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Investigation of Deuterium Permeation and Retention in RAFM Steel

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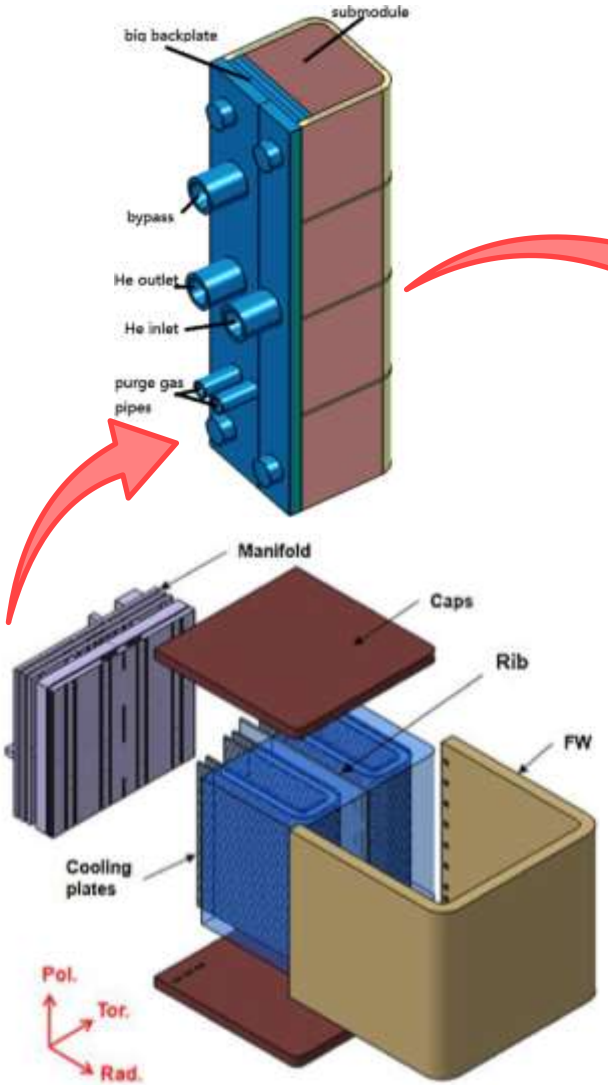
The 3rd Research Coordination Meeting of the CRP on Plasma-wall Interaction with Reduced-activation Steel Surfaces in Fusion Devices, 25 - 27 March 2019, IAEA Headquarters, Vienna

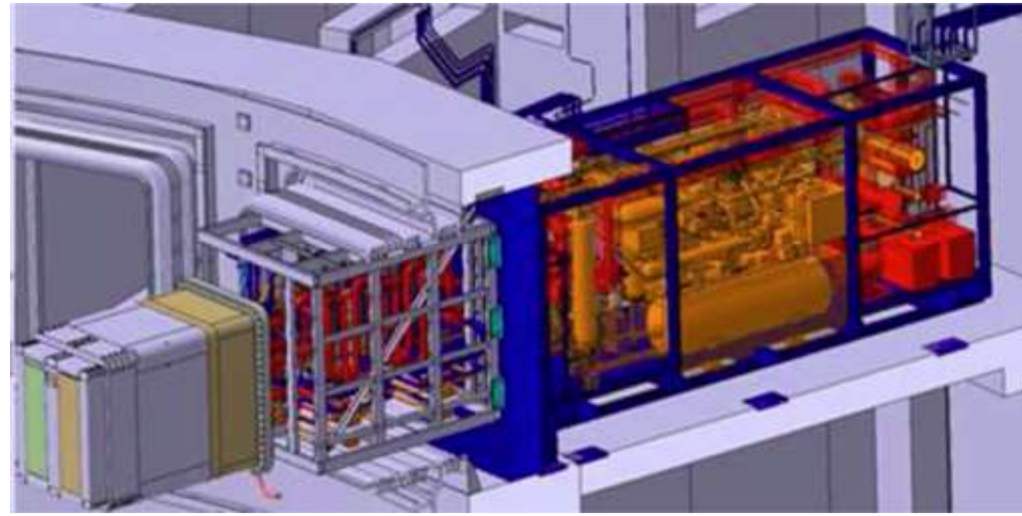
Outline

- **Motivation**
  - RAFM as first wall of TBM in ITER
  - T permeation issue
- **PMI studies on RAFM**
  - D plasma-driven permeation through RAFM
  - He effects on sputtering and D retention
  - D PDP through PFC mockup made by RAFM
- **Summary**

Motivation

Chinese Helium Cooled Ceramic Breeder TBM



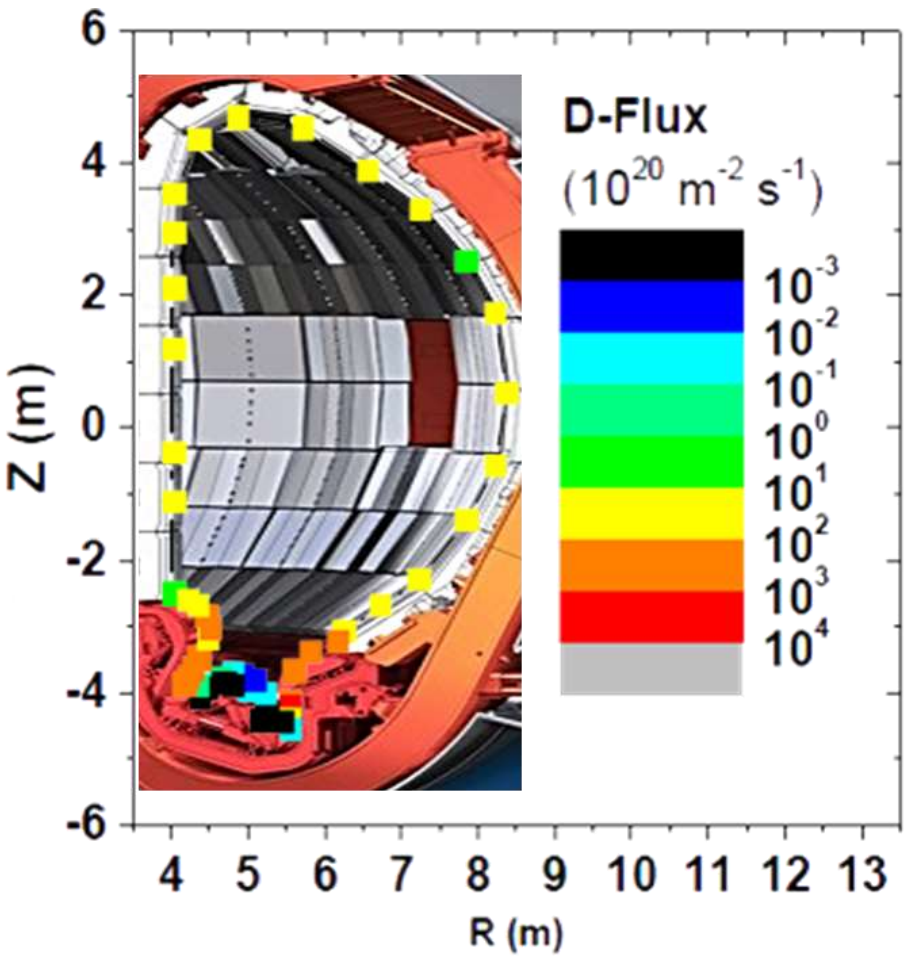


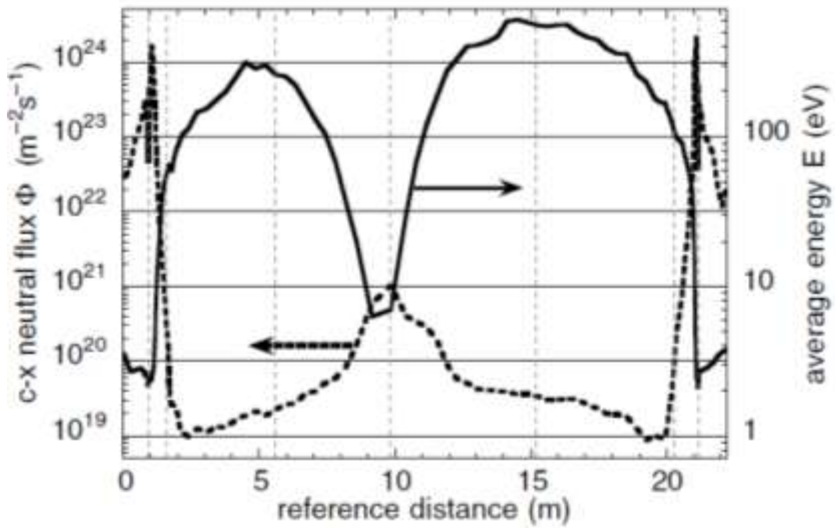
K.M. Feng et al., FED 89 (2014) 1119

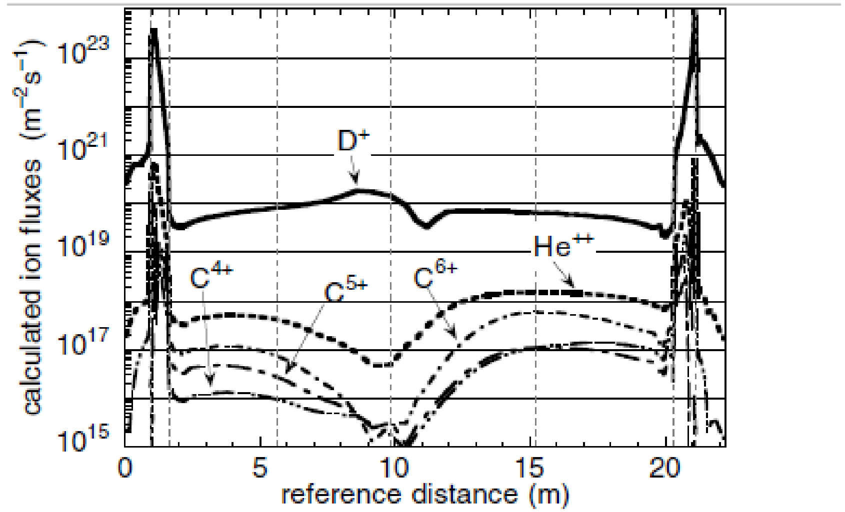
- **Tritium breeding blanket concepts will be tested in ITER.**
- **The helium-cooled ceramic breeder (HCCB) test blanket module (TBM) is the primary option of the Chinese TBM program.**

RAFMs will be used to fabricate the first wall of ITER TBM (~mm thickness).

H particle flux to the wall





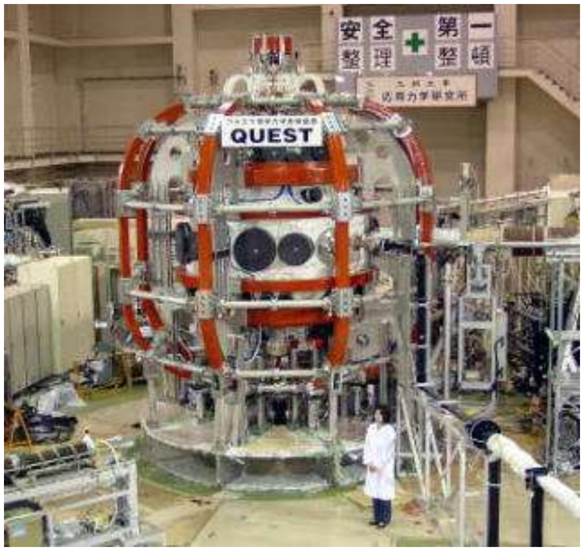


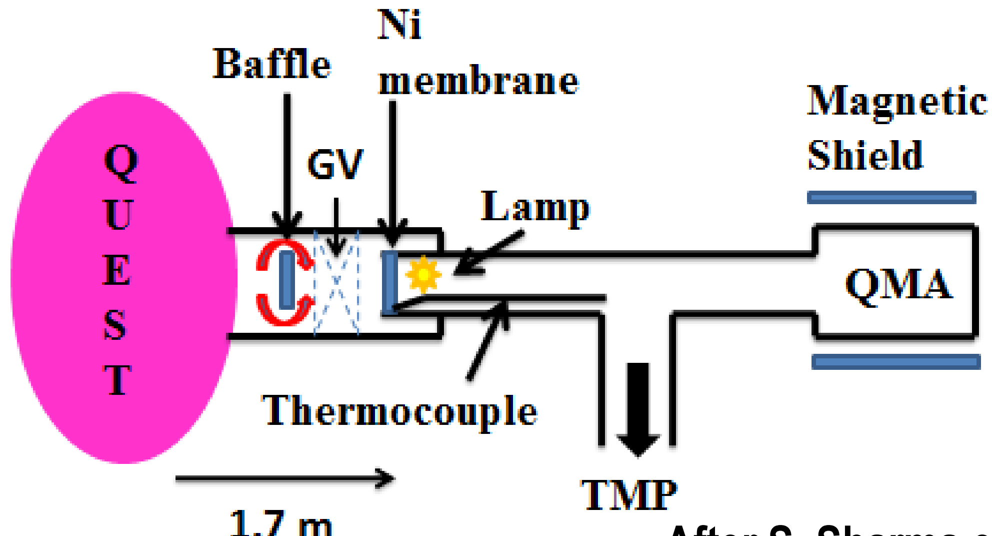
After R. Behrisch and A.S. Kukushkin et al.

	H flux ($H\ m^{-2}s^{-1}$)	Energy (eV)	Temperature
First wall	10^{20}-10^{21}	~100 eV	~500 C

T permeation through the first wall

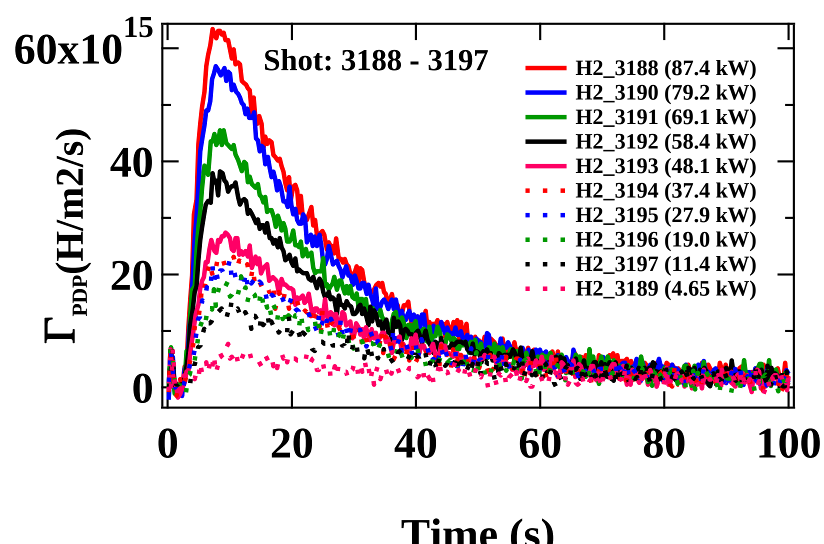
Knowledge learned from QUEST permeation experiments





After S. Sharma et al.

Un-confined neutral H particles can go to anywhere in the vacuum vessel and induce H permeation!



Plasma driven permeation of D through a Chinese reduced activation martensitic/ferritic steel CLF-1

H.D. Liu et al., J. Nucl. Mater. 514 (2019) 109-113.

Sample preparation and experiments

Materials: 0.75 mm RAFMs membrane, polished

(wt %)	C	Si	Mn	Cr	Ni	Mo	W	Ta	V	Nb	Al	N	P
CLF-1	0.12	<0.05	0.51	8.50	<0.01	<0.01	1.5	0.10	0.25	<0.01	<0.03	0.0067	<0.005

The authors would like to thank Profs. K.M. Feng and Y.J. Feng from SWIP for providing CLF-1.

Experiments:

Methods	Plasma-driven permeation (PDP)	Gas-driven permeation (GDP)
Purpose	Surface effects	Permeation parameters measurements

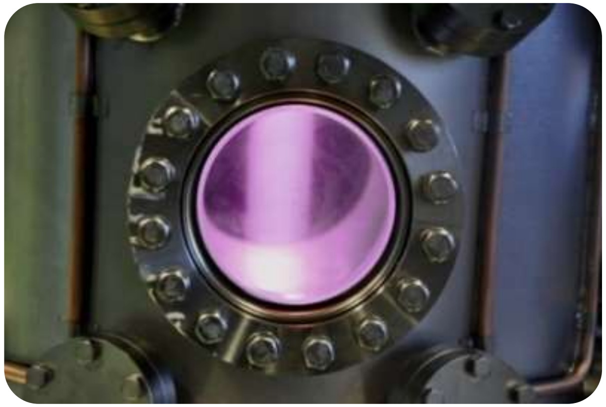
GDP → permeability and diffusivity

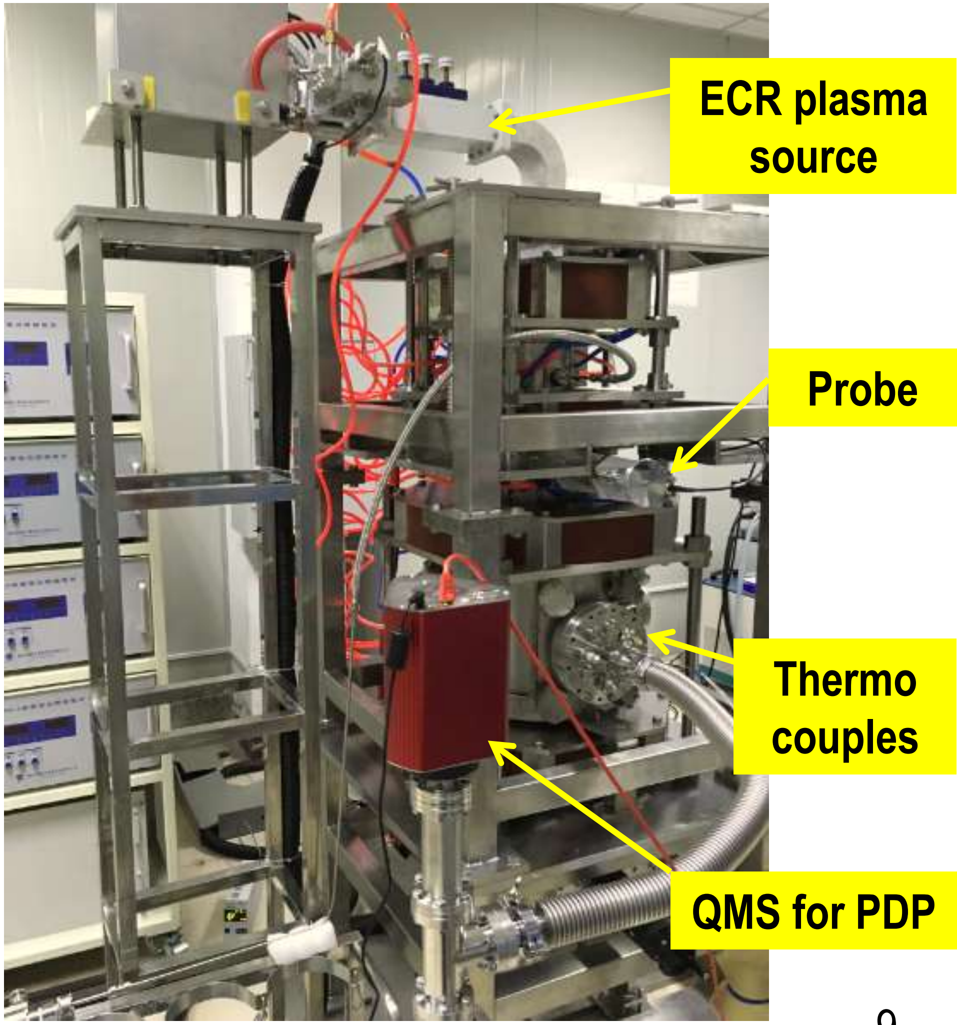
The PREFACE facility

Permeation and Retention Evaluation FACility for fusion Experiments (PREFACE) at ASIPP

