ERO Modelling of Plasma-Surface Interaction Experiments and Predictions for ITER

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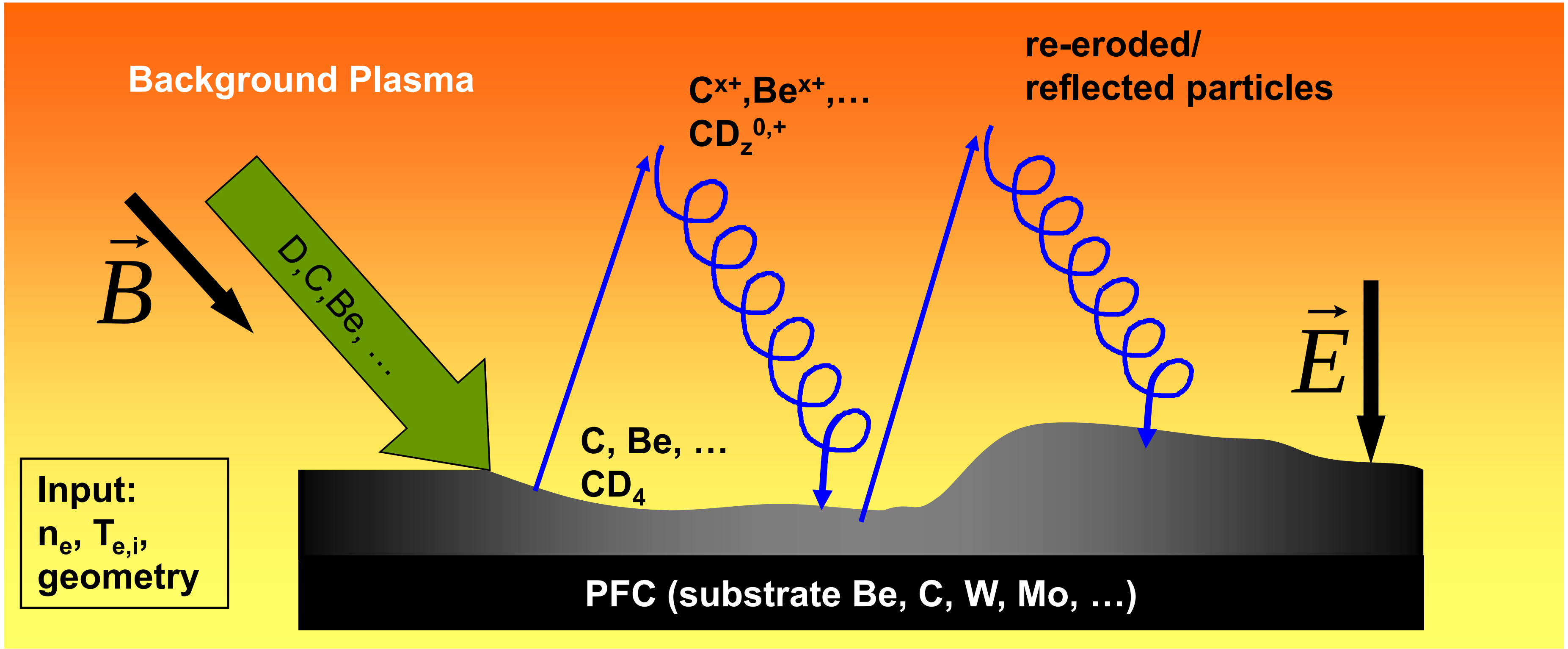
Outline

- **Introduction to ERO code**
- **Examples of simulations**
  - **Linear devices: PISCES-B, Pilot-PSI**
  - **PSI experiments at TEXTOR**
- **Predictive modelling of ITER**
- **Summary**

The overview is neither complete, nor detailed!..

1) ERO-SDTrimSP
2) 3D-GAPS
3) ERO-collaborations
4) . . .

3D MC impurity transport code ERO



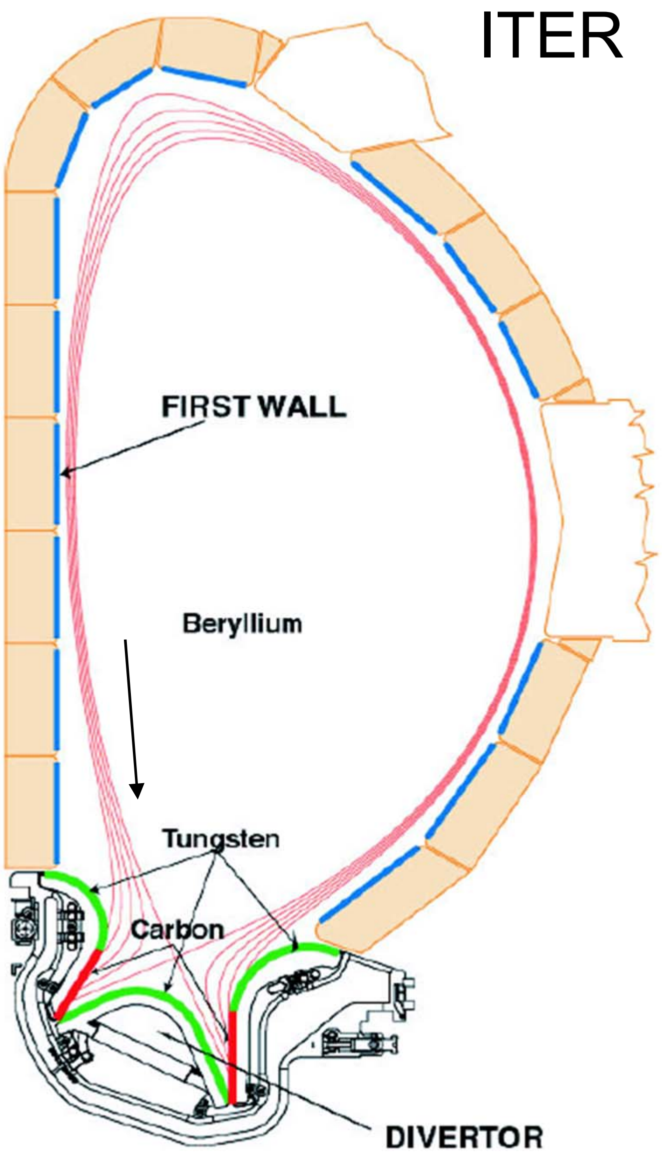
Local transport:

- ✓ ionisation, dissociation
- ✓ friction (Fokker-Planck), thermal force
- ✓ Lorentz force (including ExB component)
- ✓ cross-field diffusion

Plasma-surface interaction:

- ✓ physical sputtering/reflection
- ✓ chemical erosion (CD_4)
- ✓ (re-)erosion and (re-)deposition
- ✓ HMM and SDTrimSP surface models

ITER – first wall materials



700 m^2 beryllium first wall

- low Z
- oxygen getter

100 m^2 tungsten baffles, dome

- high Z
- low sputtering

50 m^2 graphite CFC target plates

- no melting

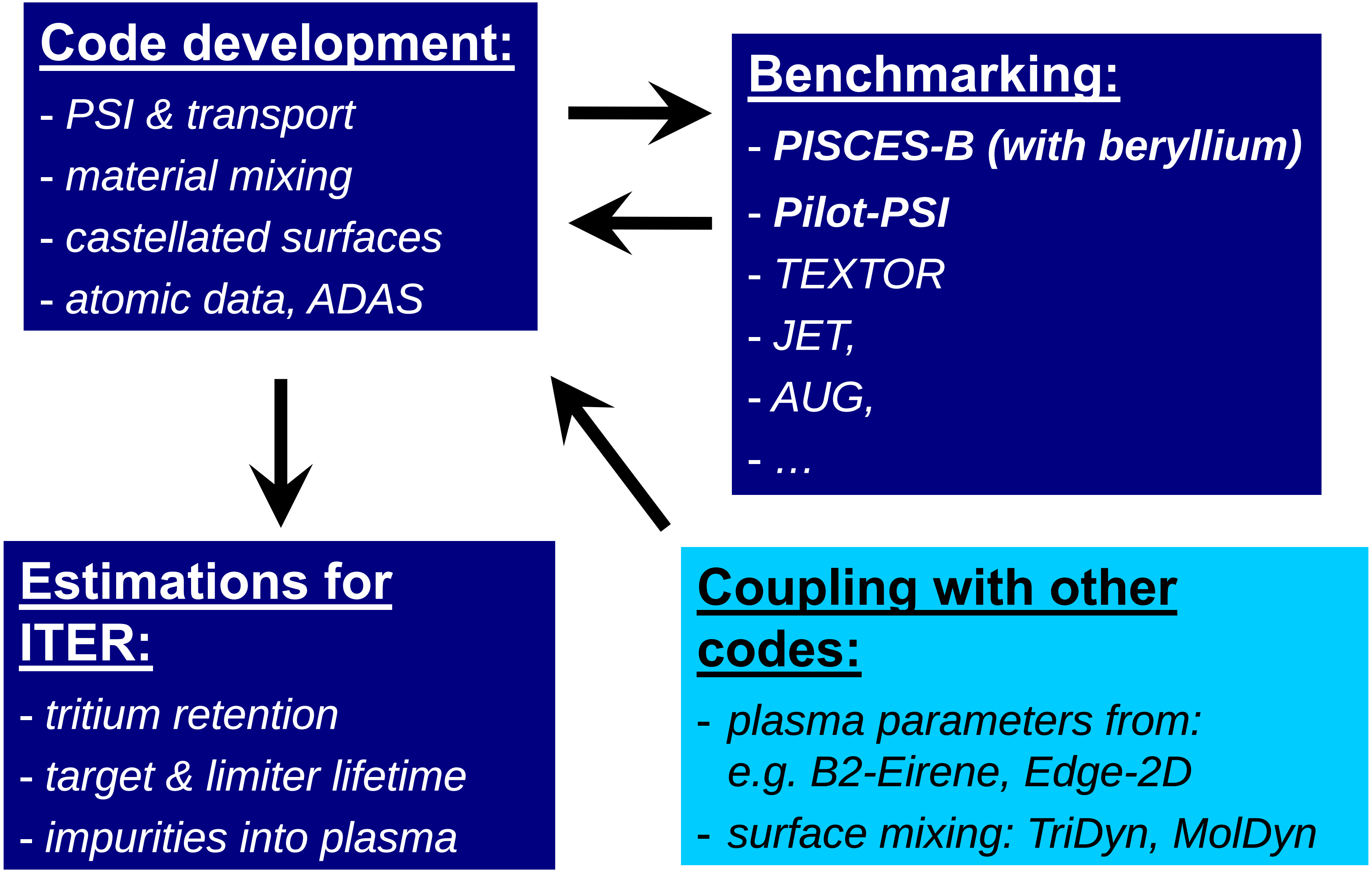
Erosion of wall materials, transport and re-deposition →

