Plasma-beryllium interactions in ITER: research needs

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With contributions from

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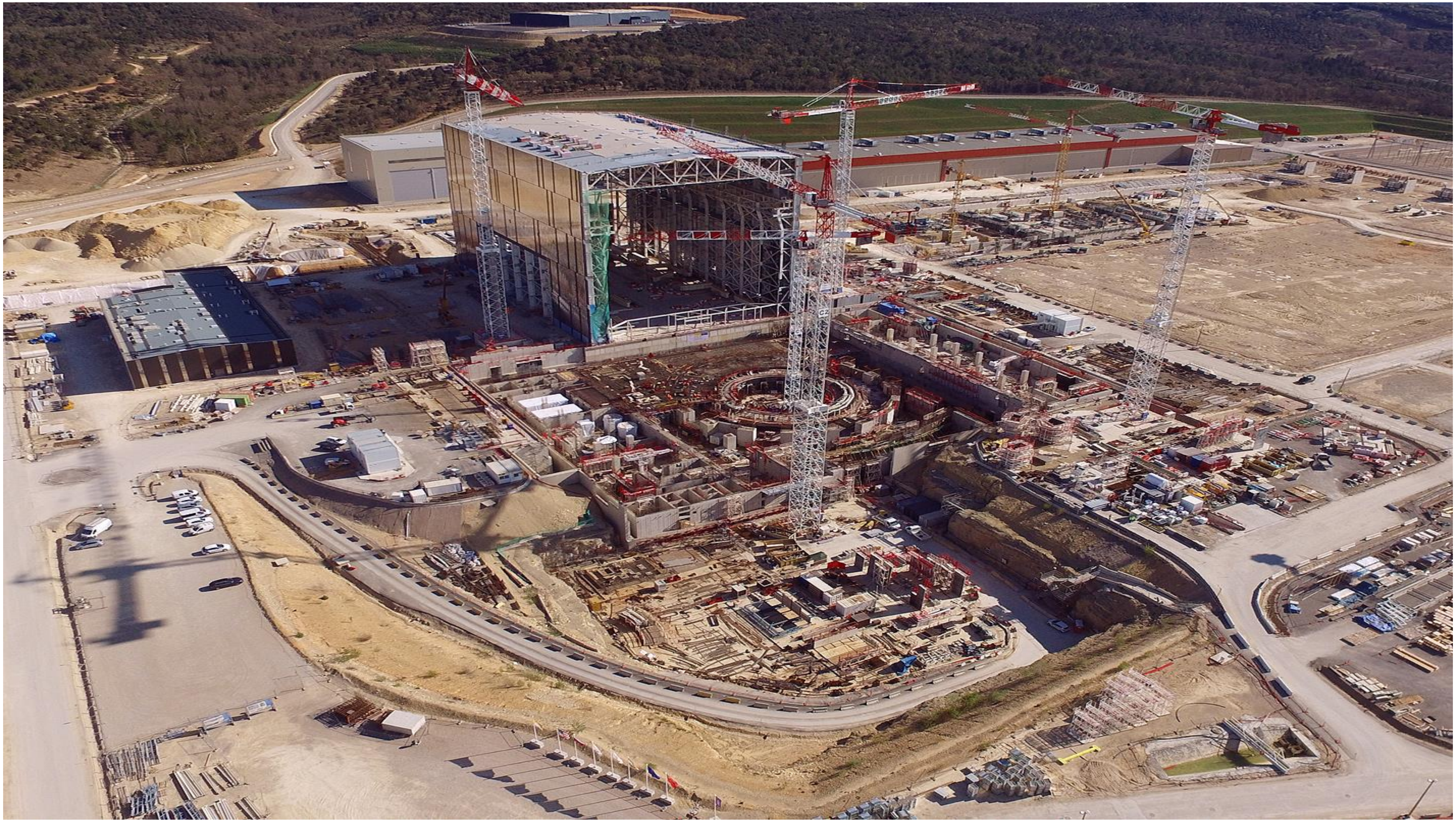
ITER is the Nuclear Facility INB no. 174. This paper explores physics processes during the plasma operation of the tokamak; nevertheless the nuclear operator is not constrained by the results of this paper. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

Content

- Status of the ITER site and construction
- Brief reminder about ITER plasma-facing components
- Some key Be-related research questions
  - Be migration
  - T retention
  - Thermal outgassing
  - Dust

Worksite progress

Worksite progress



Tokamak Complex

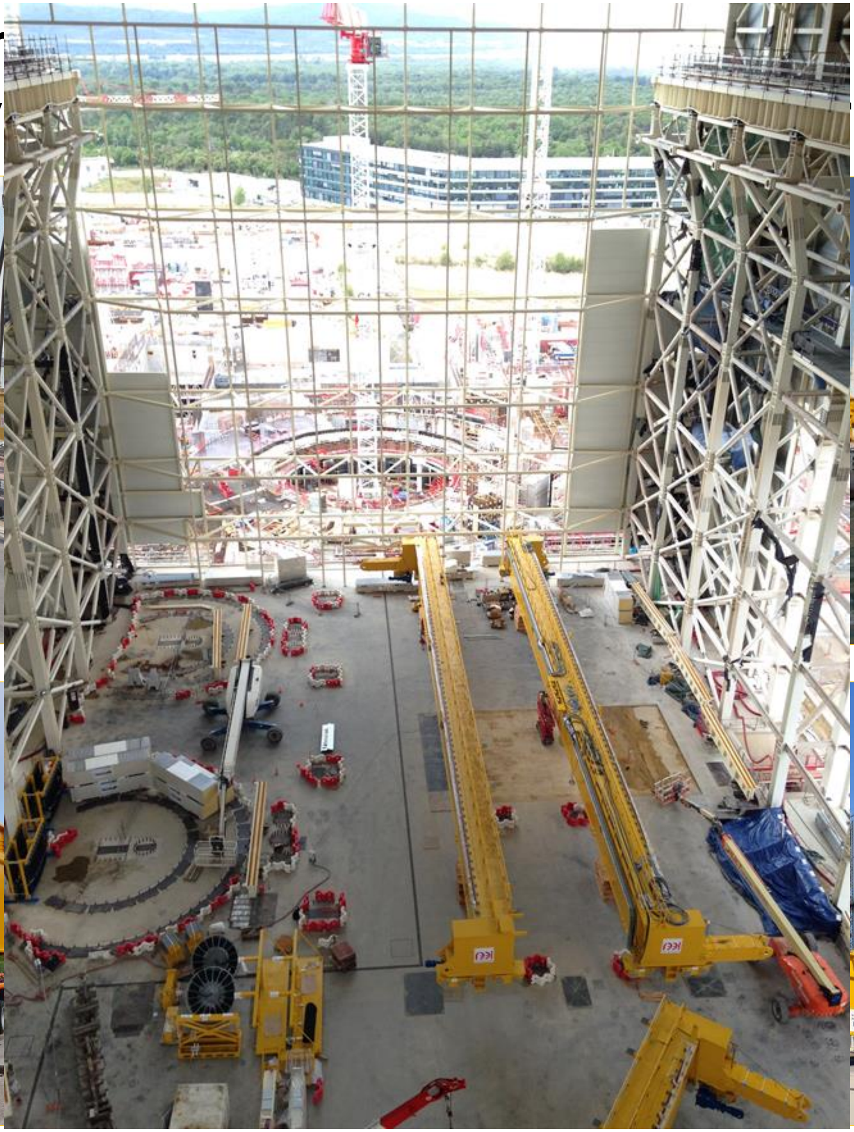
Resting on 493 seismic pads, the reinforced concrete “B2” slab bears the 440 000-ton Tokamak Complex. Concrete casting of the B2 slab was finalized on August 27, 2014. Diagnostic Building (left) B1 level slab now complete; installation of interior walls and reinforcement for BioShield ongoing.

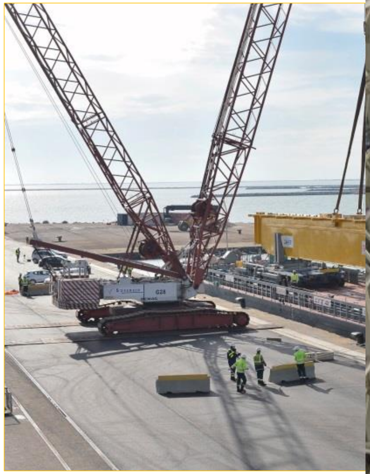
Assembly Hall

Before being integrated in the machine, the components will be prepared and pre-assembled in this 6,000 m2, 60-metre high building. The Assembly Hall will be equipped with a double overhead travelling crane with a lifting capacity of 1,500 tons, whose installation is scheduled in June.

Assembly hall

Four cr … double ov … ed

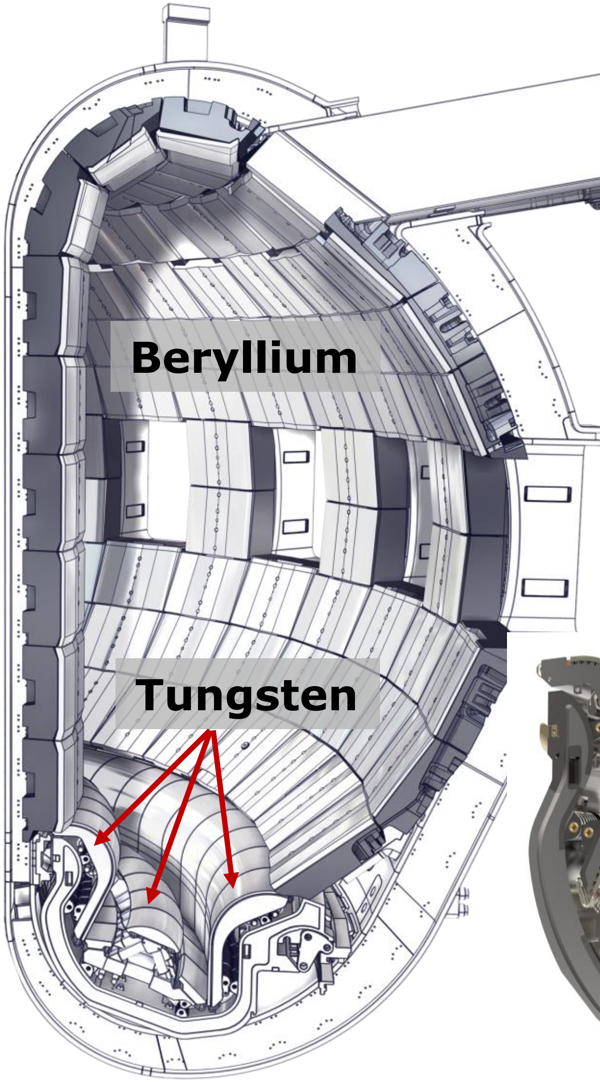




Cryoplant

Foundation works are ongoing on what will be the largest cryoplant in the world. The ITER Cryoplant will distribute liquid helium and nitrogen to various machine components (supraconducting magnets, thermal shield, cryopumps, etc). The cryoplant's cold boxes are currently being equipped with internal components by *Air Liquide* in Grenoble, France.

