ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SWISS PLASMA CENTER

Numerical optimization of the ramp-down phase with the RAPTOR code

A.A. Teplukhina[1], O. Sauter[1], F. Felici[2], A. Merle[1], the TCV team[a], the ASDEX-Upgrade team[b], the EUROfusion MST1 team[c] and JET contributors[d]

[1] Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland
[2] Eindhoven University of Technology, Department of Mechanical Engineering, PO. Box 513, 5600 MB Eindhoven, The Netherlands

MODEL

Research directions

1. Development of an optimization procedure for the ramp down phase of the plasma discharge to terminate plasmas in the fastest and safest way:

- Determination of **the optimal time evolution** of the plasma parameters, like **plasma current I_p, plasma elongation κ, auxiliary power P_{aux}** to terminate plasmas (decrease I_p) as fast as possible.
- For the safe termination **physical constraints** have to be specified: a constraint on **normalized β_N and poloidal β_{pol}** (not too high) to avoid MHD modes, a constraint on **the plasma inductance l_i** to avoid vertical instability,…
- Define **technical constraints** to match experimental limits, like **the max ramp rate of the plasma current I_p**, a constraint on **the rate of change in the vertical magnetic field B_v** for radial position control,…
- Determination of the optimal **time of H- to L-mode transition**.

2. Development of the RAPTOR code:

The RAPTOR code – Rapid Plasma Transport simulatOR [1,2]:

- The 1D control-oriented transport code without an equilibrium solver.
- A time dependent geometry can be used.
- The **gradient-based transport models** [3,4] for the electron heat and particles transport have been implemented.
- Successful validation via simulations of TCV and AUG entire plasma discharges and comparison with the experimental measurements [5].

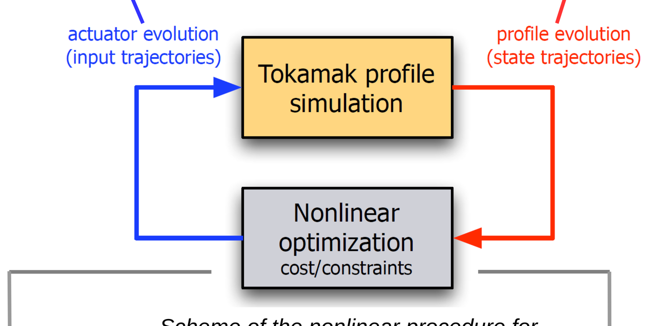
[1] F. Felici et al 2011 Nucl. Fusion **51** 083052
[2] F. Felici, O. Sauter 2012 PPCF **54** 025002
[3] O. Sauter et al 2014 Phys.of Plasma **21** 055906
[4] D. Kim, A. Merle et al 2016 PPCF **58** 055002
[5] A.A. Teplukhina et al 2017 PPCF doi:10.1088/1361-6587/aa857e

The trajectories optimization [2]

To get a good trajectory optimization
1) **realistic predictive simulations** => appropriate transport models;
2) **a fast solver** => RAPTOR.

- Plasma current I_p
- ECH power P_{ECH}
- NBI power P_{NBI}
- Plasma elongation κ

- Poloidal flux ψ(ρ,t)
- Electron temperature T_e(ρ,t)
- Electron density n_e(ρ,t)
- Ion temperature T_i(ρ,t)



Scheme of the nonlinear procedure for the actuator trajectories optimization [2].

Cost function:

$$J=\sum_{i=1}^{n} v_i J_i; min(J)$$

Examples:
$$J_\iota=\|\iota(t_f)-\iota_{ref}\|^2_{W_\iota}$$
$$J_{ss}=\|\partial U_p/\partial\rho\|^2_{W_{ss}}$$
$$J_{Ip}=\int I_p dt$$

Constraints:

- Safety factor q (>1.0)
- Plasma inductance $l_i(3)$
- Edge loop voltage U_{pl}
- … various physical and technical constraints (I_p max ramp rate)

The RAPTOR code transport equations

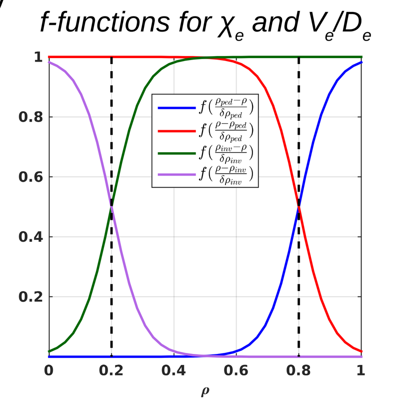
Diffusion equations: the poloidal flux, the electron temperature and density

