P-16
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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SWISS PLASMA CENTER

Numerical optimization of ramp-down phases for TCV and AUG plasmas

ASDEX Upgrade

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MODEL

1. 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 safe termination **physical constraints** have to be specified: constraint on **normalized β_N and poloidal β_{pol}** (not too high) to avoid MHD modes, constraint on **plasma inductance l_i** to avoid vertical instability,…
- Define **technical constraints** to match experimental limits, like **max ramp rate of plasma current I_p**, constraint on **rate of change in vertical magnetic field B_v** for radial position control,…
- Determination of optimal **time of H- to L-mode transition.**

2. Development of the RAPTOR transport model:

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

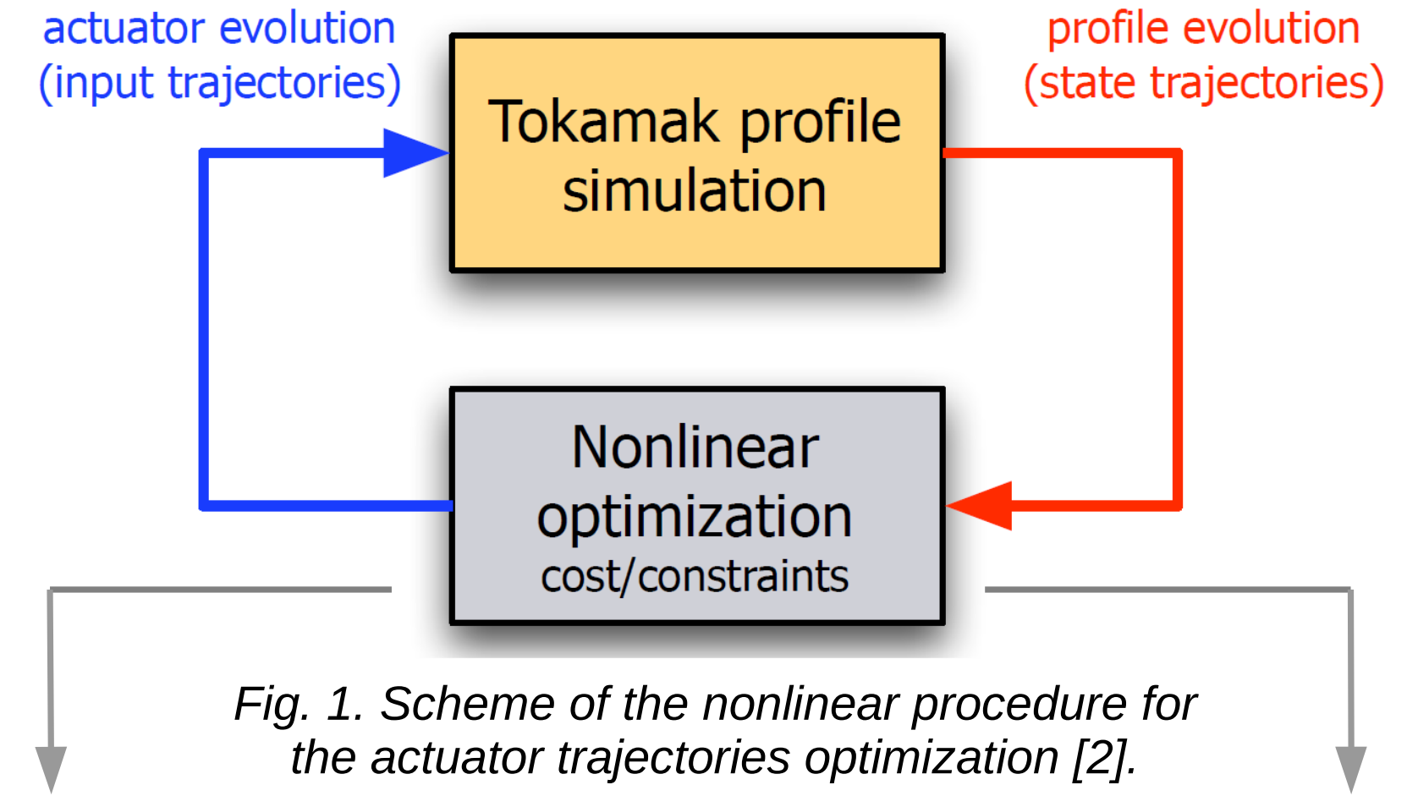
1D transport code without an equilibrium solver oriented to plasma real-time control.

- Time dependent geometry can be used.
- A new **gradient-based transport model** [3,4] for electron heat transport has been implemented.
- Successful validation via simulation of TCV and AUG full plasma discharges and comparison with the experimental measurements.

[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 *et al* 2016 *PPCF* **58** 055002

2. Trajectory optimization [2]

To get a good trajectory optimization
1) **realistic predictive simulations** (=> an appropriate transport model) and
2) **fast solver** (=> RAPTOR) are needed.