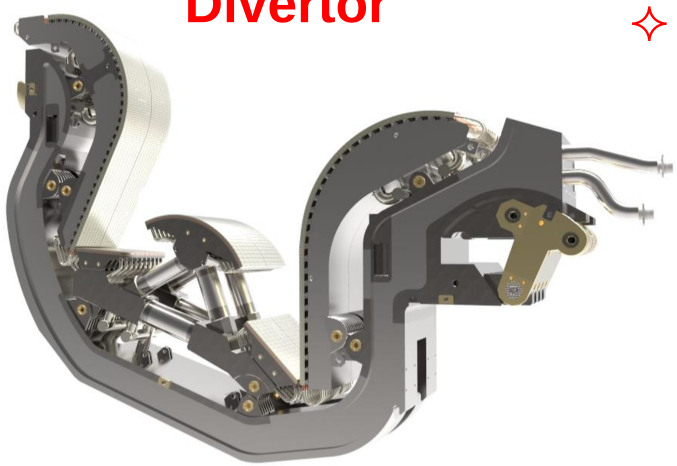
ITER plasma-facing materials



Be Blanket module

- ✧ **~700m² beryllium**
  - ✧ **First wall**
  - ✧ **Low Z- good plasma compatibility**
  - ✧ **Good oxygen getter**
  - ✧ **Good thermal conductivity**

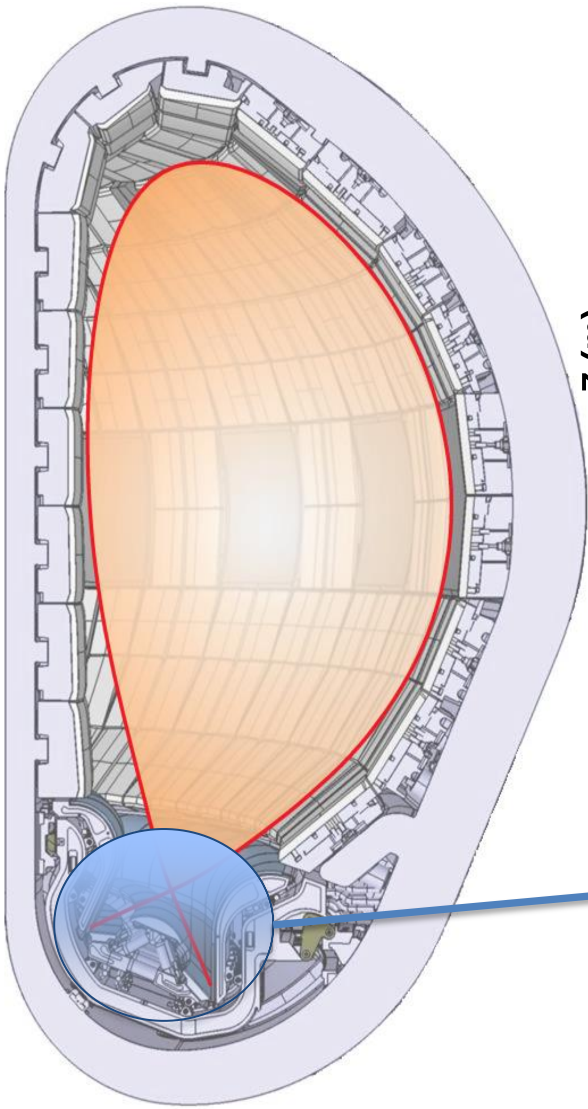
Divertor

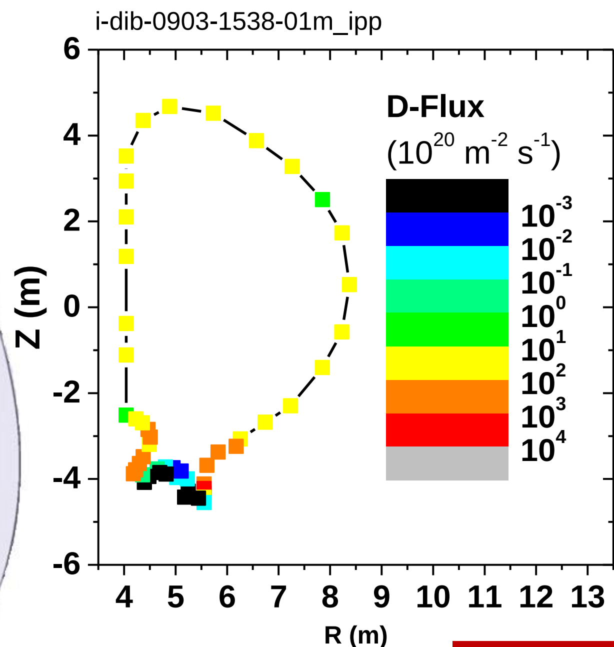


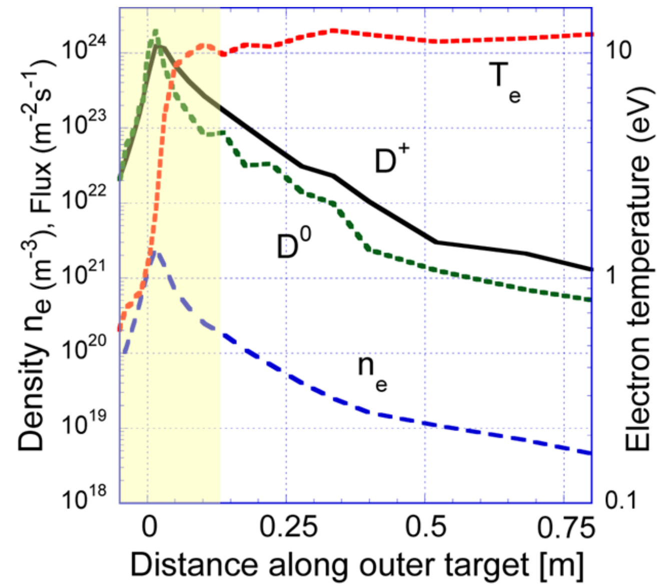
- ✧ **~150m² tungsten**
  - ✧ **Low sputtering yield**
  - ✧ **highest melting point (3422C)**

The plasma-wall interaction challenge

B2-Eirene simulations (A.S. Kukushkin)







Heat

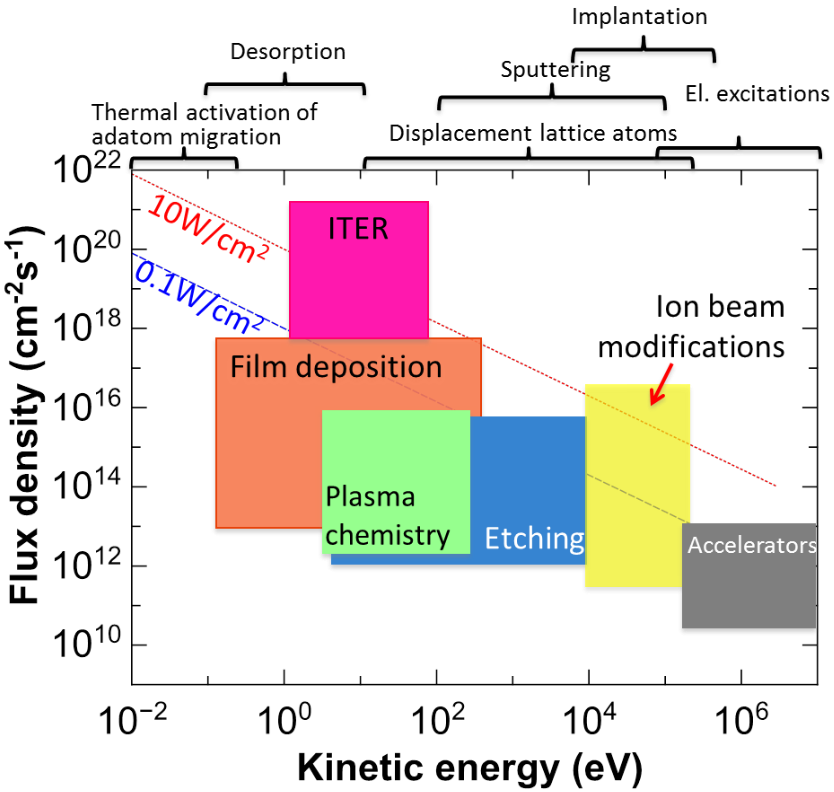
10MW.m^{-2} steady-state
1-10GW.m^{-2} (ms)

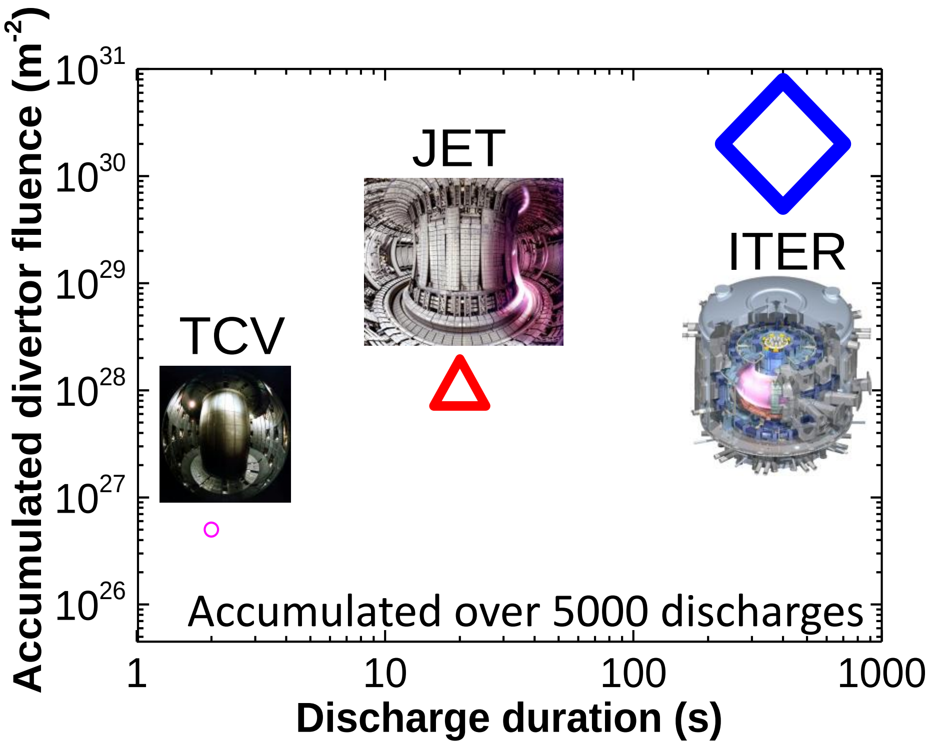
Particles

10^{24}m^{-2}s^{-1} (10^{5}A.m^{-2})
E_{ion}<50eV

High particle fluences expected in ITER

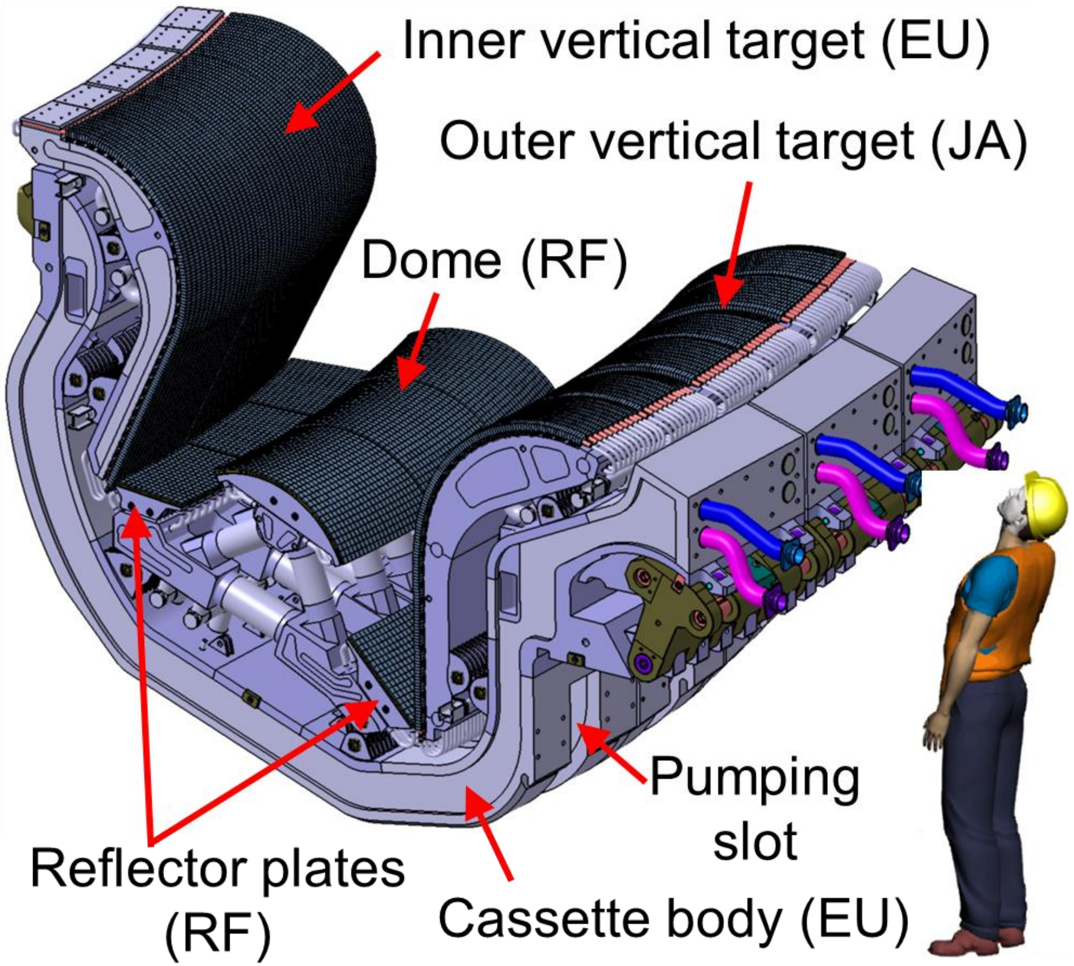
- Very high particle fluxes expected in ITER divertor ~$10^{24} m^{-2} s^{-1}$
  - Limited number of experiments can reach those conditions





What is the influence of such high fluences on materials properties?