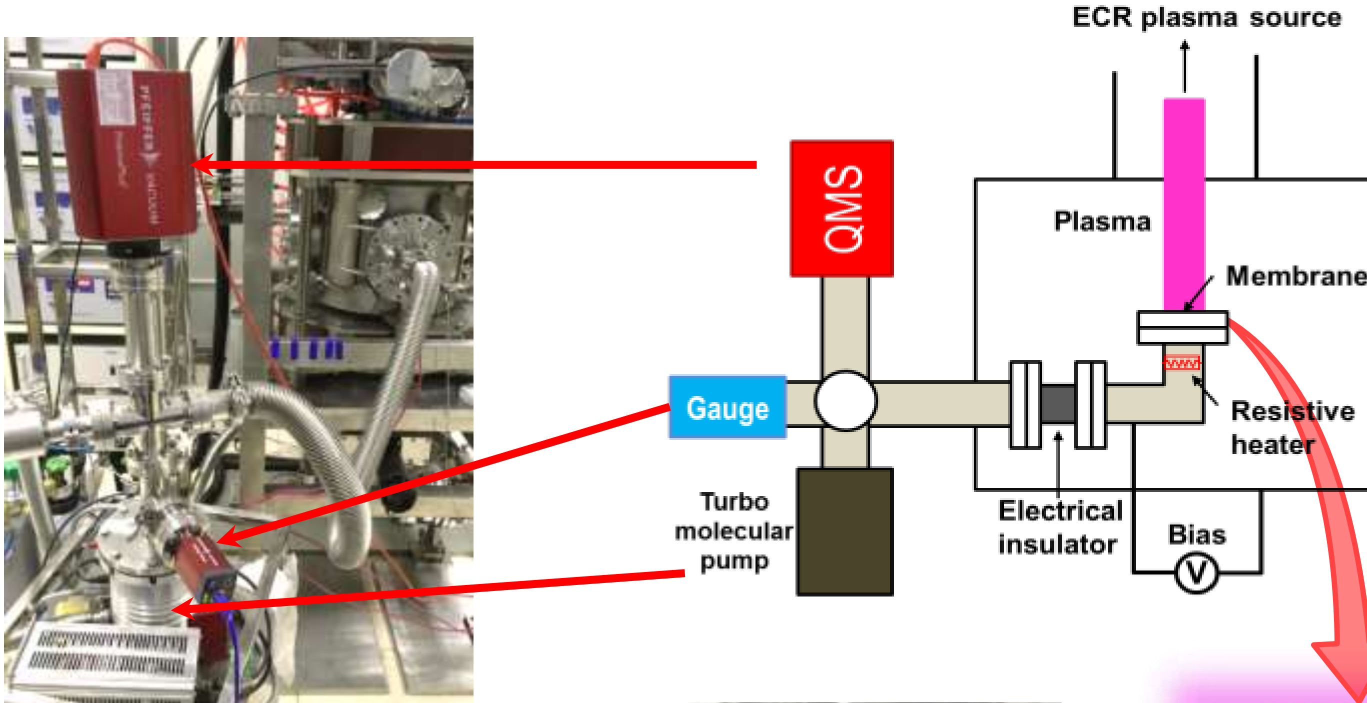
Facility parameters:

- Max. ECR power: 2 kW
- n_e: 10^{14} - 10^{17} m^{-3}
- T_e: 3-6 eV
- Ion flux : 10^{18} - 10^{21} $m^{-2}s^{-1}$

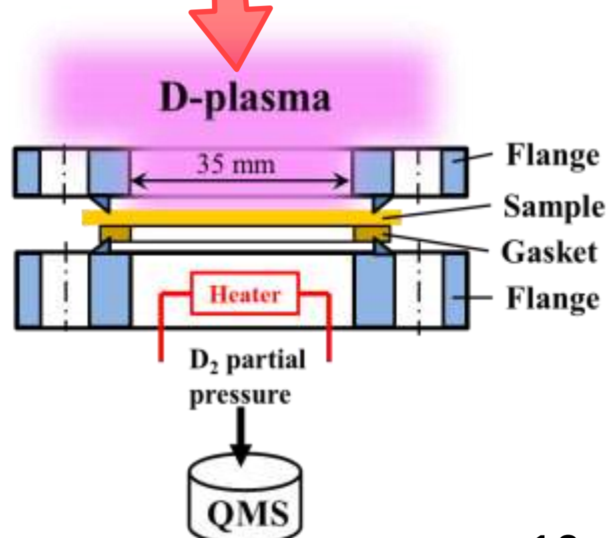




Plasma-driven permeation setup

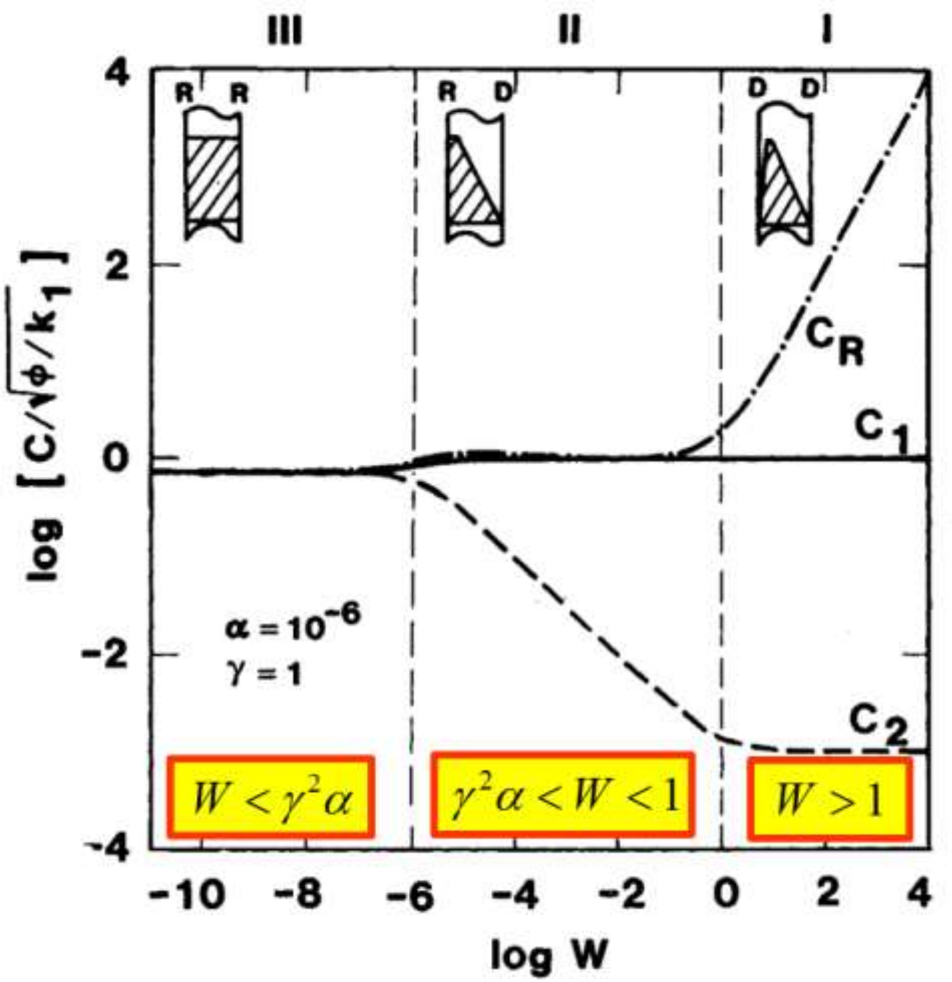


CLF-1 sample for PDP studies



H. Zhou et al., J. Nucl. Mater. 493 (2017) 398
H. Zhou et al., Nucl. Fusion 58 (2018) 056017

Steady-state PDP model



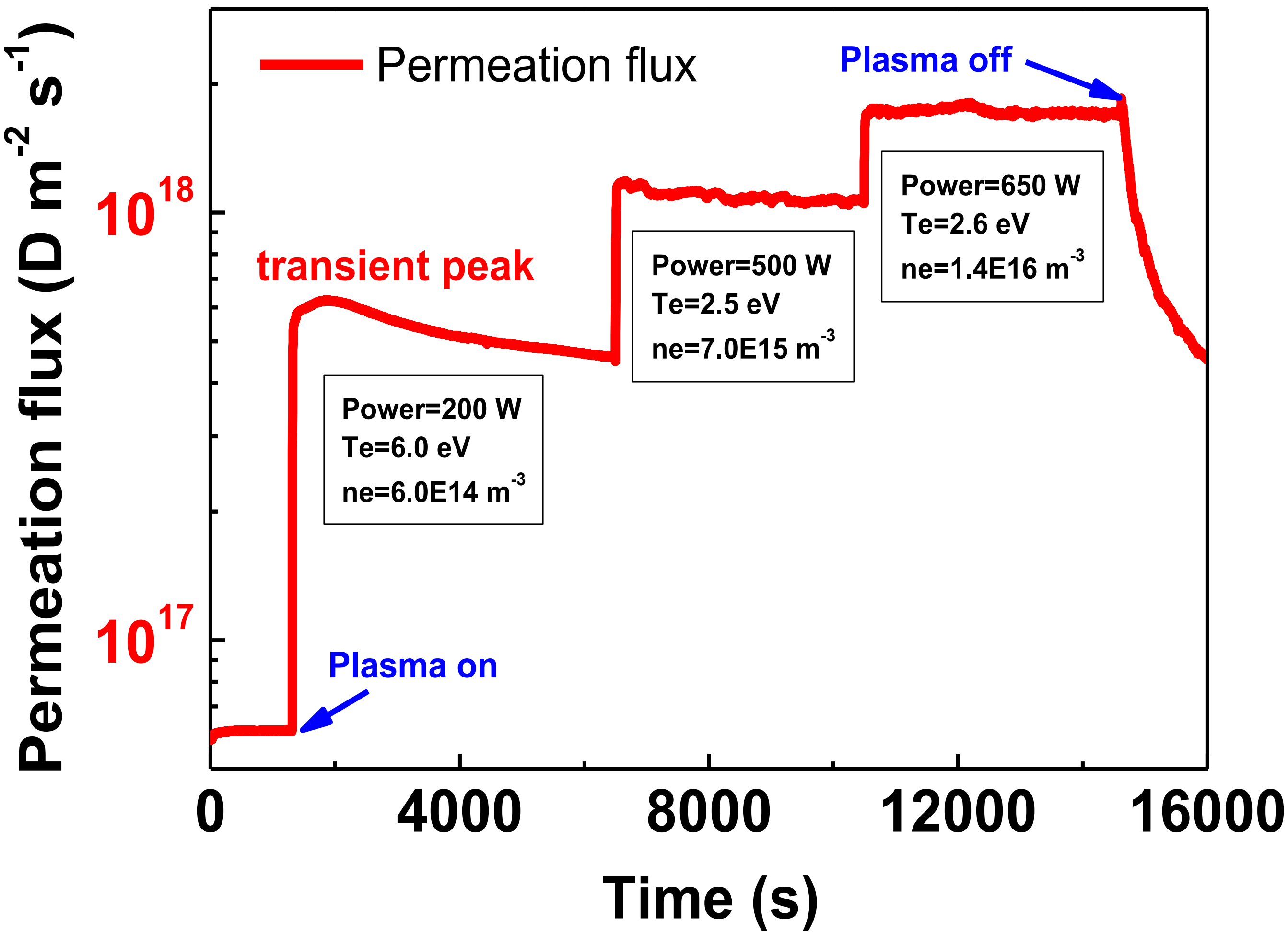
B. L. Doyle, JNM 111&112 (1982) 628.

R: recombination

D: diffusion

- RR $$J_p = \frac{K_{up}}{K_{up} + K_d} J_{\mathrm{i}}$$
- RD $$J_p = \frac{D}{L}\sqrt{\frac{J_i}{K_{up}}}$$
- DD $$J_p = \frac{R}{L} J_{\mathrm{i}}$$

Permeation flux *vs* incident flux

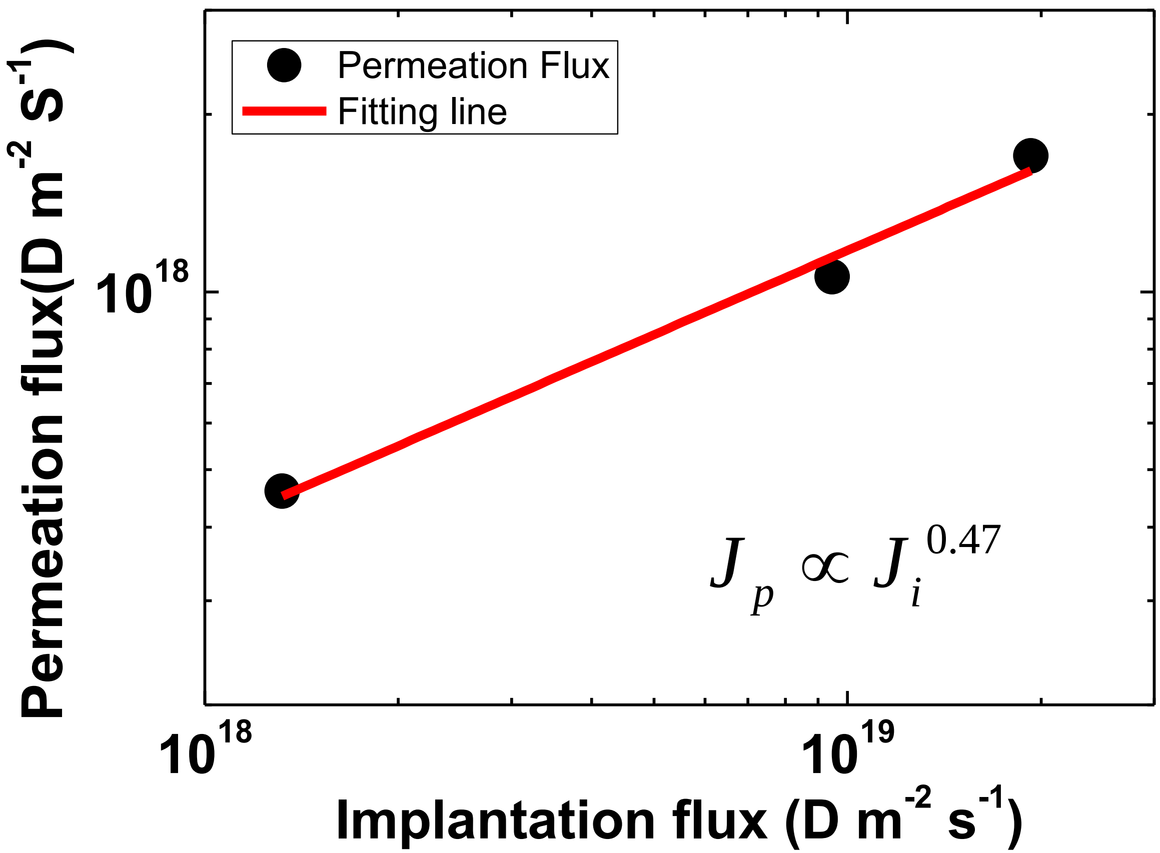


The incident flux is controlled by changing ECR input power.

$$J_0 = \sum_{j=1}^{3} \frac{(1-R_j)\, j\, N_j}{2} \sqrt{\frac{k(T_e+T_i)}{m_{D_j^+}}} \ *$$

*H. Zhou et al., FST **63** (2013) 36.

Permeation regime

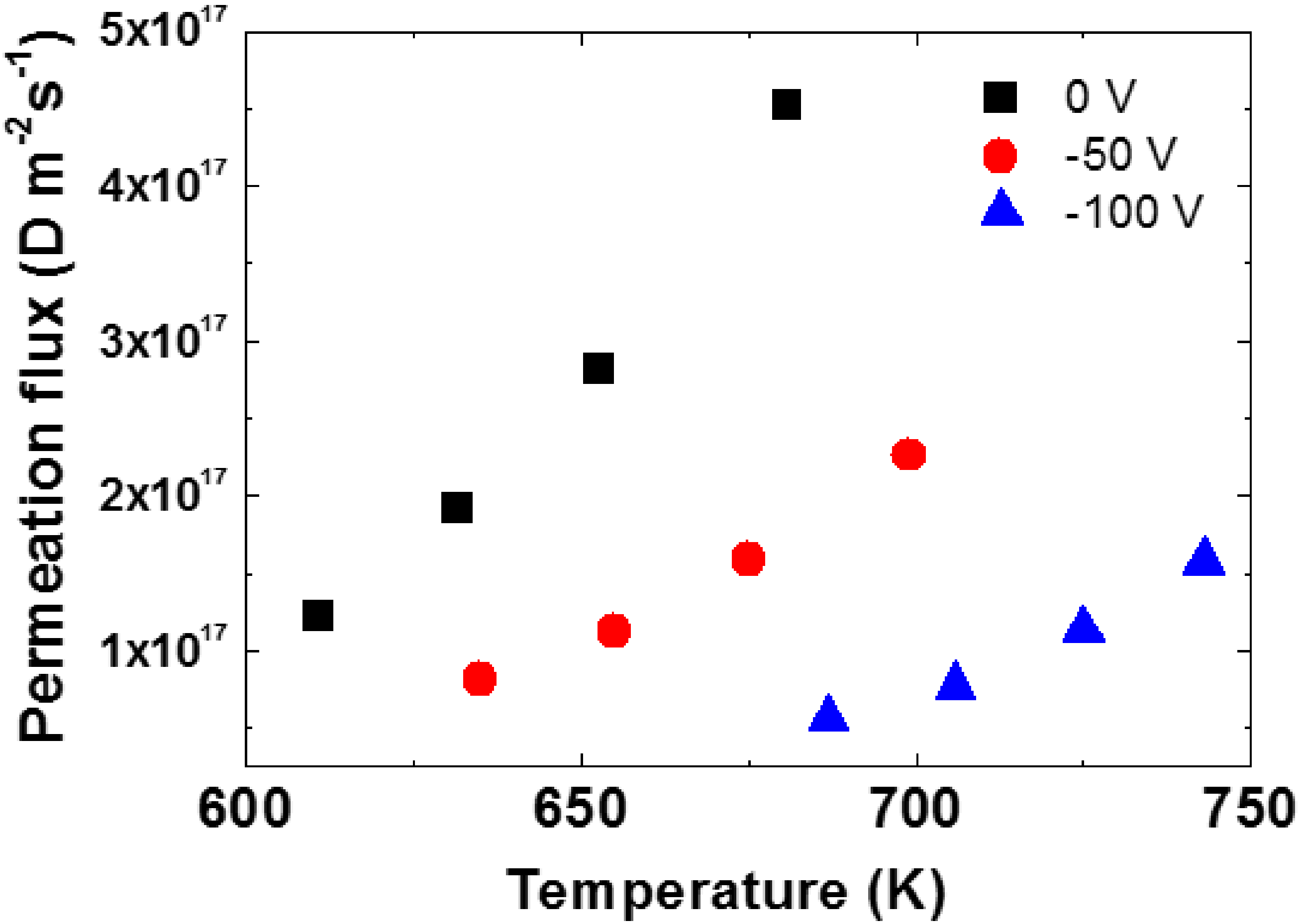


- RR $$J_p = \frac{K_{up}}{K_{up} + K_d} J_\mathrm{i}$$
- RD $$J_p = \frac{D}{L}\sqrt{\frac{J_i}{K_{up}}}$$
- DD $$J_p = \frac{R}{L} J_\mathrm{i}$$

Permeation takes place in the recombination-diffusion regime.

