2003 US-Japan Workshop on
High Heat Flux Components and Plasma Surface Interactions for Next
Fusion Devices & High Power Density Devices and Designs
Manresa Hotel, Port Townsend, Washington, USA, July 28-31, 2003 7th inter.

PMI studies in JT-60U

- Hydrogen retention and erosion/deposition of carbon & Effort of tritium removal

Joint research work between JAERI and Japanese university group

Presented by

T. Tanabe Nagoya University

Workshop Agenda

JAERI

Cooperation with

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1. Introduction (PMI Issues)
2. Postmortem analysis of PFM tiles
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   2-2. Retention of Hydrogen/Deuterium
   2-3.Tritium distributions on PFM
3. Tritium removal by discharge technique
4. In vessel PMI studies
5. Future plan

1. Introduction - PMI issues

Erosion an deposition

Impurity transport and accumulation

Hydrogen recycling in long time discharge

Tritium retention in redeposits and dust/debris

Removal of tritium

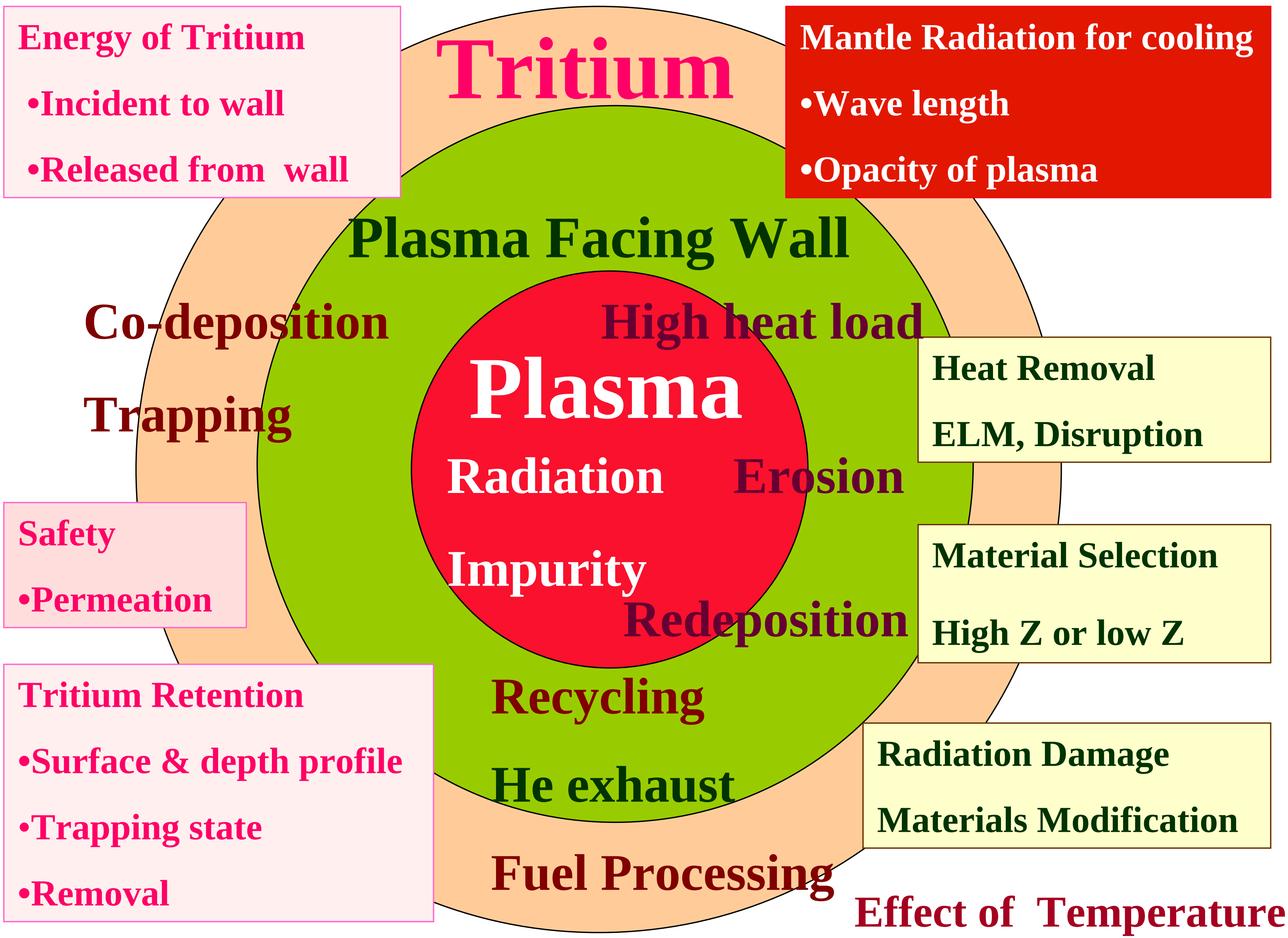
Selection of PFM (Be, C, V, W, Ferritic steel, Liquid metal)

Response to high heat load (Type I ELM and Disruption)

Behavior of molten layer

Tolerance to radiation (Soft X-ray)

