EUROfusion

Measuring the plasma composition using an integrated analysis of multiple diagnostics

Marco Sertoli

JET

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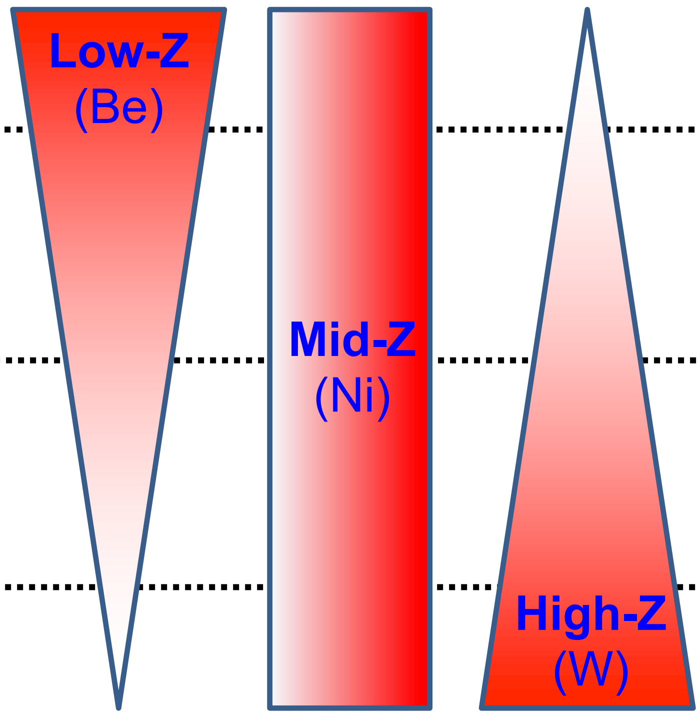
Plasma composition with metallic walls

The presence of **multiple impurities of very different charge and mass** complicate the interpretation of diagnostic measurements:

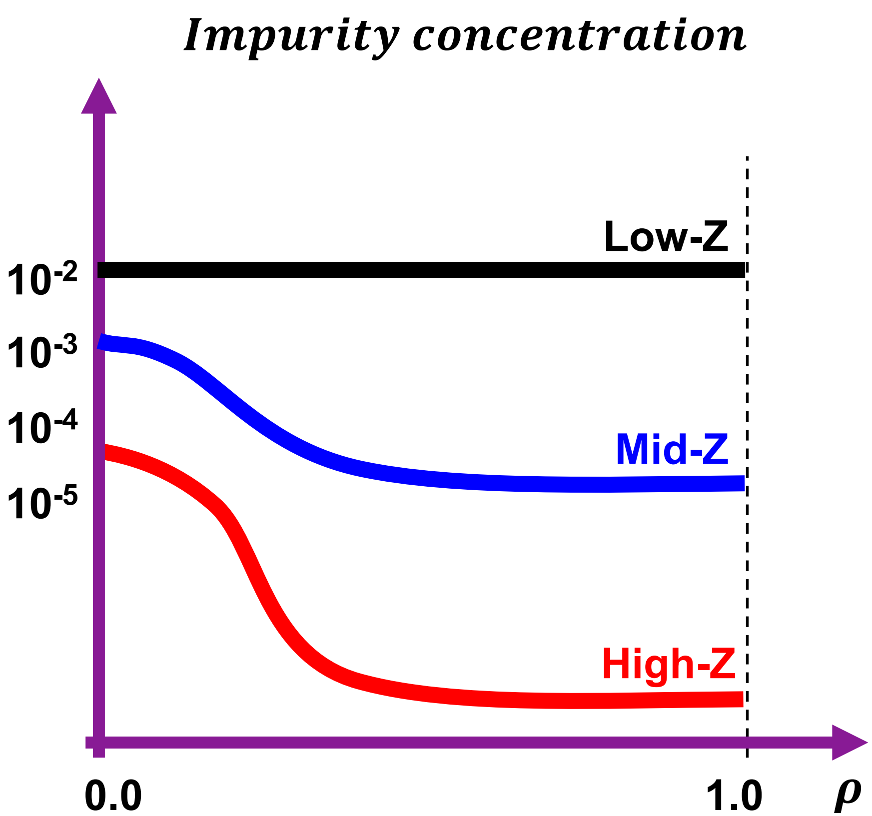
- **Dilution** $\propto q$
- **Effective charge Zeff** $\propto q^2$
- **Radiated power** $\propto f(q)$

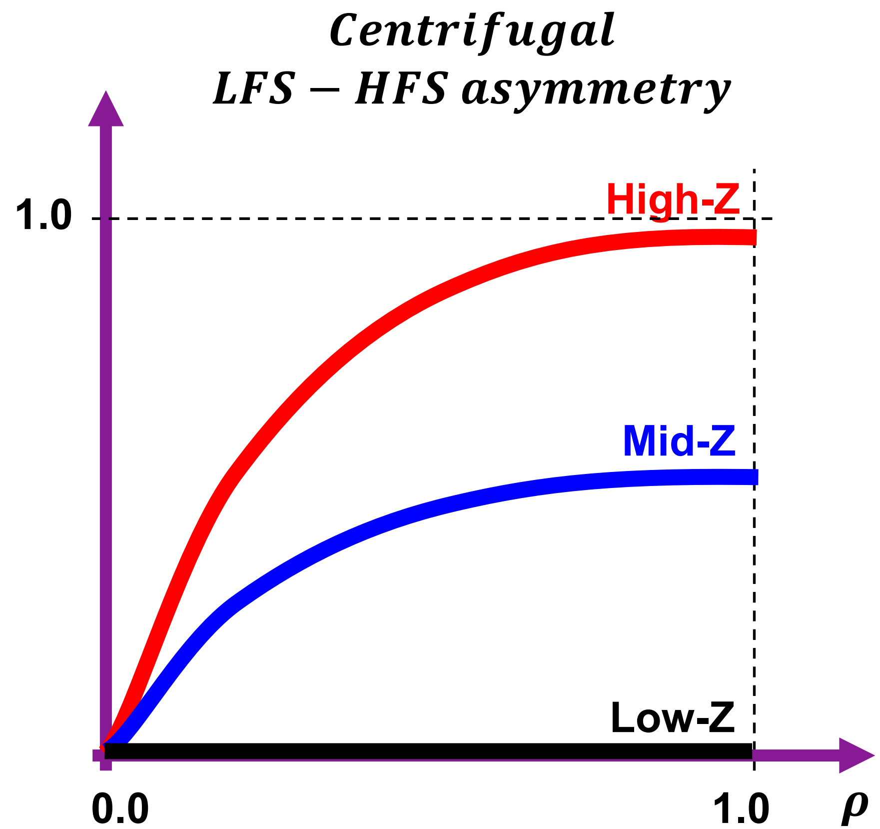


Plasma composition with metallic walls

Because of differences in:

- **absolute value** (*concentration*)
- **profile shapes** (*transport*)
- **radiative cooling functions** temperature dependence (*atomic physics*)





