P2.12

16th European Fusion Theory Conference (EFTC 2015), Lisbon, Portugal, 5th – 8th October 2015

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE | SWISS PLASMA CENTER

Current ramps optimization study with the RAPTOR code

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1. Research goals

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, input power P_{input},** to terminate plasmas as fast as possible.
- Specification of **physical constraints** to terminate plasmas as safely as possible: constraint of **normalized β_N and poloidal β_{pol} pressures** (not too high) to avoid MHD modes, constraint of **plasma inductance l_i** to avoid vertical instability.
- Specification of **technical constraints**, like **max ramp rate of plasma current I_p**, to conform to experimental constraints.
- Determination of parameters which can change plasma state significantly: **time of H- to L-mode transition.**

2. The RApid Plasma Transport simulatOR

The RAPTOR code:
- 1D transport code.
- Fixed equilibrium assumption.
- Real-time simulation.

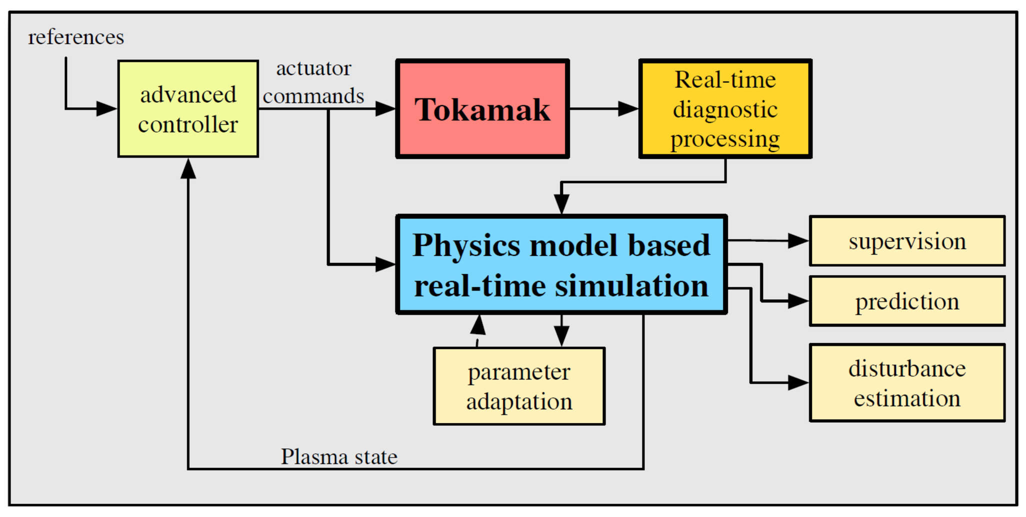
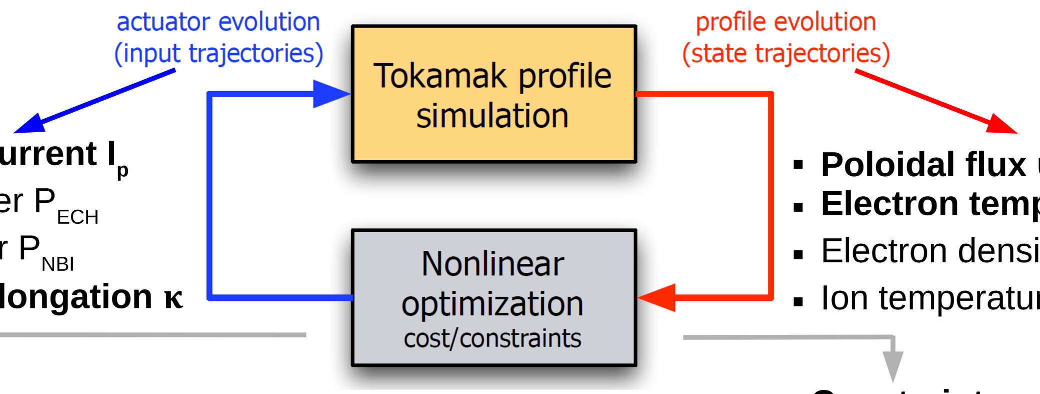


Fig. 1. Tokamak real-time control scheme [1].