- Lifetime & tritium retention

- Material mixing effects

*Plasma-surface interaction in divertor can determine the **ITER availability** . . .*

ERO modelling strategy



Code development:

- *PSI & transport*
- *material mixing*
- *castellated surfaces*
- *atomic data, ADAS*

Benchmarking:

- ***PISCES-B (with beryllium)***
- ***Pilot-PSI***
- *TEXTOR*
- *JET,*
- *AUG,*
- *…*

Estimations for ITER:

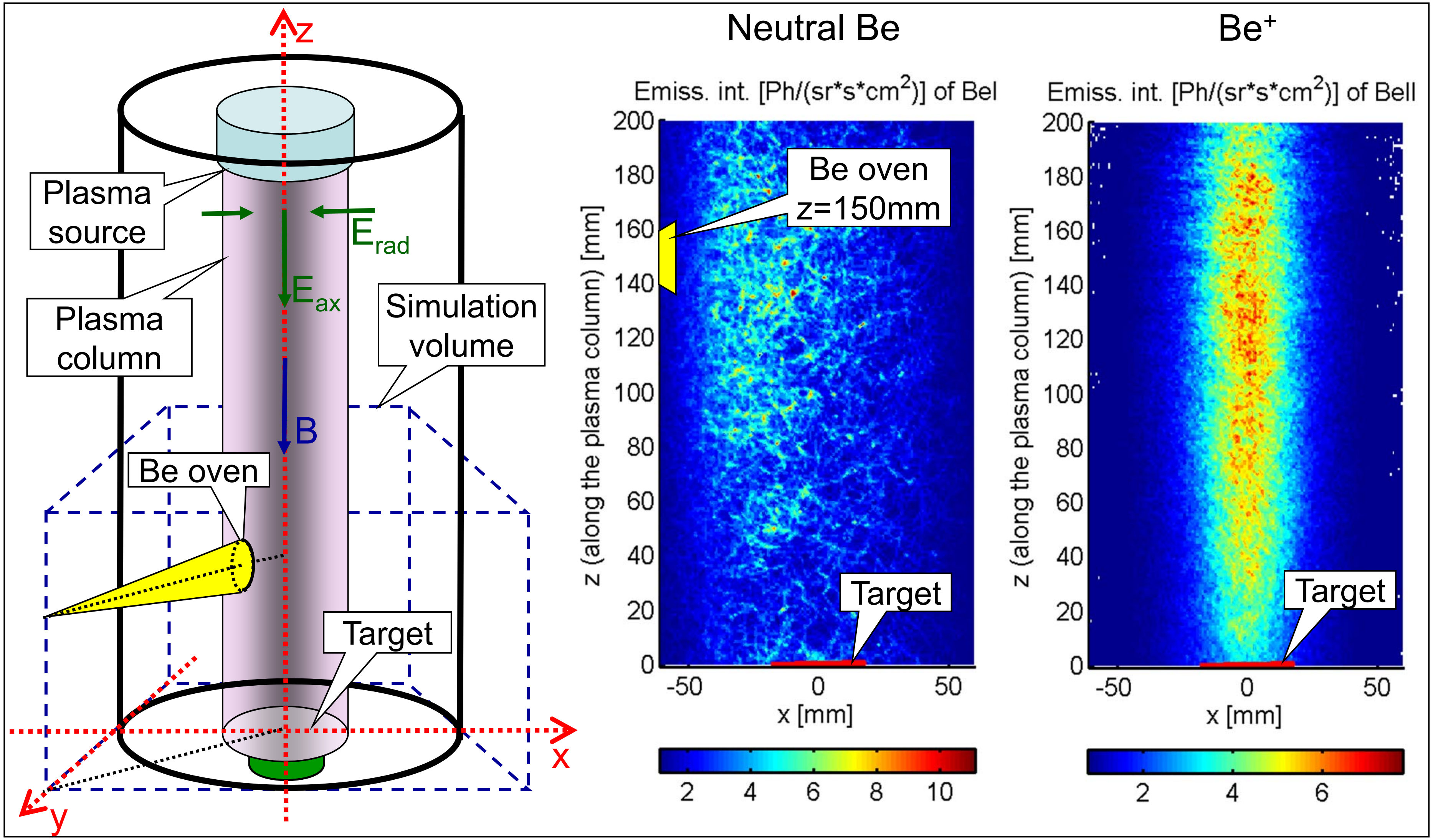
- *tritium retention*
- *target & limiter lifetime*
- *impurities into plasma*

Coupling with other codes:

- *plasma parameters from: e.g. B2-Eirene, Edge-2D*
- *surface mixing: TriDyn, MolDyn*

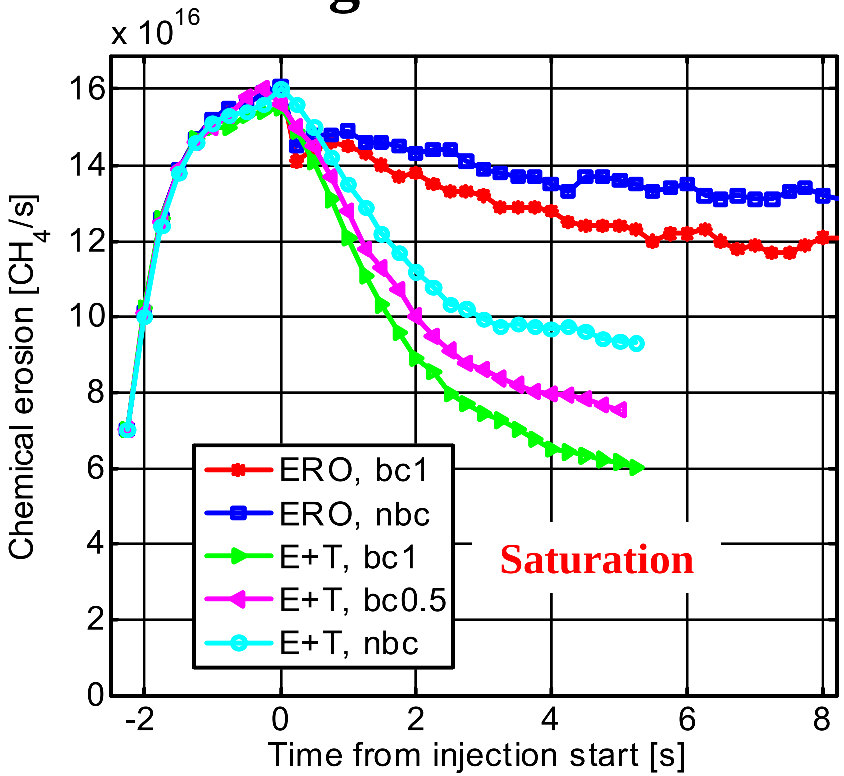
Be/C mixing at PISCES-B: mitigation of chemical erosion

