Predicting time evolution of hydrogen co-deposition in ITER based on self consistent global impurity transport modeling

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Motivation

❖Current predictions for co-deposition in ITER are based on **local** simulations at the CFC targets

- ➢Requires **ad-hoc** assumption about Be influx
- ➢No global flux or material balance
- ➢“Ignores” co-deposition at other locations in the divertor

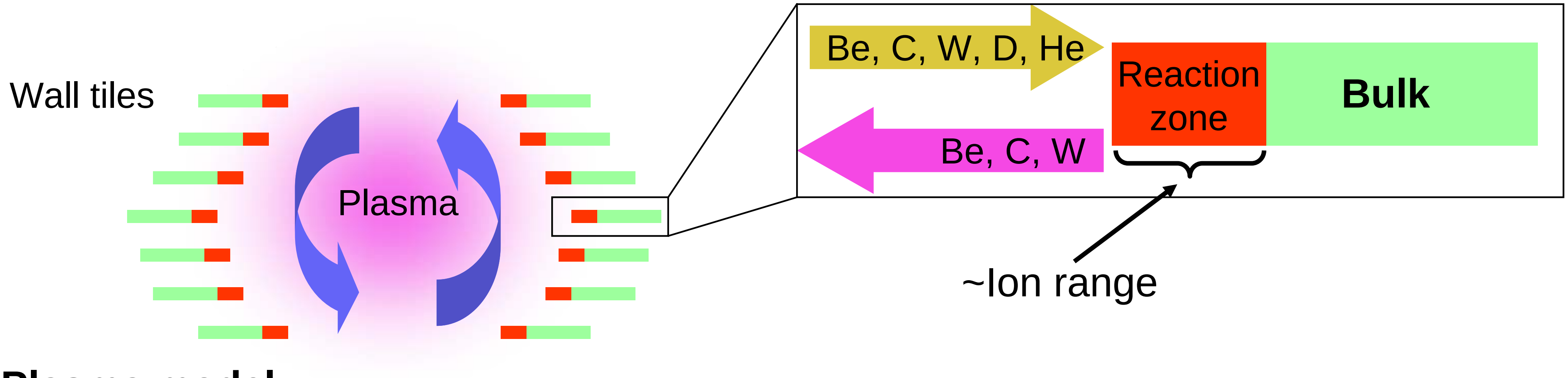
→ Use WallDYN[1] to perform self consistent, **global** erosion deposition modeling of Be, C and W in ITER

- ➢Self consistently calculates impurity fluxes (Be, C, W) onto the wall and erosion fluxes back to the plasma.
- ➢Calculates the time evolution of the surface composition
- ➢Maintains a global material and flux balance
- ➢Calculates deposition of Be, C and W over the entire poloidal circumference of the ITER first wall

[1] K. Schmid et Al ***“An integrated model of impurity migration and wall composition dynamics for tokamaks”*** PSI-19

Model description

❖ Subdivide the first wall into N-tiles



❖ **Plasma model:**

- ❖ Time scale of plasma transport is short compared to time scale of wall evolution
- ❖ Impurity concentrations in the plasma are low enough not to disturb the plasma
- ➢ Plasma transport can be characterized by a re-deposition matrix:

$$r_{i,j}^{m,q} \equiv \textbf{Fraction of eroded flux of element m at charge state q from tile j that ends up on tile i}$$

❖ **Surface model:**

- ➢ Reaction zone composition is variable, Bulk composition is constant
- ➢ All erosion & deposition is assumed to occur homogeneously in the reaction zone
- ➢ Total areal density of the reaction zone is kept constant via exchange with Bulk

Model description

❖Influx from plasma transport

$$\Gamma^{\mathrm{In}}_{ei,qi,wr} = \sum_{ws=1}^{\mathrm{NElem}} \left(\Gamma^{\mathrm{Ero}}_{ei,ws}\left(\Gamma^{\mathrm{In}}_{ej,qj,ws}\right) + \Gamma^{\mathrm{Refl}}_{ei,ws}\left(\Gamma^{\mathrm{In}}_{ei,qi,ws}\right)\right) * \xi_{ei,qi,ws,wr}$$

➢Defines an algebraic equation system for the incident fluxes

$$\xi_{ei,qi,wr,ws} = \frac{N^{ei,qi}_{ws}}{N^{ei}_{wr}} * \frac{l_{wr}}{l_{ws}}$$

$$N^{ei}_{wr} = \#\text{ of eroded, neutral particles launched from wr}$$

$$N^{ei,qi}_{ws} = \#\text{ of particles launched from wr that impacts}$$

$$= \text{in ws at charge state qi}$$

$$l_{wr}, l_{ws} = \text{Length of tile wr and ws respectively}$$

❖Redistribution matrix from plasma transport code e.g DIVIMP
= Fraction of element ei eroded at wr that ends up on ws at charge state qi

Model description

❖Change in areal density[1] of element ei on wall wr

$$\frac{d\delta_{ei,wr}}{dt} = \Gamma^{\mathrm{Dep}}_{ei,wr} - \Gamma^{\mathrm{Ero}}_{ei,wr} + \Gamma^{\mathrm{Bulk}}_{ei,wr}$$

For non depositing species e.g D no surface composition is calculated

$\Gamma^{\mathrm{Dep}}_{ei,wr} =$ … on wall element wr

$\Gamma^{\mathrm{Ero}}_{ei,wr} =$ … wall element wr

$\Gamma^{\mathrm{Bulk}}_{ei,wr} =$ … h bulk to keep total areal density constant in reaction zone

Additional material loss channels and sources can be added here
→ Simulate chemical reactions
(see M. Reinelt PSI-19)

❖total areal density: $\delta_{TOT,wr} = \sum_{ei=1}^{\mathrm{NElem}} \delta_{ei,wr}$

➢In net erosion cases material has to be moved from the bulk to the reaction zone to keep the total areal density constant

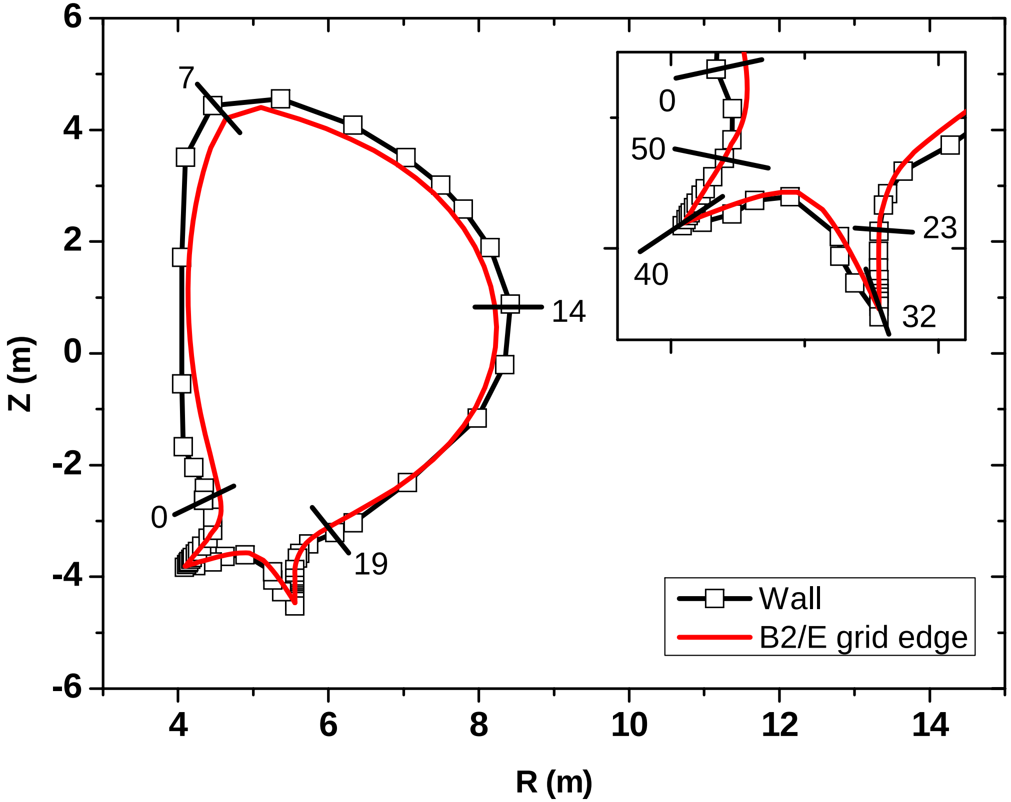
➢In net deposition cases material has to be moved to the bulk from the reaction zone to keep the total areal density constant

