Role of impurities in ITER-like ramp-up in JET

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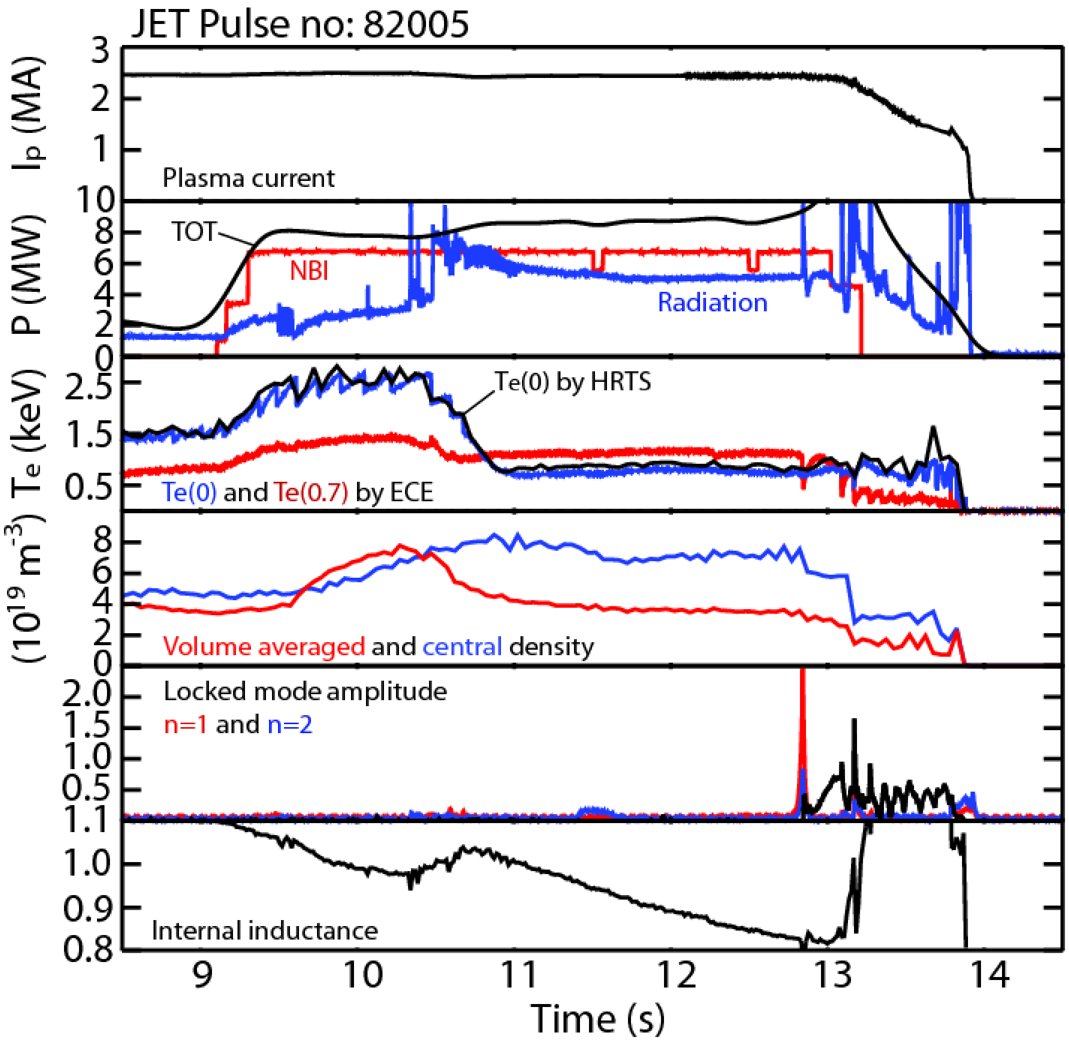
Motivation: with ILW in JET some discharges develop strong core ratiation



Example pulse 82005:

P_{rad} (suddenly) increases (10.5s)

(P_{rad} remains below P_{tot})

Observations:

- Temperature profile hollow; Sawteeth disappear
- Strong density peaking
- Although n_e and T_e stabilize, l_i and q keep changing
- n=1,n=2 MHD activity → mode locking →disruption

Question: what W concentration can the plasma "survive"

in JET-ILW as template for ITER

Here we concentrate on the current ramp-up phase (which is most vulnerable)

