Optimizing the current ramp-up phase for the hybrid ITER scenario

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Research Questions to be addressed:

1. Find ”best scenario” for current ramp-up phase of hybrid ITER discharges:
    1. arrive at hybrid q profile (q0~1, large low shear region) at L-H transition
    2. while minimizing flux consumption

    Knobs: settings of heating systems , density, I_p ramp rate
2. Assess sensitivity of result with regard to choices like

    - transport model used
    - density profile shape
    - density
    - Z_{eff}
    - boundary conditions (T_e, T_i)
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Note:

Optimization of Current Ramp-up for baseline 15 MA ITER scenario well documented and well validated *(e.g. Hogeweij EPS2010; Imbeaux Nuc.Fus.2011)*

However this phase not well established for hybrid scenario (~12 MA)

1. Choice of transport model – validation

Various transport models have been validated to current ramp-up phase of JET, AUG, TS, and (recently) also to DIII-D:

1. Empirical scaling-based model with a prescribed radial shape of $\chi_e = \chi_i$ (parabola plus high power of ρ to have high edge diffusivity), renormalised to H-mode scaling of global energy content H98 = 0.4; *[or, equivalently, L-mode, L97=0.6]*
2. Semi-empirical Bohm/gyro-Bohm model (L-mode version, ITB shear function off)
3. Semi-empirical Coppi-Tang model – *will not be used here*
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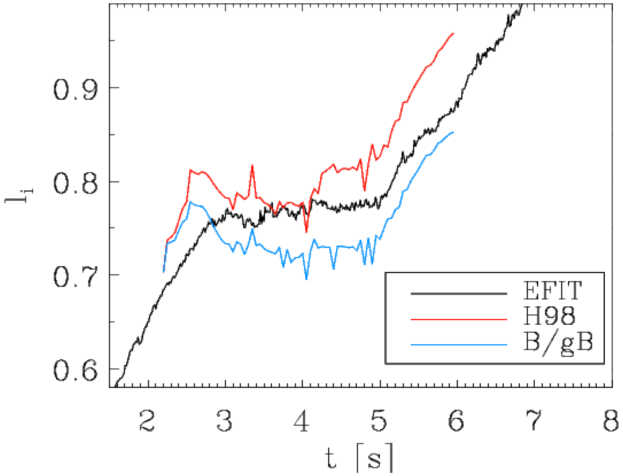
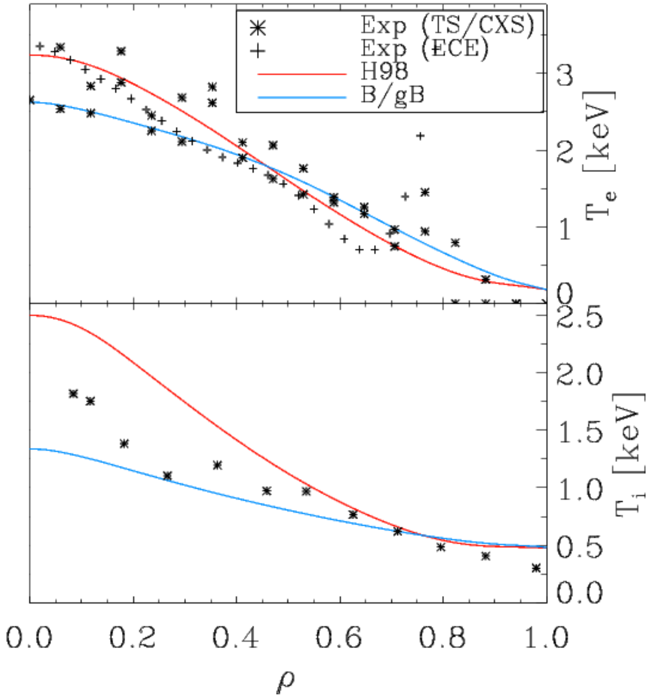
Generally both scaling-based model with H98 = 0.4 and Bohm/gyro-Bohm (L-mode version) do a good job on existing experiments

Next sheet: some examples from DIII-D and JET

1. Choice of transport model – validation *(ctd)*





Left: JET, LHCD-assisted ramp-up case

Black: data

Cyan: Bohm-gyroBohm

Red: scaling-based

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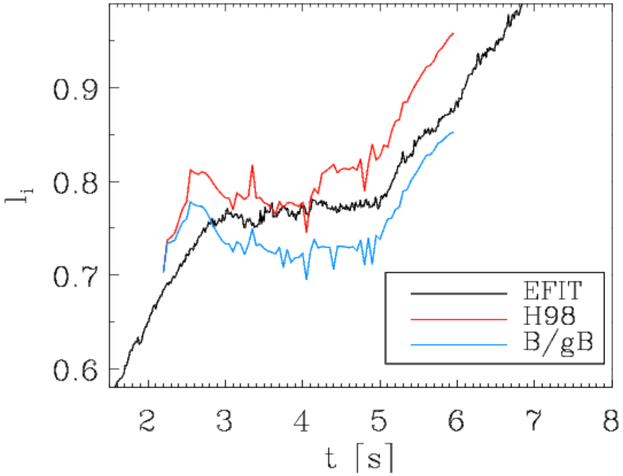

