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Simulation of the plasma profiles evolution for a tokamak discharge including time varying geometry

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1. Tokamak plasma typical time traces and plasma heating

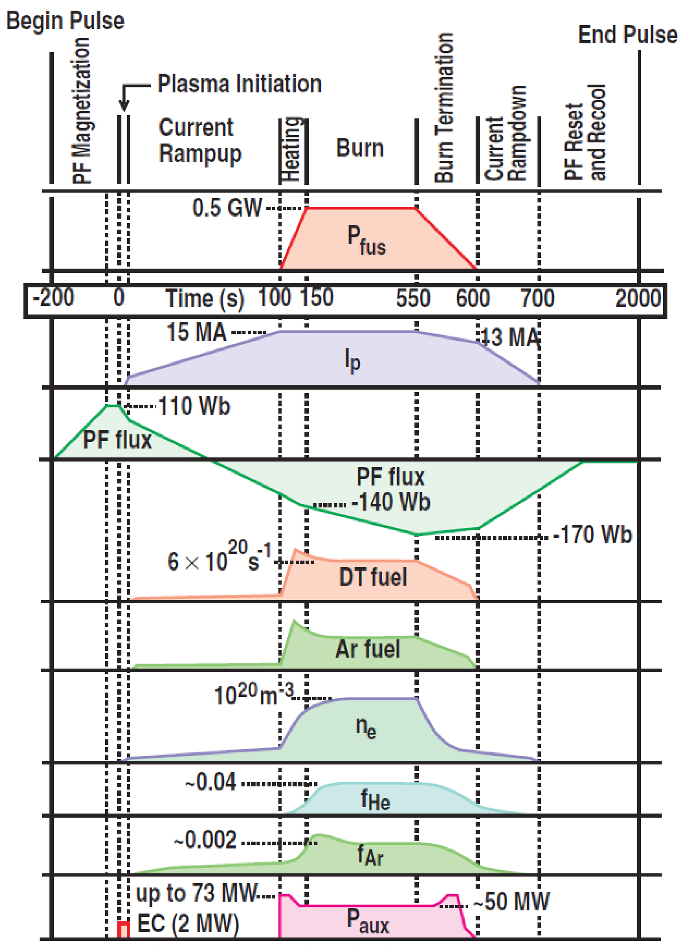

Fig. 1. Typical time traces for ITER plasma operation scenario [1].