Outline

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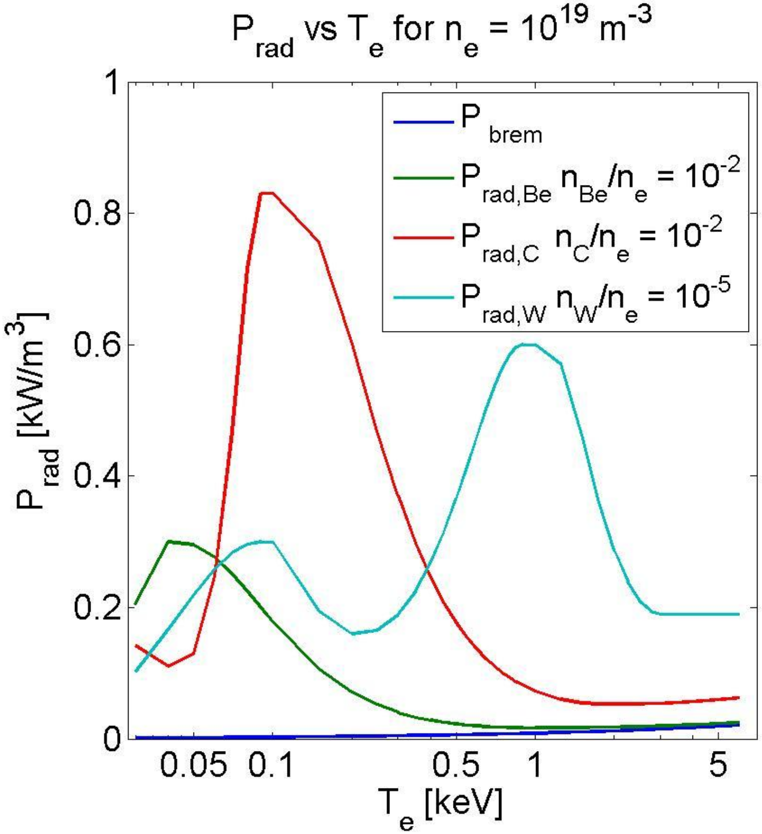
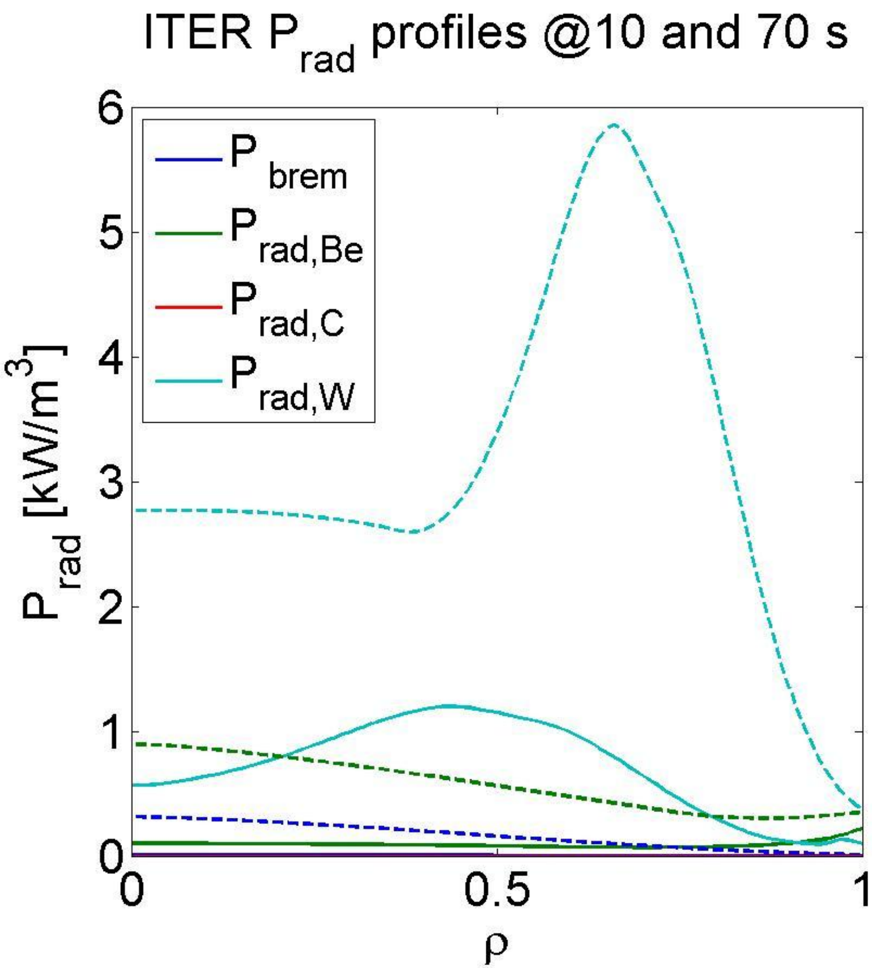
- What radiation can we expect
- Identify 2 pairs of similar ramp-ups, one with C-wall and one with ILW
  one pair ohmic, one pair with few MW of ICRH
- Note on modelling of q profile evolution during ramp up
  need peaked Z_{eff} profile to get correct q profile evolution
- Effect of replacing C^{6+} → Be^{4+} → Be^{4+} + small conc. of W for ohmic ramp-up:
  - ✓ ***interpretative***: *effect on q profile evolution and radiation (using exp. n_e , $T_{e,i}$, Z_{eff})*
  - ✓ ***predictive:*** *effect on T_e & q profile evolution and radiation (using exp. n_e ,T_i , Z_{eff})*
- Same exercise for ohmic ITER ohmic ramp-up

What next:

- Compare with q profile evolution and radiation in similar ILW ramp-up
- Repeat modelling for JET discharge with ICRF heated ramp-up
- H-mode transition during ramp-up

What radiation to expect from C, Be and W?





Radiation as function of T_e

(assuming corona equilibrium)

Note W conc. 10^3 times lower than C, Be

W radiation peak at 1 keV

Identity pairs

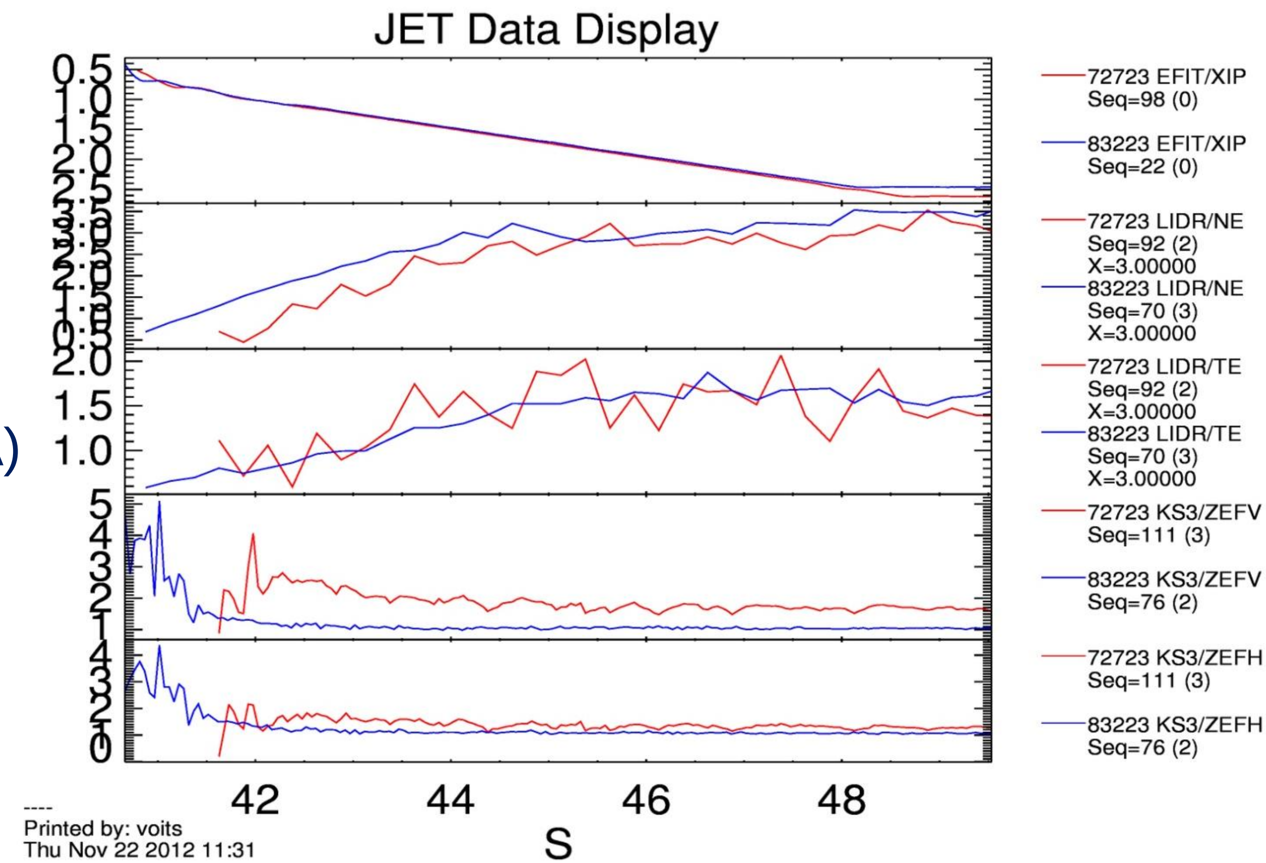
Ohmic identity pair:

✓same dI_p/dt: 0.28MA/s

✓similar n_e

C: 72723 (2.4T/2.6MA),

ILW: 83223 (2.4T/2.5MA)



Identity pair with ICRH heating:

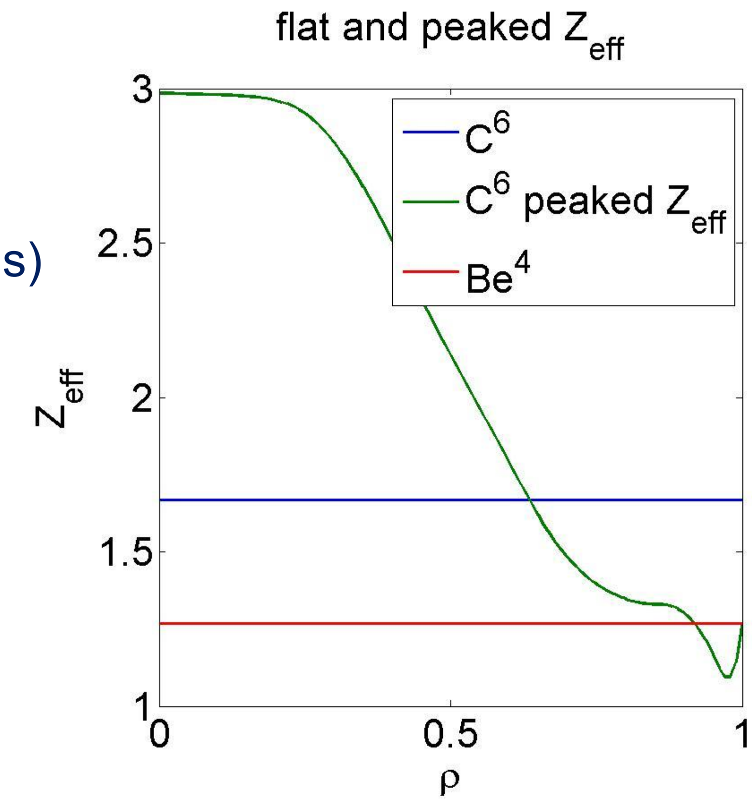
C: 72507

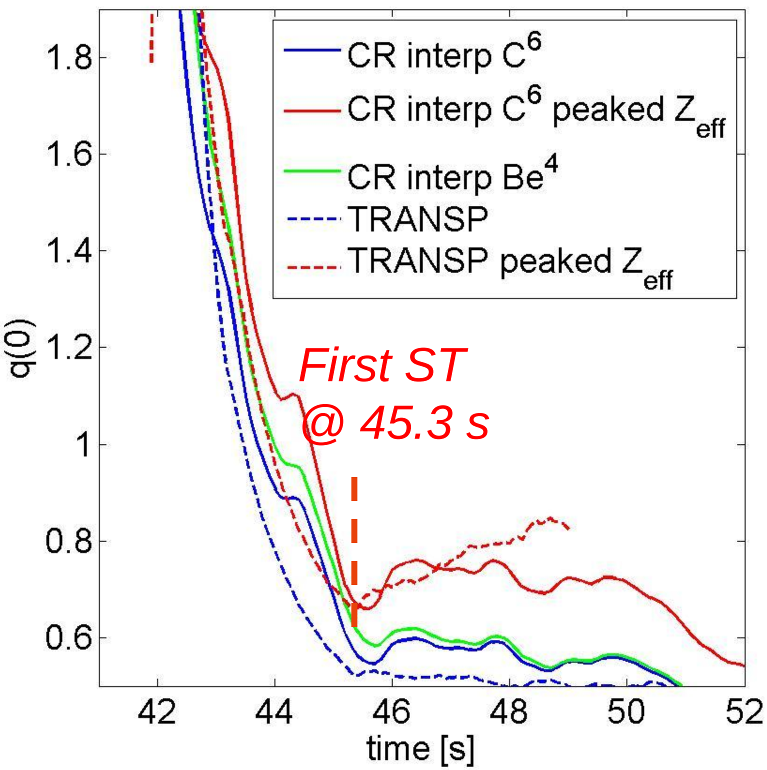
ILW: 83449 (lower ICRH power, different wave form)

q profile evolution # 72723
get evolution right with peaked Zeff

Interpretative CRONOS runs:

- Start at 41.5 s with exp. Te, ne etc.
- Use exp data, calculate q profile evolution
- Use exp Zeff, assuming flat or peaked profile (the latter taken from Irina's TRANSP runs)





Correct q profile evolution:
NOT q(0) = 1 at time of first ST,
BUT q(0) < 1 and $q(\rho_{inv}) = 1$ at first ST crash

q profile evolution # 72723
get evolution right with peaked Zeff

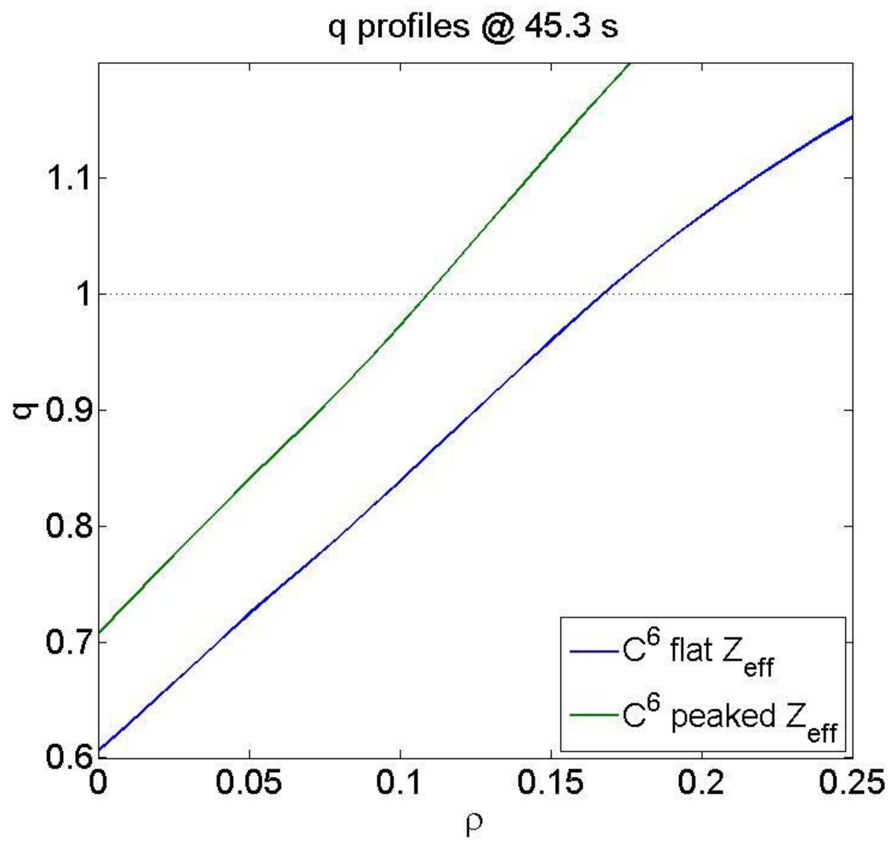
Correct q profile evolution:
NOT q(0) = 1 at time of first ST,
BUT q(0) < 1 and q(ρ_{inv}) = 1 at first ST crash