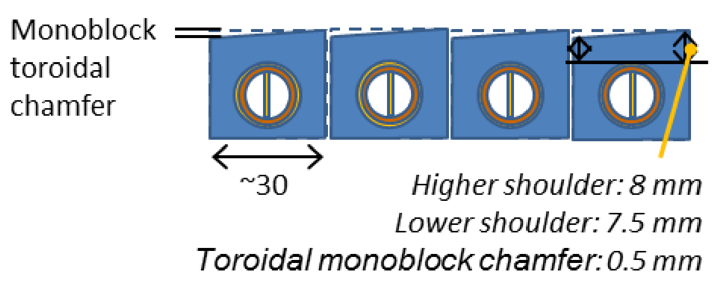
Full tungsten divertor



54 divertor assemblies (~9 tonnes each)

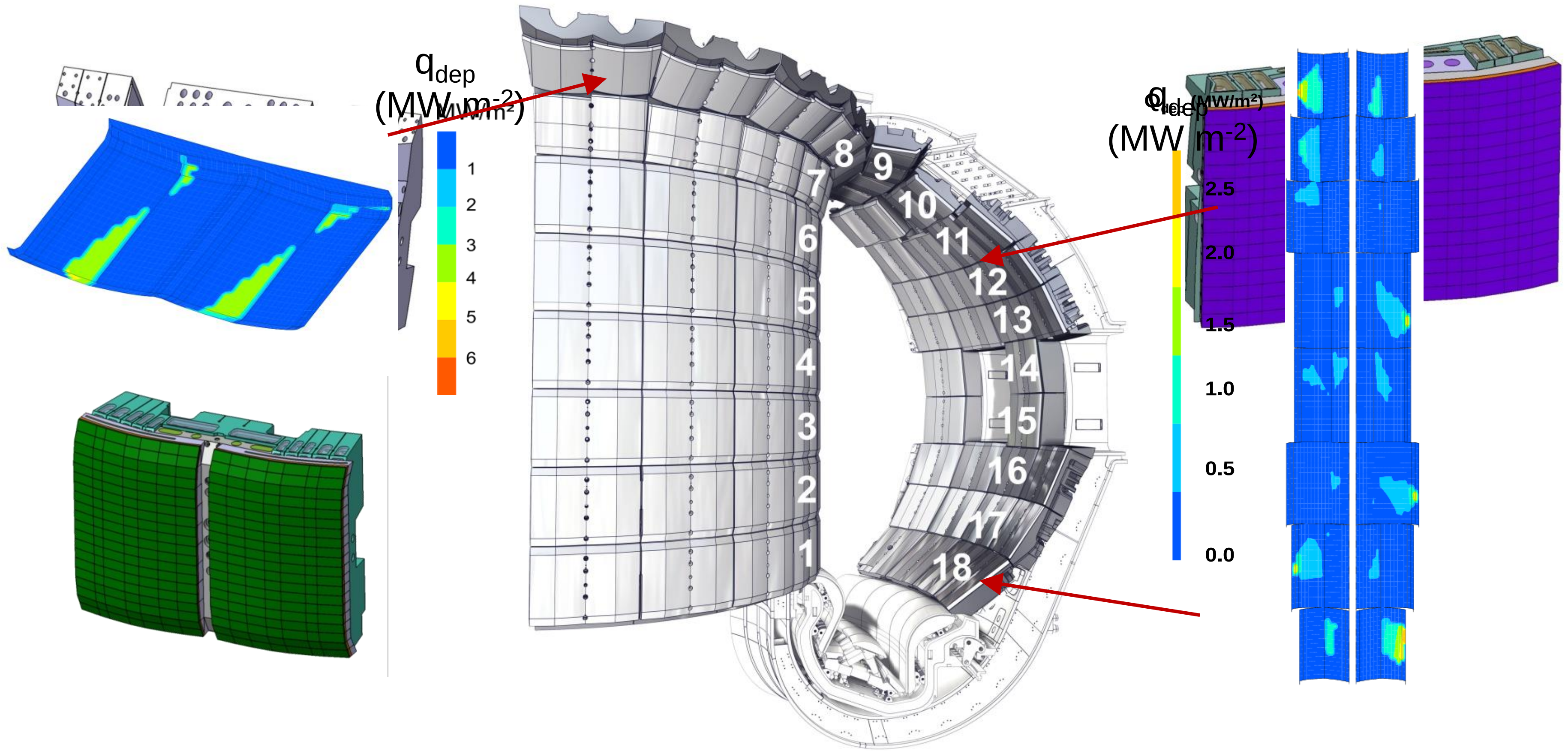
Bakeable to 350°C

Implementation of individual monoblock shaping under discussion



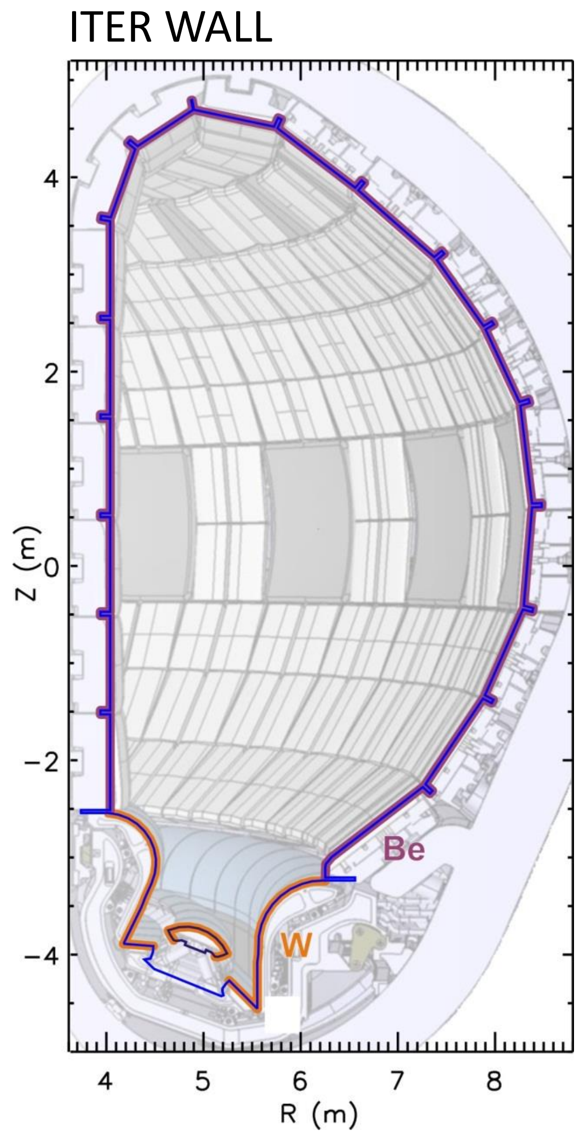
Reminder: full-W divertor

- ITER has a close-fitting and shaped first wall



- Peaking in erosion pattern expected, magnitude being estimated

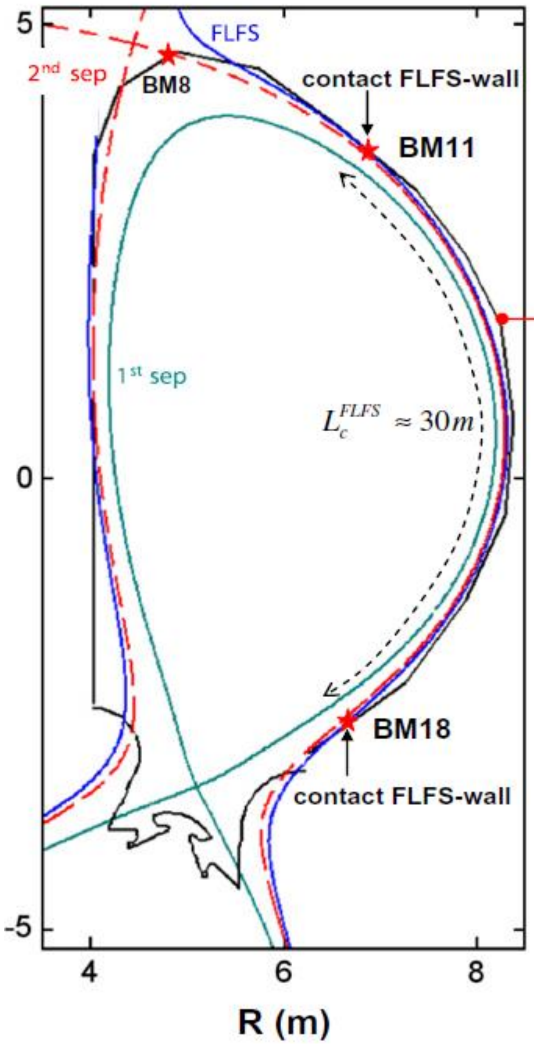
First wall erosion in ITER



- **Be erosion from plasma exposure during normal operations**
  - **start-up on the high- and low-field sides**
  - **main chamber charge-exchange neutral particle loads**
  - **close-fitting, shaped wall geometry- potential for co-deposition on first wall**

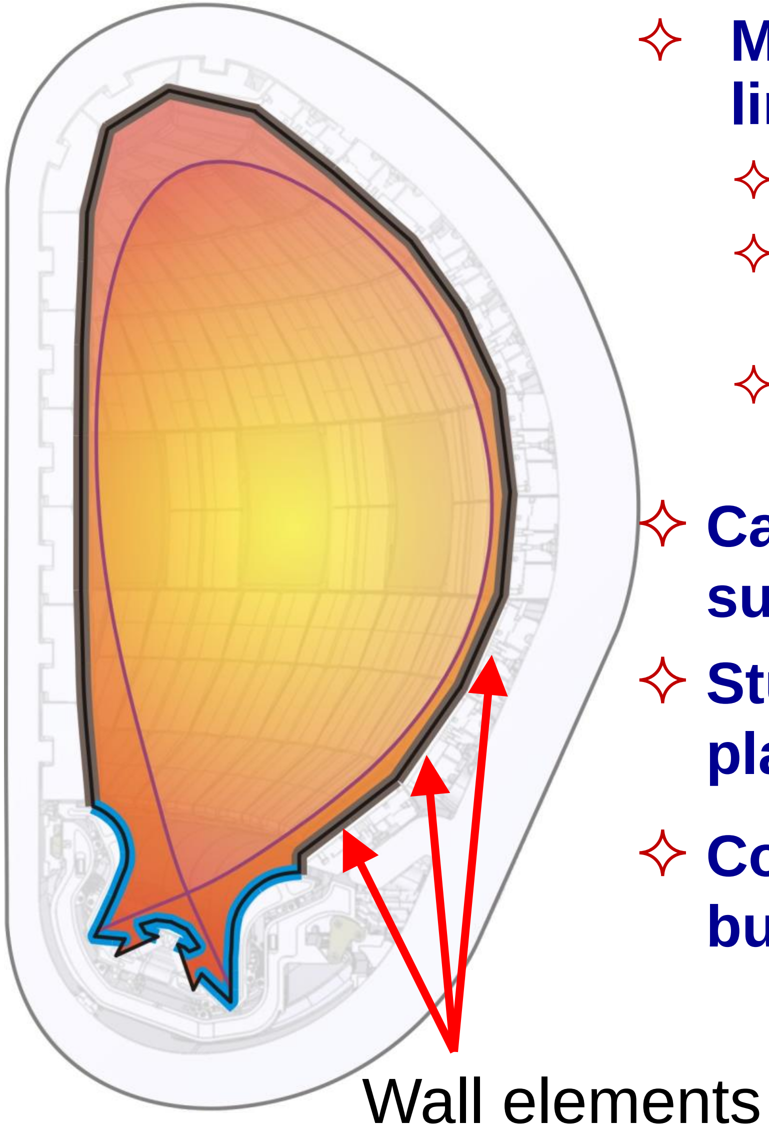
First wall erosion in ITER

ITER WALL



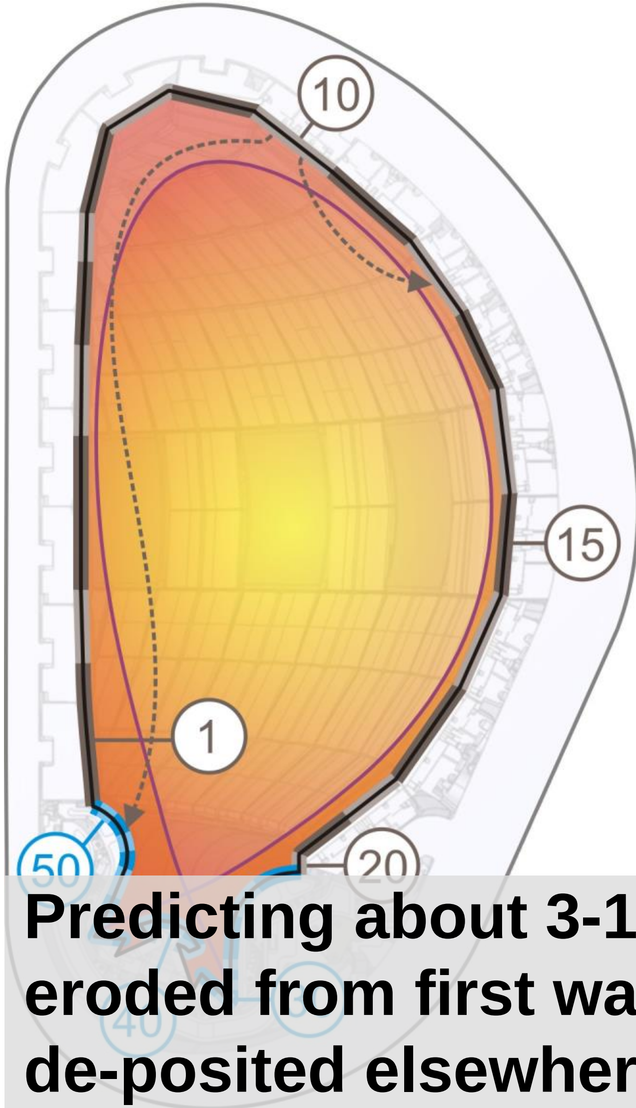
- ✧ **Be erosion from plasma exposure during normal operations**
  - ✧ **start-up on the high- and low-field sides**
  - ✧ **main chamber charge-exchange neutral particle loads**
  - ✧ **close-fitting, shaped wall geometry- potential for co-deposition on first wall**
- ✧ **Regions of particular interest include:**
  - ✧ **the upper target area (quasi-double null operations)- BM8 and BM9**
  - ✧ **BM11 and BM18 where plasma contact is though to be concentrated (interaction of 2nd separatrix with PFC)**

