Impact of W on current ramp-up phase in JET & ITER

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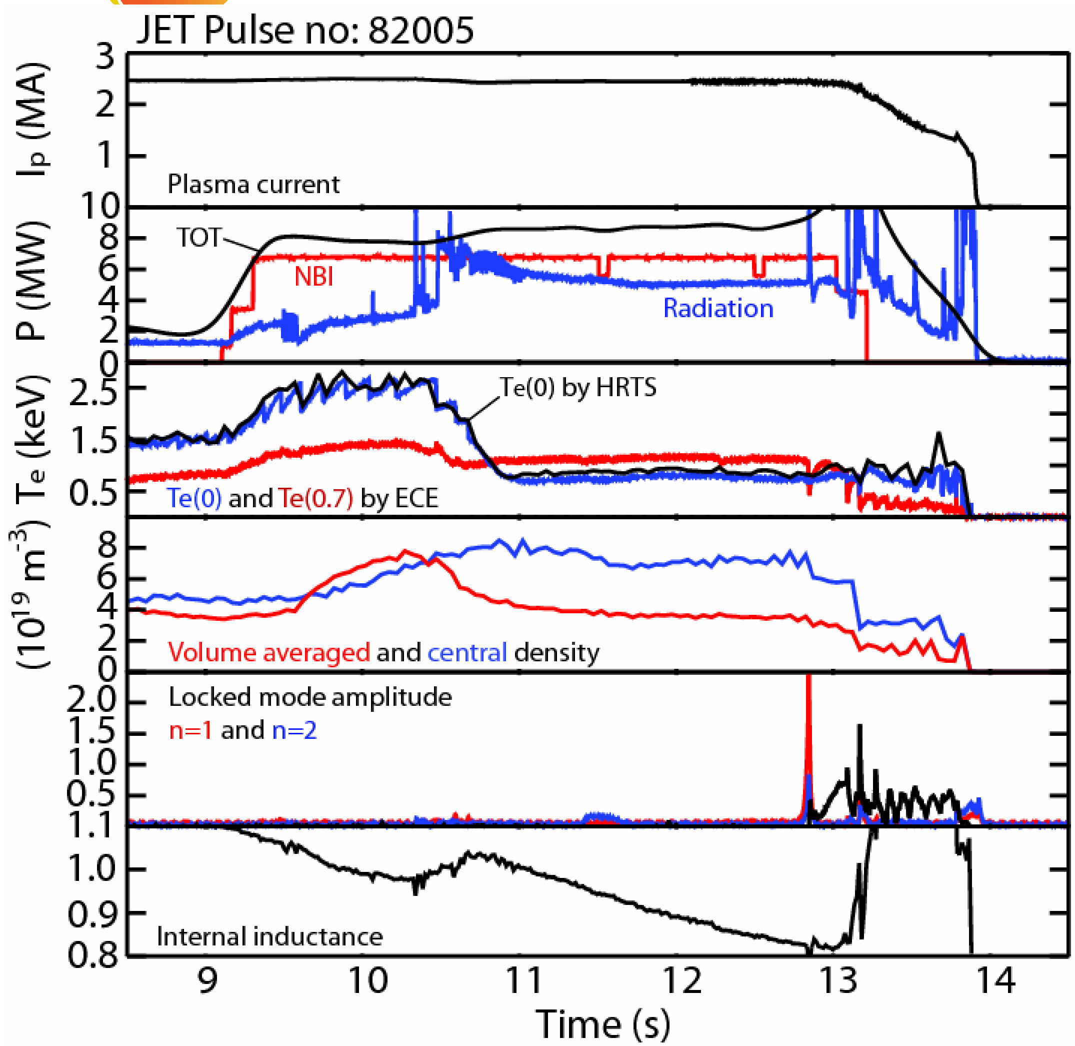
Motivation: with ILW in JET some discharges develop strong core radiation



Example pulse 82005:

P_{rad} (suddenly) increases (10.5s)
(P_{rad} remains below P_{tot})

Observations:

- T_e 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" (i.e. without strongly perturbing Te, q, li, etc.) in JET-ILW as template for ITER

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

Outline

Outline:

- ➢ 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
- ➢ 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:

- ➢ Analyze q profile evolution and radiation in ILW ramp-up case with
  strong W radiation (e.g. 82074)
- ➢ Repeat modelling for JET discharge with ICRF heated ramp-up
- ➢ H-mode transition during ramp-up