[1] K. Schmid et al., Nuclear Technology, 159, No. 3, (2007) 238

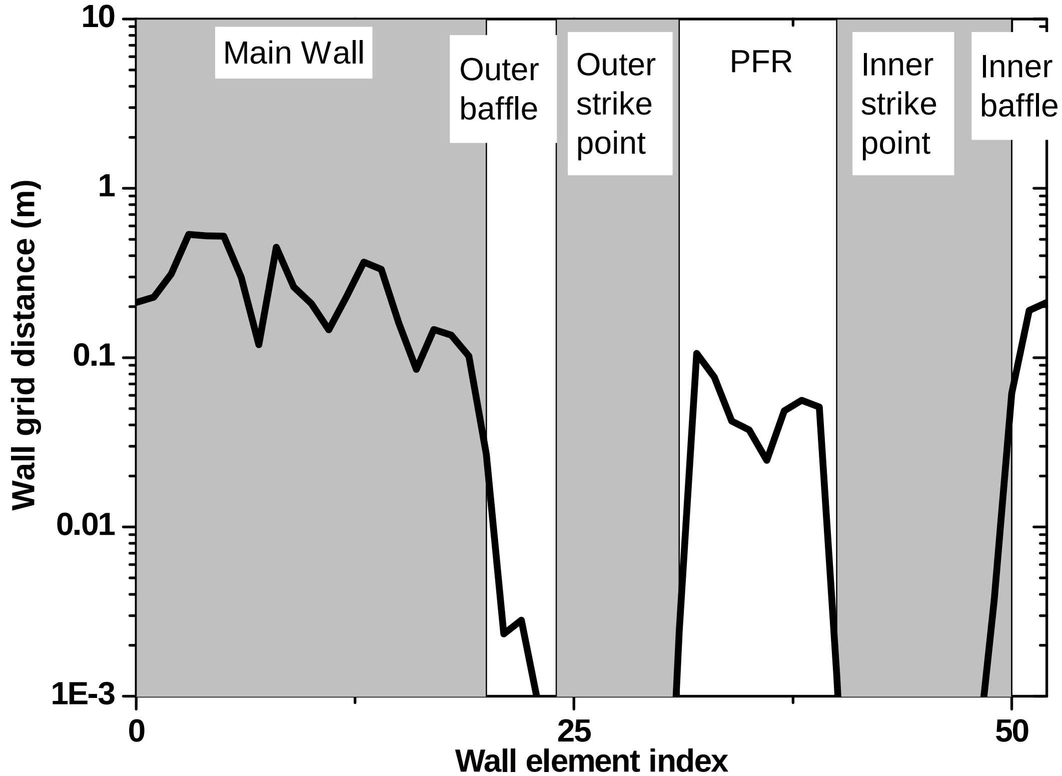
Input data

❖High power & high density ITER case [1]: iter812

➢WallDYN wall and B2/E grid boundary



➢Grid-Wall distance



➢ Grid wall distance up to 60 cm!

? Extrapolation of plasma to wall ?

➢Te, Ti

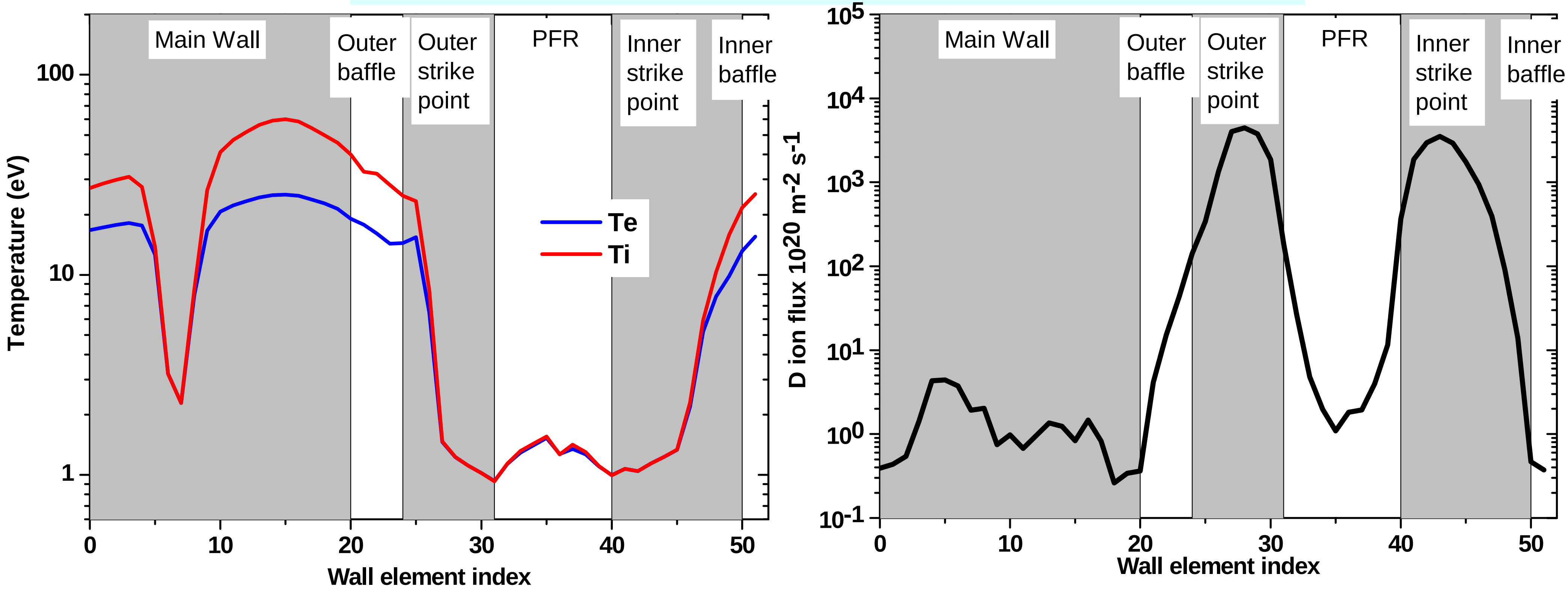
➢D, He, C fluxes

[1] A. S. Kukushkin et al. Journal of Nuclear Materials 337–339 (2005) 50–54

Input data

❖Ion fluxes and plasma parameters at the wall

➢Flat extrapolation from B2/E calculation grid to wall



➢ Very high Te, Ti at W baffles and main chamber → Strong physical sputtering

➢ Gap between grid and wall ~ 5 cm at baffles and ~ 20 cm at main wall

➢Significant decay of flux & temperatures is likely

Input data

❖Decay of ion fluxes and plasma temperatures towards the wall

➢Flux decays exponentially with a decay length λ

$$\lambda = \sqrt{\frac{D_\perp l}{c_s}}$$

$$\left.\begin{array}{l} l \approx 180\,\mathrm{m} \\ D_\perp \approx 10\,\mathrm{m^2/s} \\ c_s \approx 10^5\,\mathrm{m/s} \end{array}\right\} \lambda \approx 0.1\,\mathrm{m}$$

Drop by factor ½ on average

➢Temperature decay is more complicated, depends on χ–parallel

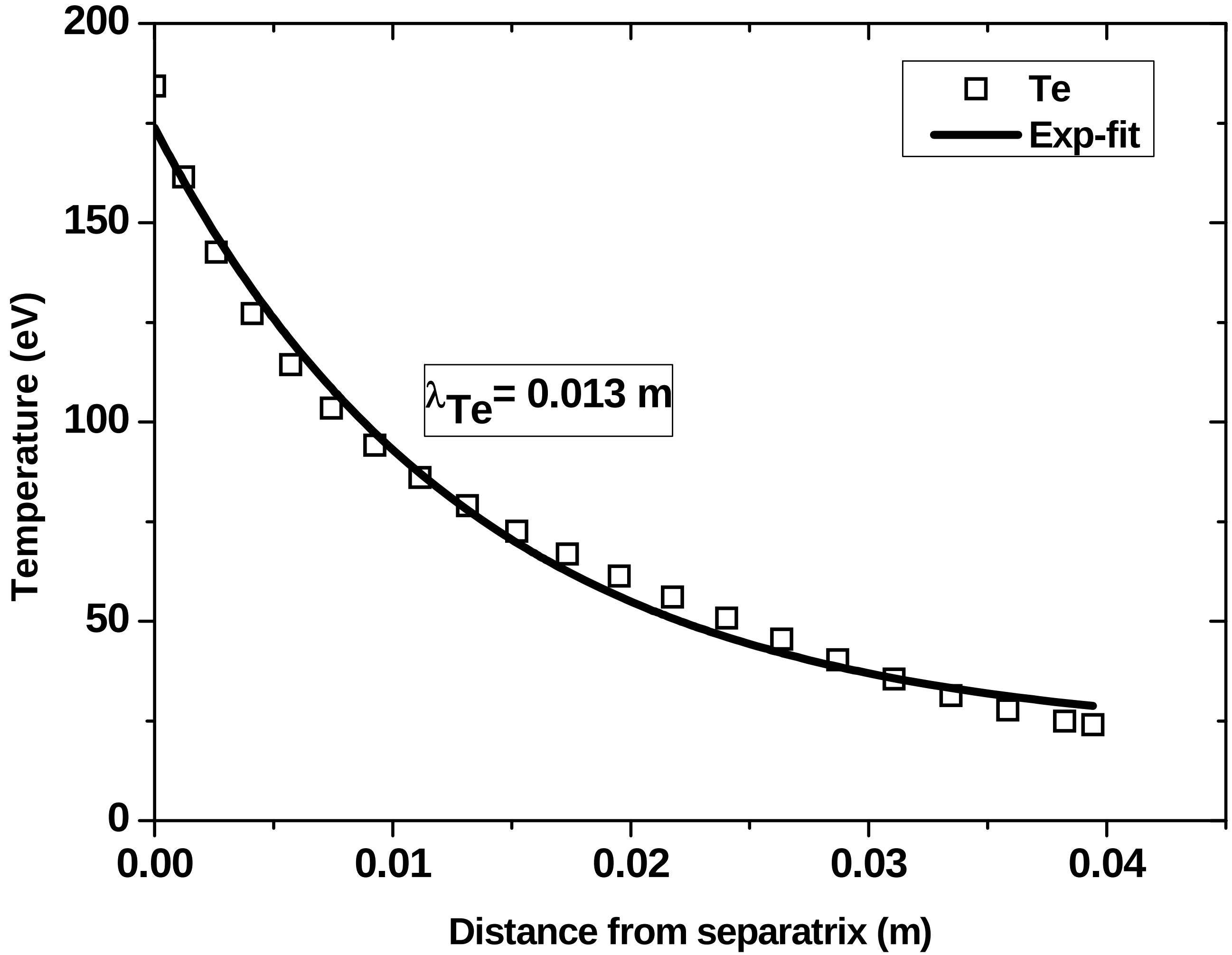
➢Ti ~ constant due to fast transport in gap (blobs)