➡ **Estimate the permeation flux for TBM.**

Bias effects



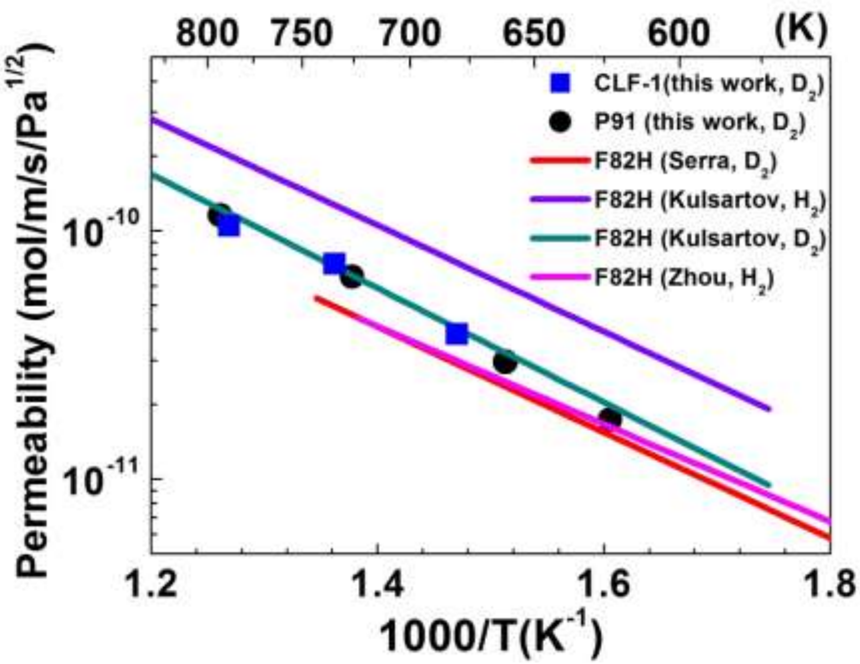
Cleaner surface, lower permeation flux*

Higher recombination at front surface

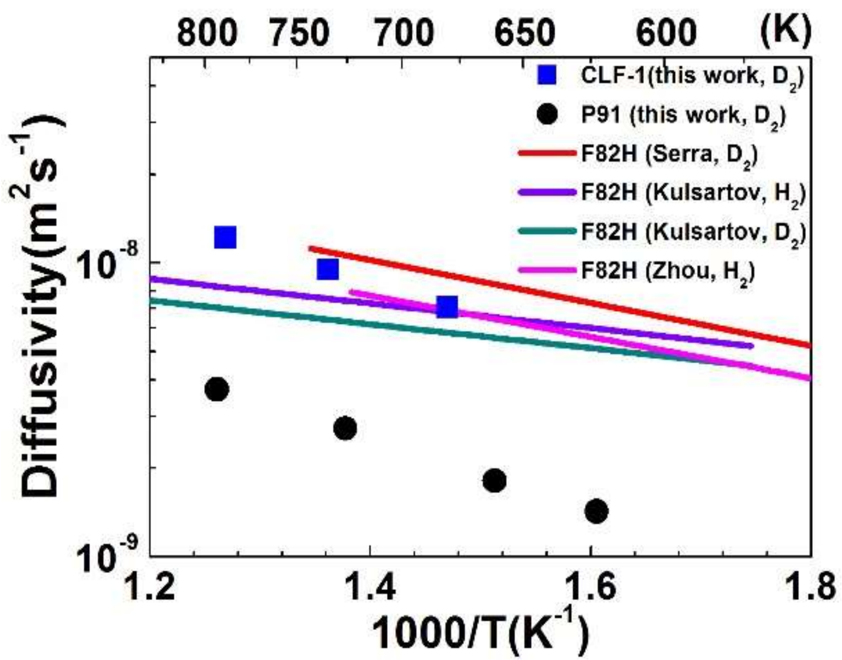
*H. Zhou et al., JNM 463 (2015) 1066

Permeability and diffusivity of CLF-1

Permeability (*P*)



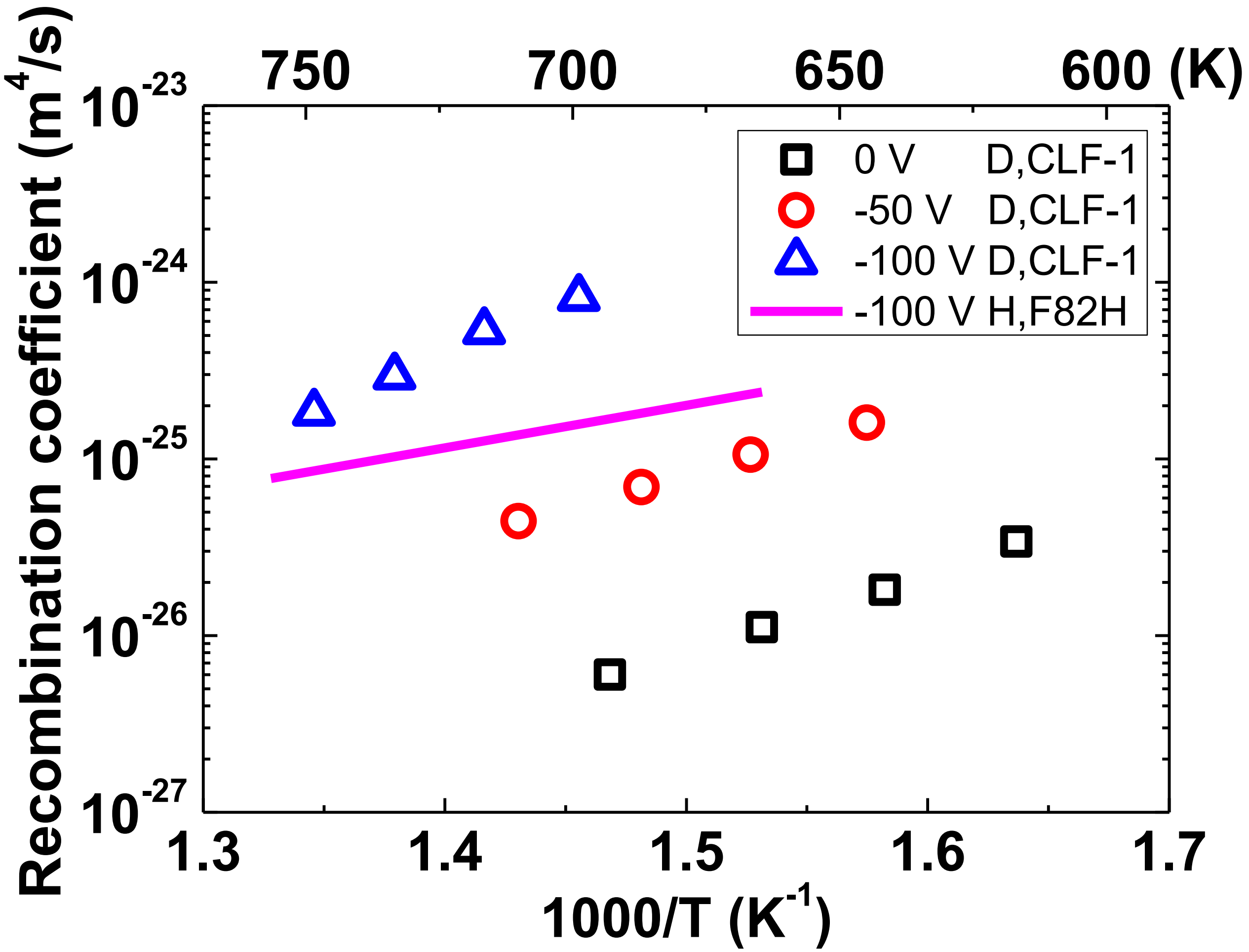
Diffusivity (*D*)



Both D permeability and diffusivity in CLF-1 are close to those of F82H.

Diffusivity + RD model $$J_p = \frac{D}{L}\sqrt{\frac{J_i}{K_{up}}}$$ ➡ K_{up}

Upstream recombination coefficients (Kr)

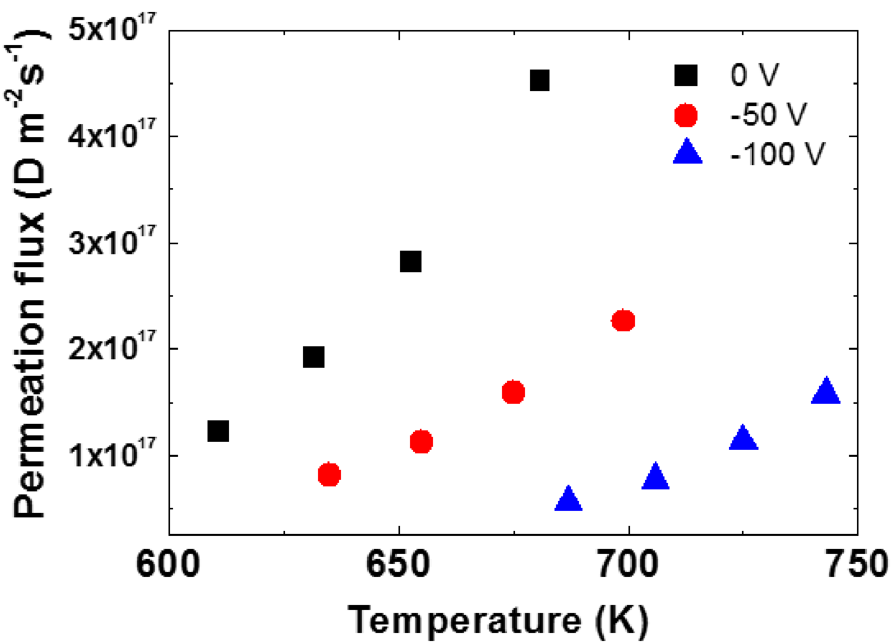


- **Assuming PDP takes place in RD regime, Kr are estimated from permeation model.**
- **D has higher Kr than H.** ⬅ **Larger mass, better cleaning effects?**

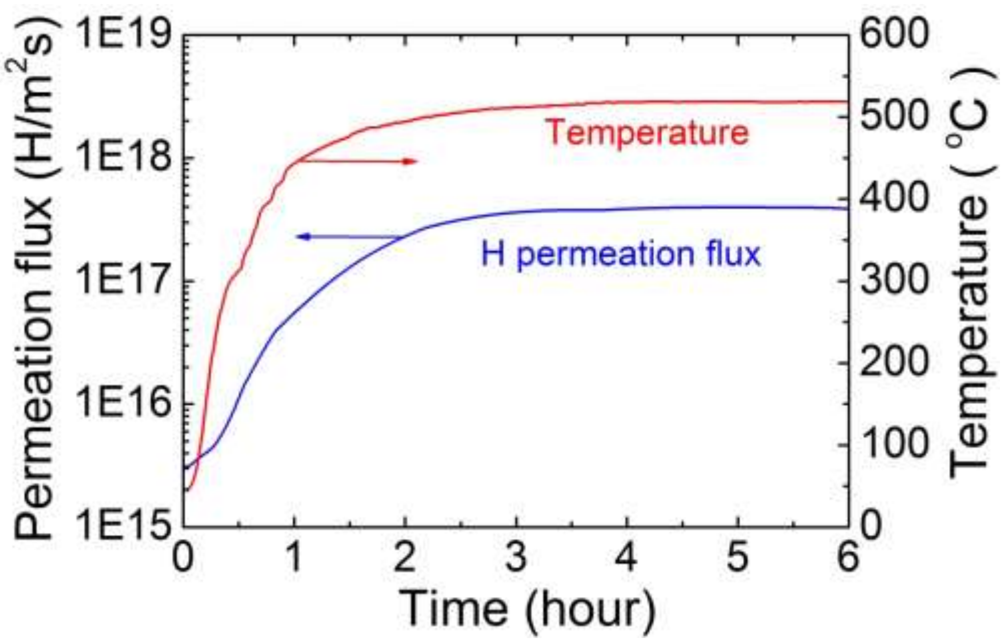
Evaluate T breeding ability of TBMs？

ITER fusion power: 500 MW   T TBR: 1.3   Surface area: 700 m^2
T produced in per m^2 blanket: 3.3×10^{17} T/s

0.75 mm CLF-1 (D data)



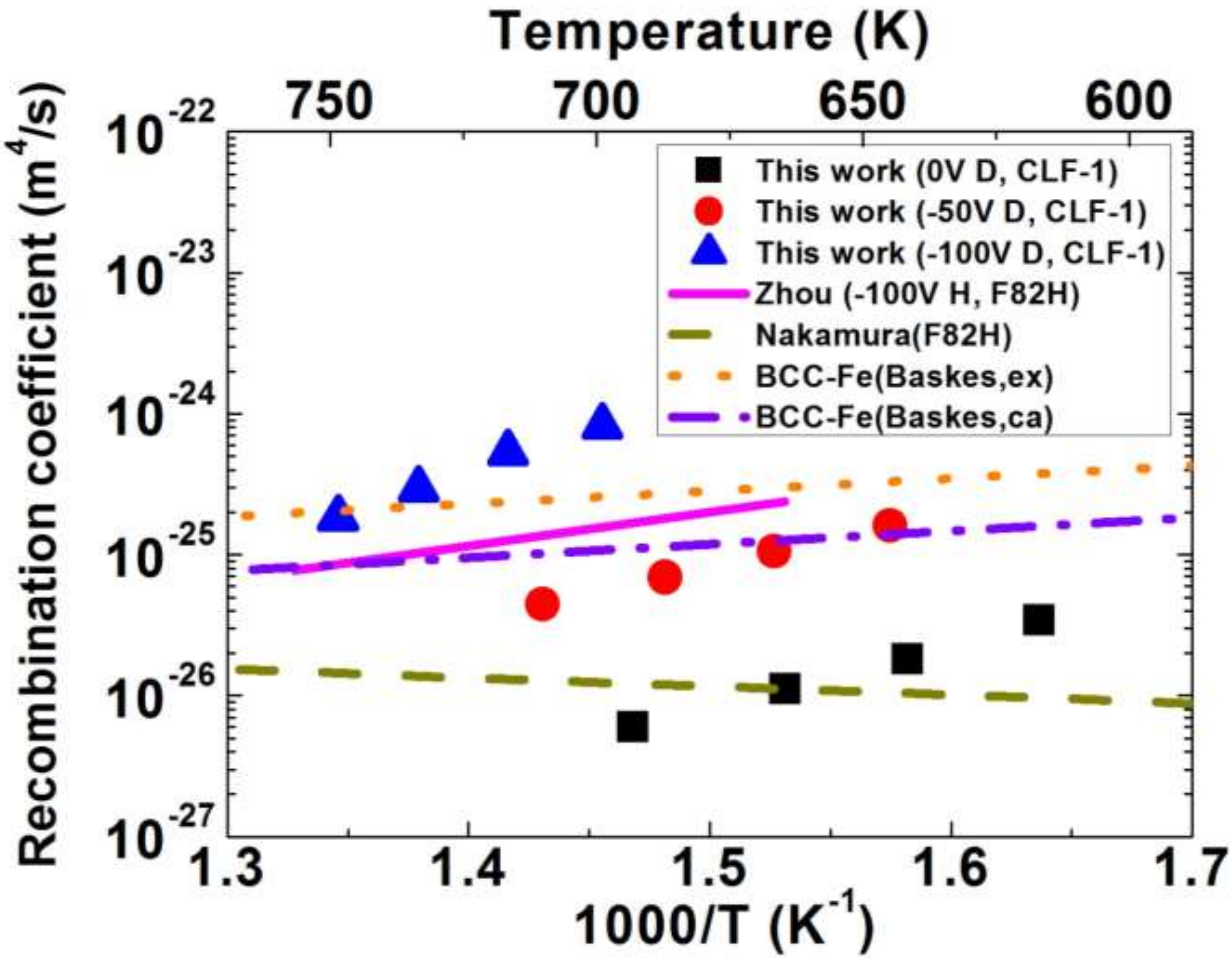
5 mm F82H (H data)



Y. Hirooka, H. Zhou et al., FST 64 (2013)345

Permeation flux may be comparable with the T breeding rate…

Evaluate T breeding ability of TBMs？



$$J_p = \frac{D}{L}\sqrt{\frac{J_i}{K_{up}}}$$

For RAFMs, the Kr estimated from existing model is so scattered.