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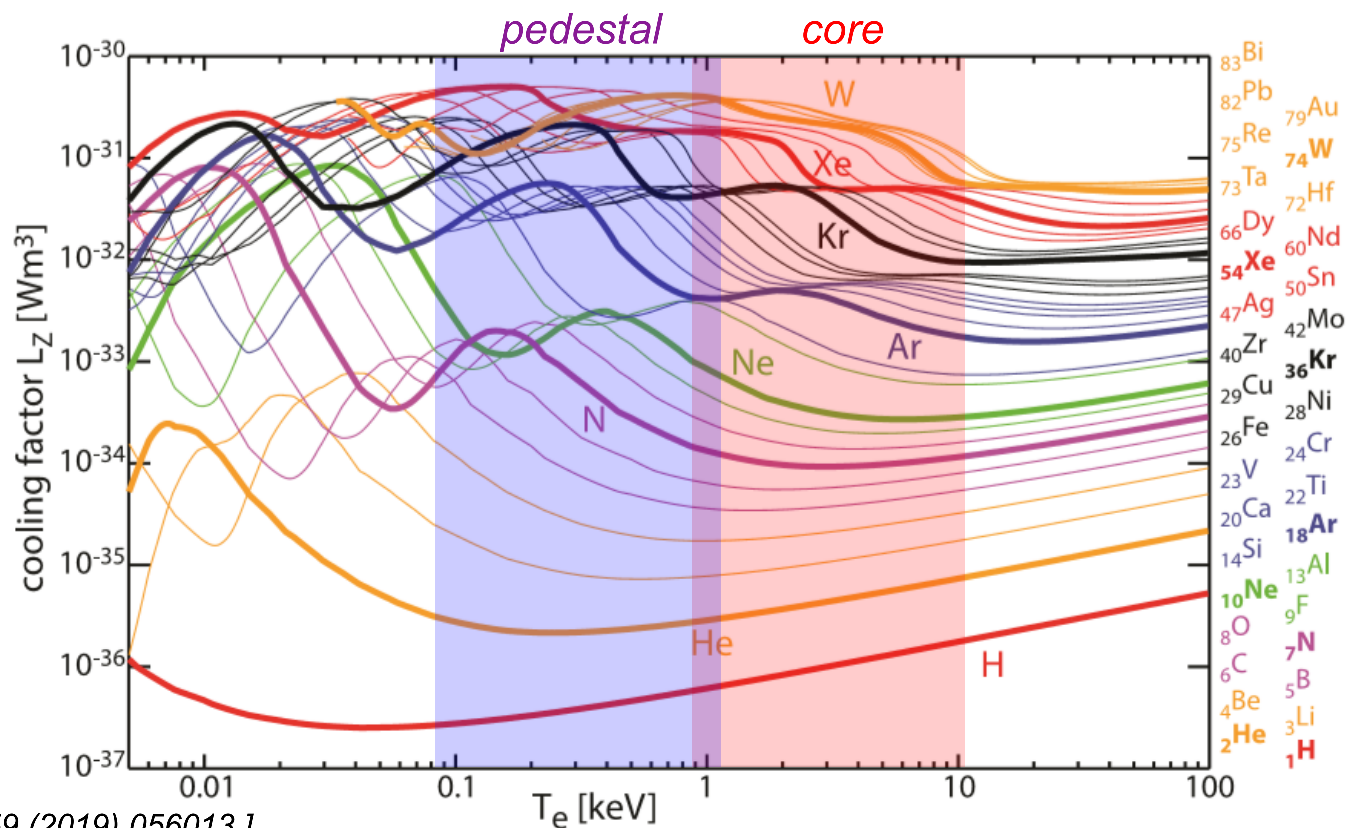
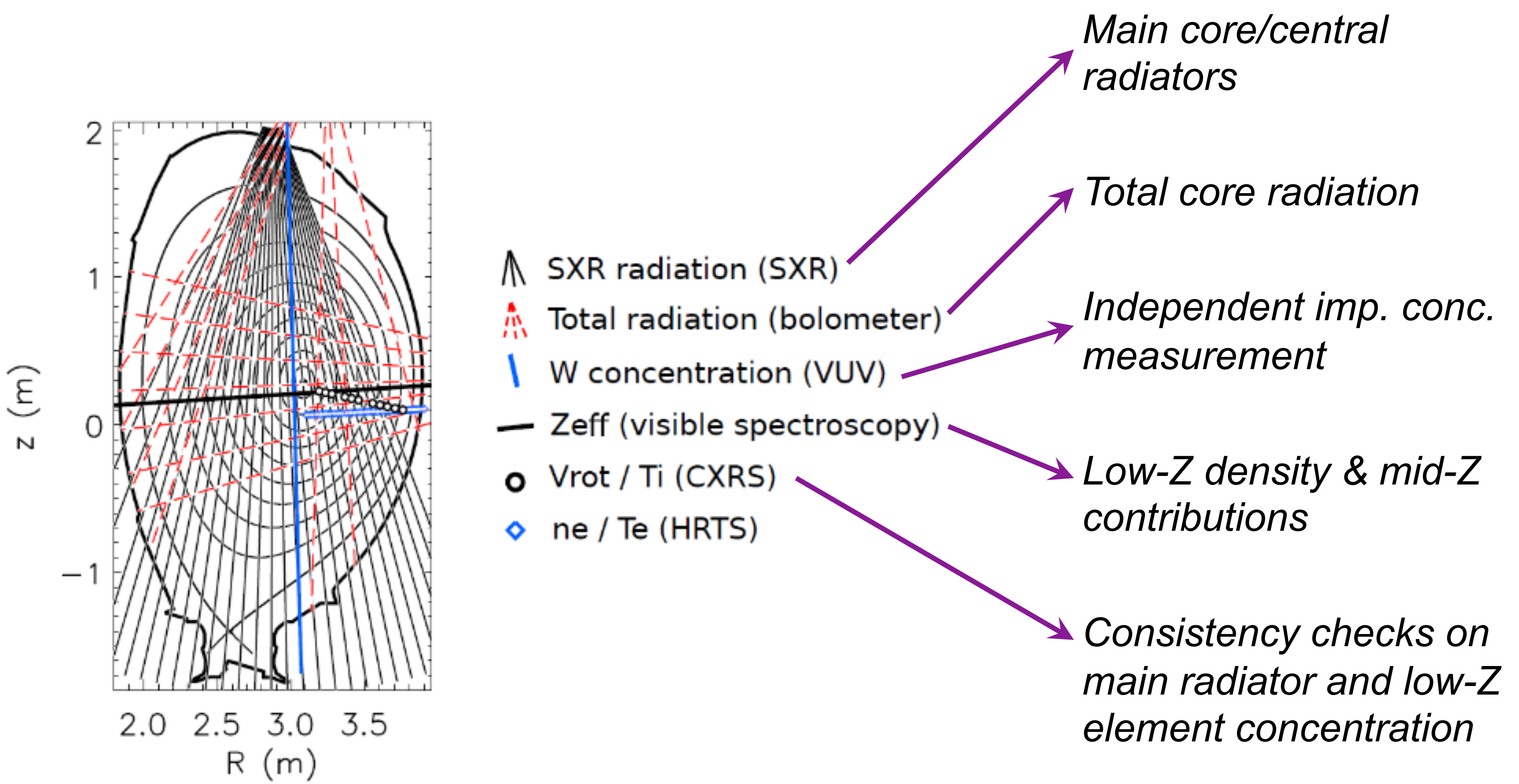


[T. Pütterich NF 59 (2019) 056013]

Integrate analysis of multiple diagnostics

Find impurity mix & **profile shapes in 2D** on a poloidal plane that match multiple measurements of different quantities



[M. Sertoli RSI (2018) 89113501 , M. Sertoli J. Plasma Phys. 85 (2019), 905850504]

Outline

- **Analysis workflow & implementation details**

- **Example results**

- **Upgrades**

[M. Sertoli RSI (2018) 89113501 , M. Sertoli J. Plasma Phys. 85 (2019), 905850504]

Impurity with max contribution to radiation

Stepwise inclusion of multiple impurities in the mix

1. Initial n_W from SXR assuming W is the main radiator
2. Cross-calibrate initial n_W vs. passive VUV c_W measurement

Equilibrium
Background plasma
Cooling factors
Ionization balance

Impurity with max contribution to radiation

Primary impurity Z_0 (*e.g. W at JET or AUG*)

- **Calculated directly from analysis without ANY assumption**

2D deconvoluted SXR poloidal map — *sum over all impurities*

$$n_{Z_0}^{SXR} = \frac{M \cdot \epsilon_{exp}^{SXR} - n_e \left[n_I \, L_I^{SXR} + \sum_{s \neq Z_0} n_s \, L_s^{SXR} \right]}{n_e \, L_{Z_0}^{SXR}}$$

Requirements:

- **Local SXR emissivity** (*model driven inversion of the LOS-integrals*)
- **Electron temperature** and **density profile fits**
- **Impurity concentration c_{Z0}** from **passive spectroscopy** (*c_W from VUV or c_{Ni} from X-ray spectroscopy*) for cross-calibration of first iteration of the computation
- **Atomic data** for all impurities (*ADAS files*)

Inclusion of low-Z impurities

Stepwise inclusion of multiple impurities in the mix

1. Initial n_W from SXR assuming W is the main radiator
2. Cross-calibrate initial n_W vs. passive VUV c_W measurement
3. Calculate $n_{low\text{-}Z}$ to match Zeff measurement

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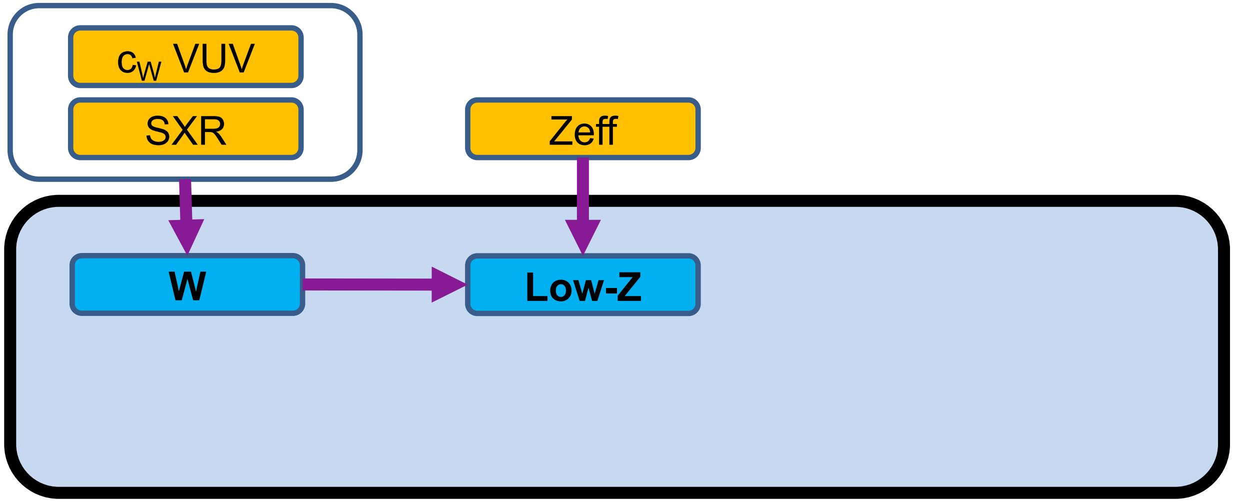

Inclusion of low-Z impurities

Low-Z impurities Z_1 and Z_2

- Flat concentration profile
- Symmetric on flux-surface
- **One** (Z_2 e.g. Be in JET) **constant in time, the other** (Z_1 e.g Ne for Ne-seeding) **calculated from Zeff measurement**

KS3 measurement — *sum over all impurities* — *accounts for asymmetries*

$$c_{Z_1}(t) = \frac{L \cdot \left(Z_{eff}^{KS3}(t) - 1\right) - \sum_{s \neq Z_1} \int_L \frac{n_s(\rho, R; t)}{n_e(\rho; t)} \left[\langle q_s(\rho; t)\rangle^2 - \langle q_s(\rho; t)\rangle\right] dl}{\int_L \left[\langle q_s(\rho; t)\rangle^2 - \langle q_s(\rho; t)\rangle\right] dl}$$

Requirements:

- **Zeff measurement** (*LOS-averaged Bremsstrahlung from visible spectroscopy*)