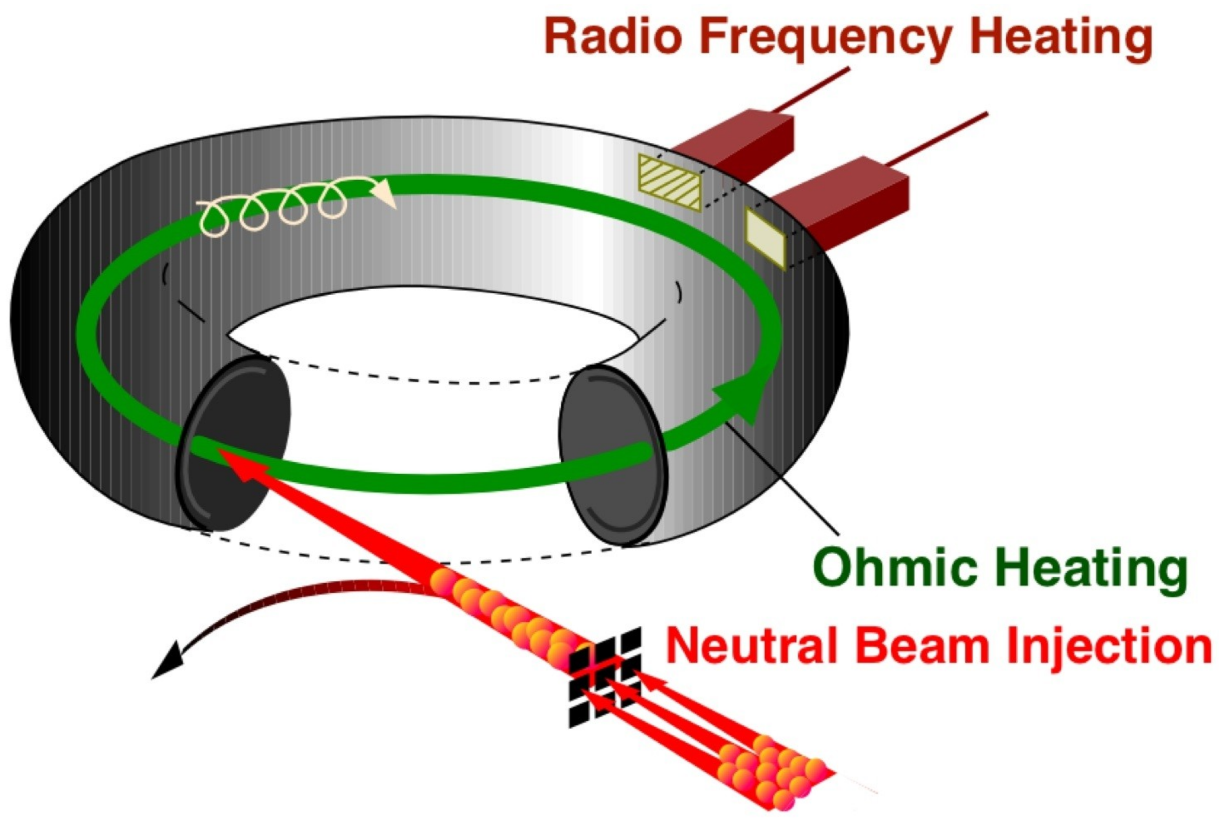

Fig. 2. Tokamak plasma heating [2].