All simulations shown were done with the CRONOS suite of codes

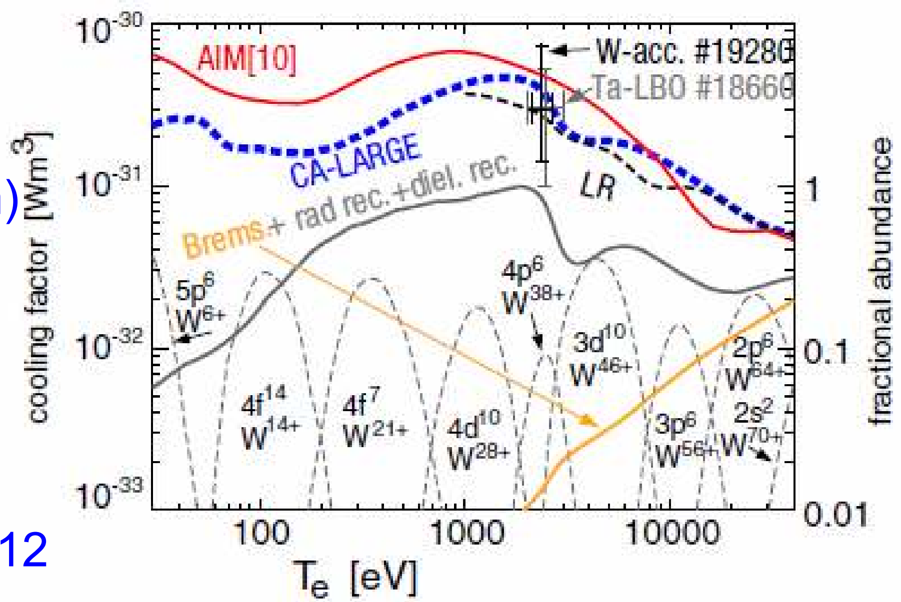
What radiation to expect: Radiation Model for W

a. Radiation data from D.Post. et al,

At. Data Nucl. Data Tables 20 (1977) 397

Uses "Average Ion Model" (corona equilibrium)

This is used in CRONOS



b. More sophisticated, using more detailed atomic physics:

Th.Pütterich et al, Nuc.Fusion 50 (2010) 025012

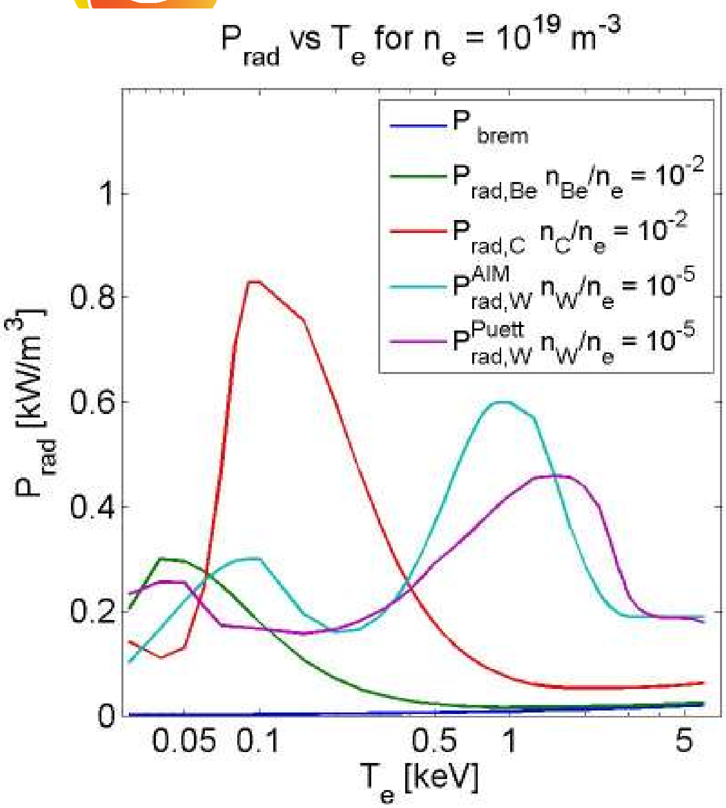
"Calculation and experimental test of the cooling factor of tungsten"

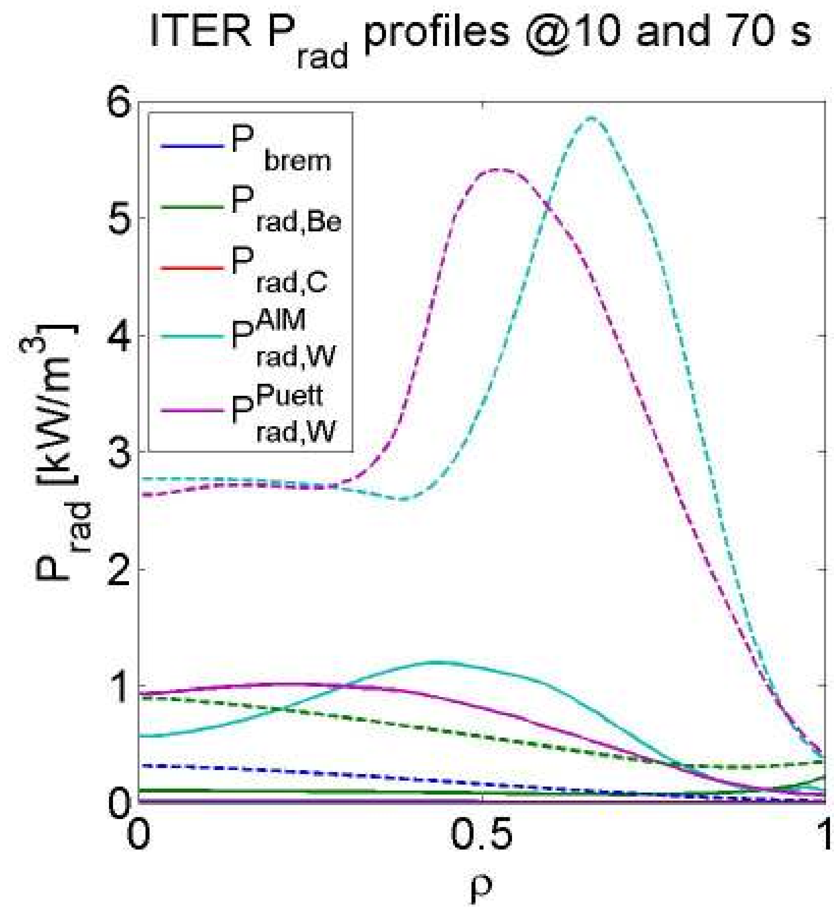
New data

- radiation peak shifted to slightly higher temperature (from 1 keV to ~1.5 keV)
- radiation peak bit lower and wider