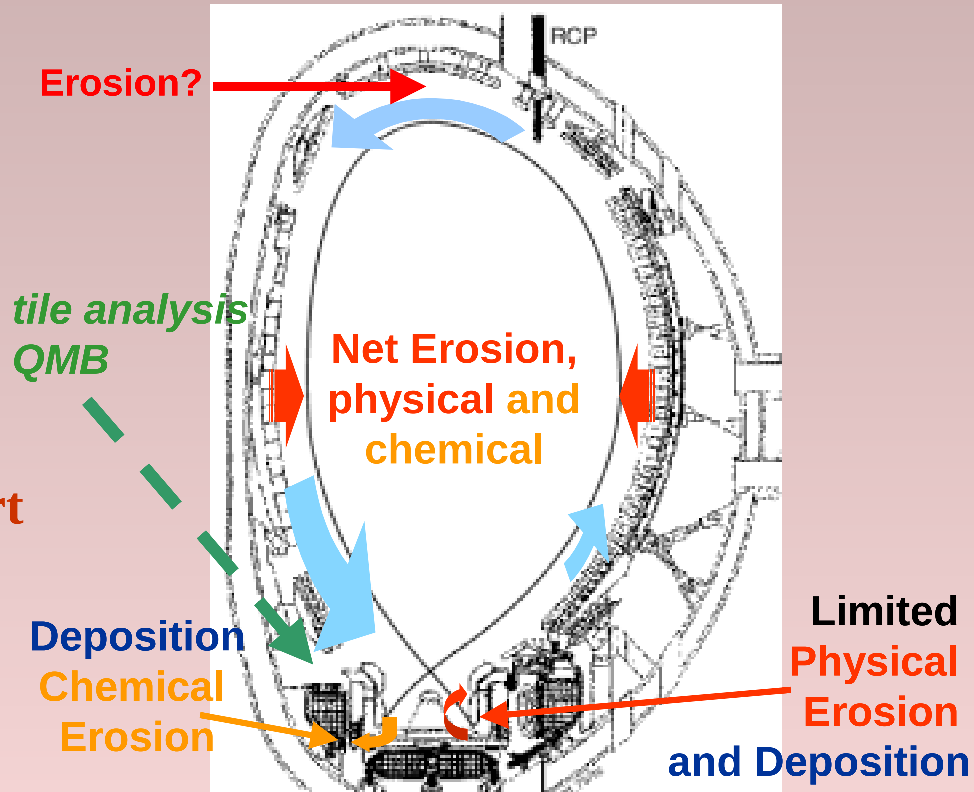
In situ tritium measurements (Tritium accountability)


Energy of Tritium
•Incident to wall
•Released from wall
Tritium
Mantle Radiation for cooling
•Wave length
•Opacity of plasma
Plasma Facing Wall
Co-deposition
Trapping
High heat load
Plasma
Heat Removal
ELM, Disruption
Radiation
Erosion
Safety
•Permeation
Impurity
Redeposition
Material Selection
High Z or low Z
Tritium Retention
•Surface & depth profile
•Trapping state
•Removal
Recycling
He exhaust
Radiation Damage
Materials Modification
Fuel Processing
Effect of Temperature

Impurity, Source, Transport and Deposition

Outer divetor erosion
First wall erosion
Inner wall deposition

Missing mass balance



Welcome, J.Pamela,
EFDA Associate Leader for JET

Tritium codeposits with carbon at shadowed area and dust

Mechanism

Local transport & Long range transport

- Deposition of HC radical or
  H & C codeposition
- Retention of tritium afterward?

How to remove?