➢Te drops due to parallel heat loss (high χ–parallel for e^-)

By how much ?

Input data

❖Drop in Te from grid to wall based on radial Te evolution in the B2/E solution



➢Radial Te, evolution well represented by exponential decay

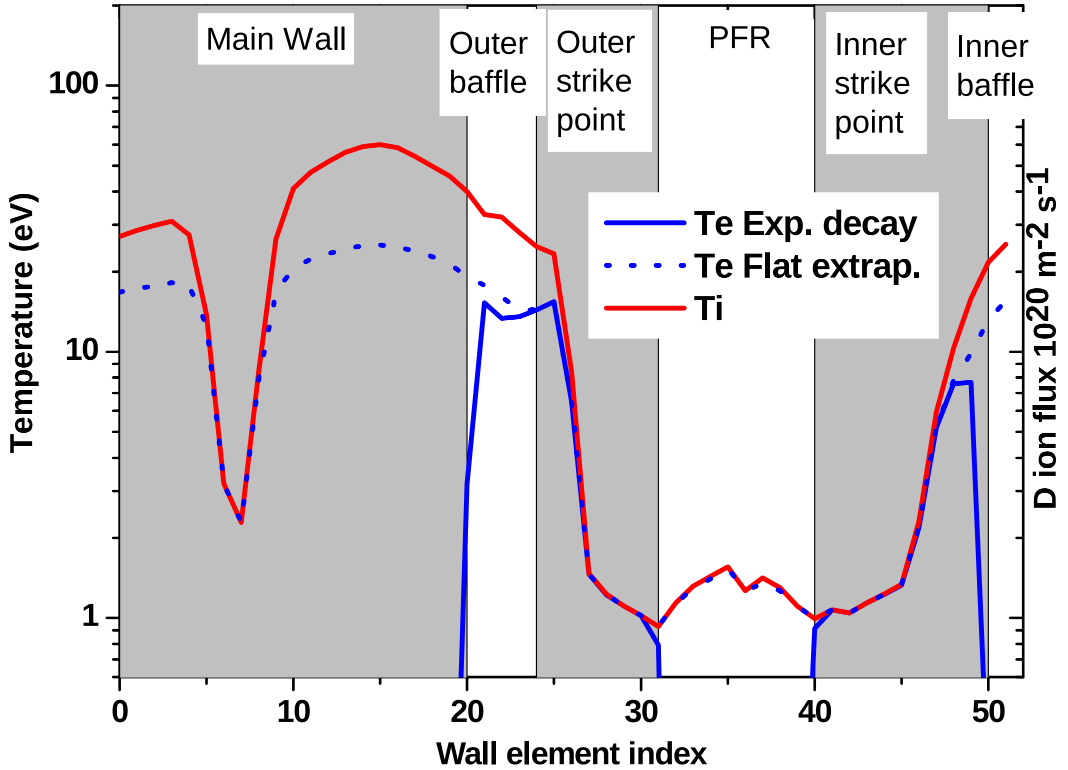
➢Use this λ values to extrapolate Te across the gap

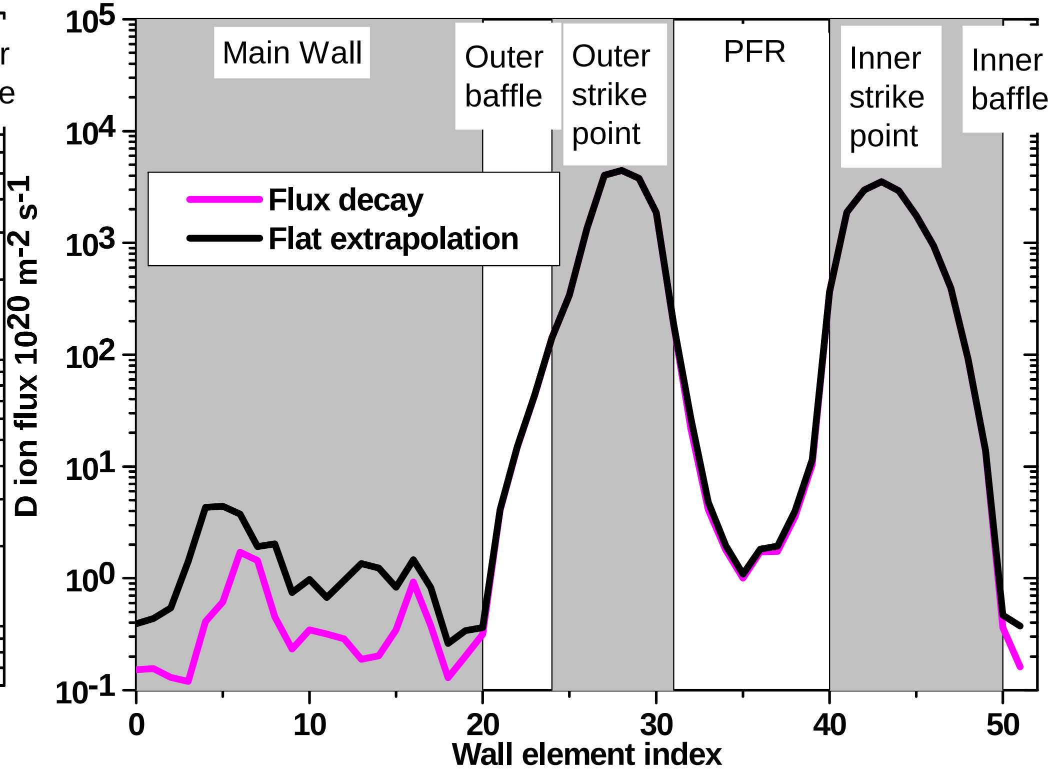
[1] A. S. Kukushkin et al. Journal of Nuclear Materials 337–339 (2005) 50–54

Input data

❖Resulting plasma parameters at wall due to Te decay

➢Exp. decay of plasma parameters from B2/E calculation grid to wall





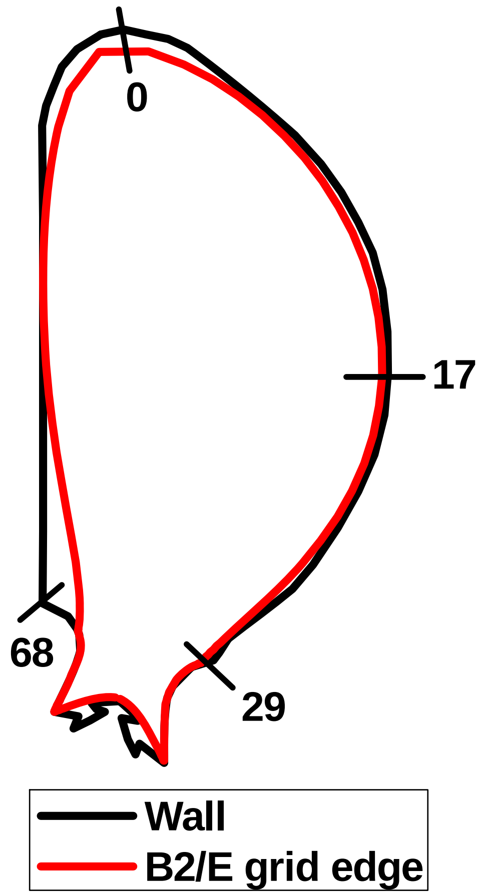
➢Decay affects main wall, divertor dome and baffle