(note logarithmic scale on both x and y axis!)

What radiation to expect from C, Be and W?





Radiation as function of T_e

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

For W both AIM and Pütterich

W radiation peak at 1 / 1.5 keV (AIM / Pütt)

Example from ohmic ITER ramp-up at modest $n_e = 0.25 * n_{GW}$ and $n_W / n_e = 10^{-5}$

full / dashed lines : @ 10 / 70 s

Identity pairs

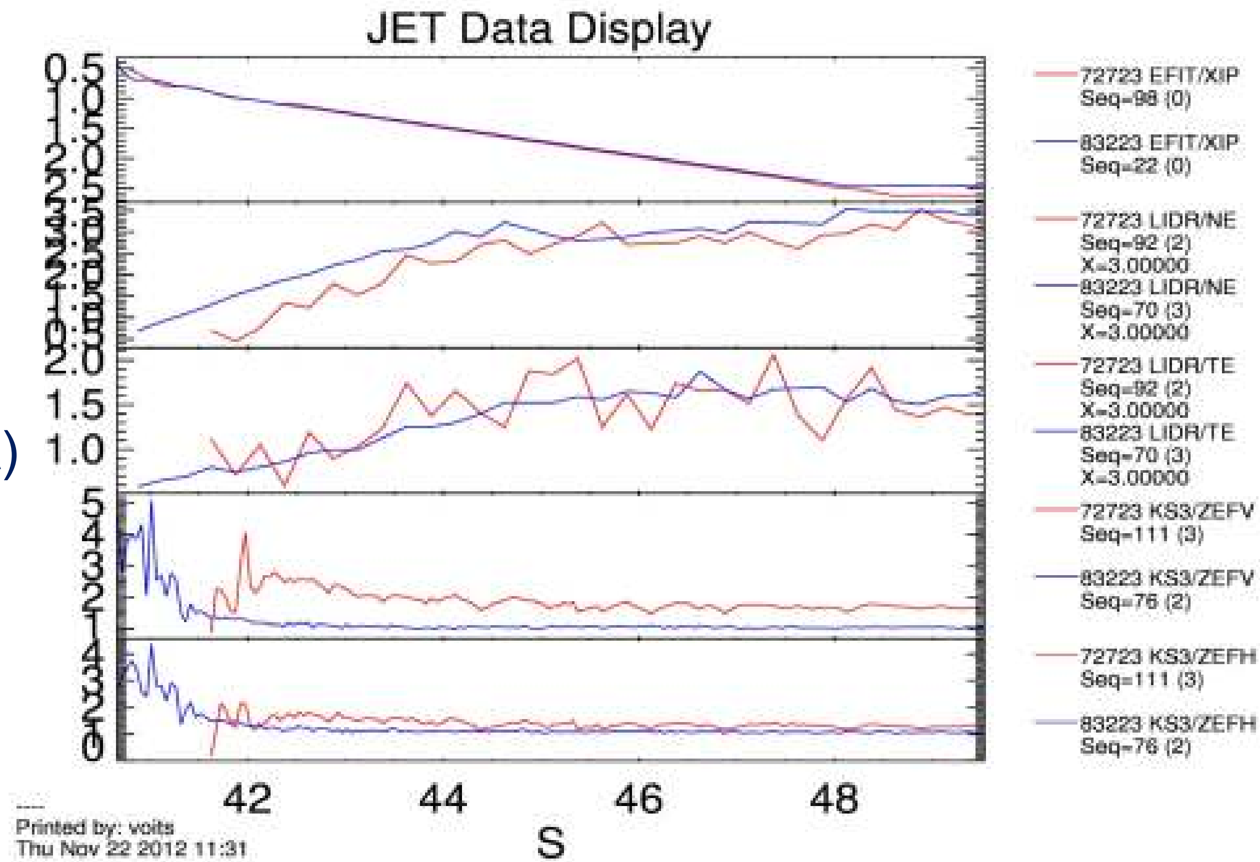
Ohmic identity pair:

✓same dI_p/dt: 0.28MA/s

✓similar n_e

C: 72723 (2.4T/2.6MA),

ILW: 83223 (2.4T/2.5MA)



