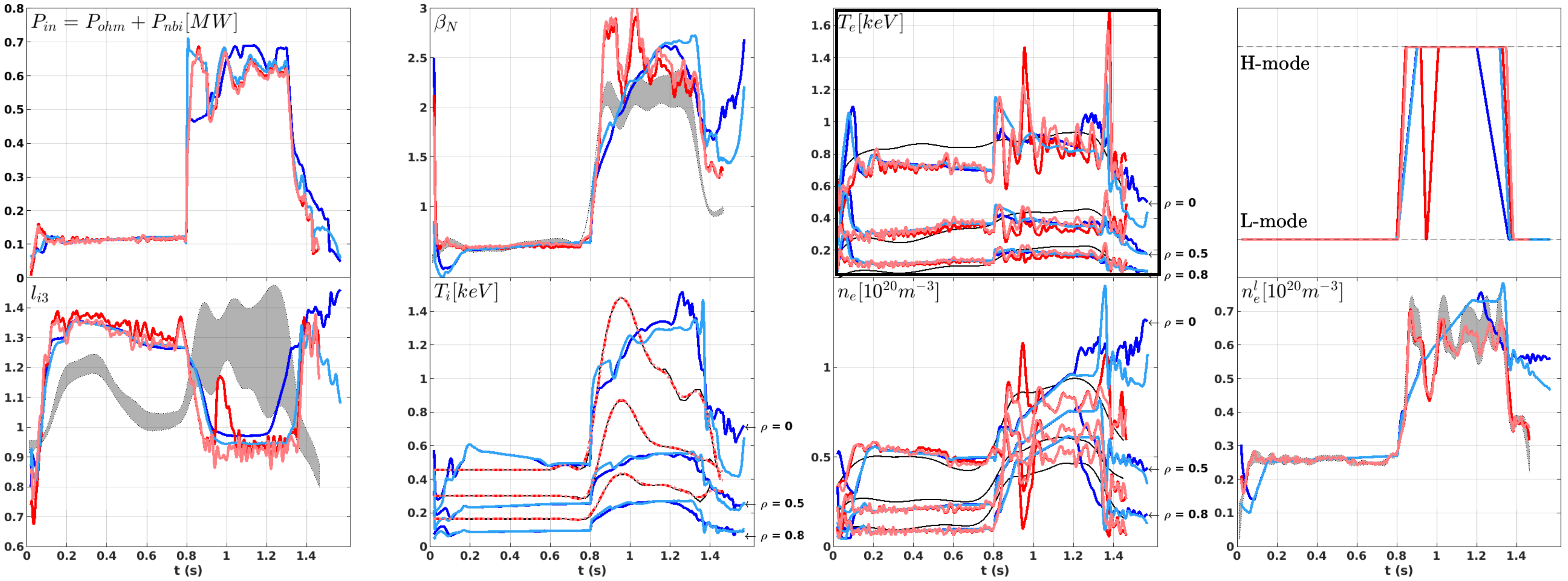


$$\sigma_\parallel \left(\frac{2\Phi_b \rho}{V'_\rho} \frac{\partial \psi}{\partial t}\bigg|_\rho - \frac{\rho^2 \dot{\Phi}_b}{V'_\rho} \frac{\partial \psi}{\partial \rho} \right) = \frac{F^2}{8\pi^2 \mu_0 \Phi_b V'_\rho} \frac{\partial}{\partial \rho} \left[\frac{g_2 g_3}{\rho} \frac{\partial \psi}{\partial \rho} \right] - \langle \mathbf{j_{ni}} \cdot \mathbf{B} \rangle$$

(current)*

*See lecture: Plasma profiles and their control, eq. **12**

RAPTOR can solve for T_e

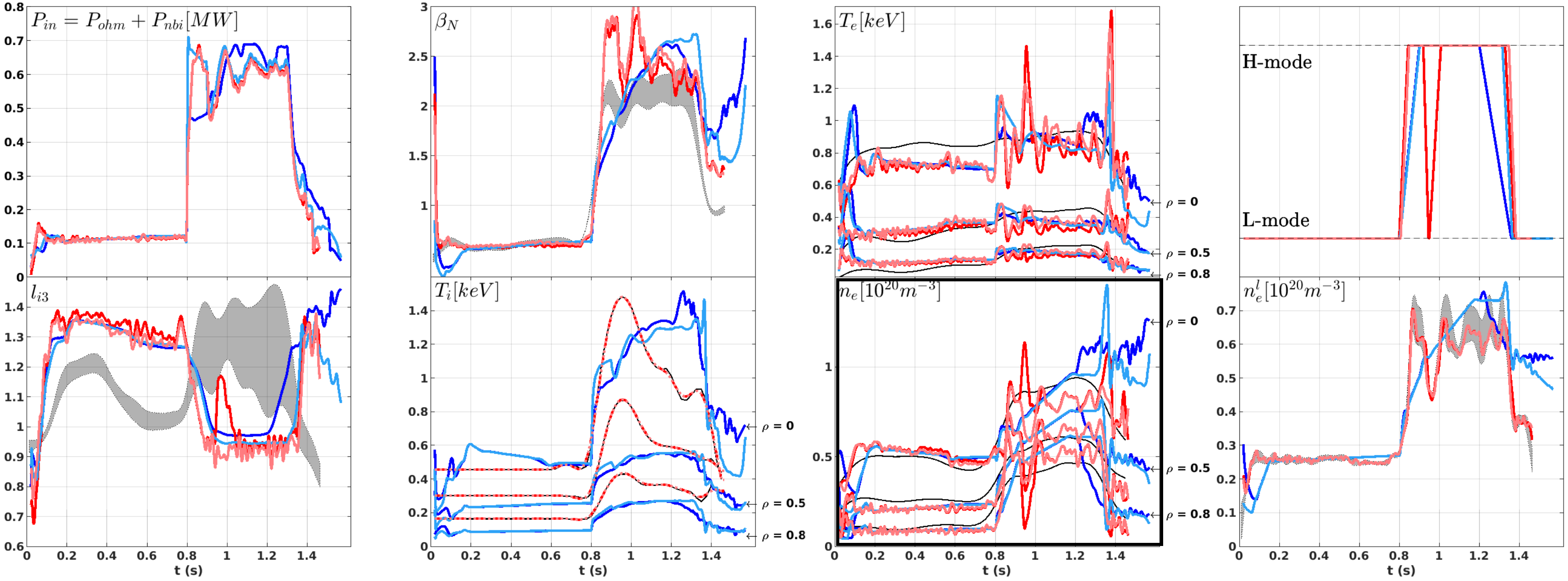


$$\frac{3}{2}(V'_\rho)^{-5/3}\left(\frac{\partial}{\partial t}\bigg|_\rho - \frac{\dot{\Phi}_b}{2\Phi_b}\frac{\partial}{\partial \rho}\rho\right)[(V'_\rho)^{5/3} n_{e,i} T_{e,i}] + \frac{1}{V'_\rho}\frac{\partial}{\partial \rho}\left(-\frac{g_1}{V'_\rho} n_{e,i}\chi_{e,i}\frac{\partial T_{e,i}}{\partial \rho} + \frac{5}{2} T_{e,i}\Gamma_{e,i} g_0\right) = P_{e,i}$$

(temperature)

