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

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MODEL

Research directions

1. Development of an optimization procedure for the ramp down phase of the plasma discharge to terminate plasmas in the safest and fastest way:
   - Determination of the optimal time evolution of the plasma parameters, like plasma current I_p, plasma elongation x, auxiliary power P_aux, to terminate plasma discharge as fast as possible.
   - For the safe termination physical constraints have to be specified, a constraint on normalized x and poloidal beta Bpol on the basis to avoid MHD modes, a constraint on the plasma inductance I_d to avoid vertical instability...
   - Define technical constraints to reach experimental limits, like the max ramp rate of the plasma current dI_p/dt, constraints on the rate of change in the vertical magnetic field B_z, for radial position control.
   - Determination of the optimal time of H- L-mode transition

2. Development of the RAPTOR code:
   - The RAPTOR code - Rapid Plasma Transport simulator[2]
   - The first code in which a 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.
   - Interpolation validation via simulations of TCV and AUG electron wall fluxes and comparison with the experimental measurements [5]


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

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

The generic ramp-down optimization

The ramp-down optimization of the plasma current and the boundary elongation at t<0 is first the AUG-like plasma with the cost function J_p(x) dt.

The reference case and the unconstrained optimum

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

Future directions

The RAPTOR code development:
   - Improved transport equilibrium:
   - A scaling law for the pedestal pressure for L- H-mode to determine p_0 directly.
   - A radial-dependent core gradient lambda_c
   - Continue the model validation with JET simulations.
   - Continue for ITER simulations.

The ramp-down optimization:
   - Constraints related to the pedestal pressure 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 dH/da).
   - JET/ITER ramp-down optimization.

OPTIMIZATION

The trajectories optimization [2]

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

The RAPTOR code transport equations

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

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot \mathbf{j}_e = 0 \]
\[ \frac{\partial T_e}{\partial t} + \nabla \cdot \mathbf{j}_e \frac{T_e}{2} + \nabla \cdot \mathbf{j}_i T_i = 0 \]
\[ \frac{\partial (\mathbf{B} \cdot \mathbf{j}_i)}{\partial t} + \nabla \cdot (\mathbf{B} \cdot \mathbf{j}_i) = 0 \]

The inverse scale length [3]:

\[ l_i = \frac{\mu_0}{e n_i} \left[ \frac{1}{1 + \frac{2\beta_p}{\beta_i}} \right] \]

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

The PLANS

The JET plasma modelling: #92207

Prescribed parameters:
   - same as for the AUG case: \( \lambda_c \approx 0.3 \) and \( p_0 \approx 0.08 \)
   - for L-H mode: \( \lambda_c \approx 0.3 \) for L-H mode.

Prescribed variables:
   - a as for the TCV case = electron density n_e

Equilibrium: 23 EFTI equilibria (marked a+ on the \( I_p \) plot).

CPU time: 4 minutes for a time grid with 10 ms step (the shot duration 20 s).

Note: L-H at 4.5, x_H at 6.5 a.