$$\sigma_{\parallel}\left(\frac{\partial\psi}{\partial t}-\frac{\hat\rho\dot\Phi_b}{2\Phi_b}\frac{\partial\psi}{\partial\hat\rho}\right)=\frac{(R\cdot B_\Phi)^2}{16\pi^2\mu_0\Phi_b^2\hat\rho}\frac{\partial}{\partial\hat\rho}\left(\frac{g_2g_3}{\hat\rho}\frac{\partial\psi}{\partial\hat\rho}\right)-\frac{B_0V'_{\hat\rho}}{2\Phi_b\hat\rho}\frac{\langle(\boldsymbol{j}_{BS}+\boldsymbol{j}_{aux})\cdot\boldsymbol{B}\rangle}{B_0}$$

$$\frac{3}{2}\frac{1}{(V'_{\hat\rho})^{5/3}}\left(\frac{\partial}{\partial t}-\frac{\dot\Phi_b}{2\Phi_b}\frac{\partial}{\partial\hat\rho}\hat\rho\right)\left[(V'_{\hat\rho})^{5/3}n_e\boldsymbol{T_e}\right]=\frac{1}{V'_{\hat\rho}}\frac{\partial}{\partial\hat\rho}\left[\frac{g_1}{V'_{\hat\rho}}n_e\chi_e\frac{\partial\boldsymbol{T_e}}{\partial\hat\rho}\right]+P_e$$

$$\frac{1}{V'_{\hat\rho}}\left(\frac{\partial}{\partial t}-\frac{\dot\Phi_b}{2\Phi_b}\frac{\partial}{\partial\hat\rho}\hat\rho\right)\left[V'_{\hat\rho}\boldsymbol{n_e}\right]=\frac{1}{V'_{\hat\rho}}\frac{\partial}{\partial\hat\rho}\left[\frac{g_1}{V'_{\hat\rho}}D_e\frac{\partial\boldsymbol{n_e}}{\partial\hat\rho}-g_0V_e\boldsymbol{n_e}\right]+S_e$$

f-functions for χ_e and V_e/D_e



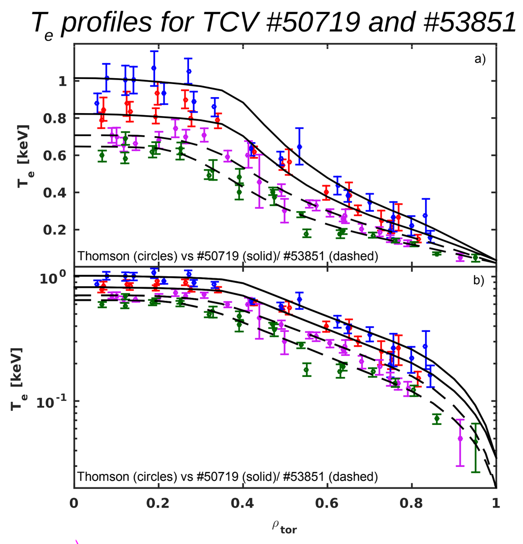
The inverse scale length [3]:

$$\frac{R}{L_{Te}}=-\frac{R_0}{a}\frac{d\ln T_e}{d\rho_V}=\begin{cases}0 & for\quad \rho_V<\rho_{Te,inv}\\ \frac{R_0}{a}\lambda_{Te} & for\quad \rho_{Te,inv}<\rho_V<\rho_{Te,ped}\\ \frac{R_0}{a}\frac{\mu_{Te}}{T_e(\rho_V)} & for\quad \rho_V>\rho_{Te,ped}\end{cases}$$