*See lecture: Plasma profiles and their control, eq. **22**

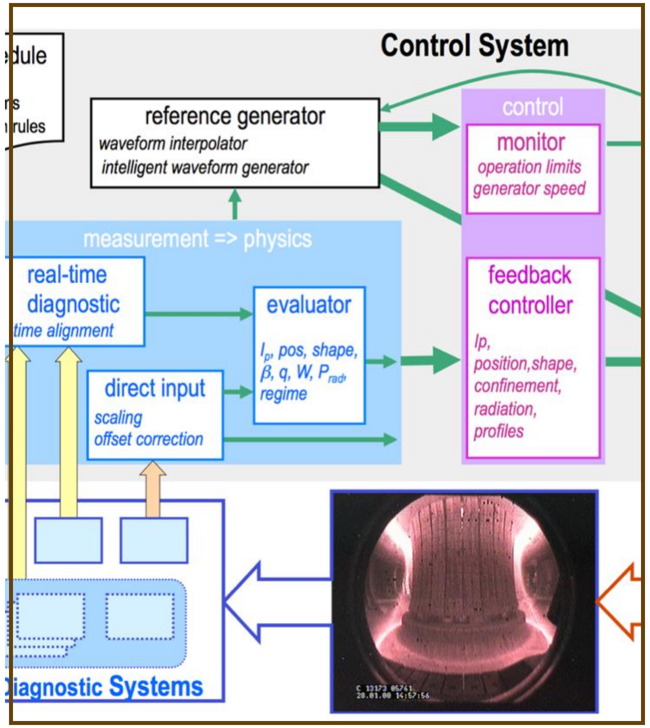
RAPTOR can solve for n_e



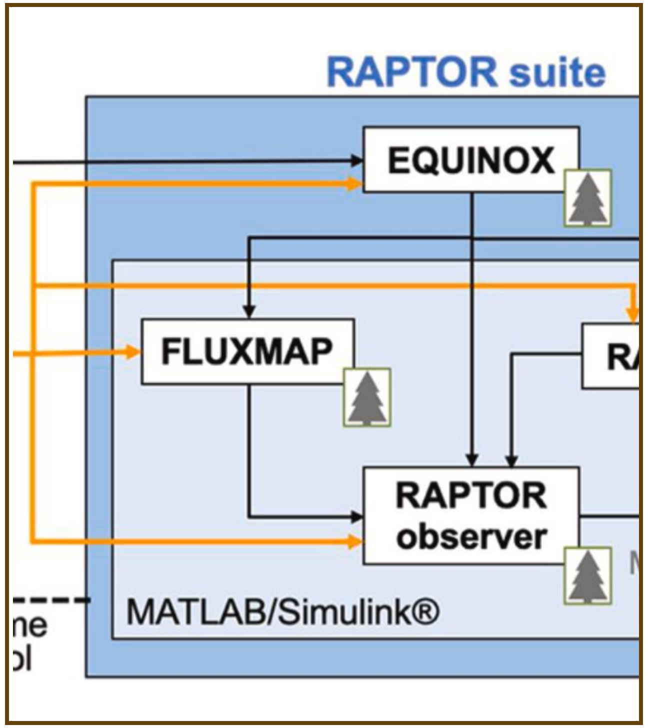
$$\frac{1}{V'_{\hat{\rho}}}\left(\frac{\partial}{\partial t}\bigg|_{\hat{\rho}} - \frac{\dot{\Phi}_b}{2\Phi_b}\frac{\partial}{\partial \hat{\rho}}\hat{\rho}\right)[V'_{\hat{\rho}} n_e] = -\frac{1}{V'_{\hat{\rho}}}\frac{\partial}{\partial \hat{\rho}}\Gamma_e + S_e$$

(density)

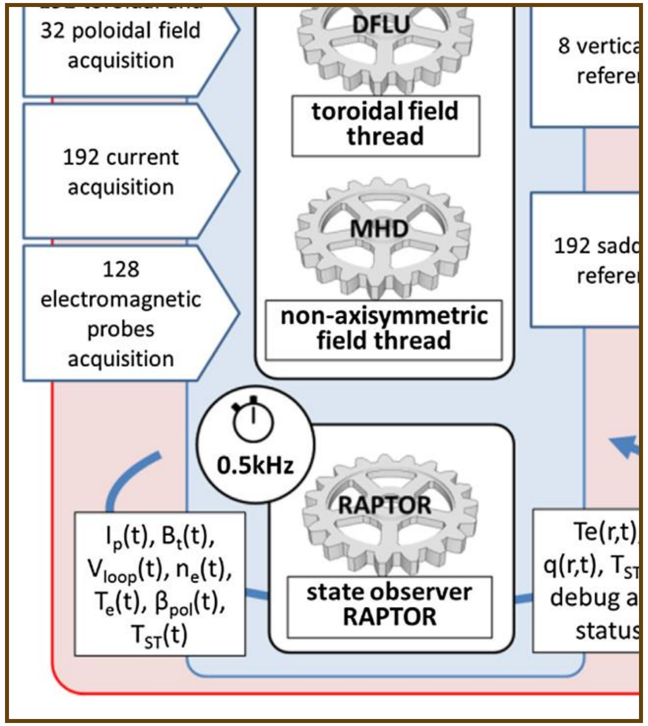
RAPTOR is implemented in RT at



AUG



JET



RFX

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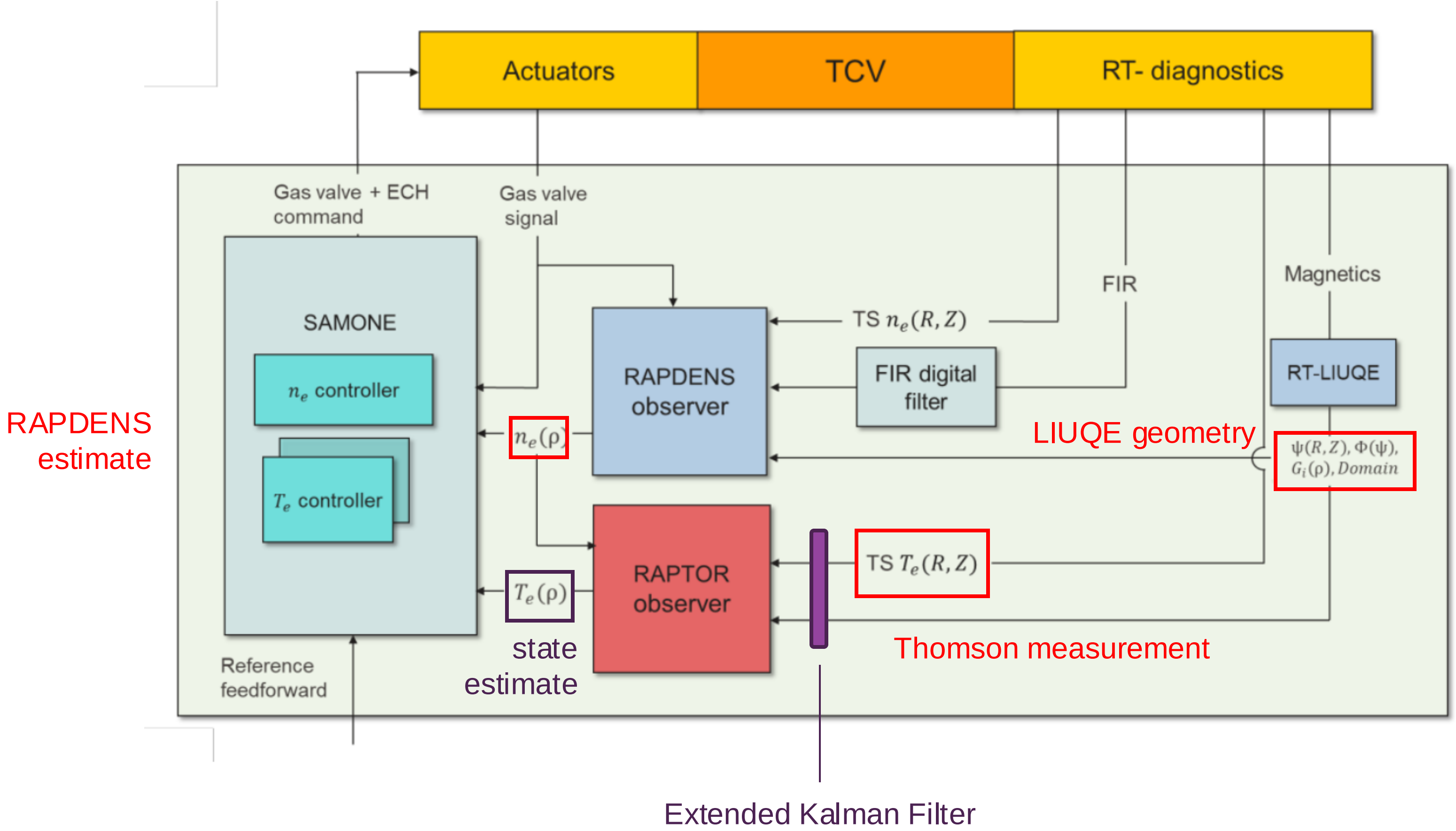
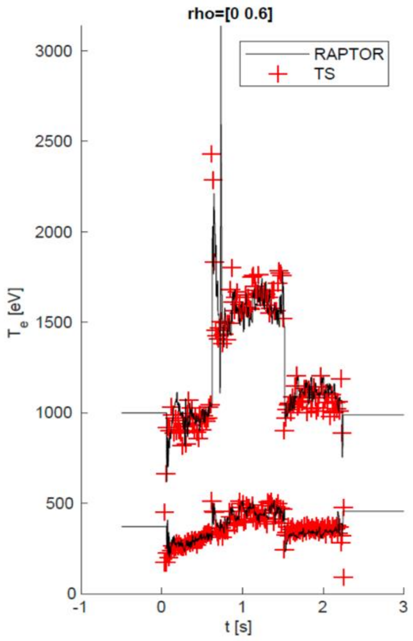
RAPTOR is implemented in RT at TCV





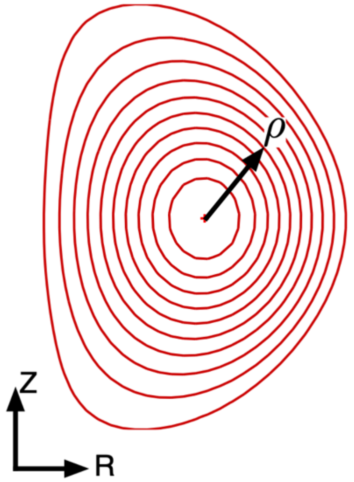
What is a Kinetic Equilibrium Prediction (KEP)?

