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Numerical optimization of the actuator trajectories in ITER hybrid scenario

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June 3, 2013

Outline

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Introduction

Verification of RAPTOR validity

Optimization of Actuators

Results

Conclusion

Introduction

What is the most efficient actuator trajectory for the ramp-up phase?

- Use RAPTOR for optimization:
  Fast simulation, suitable for numerical optimization
- Verify results using CRONOS:
  More complete model to verify RAPTOR outcome

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What needed to be done?

- Adapt RAPTOR for ITER usage
- Compare RAPTOR results with respect to CRONOS
- Start optimization of ITER hybrid scenario

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RAPTOR vs CRONOS

The two main evolution equations in RAPTOR are:

$$\sigma_{\parallel}\left(\frac{\partial\psi}{\partial\rho}-\frac{\rho\dot{B}_0}{2B_0}\frac{\partial\psi}{\partial\rho}\right)=\frac{R_0 J^2}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\psi}{\partial\rho}\right)-\frac{V'}{2\pi\rho}(j_{bs}+j_{cd}).$$

$$\frac{3}{2}V'^{5/3}\left(\frac{\partial}{\partial t}-\frac{\rho\dot{B}_0}{2B_0}\frac{\partial}{\partial\rho}\right)\left[V'^{5/3}n_\alpha T_\alpha\right]+\frac{1}{V'}\frac{\partial}{\partial\rho}\left(q_\alpha+\frac{5}{2}T_\alpha\Gamma_\alpha\right)=P_\alpha$$

Next: identify differences in the evolution equations of CRONOS and RAPTOR.

Poloidal flux diffusion

$$\sigma_{\parallel}\left(\frac{\partial\psi}{\partial\rho}-\frac{\rho\dot{B}_0}{2B_0}\frac{\partial\psi}{\partial\rho}\right)=\frac{R_0J^2}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\underbrace{\boxed{\frac{G_2}{J}}}\frac{\partial\psi}{\partial\rho}\right)-\frac{V'}{2\pi\rho}(j_{bs}+j_{cd}).$$

RAPTOR:

- $2D$ MHD equilibrium fixed
- Geometric factors (G_1, G_2, V' and J) are fixed in time

Poloidal flux diffusion

$$\underbrace{\boxed{\sigma_{\|}}}\left(\frac{\partial\psi}{\partial\rho} - \frac{\rho\dot{B}_0}{2B_0}\frac{\partial\psi}{\partial\rho}\right) = \frac{R_0 J^2}{\mu_0\rho}\frac{\partial}{\partial\rho}\left(\frac{G_2}{J}\frac{\partial\psi}{\partial\rho}\right) - \frac{V'}{2\pi\rho}(\underbrace{\boxed{j_{bs}}}+j_{cd}).$$

RAPTOR:

$\sigma_{\|}$ and j_{bs} calculated using the equations in Sauter *et al*.

CRONOS:

$\sigma_{\|}$ and j_{bs} taken from *NCLASS* routine.

Energy Transport

The diffusive heat flux q_α:

$$\frac{3}{2}V'^{5/3}\left(\frac{\partial}{\partial t}-\frac{\rho\dot{B}_0}{2B_0}\frac{\partial}{\partial\rho}\right)\left[V'^{5/3}n_\alpha T_\alpha\right]+\frac{1}{V'}\frac{\partial}{\partial\rho}\left(\underbrace{\boxed{q_\alpha}}+\frac{5}{2}T_\alpha\Gamma_\alpha\right)=P_\alpha$$

RAPTOR and CRONOS:

Equivalent Bohm-Gyrobohm transport model implemented.