λ_s – a fixed parameter for L-/H-mode for the T_e/n_e core gradient

μ_s – a controlled parameter to get given H_e or n_{el}

T_e profiles for TCV #50719 and #53851



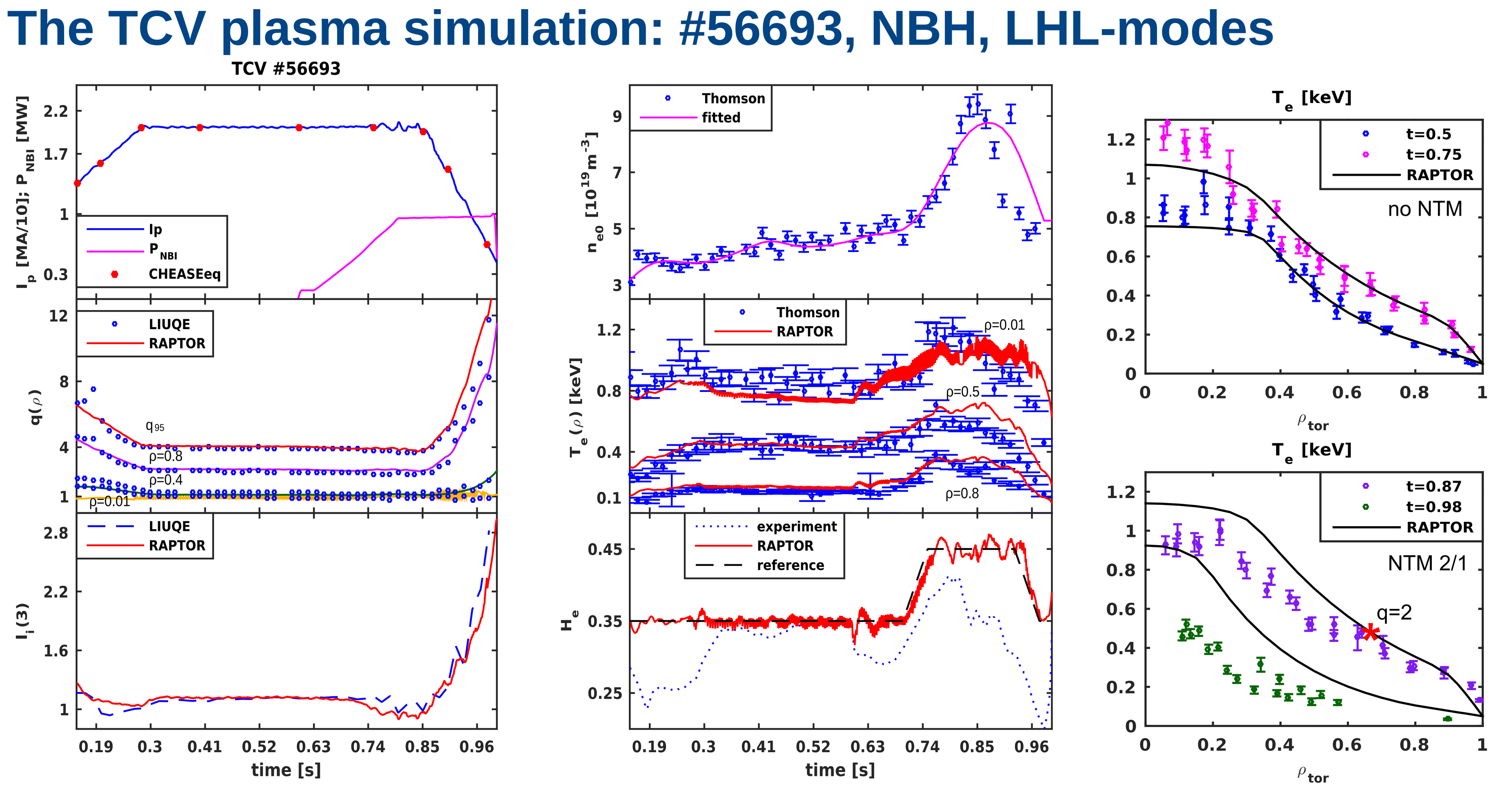
Transport coefficients: the gradient-based model [3,4]

$$\frac{V_e}{D_e}=-\left[\frac{\mu_{ne}}{n_e\rho_{edge}}f\left(\frac{\rho_{ped}-\rho}{\delta\rho_{ped}}\right)+\frac{\lambda_{ne}}{\rho_{edge}}f\left(\frac{\rho-\rho_{ped}}{\delta\rho_{ped}}\right)\right]^{-1}\times f\left(\frac{\rho_{inv}-\rho}{\delta\rho_{inv}}\right)\qquad D_e=0.2\cdot\chi_e$$

$$\chi_e=\frac{q_e}{V'\langle(\rho)^2\rangle n_eT_e}\left[\frac{\mu_{Te}}{T_e\rho_{edge}}f\left(\frac{\rho_{ped}-\rho}{\delta\rho_{ped}}\right)+\frac{\lambda_{Te}}{\rho_{edge}}f\left(\frac{\rho-\rho_{ped}}{\delta\rho_{ped}}\right)\right]^{-1}\times f\left(\frac{\rho_{inv}-\rho}{\delta\rho_{inv}}\right)+\chi_{ST}f\left(\frac{\rho-\rho_{inv}}{\delta\rho_{inv}}\right)$$