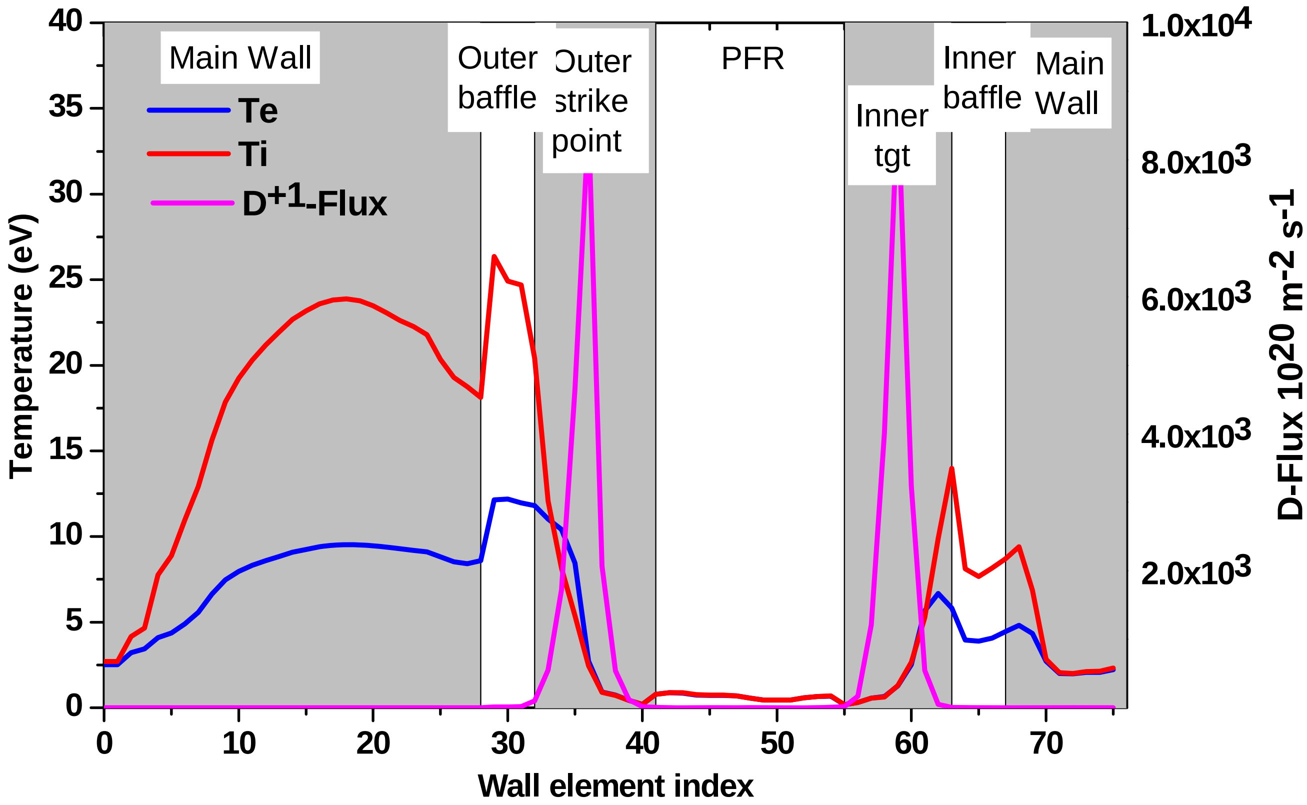
➢Lower Be source at main wall → Less mitigation of C erosion

Input data

❖New ITER design case [1]: F57_Series 1511

❖**Flat plasma extrapolation**





❖Similar D ion fluxes but plasma temperatures are lower by factor ~3 (Grid extends farther outward)

➢Smaller difference between flat extrapolation and plasma decay

[1] H.D. Pacher, A.S. Kukushkin et Al, J. Nucl. Mat. 3909-391 (2009) p. 259

Input data

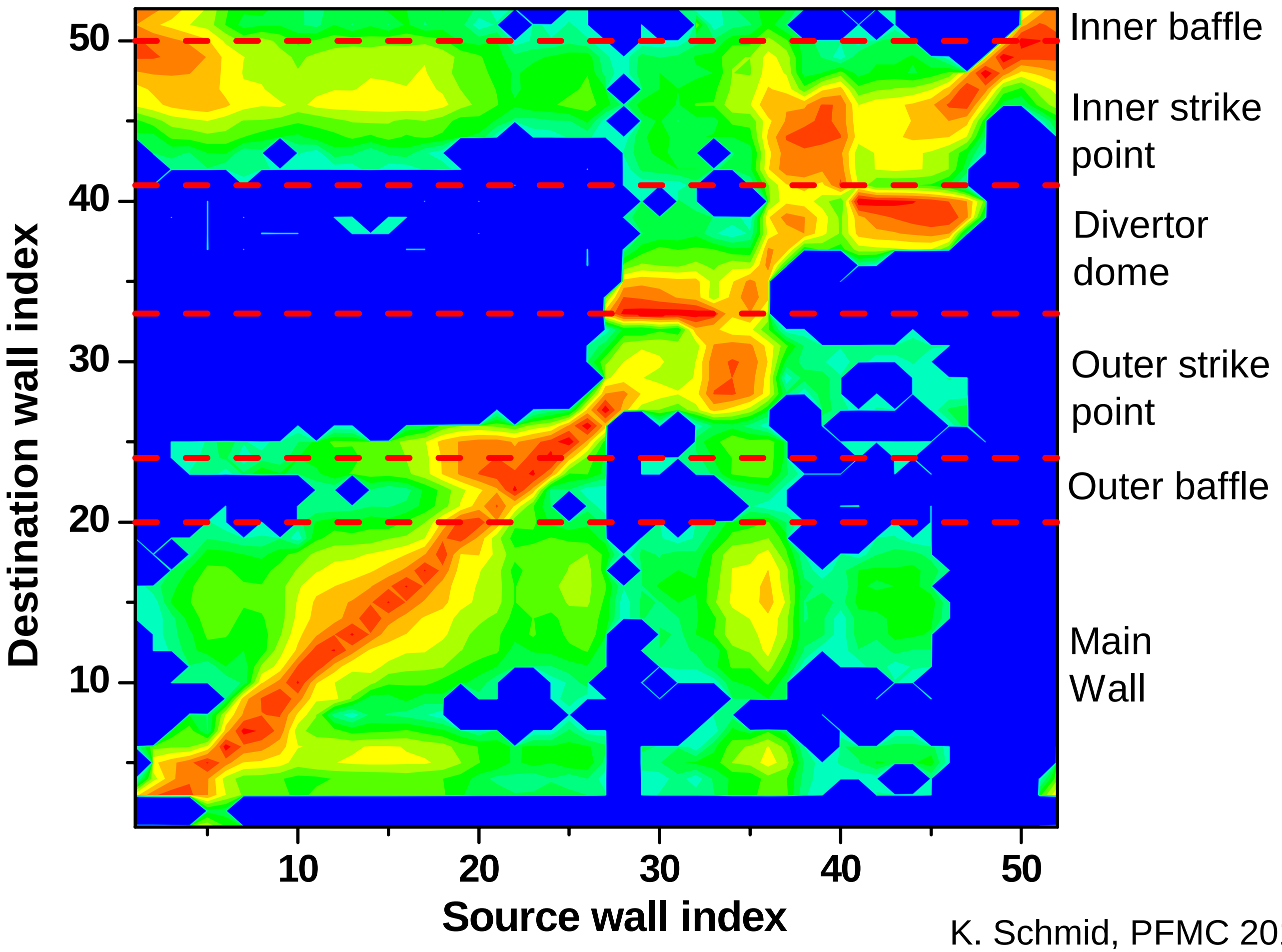
❖ Plasma model input data the **redistribution matrix** calculated by DIVIMP

❖ Launch impurities at a poloidal position

❖ Record impact position and charge state

Charge state resolved re-deposition matrix

$r_{i,j}^{Be}$ Be charge state integrated



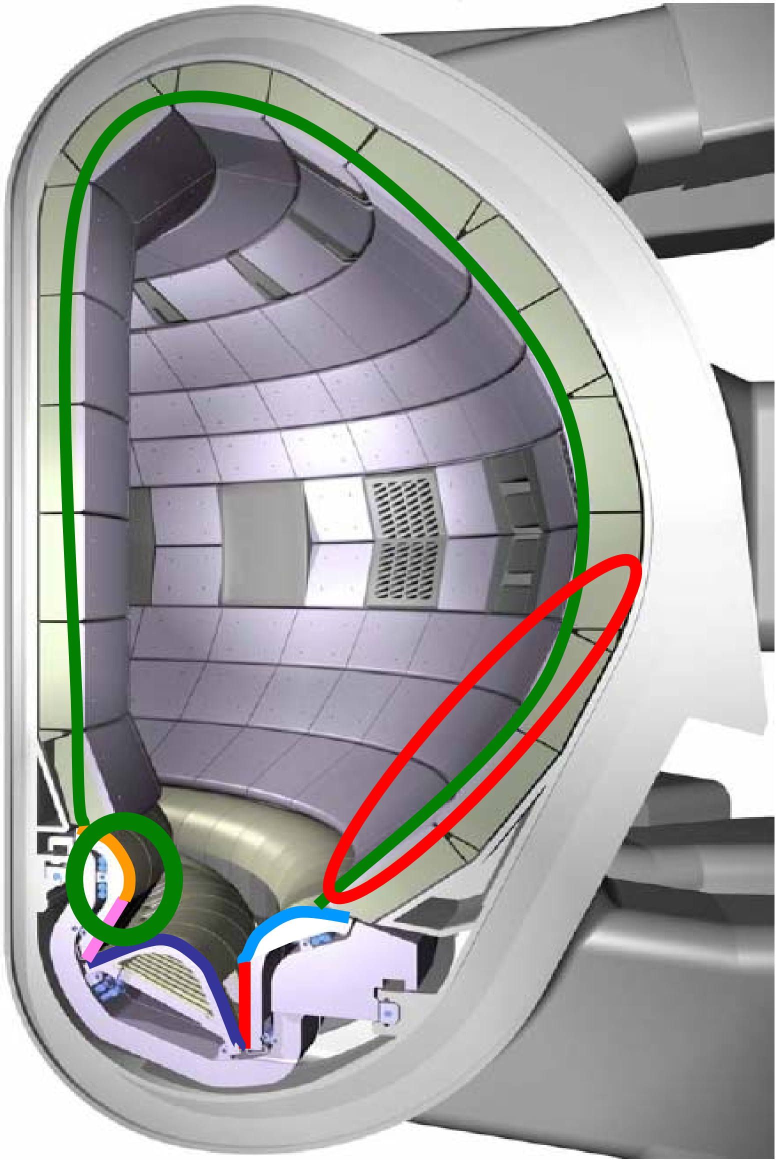
➢Strong diagonal
→ Transport is step wise