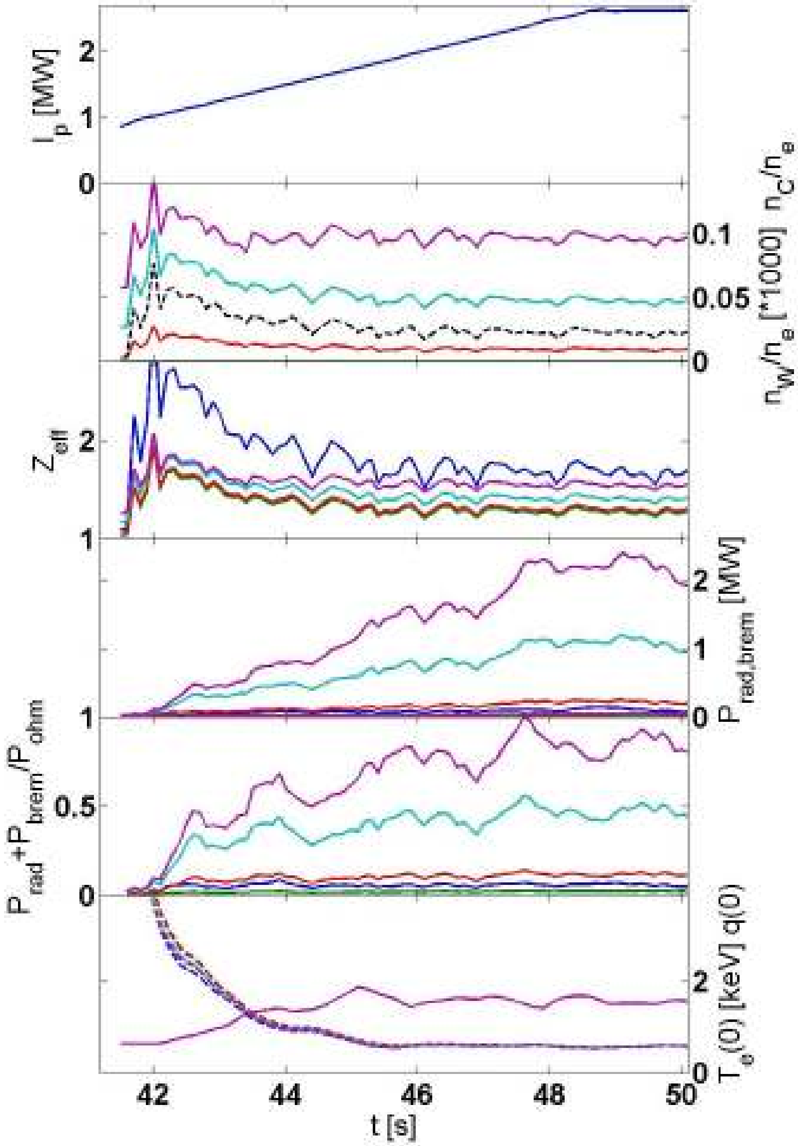
Identity pair with ICRH heating:

C: 72507

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

Interpretative 72723
Replacing $C^{6+} \rightarrow Be^{4+}$ 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, $n_W/n_e = 5\ 10^{-5}$
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)