Main ion contribution

Stepwise inclusion of multiple impurities in the mix

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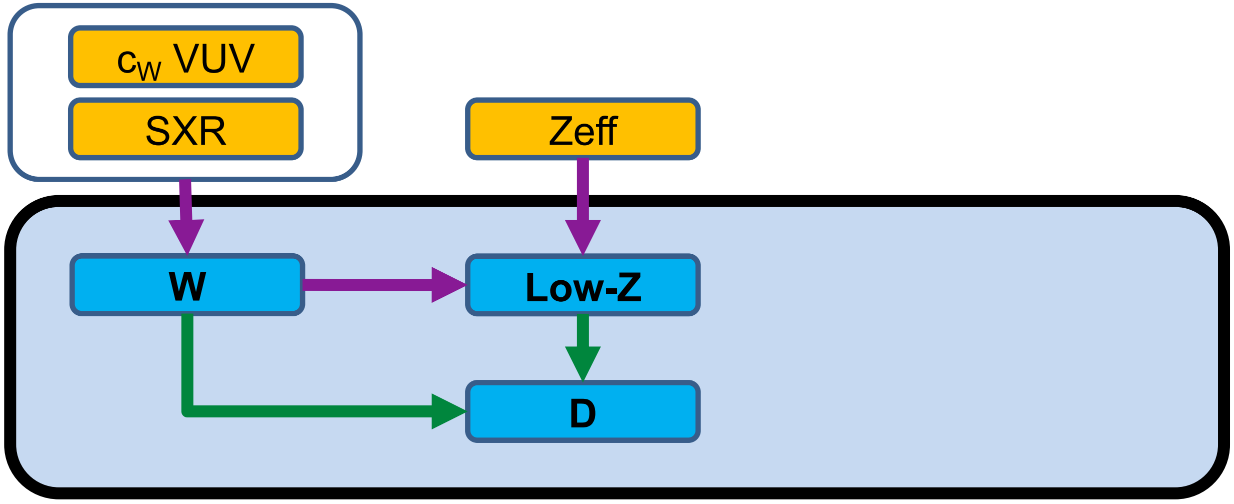
2. Cross-calibrate initial n_W vs. passive VUV c_W measurement
3. Calculate n_{low-Z} to match Zeff measurement
4. Calculate main ion dilution

Equilibrium
Background plasma
Cooling factors
Ionization balance



Iterate…

Stepwise inclusion of multiple impurities in the mix

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5. *Re-calibrate SXR accounting for all contributions*
6. Re-calculate n_W subtracting all other contributions

Equilibrium
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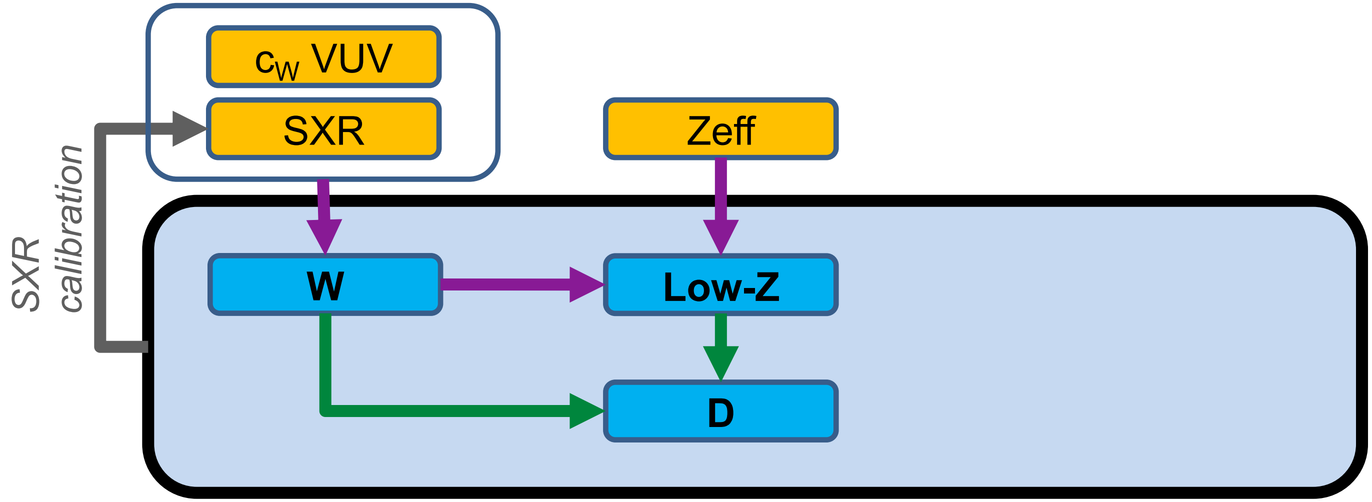

Iterate…

Stepwise inclusion of multiple impurities in the mix

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5. *Re-calibrate SXR accounting for all contributions*
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Equilibrium
Background plasma
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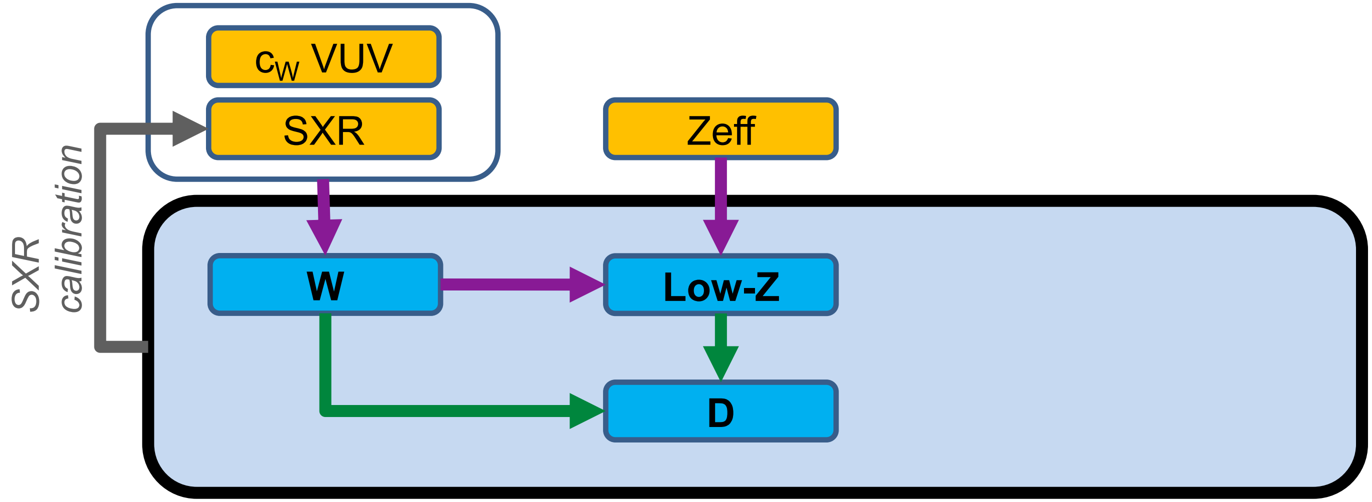
Ionization balance



Check for consistency

Stepwise inclusion of multiple impurities in the mix

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7. Check result consistency with other diagnostics (e.g. rotation, P_{rad}, ...)

Equilibrium
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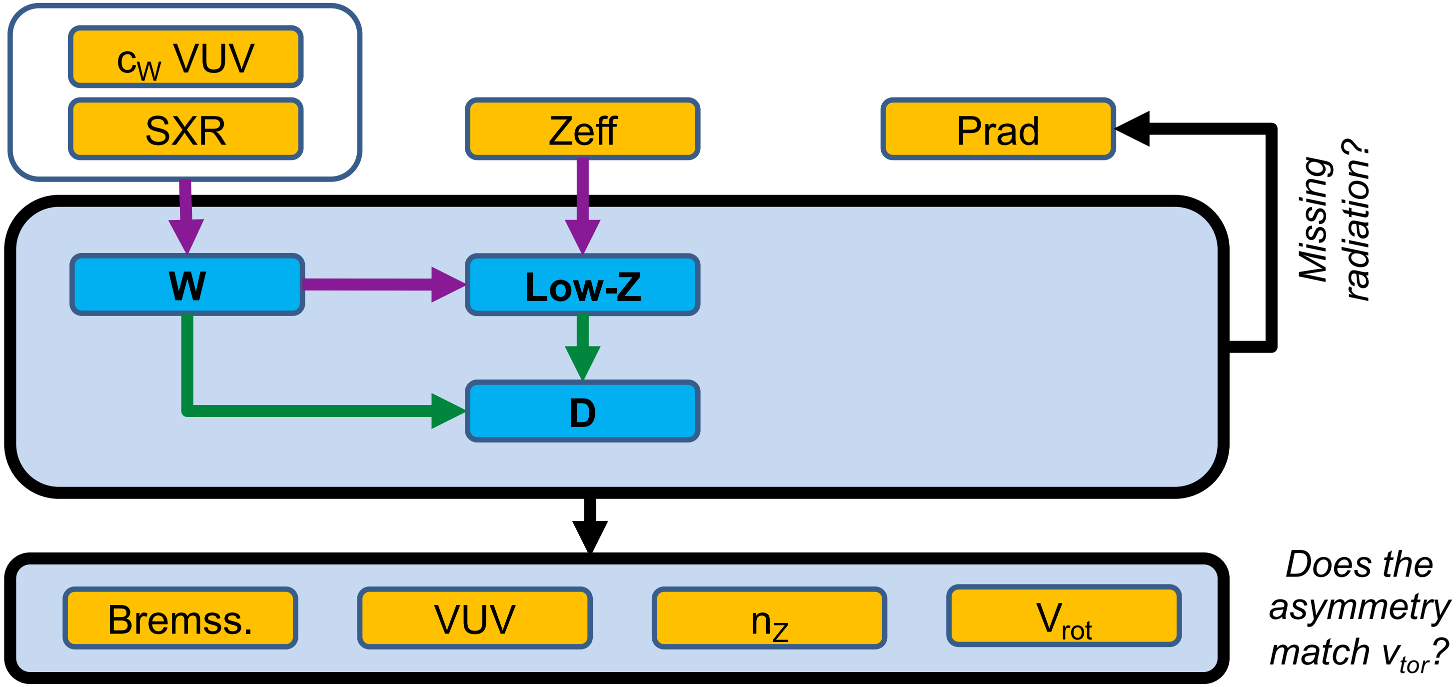
Ionization balance



Inclusion of secondary mid-/high-Z

Stepwise inclusion of multiple impurities in the mix

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7. Include mid-Z element to match Prad