PISCES-B linear divertor simulator

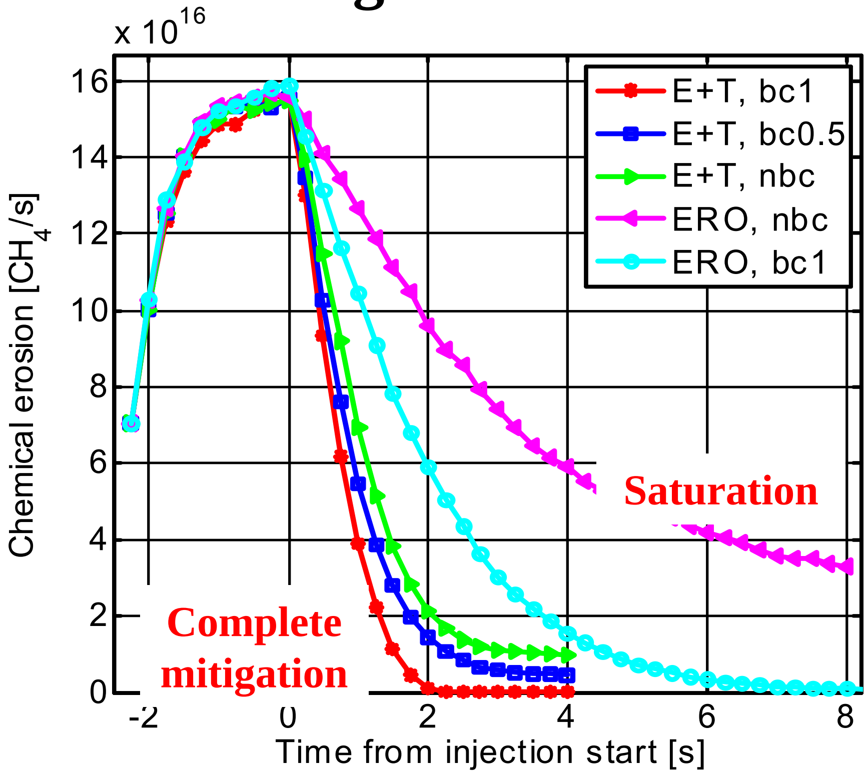


Surface models and carbide formation

Seeding rate 6*10^{18} Be/s



Seeding rate 3*10^{19} Be/s

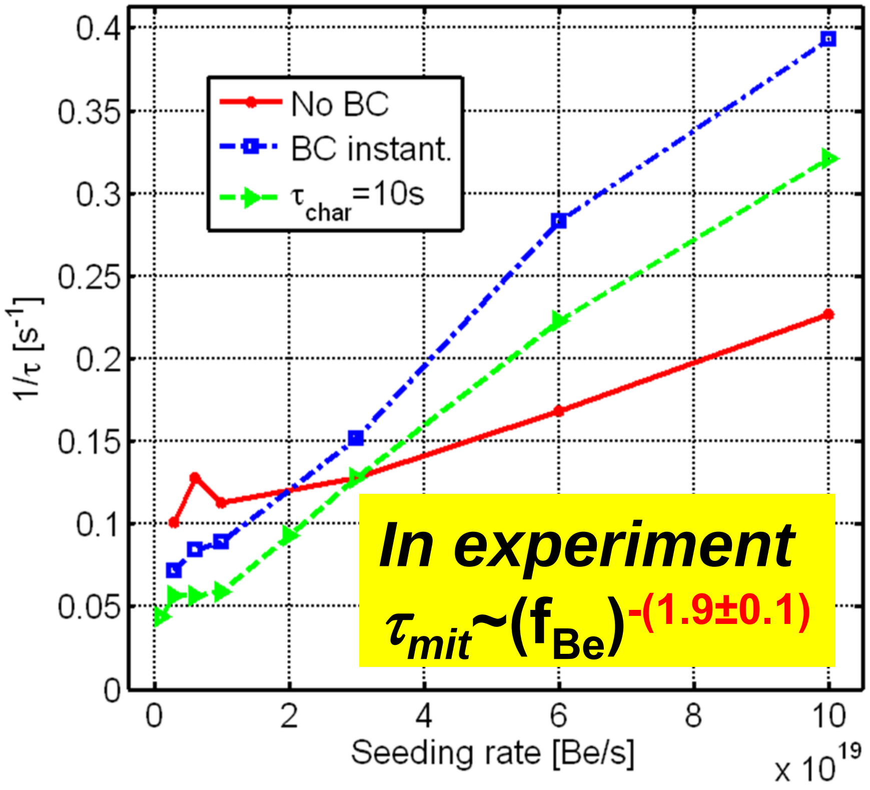


Carbide formation leads to stronger mitigation

The effect is similar for both HMM and SDTrimSP surface models

In ERO-SDTrimSP time scale is absolute, in HMM it is a subject of Interaction Layer (IL) depth choice

Effective mitigation time – effect of τ_{char}



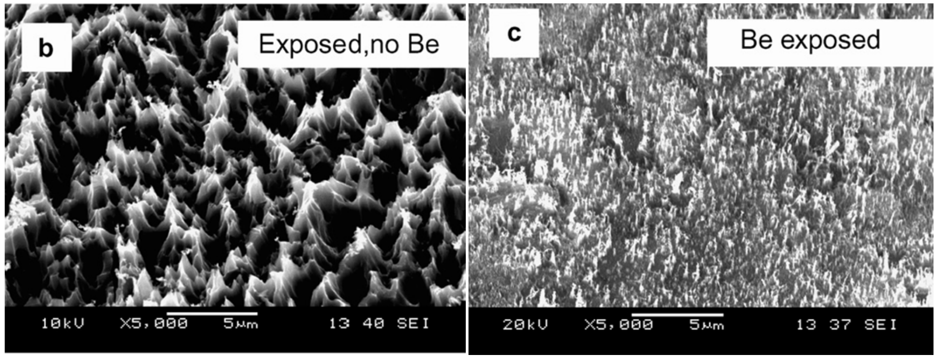
In experiment

$\tau_{mit} \sim (f_{Be})^{-(1.9\pm0.1)}$

Simulations lead to a linear dependence of τ_{mit} on the Be concentration in plasma.

- Effect of Be-D molecules formation?
- Effect of surface morphology evolution?
- Surface roughness?
- Other effects?

Surface changes observed at PISCES



Particularities for linear devices

- **Elastic collisions with residual gas (D_2)**
- **Different impact energies for molecular ions (D^+, D_2^+, D_3^+)**
- **Be carbide formation (suppressing chemical erosion of C)**
- **Tracking of metastable state (MS) in Be**
- **Bohm diffusion**
- **Be-D molecules – missing in ERO!**

Physical effects implemented for linear devices can be relevant for tokamaks as well!

Technical issues:

- Geometry, target, Be oven, …
- Plasma parameters (3D) - fitting formulas for radial and axial profiles
- Electric field (3D), target biasing, . . .
- . . .

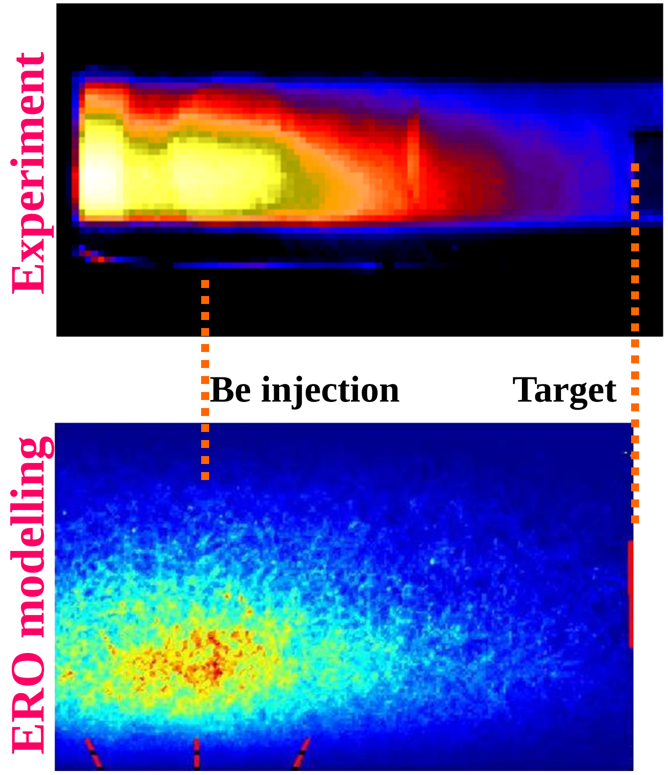
Be spectroscopy at PISCES - BeI

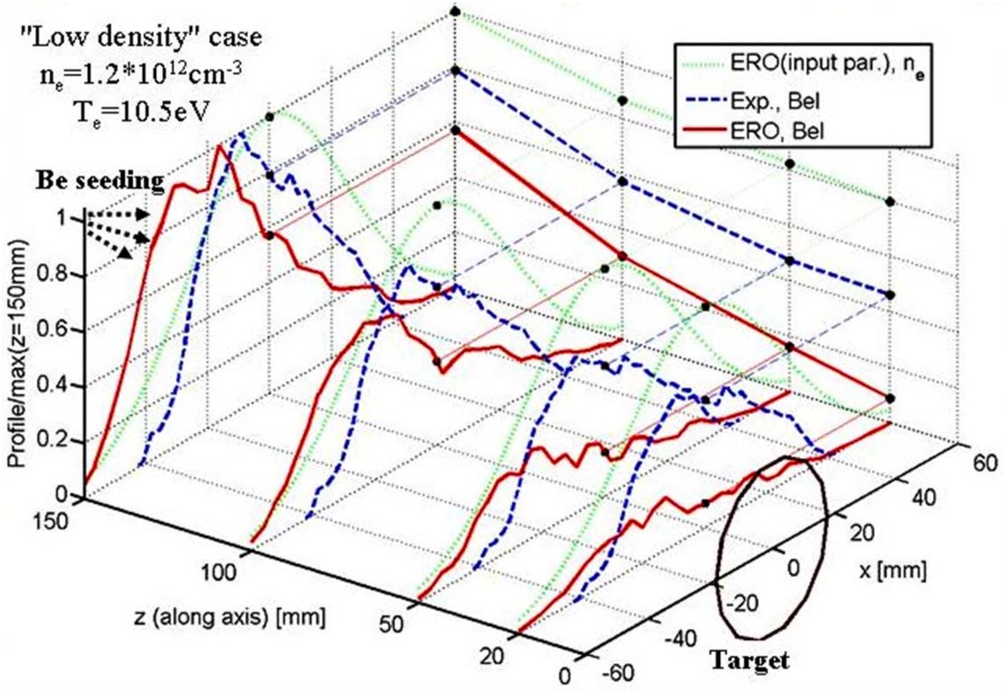
BeI, BeII emission is registered:

by 2D camera

"Low density case"
($1.2*10^{12}cm^{-3}$, T_e=10.5eV)

by spectrometer with a spatial resolution (the radial profile position and direction can be varied)