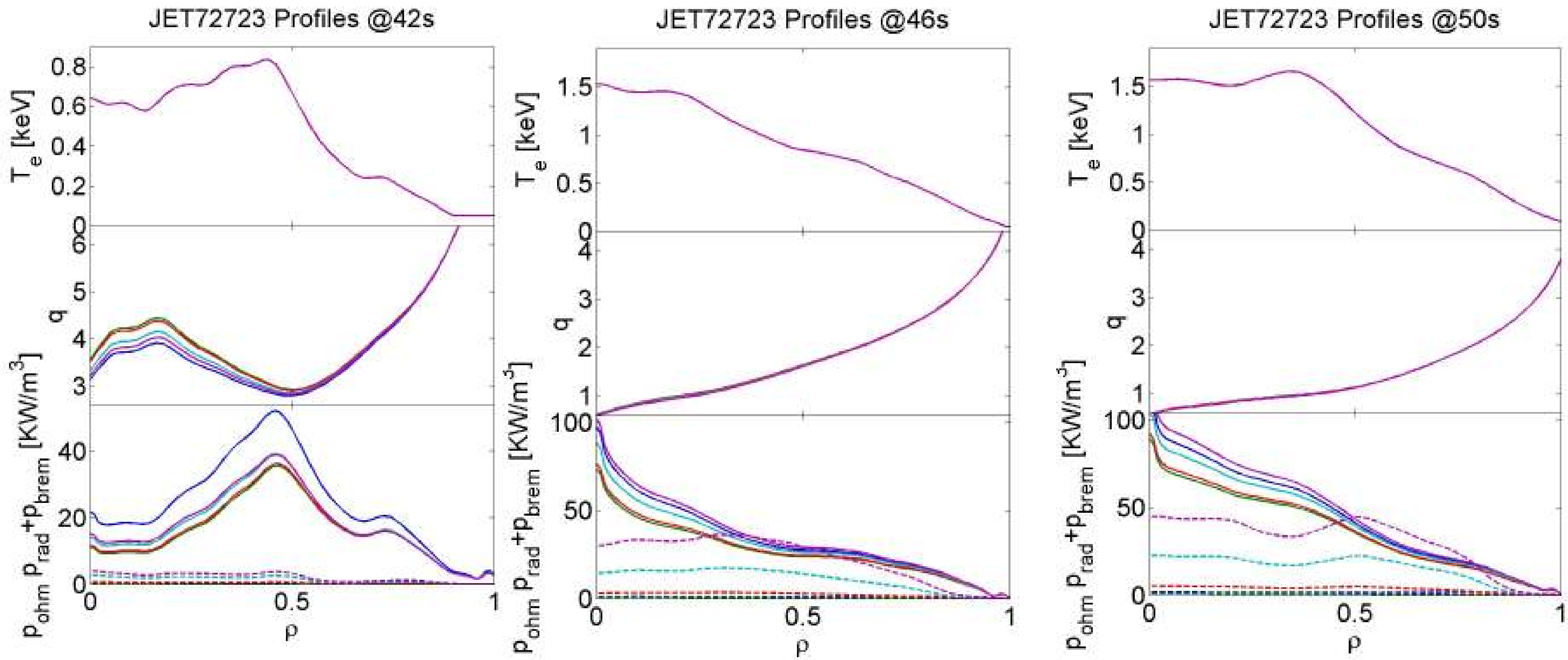


Notes:

- Simple AIM model for W used
- Flat Z_{eff} assumed
- These are interpretative runs, i.e. T_e taken from data – unrealistic when strong radiation present
- Addition of 10^{-4} 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 41.5 s (i.e. 1.5 s after break-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

  However, does not work well when $P_{rad} \sim P_{inp}$ so will not be used heree
- Semi-empirical Bohm-gyroBohm model *[original, L-mode form]*

  will be used in the following

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

Predict.72723 – Bohm-gyroBohm

Replacing $C^{6+} \rightarrow Be^{4+}$ 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, $n_W/n_e = 5\ 10^{-5}$

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

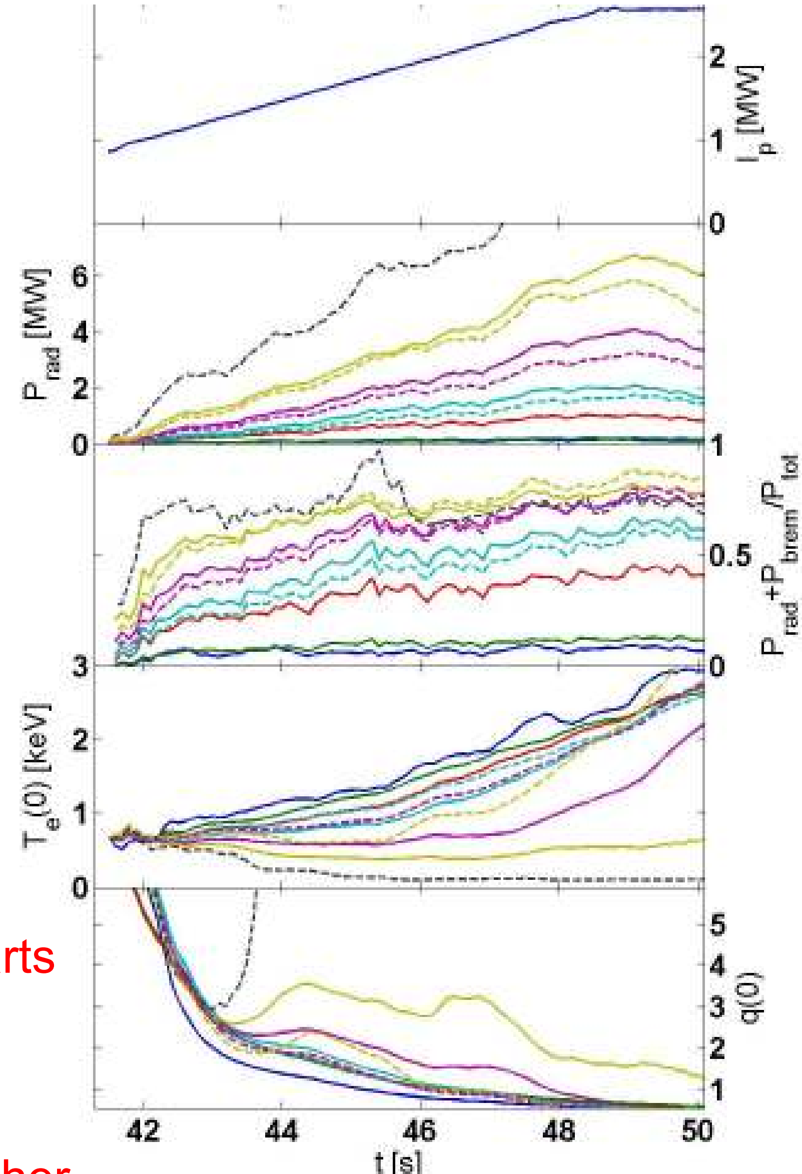
Magenta: same Be^{4+}, added W, $n_W/n_e = 2\ 10^{-4}$

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

Black: same Be^{4+}, added W, $n_W/n_e = 7\ 10^{-4}$

Full lines: AIM (not for highest concentration)

Dashed lines: Pütterich (not for all cases)