2. The RApid Plasma Transport simulatOR

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

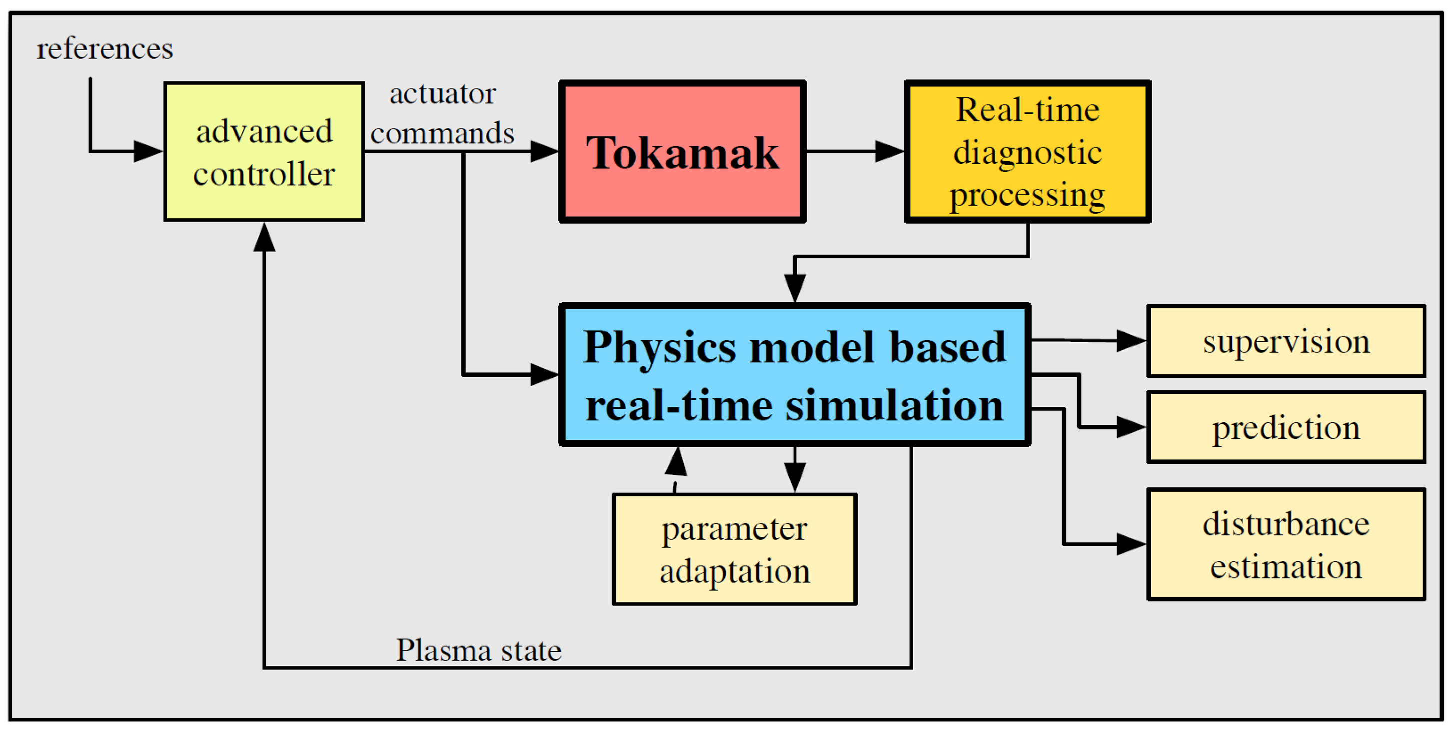

Fig. 3. Tokamak real-time control scheme [3].

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

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

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

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

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

With time-varying terms:

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

4. Comparison with the ASTRA code

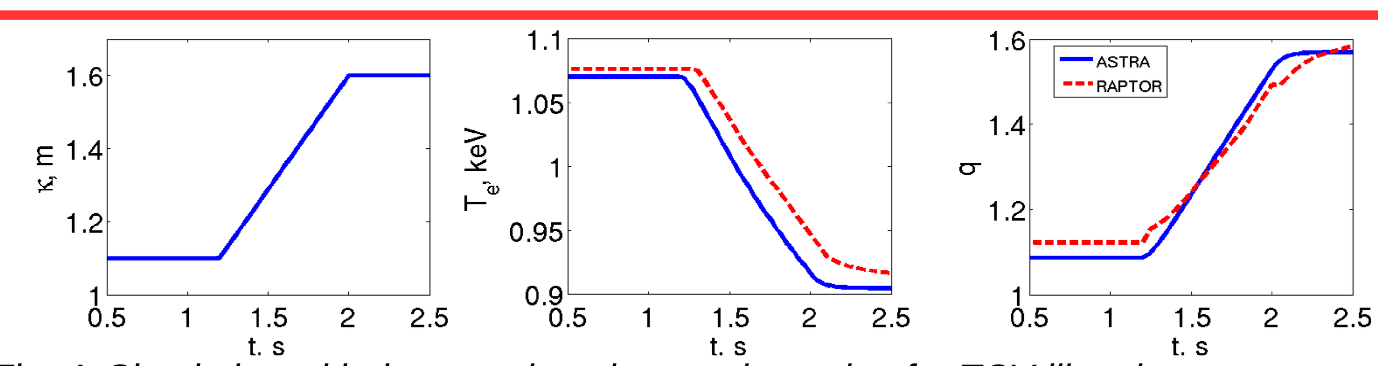

Fig. 4. Simulation with time-varying plasma elongation for TCV-like plasma parameters. Comparison of the ASTRA [4] and RAPTOR simulation results. T_e and q values for ρ_{tor} = 0.35.