Migration modeling



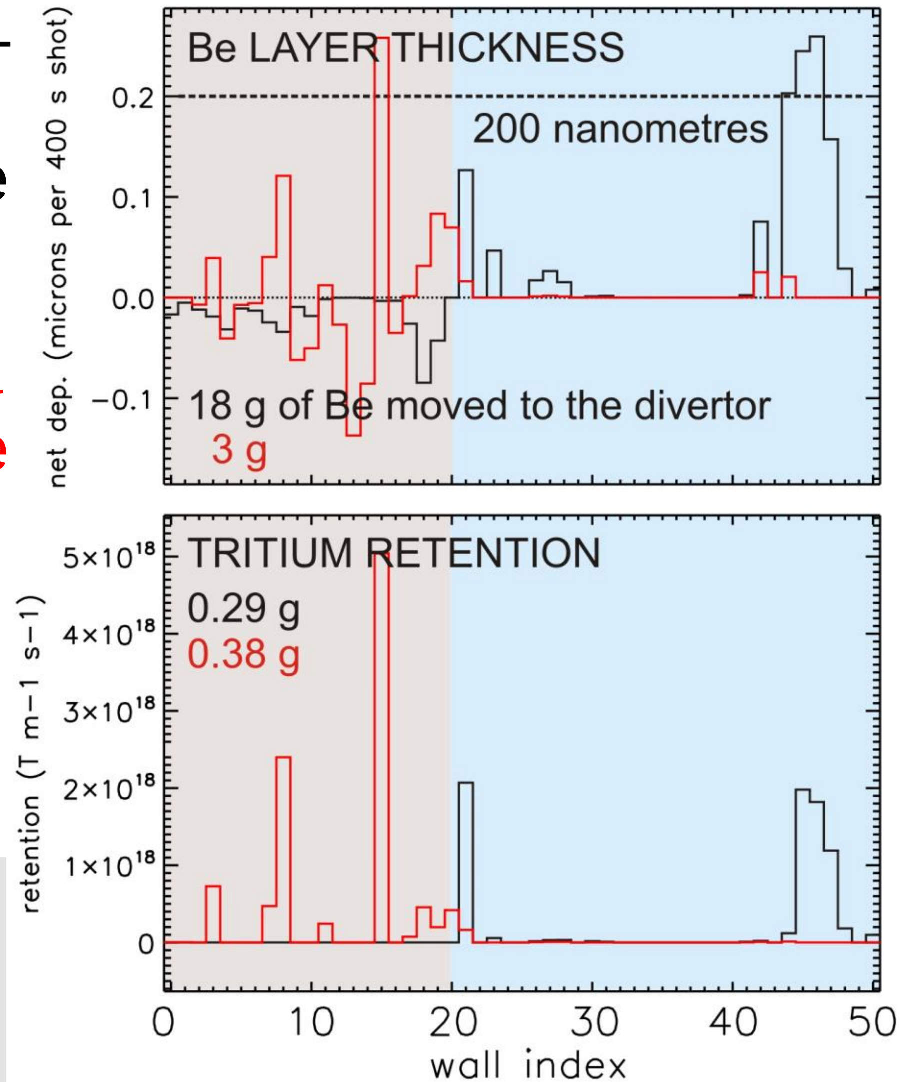
- Method: Use state-of-the-art codes linking predicted:
  - plasma background solutions (SOLPS),
  - global impurity transport in the plasma (DIVIMP)
  - PFC surface evolution due to erosion/re-deposition (WALLDYN)
- Calculate the time evolution of the surface composition of PFCs
- Study sensitivity to different background plasmas
- Computational grids out to the walls – but only 2D so far

Predicted co-deposition rates



Low far-SOL plasma density case

High far-SOL plasma density case

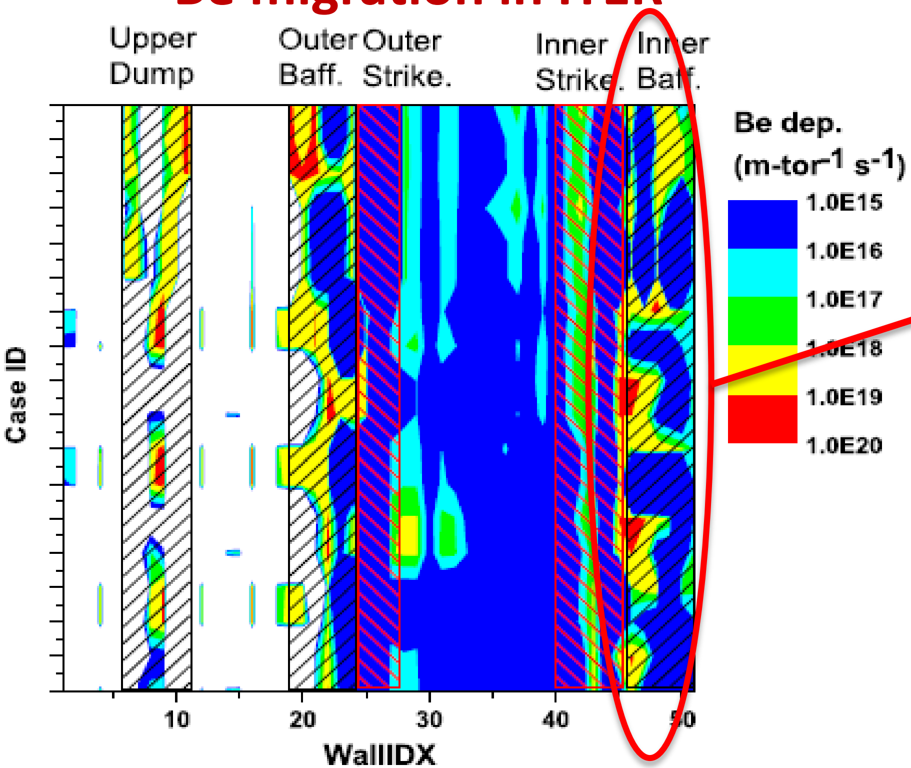


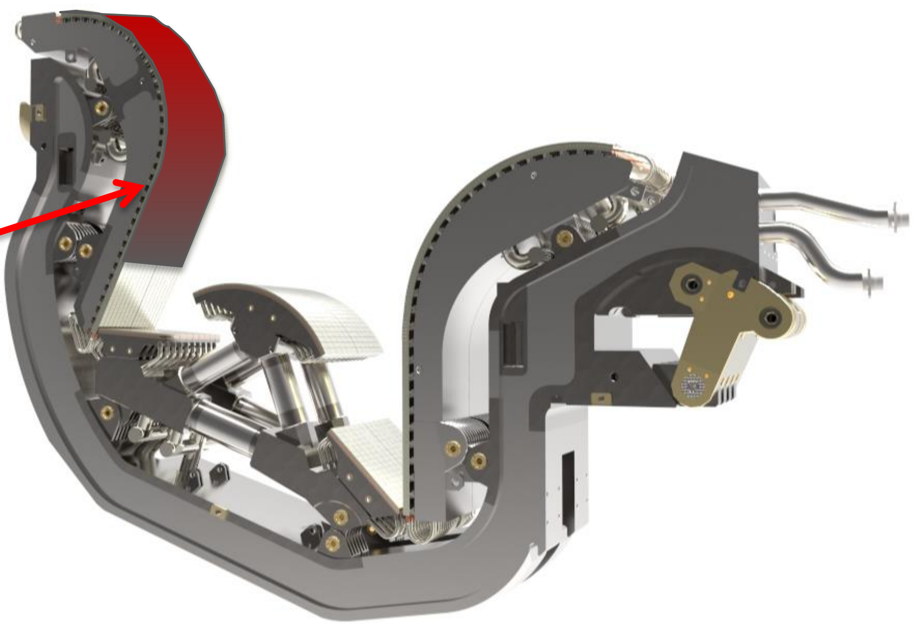
Predicting about 3-19g of Be eroded from first wall and re-de-posited elsewhere

T-retention in ITER and inventory limits

- T retention is limited by nuclear license: 1kg of in-vessel T
  - Minimize environmental release during accidents
- T-retention in ITER largely driven by co-deposition of T with Be
  - Estimated from WALLDYN for wide range of plasma scenarios

Be migration in ITER





K. Schmid et al, NF, 55 (2015)

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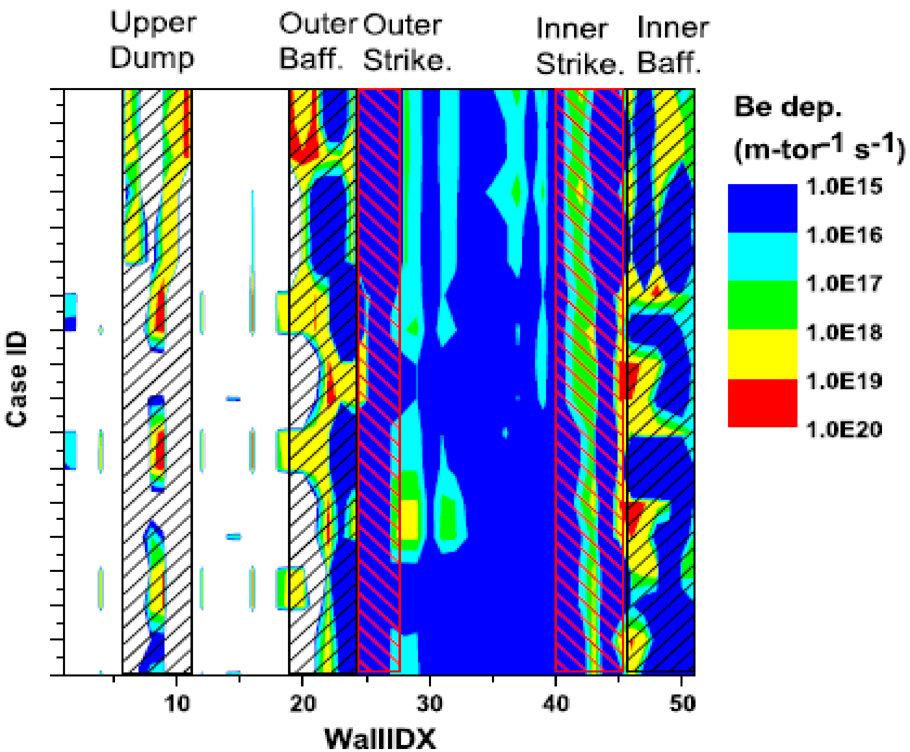
Be migration in ITER



