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

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**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, the plasma current $I_p$, plasma elongation $\kappa$, auxiliary power $P_{aux}$ to terminate the plasma discharge as fast as possible.
   - For the safe termination physical constraints have to be specified: a constraint on normalized $\kappa$, not allowed $P_{aux}$ too low (to avoid MHD modes), a constraint on the plasma elongation $\kappa$ to avoid vertical instabilities.
   - Define technical constraints to match experimental limits, the maximal ramp rate of the plasma current $I_p$, constraints on the rate of change in the vertical magnetic field $B_t$ for radial plasma 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 RAPTOR control-oriented transport code without an equilibrium solver.
   - A lone degree of freedom can be computed.
   - The gradient-based transport models [3,4] for the electron heat and particle transport have been implemented.
   - Successful validation via simulations of TCV and AUG entire plasma discharges and comparison with the experimental plasma scenarios [5].

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**The trajectories optimization [2]**

To get a good trajectory optimization:

1. realistic predictive simulations $\rightarrow$ appropriate transport models;
2. fast solver $\rightarrow$ RAPTOR.

- Plasma current $I_p$
- ECH power $P_{ECH}$
- NBI power $P_{NBI}$
- Plasma elongation $\kappa$

**Cost function:**

- Safety factor $q(z)$
- Plasma stability $\lambda_e$
- Edge local voltage $V_e$
- Various physical and technical constraints ($I_p$ max ramp rate)

**Predicted variables:** same as for the TCV case except $\delta_{el}$ profiles, $H=0.20.25$ and $3.20.35$ for L-/H-mode, the line-averaged electron density $n_{el} \geq 2.0.350.3$ for L-/H-mode.

**Transport coefficients:** the gradient-based model [3,4] or $n_{el}$.

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

- Prescribed parameters: the total plasma current $I_p$ and profiles of the electron density $n_{el}$, the total input NB power with central deposition and the prescribed Gaussian radial profile $H=0.50.45$ and $l=0.320.3$ for L-/H-mode.
- Predicted variables: the electron temperature $T_e$, the poloidal flux $\Omega$, the electron heat diffusivity $\chi_e$, various physical quantities.

**Equilibrium:** 9 CHEASE equilibria (marked as solid on the $I_p$ plot)."}

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

- Prescribed parameters: same as for the TCV case except $\delta_{el}$ profiles, $H=0.20.25$ and $3.20.35$ for L-/H-mode, the line-averaged electron density $n_{el} \geq 2.0.350.3$ for L-/H-mode.
- Predicted variables: as for the TCV case except $\delta_{el}$, $n_{el} \geq 2.0.350.3$ for L-/H-mode, the line-averaged electron density $n_{el} \geq 2.0.350.3$ for L-/H-mode.
- Transport coefficients: the gradient-based model [3,4]

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**The generic ramp-down optimization**

The ramp-down optimization of the plasma current and the boundary elongation at $H=0.3$ for the AUG-like plasma with the cost function $\int_0^T L dt$. The reference case and the unconstrained optimum.

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

TCV #55520: L-mode, the optimization of $I_p$ and $n_{el}$ at $t=[0.1-1.0]$ s with 10 ms step.
- Technical constraints: $dV_e/dt < 1.0 (MV/m)$; $dI_p/\lambda_e < 0.0 (T/s)$
- The cost function $J = \int_0^T L dt$
- Further $J$ and $\lambda_e$ ramp-down can be programmed.

**TCV #55672:** an experimental test of the TCV #55520 optimized trajectories.
- Further $J$ but slower $\lambda_e$ ramp-down obtained.
- $\lambda_e$ is within the required limit except waist peaks.

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**Future directions**

- The RAPTOR code development:
  - Y and impurities transport modeling.
  - A scaling law for the pedestal pressure for L-/H-mode to determine $\mu_e$ directly.
  - A radial-dependent core gradient $\lambda_e$.
- Continue to 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 change.
  - Technical constraint on the vertical position control (constraint on $d\delta_{el}/dt$).

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**PLANS**

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

**OPTIMIZATION**

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

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

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**Refrences**


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**Figures**

- The constraints for $J$ are shown with the solid circles and the values of $\lambda_e$ are at 0.15. An area where the constraint parameter violates the constraint is in yellow-marked.
- The contours for $J$ are shown with the solid circles which correspond to values of $\lambda_e$ at 0.15. An area where the constraint parameter violates the constraint is in yellow-marked.

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**Technical report**

- JET plasma modelling: #9207
- The RAPTOR code transport equations
- The inverse scale length [3]: $l_e = \frac{e}{\gamma(1-\beta_0^2)T_e} \left( \frac{m_e}{2\pi} \right)^{1/2}$.