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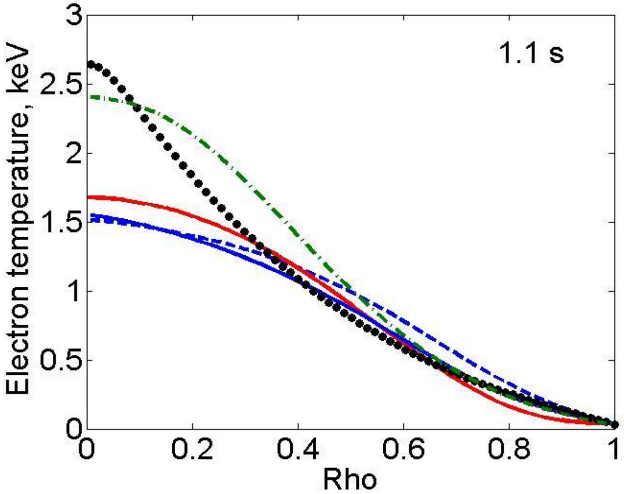
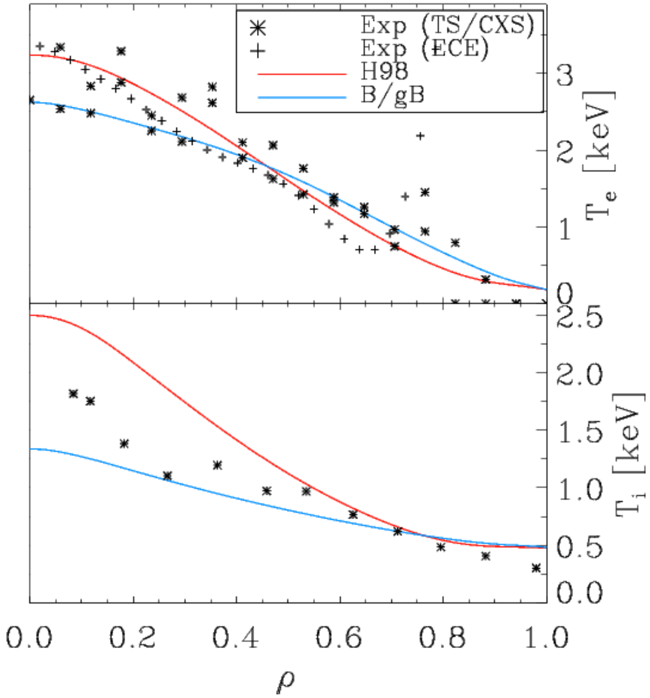




Right: DIII-D, NBI-heated ramp-up case

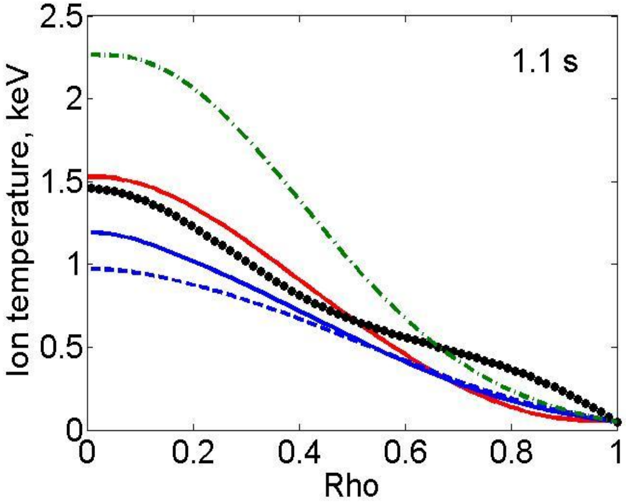
Black: data

Blue: Bohm-gyroBohm (ASTRA: solid, CRONOS: dashed)

Red: scaling-based

Green: Coppi-Tang

[Voitsekhovitch, ITPA pres., Oct 2011]



2. Assumptions made

(i) Expanding ITER shape, starting on LFS of torus (geometry taken from ITER team)

X-point formation takes place after 15s, when Ip = 3.5 MA.

(ii) Z_{eff} profile flat, decreasing in time with increasing n_e, with final value of 1.7

(iii) A rather low density of n_e = 0.25 n_{eGW} is taken.

(iv) n_e profile parabolic with moderate peaking factor $n_e(0)/<ne>$ = 1.3

Compromise between the (unrealistic) flat ne profile used by the ITER team and the peaking factor of ~1.5 predicted by scaling studies

(v) Total input power below the L-H threshold during whole ramp-up phase;

(vi) I_p ramp rate is chosen such that I_p = 12 MA is reached after 80 s.

(vii) Other assumptions ($T_{e,i}$ (edge), initial $T_{e,i}$, initial l_i) based on experimental evidence

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The simulations start 1.5 s after breakdown, when Ip = 0.5 MA

Simulations are done with CRONOS suite of transport codes

3. What is a “good” q profile

ITG theory predicts critical gradient like

(this one from Romanelli, but many similar formulas)

$$R / L_{T\,i}{}^{ITG} \sim \left(1 + \frac{T_i}{T_e}\right) \cdot \left(1 + 2\frac{s}{q}\right)$$

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Therefore hybrid regime: q profile characterized by

- q(ρ) >~ 1 everywhere: avoid sawteeth, thus avoid triggering NTMs
- large region of flat q(ρ), in order maximize magnetic shear in outer region

In this talk we will judge the shape of the q profiles “by eye”

instead of calculating volume integrated s/q

4. Reference scenarios with and without LHCD

a. Choice of heating and current drive scheme

To avoid too fast drop of q profile we need *off-axis heating & current drive*
When we look at the systems available on ITER:
ICRH and ECCD from Equatorial Launcher heat very centrally (for ramp-up parameters)
Useful systems are

- NBI (off-axis mode) – wide power deposition, typical ρ_{dep} ~0.3
- ECCD from Upper Port Launcher – narrow power deposition,
  typical ρ_{dep} >~ 0.4 / 0.6 for 4th / 5th antenna
- LHCD – narrow power deposition, typical ρ_{dep} ~0.3-0.6 depending on plasma params