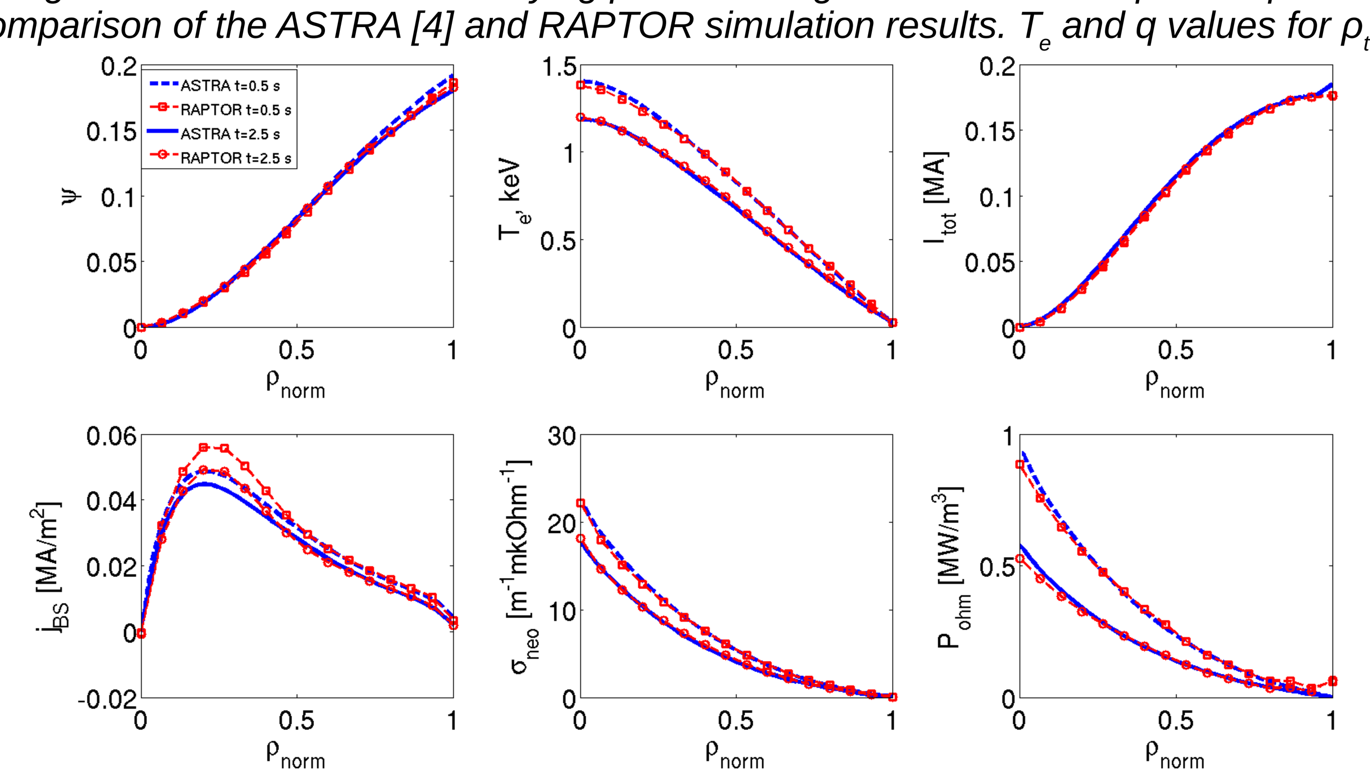

Fig. 5. Comparison of the radial profiles computed by ASTRA and RAPTOR at t=0.5 s and t=2.5 s.