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

- **Poloidal flux $\psi(\rho,t)$**
- **Electron temperature $T_e(\rho,t)$**
- Electron density $n_e(\rho,t)$
- Ion temperature $T_i(\rho,t)$

actuator evolution (input trajectories)

profile evolution (state trajectories)

Tokamak profile simulation

Nonlinear optimization
cost/constraints

Fig. 1. Scheme of the nonlinear procedure for the actuator trajectories optimization [2].

Cost function

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

Examples:

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

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)

3. The transport model

Diffusion equations: electron temperature and poloidal flux

$$\frac{3}{2}(V')^{-5/3}\left(\frac{\partial}{\partial t}-\frac{\dot B_0}{2B_0}\frac{\partial}{\partial\rho}\rho\right)\left[(V')^{5/3}n_e\boldsymbol{T_e}\right]=\frac{\partial}{\partial\rho}V'G_1n_e\chi_e\frac{\partial\boldsymbol{T_e}}{\partial\rho}+V'P_e$$

$$\sigma_\parallel\left(\frac{\partial\boldsymbol{\psi}}{\partial t}-\frac{\rho\dot B_0}{2B_0}\frac{\partial\boldsymbol{\psi}}{\partial\rho}\right)=\frac{J^2R_0}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\boldsymbol{\psi}}{\partial\rho}\right)-\frac{V'}{2\pi\rho}(j_{BS}+j_{CD})$$

Electron heat diffusivity: gradient-based model [3,4]

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

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

λ_{Te} – fixed parameter for L- and H-modes
3.2 for TCV L-mode, 3.0/2.3 for AUG L-/H-mode.

$$\mu_{Te}=\left\langle\frac{H_e\tau_{scl}}{\tau_{Ee}}\right\rangle_{time}$$

or controlled parameter to get a given H_e

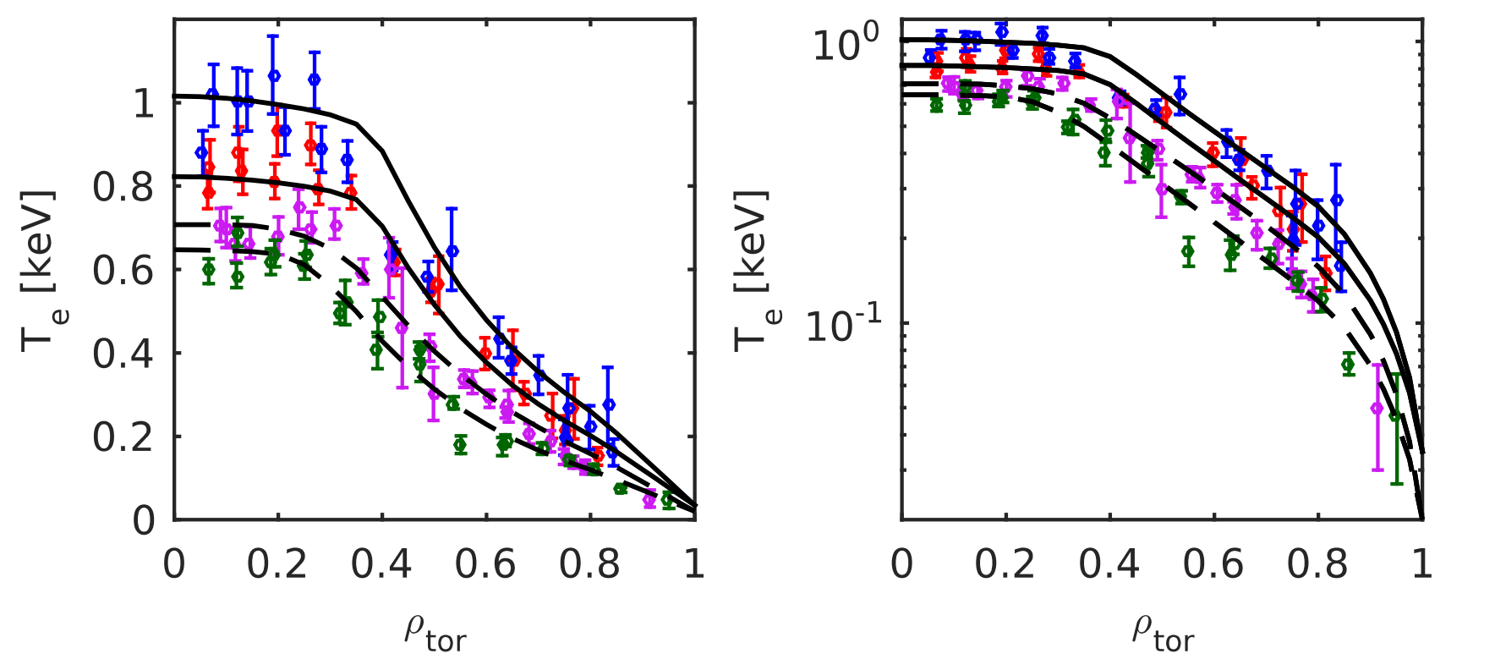


Fig. 2. RAPTOR simulated profiles (black solid) vs the experimental ones for the TCV shots: 🔴 – #50719 I_p=195 kA, 🔵 – #50719 I_p=206 kA, 🟢 – #53851 I_p=205 kA, 🟣 – #53851 I_p=185 kA.