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- LH system does not belong to ITER base line, so we will optimize both with and without LHCD, to see what one wins with LHCD
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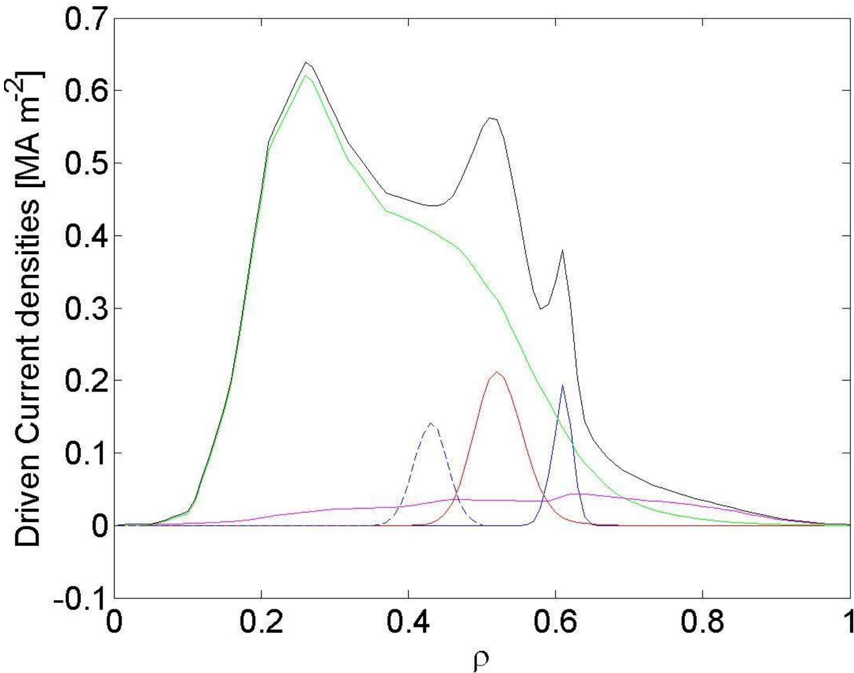
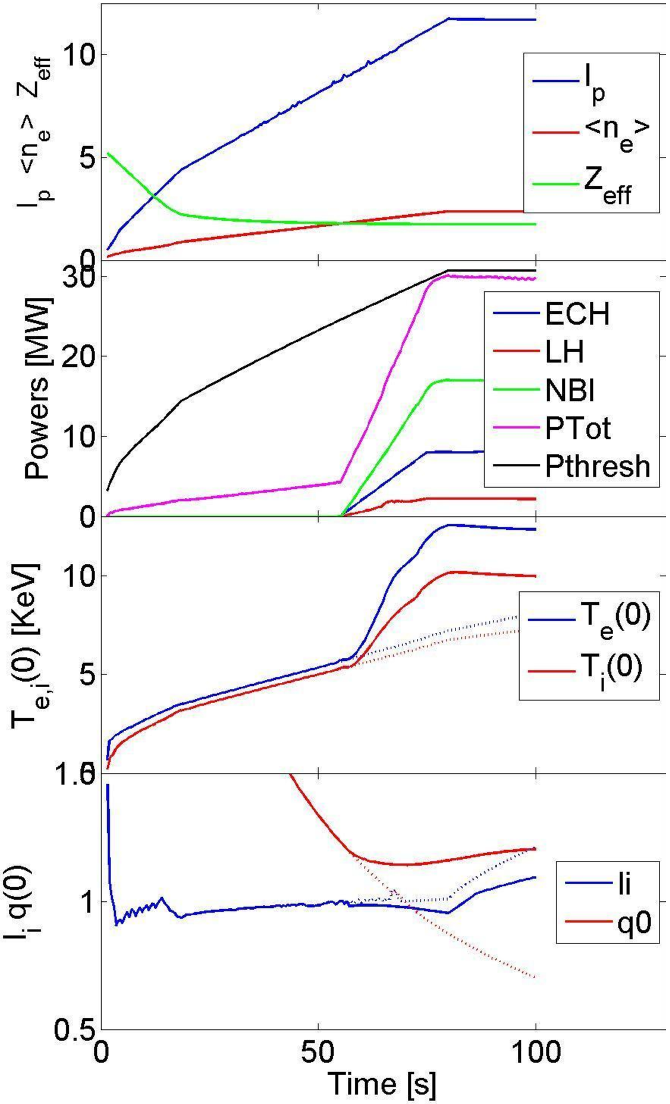


Example of driven current density profiles:
8 [+5] MW of ECCD from UPL
3 MW of LHCD
16.5 MW of NBI (green).
Plus bootstrap current
And total non-inductive current

4. Reference scenario with and without LHCD *(ctd)*

b. Best scenario with LHCD using scaling model



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Lower frames: also time traces without additional heating (dotted)

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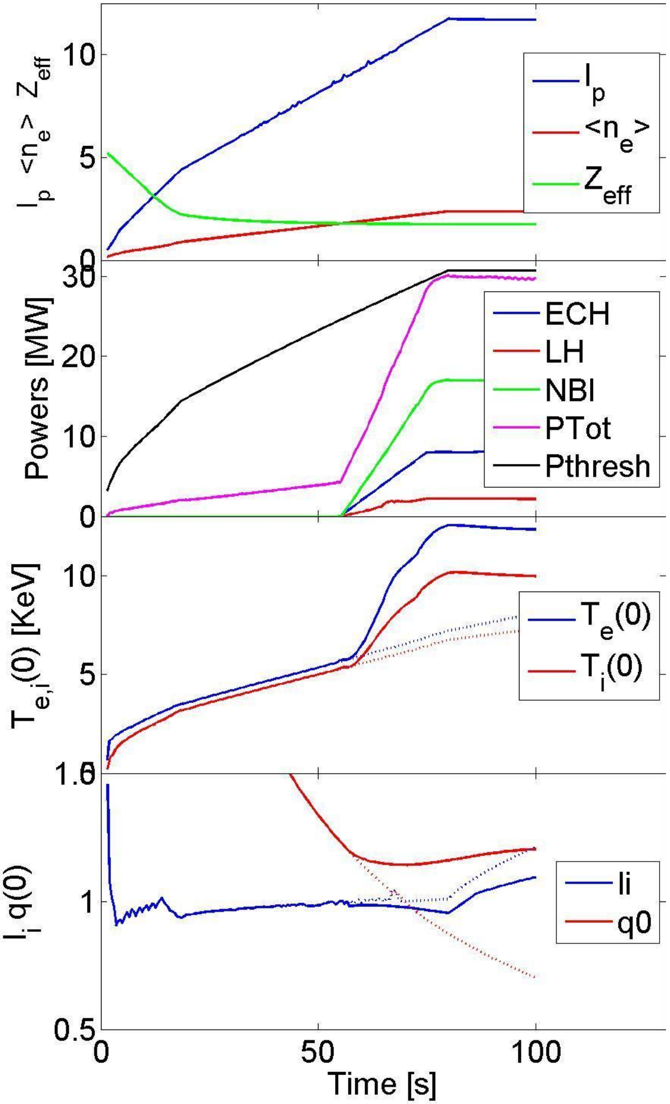