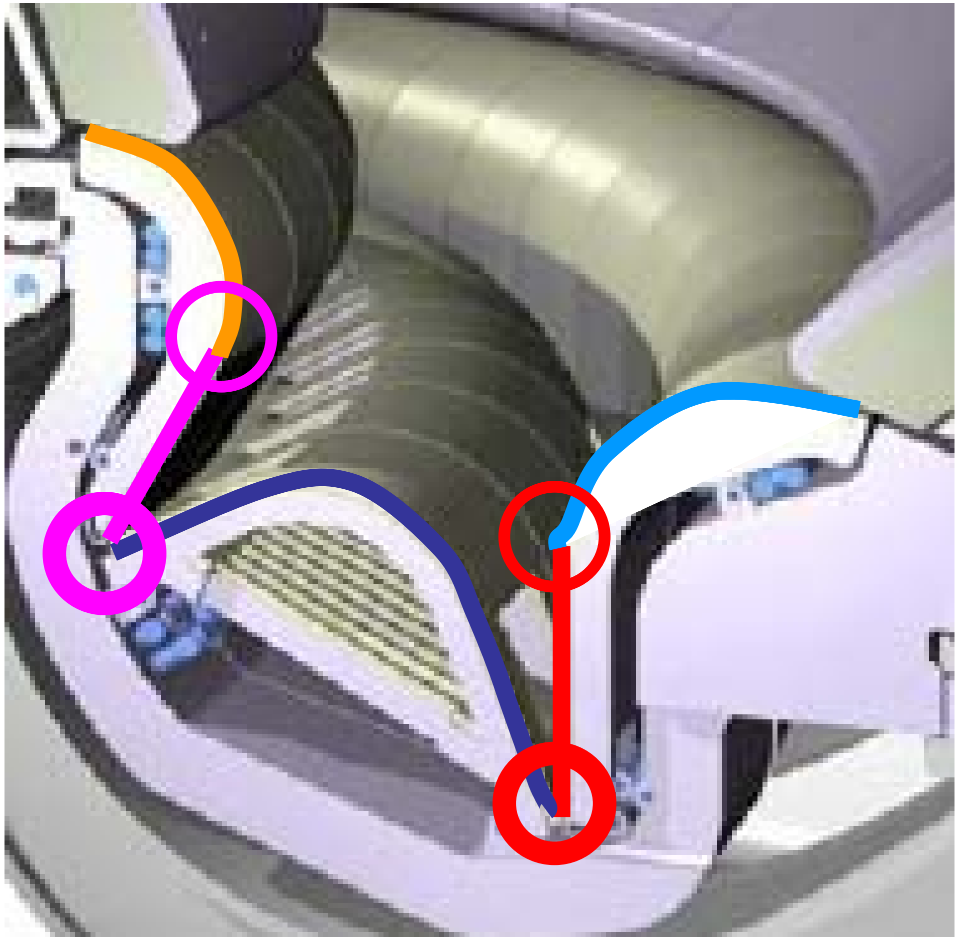
➢Most material ends up in inner divertor

Input data

❖Given the redistribution matrices, where is eroded material qualitatively transported to

❖Material is transported in small steps and generally ends up at:





❖But that does not mean it stays there!
❖In the divertor material is recycling

K. Schmid, PFMC 2011

Input data

❖ Surface model input data

- ➢ Erosion yields as function energy and surface composition
- ➢ Reflection yields as function energy and surface composition

?

20 Years of MD, TRIM & Experimental data yield a solid basis for a scaling law based parameterization of the required yields

❖ Current approach: Fit TRIDYN data with scaling law

Composition dependence

$$Y_{ei,ej}\left(E_{qj,ws},\delta_{ek\ldots N}\right)=Y_{ei,ej}(E_{qj,ws})*\left(1+\sum_{ek=1}^{NElem}\delta_{ek,ws}\,a_{ek}\right)$$

$Y_{ei,ej}(E_{qj,ws})$ = Energy dependence of sputtering of ei by ej

$\delta_{ek,ws}$ = Areal density of component ek on wall element ws

$E_{qj,ws}$ = Impact energy of element at charge state qj on wall ws

a_{ek} = Free parameter describing the composition dependence

Energy dependence (Bohdansky formula)

❖Similar approach also for reflection yield

Results

❖Calculations produce huge amount of information → difficult to visualize

→ Only excerpts & averages are shown

❖Old and new ITER design B2/E backgrounds yield qualitatively the same results

→Not ever result will be shown for every case

→Only examples of observed effects will be shown

❖Main influence on results comes from different extrapolation of main wall plasma

→ Comparison of flat extrapolation with plasma decay case

flat extrapolation	plasma decay
High Te, Ti & flux → **Strong** Be source	Low Te, Ti & flux → **Weak** Be source

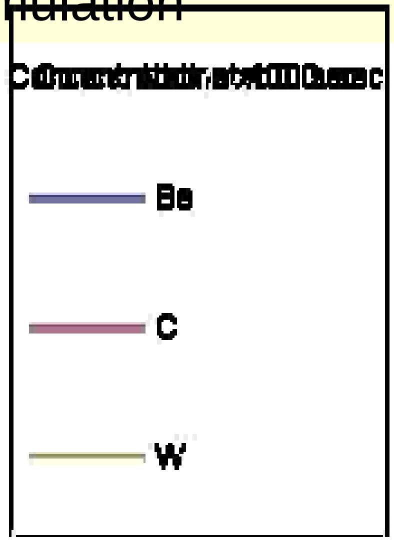
Surface composition evolution

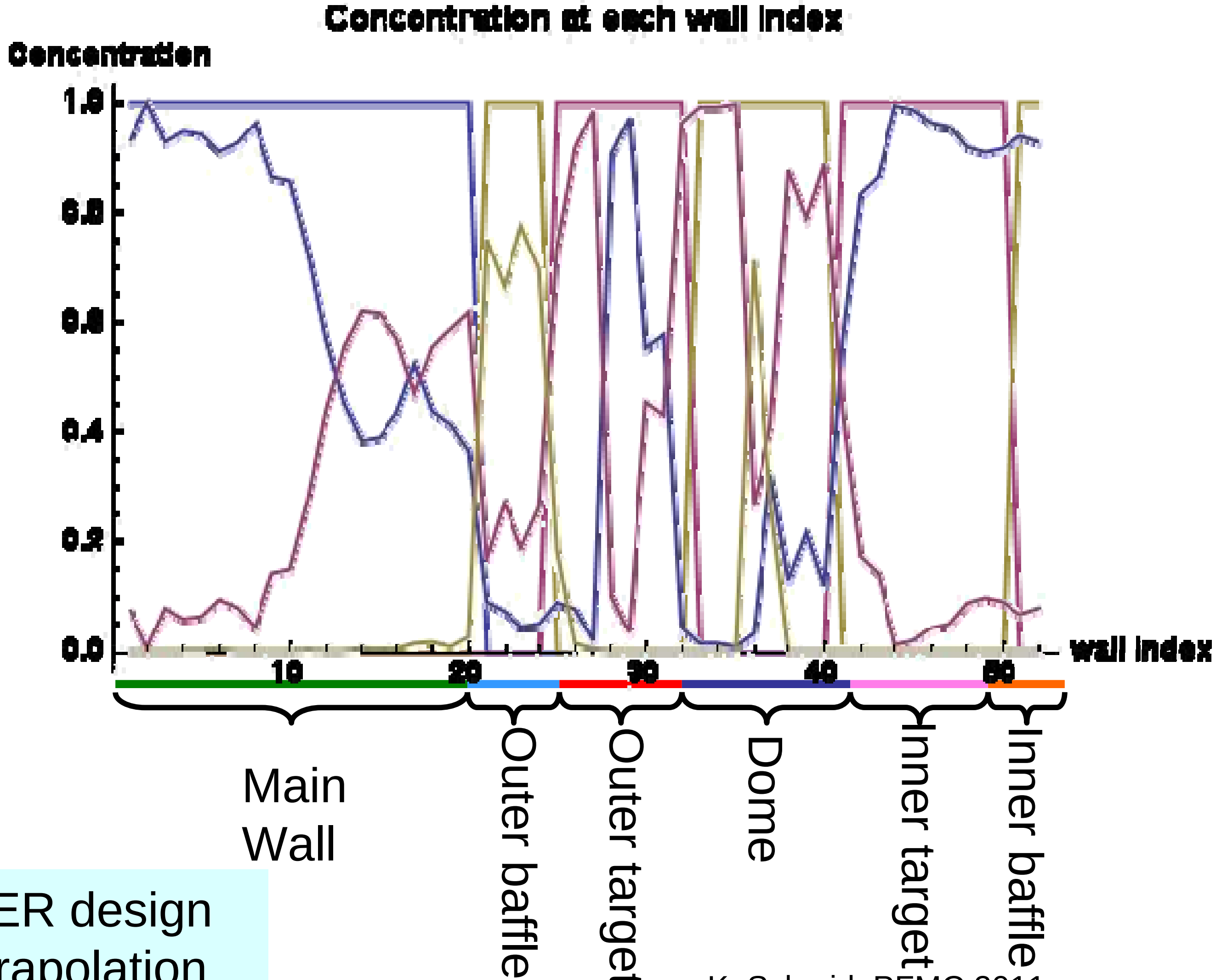
❖Erosion fluxes of Be, C & W vary with time due to changes surface composition