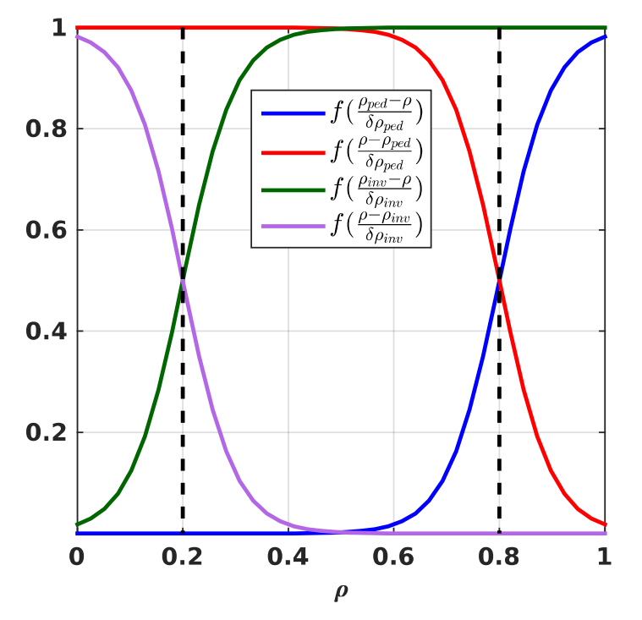
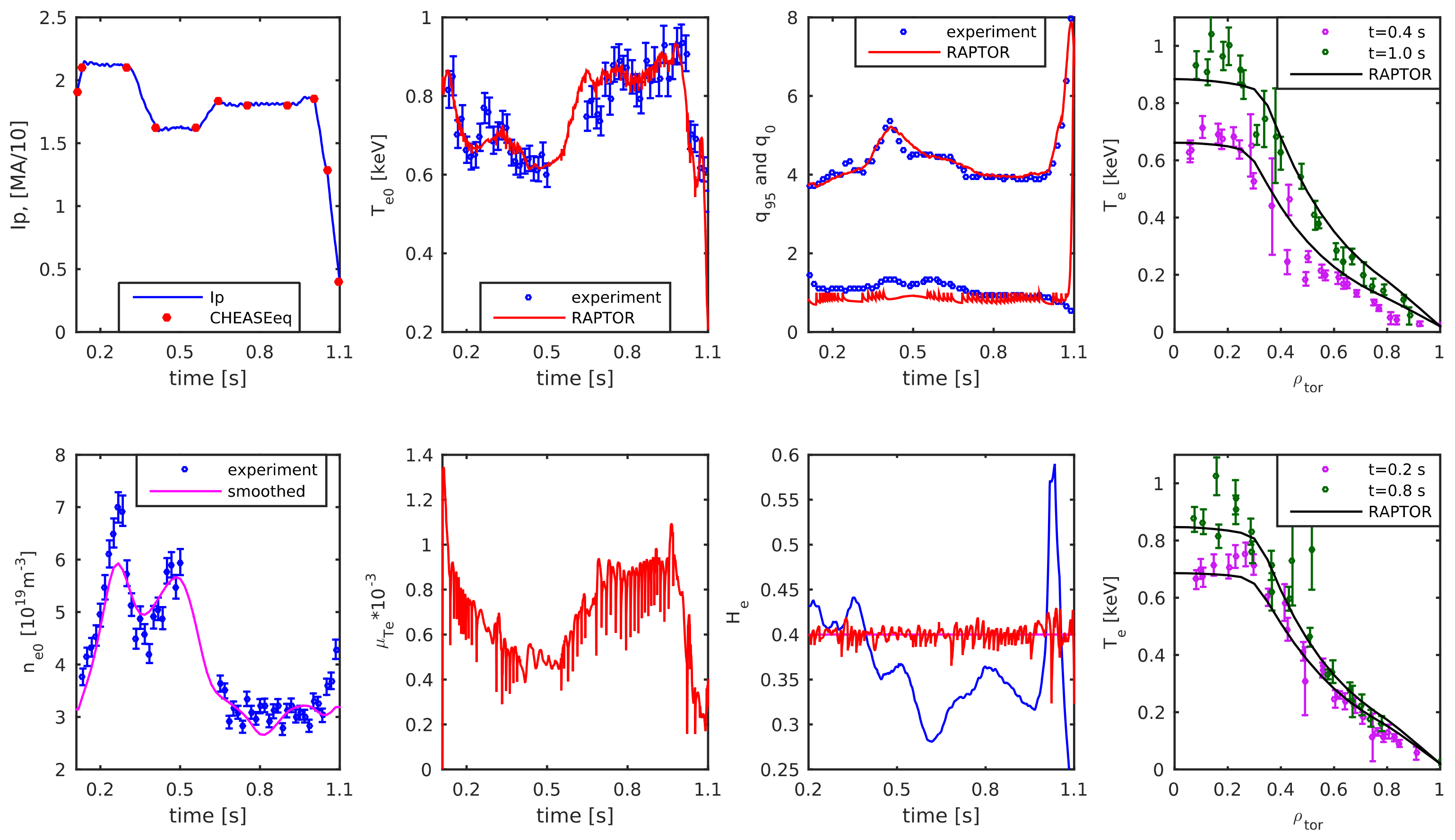


Fig. 3. f-functions from the formula for χ_e.