5. Trajectories optimization

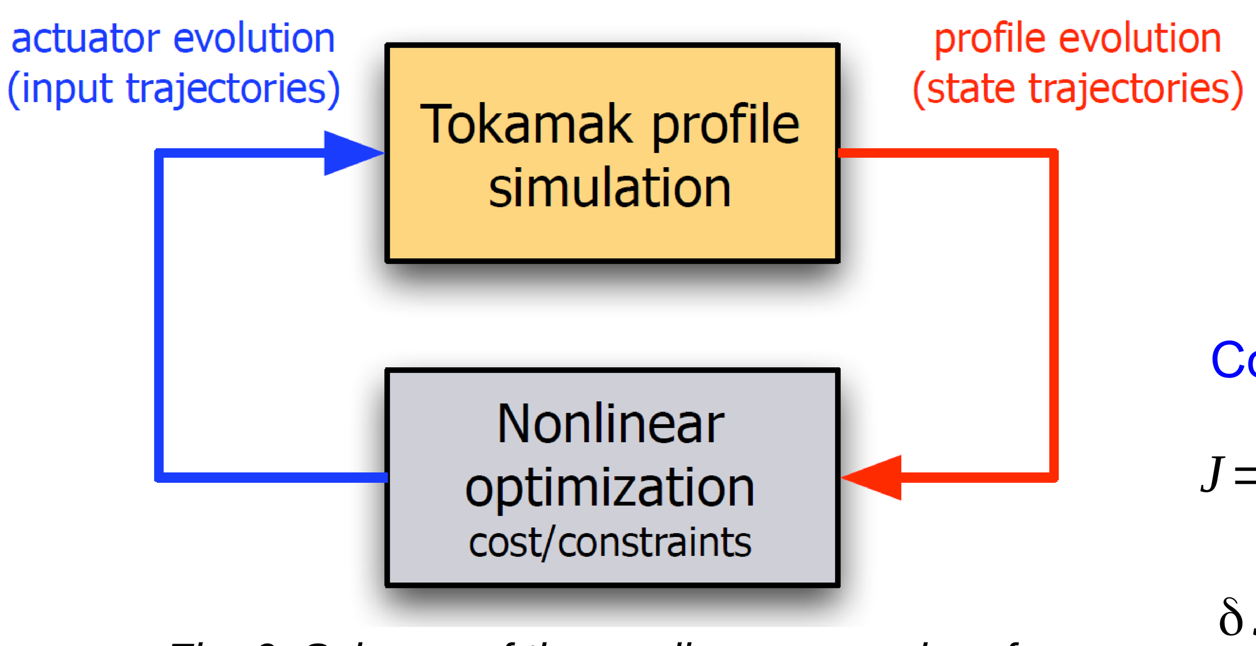

Fig. 6. Scheme of the nonlinear procedure for the actuator trajectories optimization [3].

Cost function:

$$J=\sum_{i=1}^{n}v_iJ_i,\ J_i=\|p(t_f)-p_{ref}\|_{W_p}^2$$

$$\delta J\approx\frac{\partial J}{\partial p}=\frac{\partial J}{\partial x(t_f)}\frac{\partial x(t_f)}{\partial p}\delta p$$

6. Trajectories optimization: ramp-down phase

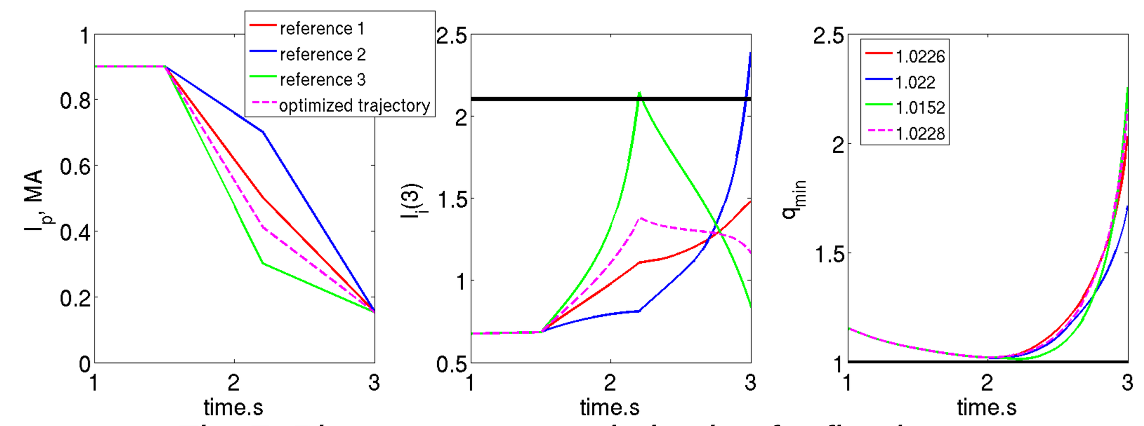

Fig. 7. Plasma current optimization for fixed geometry.

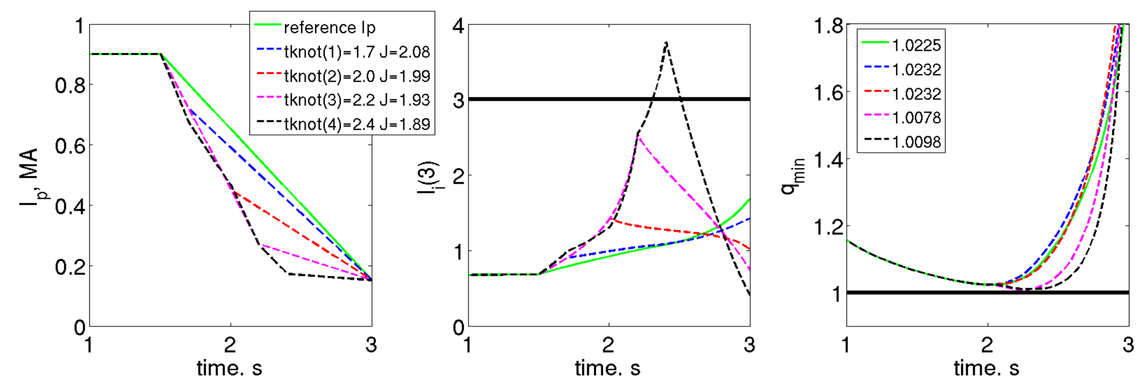

Fig. 8. Sequential optimization of the plasma current for fixed geometry. Plasma current is parametrized with the increased number of the parameters at the following time points t_n=[1.7 2.0 2.2 2.4].