Surface erosion of F82H by He-plasma exposure

Y.-P. Xu et al., Nucl. Fusion 57, 056038 (2017)

Facilities

STEP in Beihang University
(**S**imulator of **T**okamak **E**dge **P**lasma)

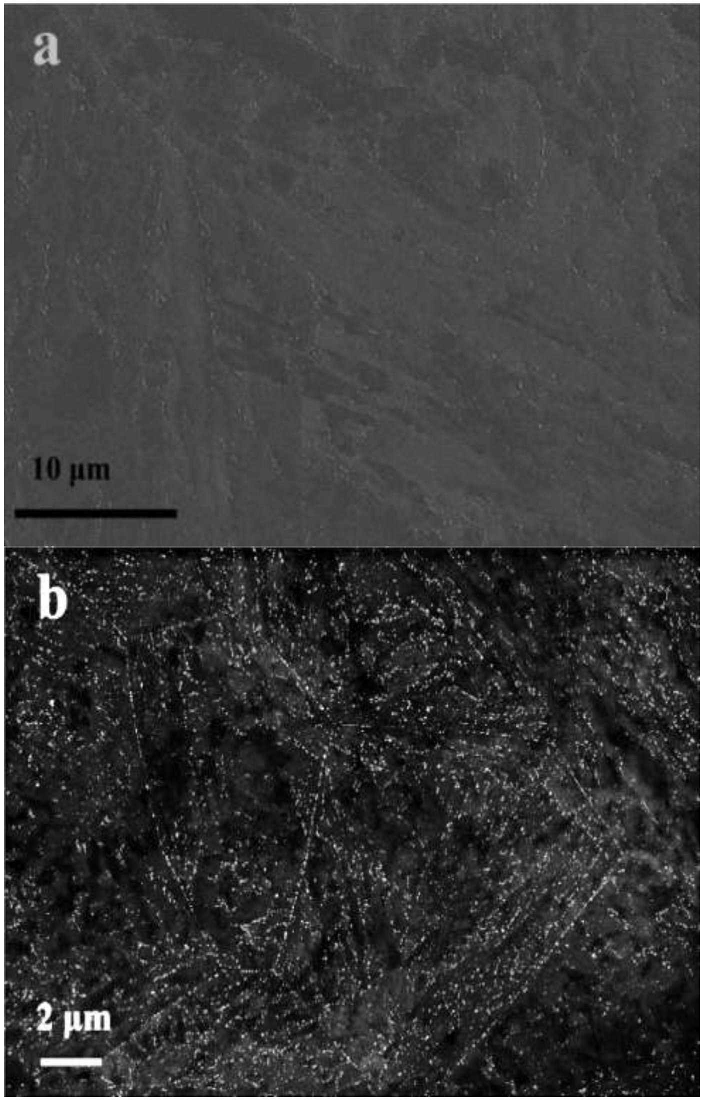
Exposure condition

Ions: He

Flux: ~1.8×10^{22} He/m^2/s;

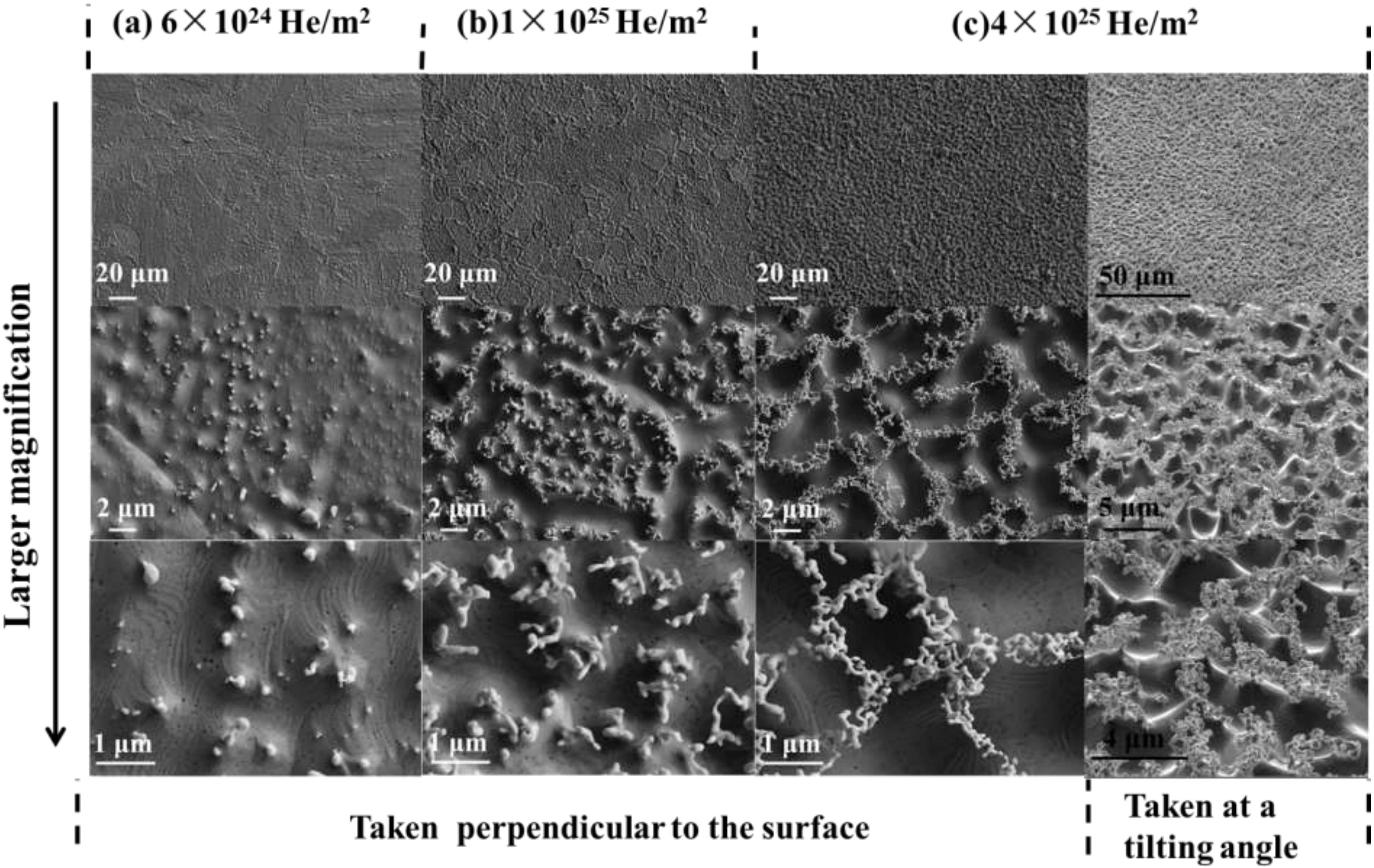
Ions energy: ~80eV;

Sample Temperature: 773 K–873 K;

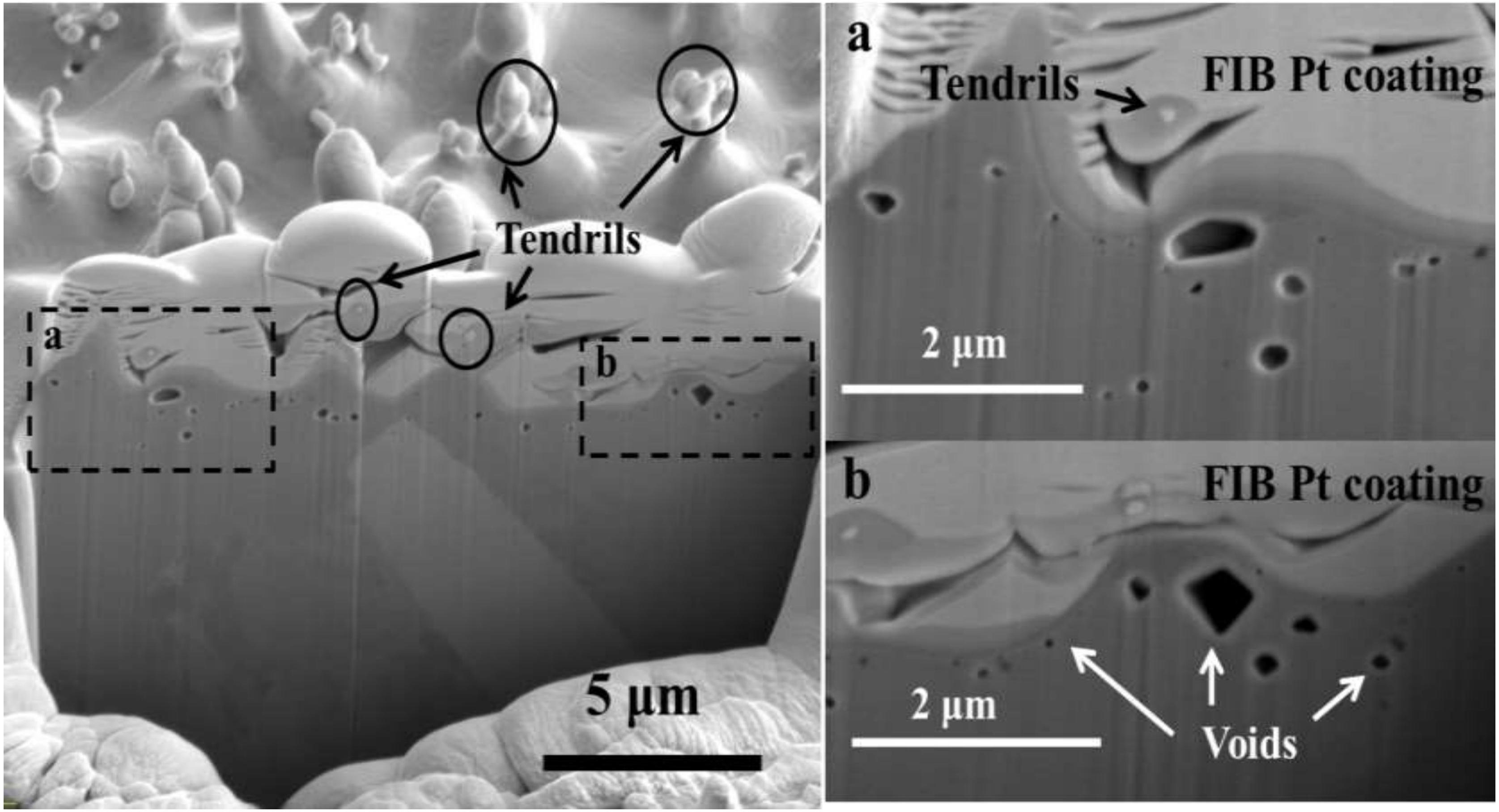


F82H before exposure

Surface morphology after plasma exposure



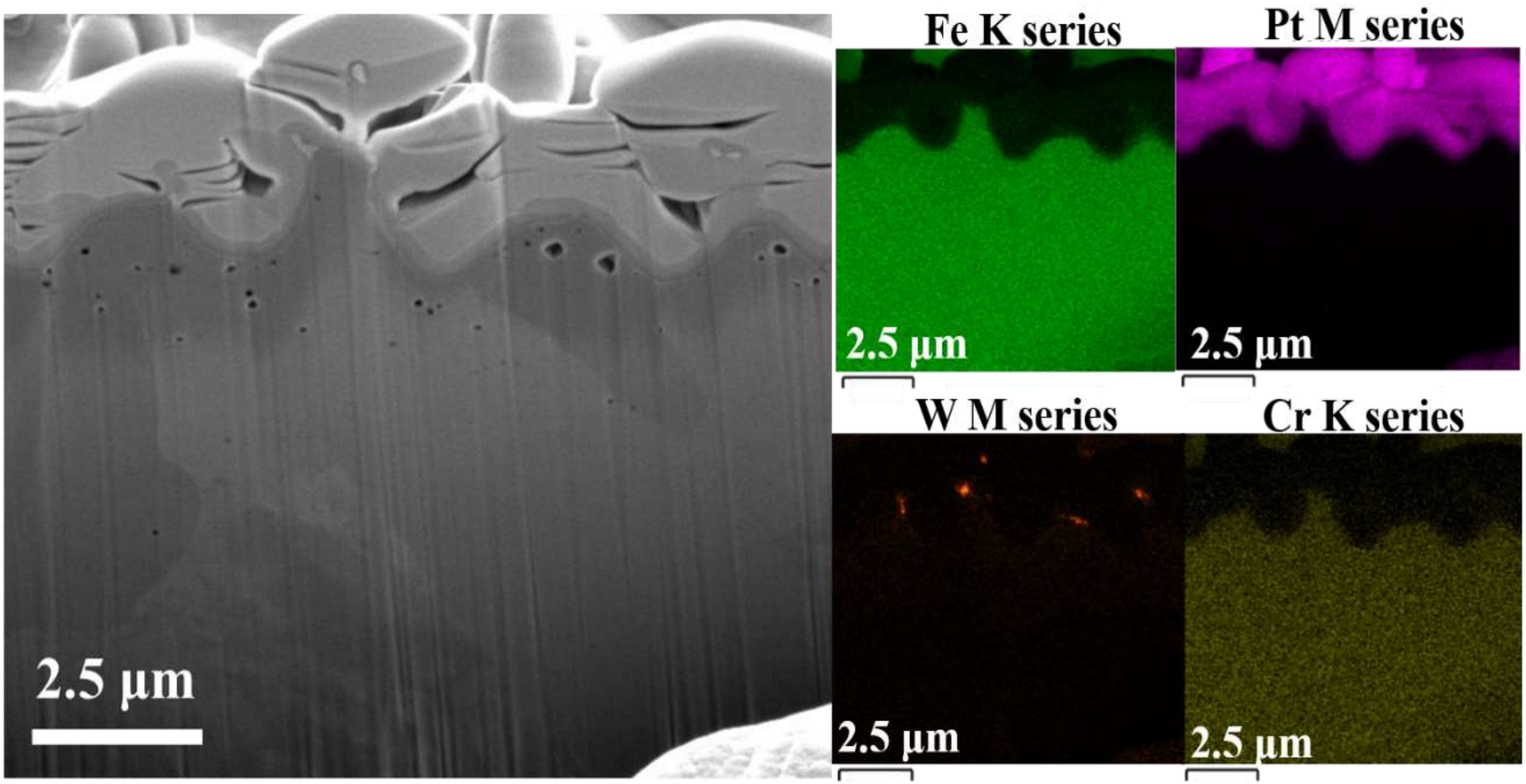
Cross-sections SEM images



1×10^{25} He/m^2 sample

Voids with different sizes and shapes can be found in the sample in a depth up to 3.5 µm.

Cross-sections EDS mapping

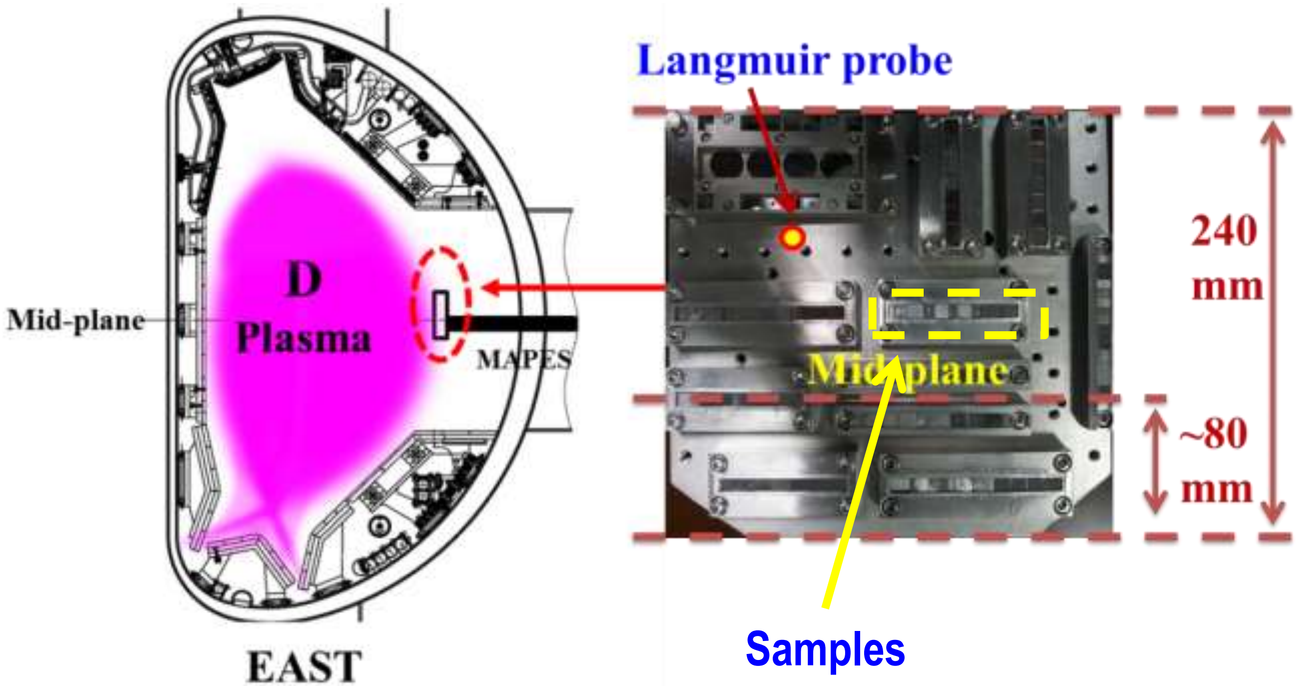


1×10^{25} He/m^2 zone

The tendrils are enriched in W. The enrichment of W can be explained by preferential sputtering between low-Z and high-Z materials with He particles.