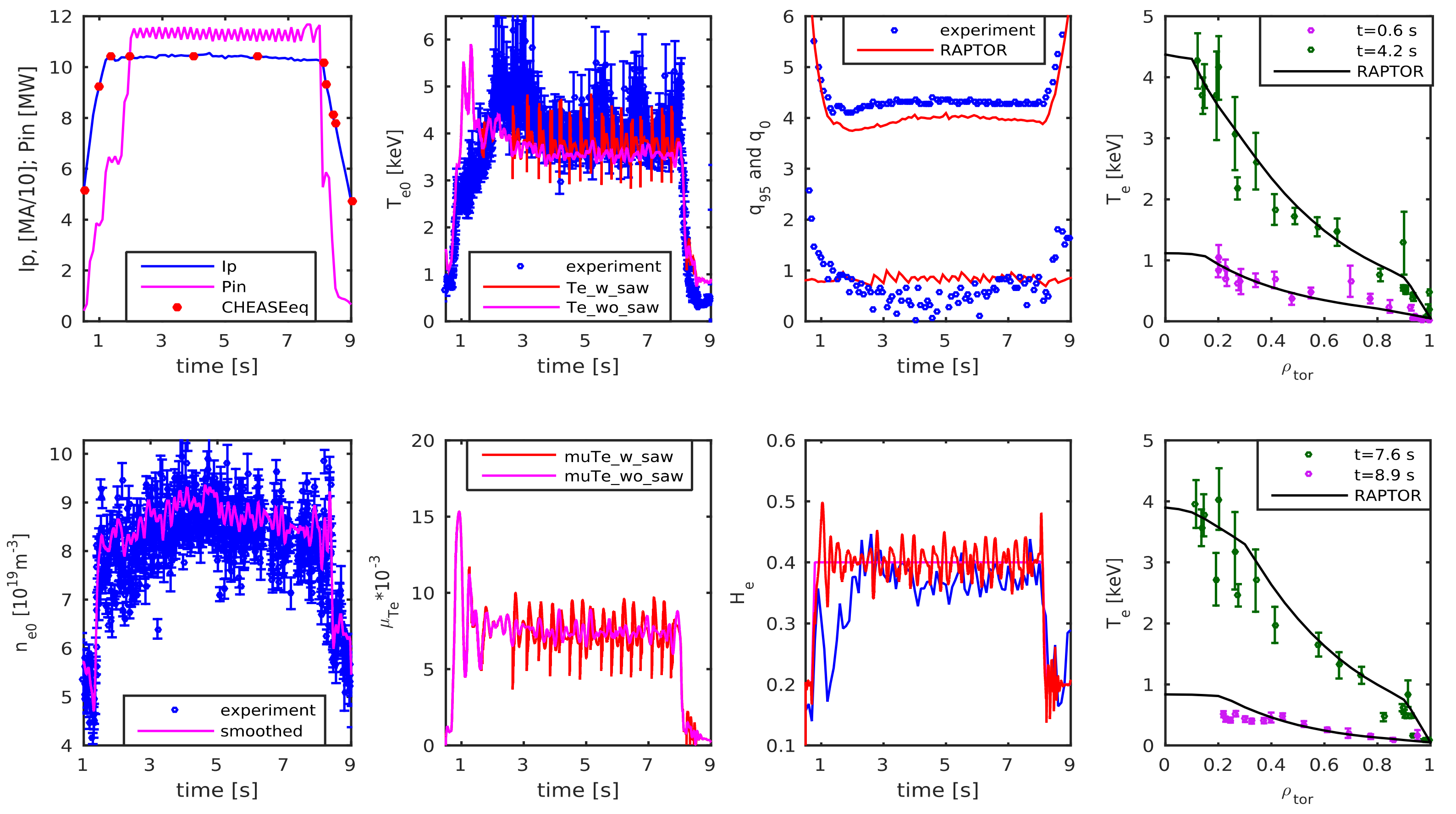
VALIDATION

4. Full TCV plasma simulation: #53852, ohmic plasma, L-mode



Prescribed parameters: total plasma current I_p over time, radial profiles of electron density n_e over time, H_e factor fixed at 0.4, λ_{Te}=3.2 (λ_{ne}, line averaged electron density n_{el} if $n_e(\rho,t)$ not provided), scaling law H98(y,2) for total confinement time.
Predicted variables: electron temperature Te, poloidal flux ψ, electron heat diffusivity χ_e, various physical quantities.
Equilibrium: 10 CHEASE equilibria (marked as 🔴 on the I_p plot).
CPU time: less than 2 min for a time grid with 1 ms step (shot duration 1 s) on a standard PC.