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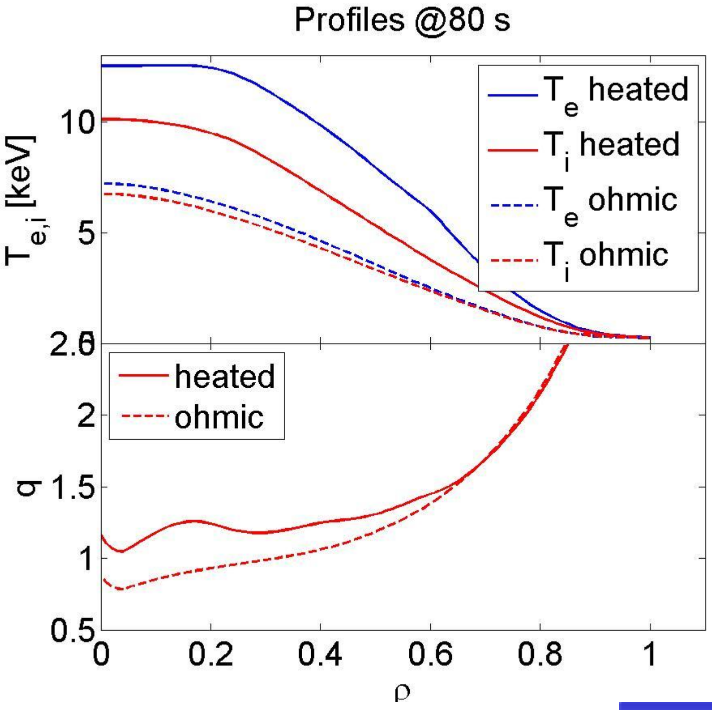


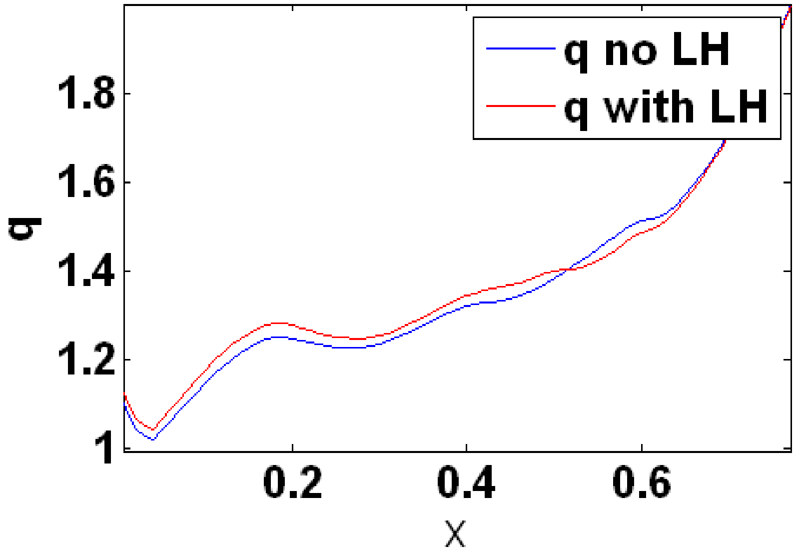
Dick Hogeweij, 21th ITC, Toki, Japan, 28 November 2011

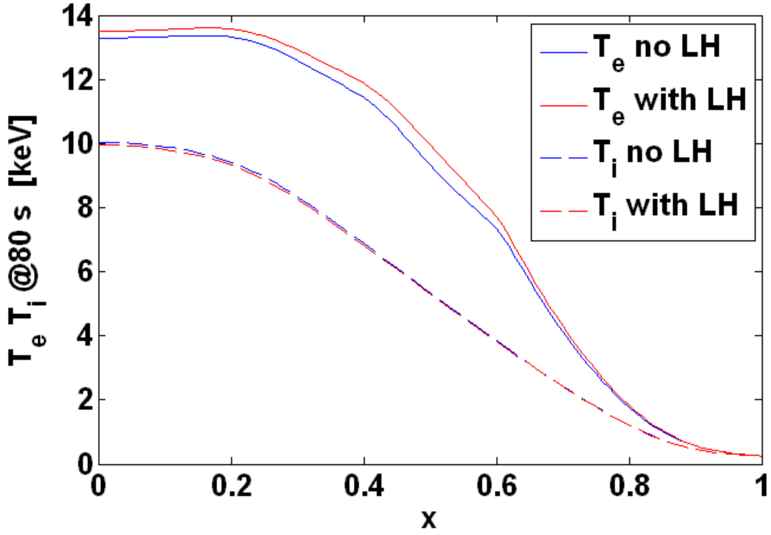
4. Reference scenario with and without LHCD *(ctd)*

c. scenario without LHCD (still using scaling model)

What happens if we do not use LH (power was 3 MW)?

Compare profiles at end of ramp-up (80 s), using scale model:





Conclusion *for end of ramp-up*: LHCD has only marginal effect both on q and on T_e (because it is so far off-axis)