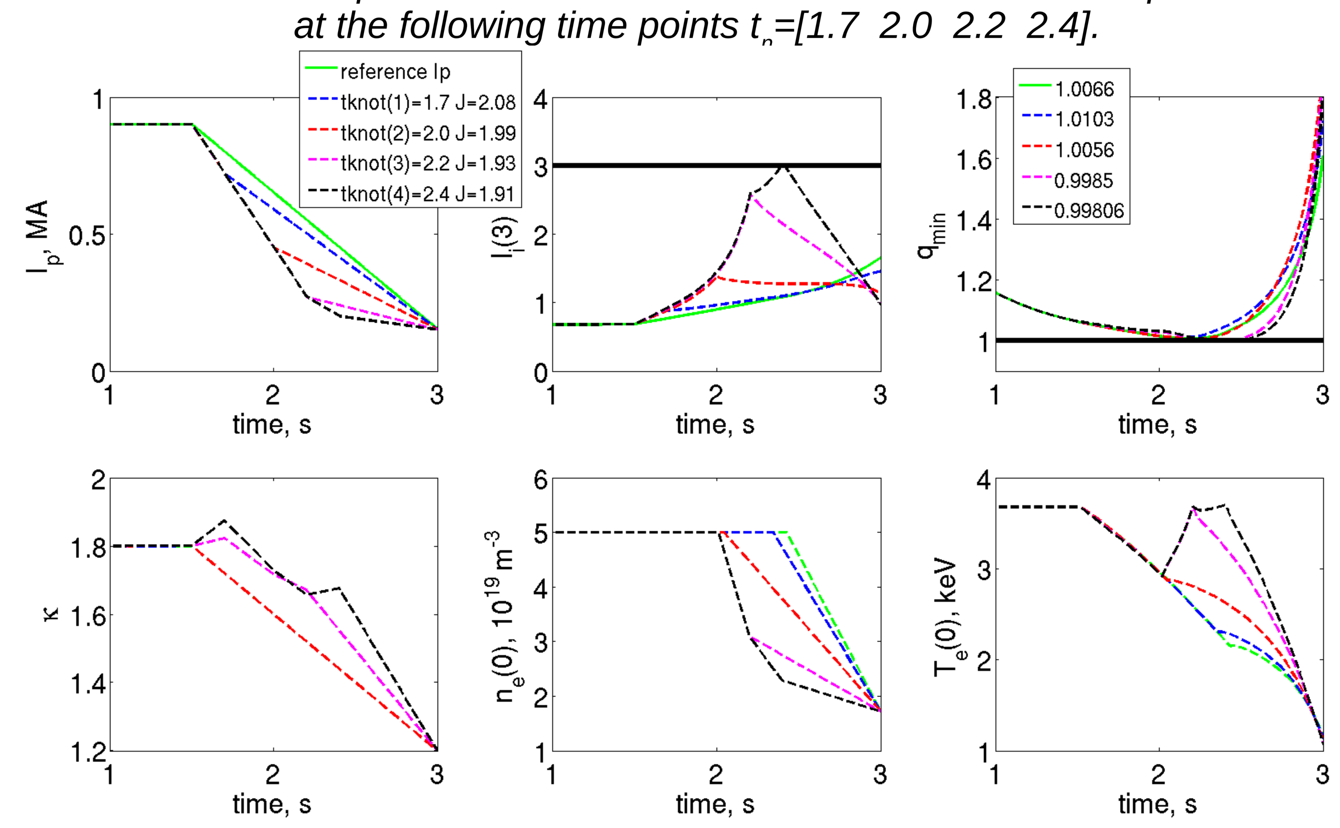

Fig. 9. Sequential optimization of the plasma current and elongation (time-varying geometry) at the following time points t_n=[1.7 2.0 2.2 2.4].

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 fixed and time-varying geometries are demonstrated.

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 to β_N, transition time from H-mode to L-mode, P_{input}.

8. References

[1] https://fusion.gat.com/iter/
[2] http://iter.rma.ac.be/en/physics/plasmaheating/
[3] F. Felici et al, Nucl. Fusion 51 (2011) 083052.
[4] G.V. Pereverzev, P.N. Yushmanov, IPP-Report 5/98 (2002).

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