5. Full AUG plasma simulation: #32546, NBH, ECRH, L-H-L modes

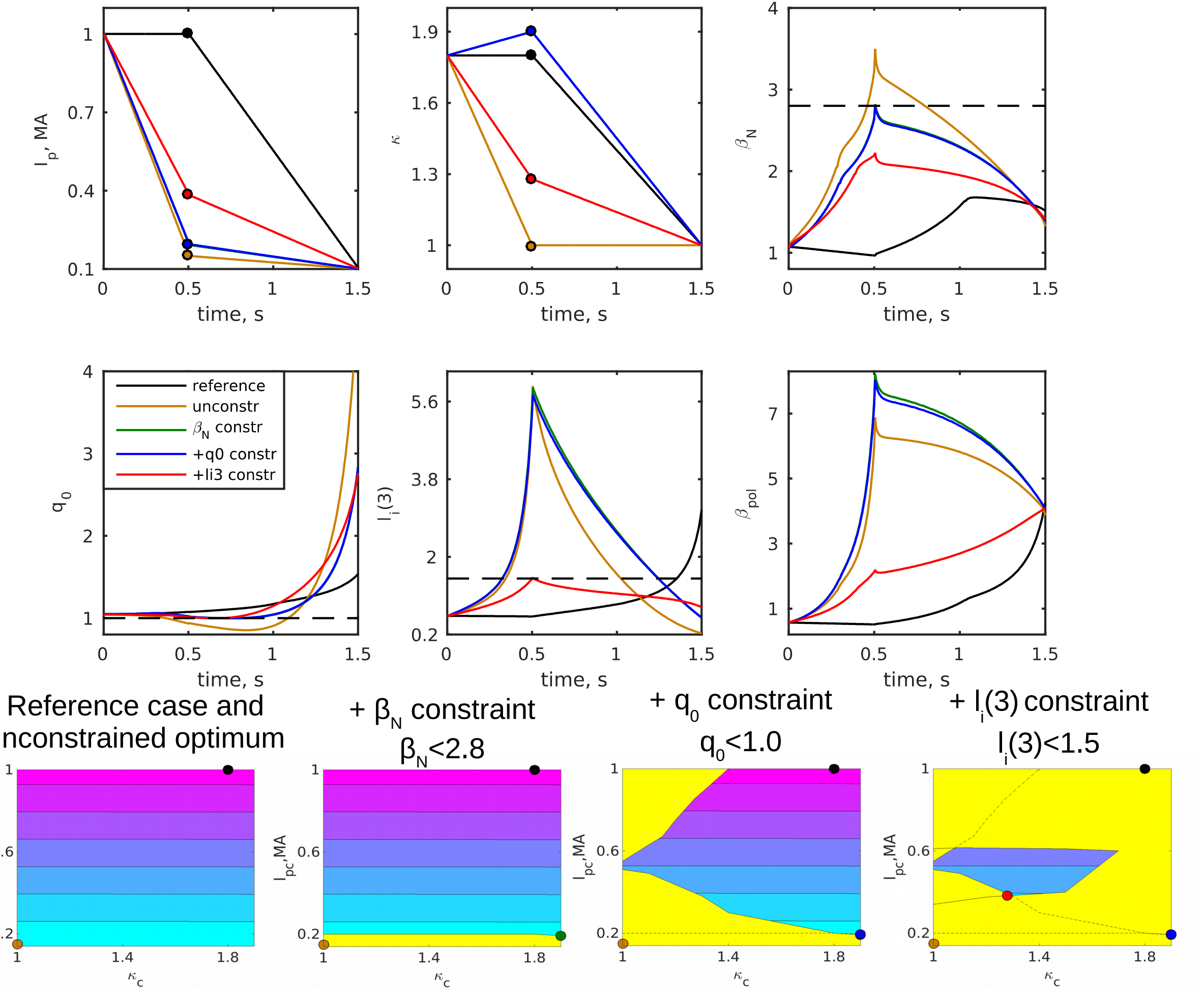


Prescribed parameters: same as for TCV case, total input NBI and EC power over time and their deposition, H_e factor fixed at 0.4 for H-mode and at 0.2 for L-mode, λ_{Te}=3.0/2.3 for L-/H-mode, Gaussian radial profiles for heating sources.
Predicted variables: as for TCV case
Equilibrium: 11 CHEASE equilibria (marked as 🔴 on the I_p plot).
CPU time: less than 10 min for a time grid with 1 ms step (shot duration 8.5 s) on a standard PC.