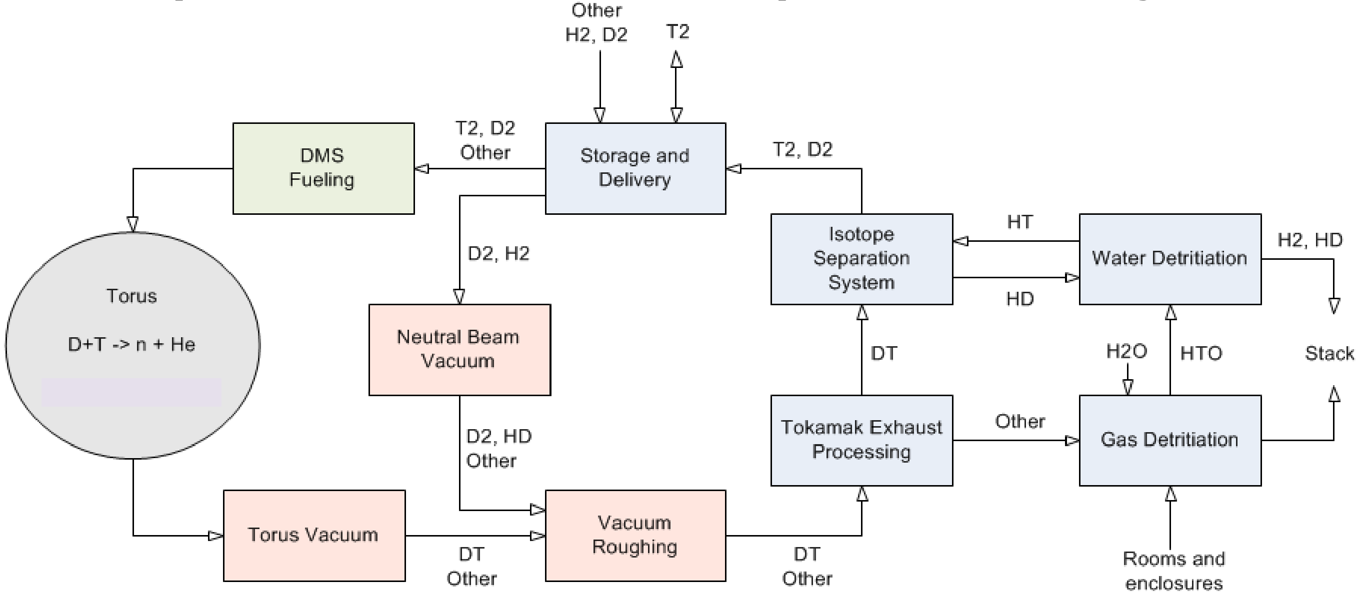
K. Schmid et al, NF, 55 (2015)

- T-limit could be reached in 3000-20000 discharges (400s-long Q=10 discharges)
- NB: major uncertainty lies in the ITER SOL plasma parameters
- Deposition occurs mainly in the divertor (baffle regions)

Global tritium measurements

✧ Closed T fuelling system for ITER:

- ✧ **Calorimetry (T decay) used to monitor transfer from material sub-accounts (sub-systems within T loop)**
- ✧ **PVT method to measure injection and exhaust**
- ✧ **Bakeout (240C FW, 350C divertor) for T recovery from PFM**

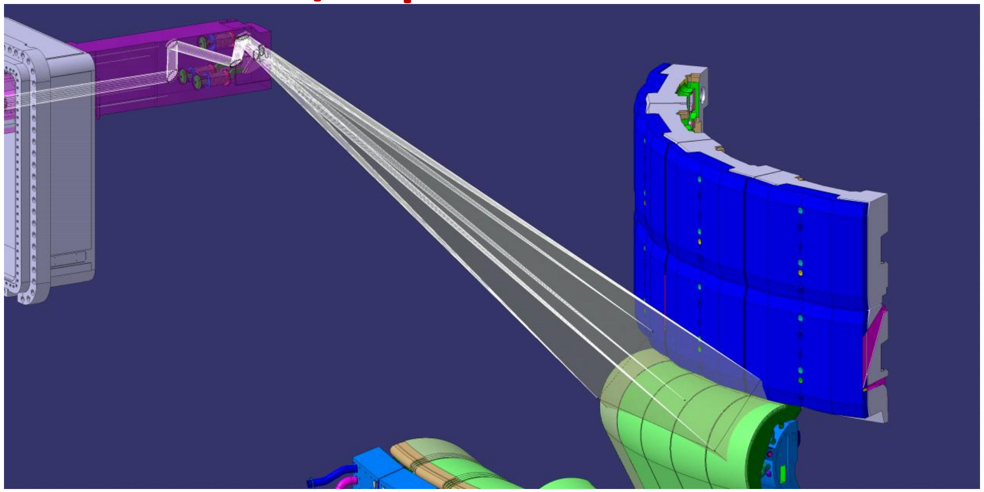


No knowledge of where the tritium is trapped. Local measurements provide additional information and help constrain simulations

Local tritium measurement (1/2)

- **Tritium and deposit monitor being designed for local measurements**
  - **Laser-induced desorption for retention**
  - **Lock-in thermography for co-deposit thickness**

FOV of T/deposition monitor



Focus is on inner divertor baffle where most of the deposition is expected to occur

FOV~ 50x10cm

Desorbed species detected by RGA/QMS

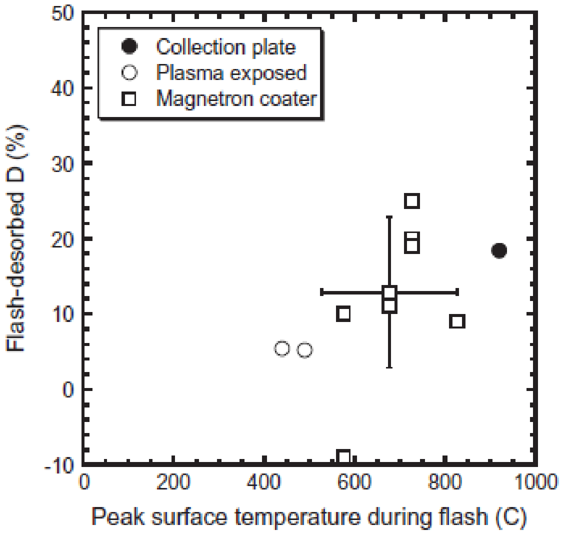
Can be used at the end of operation day

How to ensure full desorption from the co-deposit using laser heating?

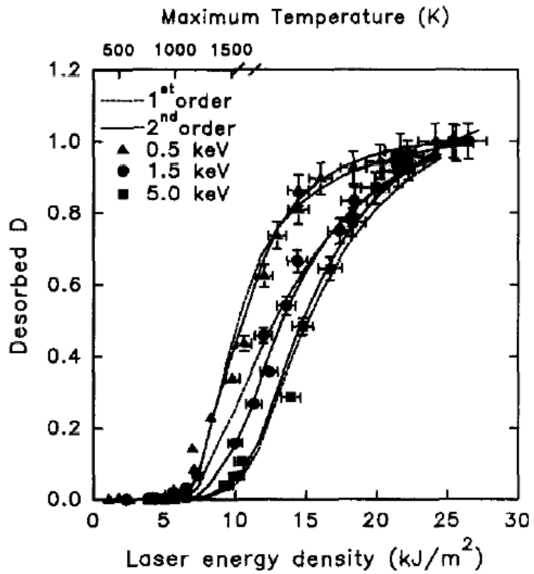
Local tritium measurement (2/2)

- **Experimental investigations of laser-induced desorption of D from Be**
  - **Be co-deposits: Yu et al**
  - **Bulk Be implanted with D: Keroack et al**

10ms laser pulse



25ns laser pulse



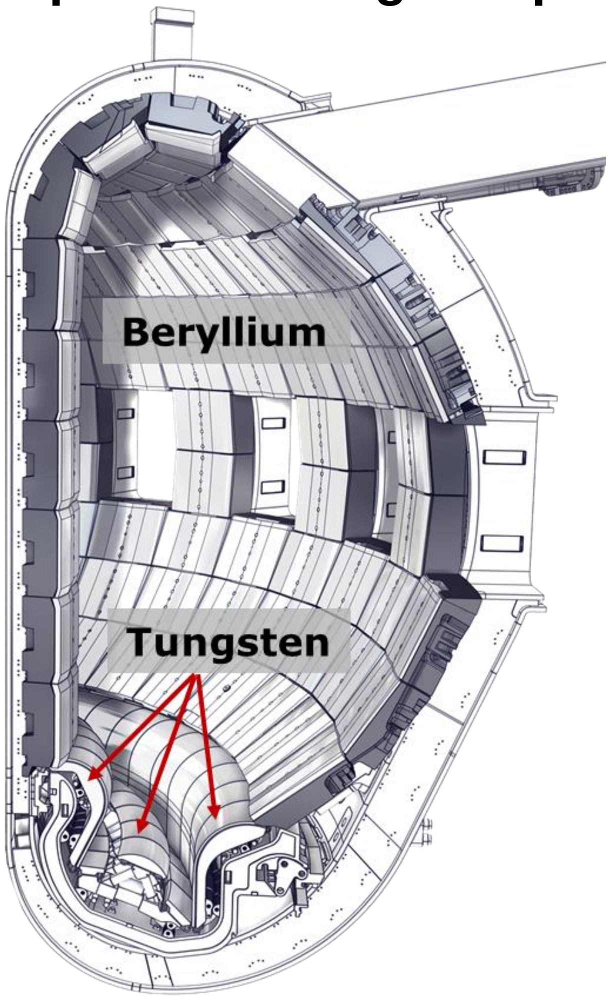
In both cases, significant release only when close or above melting

J.H. Yu et al, JNM 438 (2013)
D. Keroack et al., JNM 212-215 (1994)

Effect of longer pulse durations and multiple heating pulses?

T removal in ITER

- **Outgassing by baking is the main technique for tritium removal from plasma-facing components**



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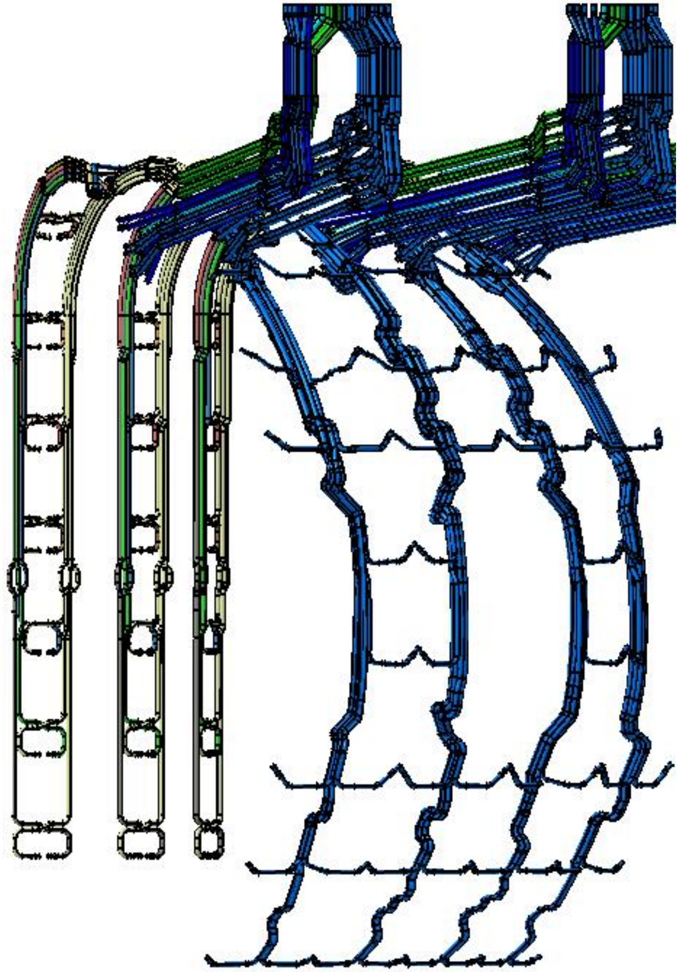
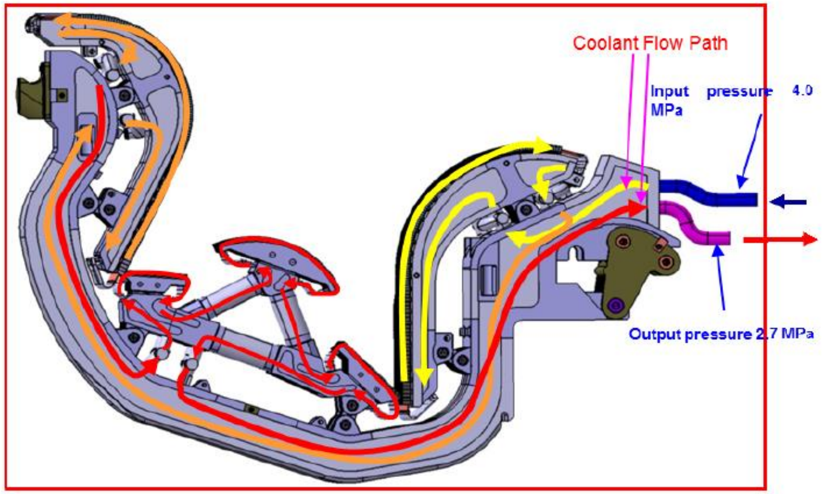


- **First wall baking at 240C**
  - **Hot water through cooling system**

T removal in ITER

- Outgassing by baking is the main technique for tritium removal from plasma-facing components