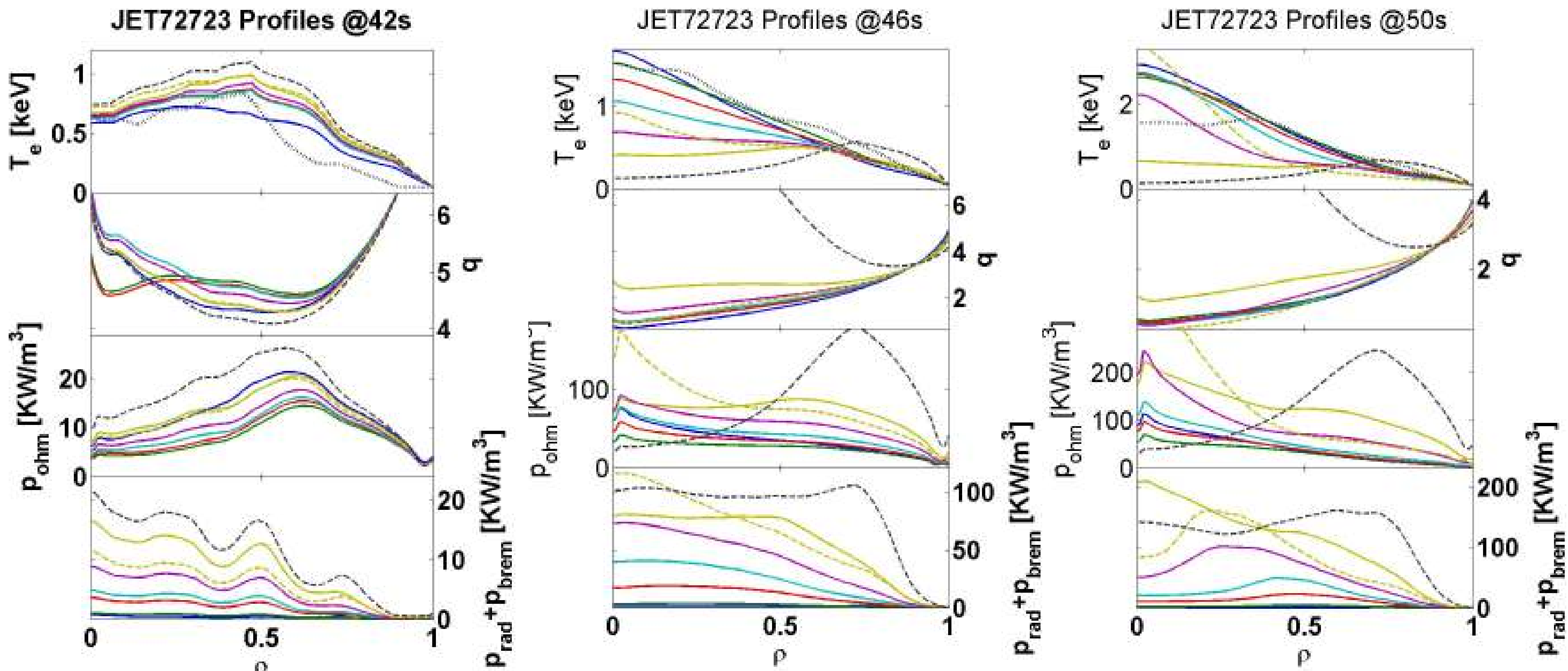


Notes:

- Addition of W with n_W / n_e up to 10^{-4} does not have strong effect on evolution of T_e and q
- With $n_W / n_e = 2\ 10^{-4}$ the evolution of T_e and q starts to be totally different, but recovers
- $n_W / n_e >= 4\ 10^{-4}$ T_e & q evolution totally different
- Improved radiation model → margin for W bit higher

Predict.72723 – Bohm-gyroBohm

Replacing $C^{6+} \rightarrow Be^{4+}$ and adding traces of W



Same colour coding as previous plot (Pütterich calculation only for highest W cases);
exp T_e = dotted black curve in upper panel