OPTIMIZATION

6. Generic ramp down optimization

Ramp down optimization of plasma current and elongation at t=0.5 s for AUG-like plasma: cost function $\boldsymbol{J_{Ip}=\int I_p\,dt}$



Reference case and unconstrained optimum

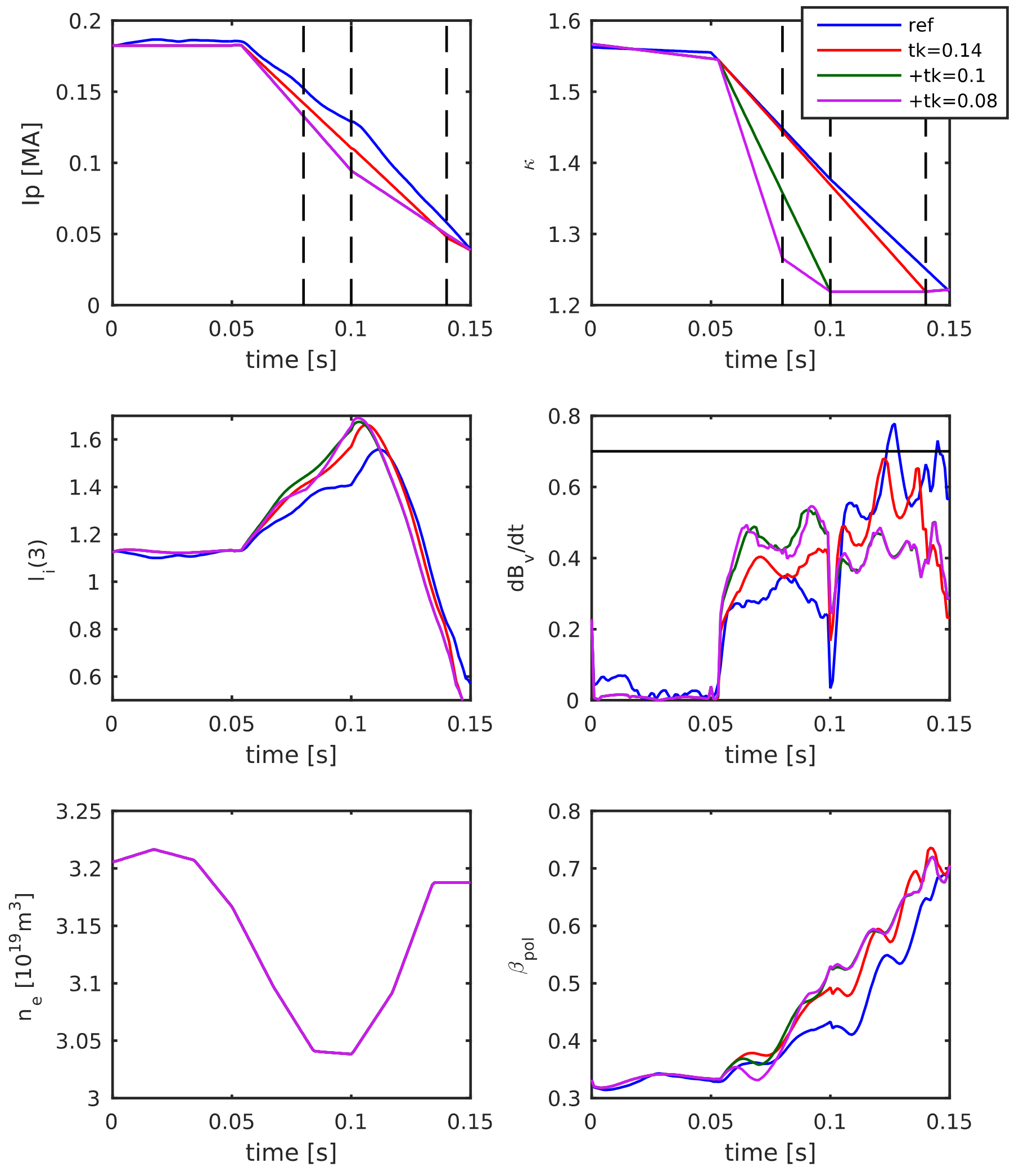
+ β_N constraint
β_N<2.8

+ q_0 constraint
q_0<1.0

+ $l_i(3)$ constraint
$l_i(3)$<1.5

Fig. 4. 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.