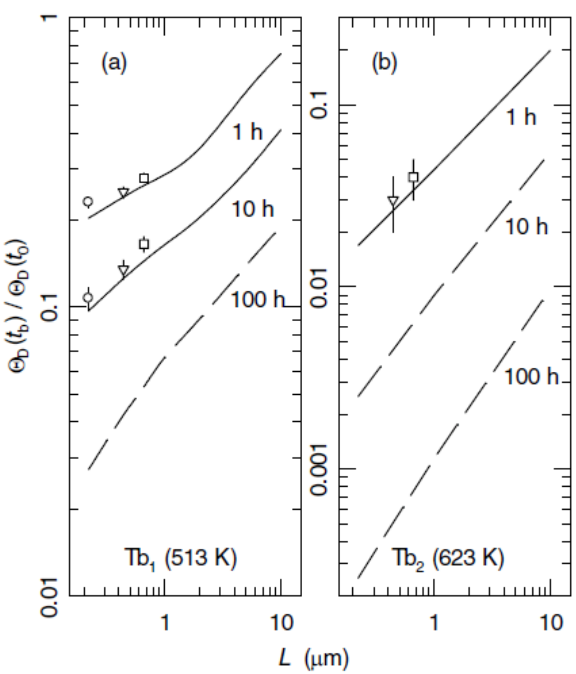
- **Divertor baking at 350C**
  - Hot gas circulated in cooling pipes
  - Needs draining and drying of cooling lines
  - Takes about 100hrs for draining/heating and then cooling
  - Bake frequency/duration not specified yet. Under investigation

Efficiency of T removal by baking

- Previous investigations point out to possible reduced bake efficiency
  - Effect of layer thickness, succession of bake cycles
  - Recent results from JET beryllium co-deposits

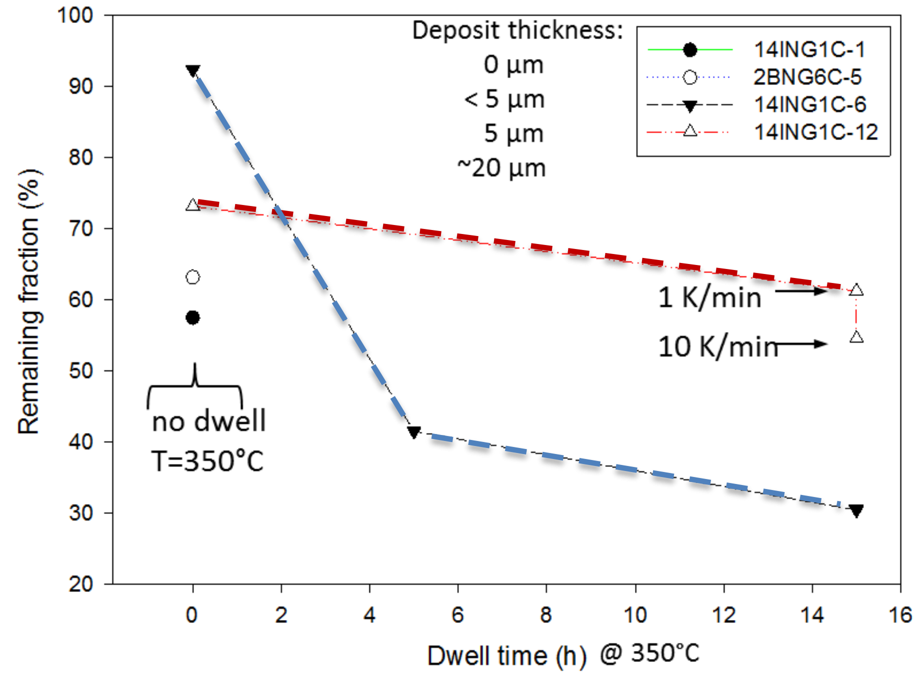
PISCES-B results

M.J. Baldwin, R.P. Doerner, Nucl. Fusion 54 (2015)



JET results

J. Likonen et al, this conference



How to extrapolate those results to ITER to assess T removal efficiency?

Assessing efficiency of thermal outgassing

PISCES, JET, NIPLRP (Romania)

Experimental TDS data

Different deposition conditions, heating rates, …

TMAP7

Modeling of experimental data

Consistent model for different data

Understand similarities and differences between different samples

Input from WALLDYN

Use of JET/PISCES models

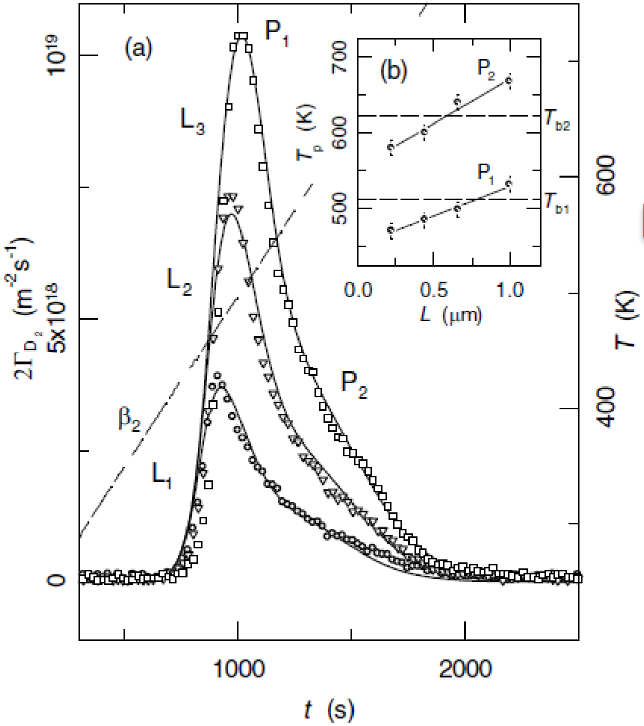
Extrapolation to ITER

Range of efficiency depending on model

TMAP7 modeling: PISCES

- TMAP7 developed at INEEL to simulate diffusion/trapping in materials
  - Model developed by Baldwin et al fit a wide range of experimental PISCES data for Be co-deposits

TMAP7 model of PISCES data



M.J. Baldwin et al, Nucl. Fusion 54 (2014) 083032
M.J. Baldwin, R.P. Doerner, Nucl. Fusion 54 (2015)

Model extended to TDS data of JET co-deposits (J. Likonen, PSI2016)

Ramp and hold experiments: different ramp rates and hold time at 350C

Diffusion coef. and recombination rates similar to Baldwin et al

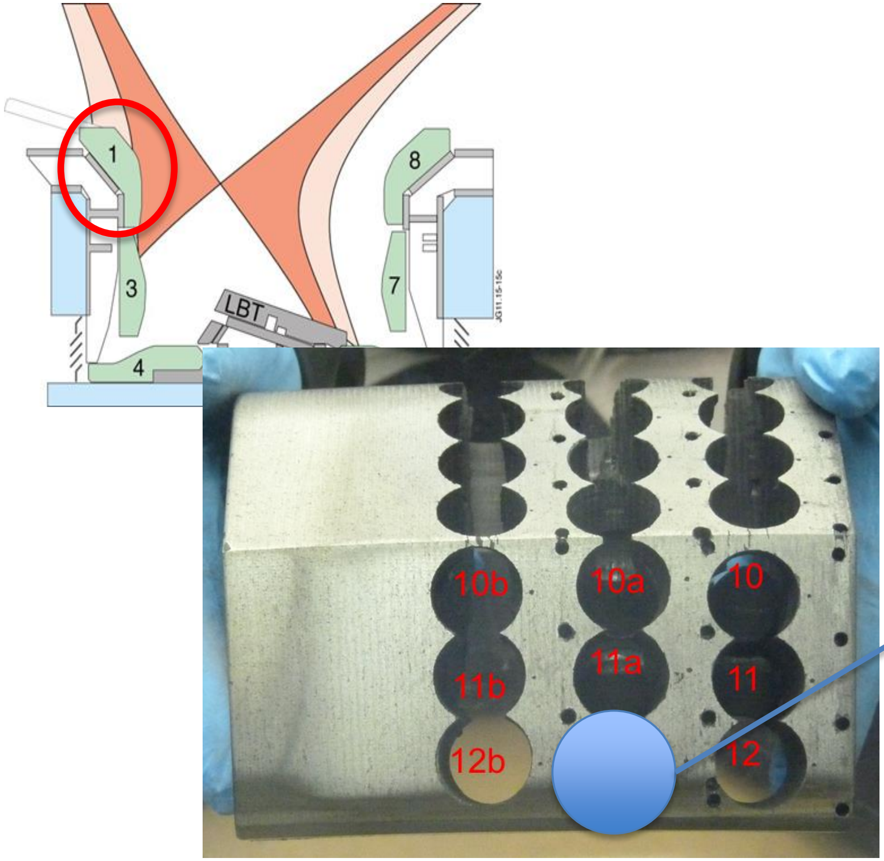
Assume a homogeneous D profile

Trap energy and occupancy used as "free parameters"

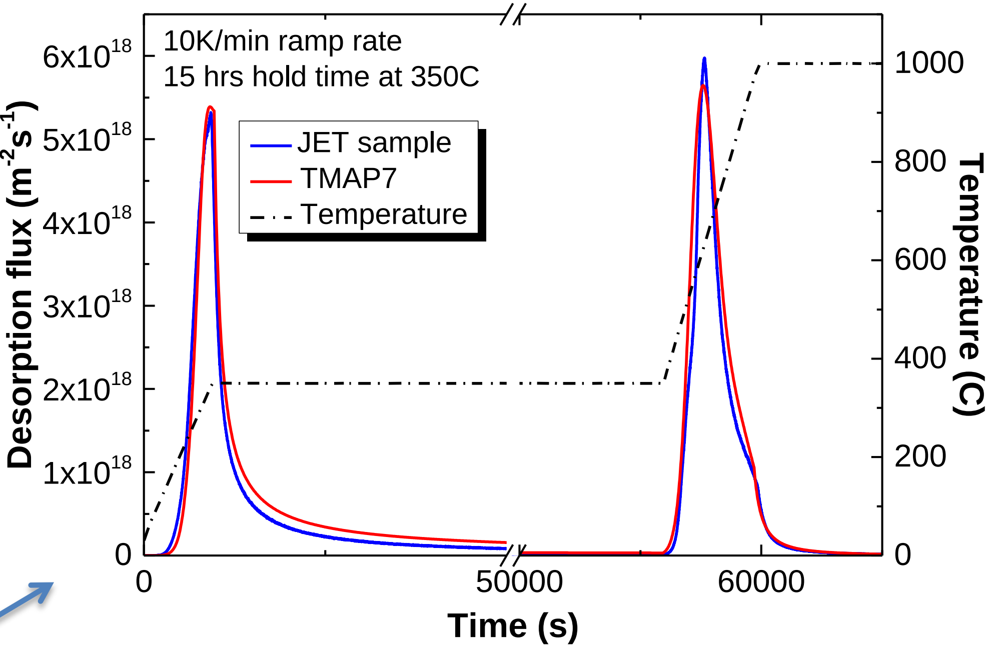
TMAP7 modeling: JET data

✧ **Simulated data from 3 samples annealed under different conditions**

Samples from tile 1 apron



TMAP7 results



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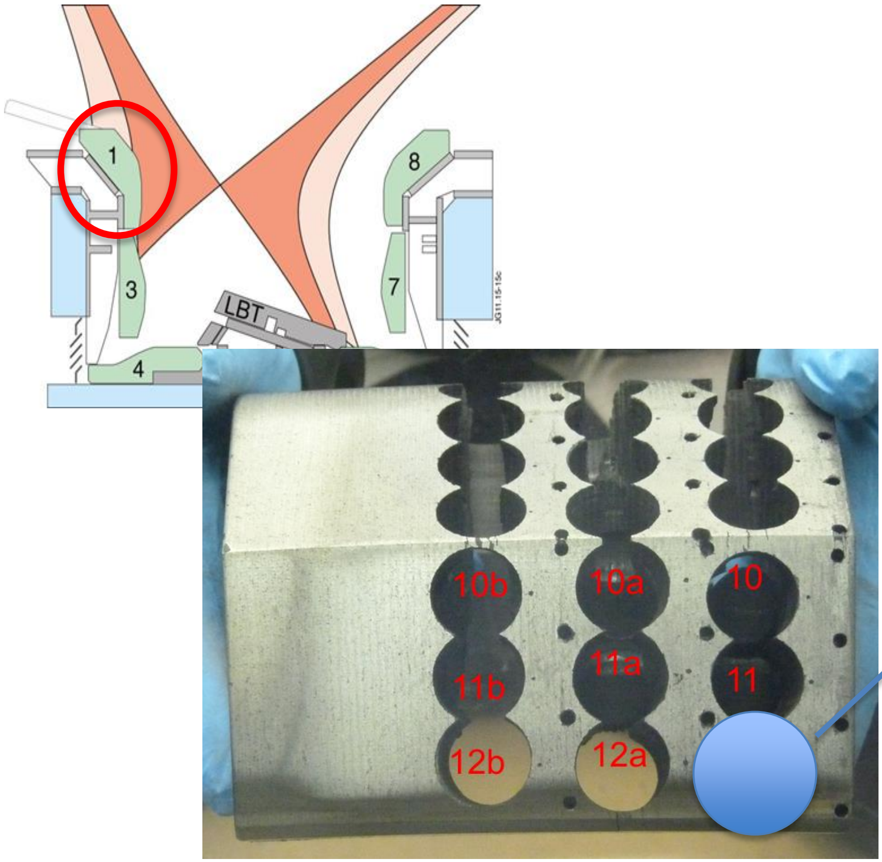