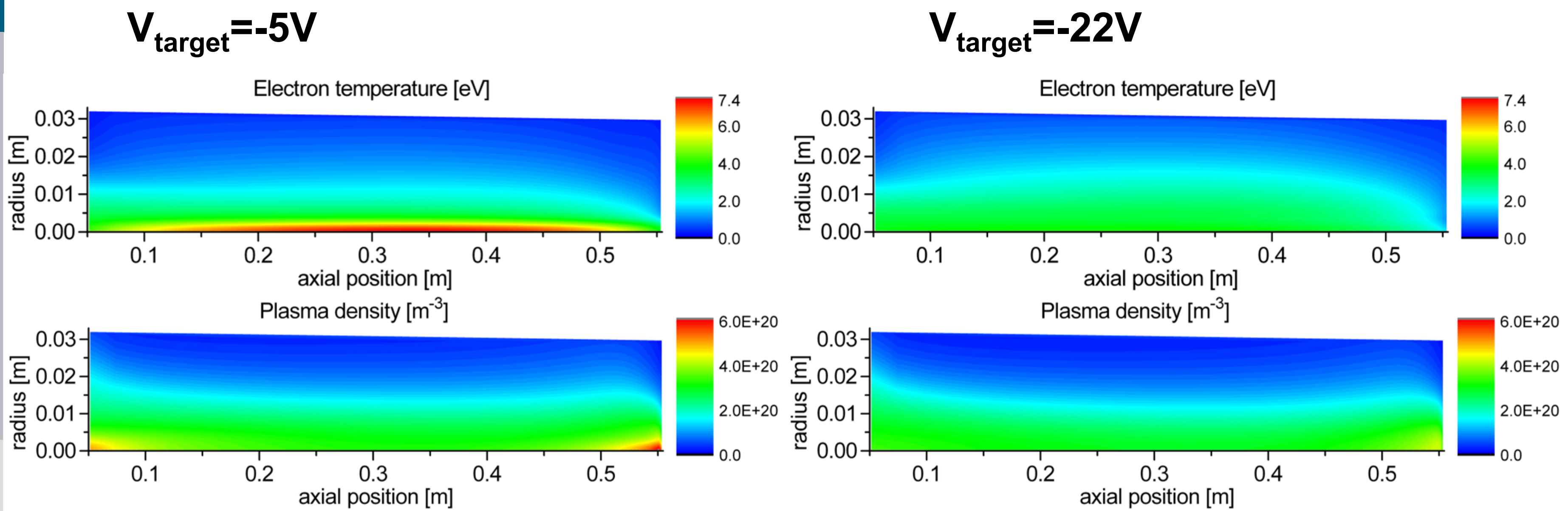


The ERO modelling is in a good agreement with experiment (PSI-2008)

Import of plasma parameters to ERO from B2.5

B2.5 [1] modeling results of Pilot-PSI plasma will be used

- 2D multifluid code describing the quasineutral plasma beam.
- Neutral particles are treated as fluid species.

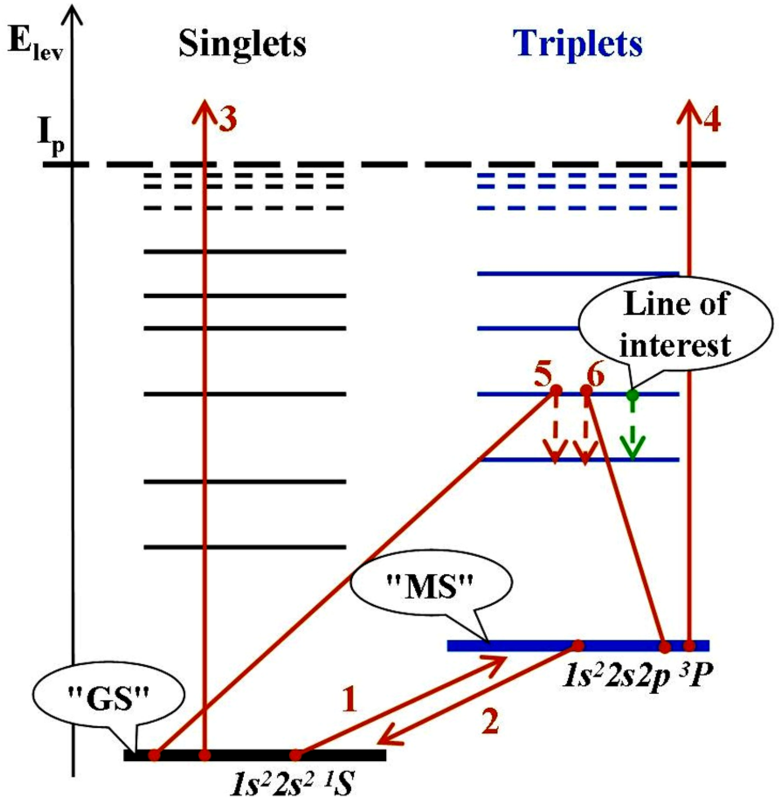


B2.5 output for two different target potentials, showing Ohmic heating and detachment, particularly in the -5V case

Presentation by PSI-2010 by R.Wieggers (FOM)

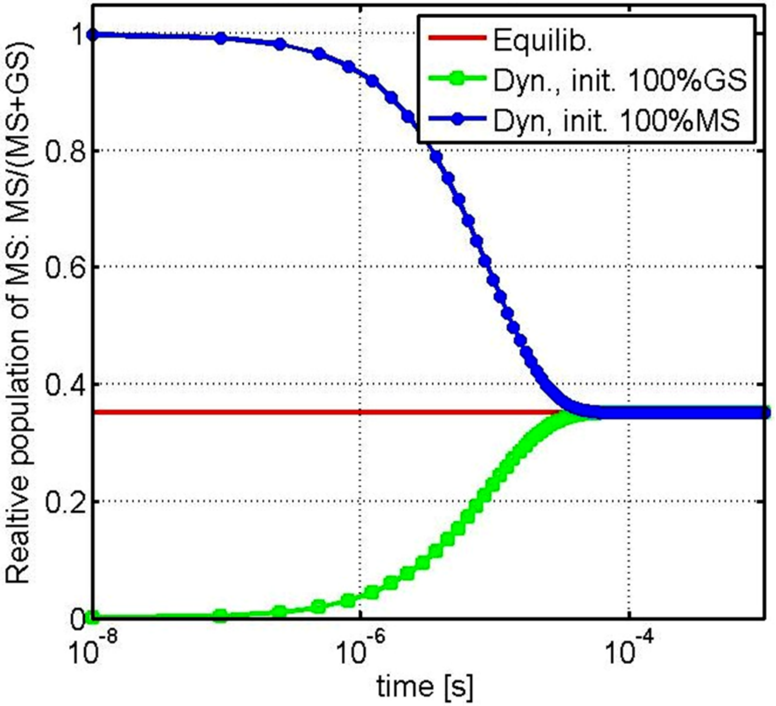
[1] R. Schneider et al., Contrib. Plasma Phys. 46, (2006) 3

Be metastable state (MS) tracking in ERO



The system of 2 balance equations can be solved analytically . . .

ADAS, T_e=1eV, n_e=2*10^{12}cm^{-3}



<u>Effective rates:</u>

<u>1,2)</u> transitions between "GS" and "MS"

3,4) ionization from "GS" and "MS"

5,6) line intensity (PEC – photon emission coefficient), contributions from "GS" and "MS"

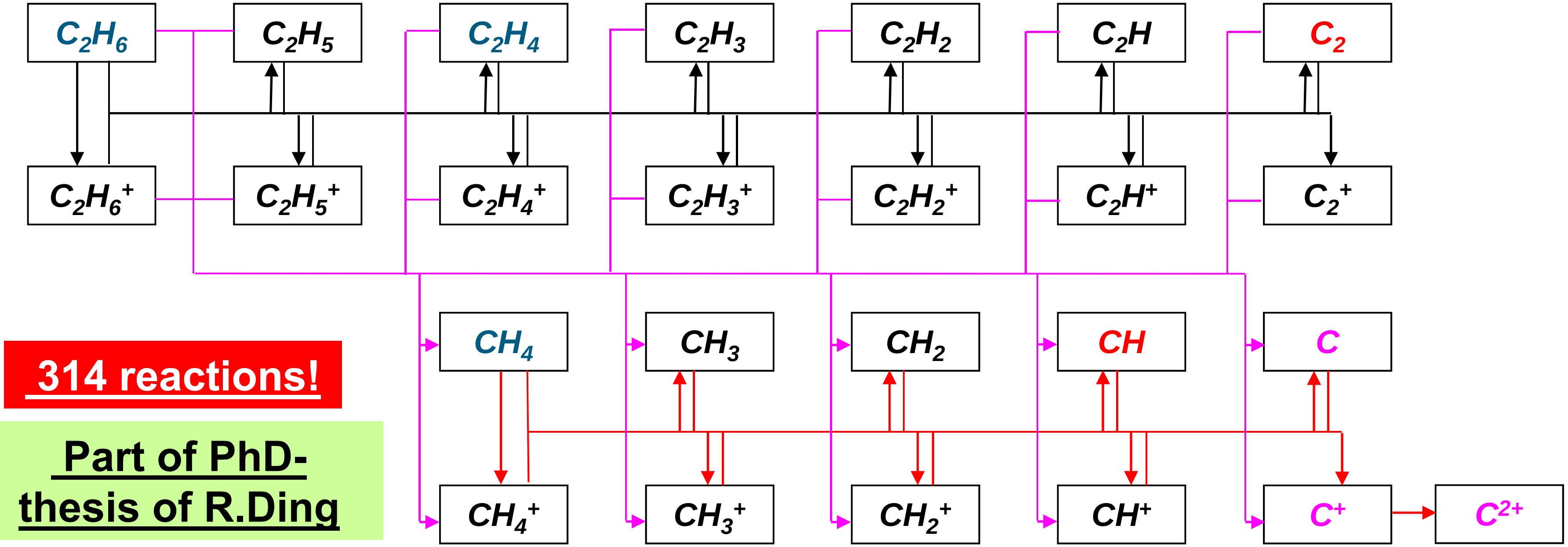
MS resolved approach allows to treat in ERO effectively the slow relaxation between triplet and singlet levels – important if MS population affected by extra processes and at high plasma parameter gradients

Pilot-PSI

(effective D/XB for CH)

C-H database in ERO code

Reaction chains of hydrocarbon molecules (Janev / Reiter)



314 reactions!