3. Trajectories optimization [2]



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

- **Poloidal flux ψ**
- **Electron temperature T_e**
- Electron density n_e
- Ion temperature T_i

Cost function

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

Examples: $J_\iota=\|\iota(t_f)-\iota_{ref}\|^2_{W_\iota}$

$$J_{ss}=\|\partial U_p/\partial\rho\|^2_{W_{ss}}$$

$$J_{Ip}=\int I_p dt$$

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

Constraints:
- Safety factor q (>1.0)
- Plasma inductance li(3) (<1.5)
- Edge loop voltage U_p
- … various physical and technical constraints (I_p max ramp rate)

3. Transport Model: full, fixed geometry, time-varying geometry

$$\begin{cases}\frac{1}{V'}\left(\frac{\partial}{\partial t}-\frac{\dot B_0}{2B_0}\frac{\partial}{\partial\rho}\rho\right)(V'n_e)+\frac{1}{V'}\frac{\partial}{\partial\rho}\Gamma_e=S_e\\ \frac{3}{2}(V')^{-5/3}\left(\frac{\partial}{\partial t}-\frac{\dot B_0}{2B_0}\frac{\partial}{\partial\rho}\rho\right)\left[(V')^{5/3}n_eT_e\right]+\frac{1}{V'}\frac{\partial}{\partial\rho}\left(q_e+\frac{5}{2}T_e\Gamma_e\right)=P_e\\ \frac{3}{2}(V')^{-5/3}\left(\frac{\partial}{\partial t}-\frac{\dot B_0}{2B_0}\frac{\partial}{\partial\rho}\rho\right)\left[(V')^{5/3}n_iT_i\right]+\frac{1}{V'}\frac{\partial}{\partial\rho}\left(q_i+\frac{5}{2}T_i\Gamma_i\right)=P_i\\ \sigma_\parallel\left(\frac{\partial\psi}{\partial t}-\frac{\rho\dot B_0}{2B_0}\frac{\partial\psi}{\partial\rho}\right)=\frac{J^2R_0}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\psi}{\partial\rho}\right)-\frac{V'}{2\pi\rho}(j_{BS}+j_{CD})\end{cases}$$

$$\begin{pmatrix}\frac{\Gamma_e}{n_e}\\ \frac{q_e}{n_eT_e}\\ \frac{q_i}{n_iT_i}\\ V'G_1\frac{\mu_0 j_{BS}}{B_p}\end{pmatrix}=-V'G_1\begin{pmatrix}D_n & D_e & D_i & D_E\\ \chi_n^e & \chi_e^e & \chi_i^e & \chi_E^e\\ \chi_n^i & \chi_e^i & \chi_i^i & \chi_E^i\\ C_n & C_e & C_i & 0\end{pmatrix}\cdot\begin{pmatrix}\frac{1}{n_e}\frac{\partial n_e}{\partial\rho}\\ \frac{1}{T_e}\frac{\partial T_e}{\partial\rho}\\ \frac{1}{T_i}\frac{\partial T_i}{\partial\rho}\\ \frac{E_\parallel}{B_p}\end{pmatrix}$$

A fixed equilibrium assumption:
- The flux surface geometry
- Magnetic field B_0
- Enclosed toroidal flux Φ

$$\begin{cases}\frac{3}{2}V'\frac{\partial}{\partial t}n_e\boldsymbol{T_e}=\frac{\partial}{\partial\rho}V'G_1n_e\chi_e\frac{\partial\boldsymbol{T_e}}{\partial\rho}+V'P_e\\ \sigma_\parallel\frac{\partial\boldsymbol{\psi}}{\partial t}=\frac{J^2R_0}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\boldsymbol{\psi}}{\partial\rho}\right)-\frac{V'}{2\pi\rho}(j_{BS}+j_{CD})\end{cases}$$

With time-varying terms:

$$\begin{cases}\frac{3}{2}(V')^{-5/3}\left(\frac{\partial}{\partial t}-\frac{\dot B_0}{2B_0}\frac{\partial}{\partial\rho}\rho\right)\left[(V')^{5/3}n_e\boldsymbol{T_e}\right]=\frac{\partial}{\partial\rho}V'G_1n_e\chi_e\frac{\partial\boldsymbol{T_e}}{\partial\rho}+V'P_e\\ \sigma_\parallel\left(\frac{\partial\boldsymbol{\psi}}{\partial t}-\frac{\rho\dot B_0}{2B_0}\frac{\partial\boldsymbol{\psi}}{\partial\rho}\right)=\frac{J^2R_0}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\boldsymbol{\psi}}{\partial\rho}\right)-\frac{V'}{2\pi\rho}(j_{BS}+j_{CD})\end{cases}$$