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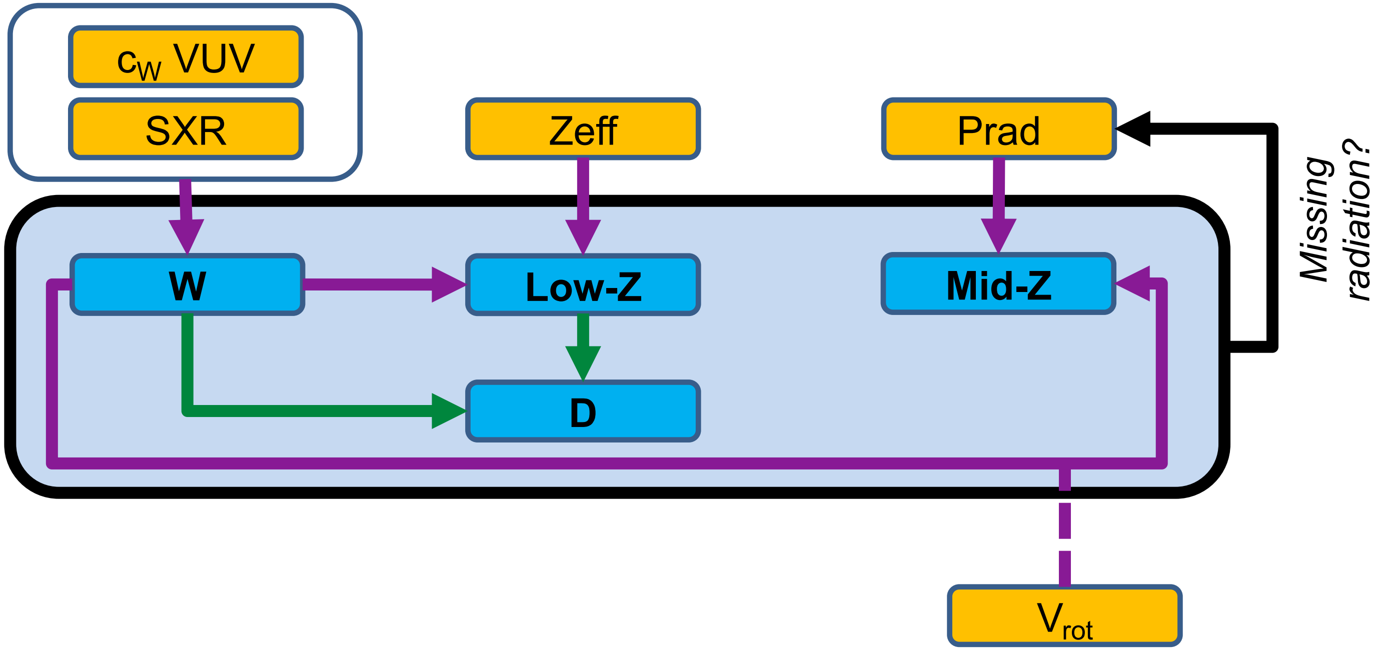

Inclusion of secondary mid-/high-Z

Mid-/high-Z impurity Z_3

- **Both Z_0 and Z_3 are at equilibrium or their sources/sinks behave identically**
- **Their radial transport is governed by neoclassical processes**
- Their poloidal asymmetries are driven mainly by centrifugal effects

main ion gradient — *Ion temperature screening* — *centrifugal effects*

$$\langle \frac{R}{L_{n_s}} \rangle_{FSA} \propto q_s \left[\frac{R}{L_{n_I}} - \frac{R}{L_{T_I}} \left(\frac{1}{2} - 0.33 \frac{m_I}{q_s^2 \sum_i \nu_{is}} \frac{P_B}{P_A} f_c \right) \right]$$

flux-surface-averaged values

Neglecting at 1st order
ion temperature screening
(*applied where profile is peaked*)

charge ratio — *primary impurity gradient*

$$\langle \frac{R}{L_{n_{Z_3}}} \rangle \approx \frac{q_{Z_3}}{q_{Z_0}} \langle \frac{R}{L_{n_{Z_0}}} \rangle$$

…then, normalize the density of Z_3 at each time-point so that the **total # of ions in the confined plasma equal to Z_0**…

Inclusion of secondary mid-/high-Z

Mid-/high-Z impurity Z_3

- **Both Z_0 and Z_3 are at equilibrium or their sources/sinks behave identically**
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- Their poloidal asymmetries are driven mainly by centrifugal effects

…and scale it (*the whole profile and time-range by a single constant*) so that **the synthetic value of the bolometer LoS matches the experimental value**, averaged over the whole time-range of analysis:

sum over all impurities

Average over all LoS

$$\frac{1}{C} = \left\langle \frac{1}{N}\sum_{k=1}^{N} \frac{\int_{L_k} \left[n_e(\rho;t) \left(n_I(\rho;t) L_I^{tot}(\rho;t) + \sum_s n_s(\rho,R;t) L_s^{tot}(\rho;t) \right) \right] dl}{B_k^{KB5}(t)} \right\rangle_t$$

experimental LoS-integrals

Requirements:

- **Total radiation** (*LOS-integrated bolometric measurements*)

Inclusion of secondary mid-/high-Z

Mid-/high-Z impurity Z_3

- **Both Z_0 and Z_3 are at equilibrium or their sources/sinks behave identically**
- **Their radial transport is governed by neoclassical processes**
- **Their poloidal asymmetries are driven mainly by centrifugal effects**

2D poloidal map can be recovered using equation:

Impurity density at reference major radius R_0

$$n_s(\rho, R; t) \approx n_s(\rho, R_0; t)\, exp\left[\lambda_s(\rho; t)(R(\rho; t)^2 - R_0(\rho; t)^2)\right]$$

$$\lambda_s(\rho; t) \approx \frac{m_s \omega_\phi(\rho; t)^2}{2T_I(\rho; t)}\left(1 - \frac{\langle q_s(\rho; t)\rangle}{m_s}\frac{m_I Z_{eff}(\rho; t) T_e(\rho; t)}{T_I(\rho; t) + Z_{eff}(\rho; t) T_e(\rho; t)}\right)$$

Where: **ω, T_I** from CXRS, **T_e** from HRTS, **Z_{eff}** from KS3 + analysis, **q_S** from atomic data

Requirements:

- **Ion temperature and impurity toroidal rotation** (*CXRS, MHD modes*)

Iterate…

Stepwise inclusion of multiple impurities in the mix

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Equilibrium
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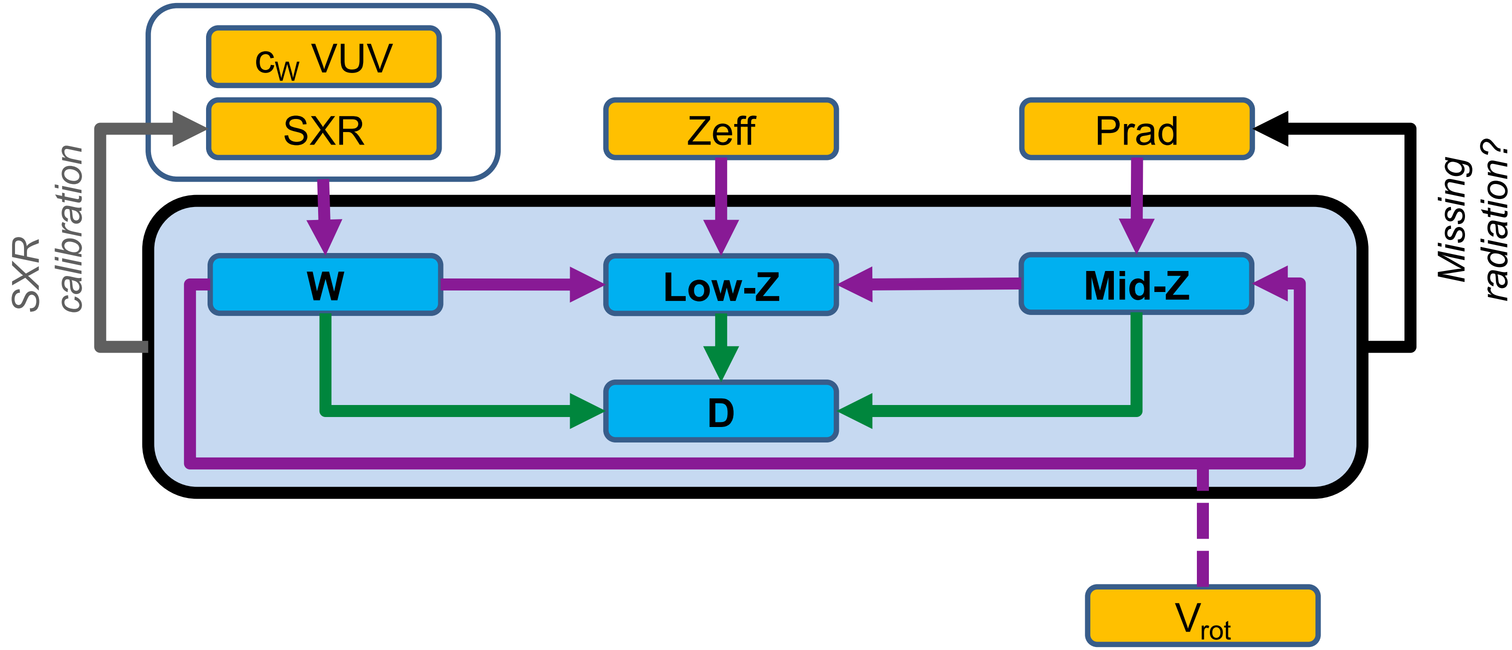