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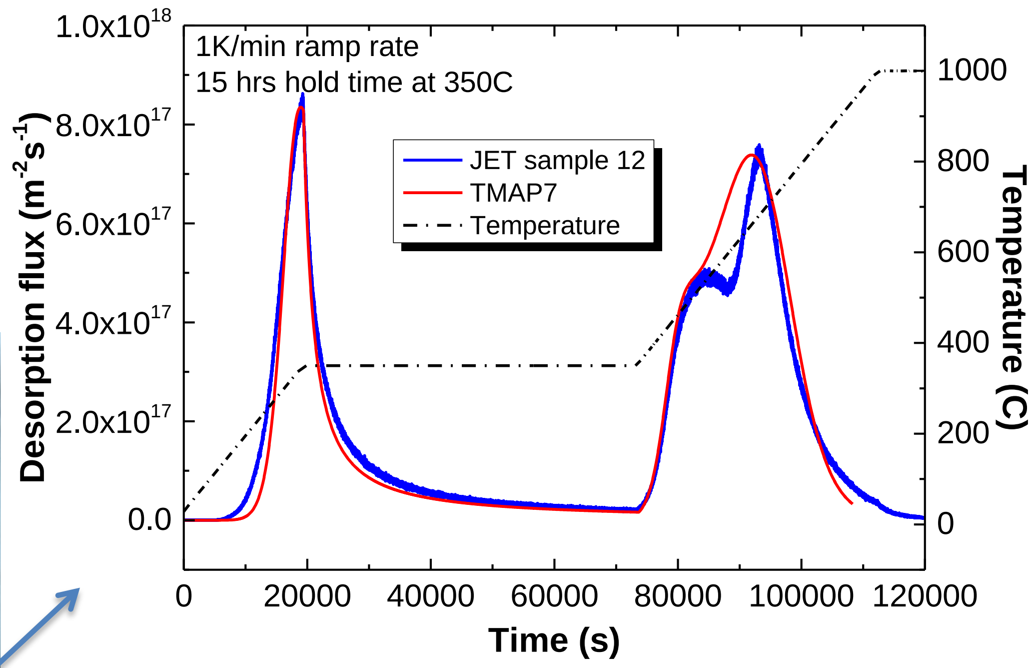

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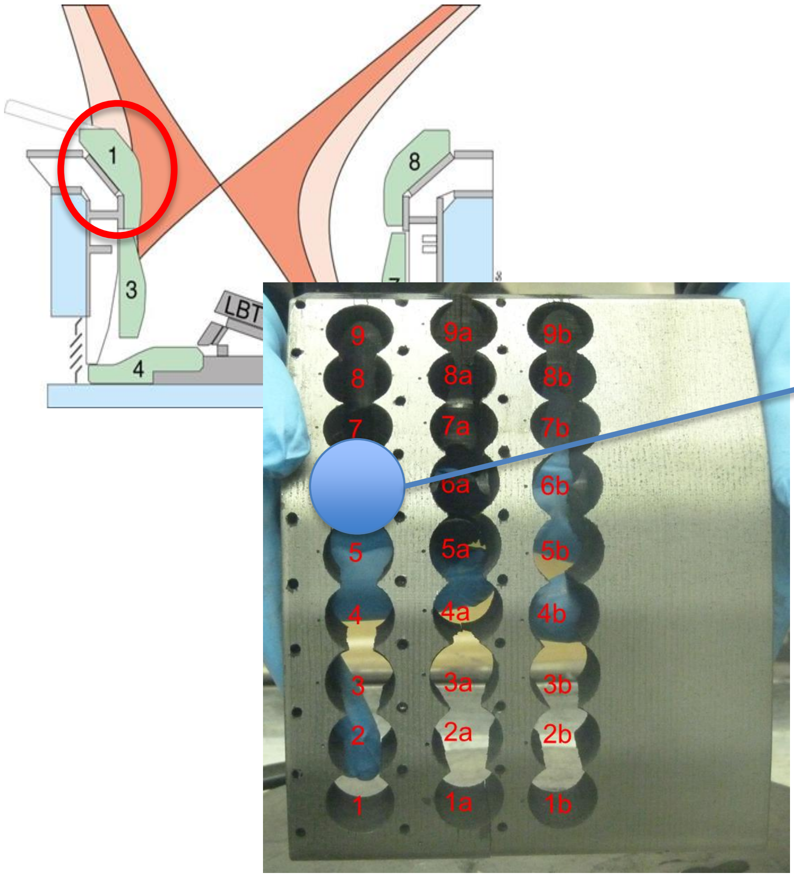

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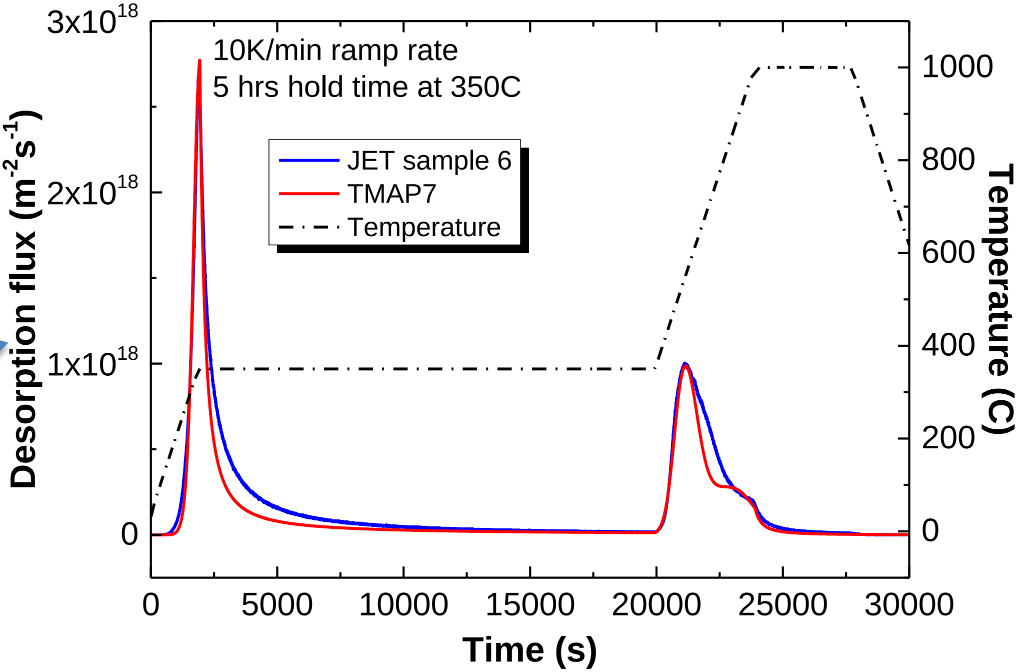


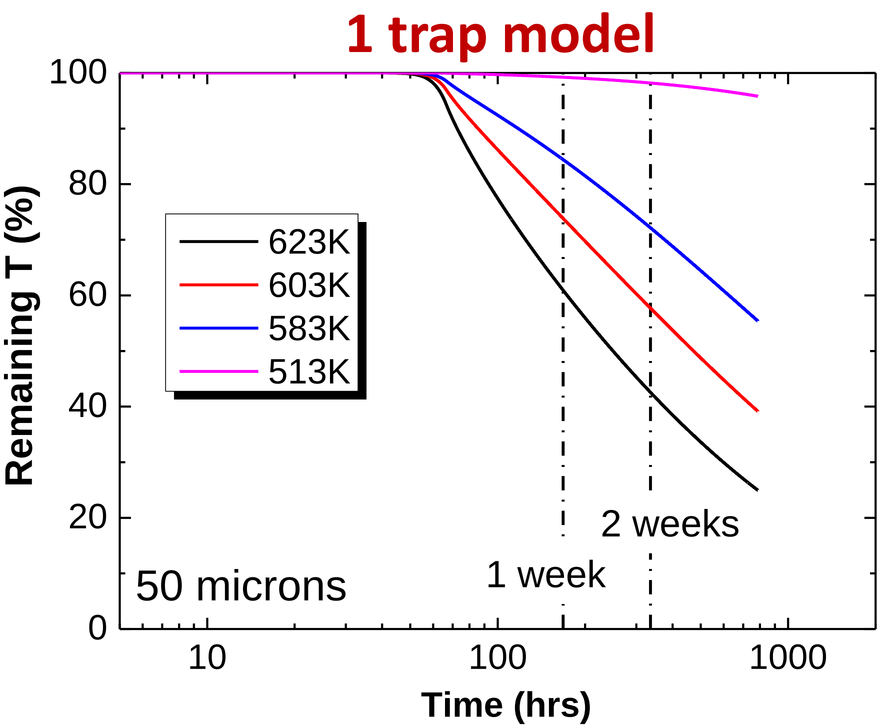
TMAP7 modeling: JET data

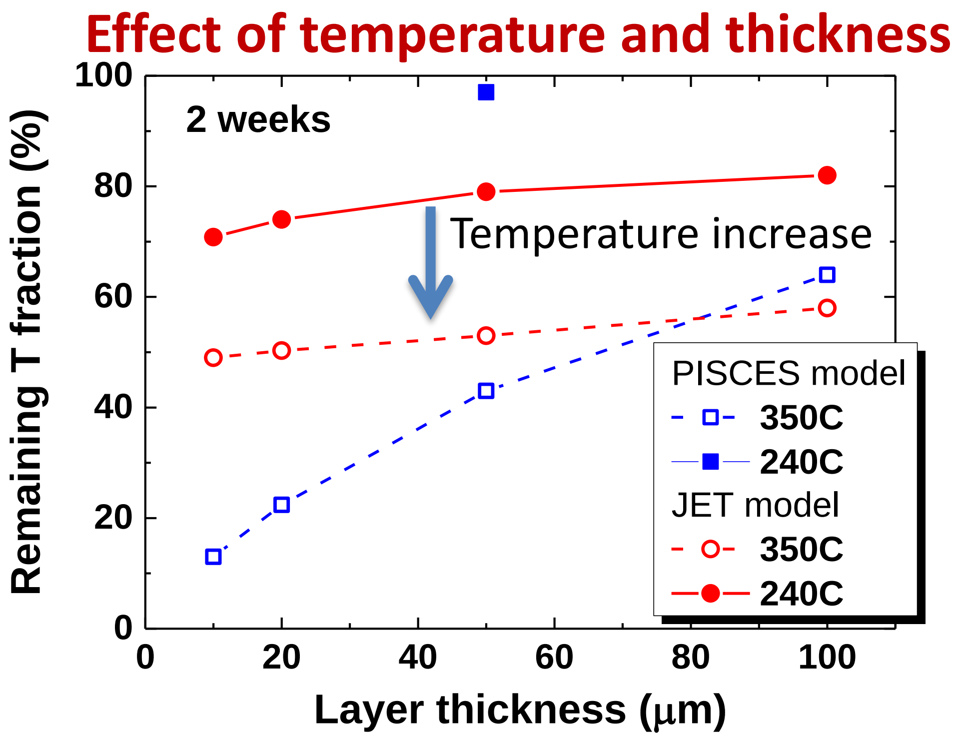
- Simulated data from 3 samples annealed under different conditions
  - See talk by J. Likonen
- Good agreement obtained with 3 traps at 0.75-0.8; 1.1 and 1.4eV
  - Relative occupancy of traps dependent on sample location (and probably conditions during plasma exposure)
  - First two traps correspond well with those observed on PISCES co-deposits (0.8 and 1eV)
  - High energy trap appears in JET: effect of impurities?
  - Data for thicker films would be benefitial
  - Temperature history of tile also needed

Provides good basis for first extrapolation to ITER

Assessing efficiency of 350C bake

- TMAP simulations using 2 sets of assumptions
  - PISCES model with 1 trap (T_{dep}>100C)
  - JET co-deposit model (sample 12, 3 traps)