EAST plasma exposure

EAST material and plasma evaluation system (MAPES)



Time: 2015 spring;

Shots： 56564-56994（367 shots）；

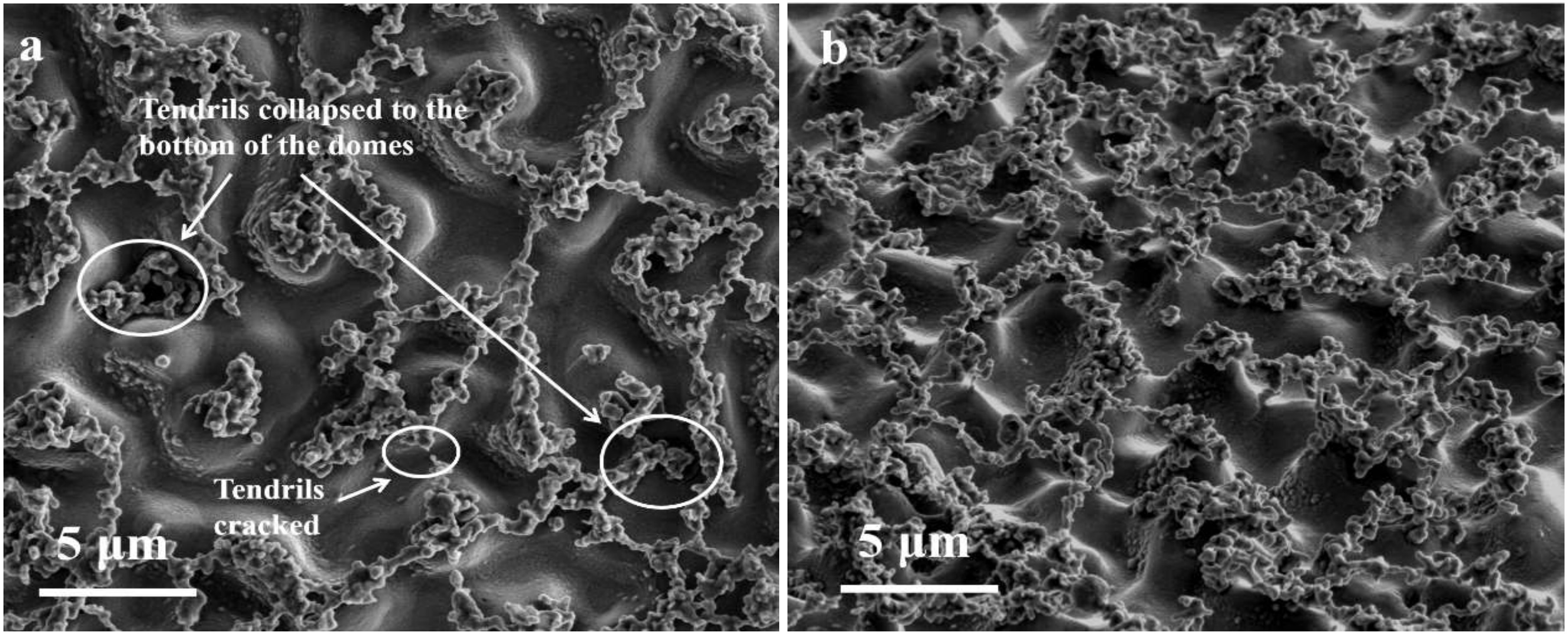
Exposure time： 2005.296s;

Plasma condition：

T_e=5-10 eV， n_e=~1×10^{18} m^{-3}；

Sample temperature： 323-623 K。

Sample after EAST plasma exposure



SEM images of the center of the sample after exposure to He plasma to a central fluence of 4×10^{25} He/m^2 and 367 D plasma pulses of varied durations in EAST

- **After exposure to D plasma in EAST, the tendril-like features with a maze-like pattern were cracked, part of tendrils collapsed to the bottom of the ridges while part of tendrils were missing.**

Outline

He effects on D retention

H.-S. Zhou et al., Nucl. Fusion 58, 056017 (2018)

He effects on H transport (1)

Our **previous permeation experiments** for RAFMs after energetic He ion irradiation:

Y.-P. Xu, H.-S. Zhou et al., NIMB, 2016.

RAFM steel

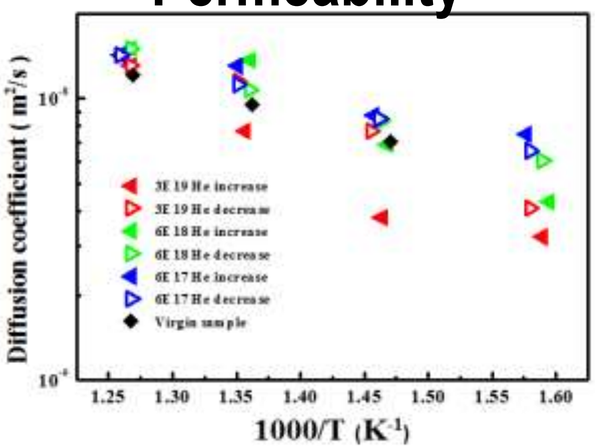
↓ 3.5 MeV He ion irradiation

D_2 gas-driven permeation

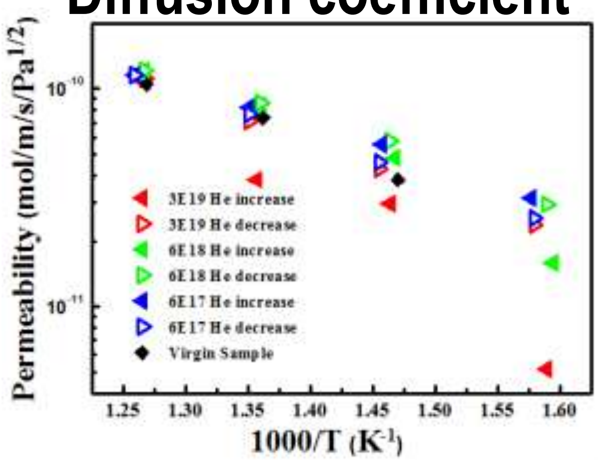
Sample No.	DPA Peak value
1	0.001
2	0.01
3	0.05

Experimental results：

Permeability



Diffusion coefficient



The permeability and diffusion coefficient of CLF-1 steel decreased after high dose He ion irradiation.

He effects on H transport (2)

Available literature data:

He pre-damage

Accelerator
Ion gun
Plasma
Energy range:
~ eV–0.8 MeV

→

H/D loading

Accelerator
Ion gun
Plasma
Energy range:
~ eV – 0.3 MeV

→

H/D retention measurement

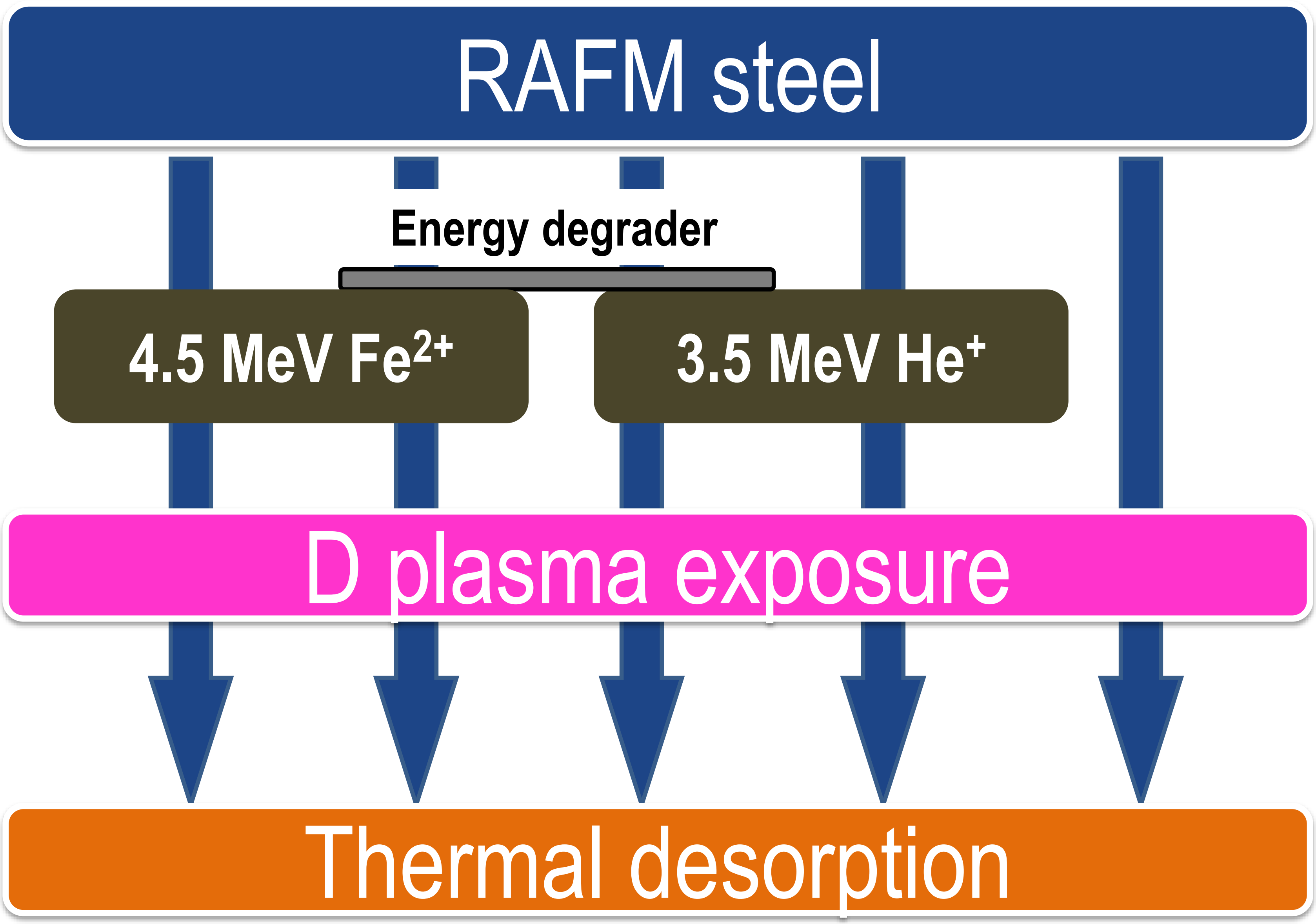
e.g. IBA
TDS

Increase?
Decrease?

Irradiation damage?
Surface condition?
He effects?

In this work, we try to investigate D retention behavior in RAFMs by separating the effects of surface conditions, bulk damage and He bubbles.

Experimental



High energy ion injection

Accelerators at Peking University

4.5 MV electrostatic accelerator

He^+ ion energy: 3.5 MeV
Sample temp.: R.T.

He implantation He/m^2	dpa peak value	He peak concentration He/m^3
6×10^{17}	0.001	1.88×10^{24}
3×10^{19}	0.05	9.373×10^{25}

2x1.7 MV tandem accelerator

Fe^{2+} ion energy: 4.5 MeV
Sample temp.: R.T.

Fe implantation $ions/m^2$	dpa peak value
8×10^{16}	0.013
4×10^{17}	0.066
4×10^{18}	0.66

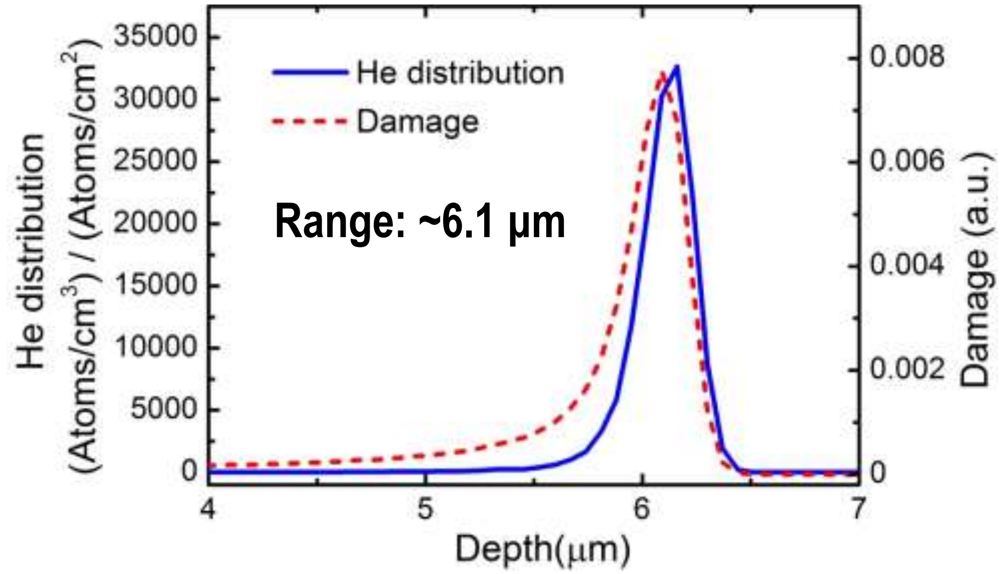
Material damages predicted by SRIM

Accelerators at Peking University

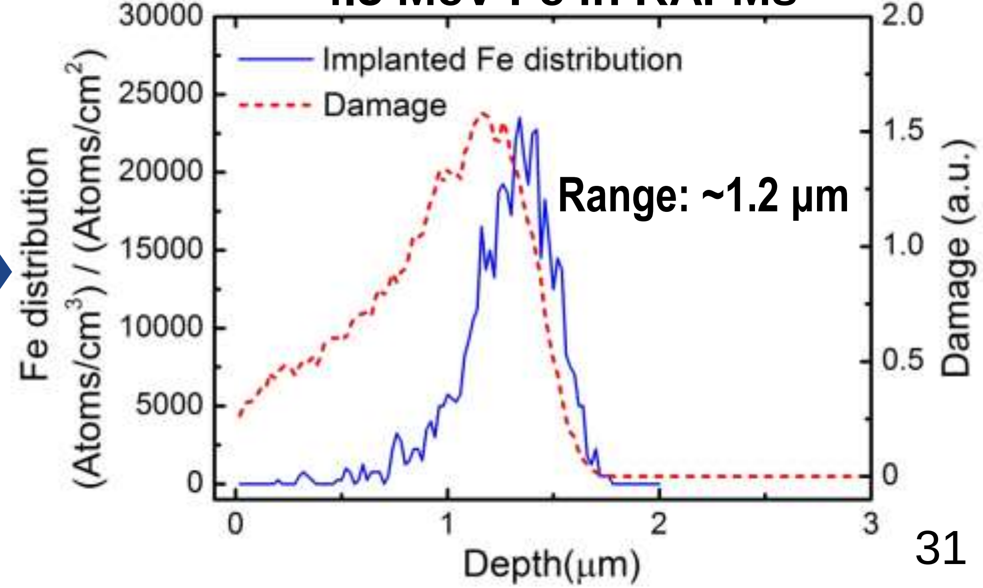
4.5 MV electrostatic accelerator

2x1.7 MV tandem accelerator

3.5 MeV He in RAFMs

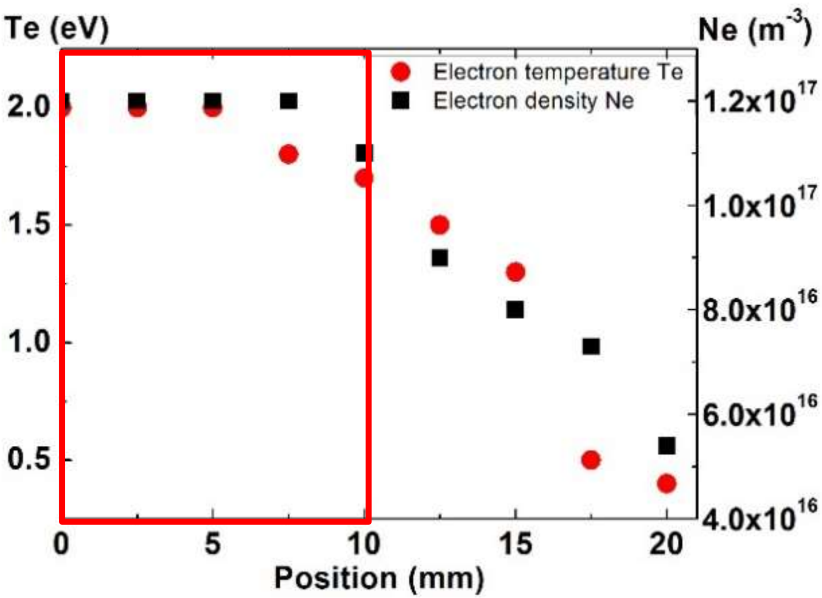


4.5 MeV Fe in RAFMs

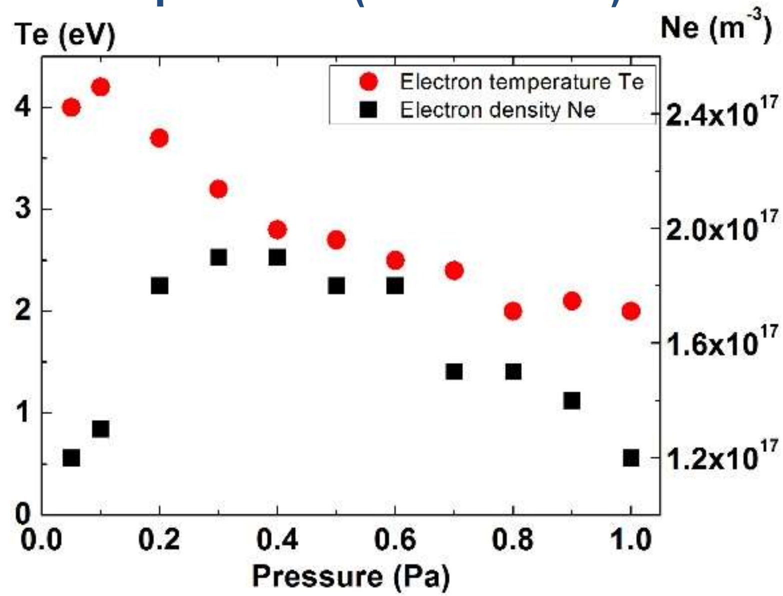


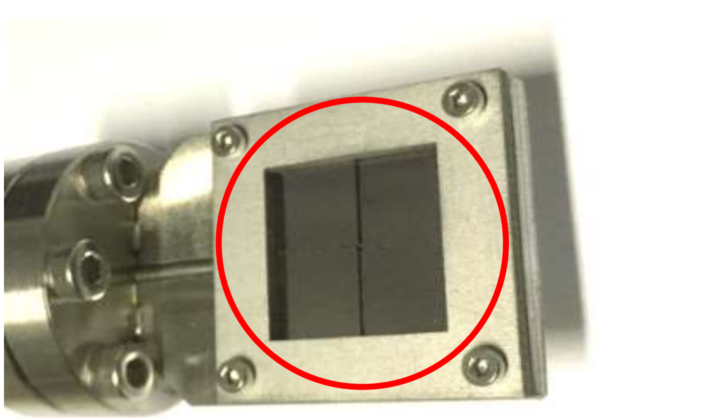
Plasma exposure in PREFACE

Te and ne profiles (~360W ECR)



Te and ne as a function of D_2 gas pressure (~360W ECR)





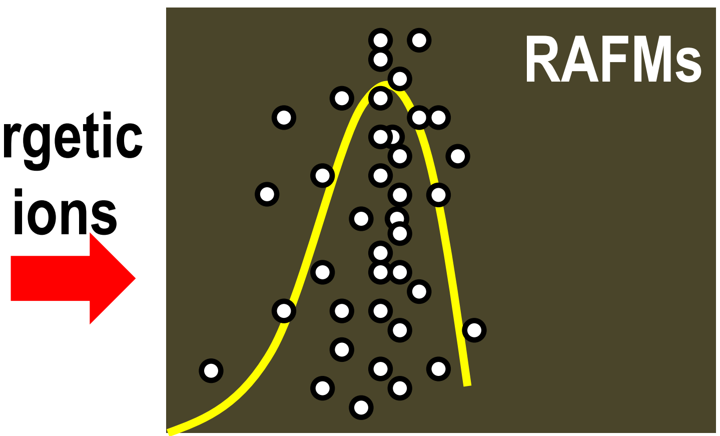
Plasma parameters in this work

- Te： ~2 eV
- ne： $(1\text{-}1.5)x10^{17}\ m^{-3}$
- Ion fluence: ~ $6x10^{23}$ D m^{-2}
- Sample temp.: 280 °C