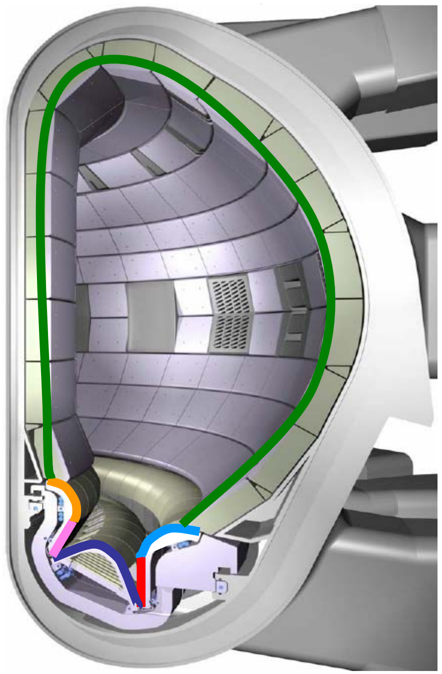
→ Impurity influx varies with time

→ There is no constant set of fluxes to be used in a local simulation

❖Equilibrium state can only be found in a **global** simulation





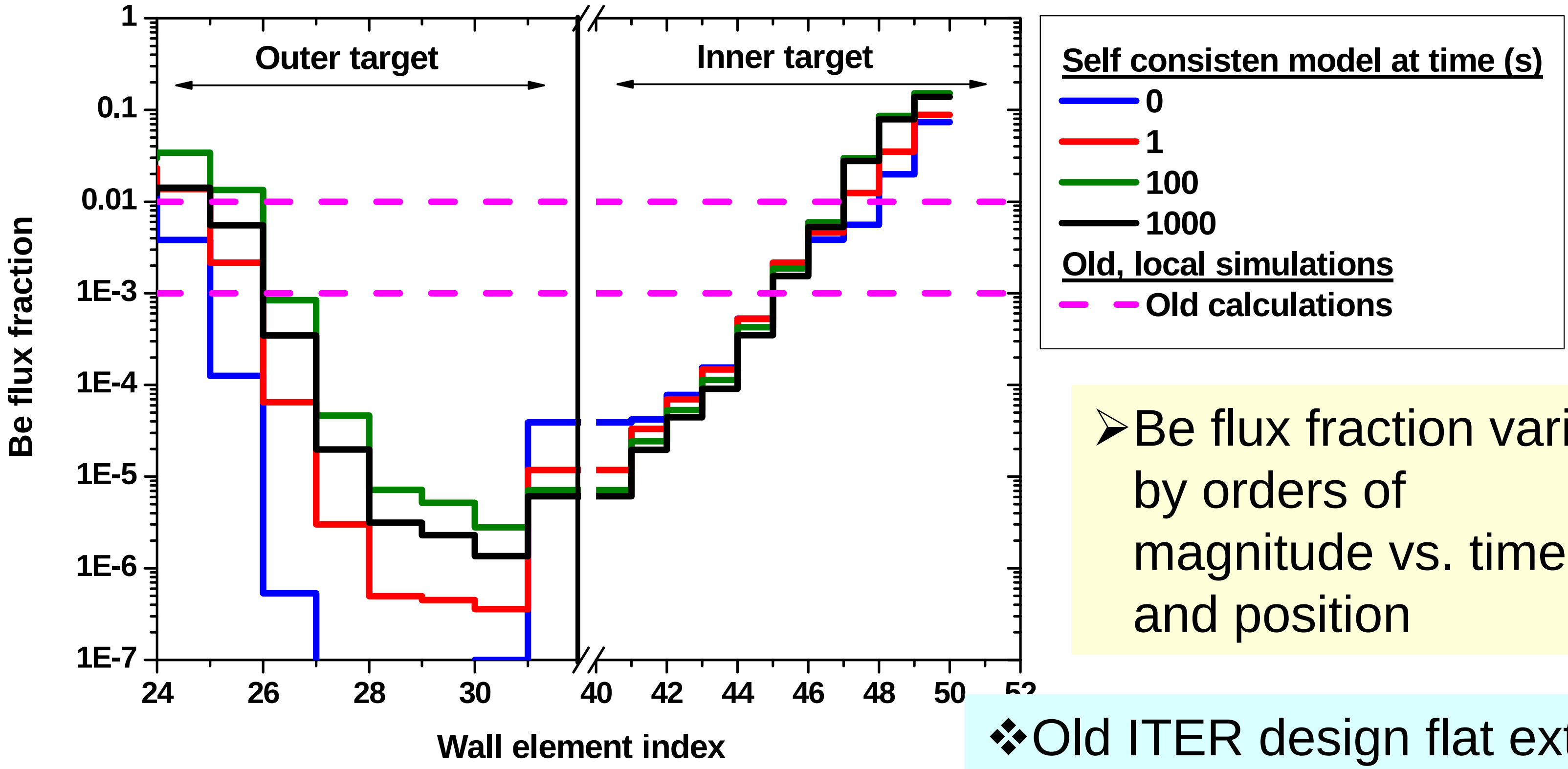


❖Old ITER design flat extrapolation

K. Schmid, PFMC 2011

Be influx onto targets

❖Be influx onto divertor targets as function of time



➢Be flux fraction varies by orders of magnitude vs. time and position

❖Old ITER design flat extrapolation

➢Old predictions based on constant Be flux fraction

→overestimate Be flux → overestimate Be deposition

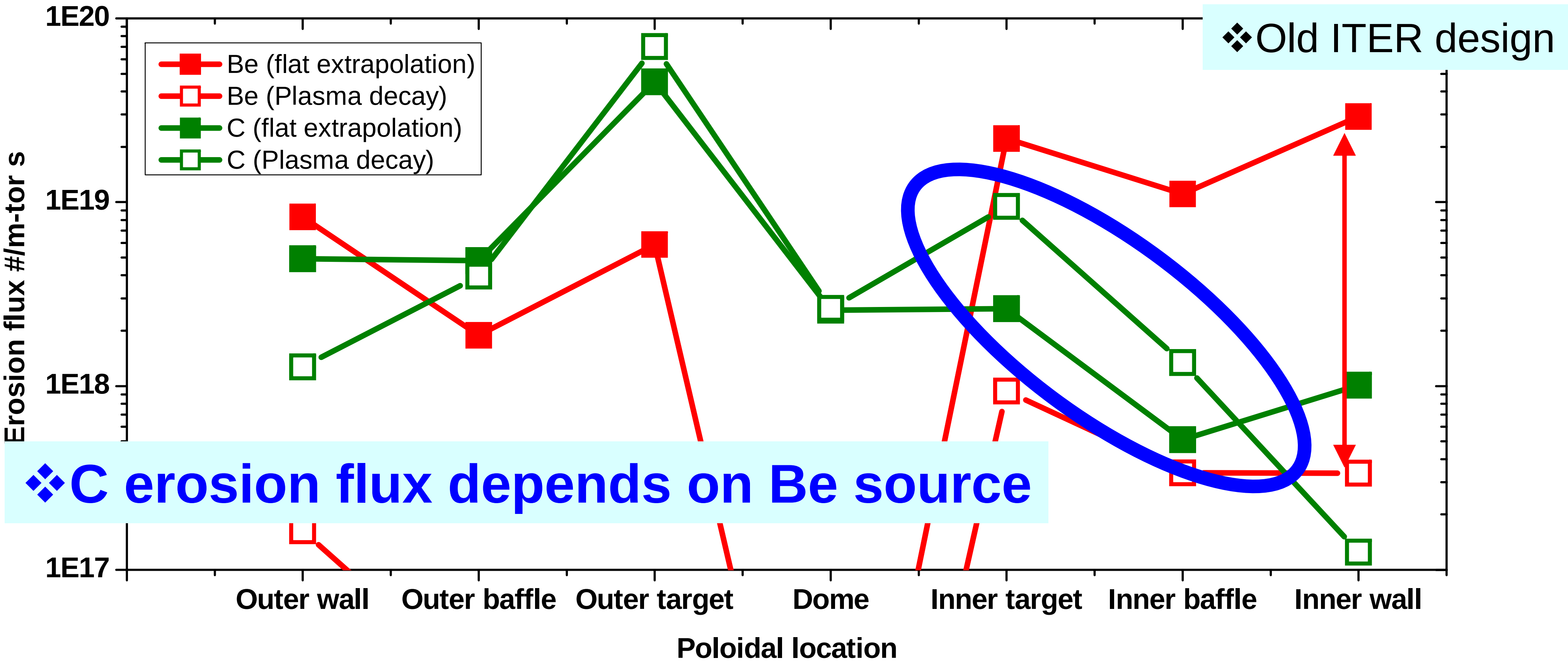
→overestimate co-deposition by Be → **under**estimate co-deposition by C