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Equilibrium
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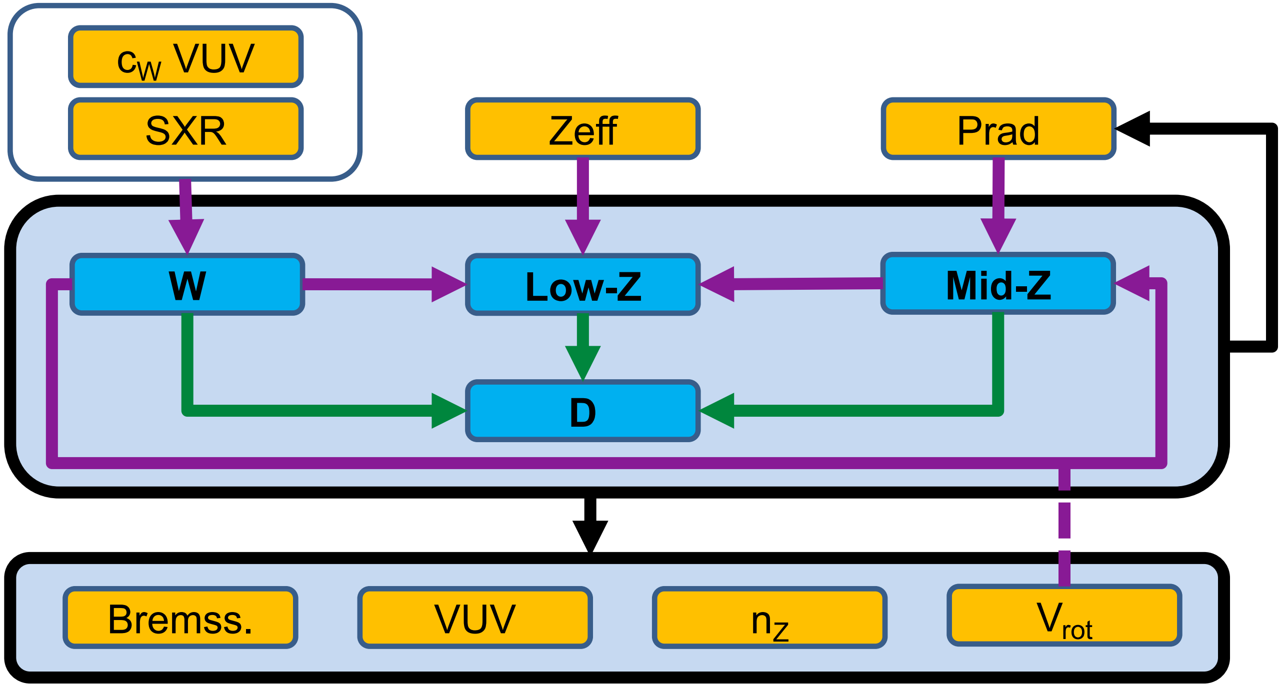

Check for consistency: parameter scans

Check consistency and impact of the various parameters:

- **Atomic data** → *global effect*
- **Equilibrium** → *global effect (e.g. asymmetry vs. V_{rot})*
- **Chosen diagnostics** → *measurement inconsistencies*
- **Zeff** → *low-Z impurity density*

Equilibrium
Background plasma
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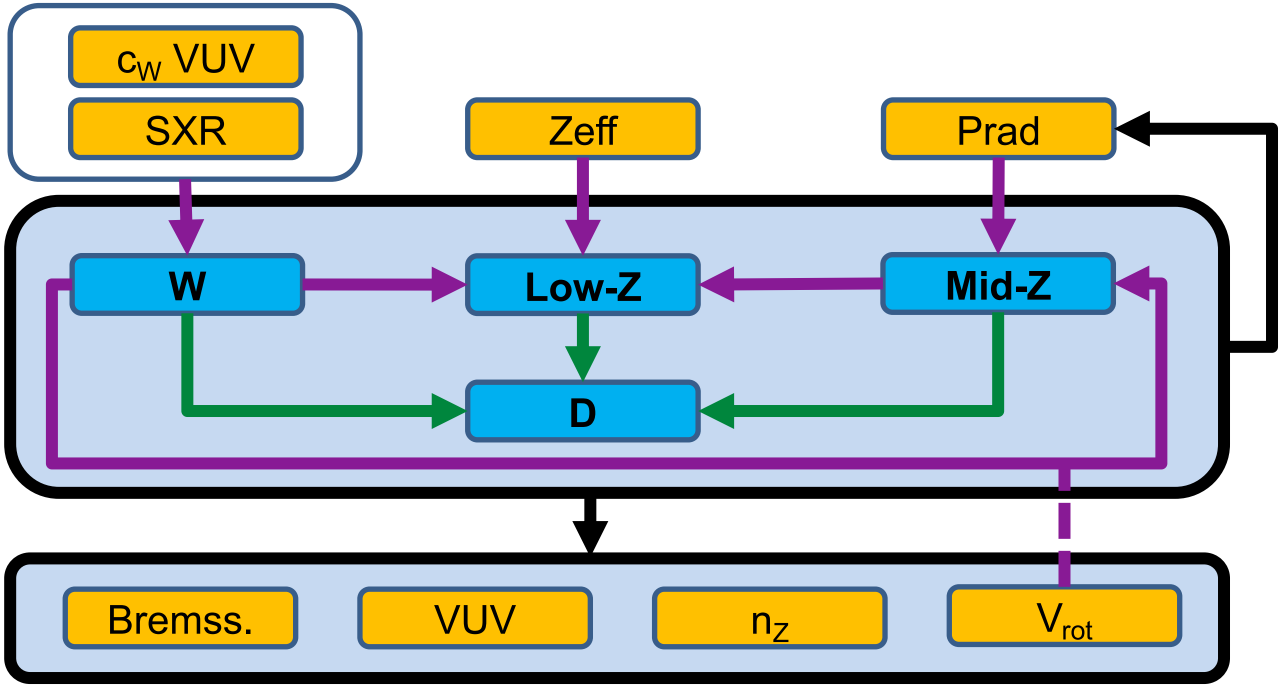

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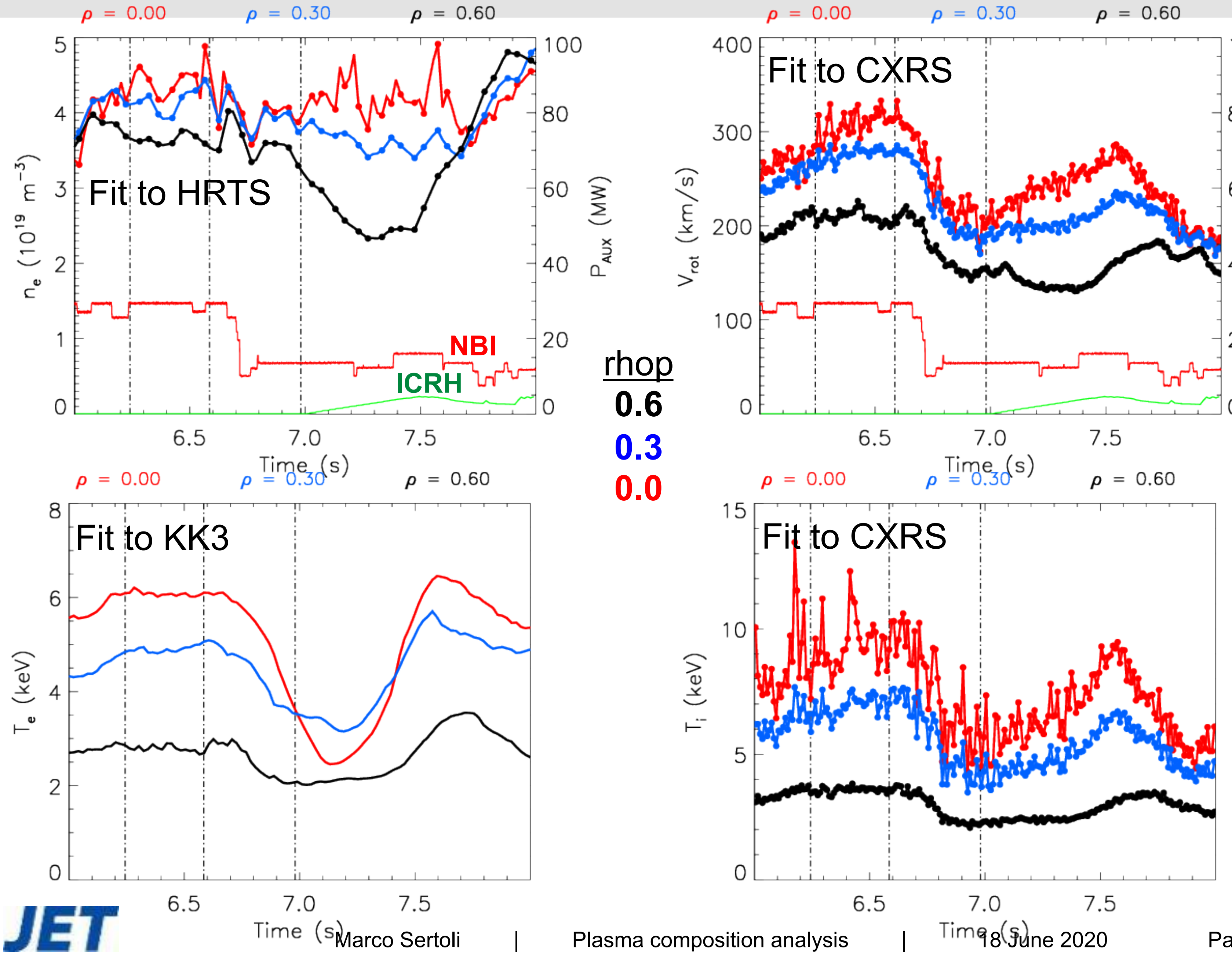
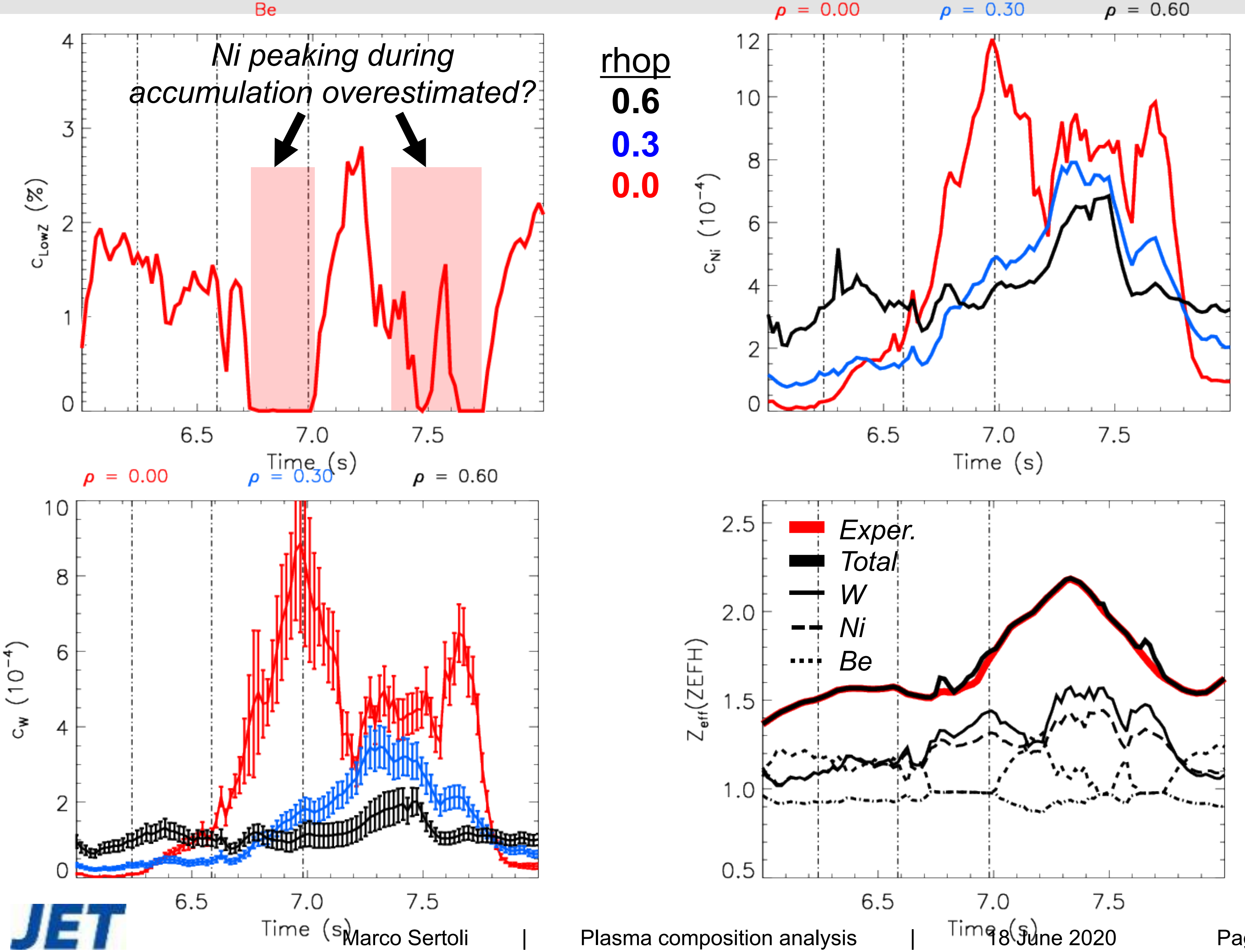
[M. Sertoli RSI (2018) 89113501 , M. Sertoli J. Plasma Phys. 85 (2019), 905850504]