Reminder

- As said in previous course*, 1D transport solvers require a **2D equilibrium** from an external Grad-Shafranov solver
- Historically, RAPTOR is run with **CHEASE**, a fixed-boundary equilibrium solver

  → *can re-compute Grad-Shafranov from almost* *<u>any free-boundary code</u>* *and* *<u>any machine</u>, if given in an EQDSK format*

- But it can also be coupled to a **free-boundary equilibrium** solver directly



*Plasma profiles and their control, slide **29**

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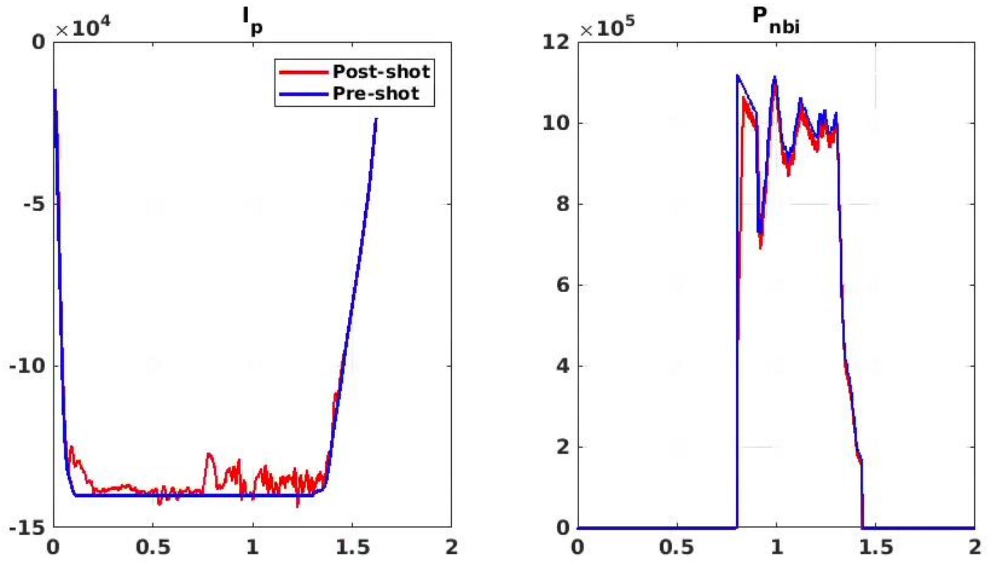
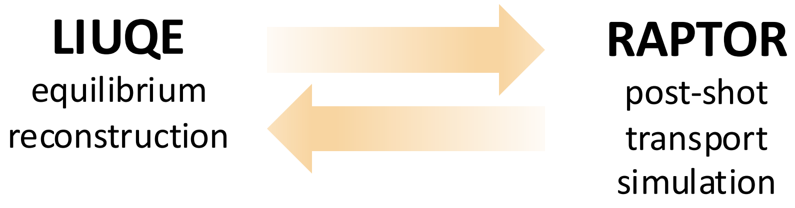
Kinetic **E**quilibrium **P**rediction

What is a pre-shot simulation?

What is a Kinetic Equilibrium Prediction (KEP)?



In post-shot, one can do a KER



Post-shot available inputs:

- LIUQE 2D equilibrium
- TS mesurement for pedestal top $\rightarrow T_e, n_e$ boundary conditions at $\rho = \rho_{ped}$
- Actuators ($I_p, P_{NBI}, P_{EC} \ldots$) actions, as observed in experiment
- Obtained line-averaged density $n_{e,l}$, current drive j_{ec}, confinement… etc.
- L-H transition, MHD events… etc.

→ we don't have all this information pre-shot!

What is a Kinetic Equilibrium Prediction (KEP)?

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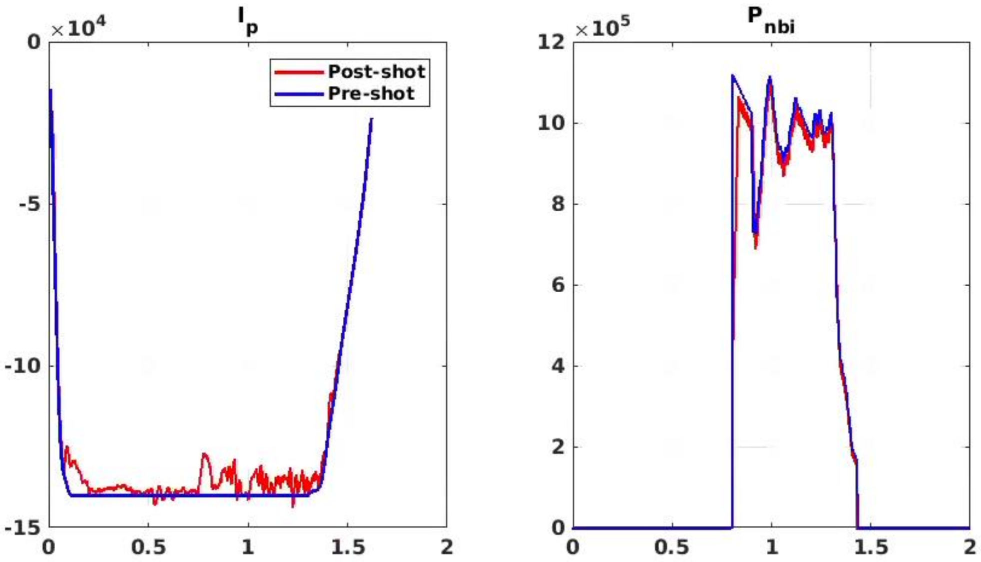


In pre-shot, equivalent is a KEP

Pre-shot available inputs:

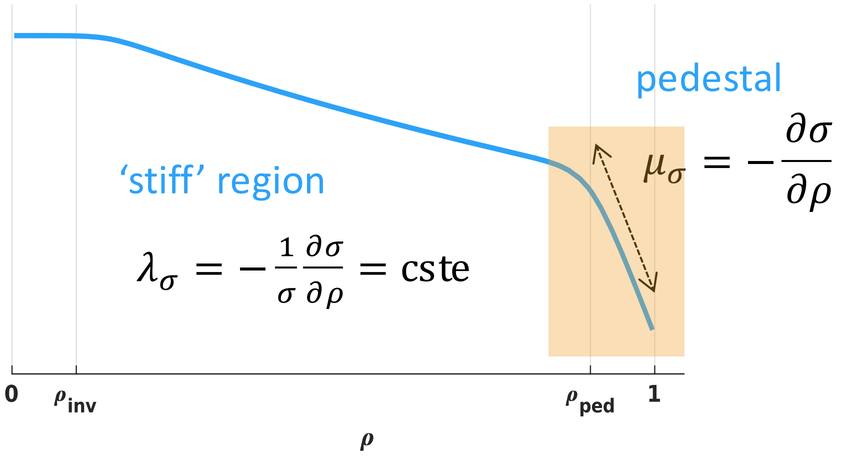
- FBT 2D equilibrium
- No a-priori information on the pedestal
- Actuators (I_p, P_{NBI}, P_{EC}…) programming
- Gas valve reference, ECRH angles… etc.
- No a-priori information on the L-H transition

What is a Kinetic Equilibrium Prediction (KEP)?

For this, we use the **gradient-based model**[1]

based on the observation that for $\sigma = \{T_e, n_e\}$

- the logarithmic gradients remain stiff[2] in an intermediate region between $\rho_{inv} \sim 0.1$ and $\rho_{ped} \sim 0.8$
- while the pedestal gradient μ_σ varies with the shot confinement [3]



Coupled to a L-H transition prediction, following **Y. Martin's scaling law**[4]

$$P_{LH} = \frac{2}{A_i} 2.15\ 10^6\ {n_e^{l,20}}^{0.782} B_0^{0.772} a^{0.975} R_0^{0.999}$$

$$P_{sep} > \alpha P_{LH}$$

$$P_{sep} = P_{oh} + P_{aux} - P_{rad} - \frac{dW}{dt}$$

[4] Y R Martin et al 2008 J. Phys.: Conf. Ser. 123 012033

What is a Kinetic Equilibrium Prediction (KEP)?