Tritium codeposits with carbon

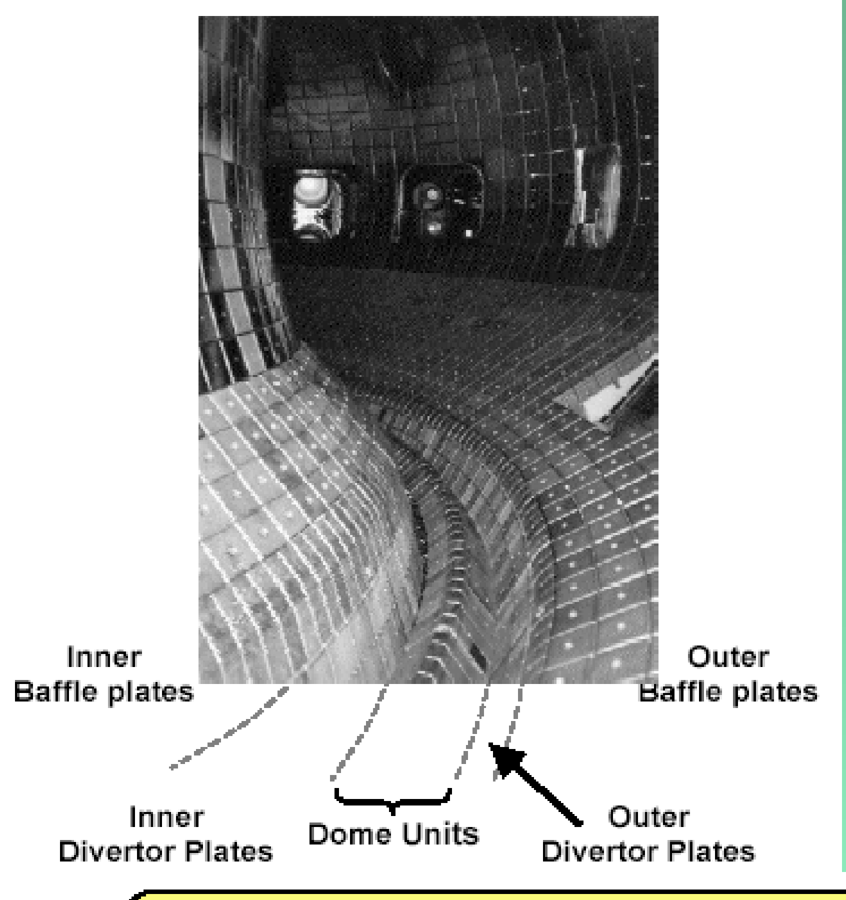
Estimation of Tritium retention in ITER

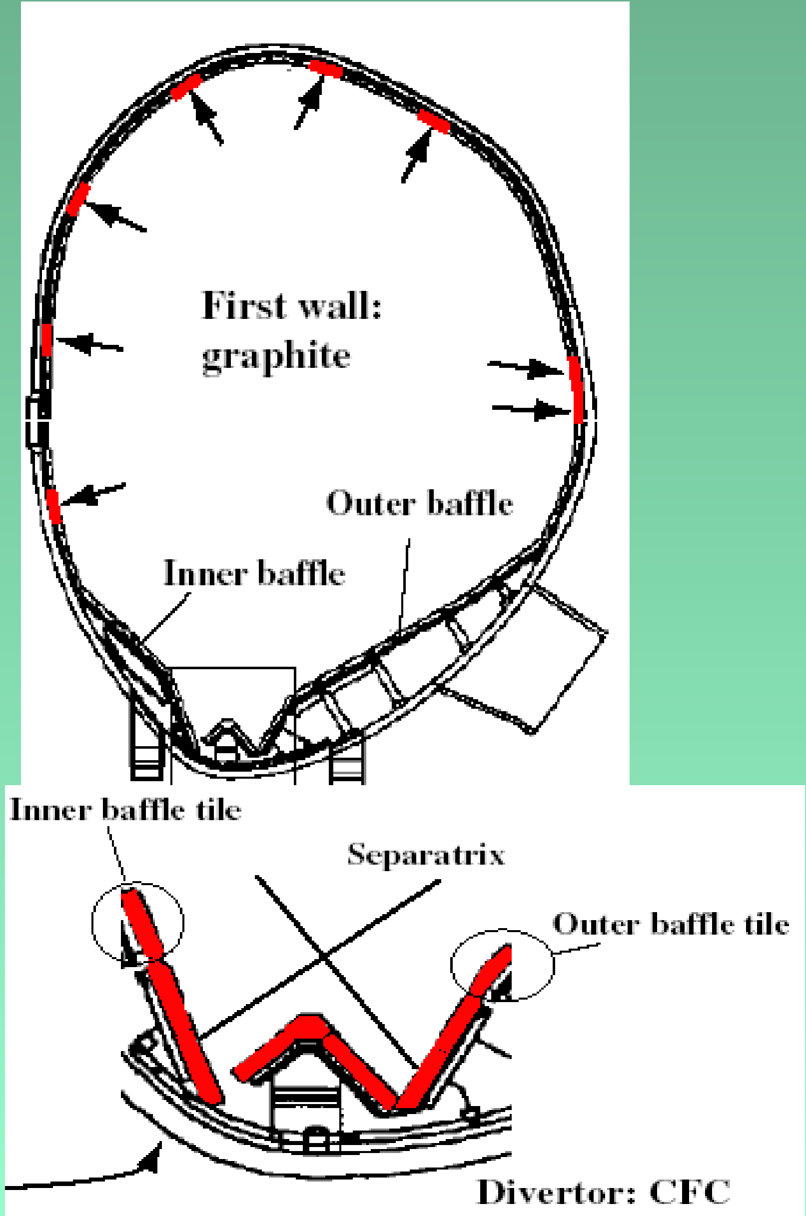
Extrapolation from experiments	T-retention rate T/ion	ITER retention gT/s Extrapolation flux 1.8 10^{24}/sc	Shots /T limit (400 sec)
TEXTOR	6.4 10^{-4}	0.0064	136
JET T experience	1.75 10^{-2} (only louver)	0.10	9
JET GB on tile	2.7 10^{-3}	0.024	36
JET C5 on louver from GB	2.9 10^{-4}	0.0026	340
Modeling			
ERO code 2% (CxHy er.)		0.006	145
WBC code		0.007	125

Only ~100 full D-T shots will give trtium retntion more than site limitation!

After Volker Phlipps(EFDA)