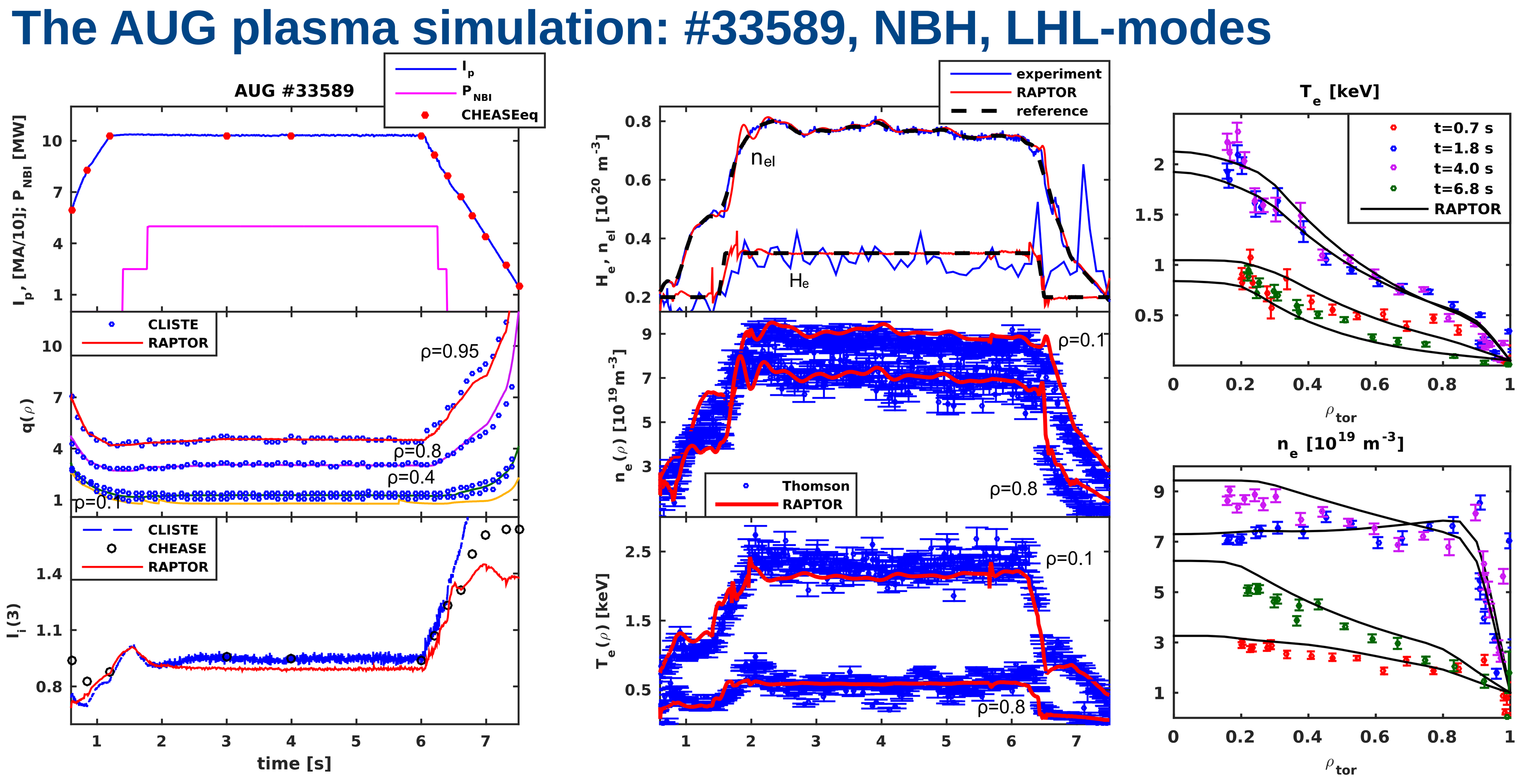
VALIDATION

The TCV plasma simulation: #56693, NBH, LHL-modes



Prescribed parameters: the total plasma current I_p, radial profiles of the electron density n_e, the total input NBI power with central deposition and the prescribed Gaussian radial profile, H_e=0.35/0.45 and λ_{Te}=3.2/2.3 for L-/H-mode.
Predicted variables: the electron temperature T_e, the poloidal flux ψ, the electron heat diffusivity χ_e, various physical quantities.
Equilibrium: 9 CHEASE equilibria (marked as ● on the I_p plot).
CPU time: ~1 min for a time grid with 1 ms step (the shot duration 1 s) on a standard PC.
Note: L-H at 0.7 s, H-L at 0.93 s, NTM 2/1 from 0.85 s.