96851 time evolution: electrons / ions

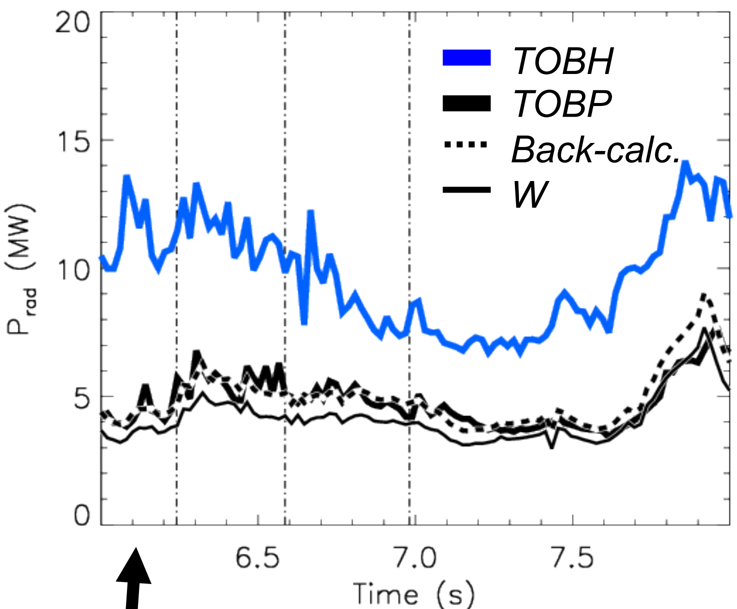


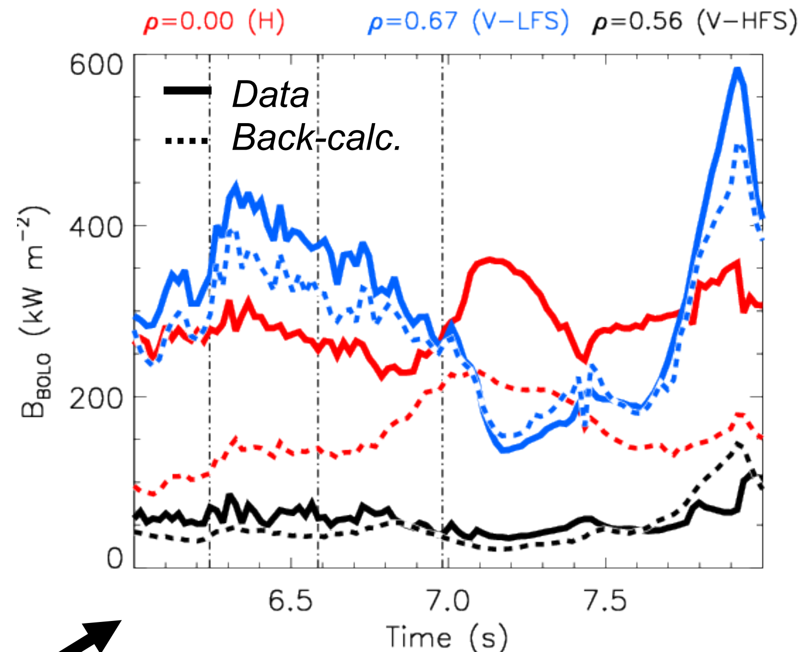
96851 time evolution: impurities / Zeff



rhop
0.6
0.3
0.0

96851 time evolution: total radiated power

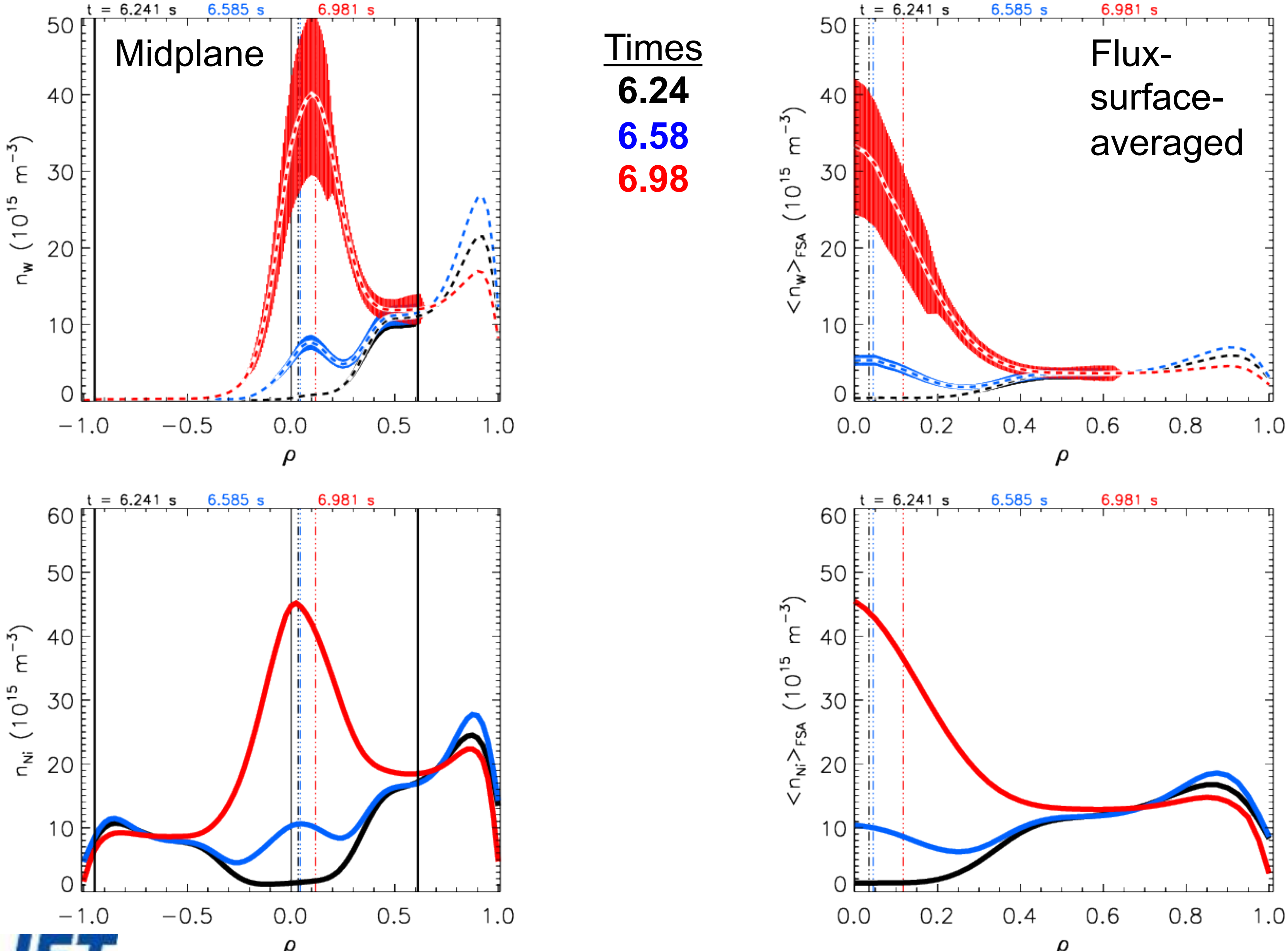




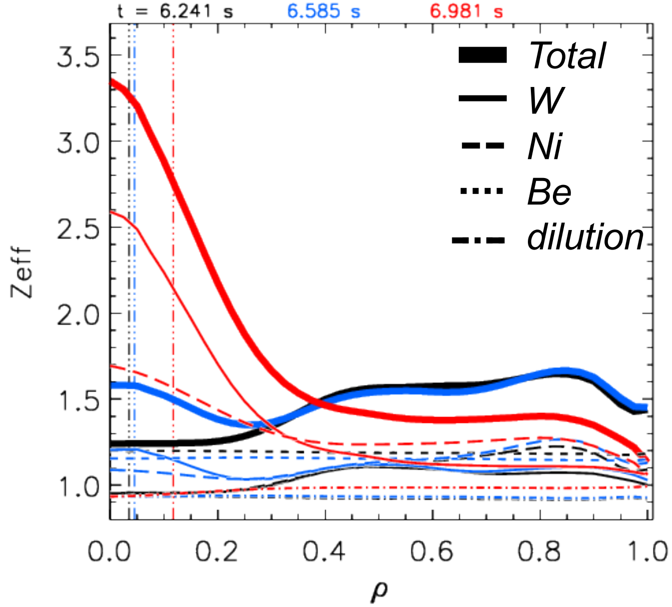
Very good match with total P_{rad} as well as with the time evolution also for single LOS integrals of camera V (see pg. 9 for profiles)