4. Comparison with the ASTRA code [3]

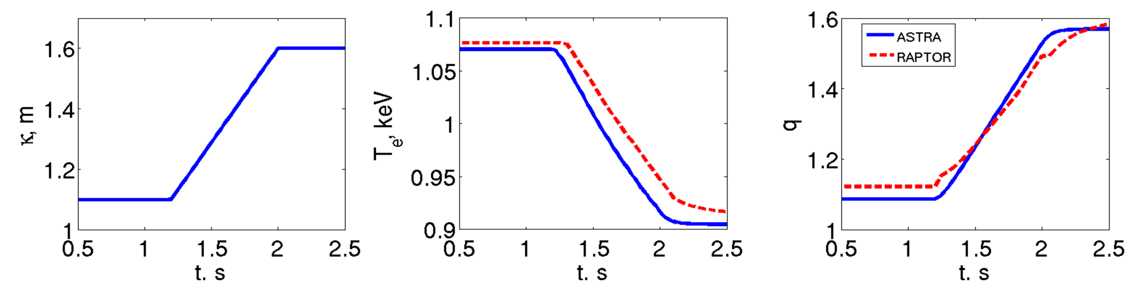


Fig. 3. Simulation with time-varying plasma elongation for TCV-like plasma parameters. Comparison of the ASTRA and RAPTOR simulation results. T_e and q values for ρ_{tor} = 0.35.

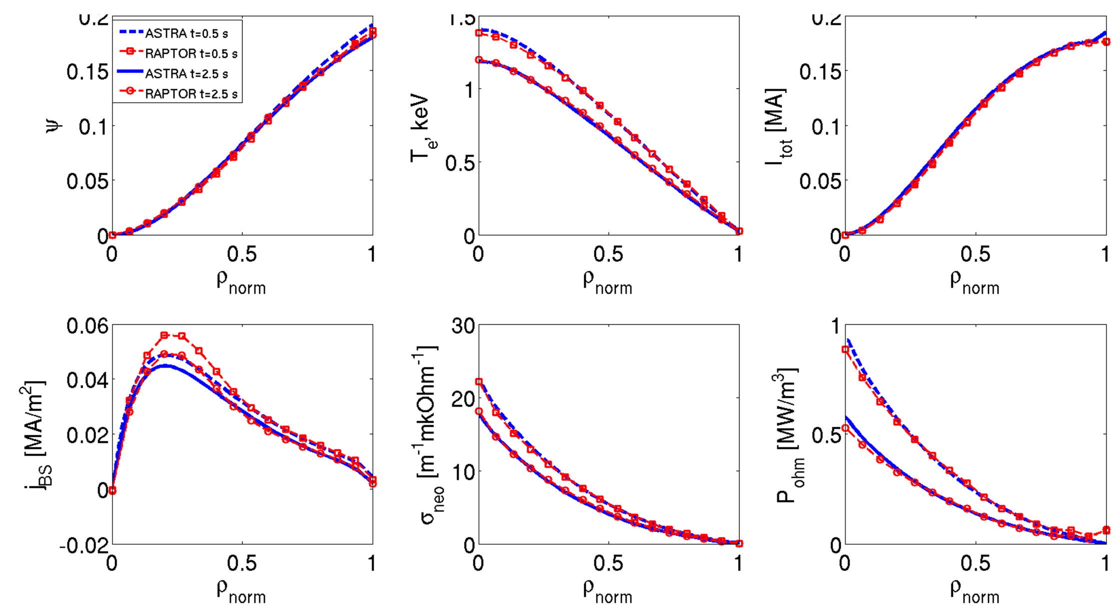
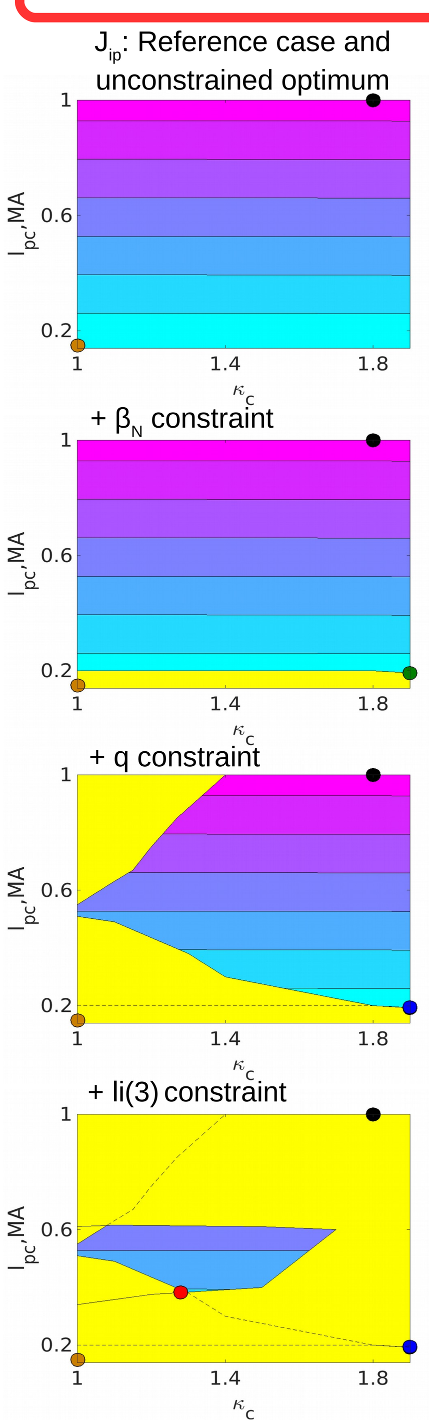