The AUG plasma simulation: #33589, NBH, LHL-modes

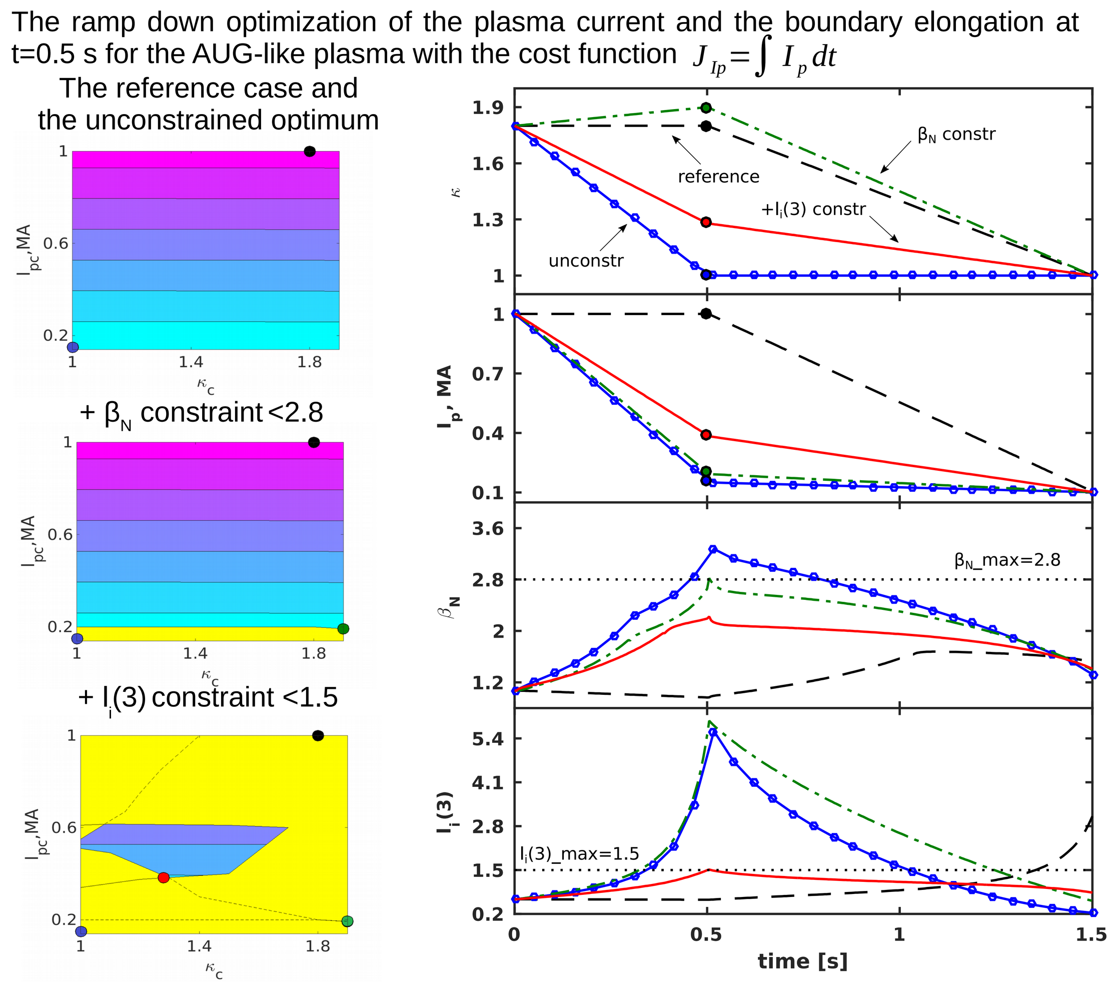


Prescribed parameters: same as for the TCV case except n_e profiles, H_e=0.2/0.35 and λ_{Te}=3.0/2.3 for L-/H-mode, the line-averaged electron density n_{el}, λ_{ne}=1.0/0.5 for L-/H-mode.
Predicted variables: as for the TCV case + the electron density n_e.
Equilibrium: 13 CHEASE equilibria (marked as ● on the I_p plot).
CPU time: ~1.5 min for a time grid with 10 ms step (the shot duration 7 s) on a standard PC.
Note: L-H at 1.5 s, H-L at 6.4 s.