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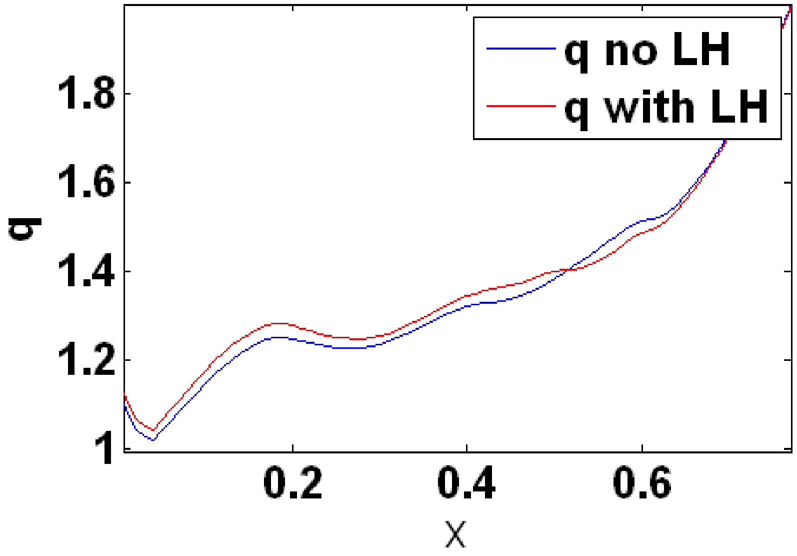
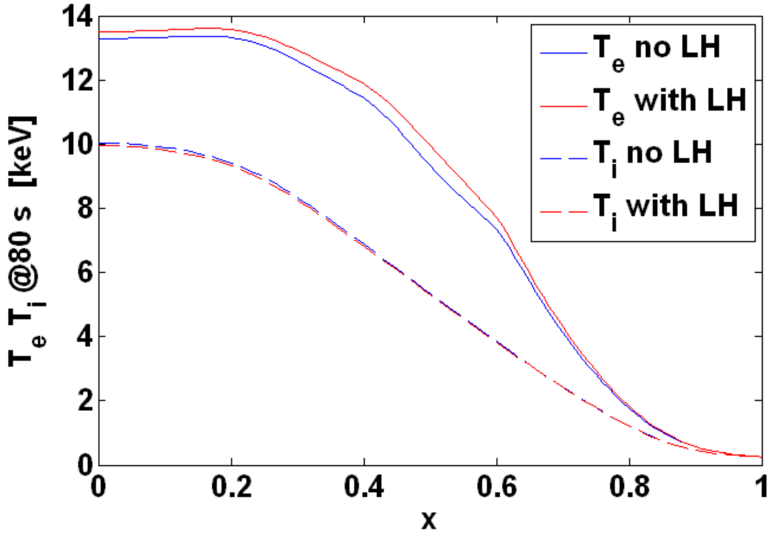




Conclusion *for end of ramp-up*: LHCD has only marginal effect both on q and on T_e (because it is so far off-axis)

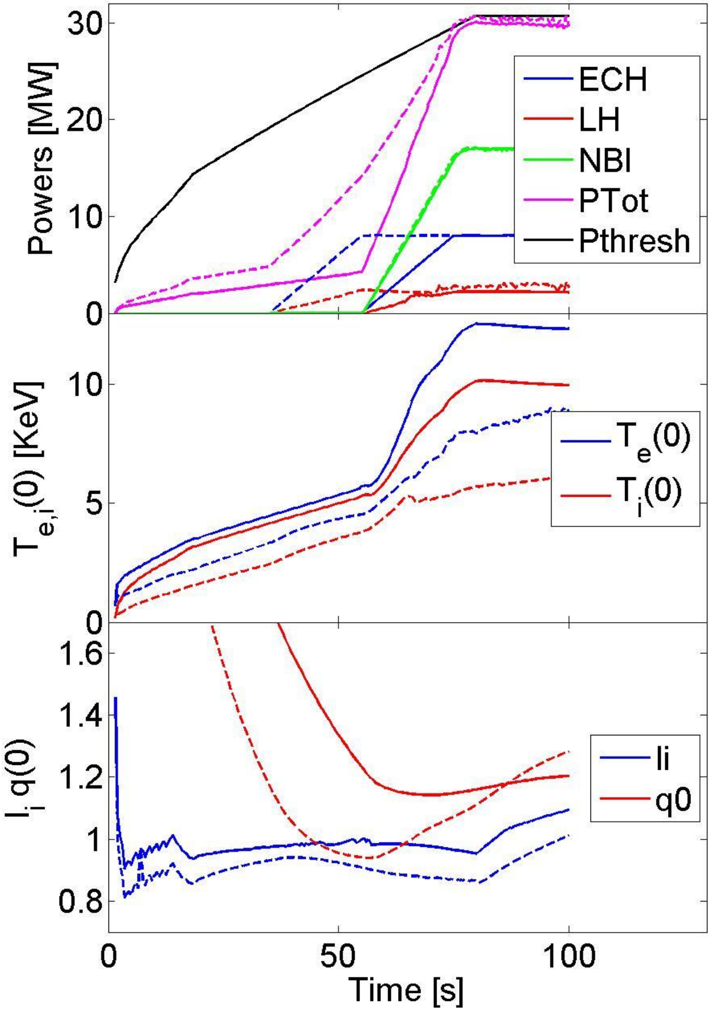
However, LHCD is most efficient current driver, in particular in early phase of ramp-up → early switch-on of LHCD can reduce flux consumption significantly (~10-15%), thus enabling extension of burn phase by several 100s of seconds

5. Sensitivity analysis

a: choice of transport model

Bohm-gyroBohm model is more pessimistic than scaling model

Predicted faster current penetration compensated by 20 s earlier switch-on of LH + ECH



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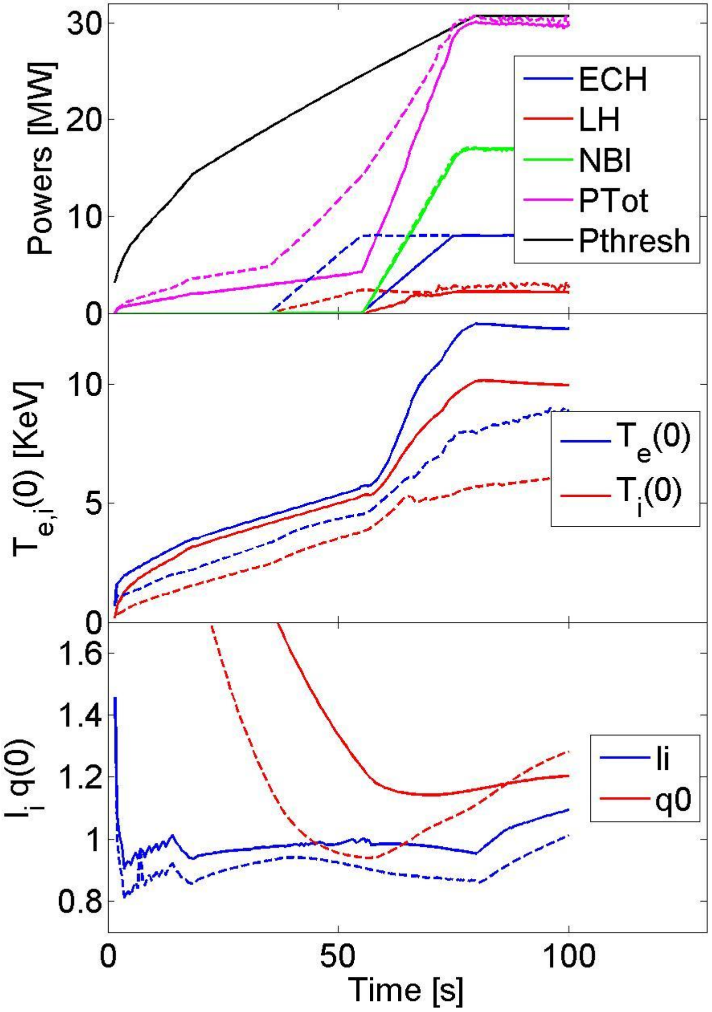