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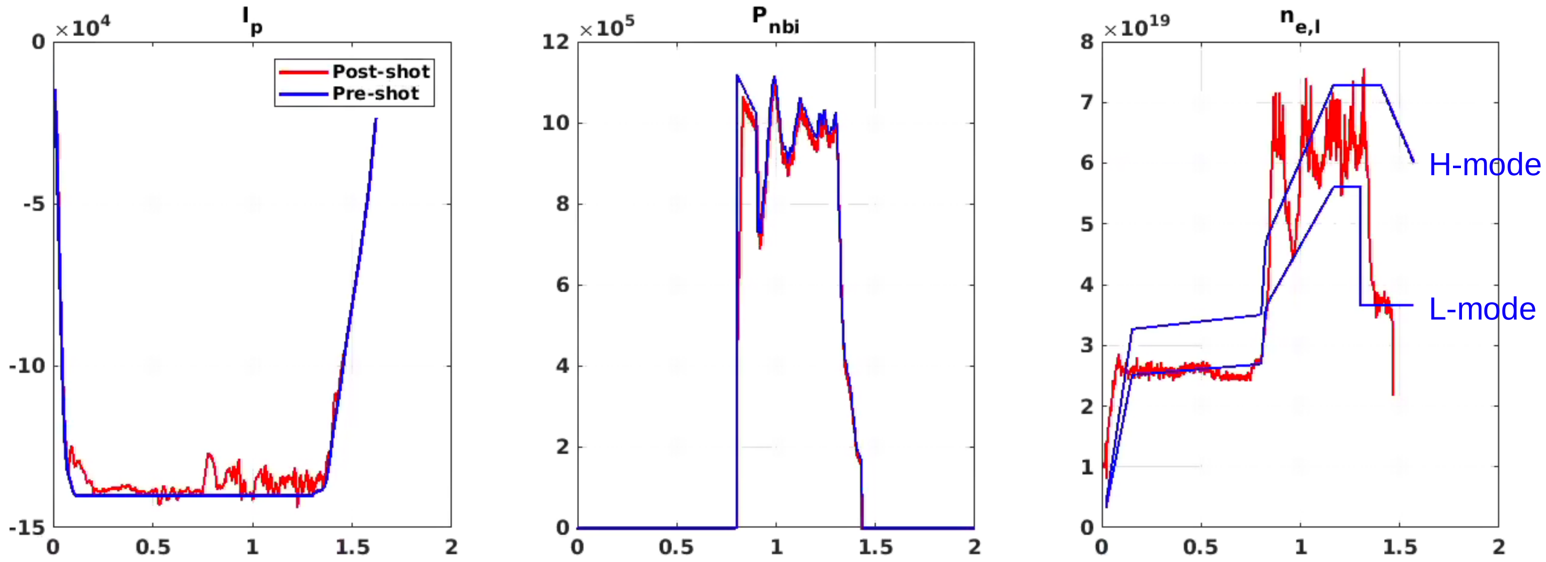


simple estimate based on gas valve programming

This model requires:

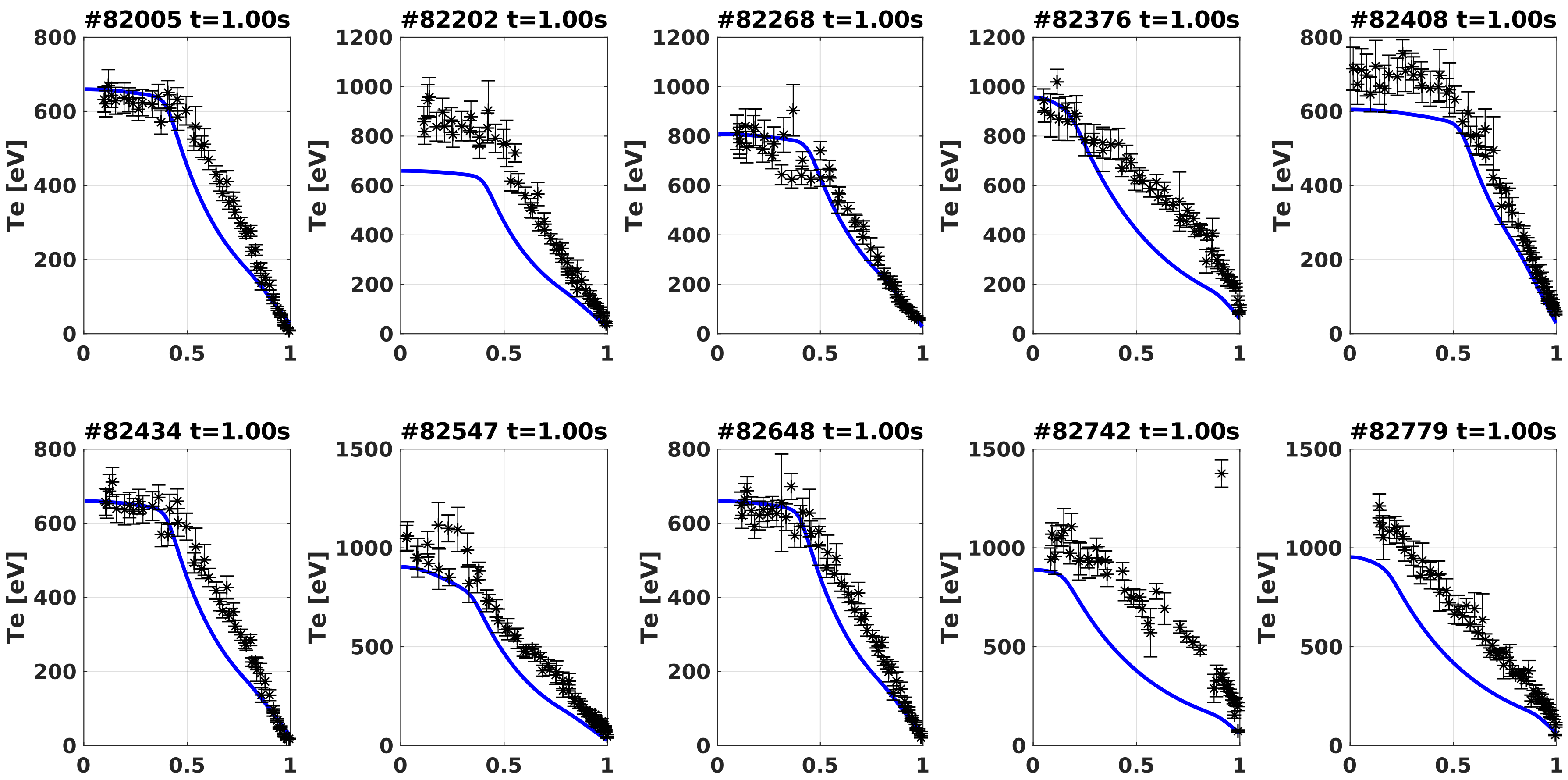
- Line-averaged density $n_{e,l}$ to control μ_{ne}
- Electron confinement quality[1] H_e^{98} to control μ_{Te}
- Logarithmic gradients λ_{ne} and λ_{Te}

Mode	Triangularity	λ_{Te}	λ_{ne}	H_e^{98}
L	PT	3.3	3	0.4
H	PT	2.7	2	0.5
L	NT	3	3	0.5

[1] ITER Physics Expert Groups. ITER Physics Basis, Chapter 2: Plasma confinement and transport, 1999a.

What is a Kinetic Equilibrium Prediction (KEP)?

- Pre-shot RAPTOR simulations for ohmic shots with/without NBI is almost automatised

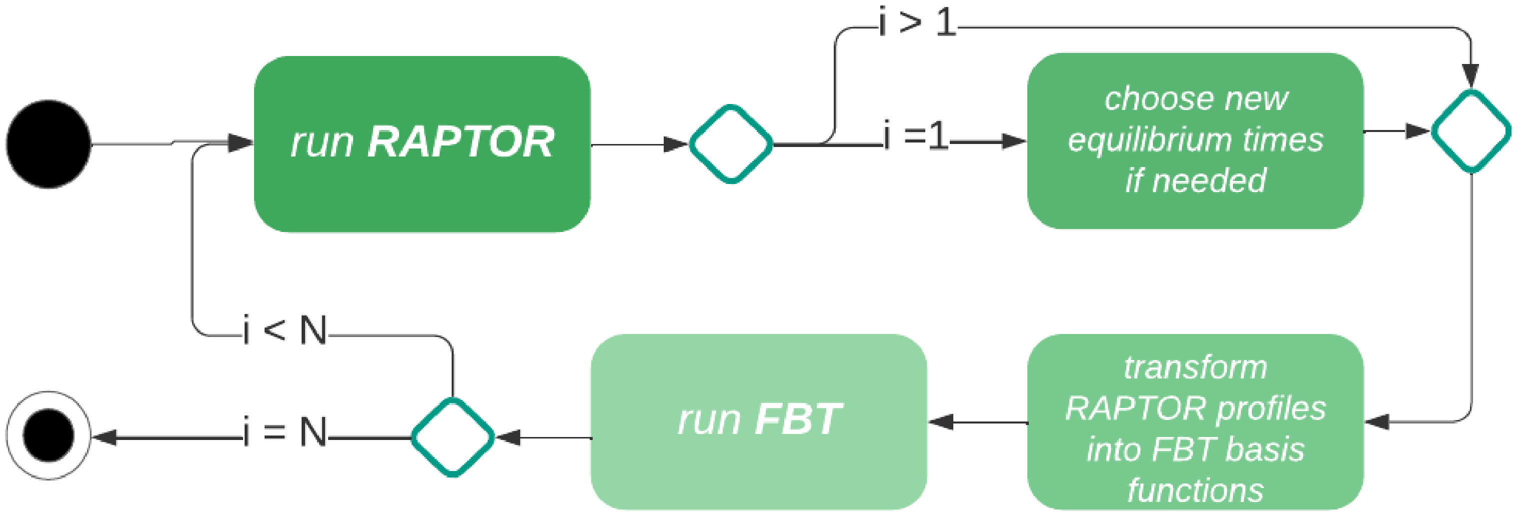


Kinetic-**E**quilibrium **P**rediction

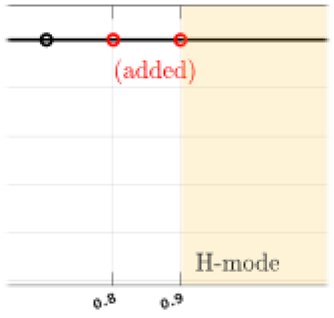
About the Kinetic-Equilibrium coupling…

Methodology

1. Prepare an initial FBT equilibrium on the standard GUI
2. Using information available prior to the shot, launch a RAPTOR simulation
3. If result is validated, launch coupling



RAPTOR informs us on the scenario dynamics



What is a Kinetic Equilibrium Prediction (KEP)?