OPTIMIZATION

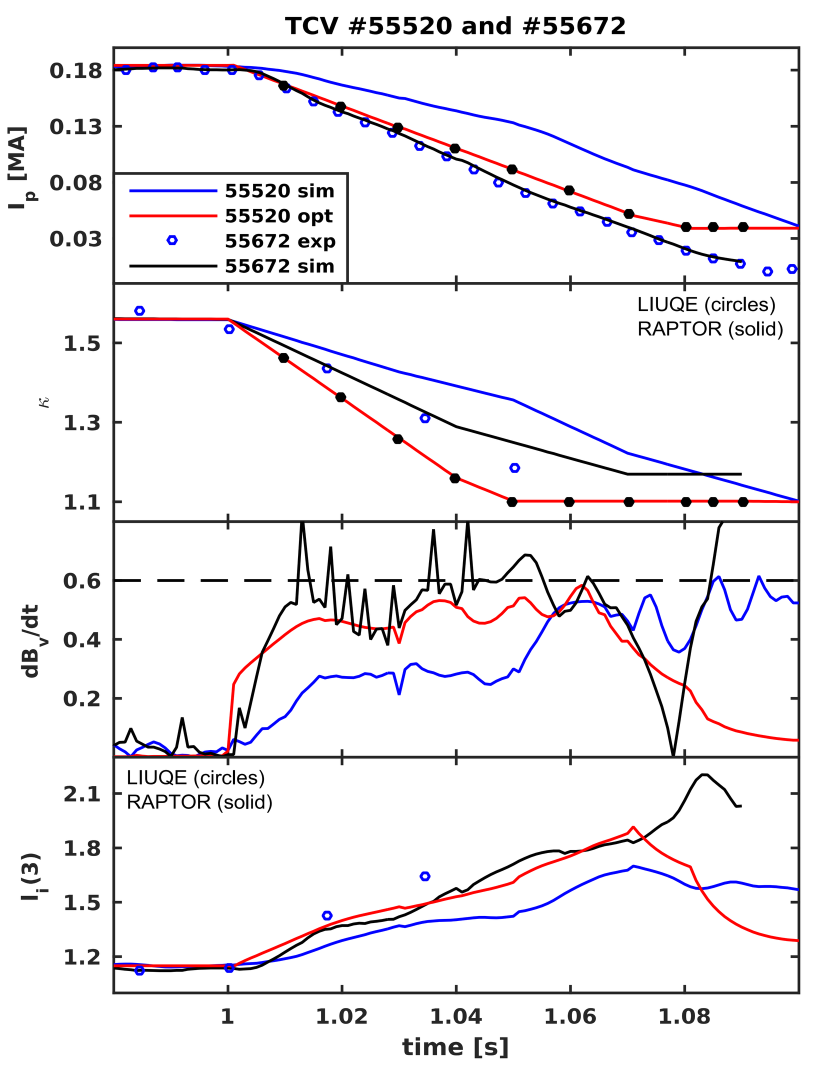
The generic ramp-down optimization

The ramp down optimization of the plasma current and the boundary elongation at t=0.5 s for the AUG-like plasma with the cost function $J_{Ip}=\int I_p dt$



The contours for J_{ip} are shown with the coloured circles which correspond to values of I_p and κ at t=0.5 s. An area where the constrained parameter violates the constraint is yellow-marked.

The ramp-down optimization: TCV #55520 and AUG #33589, test TCV #55672



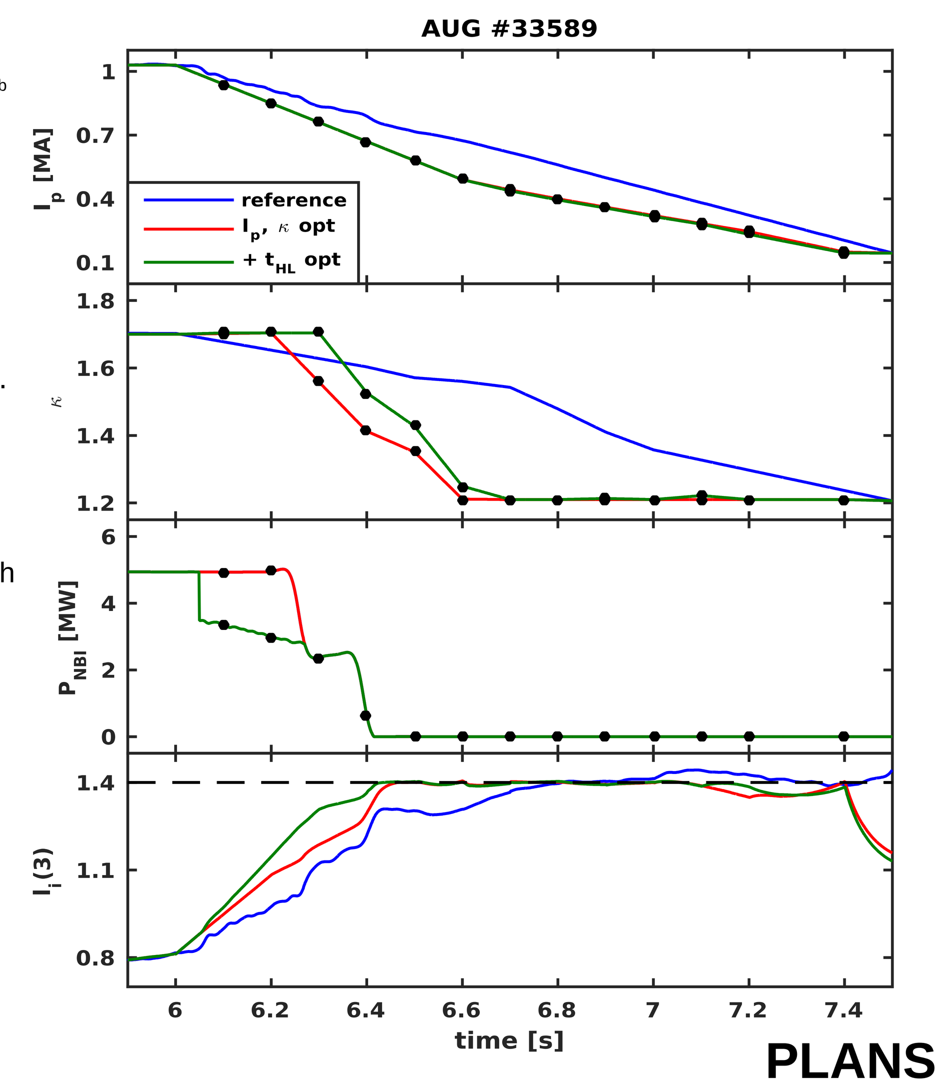
TCV #55520: L-mode, the optimization of I_p and κ_b at t = [1.01-1.09] s with 10 ms step.
Technical constraints:
dI_p/dt < -1.9 [MA/s], dB_v/dt<0.6 [T/s]