Infer dimensionless inversion radius from fast ECE diagnostic (KK3):

ρ_{inv}~0.075 at first ST

Looking at CRONOS q profile:
ρ_{inv} is too large @ 45.3s, correct @ 44.7 s
So evolution is "only" 0.6 s too fast

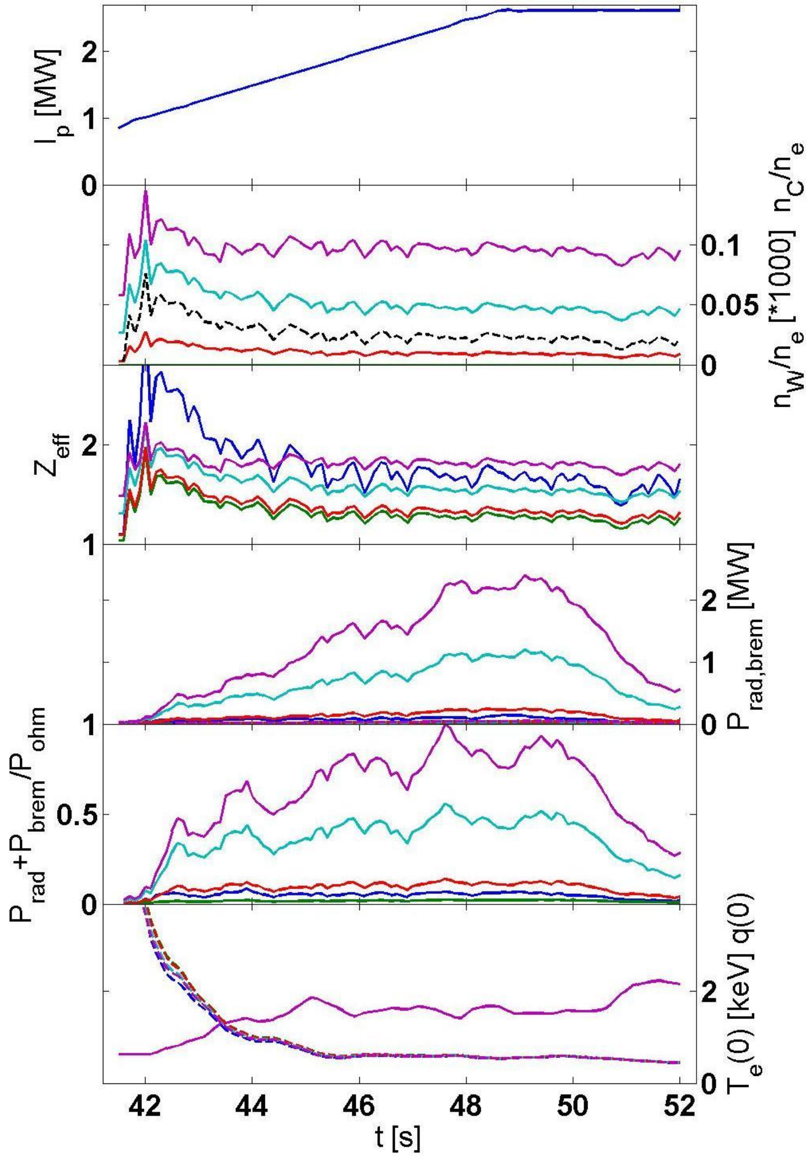
With moderately peaked Z_{eff} profile
q profile evolution is "on time" *(see plot)*



Note: in the rest of the presentation we do not bother about too fast q evolution, we simply assume flat Z_{eff} profile

Interpretative 72723
Replacing C^{6+} → Be^{4+} and adding traces of W

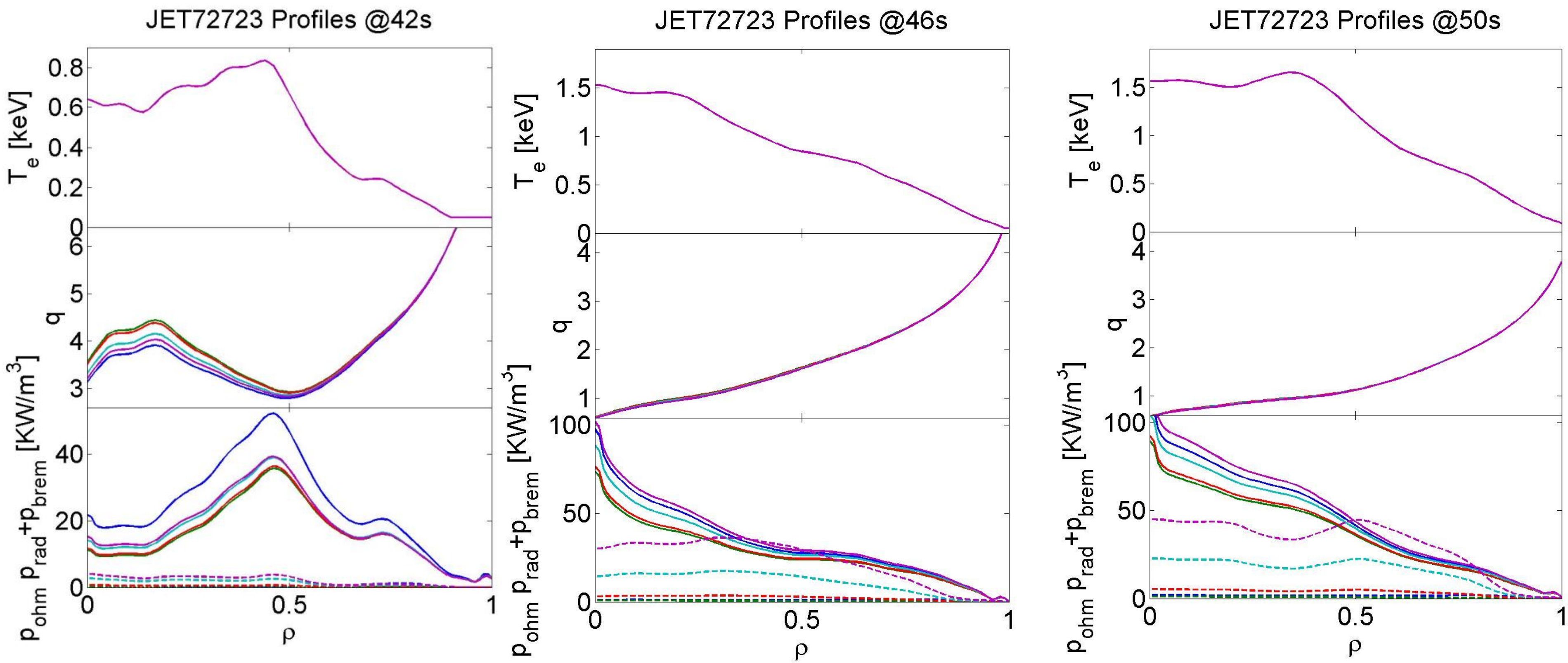
Blue: only impurity is C^{6+}, Z_{eff} as measured
Green: C^{6+} replaced by same concentration Be^{4+} (hence with lower Z_{eff})
Red: same Be^{4+} , added W, $n_W/n_e = 10^{-5}$
Cyan: same Be^{4+} , added W, $n_W/n_e = 2\ 10^{-5}$
Magenta: same Be^{4+} , added W, $n_W/n_e = 10^{-4}$
Black dashed line in 2nd frame: n_C/n_e (=nB_{Be}/n_e)