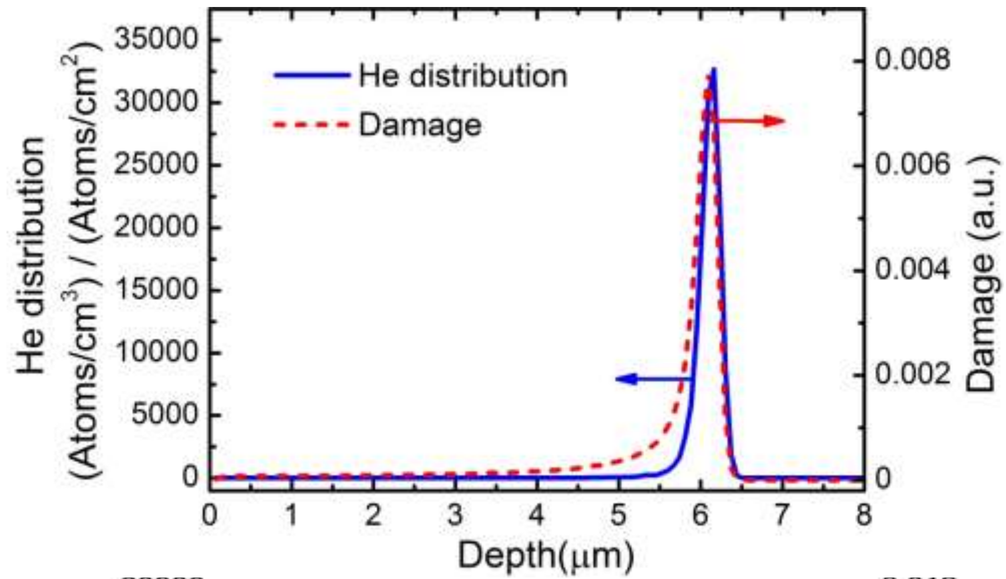
Surface damage by shifting dpa peak

“Bulk” damage

Energetic
He ions

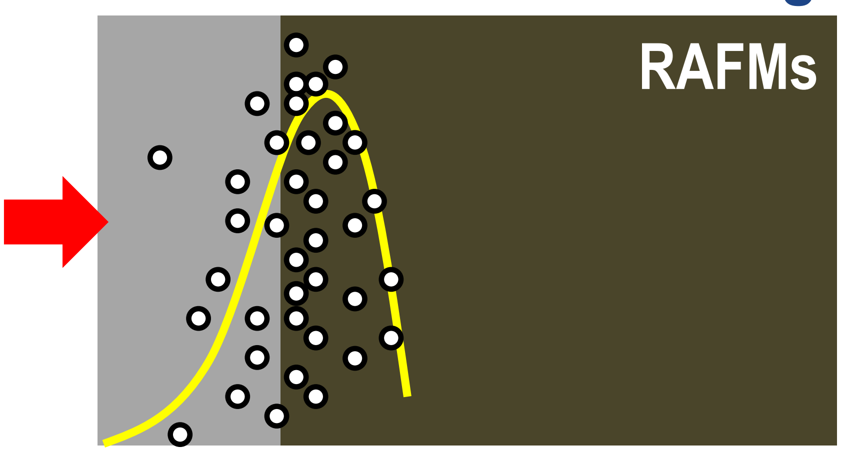


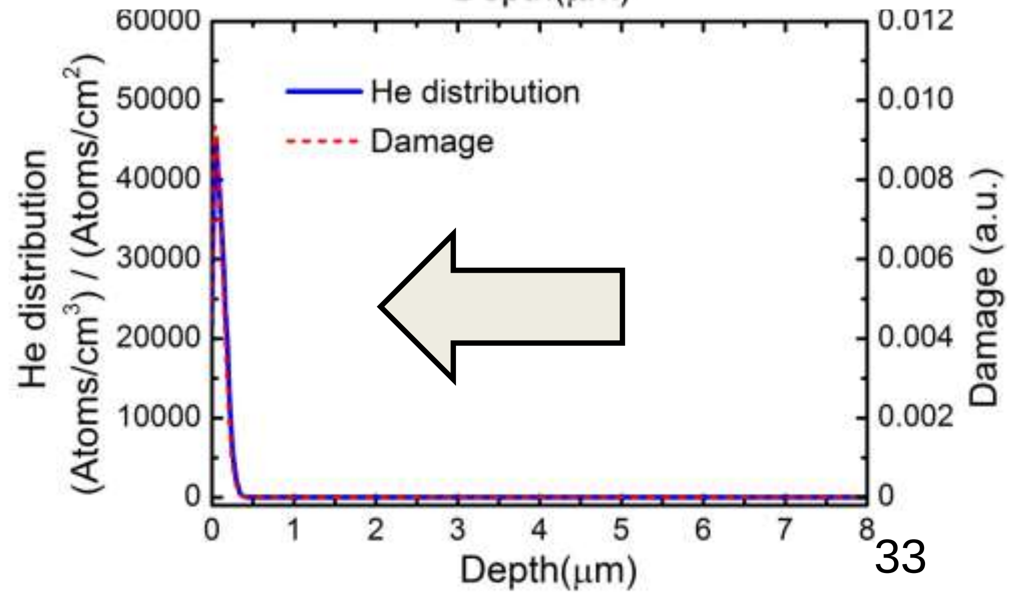
SRIM-2008: 3.5 MeV He in RAFMs



13 μm or 2 μm
Al foil

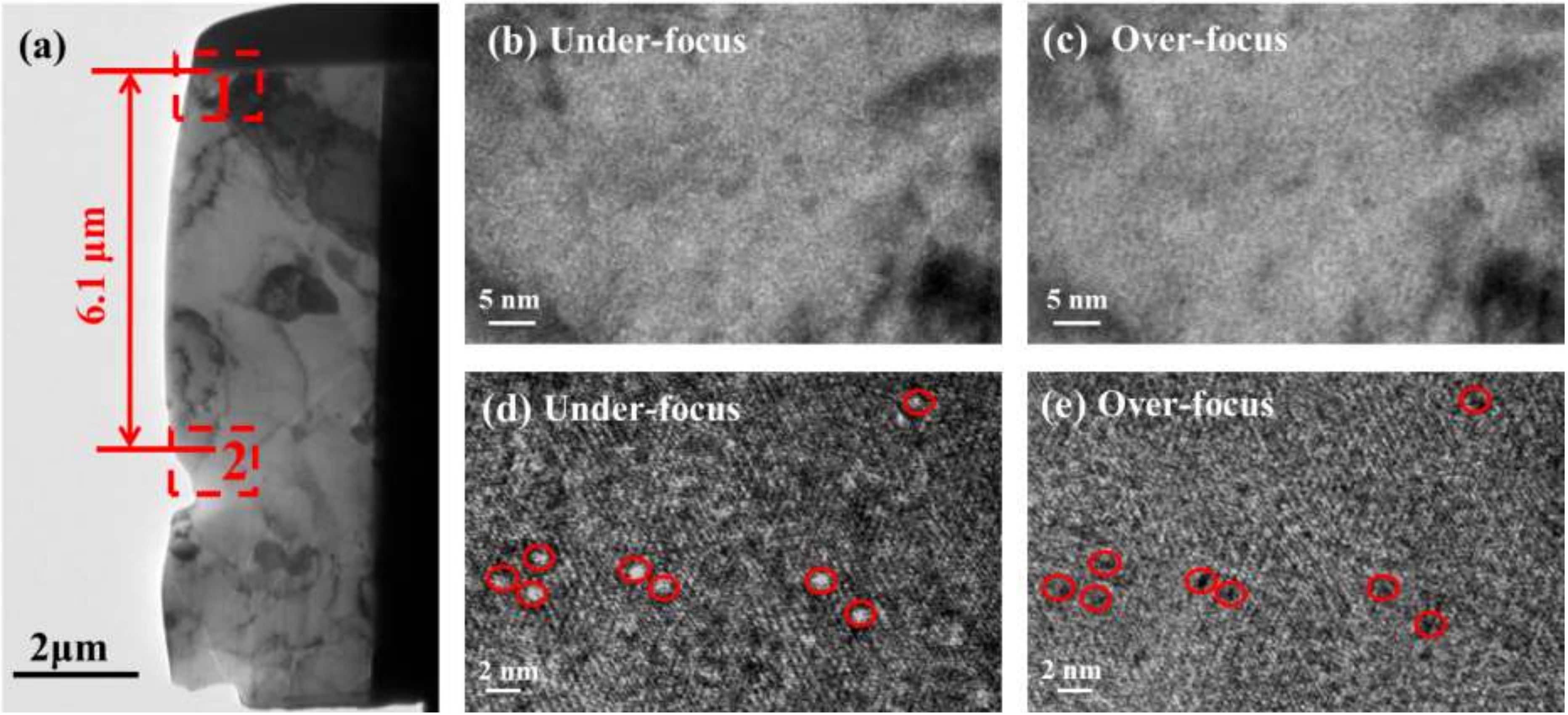
“Surface” damage





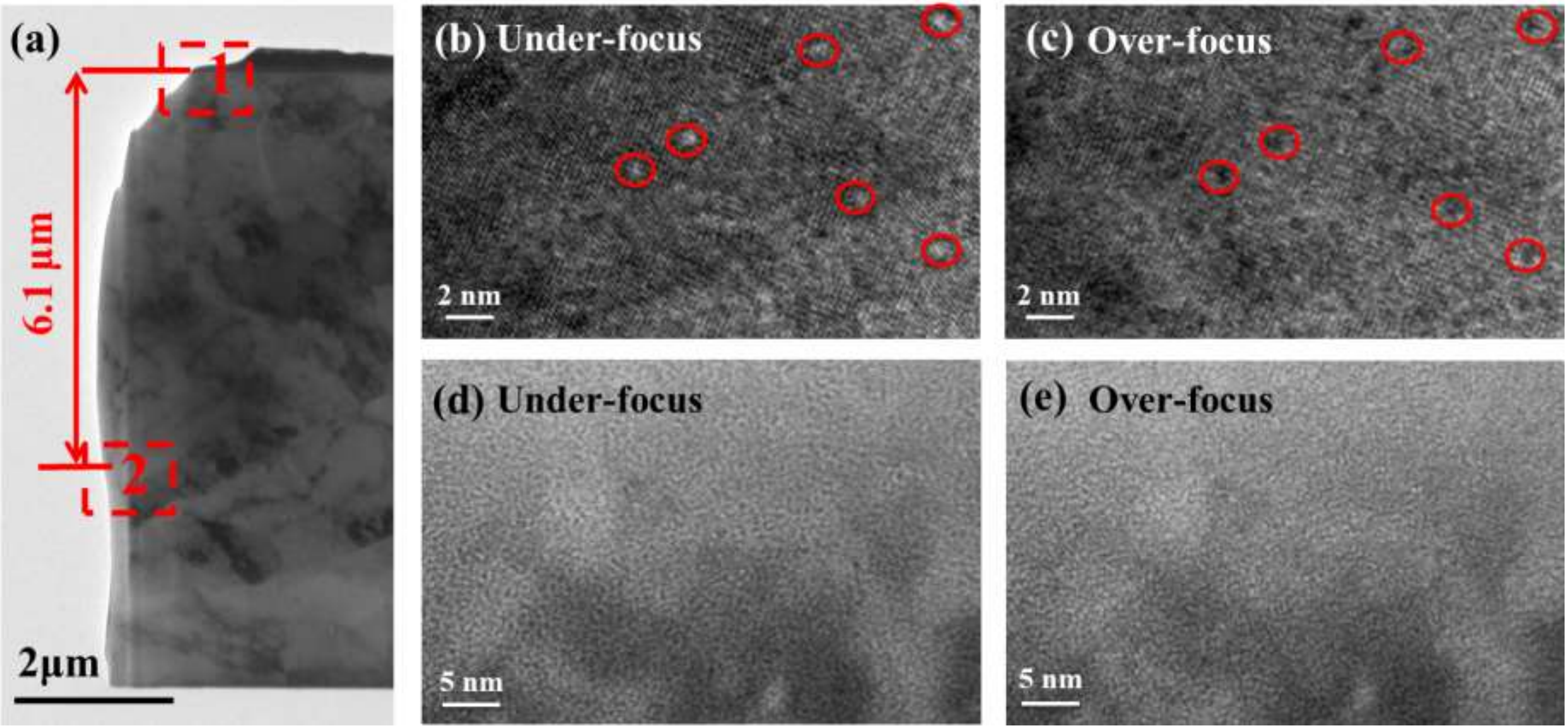
He bubbles in RAFMs

TEM after irradiation by 3.5 MeV He^+ (without Al foil)

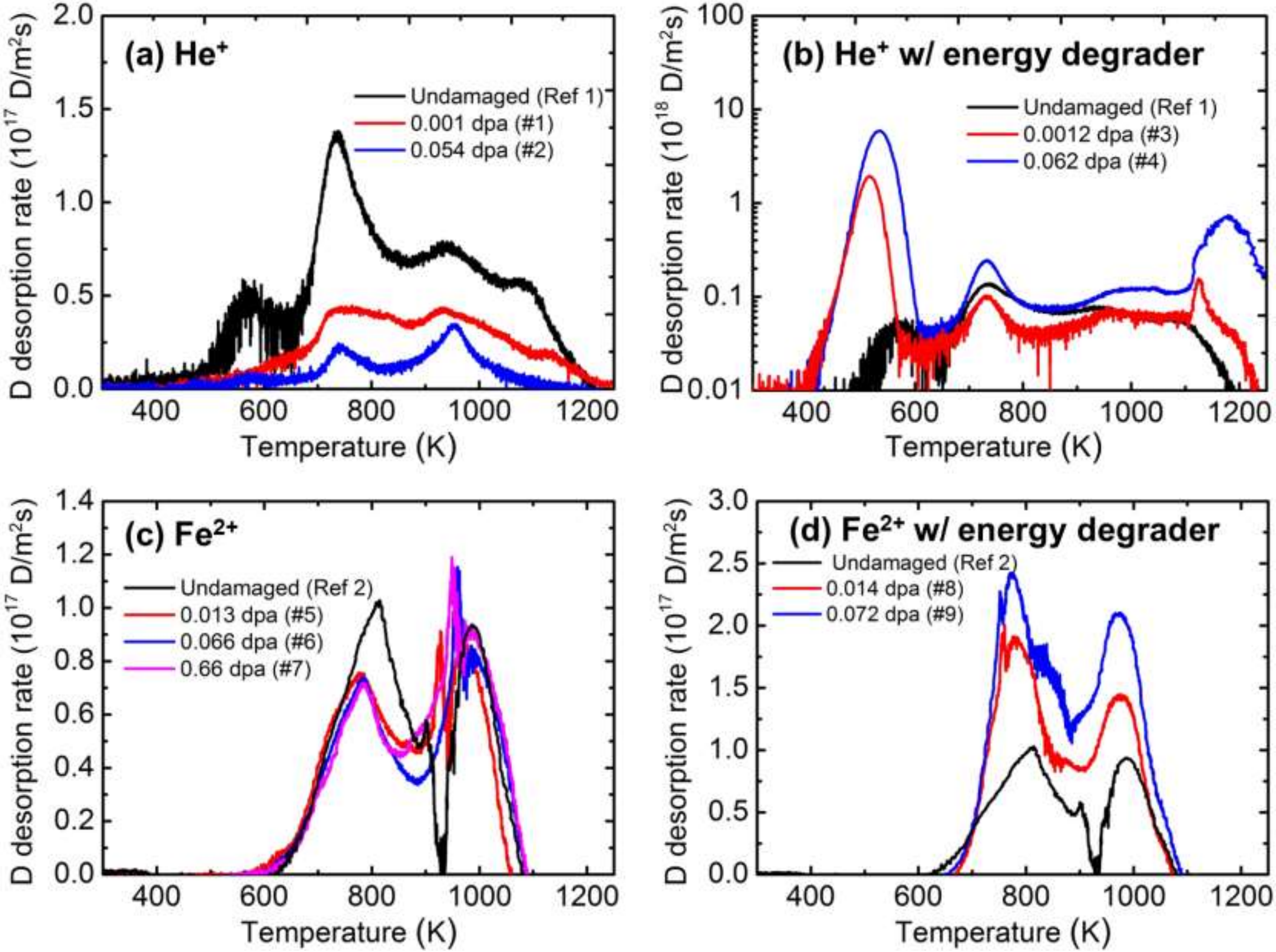


He bubbles in RAFMs

TEM after irradiation by 3.5 MeV He^+ (with Al foil)

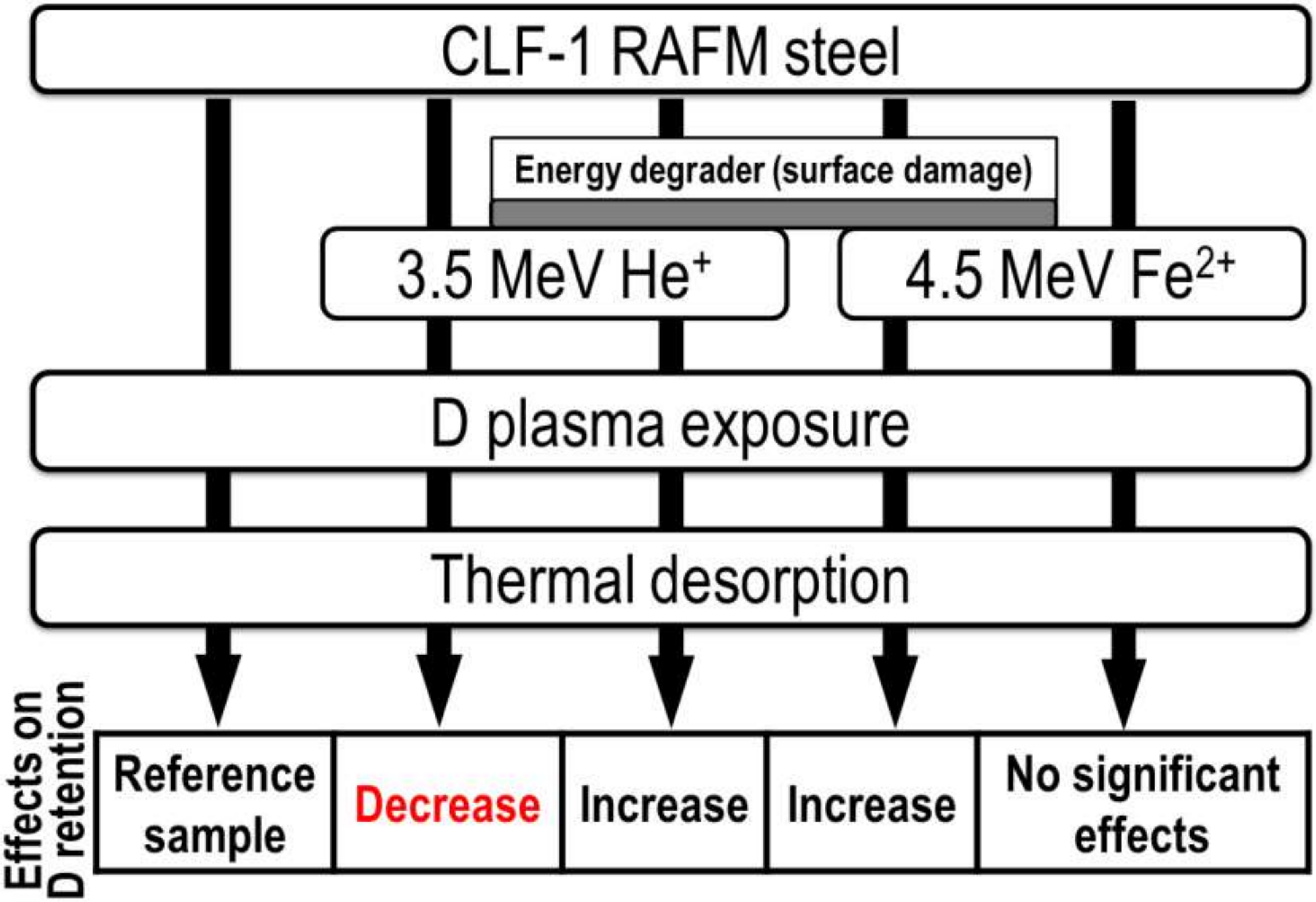


D retention



(a) He⁺
Undamaged (Ref 1)
0.001 dpa (#1)
0.054 dpa (#2)
D desorption rate (10¹⁷ D/m²s)
Temperature (K)
(b) He⁺ w/ energy degrader
Undamaged (Ref 1)
0.0012 dpa (#3)
0.062 dpa (#4)
D desorption rate (10¹⁸ D/m²s)
Temperature (K)
(c) Fe²⁺
Undamaged (Ref 2)
0.013 dpa (#5)
0.066 dpa (#6)
0.66 dpa (#7)
D desorption rate (10¹⁷ D/m²s)
Temperature (K)
(d) Fe²⁺ w/ energy degrader
Undamaged (Ref 2)
0.014 dpa (#8)
0.072 dpa (#9)
D desorption rate (10¹⁷ D/m²s)
Temperature (K)