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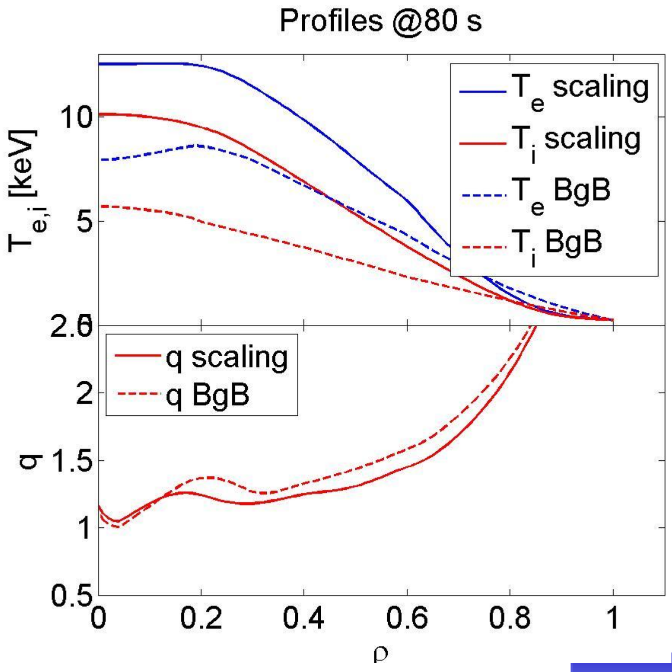

Right: $T_{e,i}$ and q profiles @ 80 s for the same cases

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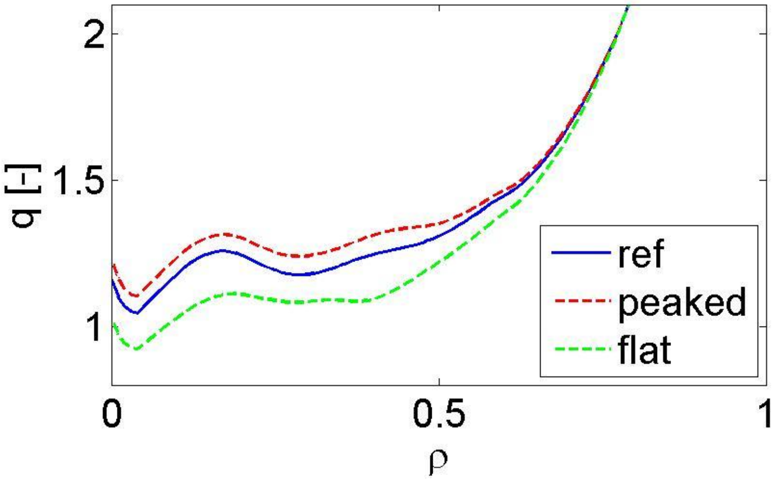
b: effect of Z_{eff} and of density profile shape

Current density evolution affected by n_e shape:

more/less peaked n_e → flatter/more peaked T_e

→ slower / faster current penetration



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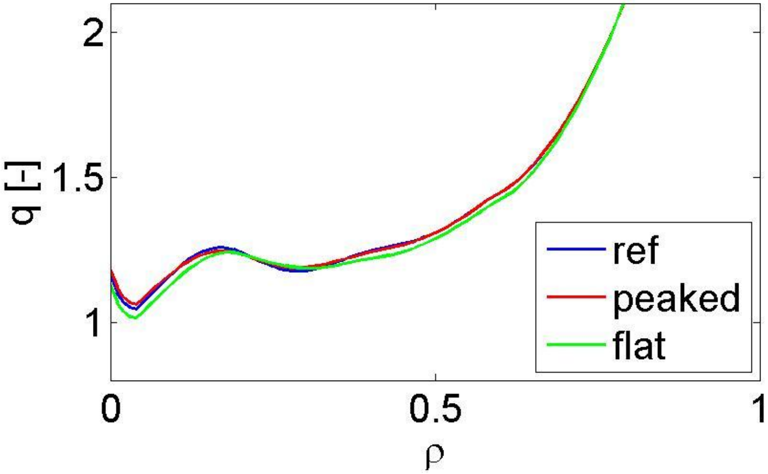

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5-10 s later / earlier heating