Notes:

- Flat Z_{eff} assumed
- These are interpretative runs, i.e. T_e taken from data – unrealistic when strong radiation present
- Addition of 10^{-5} W brings Z_{eff} more or less back to original level *(2nd panel)*
- With 10^{-4} W the radiation loss nearly equals ohmic input power at end of ramp-up*(4th panel)*
- Tiny effect on q profile evolution *(5th panel)*

Interpretative 72723 (ctd)
Replacing C^{6+} → Be^{4+} and adding traces of W



Same colour coding as previous plots

Notes:

- Initial off-axis peak in j and thus in p_{ohm} (due to off-axis peaked Te)
- Effect of addition of 10^{-4} W on power balance becomes strong towards end of RU
- Effect on q profile evolution only in very early phase

Predictive modelling JET ramp-up

Notes:

- Start from experimental profiles at 41.s (i.e. 1.5 s after brak-down)
- Use experimental n_e and Z_{eff}
- Assume flat Z_{eff}
- Calculate self-consistently evolution of T_e, T_i and q

In the past 2 models were successful in predicting the evolution durint ramp-up:

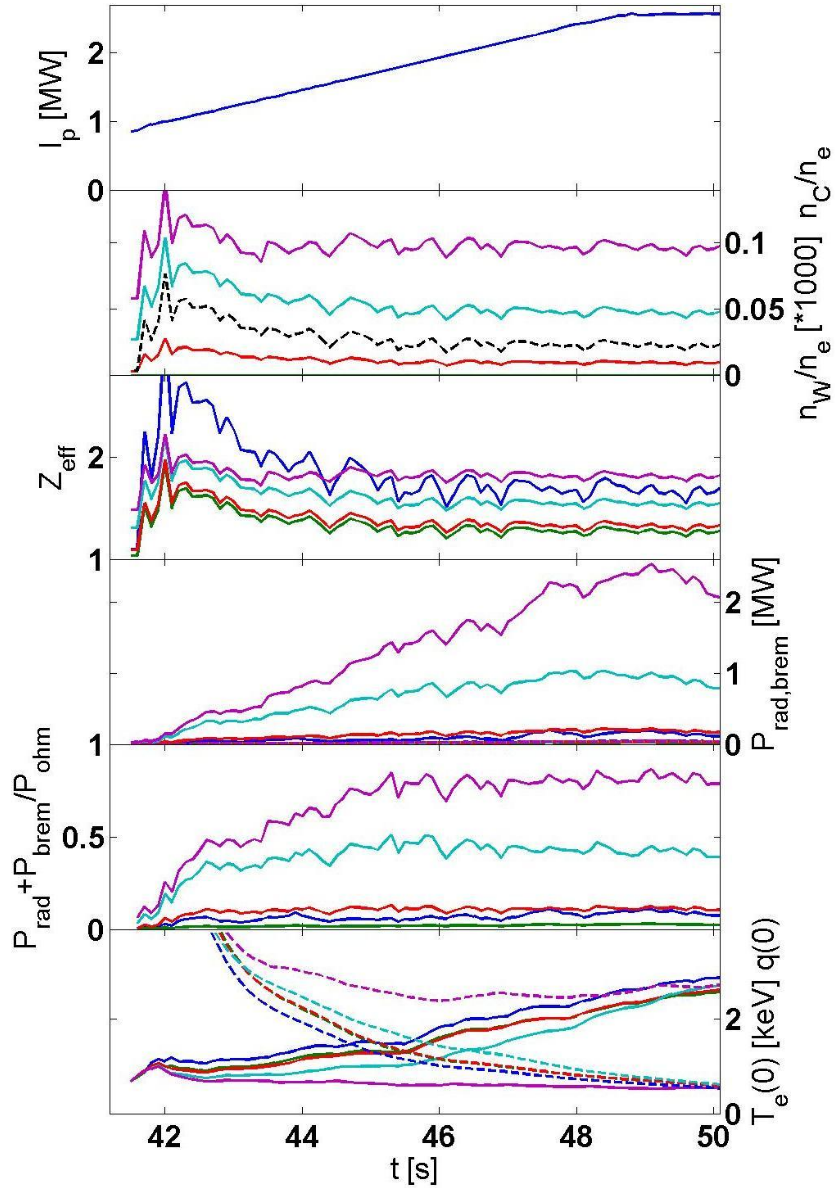
- Empirical scaling model, using either L- or H-mode scaling law,
  with correction factor 0.6 / 0.4 for L / H scaling
  (both equally good, use H-mode scaling here)
- Semi-empirical Bohm-gyroBohm model *[original, L-mode form]*

Both will be used in the following

Note: first-principle model like GLF23 does not work well in L-mode ramp-up phase

Predictive 72723 – scaling model
Replacing $C^{6+} \rightarrow Be^{4+}$ and adding traces of W