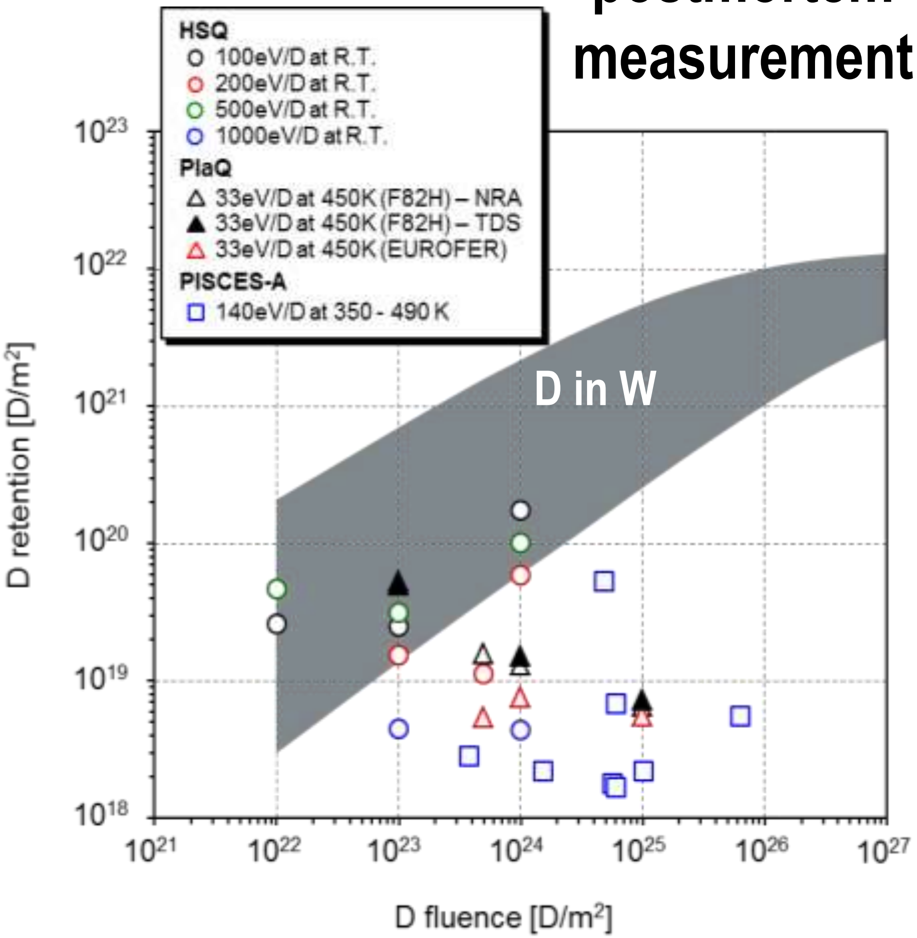
A short summary



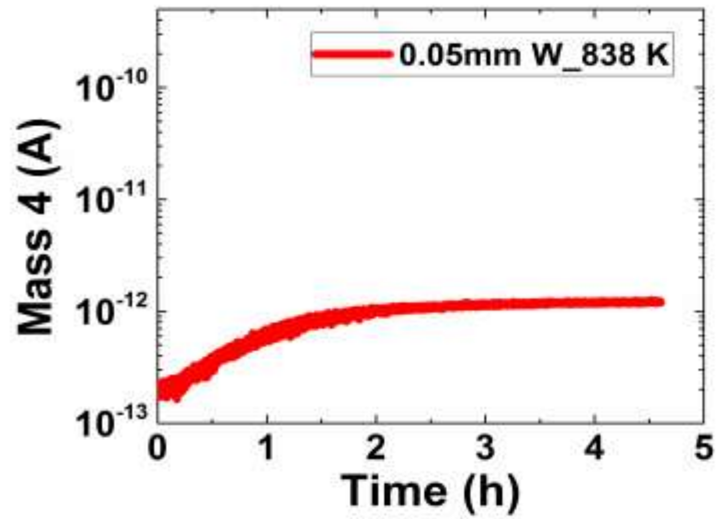
Knowledge from retention & permeation studies on RAFMs

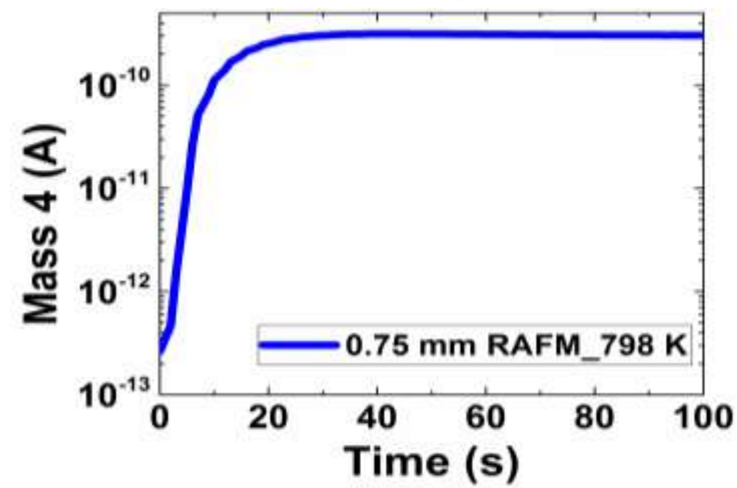
W. Jacob, IAEA steel CRP meeting

Retention from postmortem measurement



Permeation data

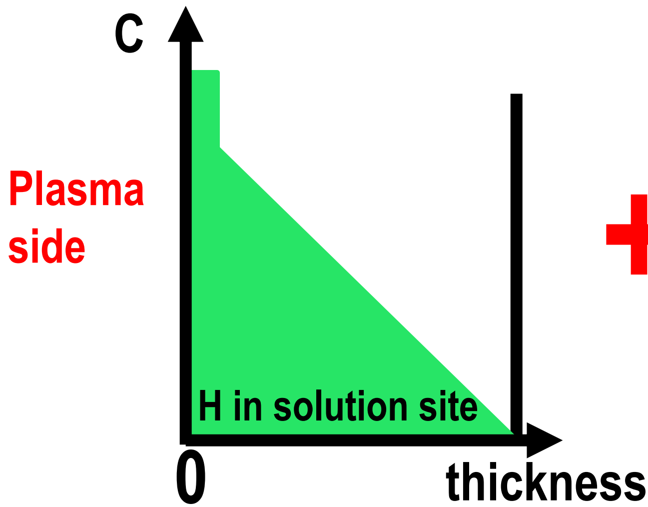


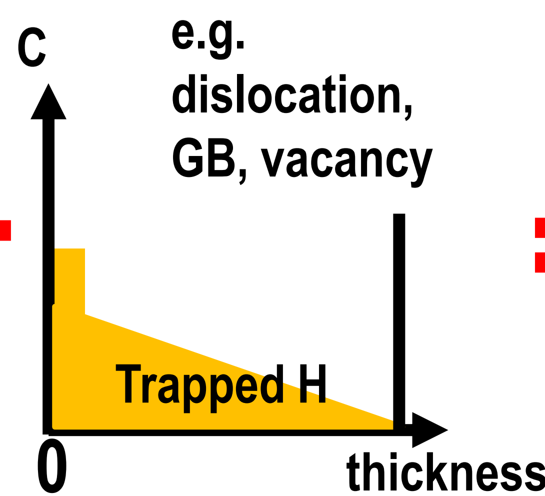


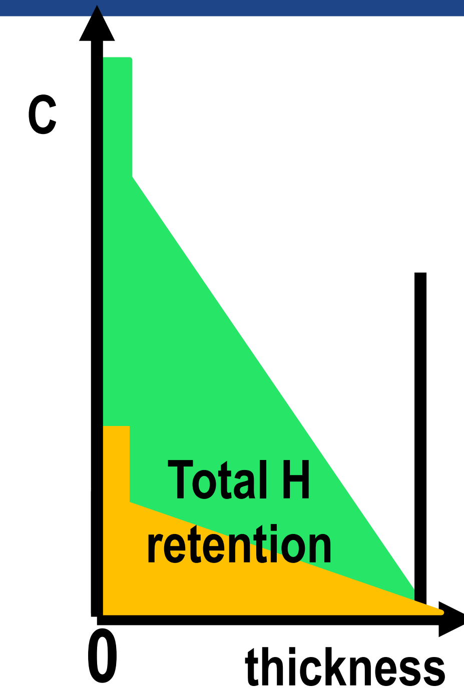
- **D retention does not increase after extended plasma exposure.**
- **D can perpetrate 1 mm thick RAFMs within tens of seconds.**

D retention in RAFMs: retention saturation?

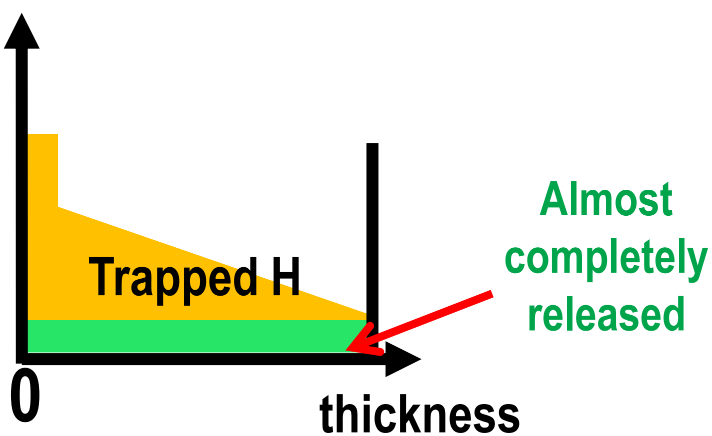
When plasma is on:

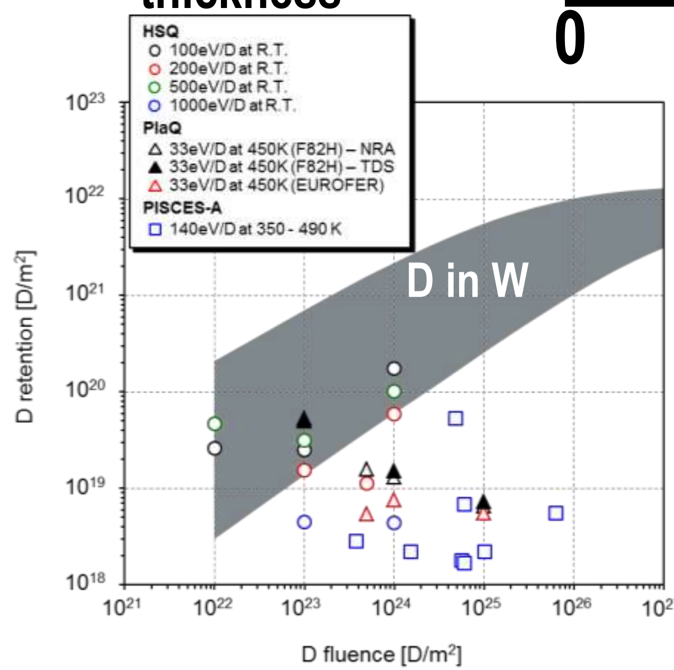






When the plasma is off:

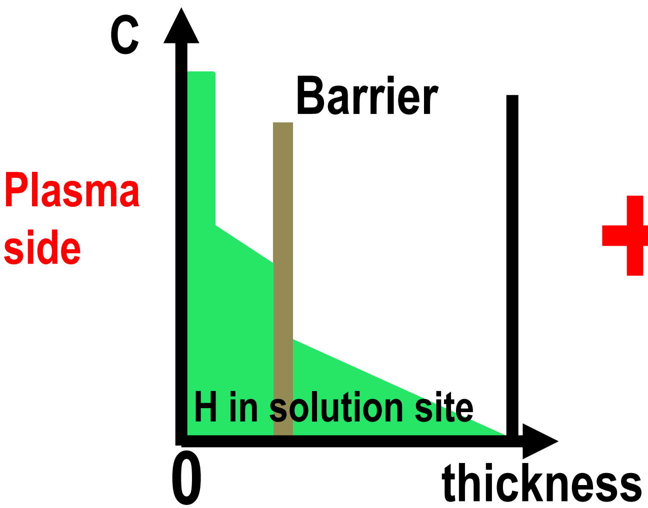




No new traps, no more retention.

Speculation: in the presence of a barrier

When plasma is on:



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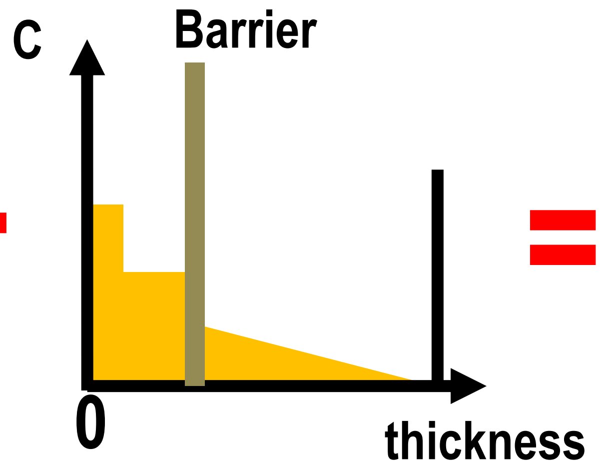

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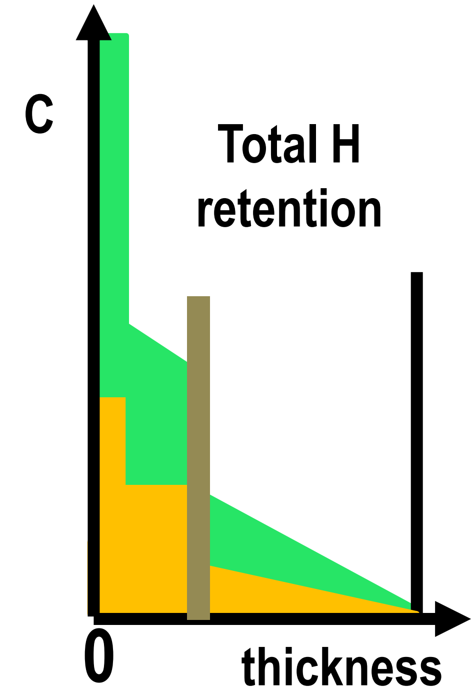
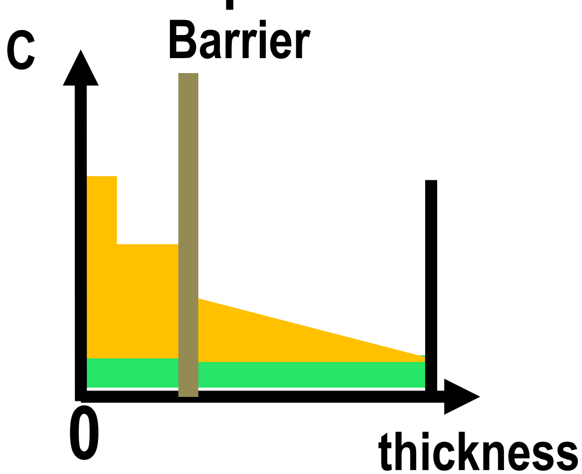
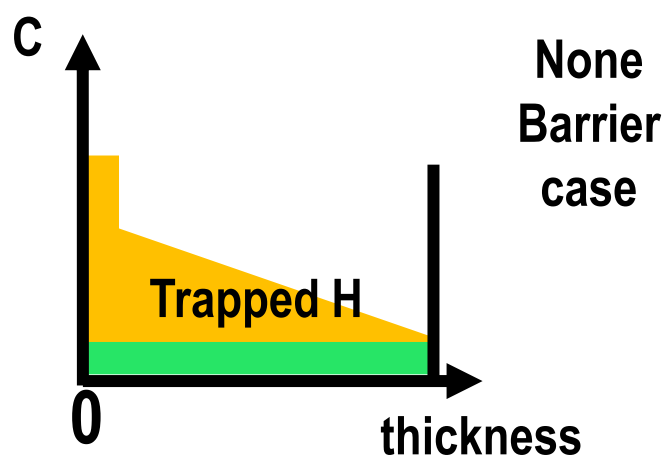


When the plasma is off:



VS.