2. Postmortem analysis for PFM tiles of JT-60U

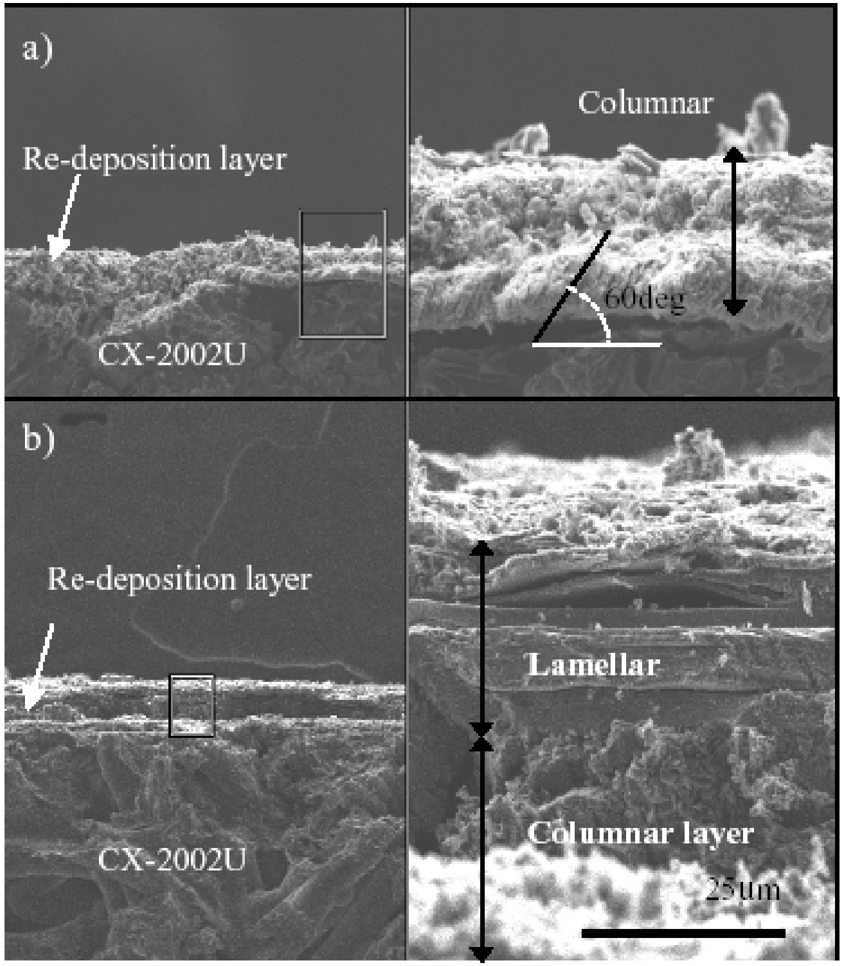


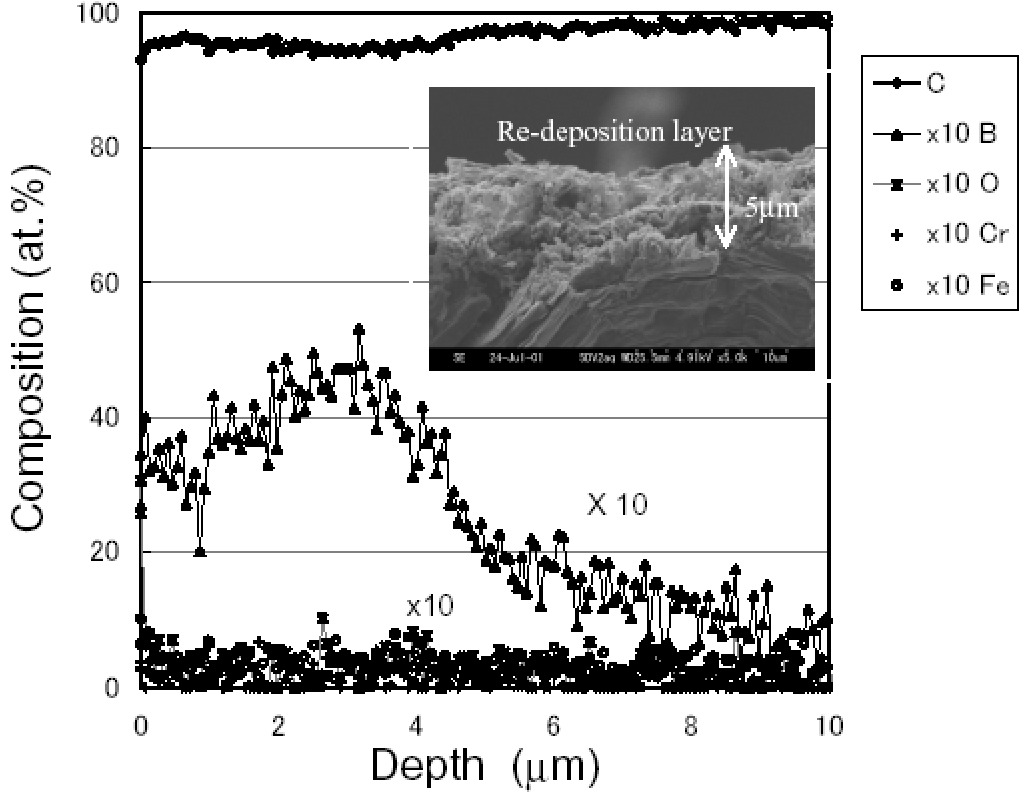


Sample tiles

First wall sample tiles: Mar. 1991 ~ Oct. 1998 (~19,000 shots)

Divertor sample tiles: Jun. 1997 ~ Oct. 1998 (~4,000 shots)