➢Self consistent calculations yield less Be deposition

→ More C erosion → **C co-deposition** dominates

Impurity influx into SOL

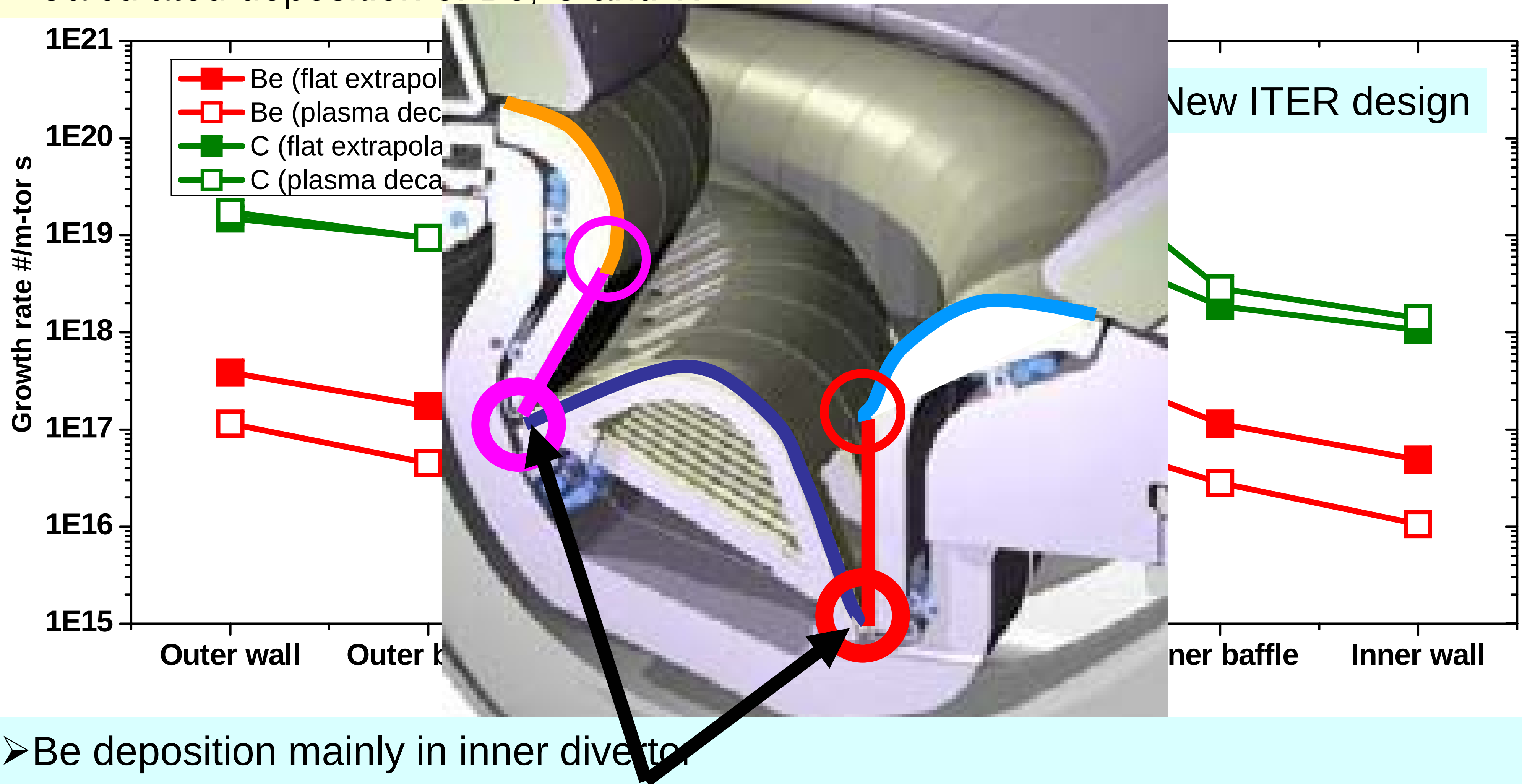
❖Erosion fluxes of Be, C & W for the equilibrium surface composition



- ➢For flat extrapolation the main wall Be erosion is higher by an order of magnitude.
- ➢C erosion is more mitigated by Be deposition in flat extrapolation case
- ➢Divertor region is still C erosion flux dominated in both cases
- ➢W Sputtering is low in both cases and limited to the outer baffle

D co-deposition

❖Calculated deposition of Be, C and W



➢Be deposition mainly in inner divertor

➢C deposition at divertor floor (dome) and outer main chamber

➢**Amount of C deposition depends on C erosion mitigation by Be i.e on the Be source**

➢C dominates deposition in all cases

Input data

❖Based on net deposition rates ($m^{-2}\ s^{-1}$) at each poloidal position + D/C, D/W and D/Be ratios [1] the D accumulation rate can be calculated

➢D/C, D/W and D/Be ratios as functions of D/x flux ratio, T(K) and D-energy

$$D/x = E_D^{\alpha} + \left(\Gamma_D/\Gamma_{Be}\right)^{\beta} + e^{\left(-\gamma/T\right)}$$

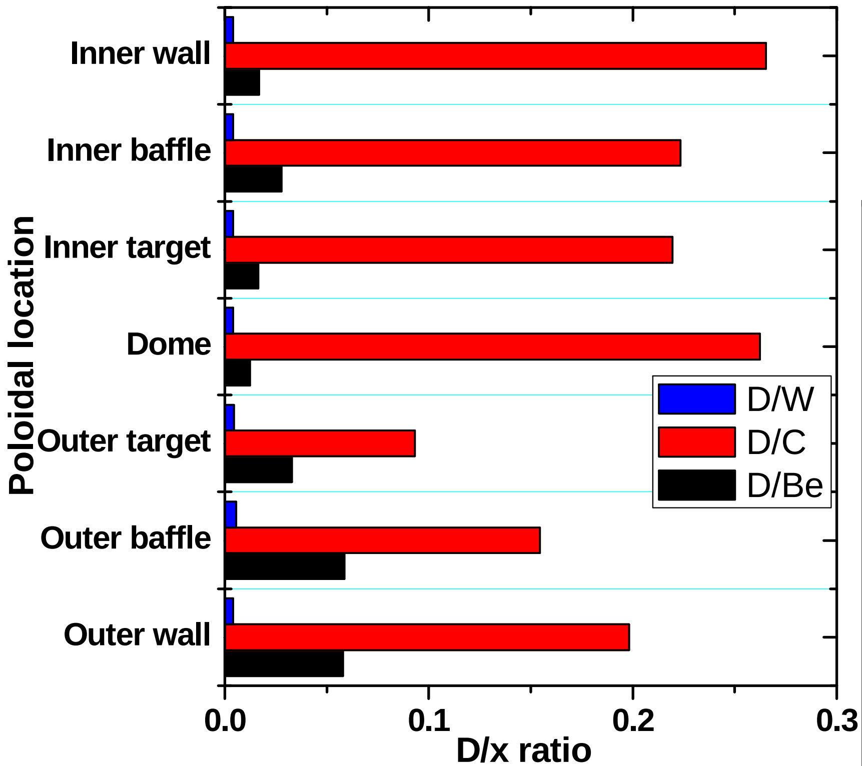
➢D/x flux ratio, T(K) and D-energy were "clamped" to validity range

❖New ITER design (Plasma decay)