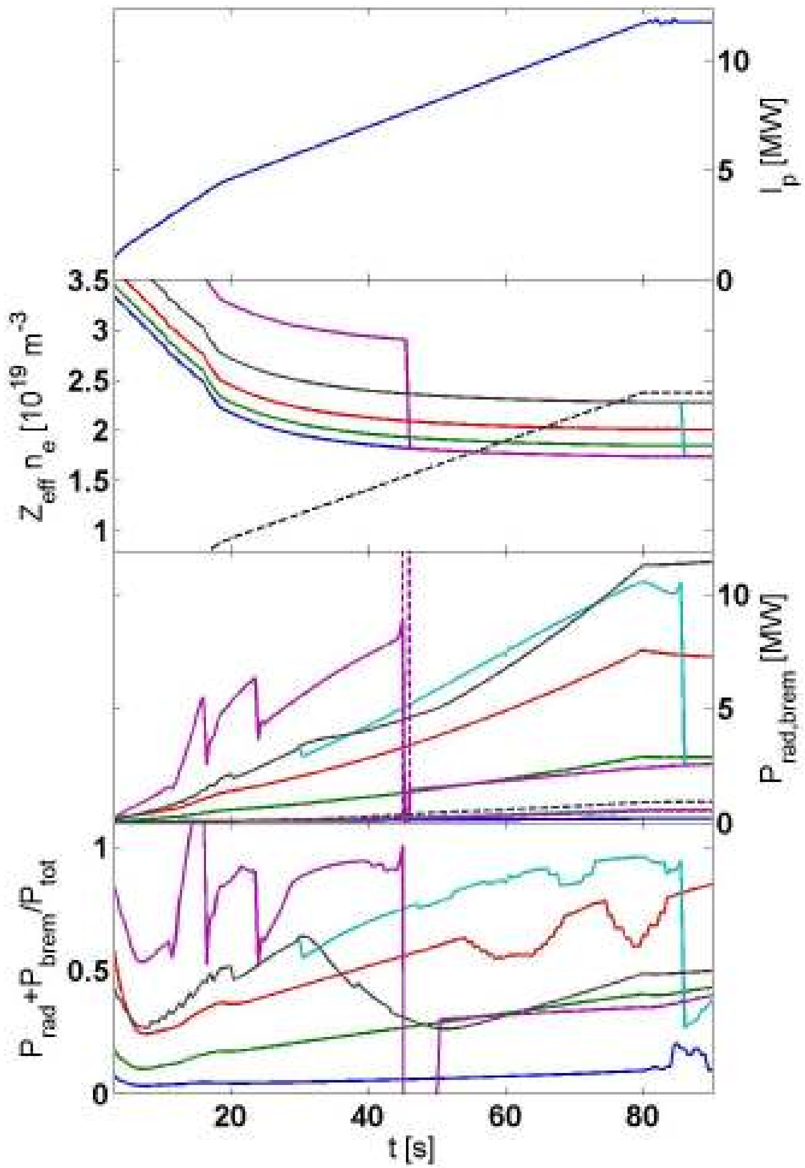
- Initial off-axis peak in j and thus in p_{ohm} (due to off-axis peaked T_e)
- n_W / n_e <= 5 10^{-5} → no strong effect on evolution of T_e and q
- n_W/n_e = 1-2 10^{-4} → T_e & q evolution modified in RU (46s), but restores in flat-top (50s)
- n_W/n_e >= 4 10^{-4} → plasma cannot cross radiation barrier,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

ITER – Bohm-gyroBohm

Now to ITER

Ohmic simulations;
Flat Z_{eff} assumed, as given by ITER team
(i.e. Z_{eff} decreasing with increasing density);
Bohm-gyro model used, original L-mode version

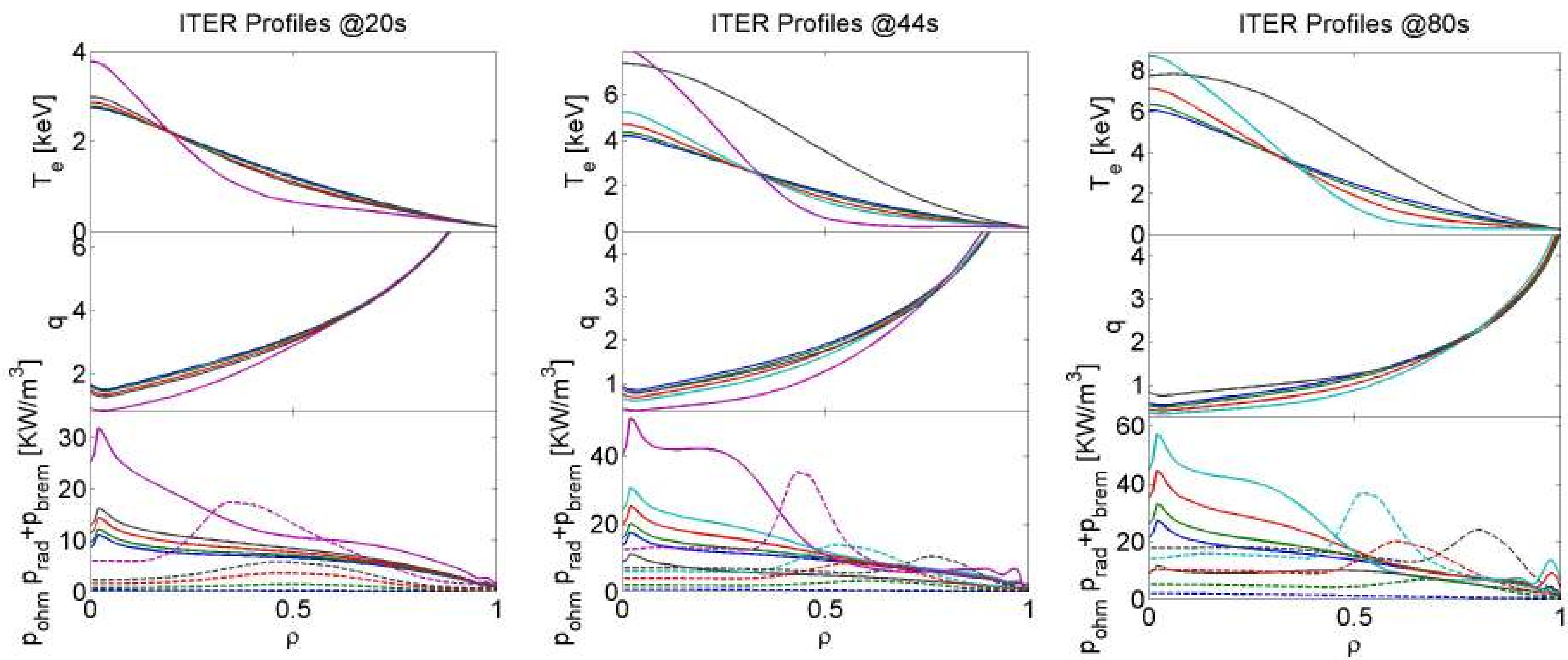
Blue: only impurity is Be4+,
Green: same Be4+, added W, nW/ne = 2 10^{-5}
Red: same Be4+, added W , nW/ne = 5 10^{-5}
Cyan: same Be4+, added W , nW/ne = 10^{-4}
Black: same, *with added off-axis ECRH* ramped to 20 MW between 30 and 50 s
Magenta: same Be4+, added W , nW/ne = 2 10^{-4}
Black dashed line in 2nd frame: line averaged n_e