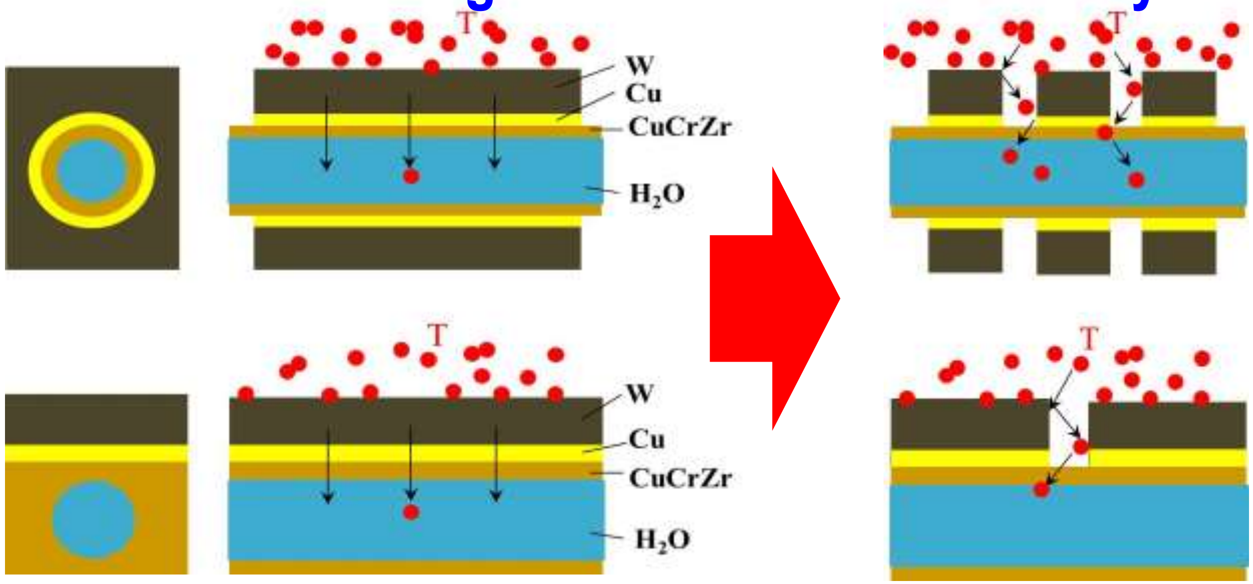
D PDP through PFC mockup made by RAFM

H.S. Zhou et al., Nucl. Fusion 59 (2019) 014003

Motivation

- Gap effects have been widely studied in erosion/deposition studies.
- How about permeation through the gap?

Intuitive image | **Reality**



Neutrals from
(i) plasma and
(ii) flection on wall
will impinge on the heat sink.

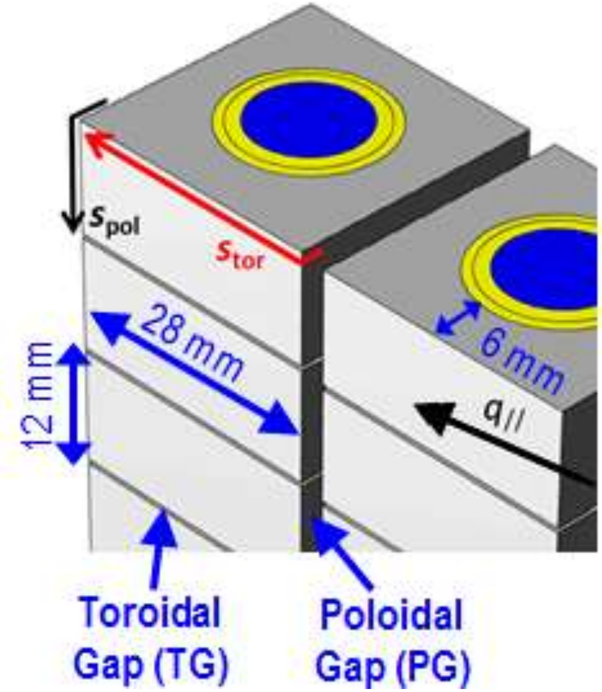
Permeation speed?

Permeation flux?

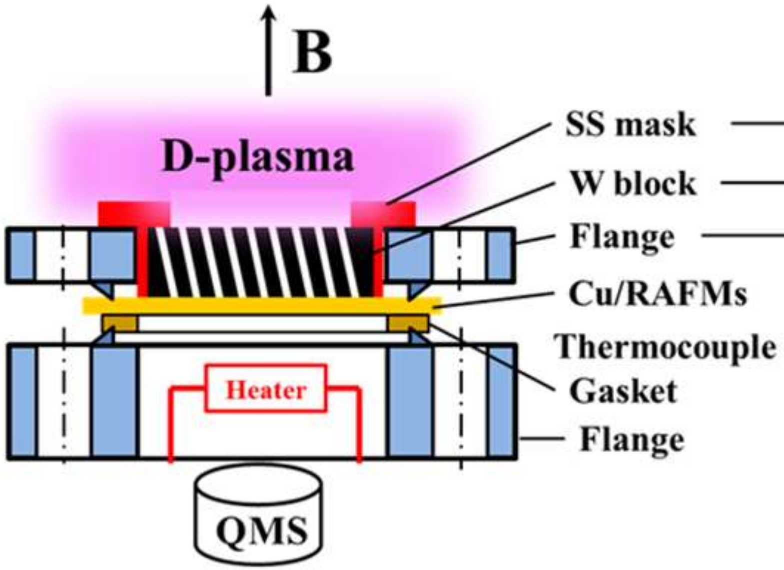
Large surface area ⟷ Small area fraction for gaps

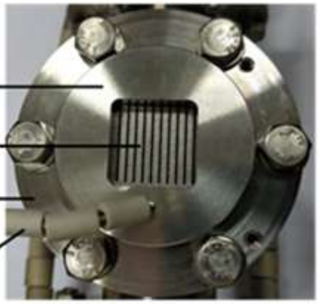
Thick W armor ⟷ Thin structural material

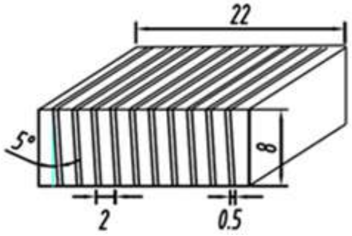
PFC mock-up



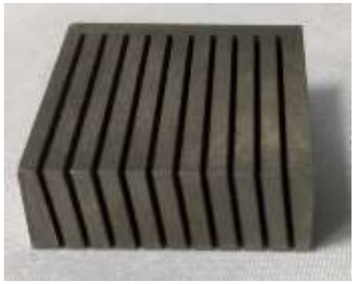
(after R. A. Pitts)







- Electron density: ~5×10^{15} m^{-3}
- Electron temperature: ~5 eV
- Implantation flux: ~5×10^{19} D $m^{-2}s^{-1}$



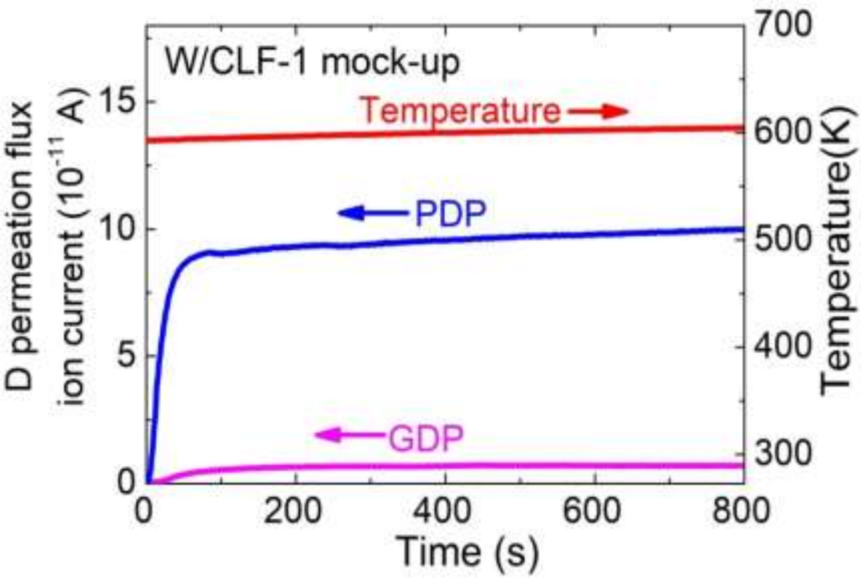
Key points of the mock-up:

– W bulk: 8 mm the thickness;
– Gaps: 0.5 mm wide, made by electrospark wire cutting;
– Angle between the gaps and magnetic field lines: 5°

H permeation through gaps is fast

- 0.06 Pa D_2 gas for plasma discharge. No gas-driven permeation can be detected.
- Significantly enhanced D permeation has been recorded when D plasma is on.
- We confirm:
  D can transport through the mock-up without passing through W because the 8 mm thick W cannot be penetrated by H diffusion.

0.69 mm thick CLF-1 membrane

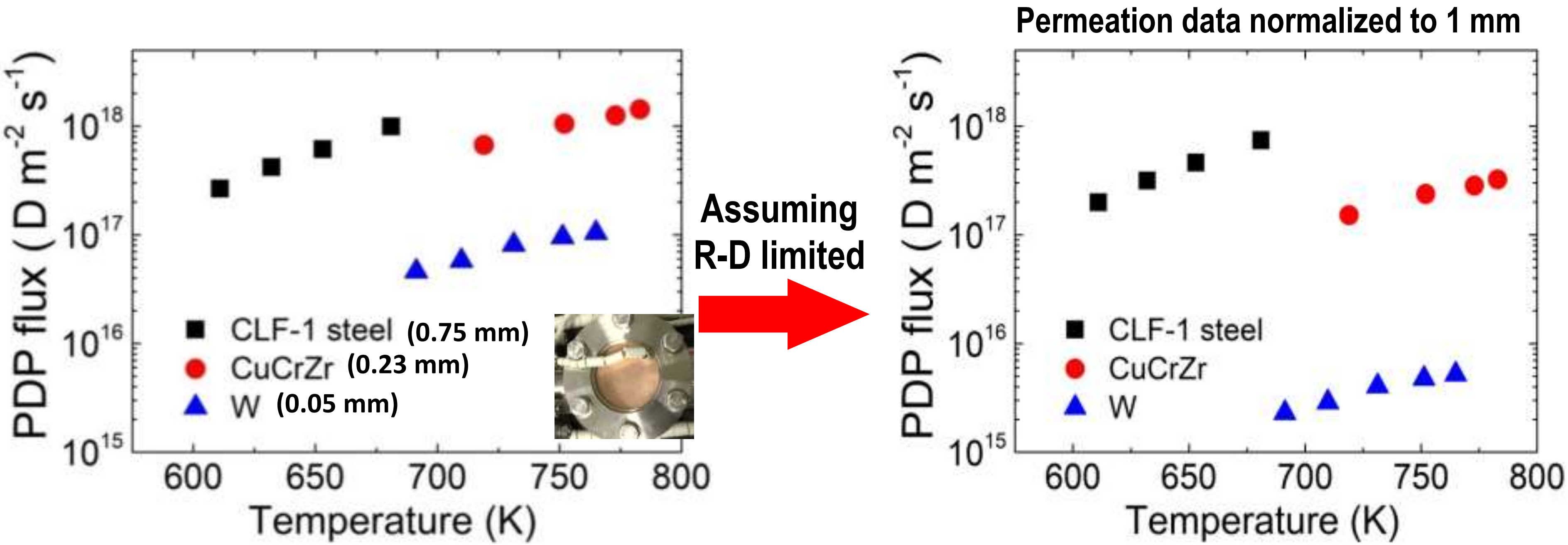


Materials	Temperature	Thickness l	Diffusivity D	Diffusion time l^2/D
	K	m	m^2s^{-1}	s
CLF-1	600	6.9×10^{-4}	4.4×10^{-9}	108
W	600	8.0×10^{-3}	2.2×10^{-10} [2]	2.9×10^{5}

[1] Xu Y.P.et al., NIMB 388(2016) 5

[2] R. Frauenfelder et al., JVST 6 (1969) 388

Comparison of PDP for W and structural materials



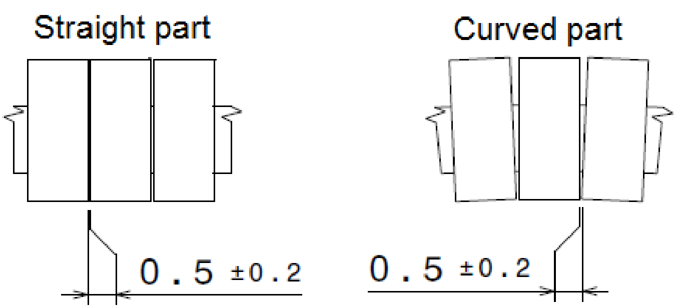
- The permeation data are normalized to the same membrane thickness, assuming the permeation is recombination-diffusion limited (B. Doyle, JNM 111&112 (1982) 628). $J_{+} = \frac{D}{l}\sqrt{\frac{J_0}{K_r}}$
- Steady-state permeation flux through CuCrZr is about one order of magnitude higher than that through W under the same incident flux and membrane thickness.

Comparison of PDP for W and structural materials

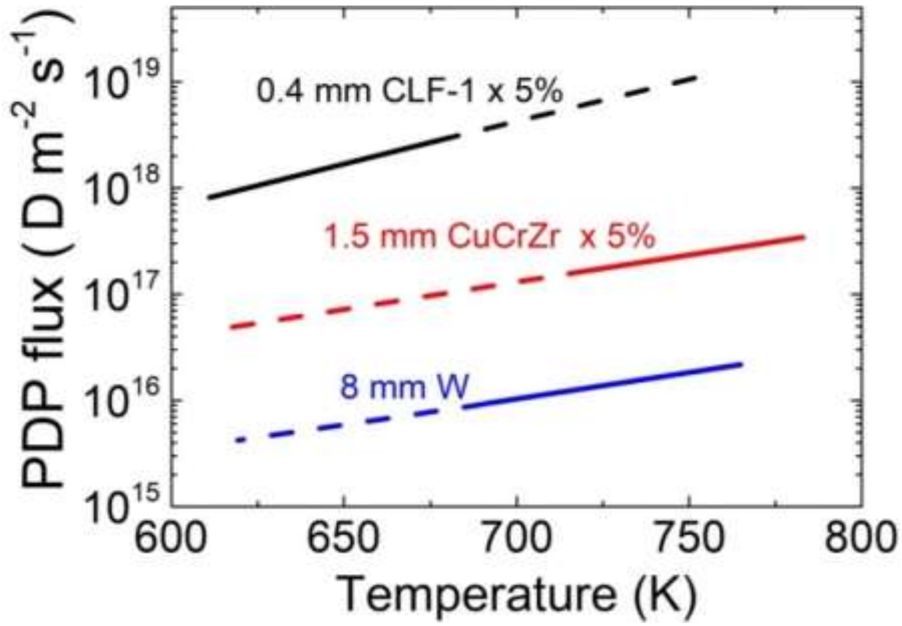
ITER divertor case:

Assuming:

- 5% surface area fraction;
- Incident flux 1×10^{24} $Dm^{-2}s^{-1}$



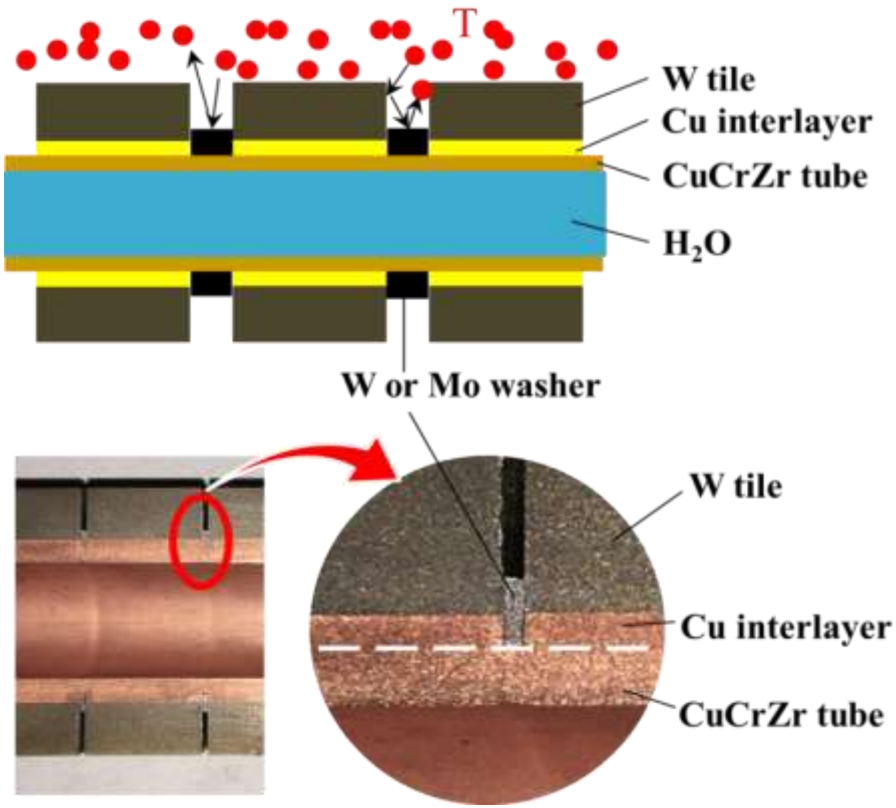
$$J_{+} = \frac{D}{l}\sqrt{\frac{J_0}{K_r}}$$

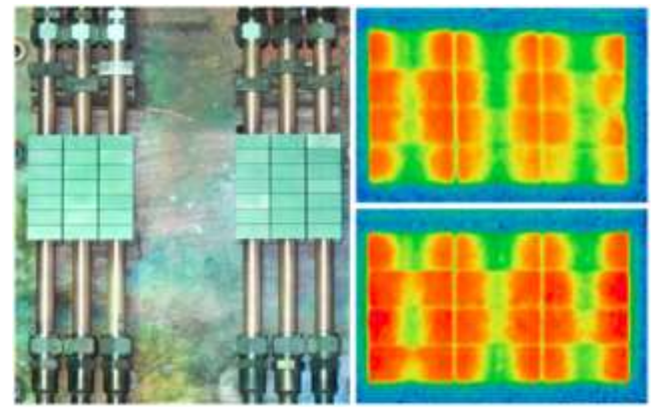


- **After taking into account the surface area coverage (5%), steady state D PDP flux through CuZrCr is still one order of magnitude higher than that through W.**

The first wall should have the same problem.

One feasible solution to the problem (EAST way)





IDTF test organized by ITER IO

Z.-X. Sun et al., FED 121 (2017) 60

5000 cycles@10MW/m^2 + 300 cycles@20MW/m^2

The washer did not show any adverse effects on the performance in HHF test .

Summary

- H permeation and retention in RAFM steel under plasma exposure conditions have been intensively investigated at ASIPP.
- H transport parameters (including Kr) in RAFM have been evaluated by experiments.
- He has significant effects on surface morphology and H behavior.
- Structural materials may be a “short cut” of T permeation for existing PFC design of DEMO. PWI on RAFM steel should be investigated in a systematic manner even if they are not directly exposed to plasma.
- Our recent interests: surface condition effects, permeation barrier…

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Thank you for your attention!