Part of PhD-thesis of R.Ding

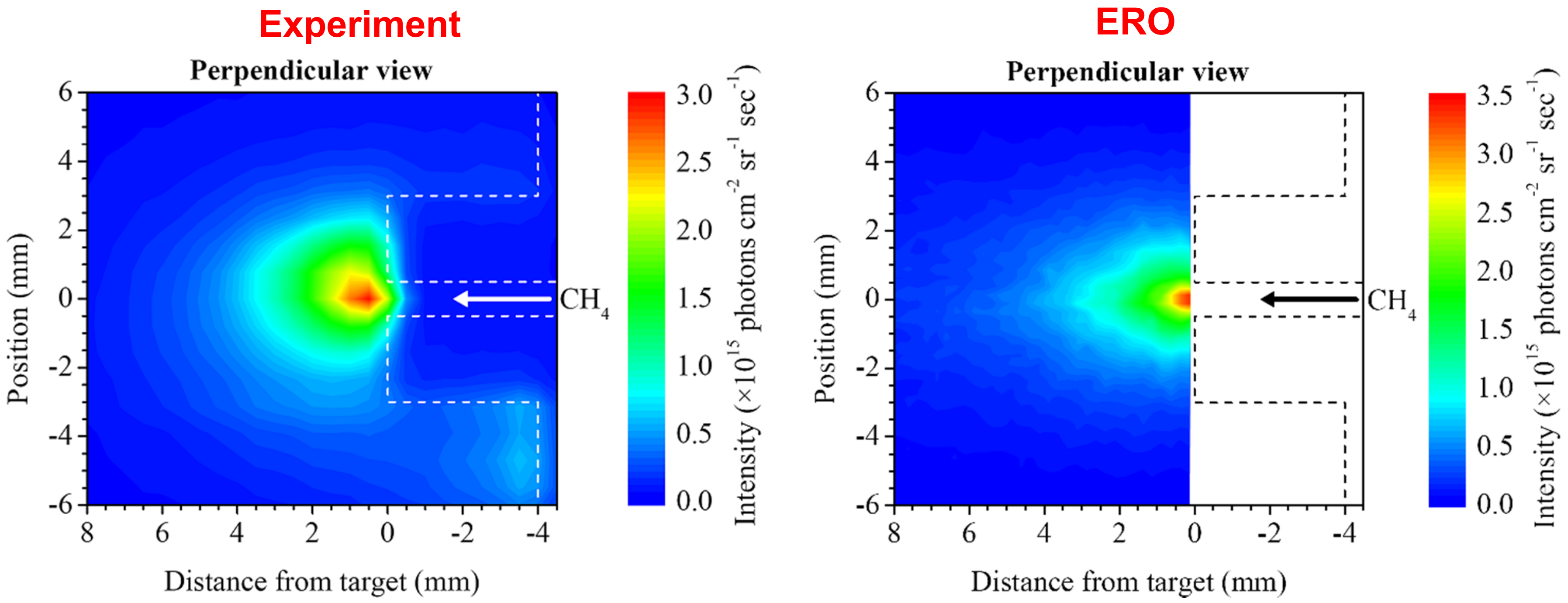
Emission data

CII, CIII ⇐ ADAS

CH A-X, C_2 d-a ⇐ U. Fantz et al. 2005

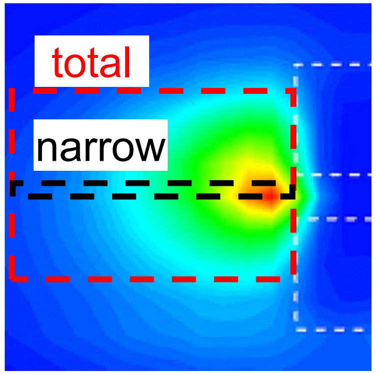
Probably this is not enough . . .

Pilot-PSI: CD light from CD4 injection (side view)



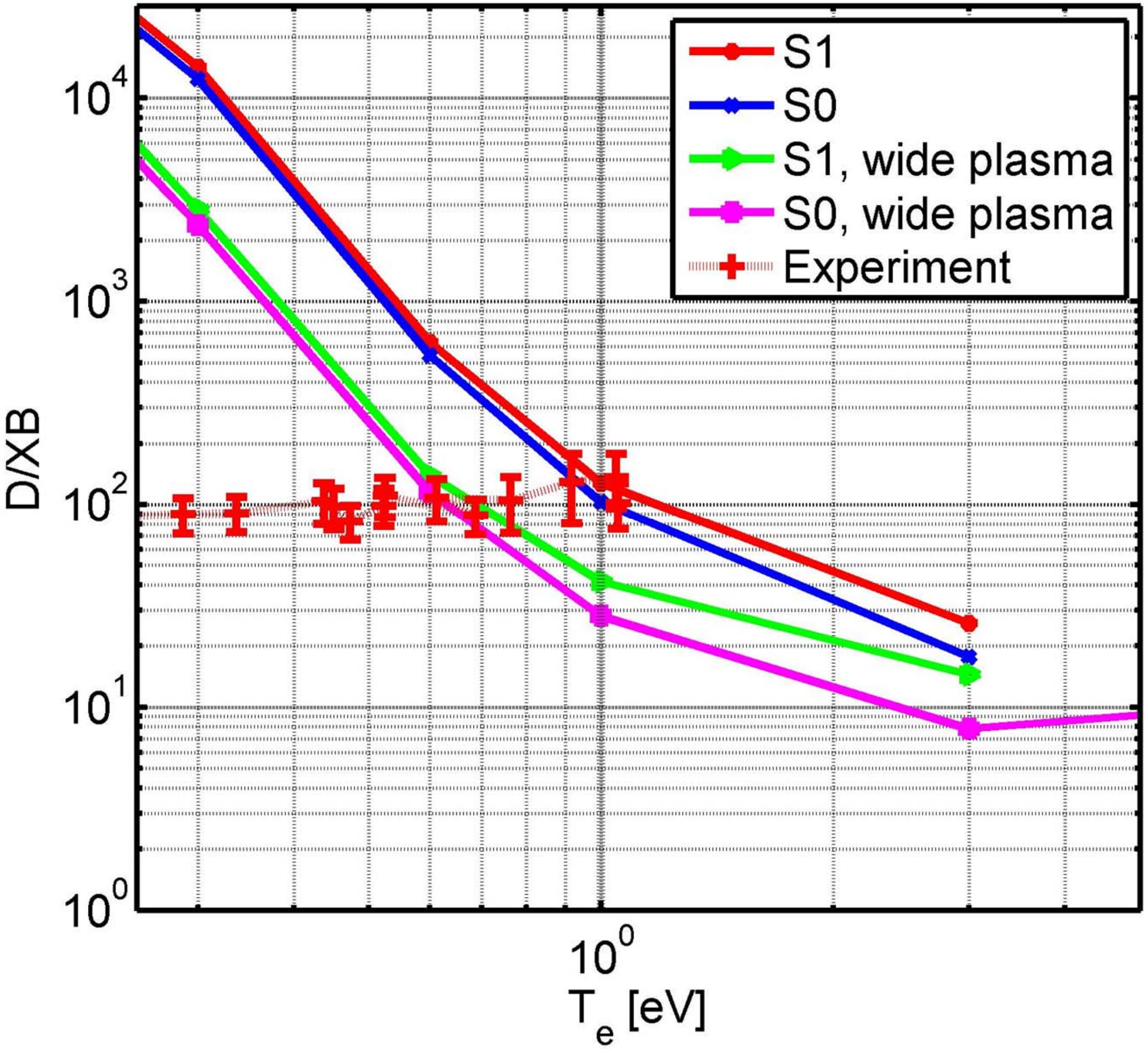
E-folding lengths of axial profiles:

- **Narrow: 2.2mm**
- **Total: 3.2mm**



- **Narrow: 1.7mm**
- **Total: 3.0mm**

Dependence of D/XB on sticking and Te



Width of plasma column is an important parameter:

main sink for the CD is not dissociation, but escape.

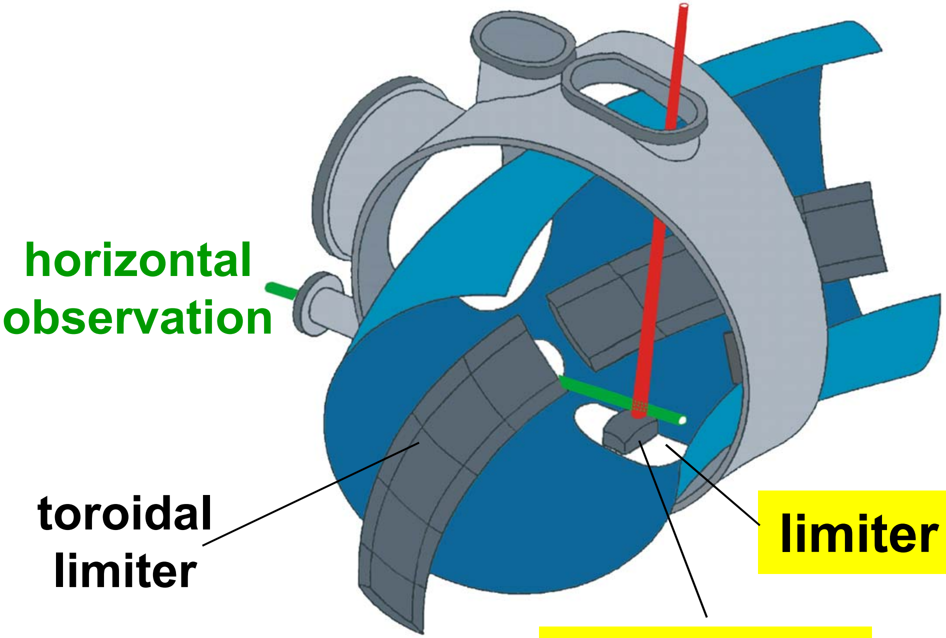
Deviations at low temperatures are probably due to additional CD excitation reactions (dissociative recombination?) . . .