Energy Transport

The convective heat flux Γ_α:

$$\frac{3}{2}V'^{5/3}\left(\frac{\partial}{\partial t}-\frac{\rho\dot{B}_0}{2B_0}\frac{\partial}{\partial\rho}\right)\left[V'^{5/3}n_\alpha T_\alpha\right]+\frac{1}{V'}\frac{\partial}{\partial\rho}\left(q_\alpha+\frac{5}{2}T_\alpha\underbrace{\boxed{\Gamma_\alpha}}\right)=P_\alpha$$

RAPTOR:

Not simulated

CRONOS:

Simulated but negligible effect on profile evolution

Sources, sinks and updated physics

The following interactions were added to RAPTOR:

- P_α - Developed fusion induced heating to electrons
- P_{ei} - Introduced electron-ion heat loss for electrons
- P_{brem} - Introduced bremsstrahlung radiation loss
- P_{line} - Developed simple line radiation loss model
- P_{NBI} - NBI heating & CD model improved by P. Geelen

Ion temperature assumption: $T_i = A(\rho) T_e$.

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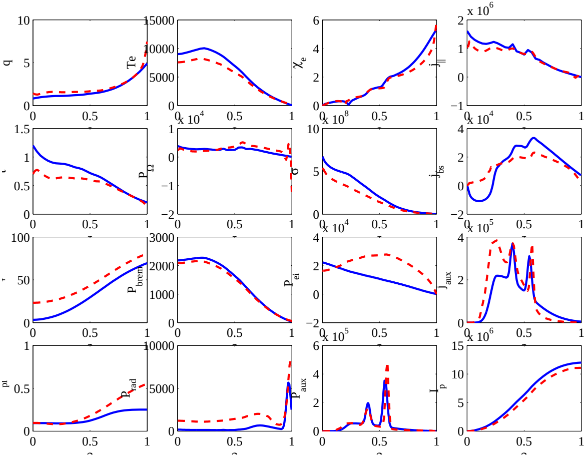
Typical profiles

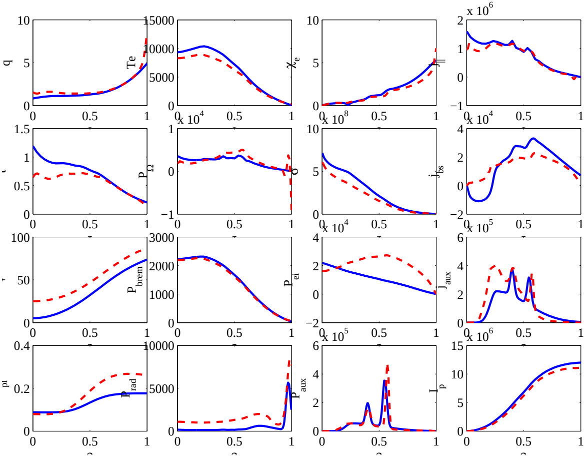
t = 80 sec

Blue solid: RAPTOR, Red dashed lines: CRONOS



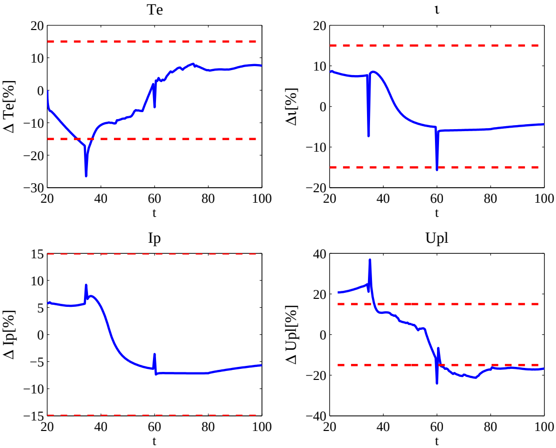
Typical profiles

t = 100 sec
Blue solid: RAPTOR, Red dashed lines: CRONOS



Profile differences

ρ-averaged difference:



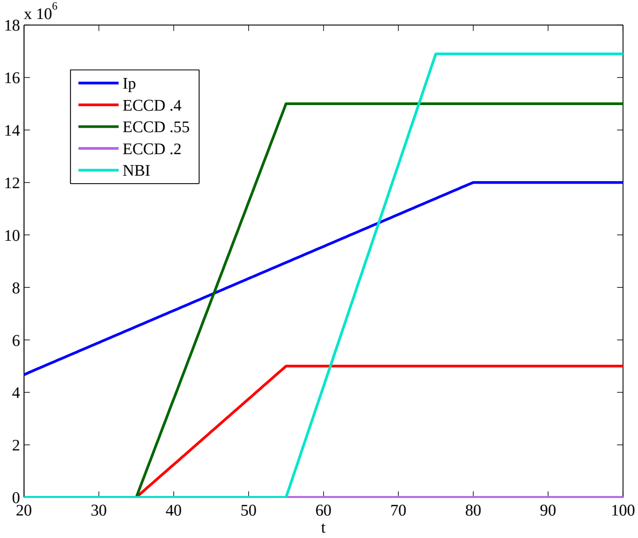
Outline

Reference scenario

Reference scenario taken from recent optimization publication:
Dick Hogeweij's paper: '*Nucl. Fusion* **013008**, 53 (2013)'

- hybrid scenario
- L-mode
- Heuristic optimization of q-profile
- I_p ramp-up until 80*sec*
- P_{ECCD} sources @ $\rho \approx .4$ & .55
- P_{NBI} source of 16.9 MW
- $J = ?$

Reference actuators



Optimization set-up

Cost function:

For ITG threshold: (1)

$$J_{s/q} = -\int W_{s/q} V'(\rho) s(\rho)/q(\rho) d\rho$$

For stationary state: (2)

$$J_{ss} = \int W_{ss} \left|\left| \frac{dU_{pl}}{d\rho} \right|\right|^2 d\rho$$

$$J_{ss} = \int W_{ss}(\rho) || U_{pl}(\rho) - U_{pl,edge} ||^2 d\rho$$

Constraints:

- $q > 1.05$
- $\sum_i P_{ECCD}^{(i)} \leq 20$ MW, $P_{NBI} \leq 16.5$ MW
- $0.5 \leq I_p \leq 15$ MA, $dI_p/dt \leq 0.3$ MA/s

Optimization set-up

Cost function:

For ITG threshold: (3)

$$J_{s/q} = -\int W_{s/q} V'(\rho) s(\rho)/q(\rho) d\rho$$

For stationary state: (4)

$$J_{ss} = \int W_{ss} \left|\left| \frac{dU_{pl}}{d\rho} \right|\right|^2 d\rho$$

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- $0.5 \leq I_p \leq 15$ MA, $dI_p/dt \leq 0.3$ MA/s

Optimization set-up

Cost function:

For ITG threshold: (5)

$$J_{s/q} = -\int W_{s/q} V'(\rho) s(\rho)/q(\rho) d\rho$$

For stationary state: (6)

$$J_{ss} = \int W_{ss} \left|\left| \frac{dU_{pl}}{d\rho} \right|\right|^2 d\rho$$

$$J_{ss} = \int W_{ss}(\rho) || U_{pl}(\rho) - U_{pl,edge} ||^2 d\rho$$

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- $0.5 \leq I_p \leq 15$ MA, $dI_p/dt \leq 0.3$ MA/s

Optimization set-up

Cost function:

For ITG threshold: (7)

$$J_{s/q} = -\int W_{s/q} V'(\rho) s(\rho)/q(\rho) d\rho$$

For stationary state: (8)

$$J_{ss} = \int W_{ss} \left|\left| \frac{dU_{pl}}{d\rho} \right|\right|^2 d\rho$$

$$J_{ss} = \int W_{ss}(\rho) ||U_{pl}(\rho) - U_{pl,edge}||^2 d\rho$$

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- $q > 1.05$
- $\sum_i P_{ECCD}^{(i)} \leq 20$ MW, $P_{NBI} \leq 16.5$ MW
- $0.5 \leq I_p \leq 15$ MA, $dI_p/dt \leq 0.3$ MA/s

Optimization set-up

Cost function:

For ITG threshold: (9)

$$J_{s/q} = -\int W_{s/q} V'(\rho) s(\rho)/q(\rho) d\rho$$

For stationary state: (10)

$$J_{ss} = \int W_{ss} \left|\left| \frac{dU_{pl}}{d\rho} \right|\right|^2 d\rho$$

$$J_{ss} = \int W_{ss}(\rho) || U_{pl}(\rho) - U_{pl,edge} ||^2 d\rho$$

Constraints:

- $q > 1.05$
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- hybrid scenario
- L-mode
- Heuristic optimization of q-profile
- I_p ramp-up until $80 sec$
- P_{ECCD} sources @ $\rho \approx .4$ & $.55$
- P_{NBI} source of 16.9 MW
- $\boxed{J_{sq} = -156.14}$ and $\boxed{J_{ss} = 0.778}$

Tracking Progress

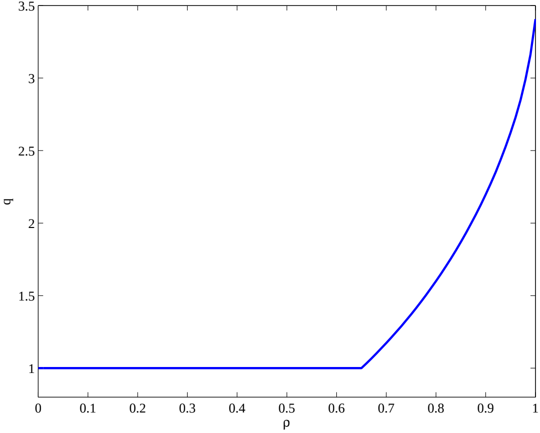
We know that J_{ss} has its optimal value at $J_{ss} = 0$

How about J_{sq}? What is its optimal value?

Using assumptions on the MHD equilibrium, an optimal q-profile can be calculated.

Monitoring the relative distance to the optimal values is a quantitative measure to track our progress.

Optimal q-profile

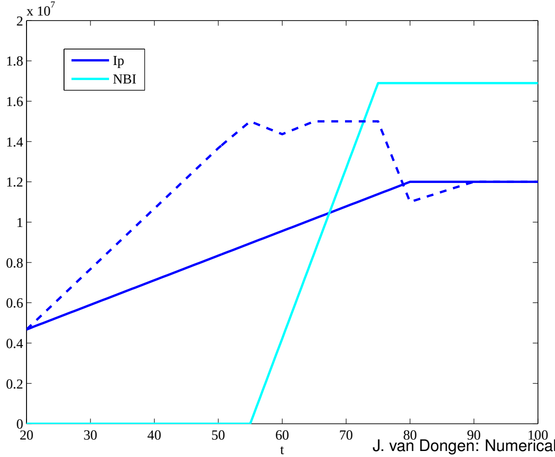


Optimal $J_{sq} = -275.25$ for RAPTOR equilibrium

Outline

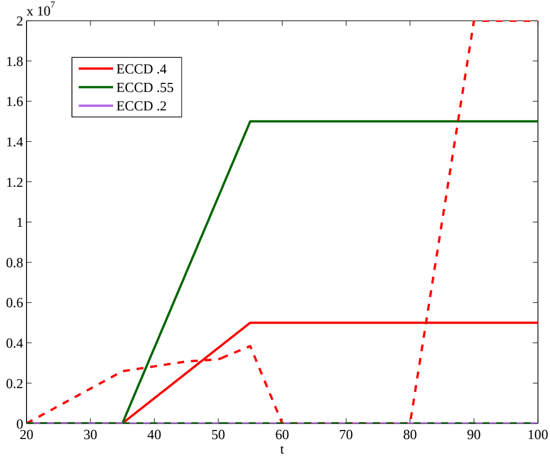
Initial results 1/4

Initial optimization results compared to reference actuators for $J = J_{ss}(= 0.911) + J_{s/q}(= -2.1508)$. Reference (solid) and Optimized case (dashed).

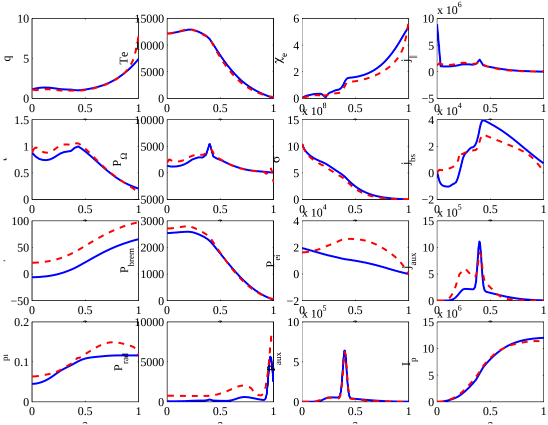


Initial results 2/4

Initial optimization results compared to reference actuators



Comparing results from RAPTOR(blue) and CRONOS (red) at $t = 100$ sec:



Initial results 4/4

Quantitative results:

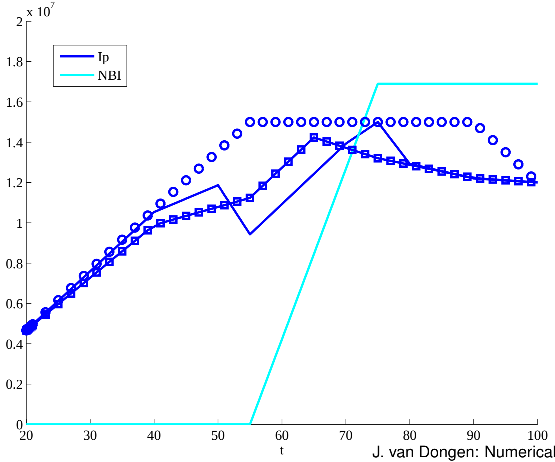
	RAPTOR	CRONOS
J_{ss}	0.009111	0.028611
rel J_{ss}	17.06 %	41.29 %
J_{sq}	-215.08	-278.62
rel J_{sq}	50.52 %	14.40 %

For relative J_{ss}/J_{sq}: reference distance to optimal is 100%

Next: Compare results from different cost function compositions

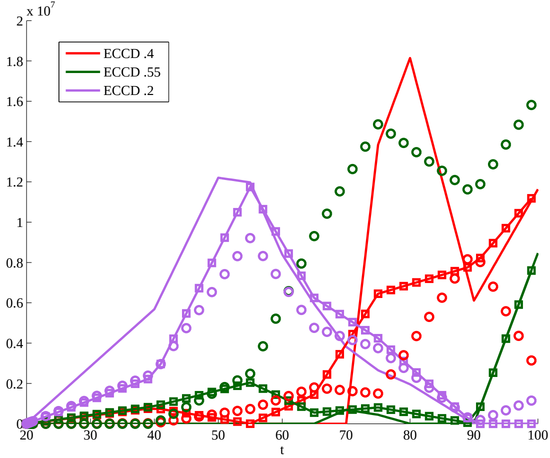
Compare J_{ss}, $J_{s/q}$ and $J_{ss} + J_{s/q}$

$J = J_{ss} + J_{sq}$ (solid), $J = J_{ss}$ (squares) and $J_{s/q}$ (circles):
Current overshoot favorable to J_{sq} and J_{ss} as previously seen in JET/TCV



Compare J_{ss}, $J_{s/q}$ and $J_{ss} + J_{s/q}$

$J = J_{ss} + J_{sq}$ (solid), $J = J_{ss}$ (squares) and $J_{s/q}$ (circles):
Choice of cost function has most effect on far off axis ECCD.



Compare J_{ss}, $J_{s/q}$ and $J_{ss} + J_{s/q}$

Quantitative results for $J = \nu_{ss} J_{ss} + \nu_{sq} J_{sq}$:

	ν_{ss}	$\nu_{s/q}$	J_{ss}	rel J_{ss}	J_{sq}	rel J_{sq}
Case 1	0	1	7.8804	1000.125 %	-233.96	34.7 %
Case 2	1	0	0.0160	2.06 %	-219.76	46.6 %
Case 3	1	1	0.01572	2.02 %	-220.14	46.3 %

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Conclusions

- Successfully updated RAPTOR to simulate ITER hybrid discharges

  Errors of most relevant profiles are within 15 % range of CRONOS results

- Shown an improved result verified in CRONOS compared to literature
- Both the J_{ss} and J_{sq} contributions can be lowered significantly in RAPTOR

Outlook

- Verify new optimization results in CRONOS
- NBI timing also optimized
- Use new NBI model recently implemented
- Extend to H-mode

Questions

Thank you all for your attention!

Any questions?

Bibliography

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