Methodology

1. Prepa
2. Using
3. If resu

Inputs:

- Desired boundary shape
- Internal p', TT' profiles

→ **FBT** →

Outputs:

- Required PF coil currents I_a
- equilibrium flux mapping

When solving for Grad-Shafranov,

FBT is given one degree of freedom to match I_p:

- $TT'_{FBT} = TT'_{RAP}$
- $p'_{FBT} = \alpha \, p'_{RAP}$

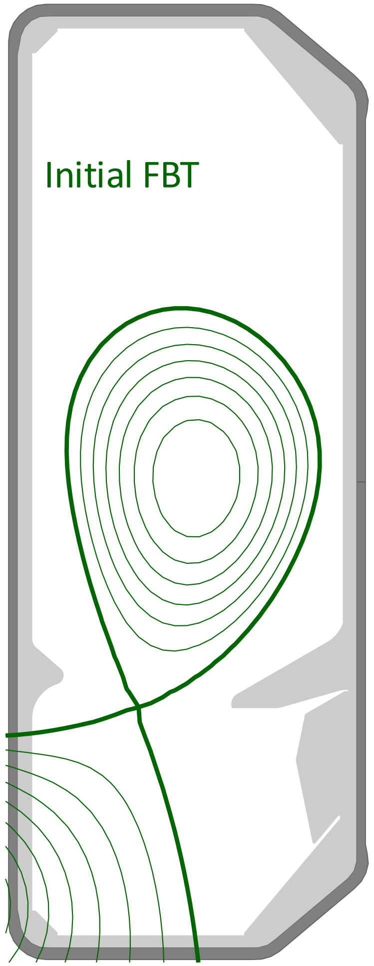
RAPTOR informs us on the scenario dynamics

What is a Kinetic Equilibrium Prediction (KEP)?

Convergence

- generally good for $I_p > 10\%\ I_p^{\max}$
- difference between p'_{RAP} and p'_{FBT} $(\alpha - 1)$ decreases with iterations & falls rapidly below $\mathbf{5}\%$
- 3-4 iterations often sufficient

Application to TCV experiments



PT-LSN-Hmode

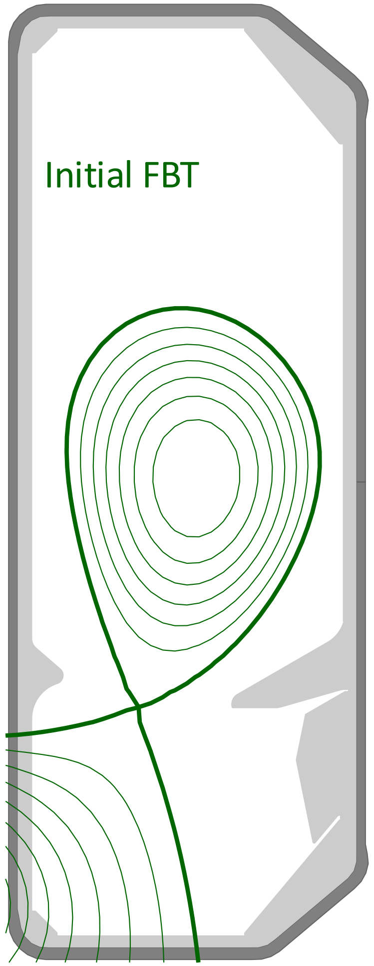
We start from a set of initial FBT equilibria prepared through the usual GUI,

assuming completely wrong values were chosen for q_A and β_p.

Then, a first RAPTOR simulation is launched.

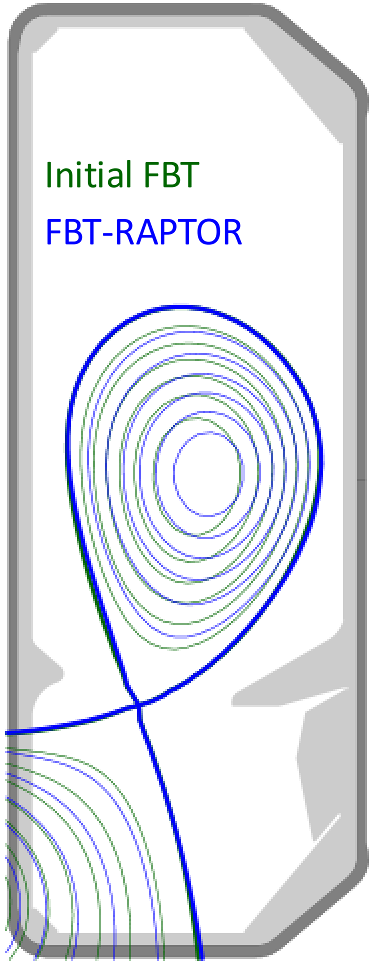
Application to TCV experiments

After 3 iterations between RAPTOR and FBT



PT-LSN-Hmode

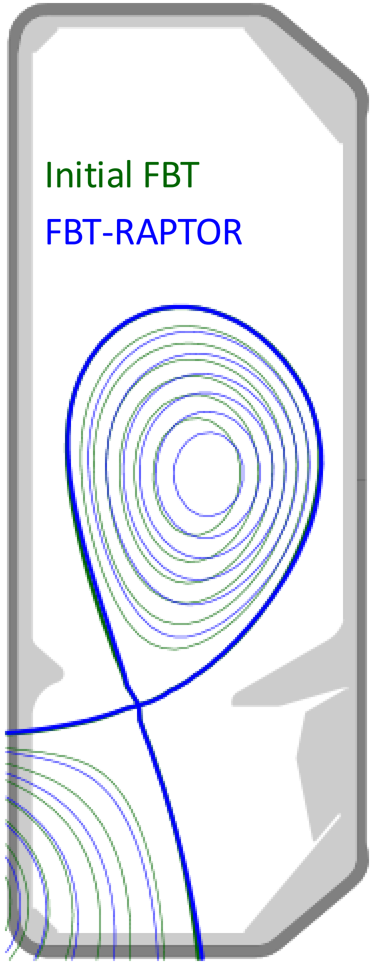
Application to TCV experiments



PT-LSN-Hmode

After 3 iterations between RAPTOR and FBT, we get a new equilibrium.

Application to TCV experiments



PT-LSN-Hmode

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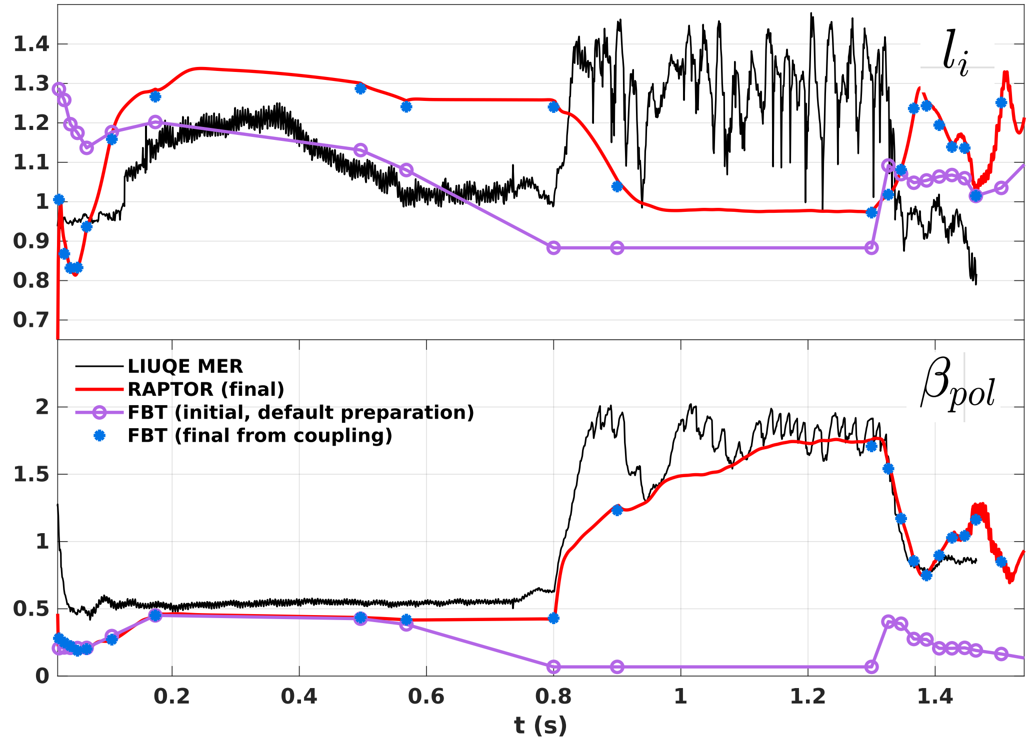
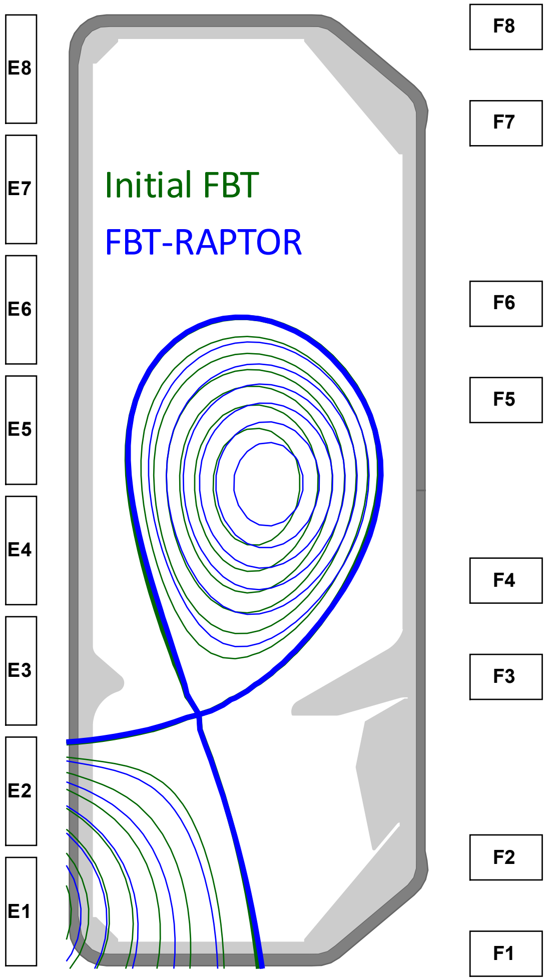