Analysis of deposited layers

Gotoh et al. 15th PSI

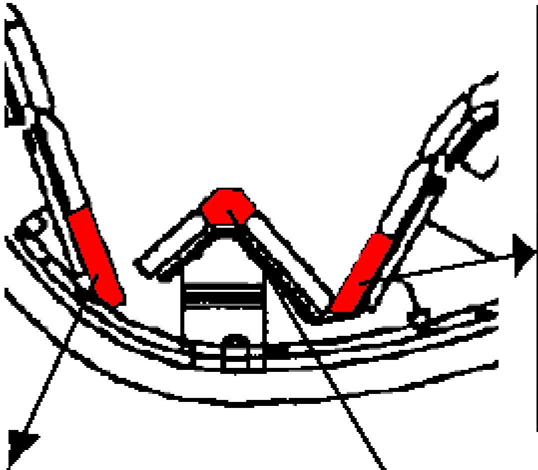
2-1. Erosion, transport and redeposition

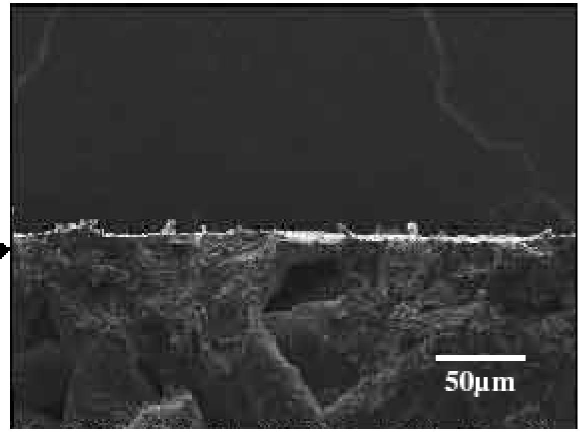
<SEM analysis resutls>

Thick deposition layers were observed on the inner divertor tile.
Max. : ~60µm

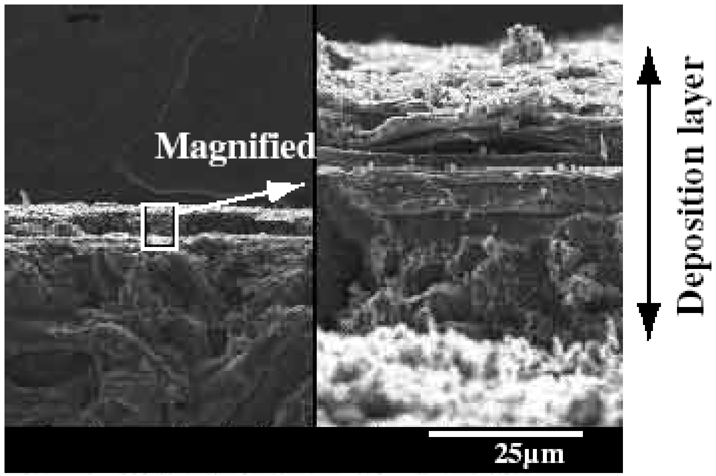
The deposition layer was not obviously observed on the dome top and the outer divertor tiles.

No correlation between the deposition layer and the tritium retention.