…usual slight mismatch with horizontal camera, not sure why…

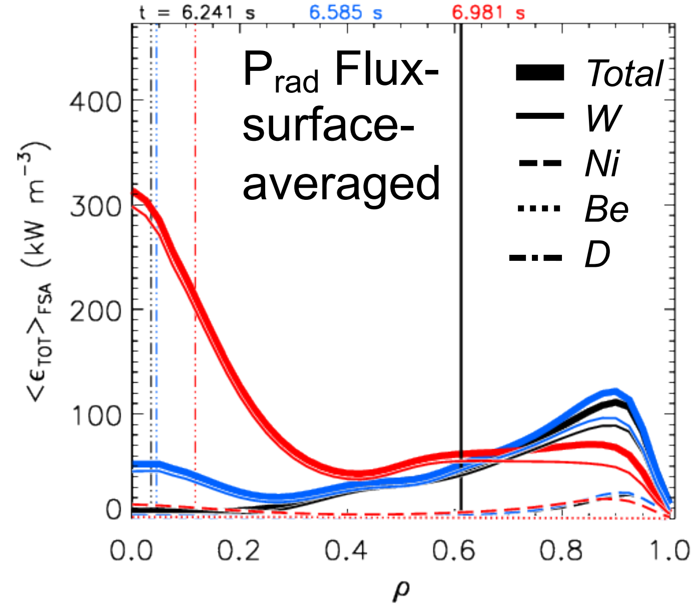
96851 profiles: W & Ni profiles

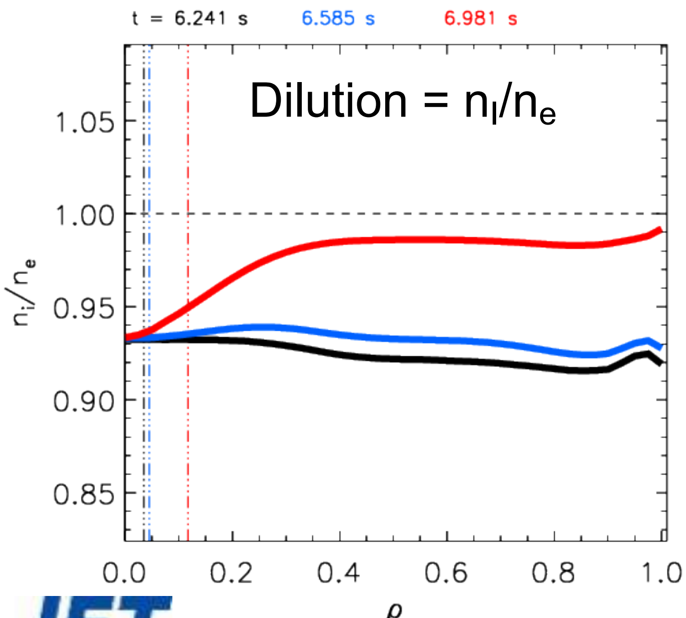


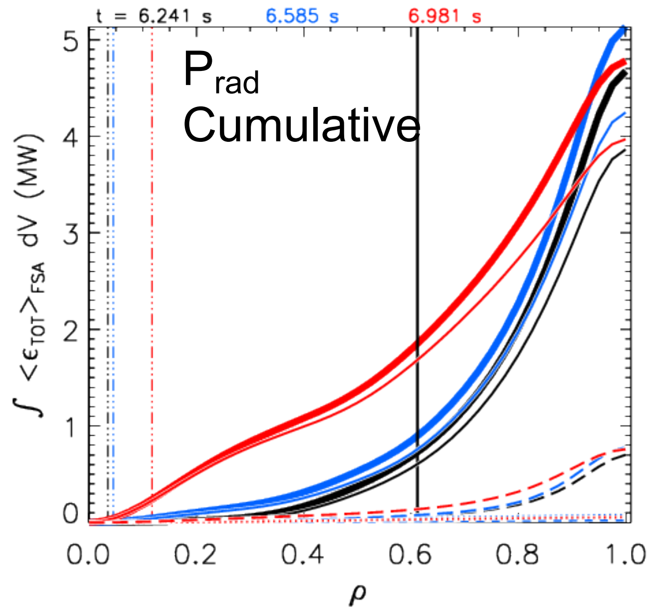
96851 profiles: Zeff, dilution and Prad



Times
6.24
6.58
6.98



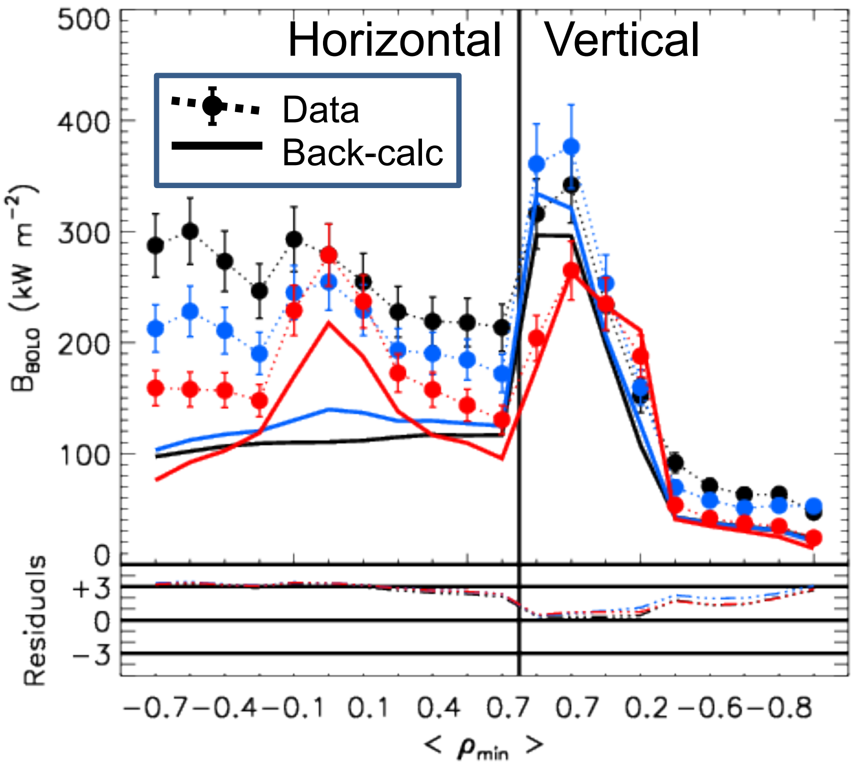




96851 consistency checks

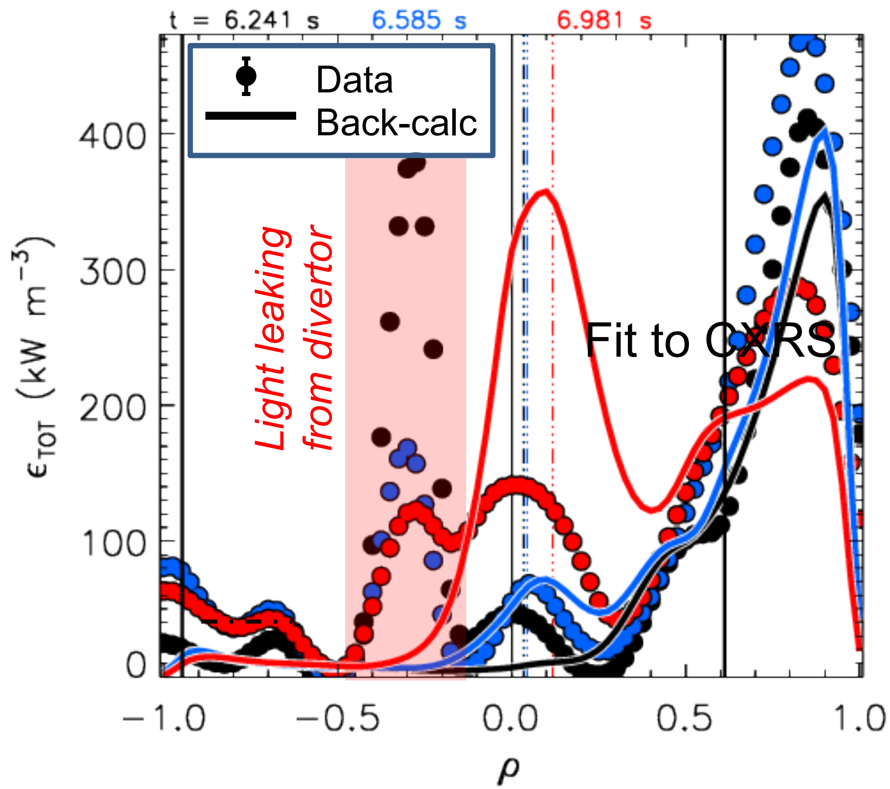
LOS integrals

Good match with camera V, mismatch with camera H still not understood



Tomographic reconstruction

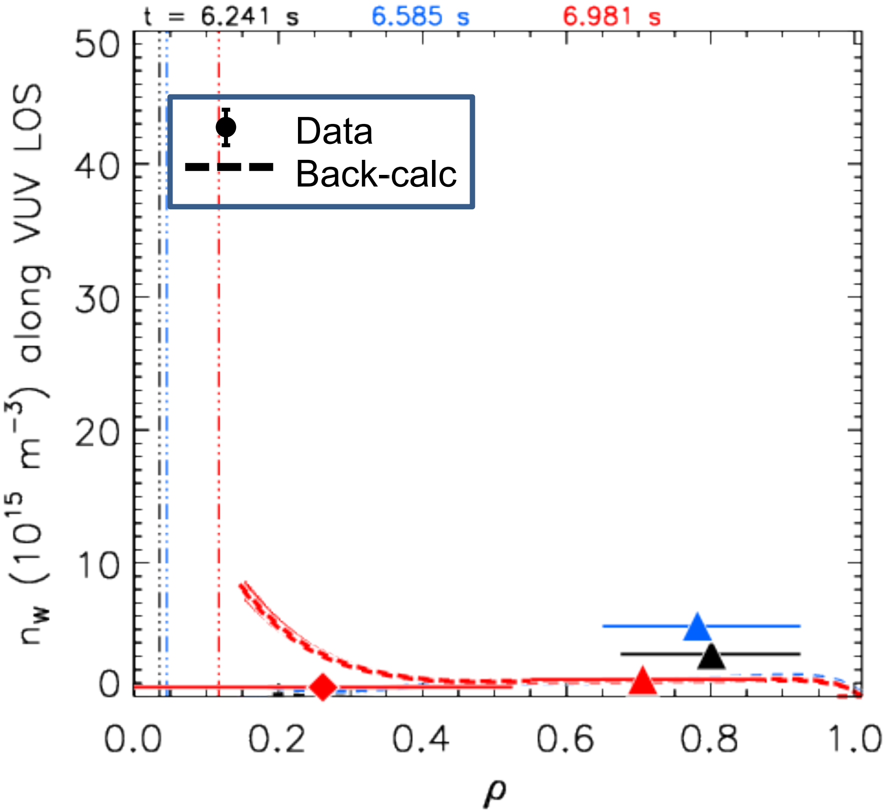
Good match, peaking overestimated ***t = 6.98 s*** *?*



96851 consistency checks

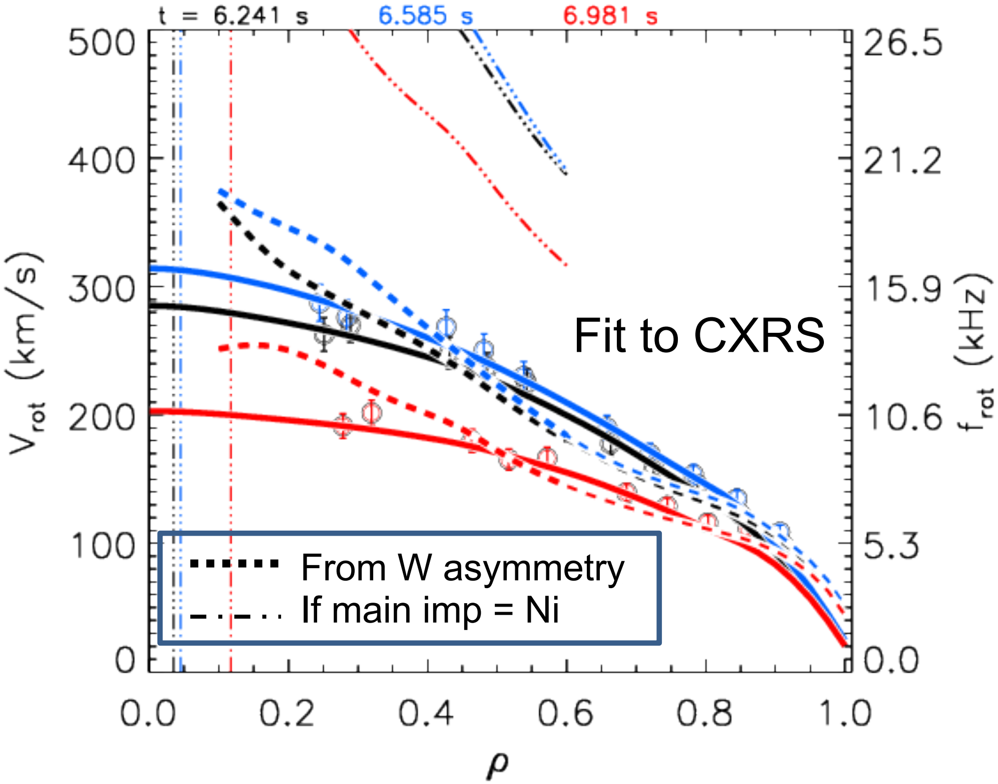
<u>VUV W concentration</u>

Decent match, considering that VUV has been cross-calibrated vs. bolometric measurements



<u>Asymmetry consistent with Z0 = W,</u>

If the Z0 = Ni, rotation should be twice as high



What needs upgrading

- **Central neoclassical transport?**

  …to determine the gradients of the secondary mid-/high-Z impurity

- **Centrifugally-dominated asymmetry?**

  …to build the 2D poloidal distribution of the secondary mid-/high-Z impurity

- **Local-ionization-equilibrium?**

  …for the ionization balance and cooling functions

- **Quasi-stationary phases** *or identical sources & sinks for mid-/high-Z?*

  …since there is no information on sources and sinks

- **Forward model of various diagnostics?**