Experiments at TEXTOR

Local deposition of ^{13}C at TEXTOR

General experimental set up:

Toroidal segment in TEXTOR:



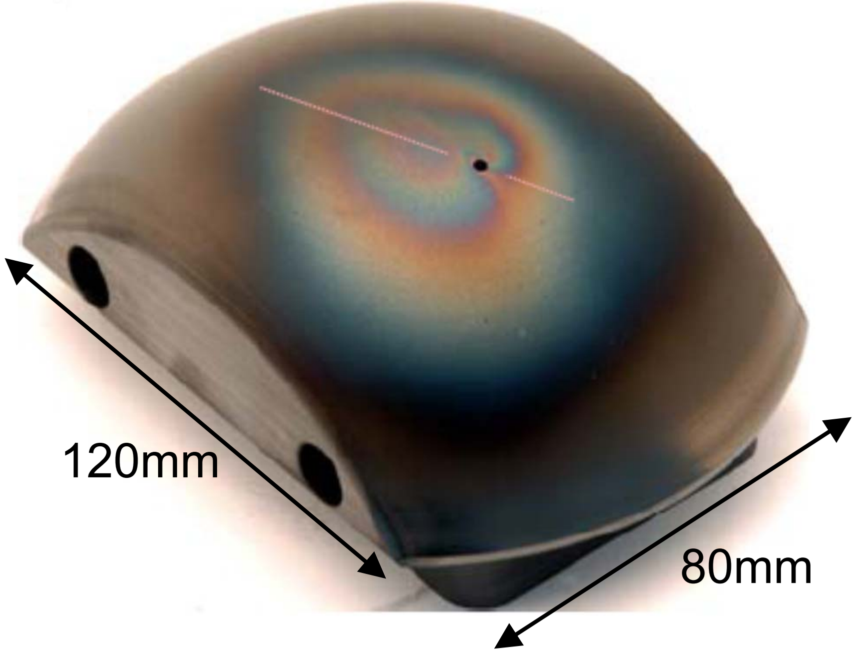
- **Injection of known amount of impurities through test limiter surface**
- **In-situ spectroscopy**
- **Post-mortem surface analysis**

Deposition efficiency:

$$\frac{\#\text{deposited atoms on test limiter}}{\#\text{injected atoms}}$$

Local deposition of ^{13}C at TEXTOR

Typical test limiter geometries in use:



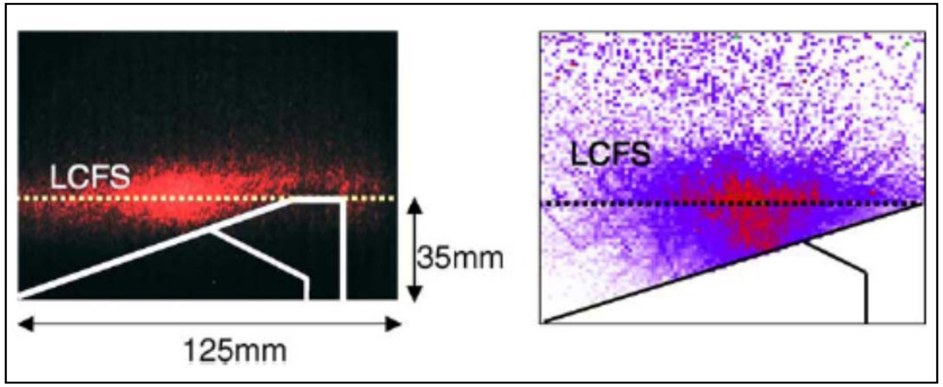
“spherical”

“roof”

Local deposition of ^{13}C at TEXTOR

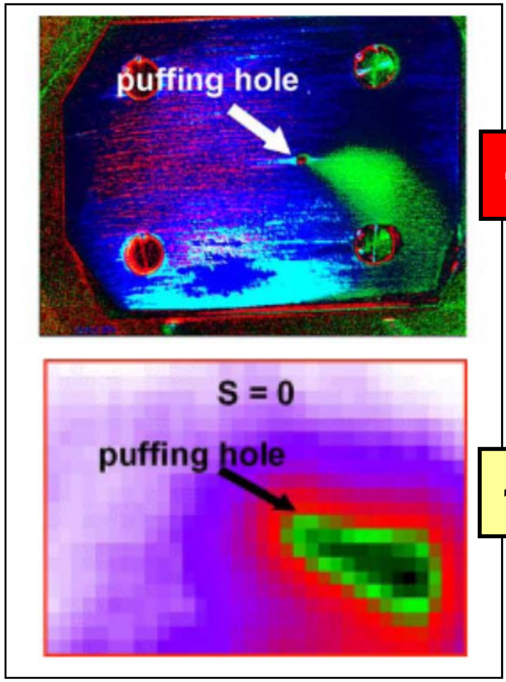
ERO modelling of $^{13}CH_4$ injection: *roof limiter (Al, C)*

CH light emission: EXP vs. ERO



A. Kirschner et al., J. Nucl. Mat. 328 (2004) 62

^{13}C deposition: EXP vs. ERO



~0.2%

~0.2%

- **Light emission well reproduced by ERO**
- **Low ^{13}C deposition efficiency modelled if:**

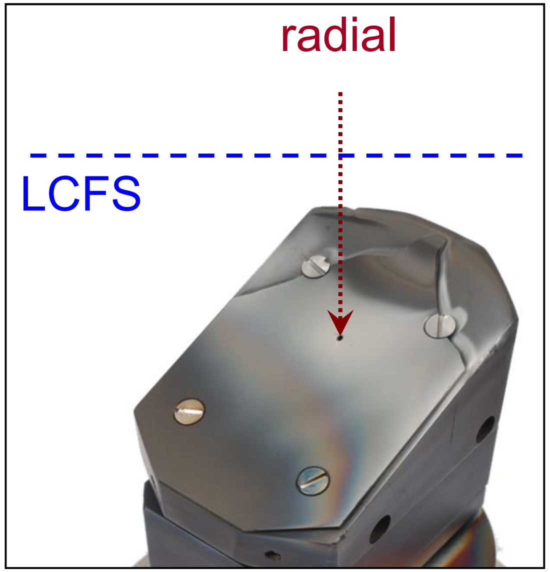
small sticking of CH_x (S~0) & enhanced chemical (×10) erosion of redeposits

W – most data is unavailable! . .

Physical issues: W influx, D/XB, erosion . . .

Sputtering experiments: badly known amount of particles (weight loss)

WF$_6$ injection: Unknown dissociation, sticking rates and influence on emission



ERO: WF$_6$ injection, *roof limiter*

Dissociation data for WF$_6$ not available ⇒ in ERO:

inject W^0 atoms & reduce ionisation rate for injected W^0 to match observed W^0 light

T_e(LCFS) = 30 eV

n_e(LCFS) = 5×10^{12} cm^{-3}

Ionisation rate for injected W^0 reduced by factor of 100!!!

ERO needs:

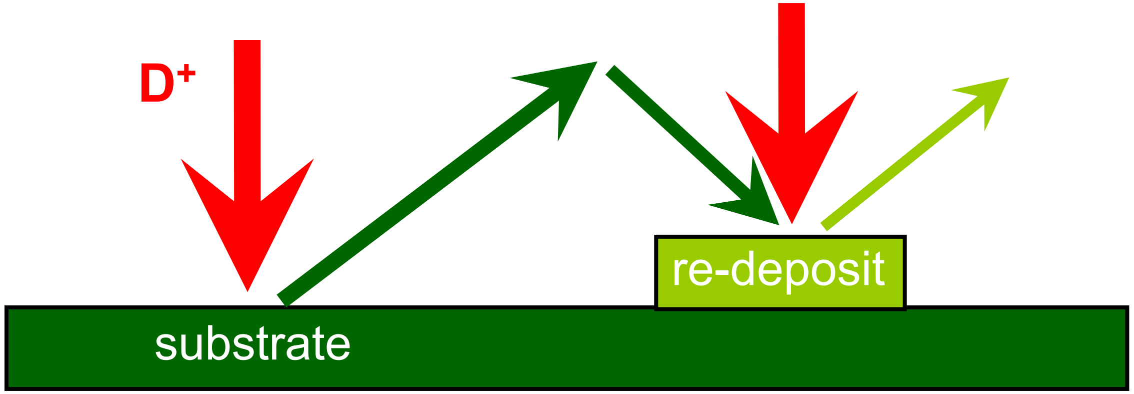
1) ionization of W^0, W^+, W^{2+}, effective PECs for "convenient" lines of WI, WII

2)a way to treat metastables and W-F molecules

Local deposition of ^{13}C at TEXTOR: motivation

Do in-situ re-deposited species in fusion experiments suffer from enhanced re-erosion???