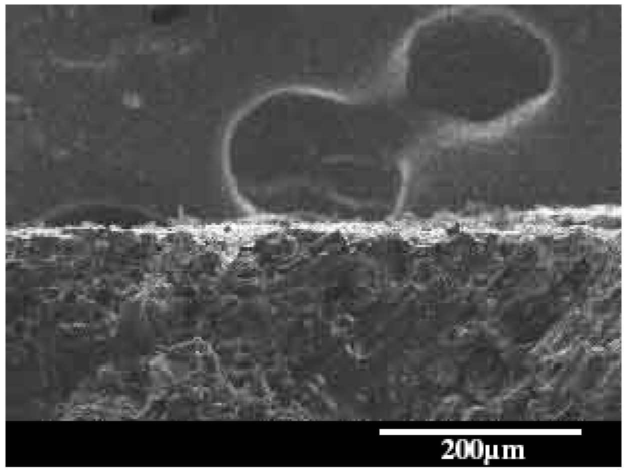




Outer Divertor: no deposition layer



Inner divertor: thick depostion layer

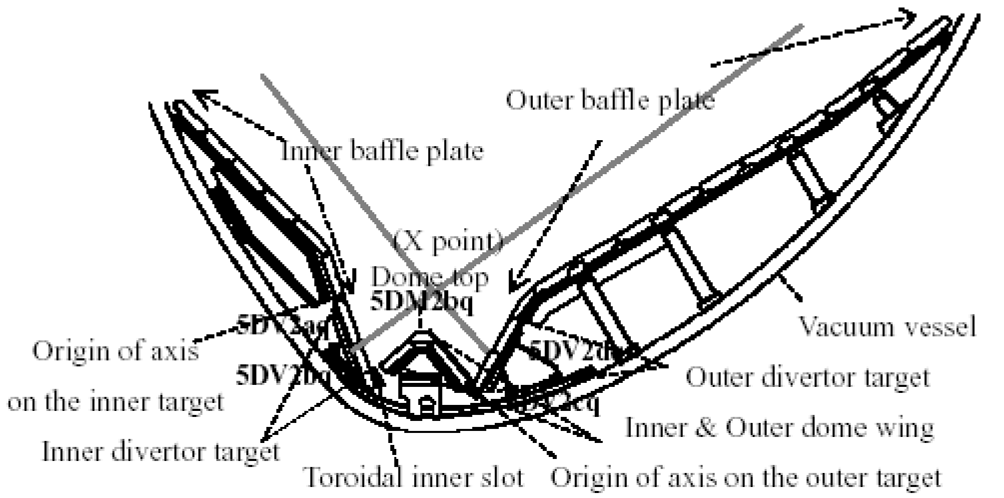


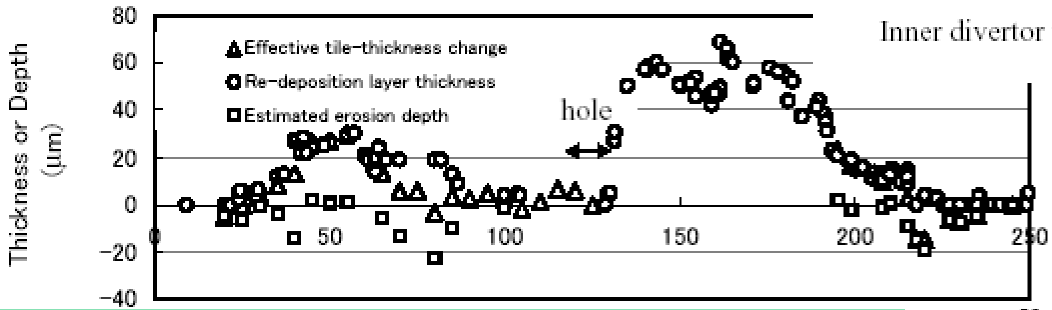
Dome top: no deposition layer

Gotoh et al. 15th PSI

Erosion/depostion Summary

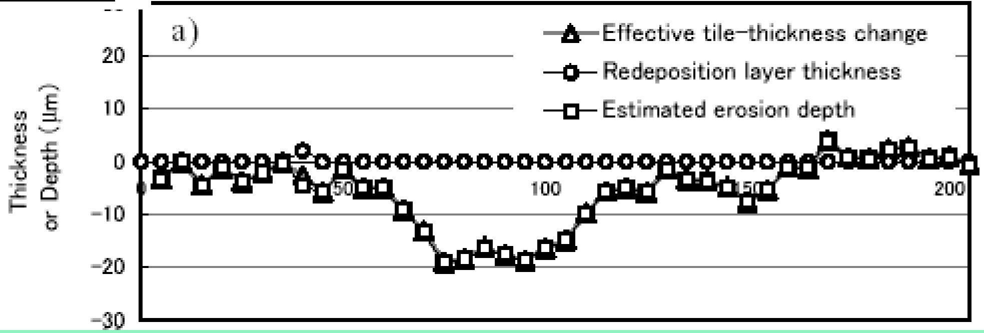
First wall:
mostly erosion dominant
max. 60 μm





Outer divertor:
erosion dominant

Inner divertor :
redeposition dominant



Carbon transport : repetition of erosion & deposition
Long migration through scrape off layer
or Short migration through private legion