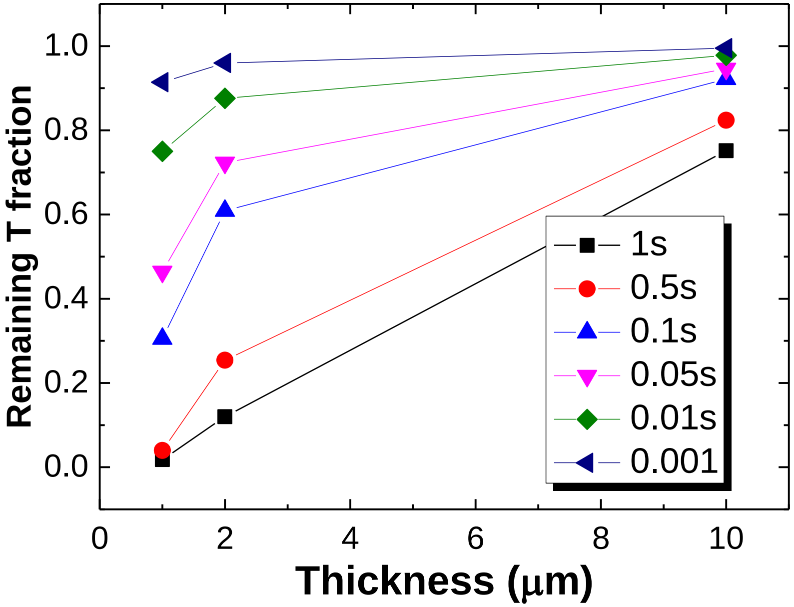


240C bake very inefficient. 350C more efficient
At 350C, efficiency decreases very quickly with thickness

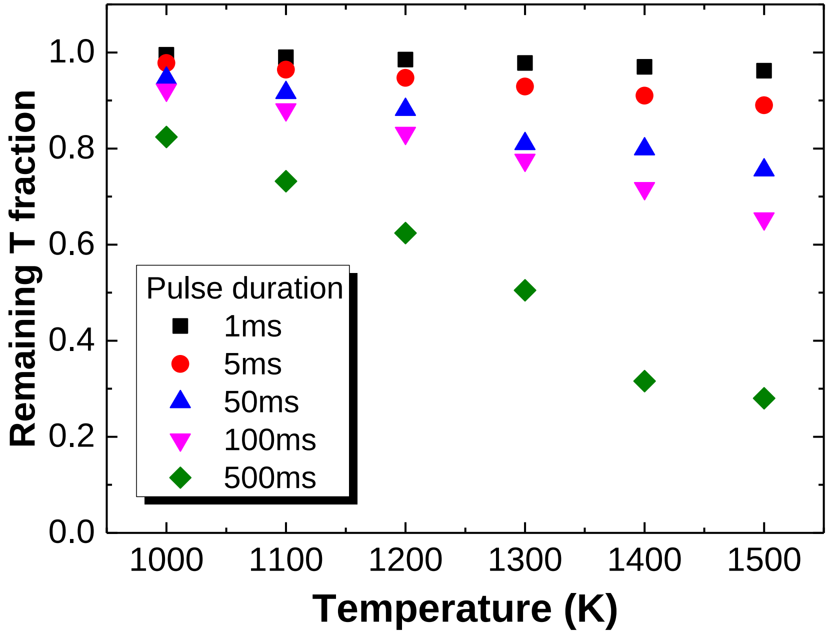
Efficiency of LID (1/2)

- Results for single pulse heating

LID for T=1000K



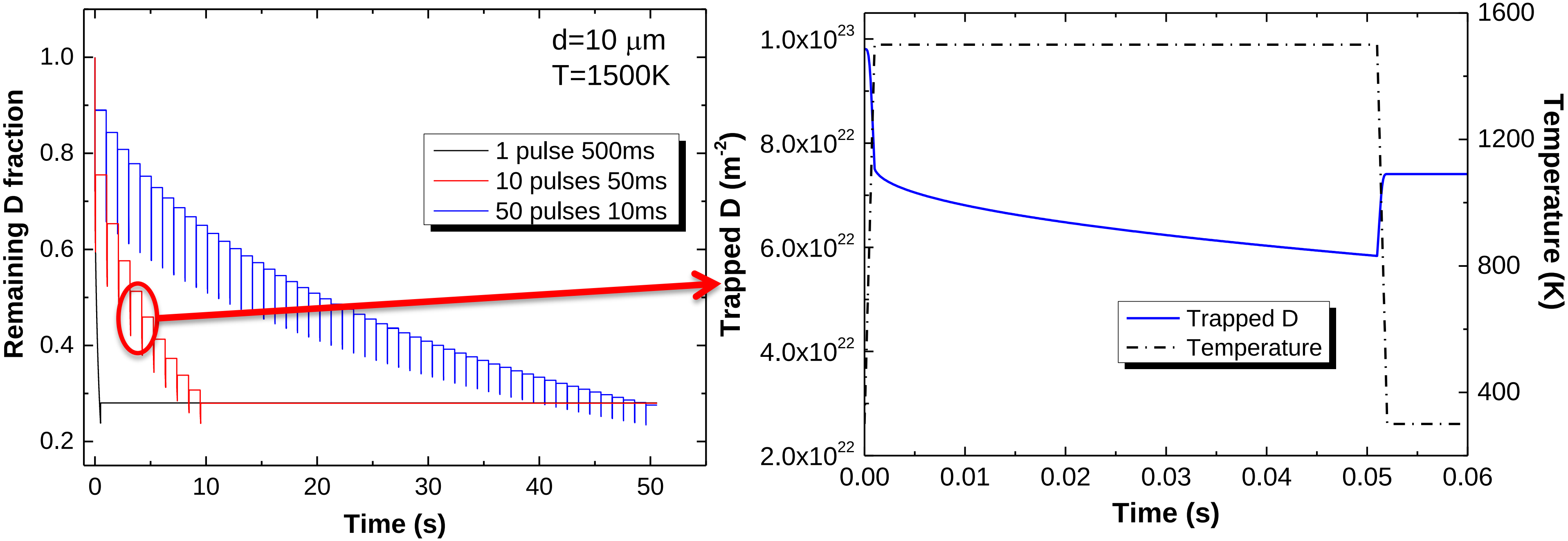
LID for 10μm thick layer



- **Desorption efficiency decreases drastically with increasing thickness**
  - **For a 10μm film, only 25% D removed for a 1s pulse**
- **Increasing temperature strongly increases desorption efficiency**

Efficiency of LID (2/2)

- Different combinations of pulse number/pulse duration investigated
  - Total heating time kept constant

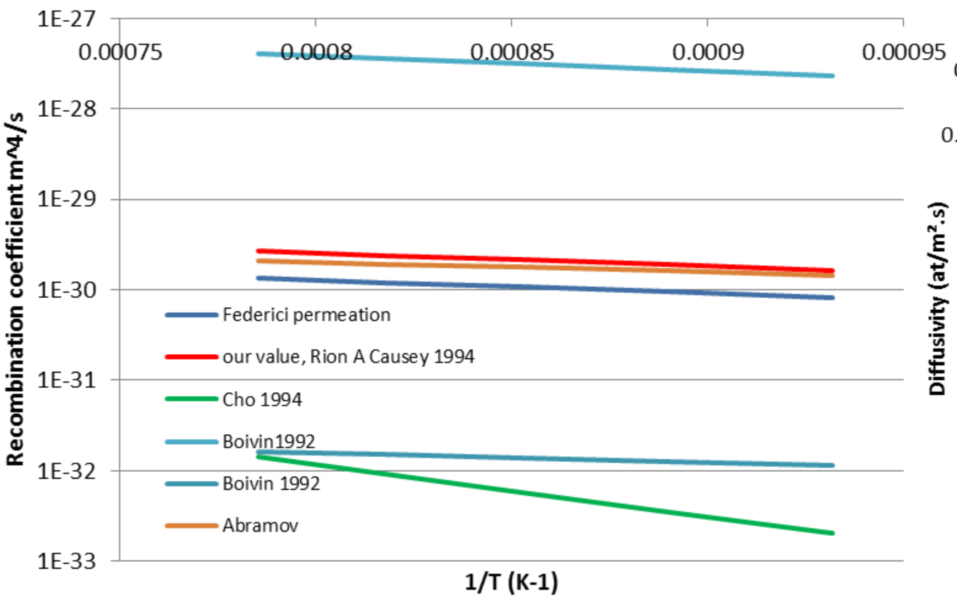


Final desorbed fraction only depends on the total heating time and is independent on the heating scenario (multiple pulses vs single pulse)

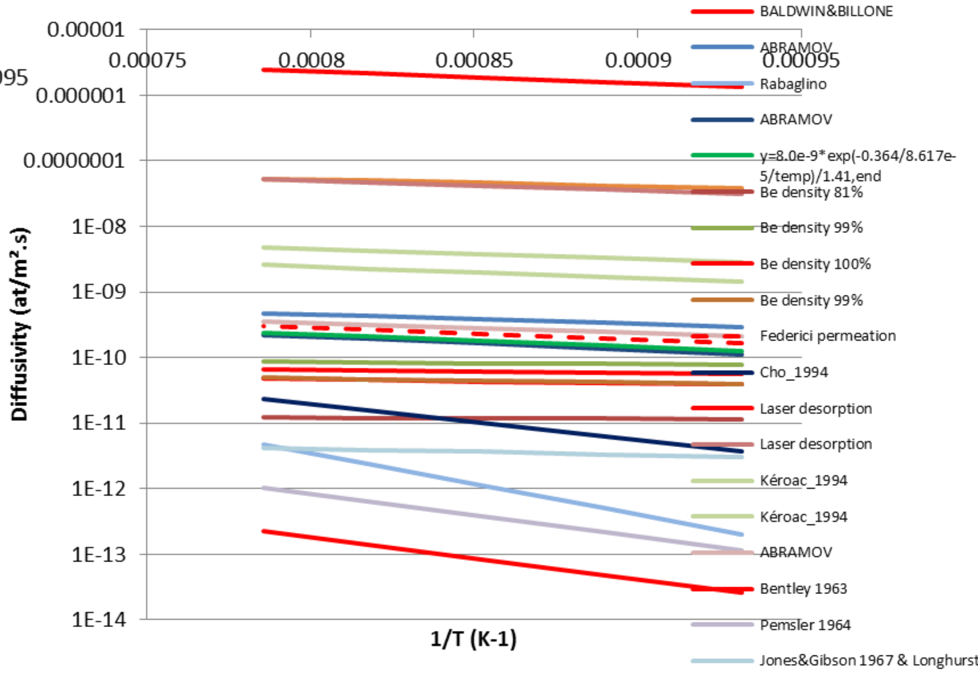
Need for improved diffusion/trapping data

- Diffusion/trapping modeling also used to assess efficiency of detritration from tokamak waste
  - Large uncertainties in existing diffusion/trapping/recombination rates

D recombination rate on Be



Diffusion coef. D in Be

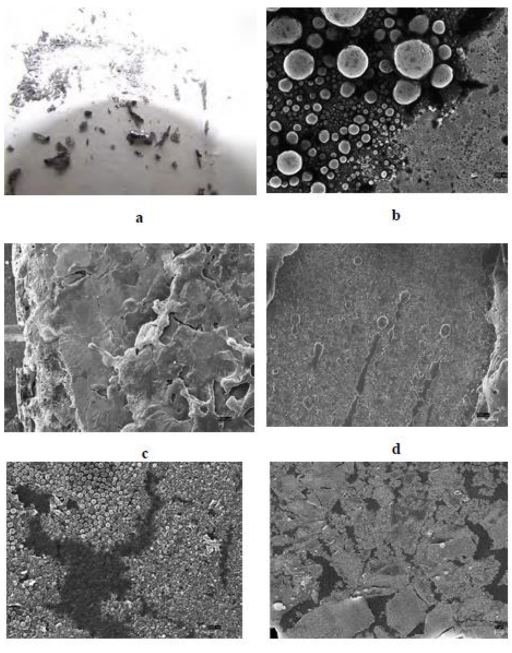


Understanding the discrepancies between those values would ease extrapolations to ITER

Be dust: what does it look like?

- **Very little (if any) existing data from relevant experiments…**
  - **Dust from JET-ILW still to be analyzed, no delamination yet…**
  - **Some data from QSPA (but remember: at higher plasma pressure)**

Dust on QSPA exposed target



- **Most probable dust size from existing experiments is <10 microns (but large size distribution)**

- **Early ITER operation phases will bring lots of information**
- **Important that sampling/analyses can be done during those phases**

Summary/Outlook

- **Good progress being made on beryllium erosion data**
- **Tritium retention estimates bound to uncertainties on SOL plasma**
- **Work ongoing to refine the T-removal strategy and develop local T measurement techniques**
  - **Important to obtain accurate data for T trapping, diffusion and recombination from bulk Be and Be co-deposits**
- **Information on Be dust from relevant experiments is needed to refine current assumptions**