Application to TCV experiments



PT-LSN-Hmode

TCV has 16 PF coil currents (E1-8, F1-8) for shaping, all individually controlled with an hybrid system.

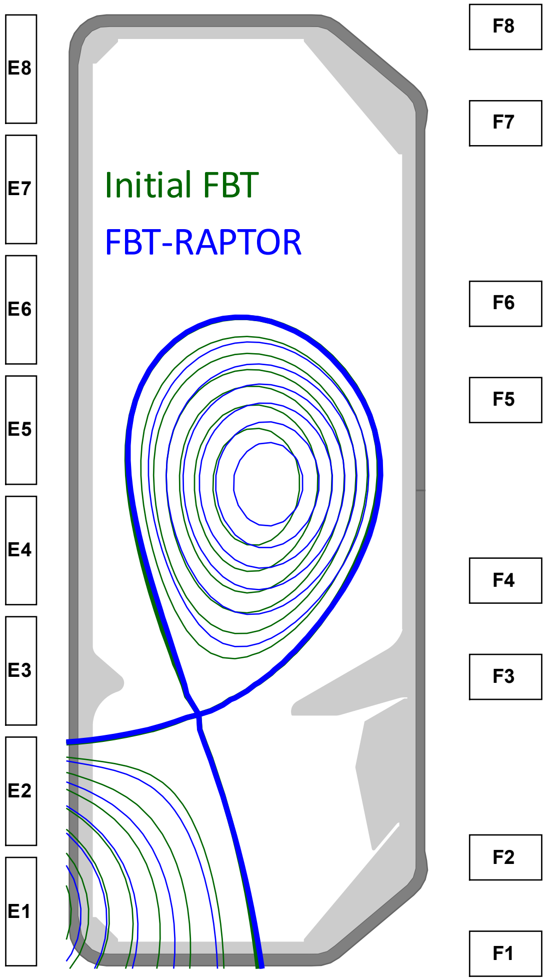
It traditionnally uses FBT to compute reference for the shape alone, to which is added:

- reference for the central solenoid (to generate I_p)
- extra control polices, including control for RZ position

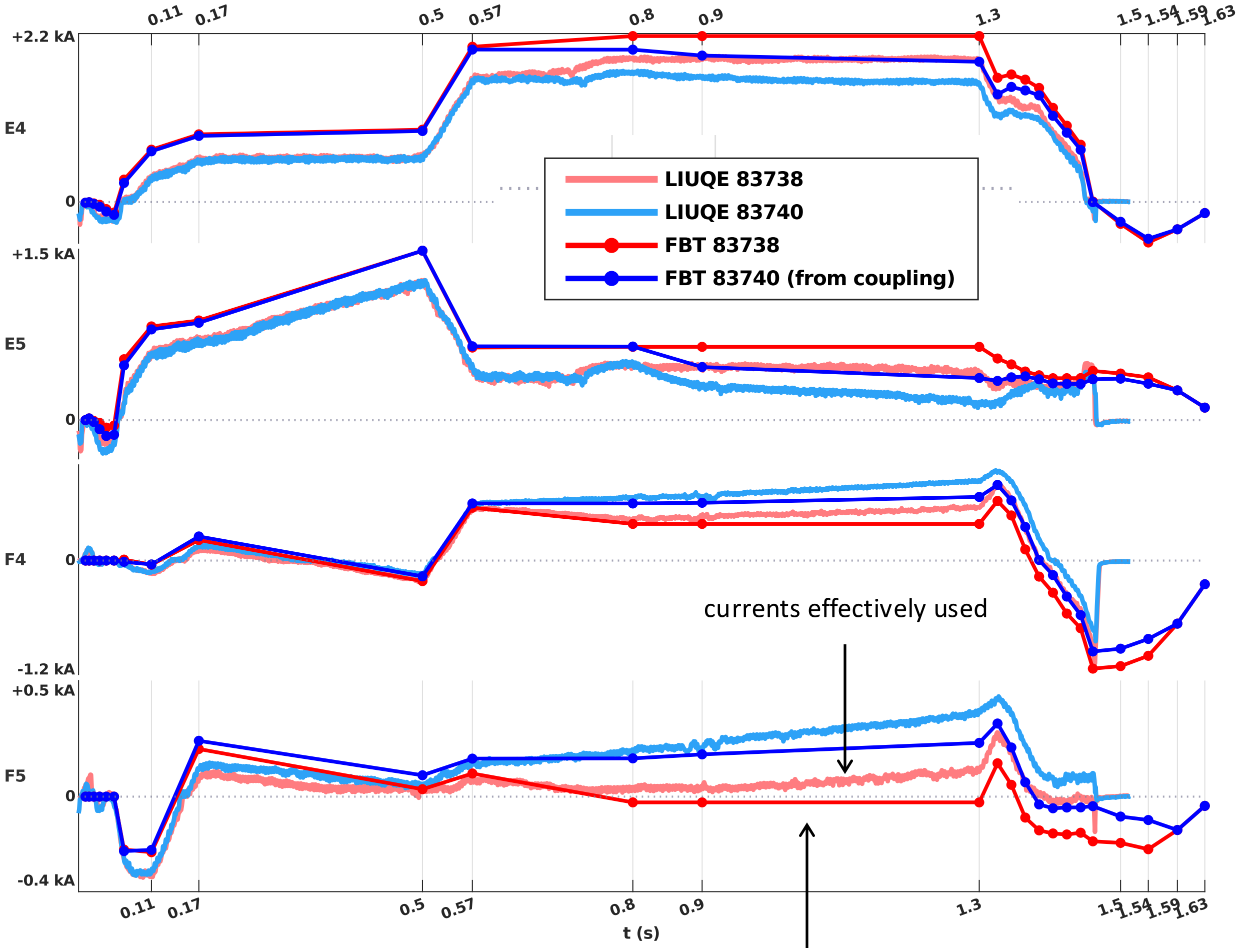
So we replicated the same shot two times in a row, only changing the reference for shaping:

- #83738 using the initial FBT
- #83740 using FBT-RAPTOR

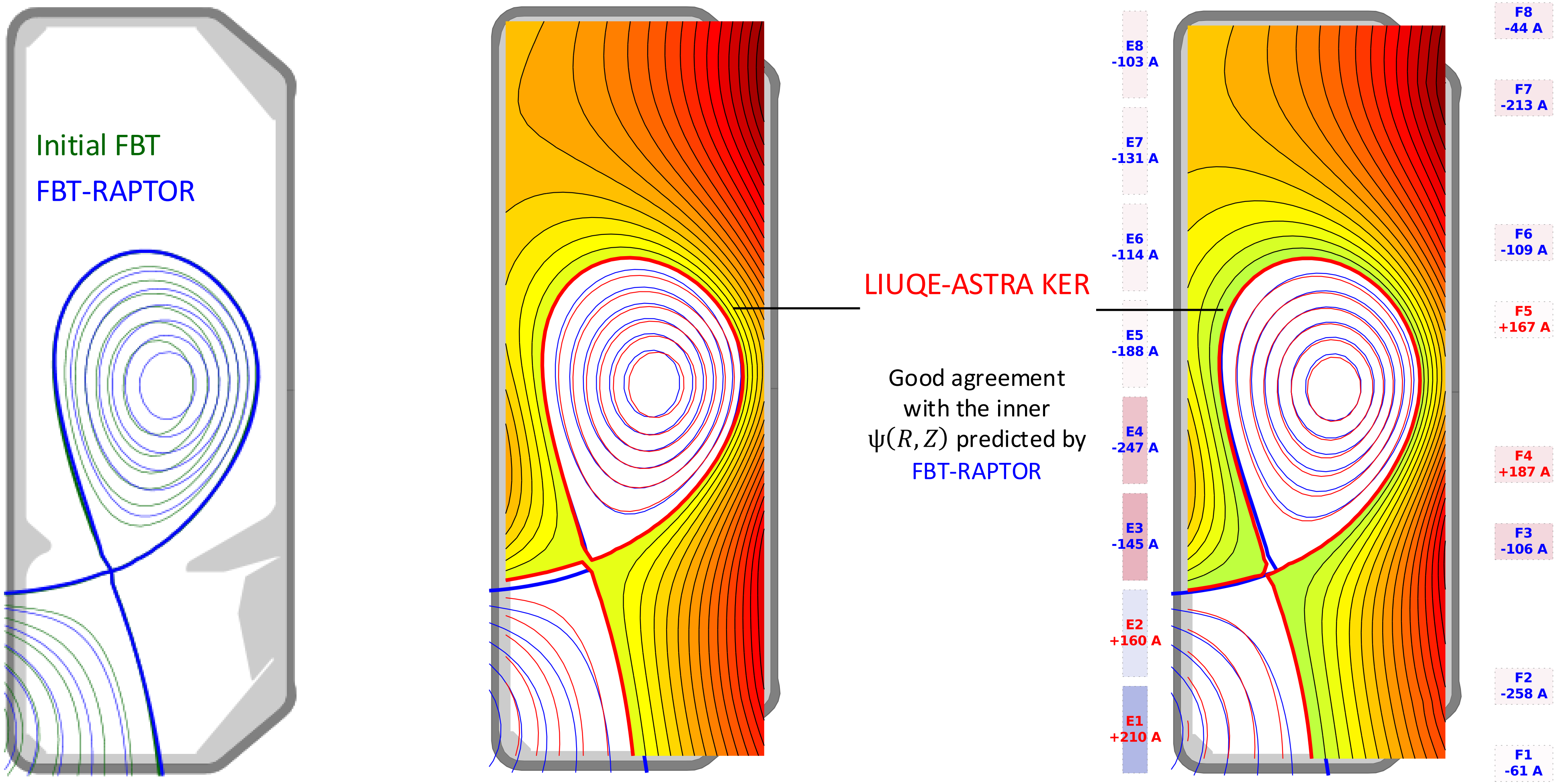
Application to TCV experiments



PT-LSN-Hmode



Application to TCV experiments

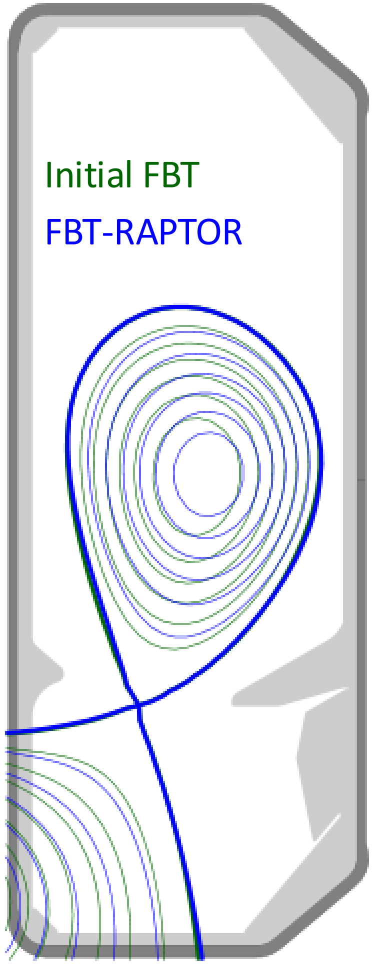


PT-LSN-Hmode

Shot prepared with FBT

Shot prepared with FBT-RAPTOR

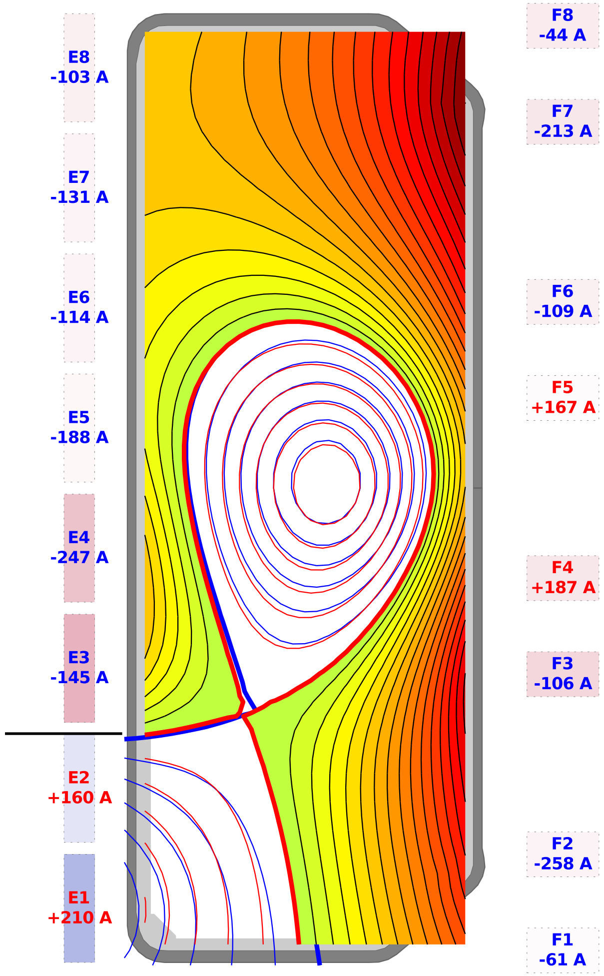
Application to TCV experiments



PT-LSN-Hmode

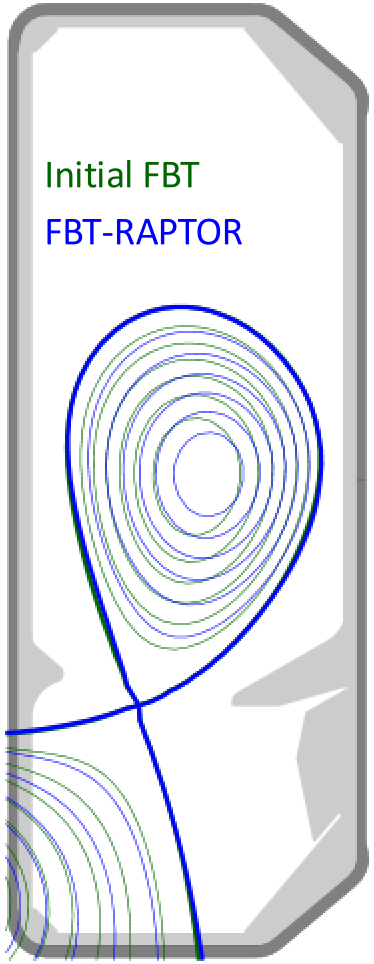
Shot prepared with FBT

Shot prepared with FBT-RAPTOR shows a better alignment with X-point target



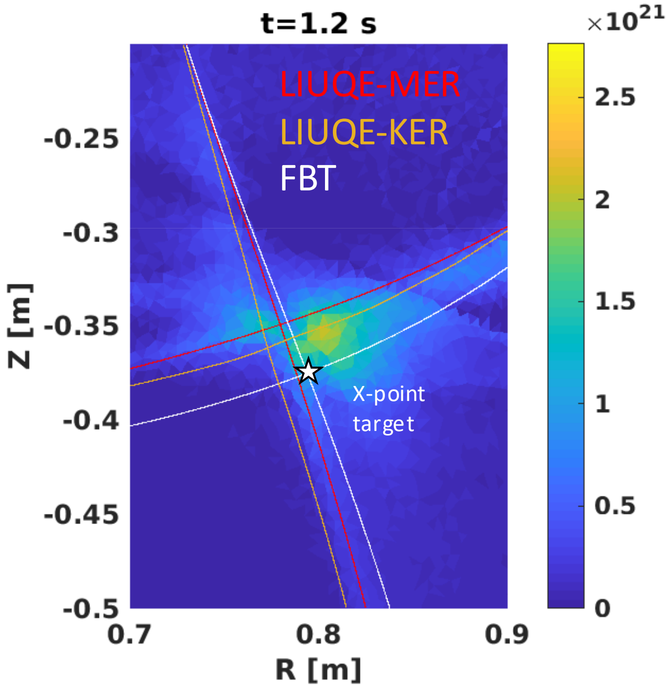
Shot prepared with FBT-RAPTOR

Application to TCV experiments

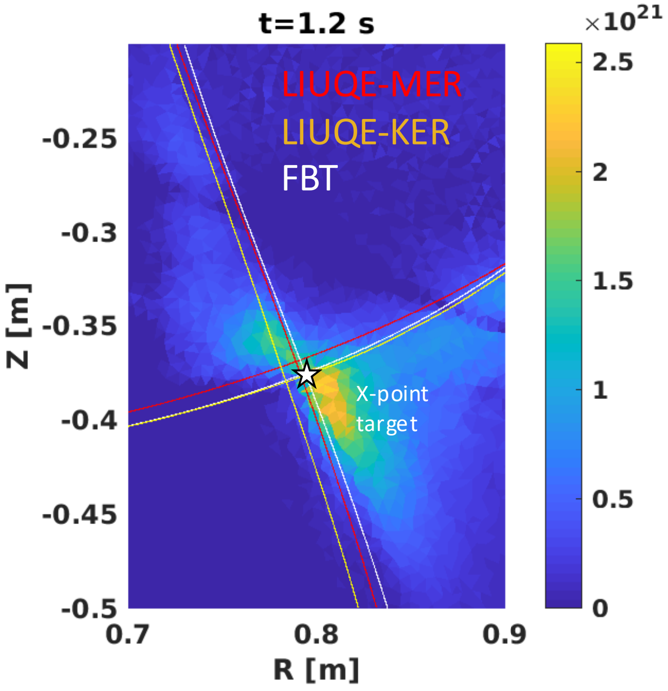


PT-LSN-Hmode

MANTIS tomographic inversion



Shot prepared with FBT



Shot prepared with FBT-RAPTOR