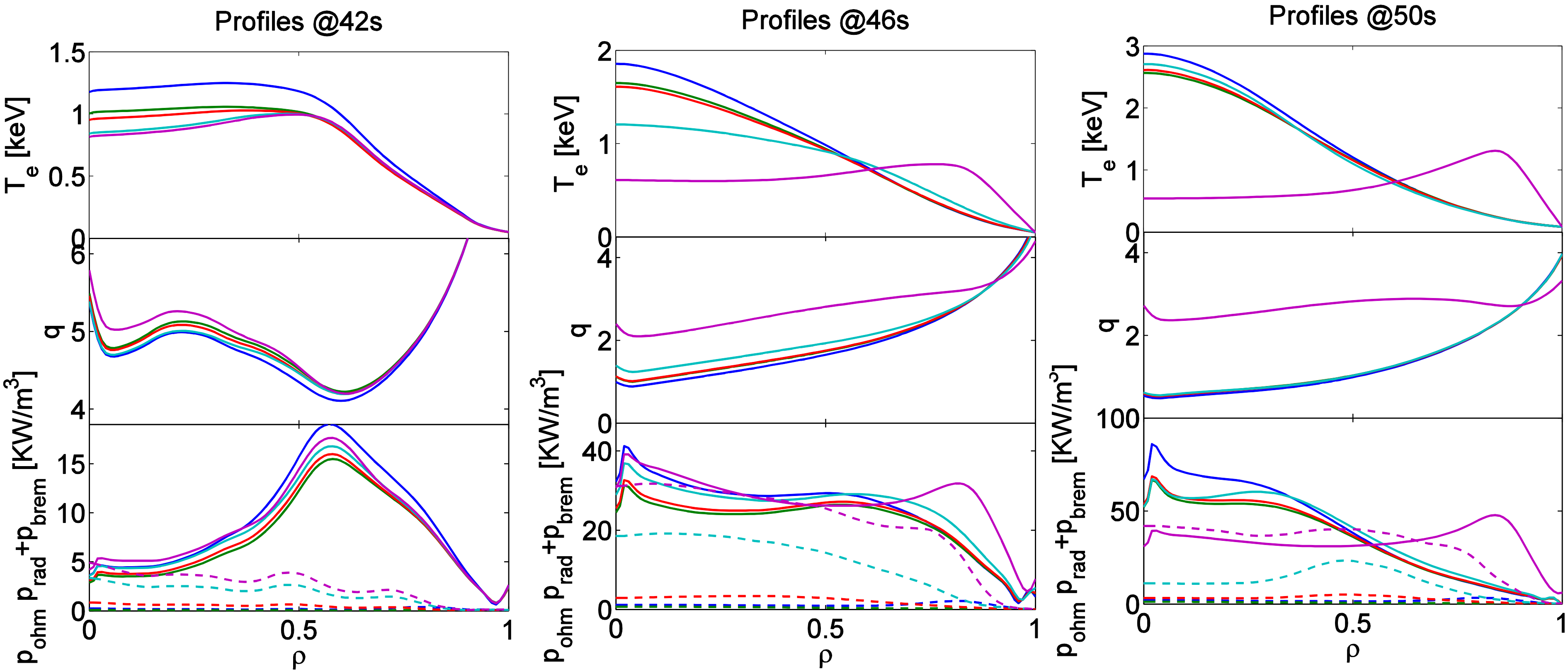
Same colour coding as previous plots



Notes:

- Addition of W with n_W / n_e up to 2 10^{-5} does not have strong effect on evolution of T_e and q *(5th panel)*
- With n_W / n_e = 10^{-4} Prad / Pohm increases to nearly 1 *(4th panel)*, and the evolution of T_e and q becomes totally different *(5th panel)*

Predictive 72723 – scaling model (ctd)
Replacing C^{6+} → Be^{4+} and adding traces of W



Same colour coding as previous plots

Notes:

- Initial off-axis peak in j and thus in p_{ohm} (due to off-axis peaked T_e)
- Add W with n_W / n_e up to 2 10^{-5} → no strong effect on evolution of T_e and q
- $n_W/n_e = 10^{-4}$ → T_e & q evolution totally different, hollow T_e, flat q *(plasma just survives)*
- *Weird results at high W conc. due to peculiarity of scaling model*

  → Bohm-gyroBohm better!

Predictive 72723 – Bohm-gyroBohm model
Replacing C^{6+} → Be^{4+} and adding traces of W

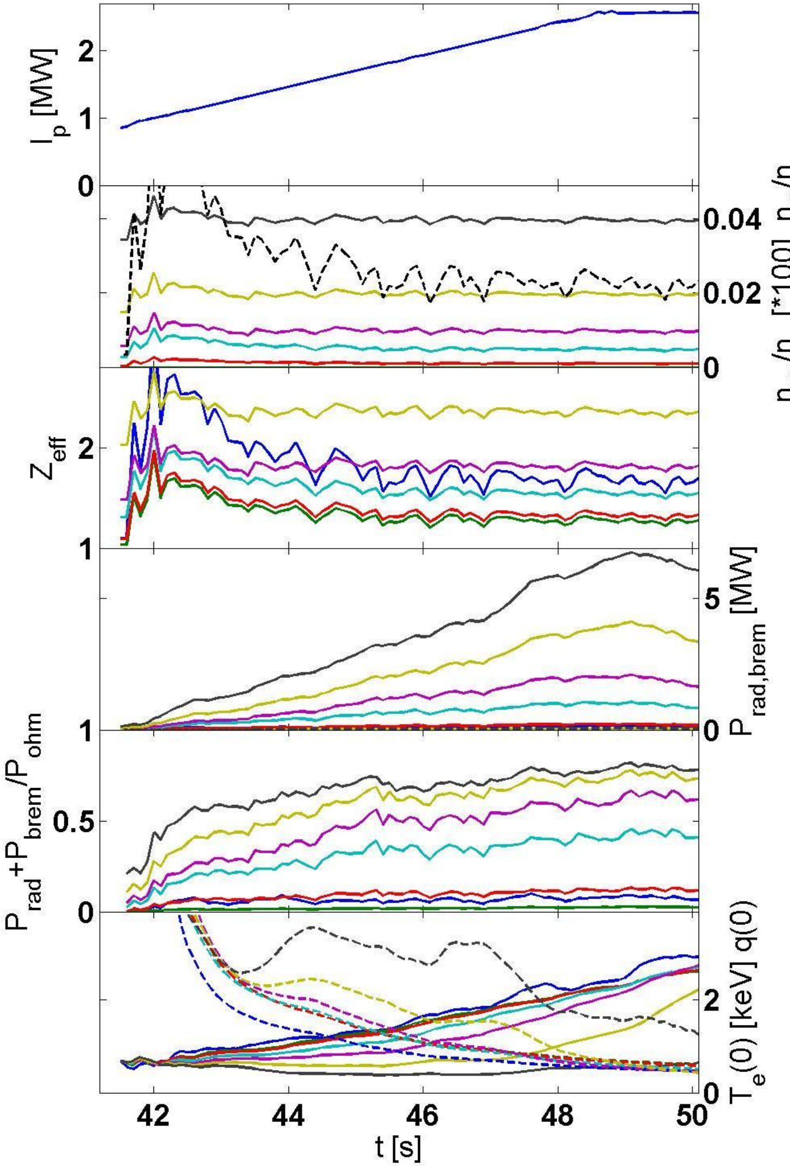
Same colour coding as previous plots, PLUS:

Pale green : same Be^{4+} , added W, n_W/n_e = 2 10^{-4}

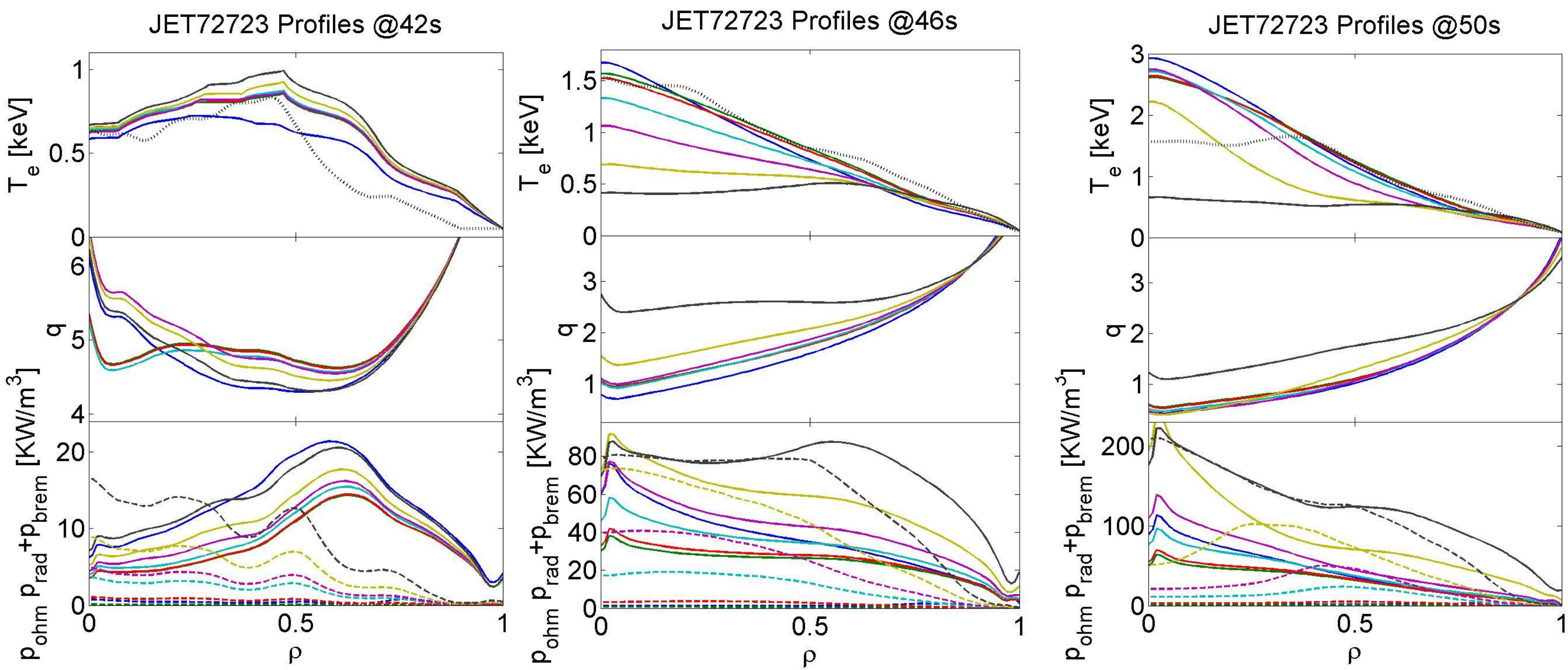
Black: same Be^{4+} , added W, n_W/n_e = 4 10^{-4}

Notes:

- Addition of W with n_W / n_e up to 10^{-4} does not have strong effect on evolution of Te and q *(5th panel)*
- With n_W / n_e >= 2 10^{-4} the evolution of Te and q becomes totally different *(5th panel)*



Predictive runs – Bohm-gyroBohm model (ctd)
Replacing C^{6+} → Be^{4+} and adding traces of W



Same colour coding as previous plots;
exp T_e = dotted black curve in upper panel

Notes:

- Initial off-axis peak in j and thus in p_{ohm} (due to off-axis peaked T_e)
- n_W / n_e up to 2 10^{-5} → no strong effect on evolution of T_e and q
- n_W/n_e = 1-2 10^{-4} → T_e & q evolution modified in RU (46s), but restores in flat-top (50s)
- n_W/n_e = 4 10^{-4} → plasma cannot cross radiation barrier, profiles totally spoiled

ITER Predictive runs – Bohm-gyroBohm model Replacing C^{6+} → Be^{4+} and adding traces of W

Ohmic simulations;

Flat Zeff assumed, as given by ITER team
(i.e. Z_{eff} decreasing with increasing density);

Bohm-gyro model used, original L-mode version

Blue: only impurity is Be4+,

Green: same Be4+, added W, nW/ne = 10^{-5}

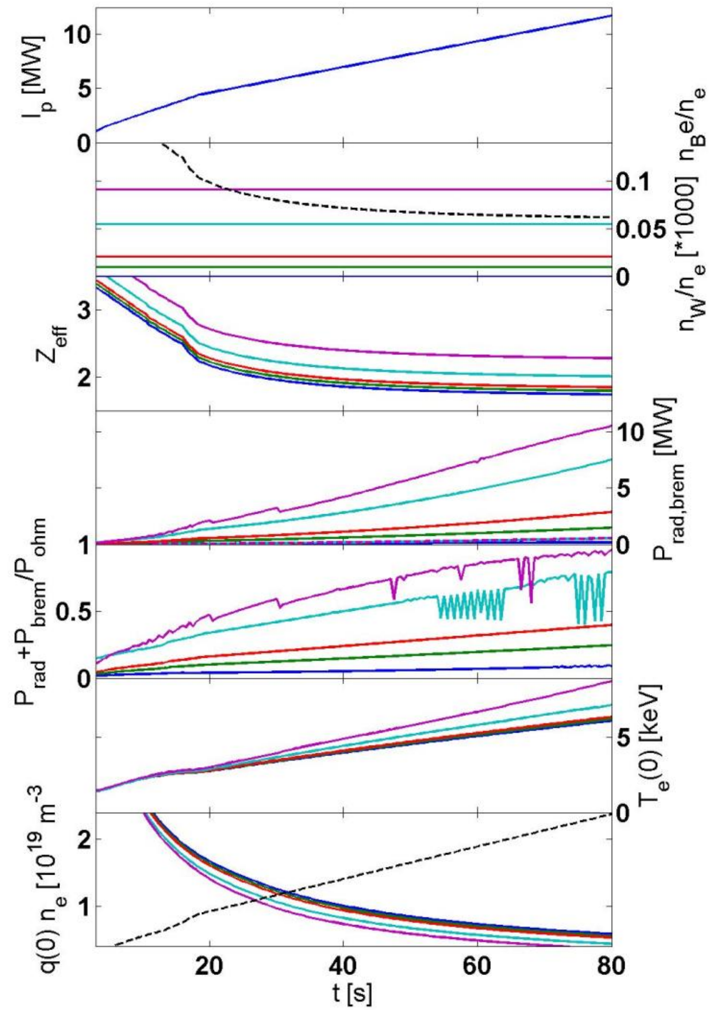
Red: same Be4+, added W , nW/ne = 2 10^{-5}