$$B_v=\frac{\mu_0I_p}{4\pi R}\left(\ln\left(\frac{8R}{a\kappa^{0.5}}\right)+\beta_p+0.5l_i-1.5\right)$$

The cost function: $J_{Ip}=\int I_p dt$
* Faster I_p and κ_b ramp-down can be programmed.

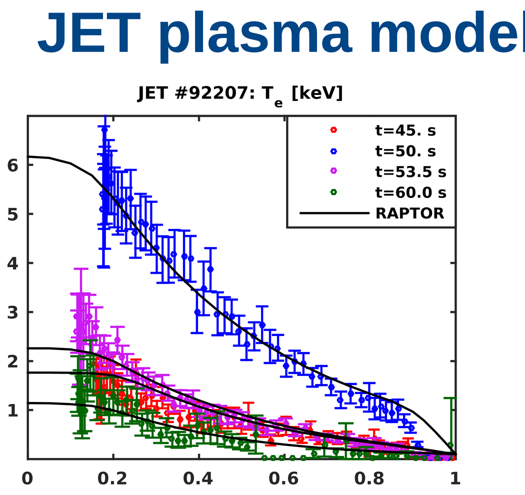
TCV #55672: an experimental test of the TCV #55520 optimized trajectories.
* Faster I_p but slower κ_b ramp-down obtained.
* dBv/dt is within the required limit except sawtooth peaks.

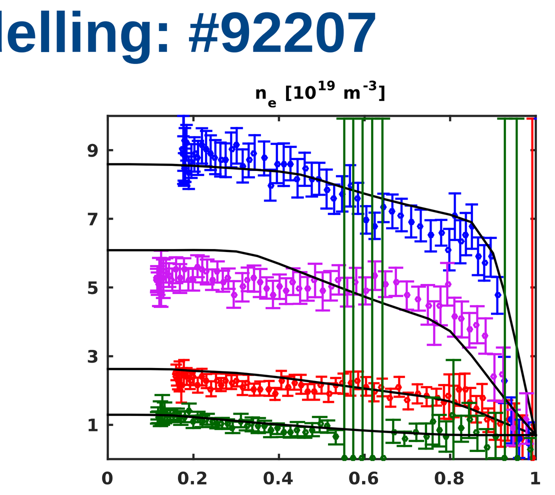
AUG #33589: the optimization of I_p, κ_b and t_{HL} at t = [6.1 6.9] s with 100 ms step.
Technical constraints:
dI_p/dt < -0.7 [MA/s], l_i(3)< 1.4
The cost function: $J_{Ip}=w_1\int I_p dt+w_2\int P_{aux}dt$
* Reducing κ_b during the ramp-down would allow to better control l_i.
* An earlier power drop might be possible.