7. Ramp-down optimization: TCV #53852

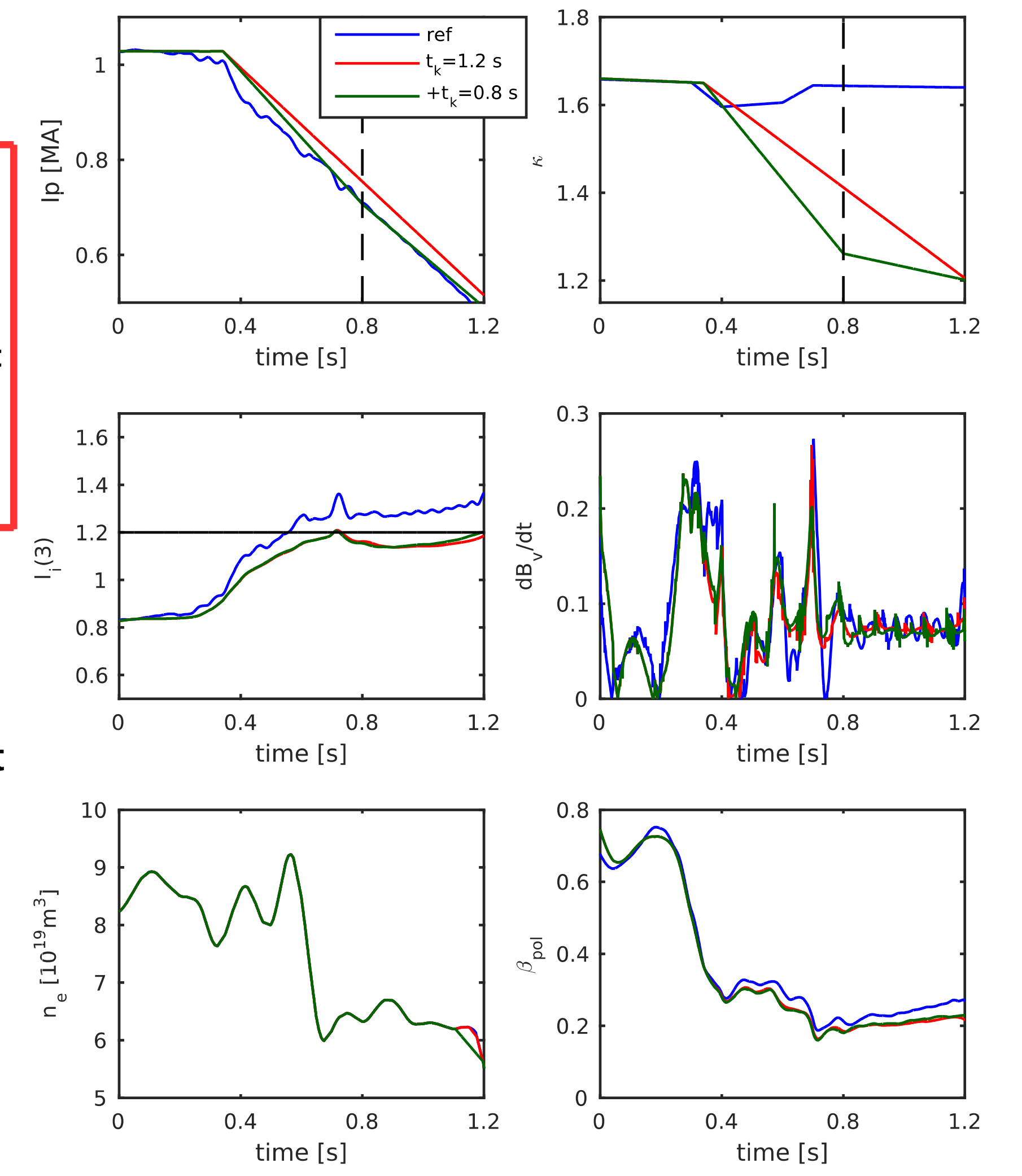


Optimization of plasma current and elongation at t = [0.14 0.1 0.08] s (in series).
Technical constraints on rate of change of plasma current and vertical magnetic field:
dI_p/dt < -1.9 [MA/s], dB_v/dt<0.7 [T/s]

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

=> Faster I_p and κ ramp down can be used.

8. Ramp-down optimization: AUG #32546



Optimization of plasma current and elongation at t = [1.2 0.8] s (in series).
Technical constraints on rate of change in plasma current and edge value of internal inductance:
dI_p/dt < -0.7 [MA/s], l_i(3)< 1.2

=> Reducing κ during ramp down would allow to better control l_i.

PLANS

9. Further research directions

1. Need better control on μ_{Te} (less oscillations):

now μ_{Te} = feed-forward + feed-back control.

$$\mu_{Te}=\underbrace{\mu^{ff}_{Te}(I_p,P_{tot},n_{el})}_{feed\text{-}forward}+\underbrace{K_p\cdot err(t)+K_i\cdot\int^{\delta t}err(t)\,dt}_{feed\text{-}back},$$