- **Local deposition efficiency from impurity injection experiments in TEXTOR always very low**
- **Agreement with modelling only with assumption of enhanced re-erosion of re-deposits at plasma-wetted areas?**



Erosion: Y ***Re-erosion: factor×Y***

^{13}C at TEXTOR: ERO vs. EDDY

Modelling of $^{13}CH_4$ injection: *roof limiter (Al, C)*

^{13}C deposition efficiency: EDDY vs. ERO
(with enhanced chemical erosion)

Sticking probability	S=0.5	S=0.1	S=0.05	S=0.01	S=0
	^{13}C deposition efficiency (%)				
EDDY	33.0	5.1	2.2	0.5*	0.1*
ERO	32.0	5.0	2.0	0.5	~0.1

*averaged between 5.29 s and 5.88 s

Exp: ~0.2%

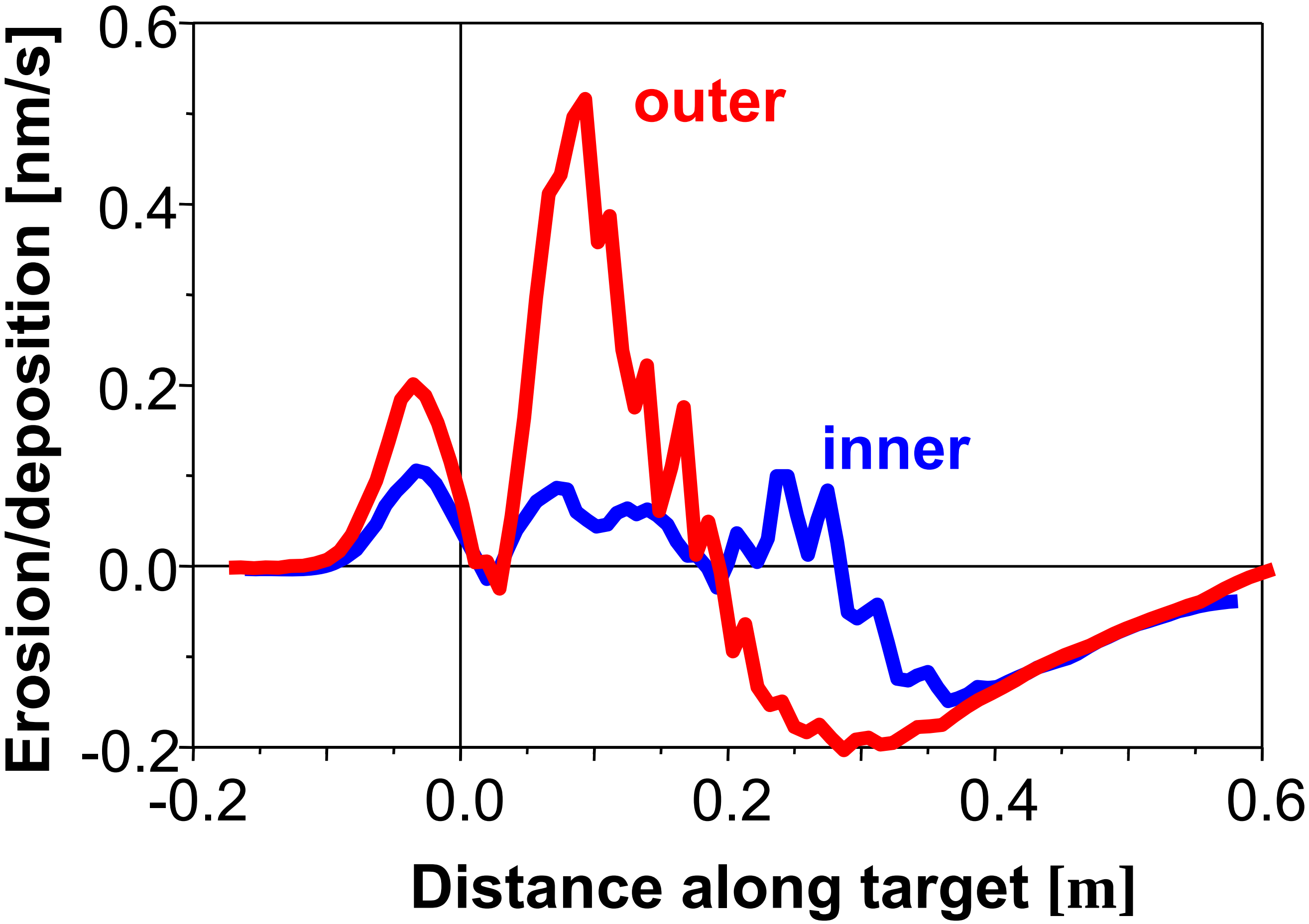
EDDY modelling supports assumptions of re-erosion and hydrocarbon sticking

K. Ohya et al., Physica Scripta T138 (2009) 014010

ITER availability

ERO: life time of C divertor plates

ERO modelling of target erosion (0.1% of Be)

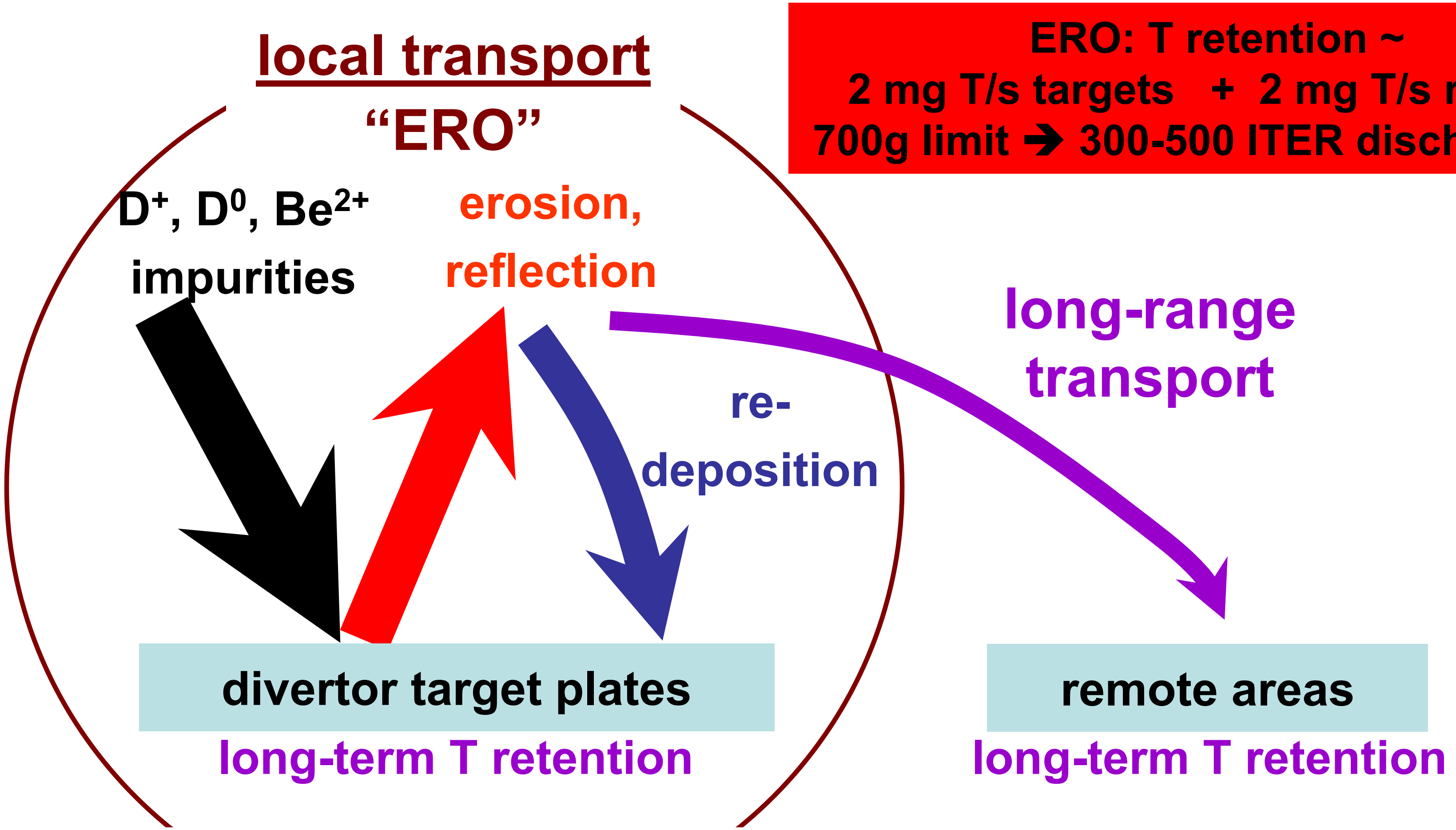


Target plates (0.5 cm) should survive at least 6900 discharges

Sweeping of strike point can increase lifetime

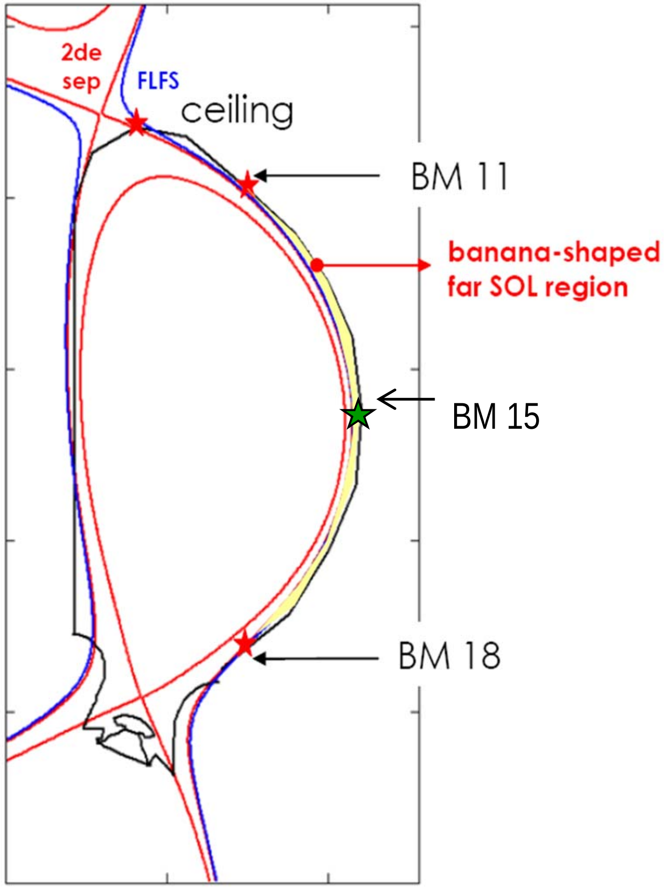
Tritium retention estimation from ERO

ERO: T retention ~
2 mg T/s targets + 2 mg T/s remote
700g limit ➔ 300-500 ITER discharges?!