Gotoh et al. 15th PSI

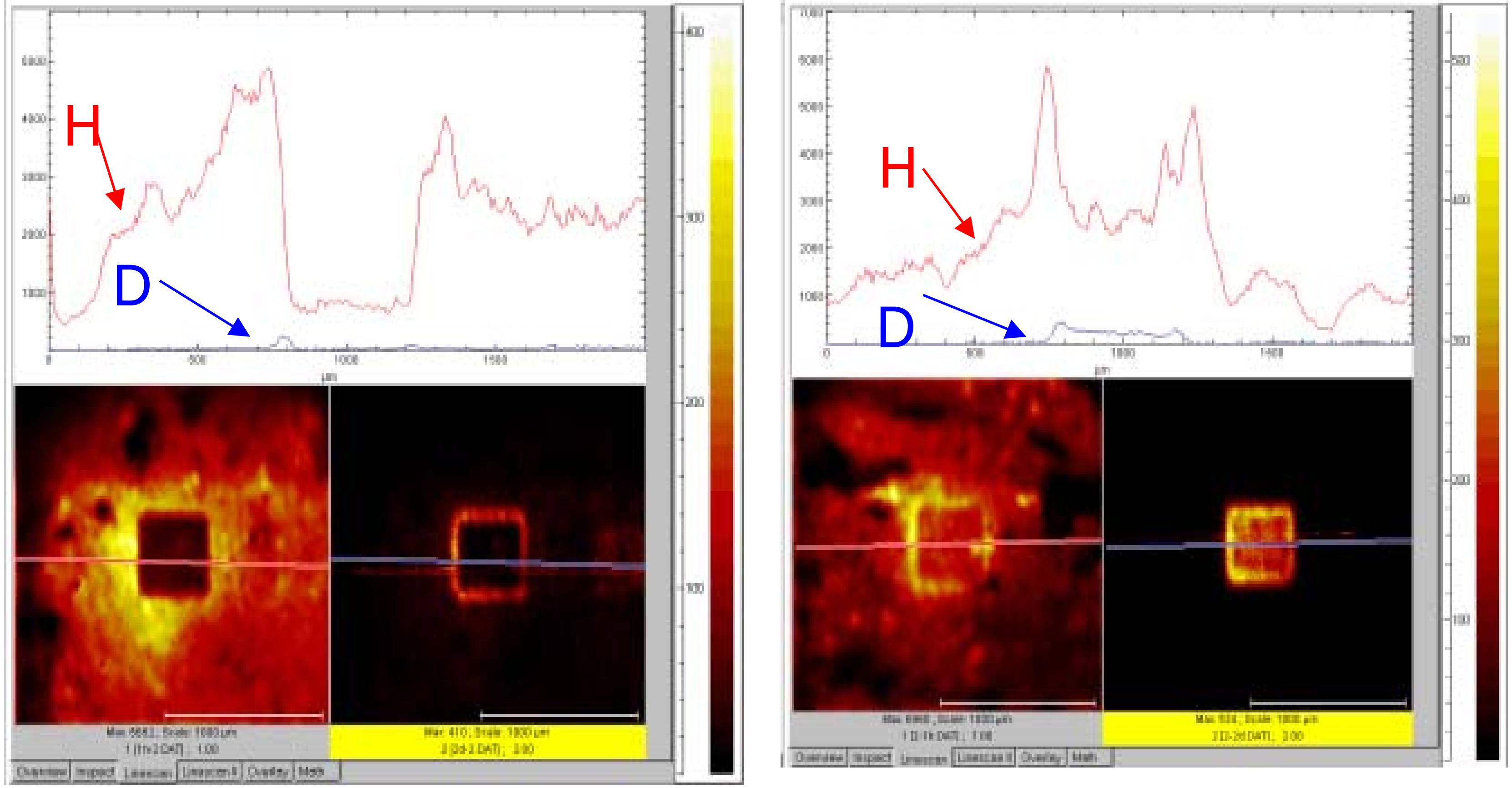
Nagoya University

JAERI

2-2. Retention of Hydrogen/Deuterium.

a) Top flat area (DM2) after sputtering of 4.1 μm

b) Inner side(DM1) 1.2 μm

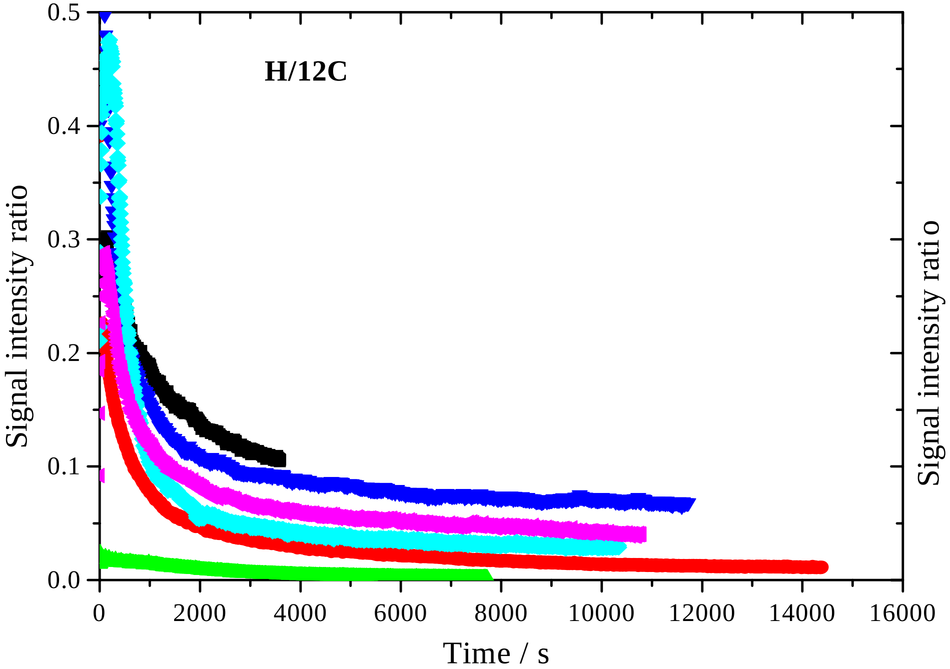


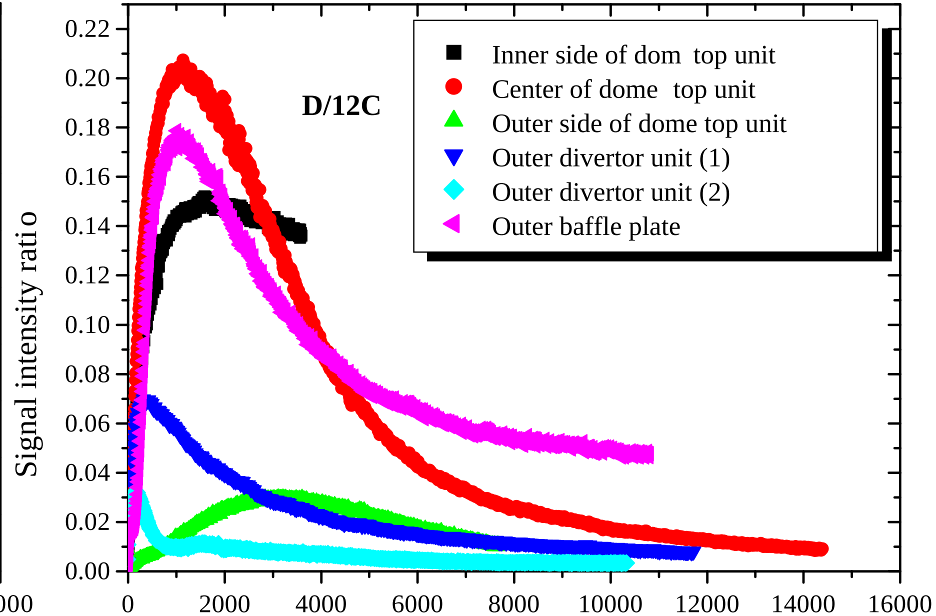
H profile **D profile** **H profile** **D profile**