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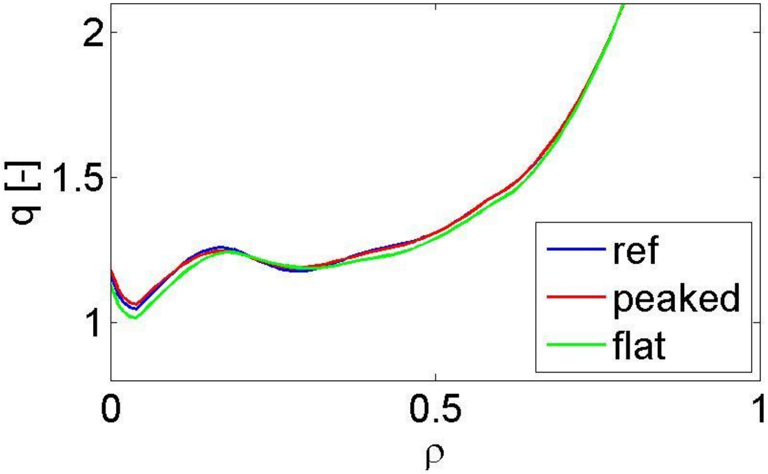
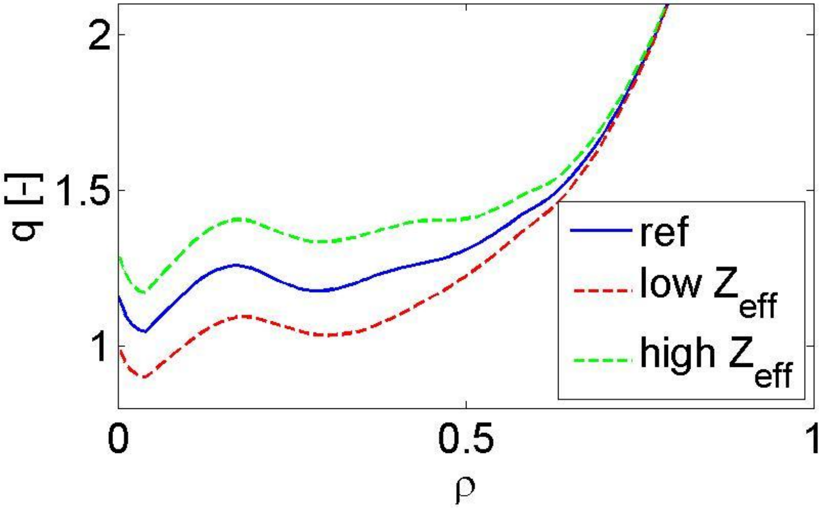
Similar effect of Z_{eff} :
lower/higher Z_{eff} →
slower / faster current diffusion





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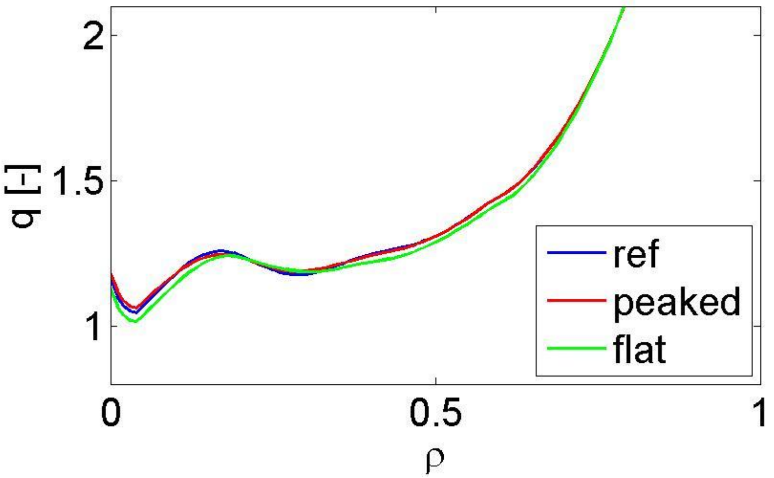

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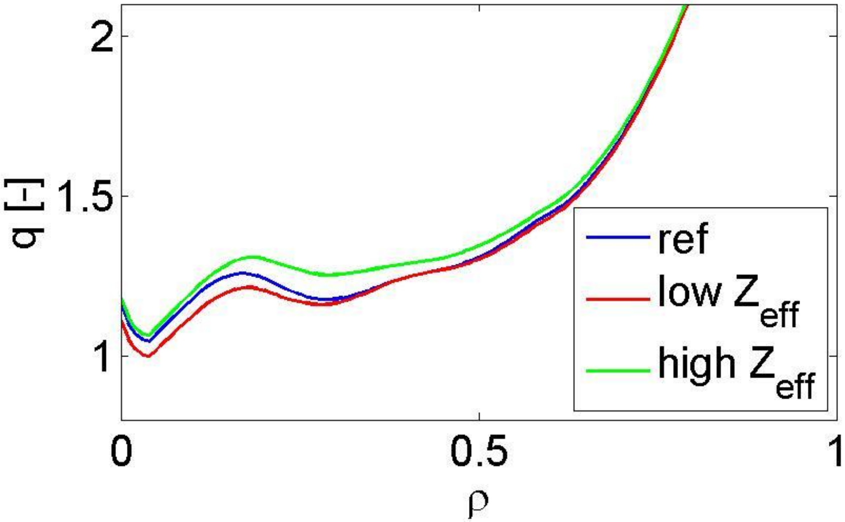

Effect can be counteracted by
10-15 s later / earlier heating

5. Sensitivity analysis *(ctd)*

c: effect of lower/higher density, of lower/higher $T_{e,i}$(edge), and of initial geometry

Lower / higher density (modelled 0.15 / 0.35 n_{eGW} in stead of 0.25 n_{eGW}):

Can be accounted for in similar way (not shown here)

higher density may be profitable:

- Higher L-H threshold power;
- NBI can be switched on earlier (less risk of shine-through)

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Lower/higher edge temperature:

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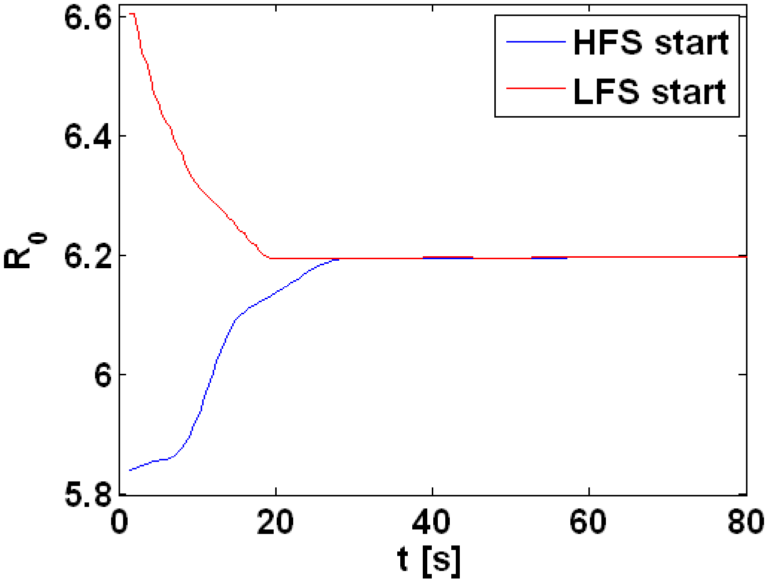
Initial geometry:

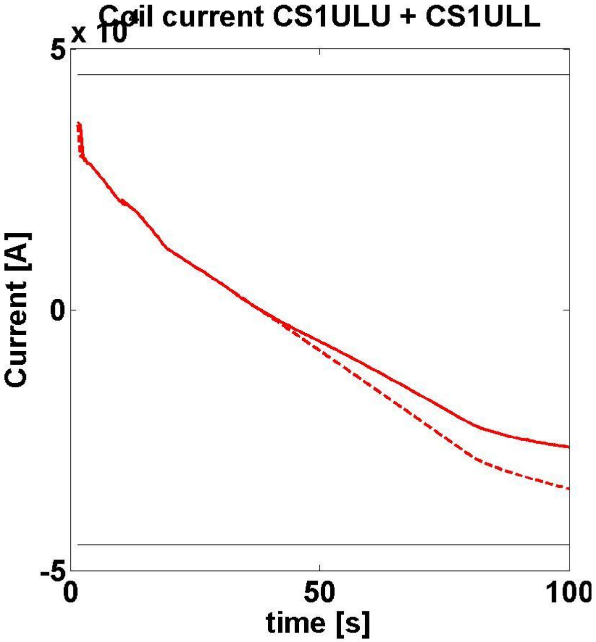
Recently the ITER team is considering breakdown at HFS instead of at LFS → different geometry in very early phase of the discharge. Effect of this on the current density evolution turns out to be negligible after ~40s

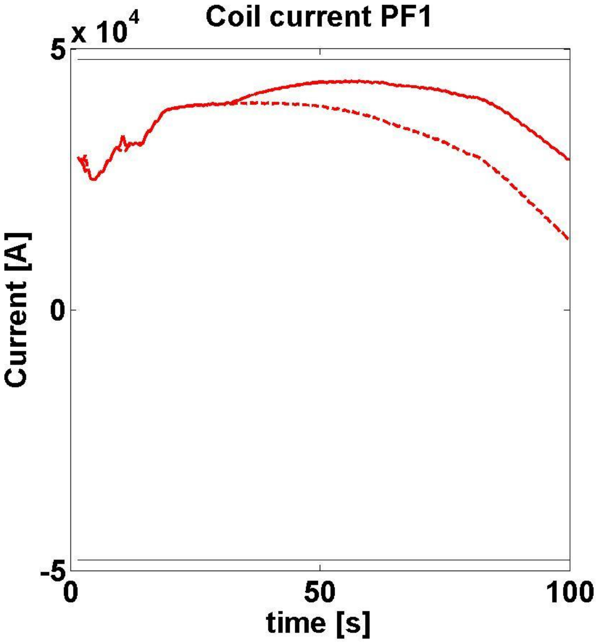


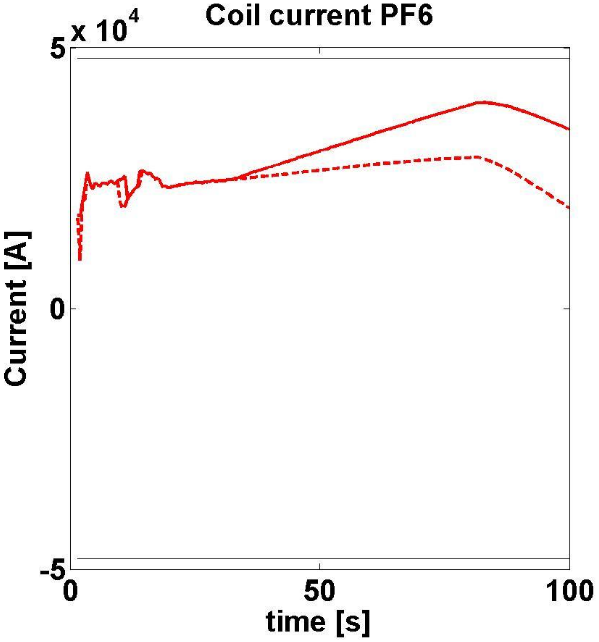
6. Check of operational limits

FREEBIE code (CEA Cadarache) has been used to post-process simulation results

It shows that scenario is well within operational limits







Currents in the most critical coils, i.e.

in central solenoid coils CS1ULU+CS1ULL

and in the poloidal field coils PF1 and PF6

for typical heating scheme (full lines) and for case with only ohmic heating (dashed)

7. Conclusions

The heating systems available at ITER allow the attainment of a hybrid q profile at the end of the current ramp-up, using NBI, ECCD (UPL) & LHCD

A heating scheme with only NBI and ECCD is almost effective for attainment of hybrid q profile

However, LHCD most effective when it comes to save flux consumption

FREEBIE post-processing shows scenario well within operational limits

7. Conclusions *(ctd)*

Regarding sensitivity analysis:

- Optimum heating scheme depends on chosen transport model.
- Modified assumptions on n_e peaking, edge T_{ei} and Z_{eff} can be easily accounted for by a shift in time of the heating scheme
- Higher density during the ramp-up phase can be accounted for equally well, and might even be profitable because it gives more freedom in the application of the CD sources

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Outlook:

Current diffusion sensitive on parameters that cannot be controlled

→ development of real time control important to assure target q profile

→ positive: effect of deviation of assumed parameters like Z_{eff} or n_e peaking can be accounted for in straightforward [linear] way, i.e. in a way suitable for a controller

Minimization of flux consumption needs further study

Discrepancy between Bohm-gyrobohm and scaling model (in contrast with results om existing experiments) calls for further analysis