➢D/C ~ 0.2

➢D/Be ~ 5E-2

➢D/W ~5E-3



Assumed temperatures

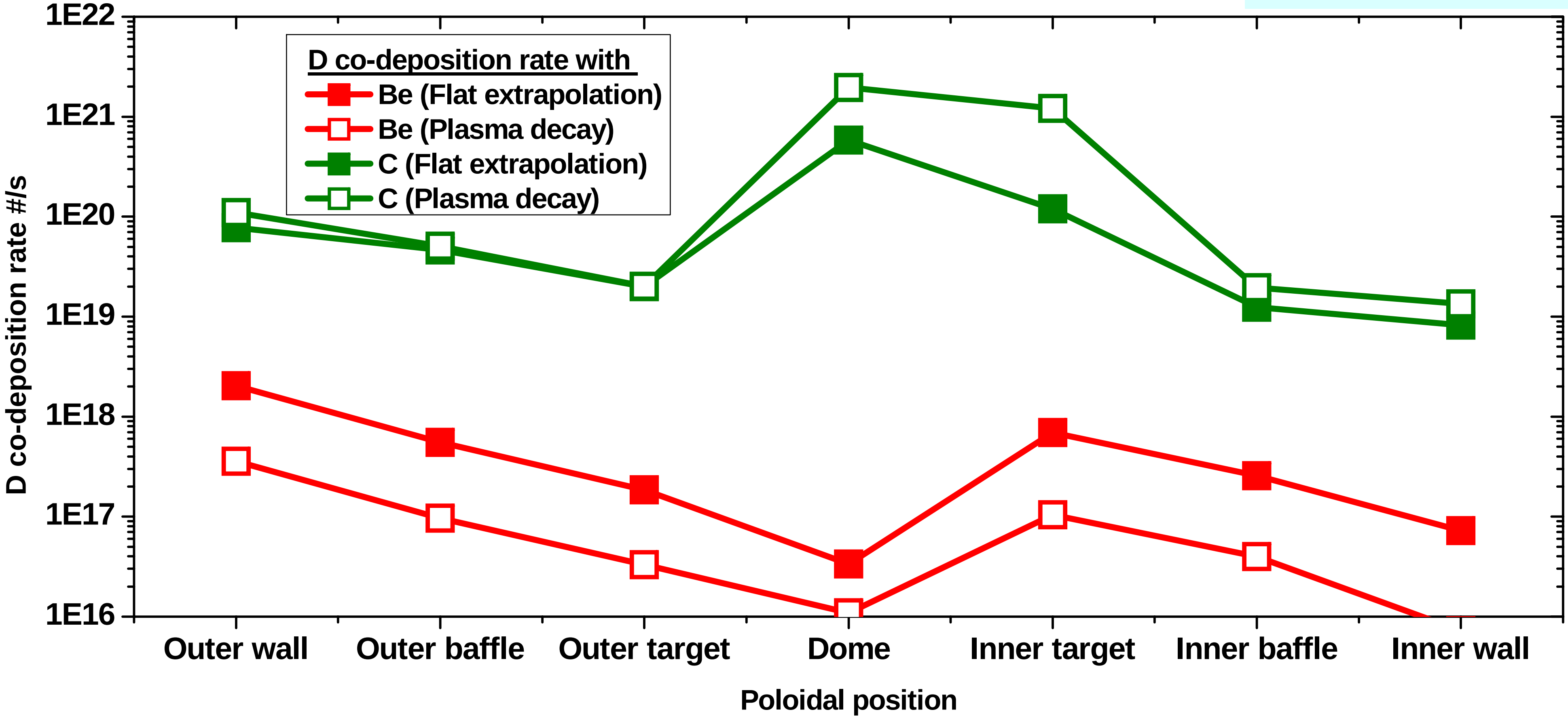
Pos.	T(K)
Inner strikep.	800
Outer strikep.	1200
Dome	600
Baffles	600
Main wall	600

[1] R.P. Doerner et. Al, Nucl. Fusion 49 (2009) 035002

D co-deposition

❖D co-deposition rates from D/x ratios (D/s)

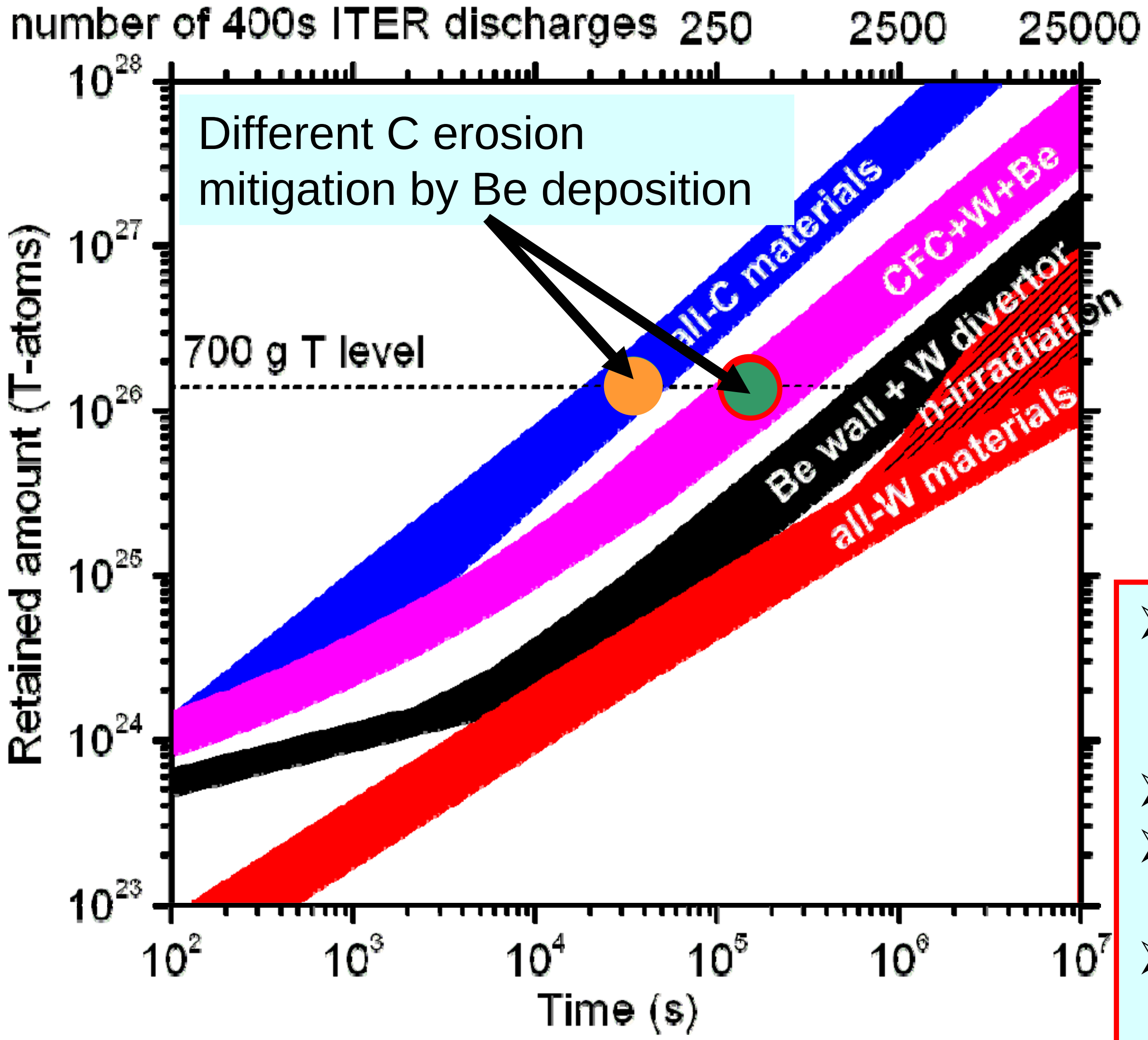
❖New ITER design



- ➢Highest D co-deposition rate located at divertor floor next to targets due chemical sputtering at target plates below strike point
- ➢C dominates total D co-deposition
- ➢A high Be source partially mitigates C erosion and thus D co-deposition

D co-deposition

❖Time to T-accumulation limit due to co-deposition



❖**Flux and Te decay**

- Iter812 (old design)
- F57_1511 (new design)

❖**Flat plasma extrapolation**

- Iter812 (old design)
- F57_1511 (new design)

- ➢Self consistent model of Be flux drops # of ITER shots by up to factor ~10!
- ➢Most retention now due to C
- ➢Divertor floor should be kept HOT
- ➢New ITER design yields same result as old design

J. Roth et. al, J. Nucl. Mat. 390–391 (2009) p. 1

Summary

- ❖The WallDYN code allows to calculate the evolution of the first tiles coupled via plasma transport
- ❖Maintaining material and flux balance it self consistently calculates erosion and re-deposition and the impurity influx into the plasma
- ❖Based on the calculated deposition rates and D/x ratios from literature the D inventory due to co-deposition can be calculated
- ❖Compared to previous estimates most of the co-deposition is due to C not due to Be. (Old local simulations overestimated Be influx)
- ❖The deposition of Be eroded from the main chamber leads to a strong reduction of C erosion in the inner and partly also in the outer divertor.
- ❖A high Be source mitigates C erosion and thus D co-deposition
- ❖The calculation was performed both for the old and the new ITER design yielding essentially the same results: Co-deposition with C instead of Be reduces # of ITER discharges to reach T limit
- ❖A lot of assumptions about the fluxes and plasma temperatures at the wall have to be made. → More experiments are required to improve modeling main wall erosion