Fig. 4. Comparison of the radial profiles computed by ASTRA and RAPTOR at t=0.5 s and t=2.5 s.

5. Ramp down optimization for AUG-like plasma discharge in H-mode



Optimization problem
- Optimization parameters → Plasma current I_p; Plasma elongation κ; I_{pc} and κ_c: optimized values at t=0.5 s
- Cost function definition → $J=\nu_{I_p}\cdot J_{I_p}+\nu_{\beta_{pol}}\cdot J_{\beta_{pol}}$; ramp down I_p as fast as possible: **min(J_{Ip})**; $J_{Ip}=\int I_p dt$; ramp down β_{pol} as fast as possible: **min($J_{\beta pol}$)**; $J_{\beta pol}=\int\beta_{pol}dt$
- Constraints of the parameters → Safety factor **q**: q > 1.0; Plasma inductance **l_i(3)**: l_i(3) < 1.5; Normalized pressure **β_N**: β_N < 2.8

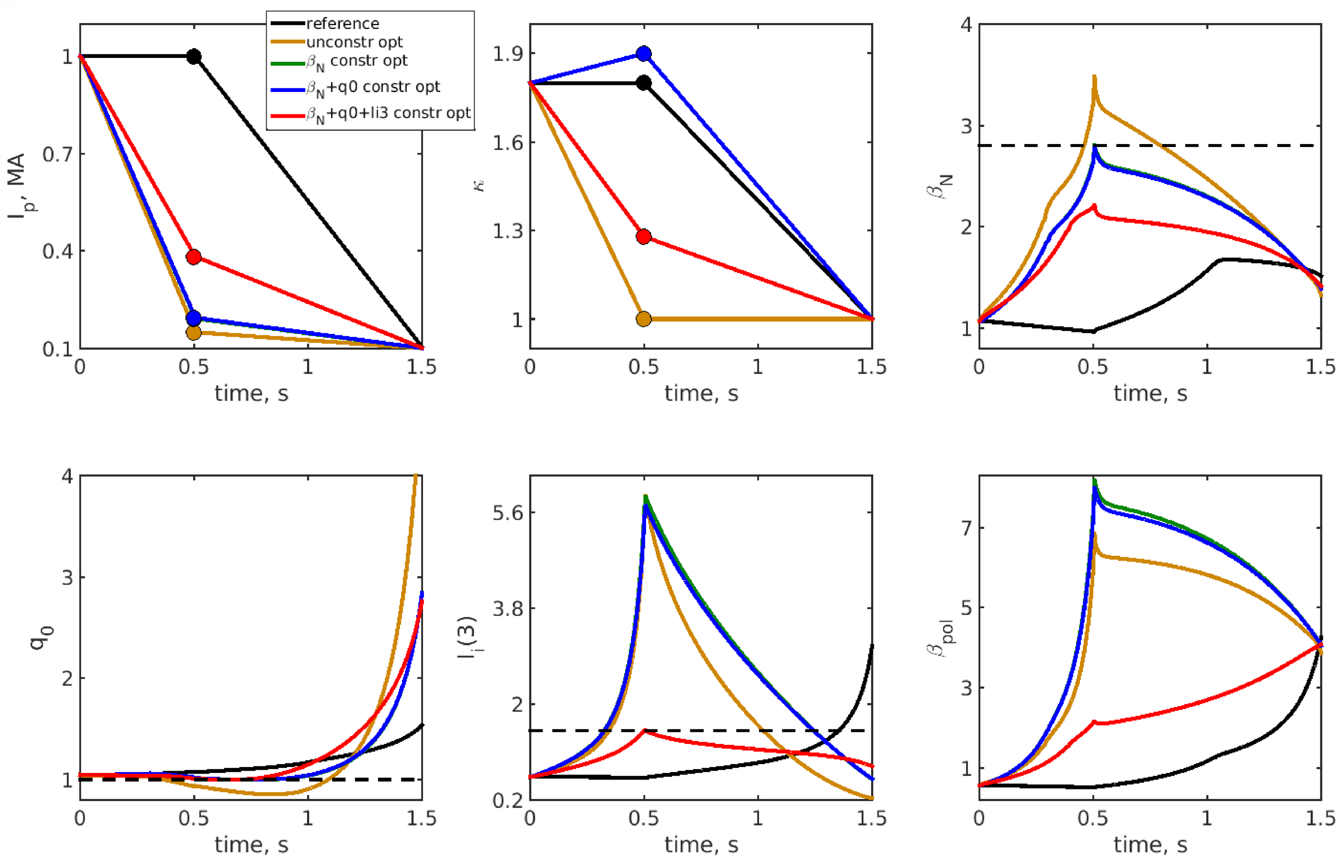
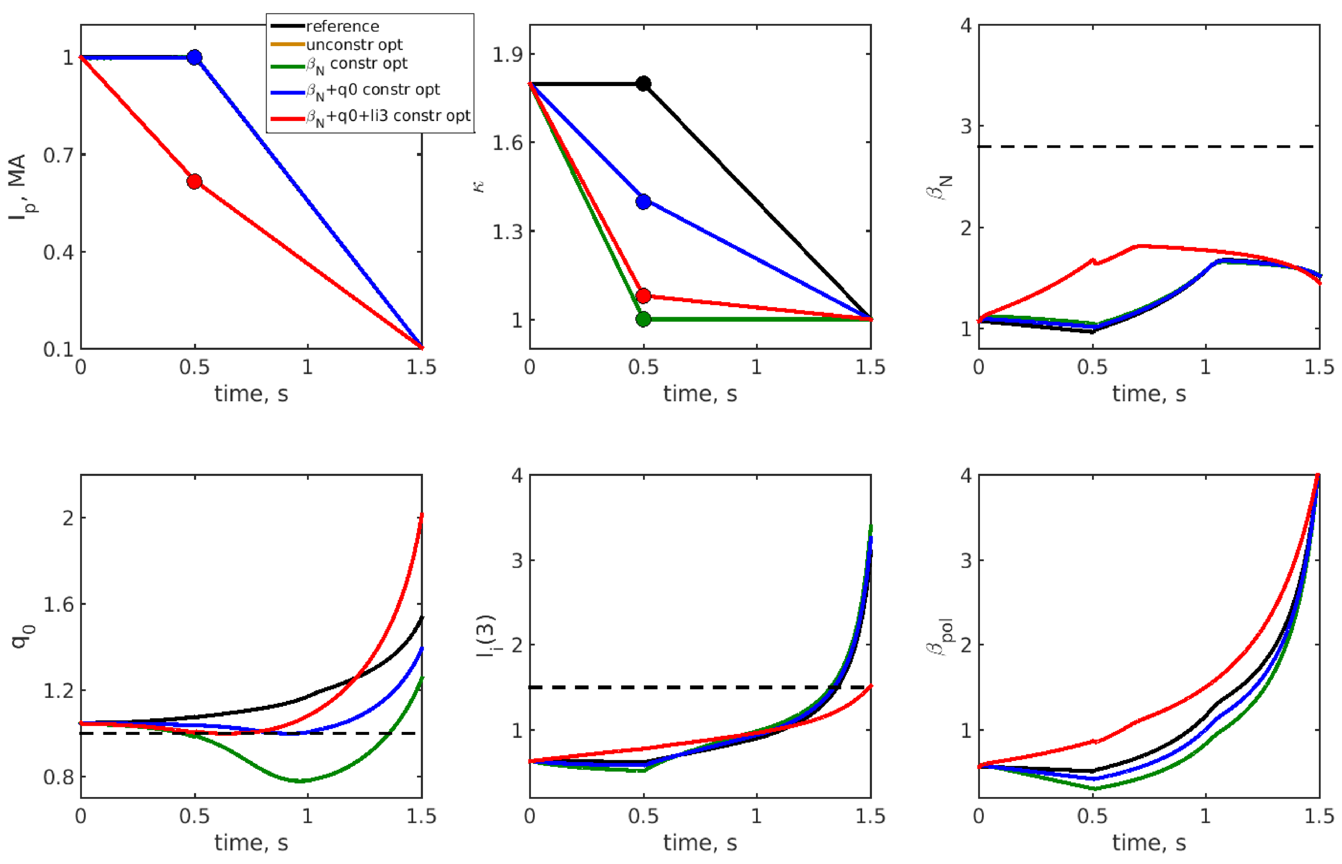