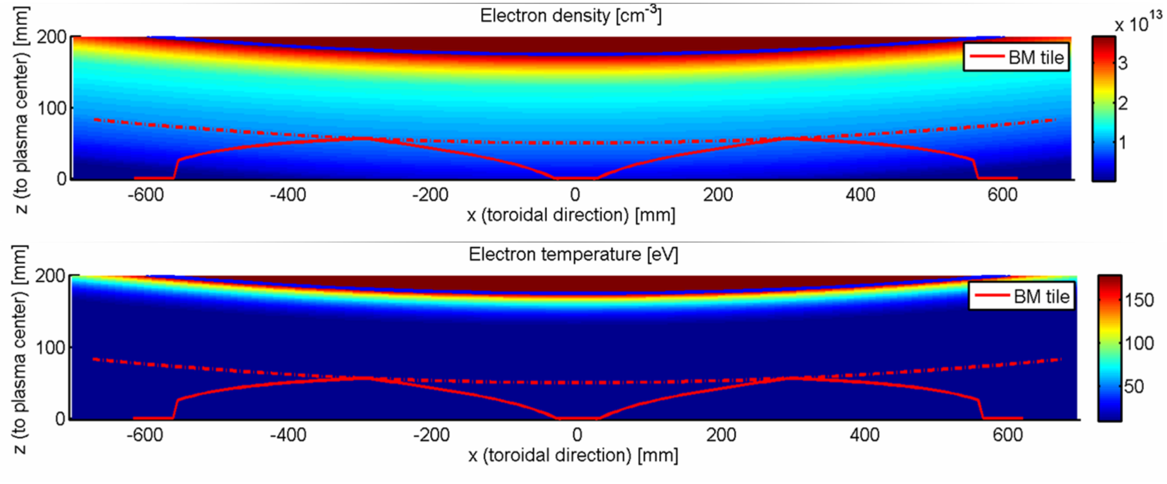
ERO:
- local transport near to divertor plates
- background plasma as input (B2 Eirene)
- layer formation (C and Be) ⇒ T retention using T/C, T/Be

ITER Be wall – „BM“ erosion



- *Blanket module (BM) shapes optimized by P.Stangeby*
- *LIM (similar to DIVIMP) modelling by S.Carpentier*
- *Benchmark with ERO – in progress . . .*

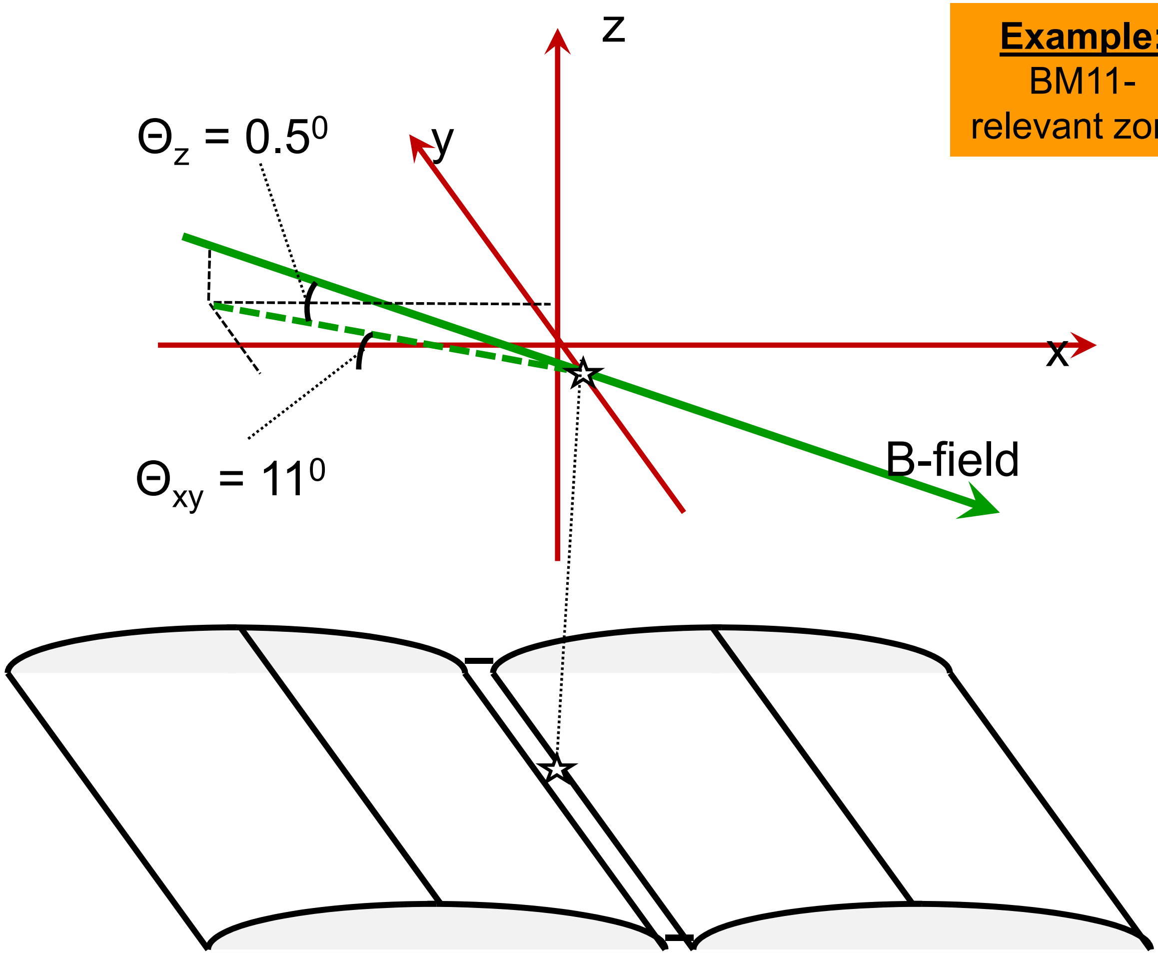
Plasma parameters (ERO input), case 1 “low density”, “BM11”



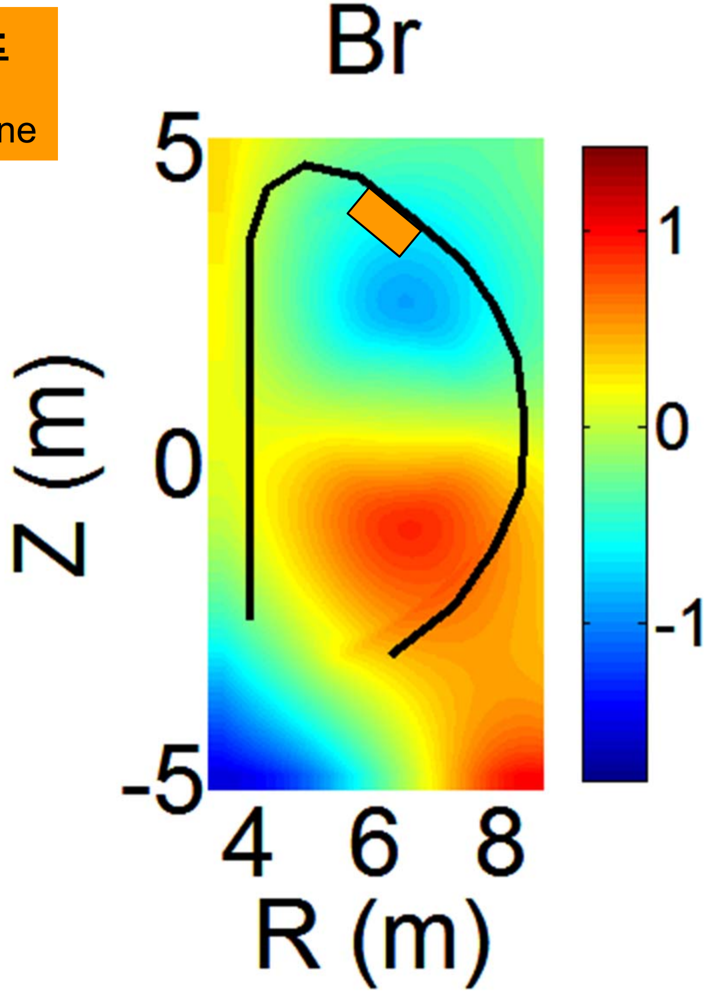
Aim – predictive modelling of ITER, including first wall erosion

Complications:
- Complex geometry e.g. leading to shadowing
- Uncertainty in atomic and surface data for Be
- Uncertainty concerning a number of unstudied physical effects for Be: enhanced re-erosion, carbide and alloy formation, Be-D molecules, etc.
- Huge simulation volume untypical for ERO

ERO - ITER BM: coordinates, B-field



Example:
BM11-
relevant zone



Complicated geometry; gradients of fields are essential!

Summary & Outlook

- ERO code is used for predictive modelling of ITER availability limited by **PFC life time** and **tritium retention**.

- The models, assumptions and underlying data used in ERO are being **benchmark**ed by simulation of various existing experiments and in some case by comparison with other codes e.g. EDDY.

- Simulation of further **dedicated experiments** is necessary to continue improvement of various particular models in ERO. These improvements can lead to corrections of **ITER predictions**.

End