  …more consistent models for e.g. Zeff Bremsstrahlung measurement

New Python version under development

Designed for being portable

- *I/O self-contained in the classes reading diagnostic data*
- *No interfacing to mapping libraries*
- *Abstract classes for easy and guided implementation on various machines*
- *As much as possible native Python*

Optimization of algorithms

- *Transform my exploratory algorithms to something mathematically rigorous…*

Profile fits using multiple measurements

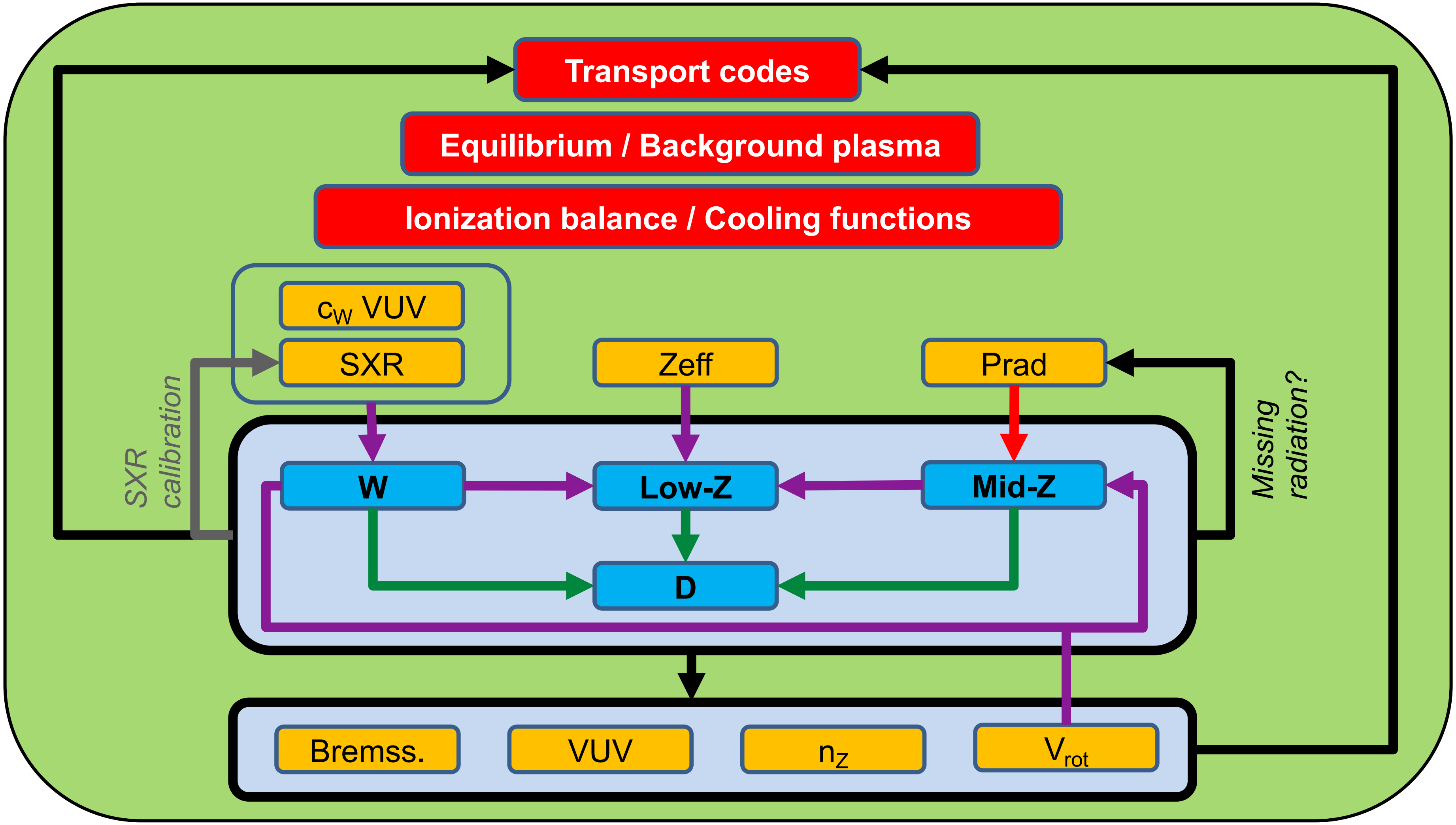
- *Combine diagnostics for better profile-fits*

Couple to fast transport codes

- *Scaling of mid-Z impurity (Z3) density gradients*
- *Modification of ionization balance and radiation loss parameters*

New Python version under development

Previously input & constant quantities **should** become part of the analysis and affect not only results but also measurement interpretation



Parallel efforts

Assess effects of these measurements on other calculations:

Equilibrium

Position of the plasma centre and shape of flux-surfaces

Beam attenuation

Using impurity density profiles in ASCOT and NUBEAM

ICRH

Direct effect of high impurity densities in front of the antenna

Indirect effect through ICRH-NBI synergies

Dilution

Neutron rate and transport stability

q-profile

Effect shape of q profile, shear and q(0)

2D effects…

Backup

96851 profiles: electrons / ions