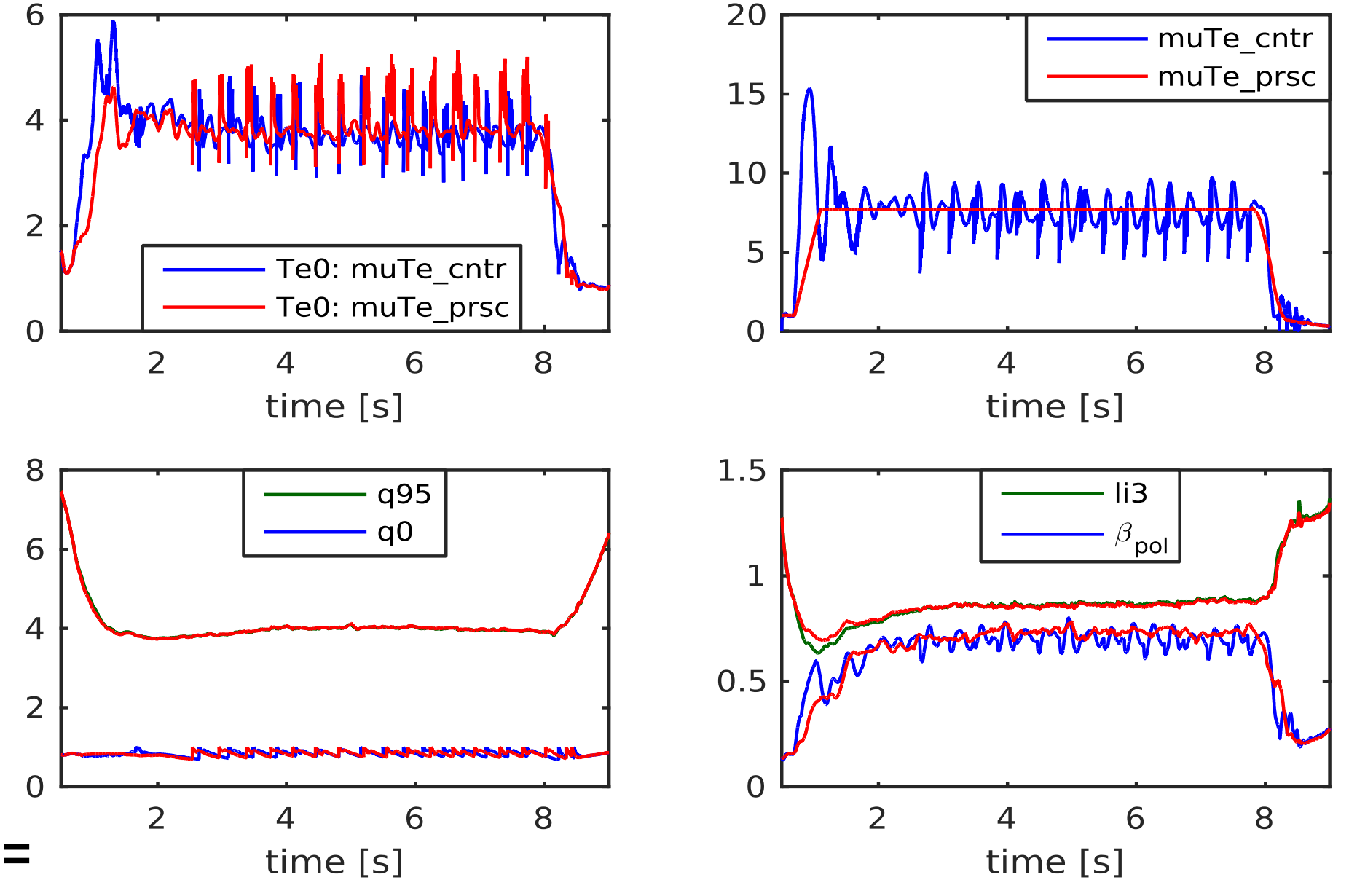
where $err(t)=H_e^{ref}-H_e^{calc}=H_e^{ref}-\tau_{eE}/\tau_{scl}$

Feed-forward law for μ_{Te} via relation with $T_e(\rho_{ped})$:

$$\mu^{ff}_{Te}=-\frac{dT_e}{d\rho}=-\frac{T_e(\rho_{ped})-T_e^{BC}}{\rho_{ped}-1.0}$$

Present oscillations do not disturb physics result <=

AUG #32546: controlled vs prescribed μ_{Te}



now $T_e(\rho_{ped})$ for μ_{Te}^{ff} is estimated: $T_e(\rho_{ped})=T_{e0}\cdot\exp(-\lambda_{Te}(\rho_{ped}-\rho_{inv}))$

T_{e0} scaling law for TCV: $T_{e0}=7.5\cdot10^3\cdot(I_p[MA])^{0.93}\cdot(P_{tot}[MW])^{0.3}\cdot(n_{el}[10^{19}m^3])^{-0.6}$

T_{e0} scaling law for AUG: $T_{e0}=3.3\cdot10^3\cdot(I_p[MA])^{0.93}\cdot(P_{tot}[MW])^{0.3}\cdot(n_{el}[10^{19}m^3])^{-0.6}$

2. Need a scaling law for pedestal pressure for L-/H-mode (to determine μ_{Te} directly).

3. Include diffusion equation for electron density to the transport model:

now prescribed n_e is used;

now to keep density within Greenwald density limit during optimization: $n_e(0,t)=min(n_{eref}(0,t),n_{GR})=min\left(n_{eref}(0,t),0.9\frac{I_p(t)}{\pi a^2}\right)$

4. Continue ramp-down optimization with an extended set of parameters:

- time of H- to L-mode transition as an optimization parameter (already implemented, need tests);
- constraints related to radiated power and impurities;
- technical constraints on rate of change of electron density, plasma shape;
- technical constraint on vertical position control (constraint on dl_i/dt).

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