Fig. 5. Ramp down optimization results with cost function $J=J_{Ip}$. In the left column contours for J_{Ip} are shown with the coloured circles which correspond to values of I_p and κ at t=0.5 s. An area where the constrained parameter violates the constraint is yellow-marked.



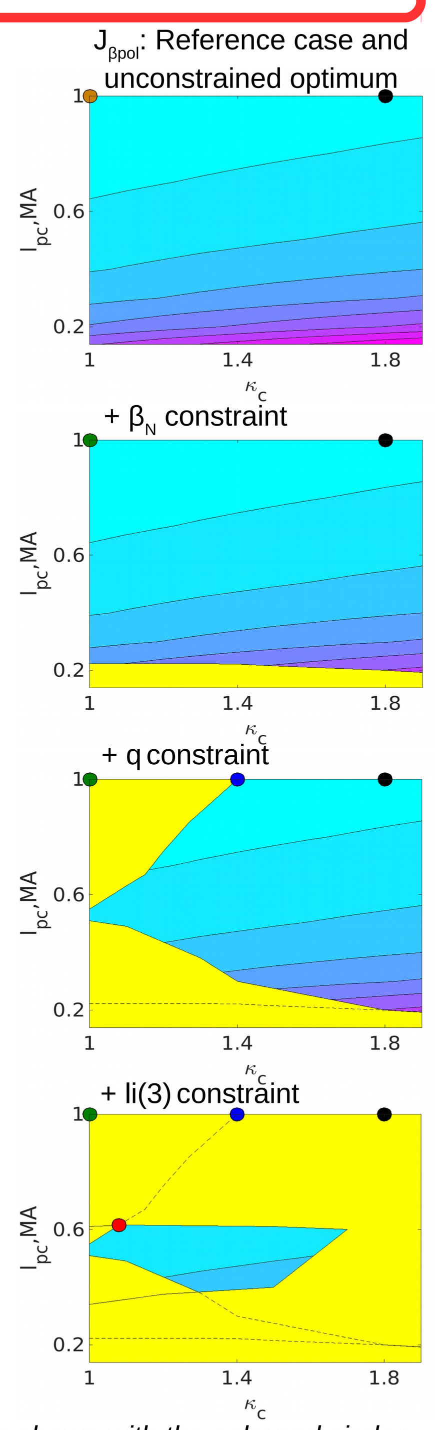


Fig. 6. Ramp down optimization results with cost function $J=J_{\beta pol}$. In the right column contours for $J_{\beta pol}$ are shown with the coloured circles which correspond to values of I_p and κ at t=0.5 s. An area where the constrained parameter violates the constraint is yellow-marked.