Notes:

- Very significant radiation when n_W / n_e >= 5 10^{-5}
- With n_W / n_e >= 10^{-4} the radiation losses lead to a "numerical disruption" (after 85 / 45 s)

ITER – Bohm-gyroBohm



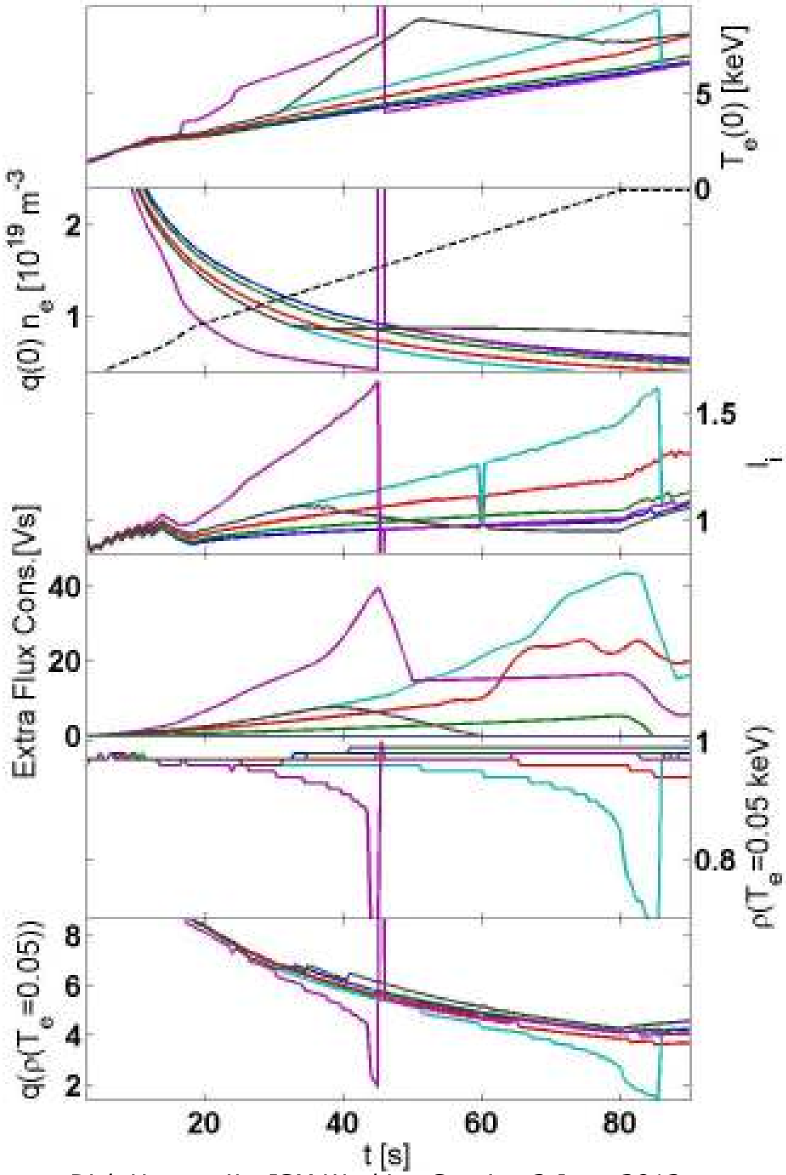
Same colour coding as previous plots

Notes:

- n_W/n_e = 2 10^{-4} W: profiles already deviate @20 s; @44 s large T_e ~ 0 region for ρ >0.6
- n_W/n_e = 1 10^{-4} : same happens at end of ramp-up;

  in this case 20 MW of ECRH restores normal evolution

ITER – Bohm-gyroBohm



Closer look – same colour coding as before

Many problems arise due to very peaked T_e profile due to strong radiation loss in ouer part:

- very low central q *(2nd panel)*
- l_i becomes far too high *(3rd panel)*
- lot of extra flux consumption *(4th panel)*
- shrinking of effective plasma volume *(5th panel)*
  - → q=2 at effective plasma edge *(6th panel)*

With timely application or ECRH all these problems can be avoided (at least up to the W concentrations considered here)

(black curves)

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 ~ 2 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, and strong problems regarding l_i, flux consumption and MHD

Conclusions & Outlook

Further work for JET:

- Analyze q profile evolution and radiation in ILW ramp-up case with strong W radiation (e.g. 82074)
- 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:

- What W concentration is acceptable when applying ECRH from early in RU