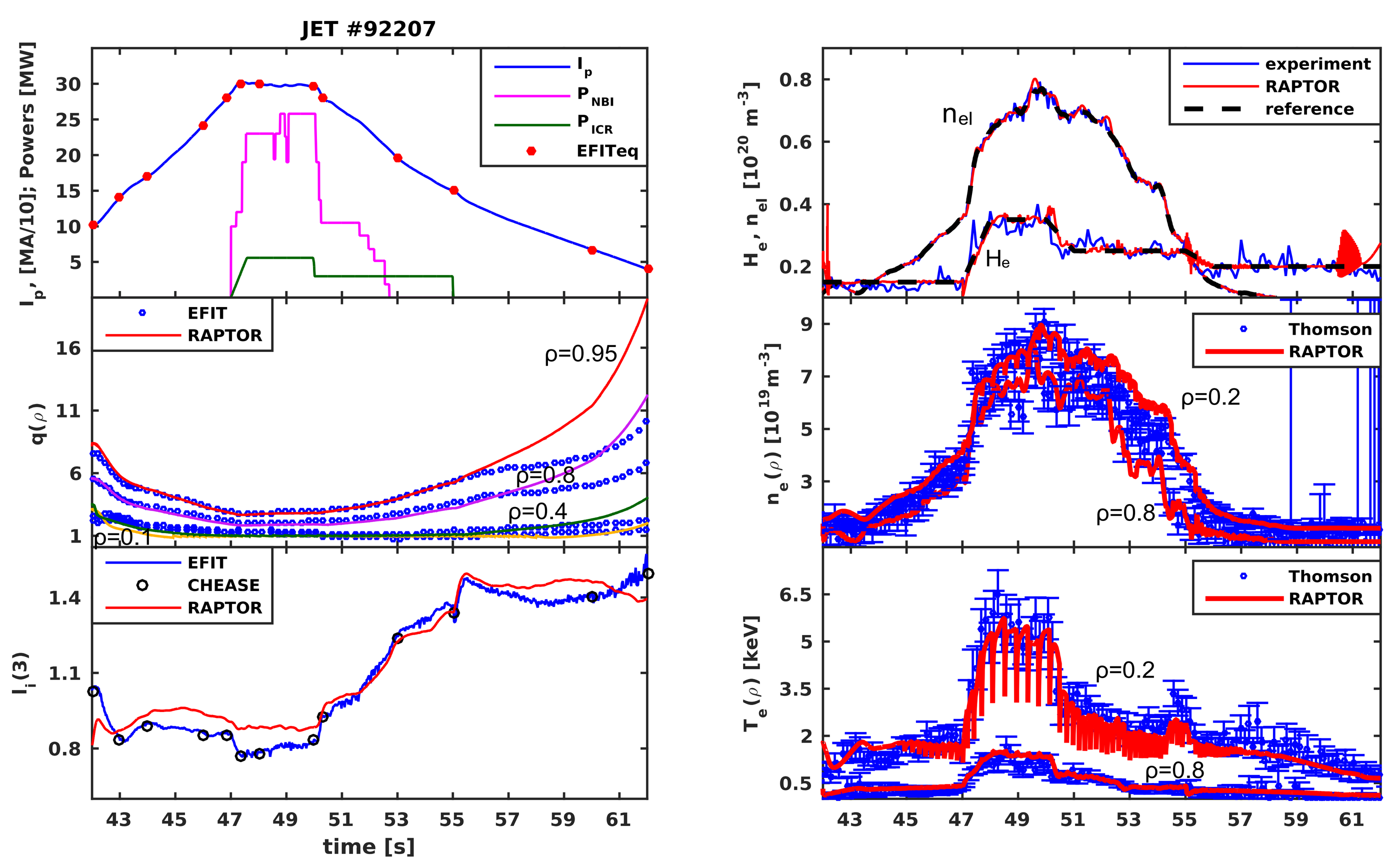


PLANS

JET plasma modelling: #92207







Prescribed parameters: same as for the AUG case; λ_{Te}=3.0/2.3 and H_e=0.15(0.2)/0.35(0.25) for L-/H-mode, λ_{ne}=1.0/0.5 for L-/H-mode.
Predicted variables: as for the TCV case + electron density n_e.
Equilibrium: 13 EFIT equilibria (marked as ● on the I_p plot).
CPU time: ~4 min for a time grid with 10 ms step (the shot duration 20 s).
Note: L-H at 47. s, H-L at 52. s.

Future directions

The RAPTOR code development:

- T_i and impurities transport equations;
- A scaling law for the pedestal pressure for L-/H-mode to determine μ_{Te} directly.
- A radial-dependent core gradient λ_{Te}.
- Continue the model validation with JET simulations.
- Continue for ITER simulations.

The ramp-down optimization:

- Constraints related to radiated power and impurities.
- Technical constraints on the rate of change in the electron density.
- Technical constraints related to the plasma shape control.
- Technical constraint on the vertical position control (constraint on dl_i/dt).
- JET/ITER ramp-down optimization.

anna.teplukhina@epfl.ch

[a] See the author list of S. Coda et al, 2017 Nucl. Fusion 57 102011
[b] See the author list of A. Kallenbach et al, 2017 Nucl. Fusion 57 102015
[c] See the author list of H. Meyer et al, 2017 Nucl. Fusion 57 102014
[d] See the author list of X. Litaudon et al, 2017 Nucl. Fusion 57 102001

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