Cyan: same Be4+, added W , nW/ne = 5 10^{-5}

Magenta: same Be4+, added W , nW/ne = 10^{-4}

Black dashed line in 2nd frame: nB_e/n_e

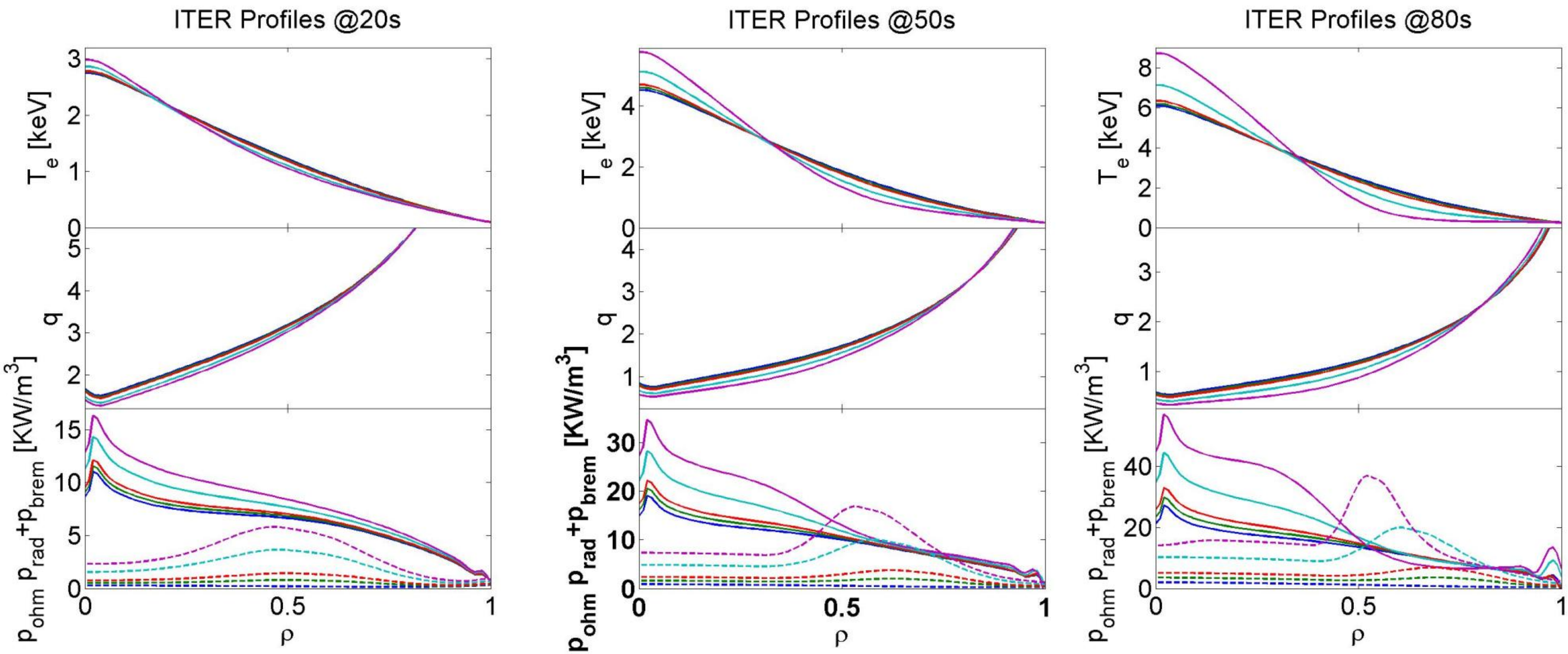
Black dashed line in last frame: line averaged n_e



Notes:

- Addition of W with n_W / n_e <= 2 10^{-5} does not have strong effect on evolution of Te and q
- With n_W / n_e = 10^{-4} the radiation loss approaches the ohmic input power, and the evolution of Te and q are more affected

ITER Predictive runs – Bohm-gyroBohm (ctd) Replacing C^{6+} → Be^{4+} and adding traces of W



Same colour coding as previous plots

Notes:

- One sees W radiation peak shift outward as Te increases
- With n_W / n_e = 10^{-4} the Te profile develops a 0 region outside ρ ~0.7, thus inducing strong peaking of current density

Conclusions & Outlook

Conclusions for JET:

- For an ohmic ramp-up at moderate density, assuming flat Z_{eff} and uniform n_W / n_e the critical W concentration is n_W / n_e is ~10^{-4}
- Above this W concentration, the plasma cannot cross the radiation barrier, thus staying at a flat/hollow T_e profile below 1 keV

Conclusions for ITER:

- For an ohmic ramp-up at moderate density, assuming flat Z_{eff} and uniform n_W / n_e the critical W concentration is n_W / n_e is ~10^{-4}
- Above this W concentration, the T_e profile develops a 0 region outside ρ ~0.7, thus inducing strong peaking of current density

Conclusions & Outlook

Further work for JET:

- Same exercise for pulse with ICRF in RU: what W concentration is acceptable?
- Look at pulses with ILW: what was measured radiation level, what can one conclude about W concentration and profile (is n_W more peaked than n_e ?)

Further work for ITER:

- Problems can be mitigated by applying ECRH from early in RU – what W concentration would then be acceptable? *(some results on this will be added to presentation next week at ITPA-IOS)*

Comments from JET TF meeting Tue 9.4

- Z_{eff} in the simulations was too high because W was taken with charge 74 instead of the real charge ~30

  I cannot redo all simulations on short notice, but I will make a note on this – the effect on the evolution will be small, the main effect is the radiation
- For ITER also control of l_i is crucial, maybe even more than radiation collapse itself

  I will add l_i time traces to the ITER simulations
- Following previous comment: also MHD stability is an issue:

  If the plasma size is effectively reduced to e.g. 0.7, then what matters is not $q(\rho=1)$ but $q(\rho=0.7)$, and fatal MHD will happen when this value reaches 2.

  I will add a note on that, and could show time trace of e.g. $q(T_e=50\ eV)$
- When W concentration rises, also high flux consumption will be an issue for ITER

  I will add time traces of flux consumption to the ITER simulations
- Regarding JET 72723 modelling: it is likely that W concentration is low before X point formation and strongly rises after X point formation

  Correct, to be taken into account later on