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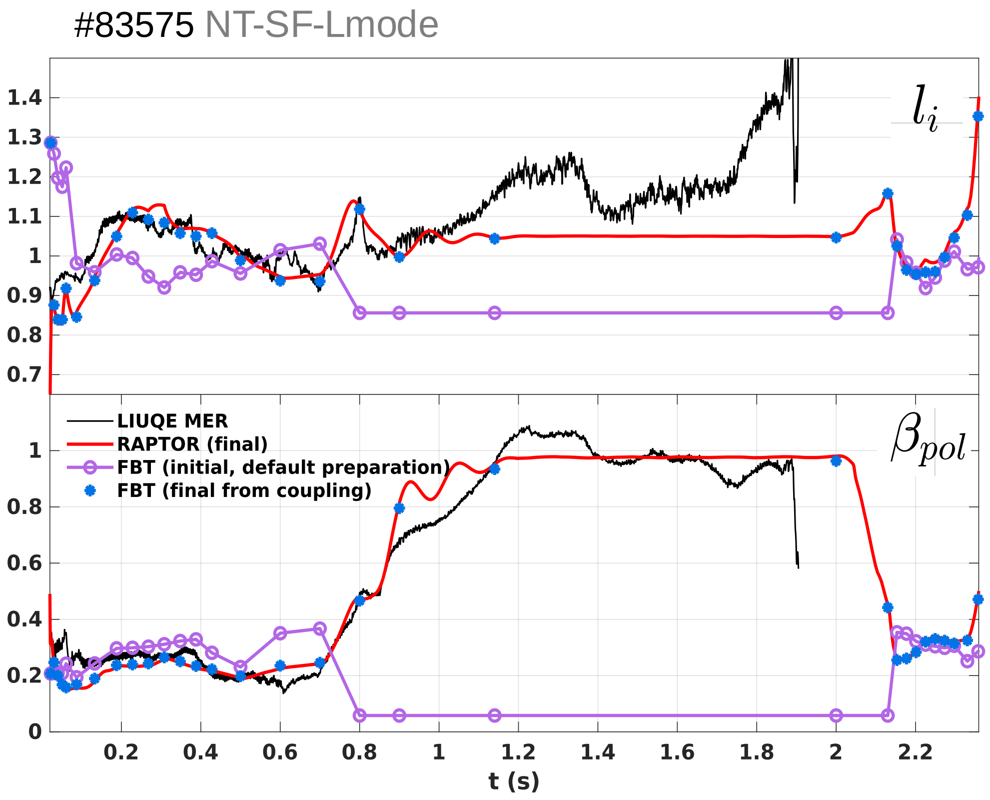
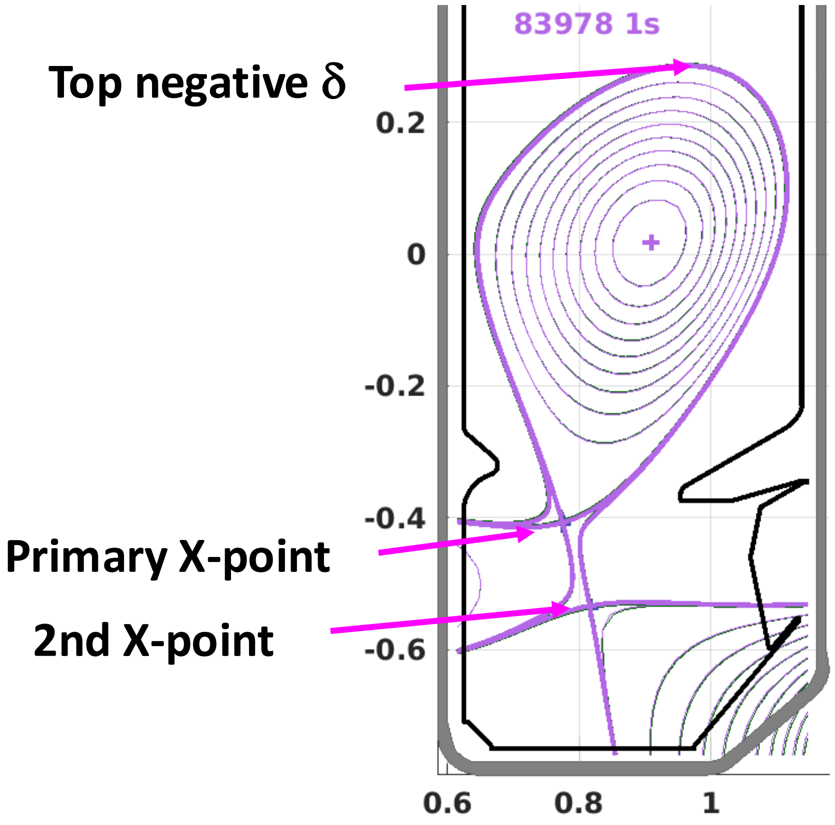
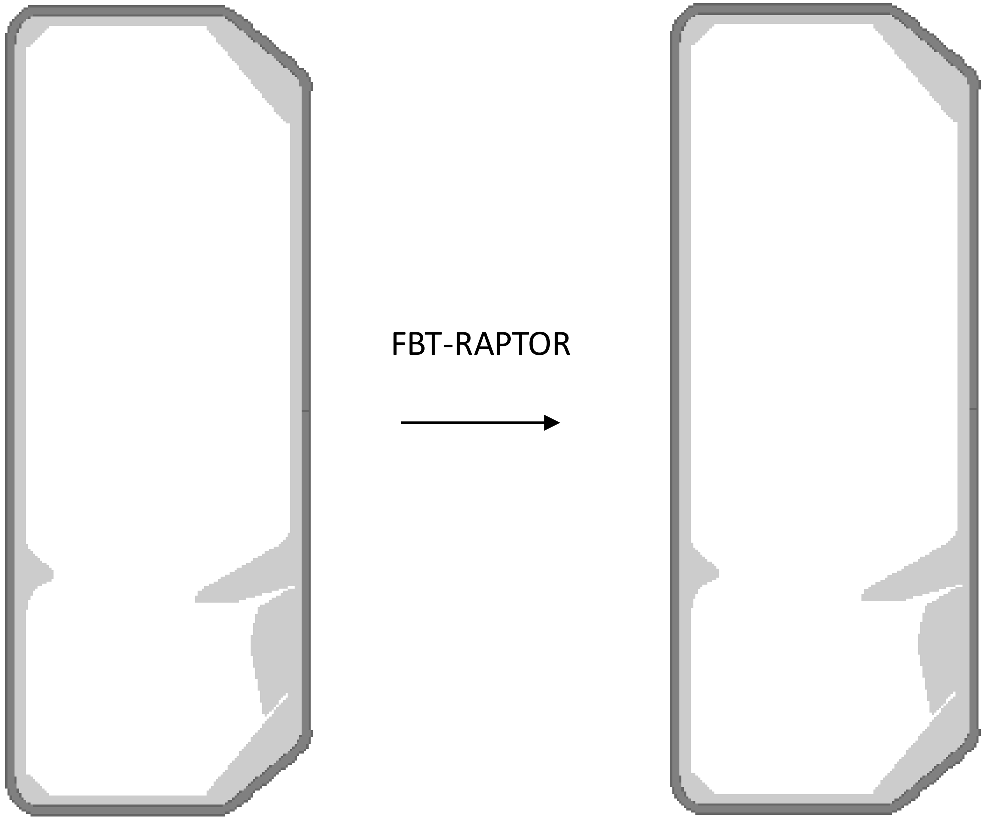
Application to a **Negative Triangularity** (NT) plasma with **Snowflake** (SF)





Application to TCV experiments



Summary

- RAPTOR is a fast transport solver of 1D tokamak plasma profiles, designed for **real-time control** and inter-discharge **optimization**

- Coupling can be performed between a transport code and an equilibrium code to inform the Grad-Shafranov equilibrium with p' and TT' estimates

- **KEP**: coupling between an inverse equilibrium solver (FBT) and a predict-first transport simulator

- FBT-RAPTOR results successfully integrated into the TCV shot preparation system, showing a <u>significant improvement of the shape</u>

Questions?