6. Further research directions

- Central electron density time evolution: $n_e(0,t)=min\left(n_{eref}(0,t),0.9\frac{I_p(t)}{\pi a^2}\right)$ → Include particle transport equation
- Include time of H- to L-mode transition: rate between $P_{threshold}$ and P_{input}
- Cost function J analysis:
  - additional terms,
  - various values of weights ν_i.

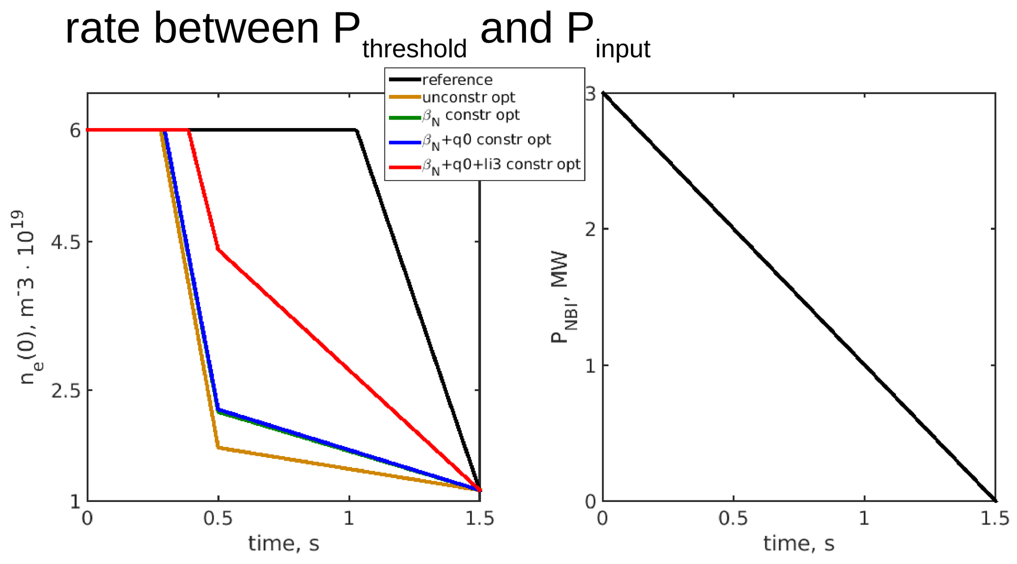


Fig. 7. Central electron density time evolution and NBI power for the cases represented at Fig.5.

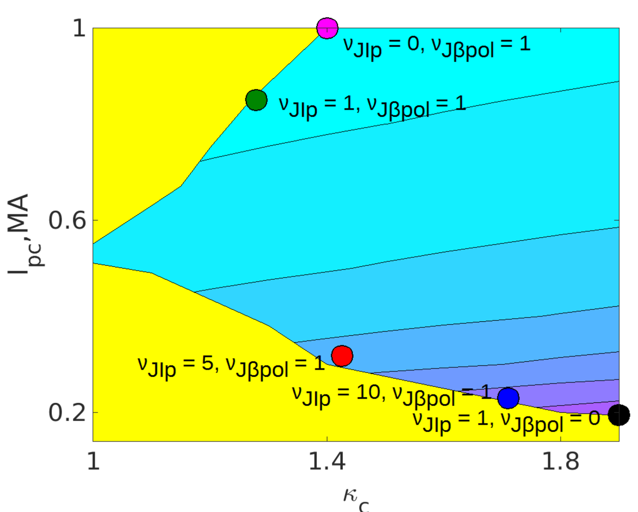


Fig. 8. Optimization results for composite cost function J.

7. Results and future plans

The RAPTOR transport model was extended by the time-varying terms. Comparison with the ASTRA code shows good agreement between the simulation results. Optimization of the plasma current and elongation during the ramp down phase has been carried out, differences of the optimization with taken into account various constraints were demonstrated for AUG-like plasma.

Future plans:
- RAPTOR transport model development: add $n_e(\rho,t)$ equation and $T_i(\rho,t)$ equations.
- Numerical analysis of the ramp down phase: technical constraints, physical constraints, trajectories optimization with the additional goals related transition time from H-mode to L-mode, P_{input}.

8. References

[1] F. Felici et al, Nucl. Fusion 51 (2011) 083052.
[2] F. Felici, O. Sauter, Plasma Phys. Control. Fusion 54 (2012) 025002.
[3] G.V. Pereverzev, P.N. Yushmanov, IPP-Report 5/98 (2002).

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