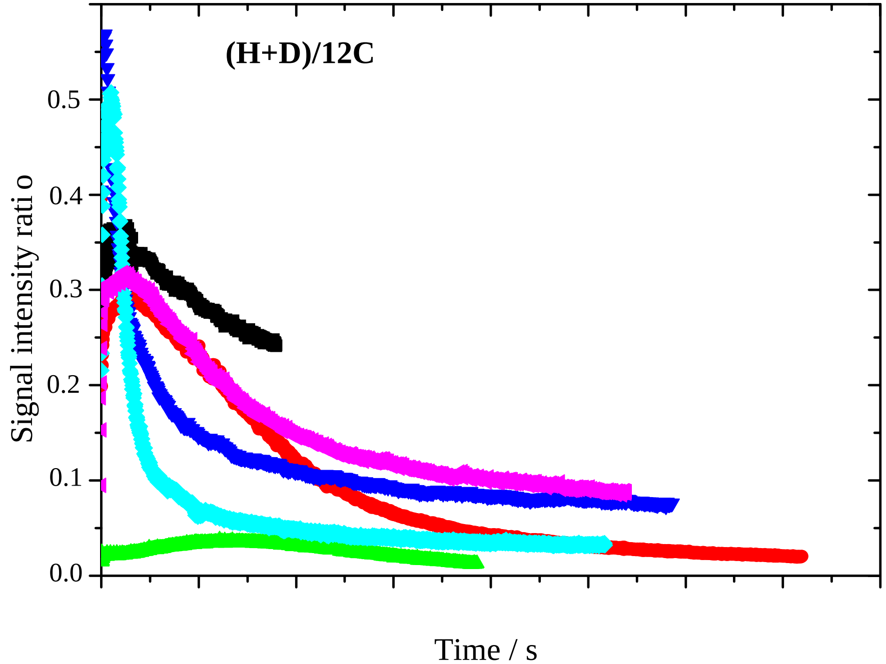
H in top surface layers, D in a little deeper zone and T in μm depth

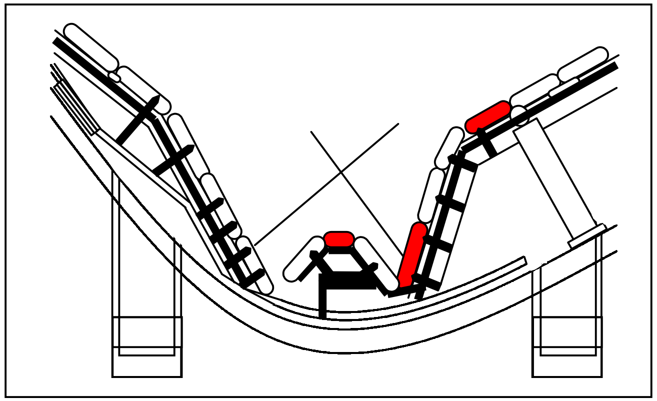
Hirohata et al. Physica Scirpta in press

Depth profiles of H and D in graphite tiles









2-3. Tritium distributions on PFM

<Simulation results using OFMC code>

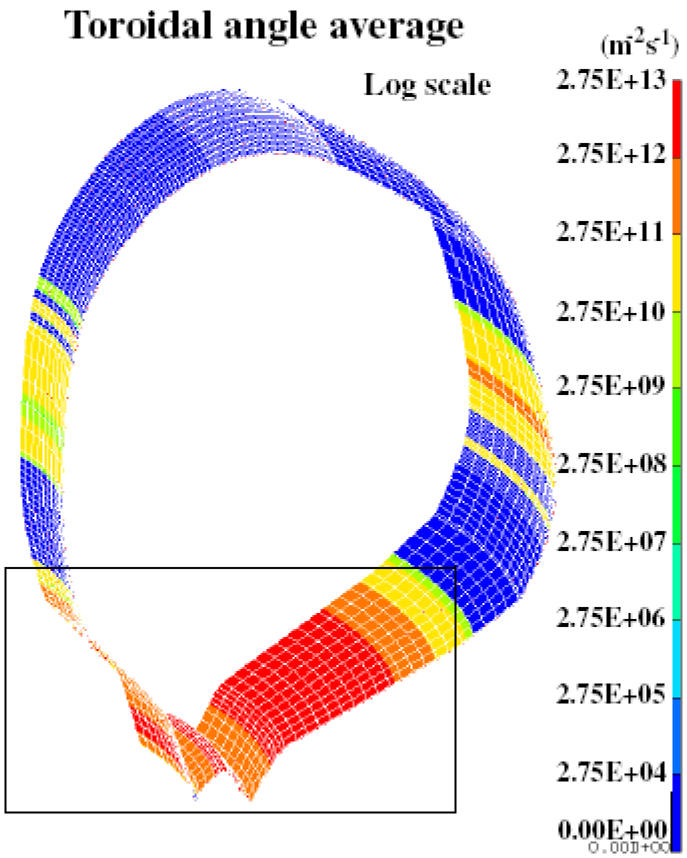
- 31% of produced tritons was lost and implanted to the wall.
- 12% of produced tritons impinged on the divertor region
- Fluxes of the tritons were

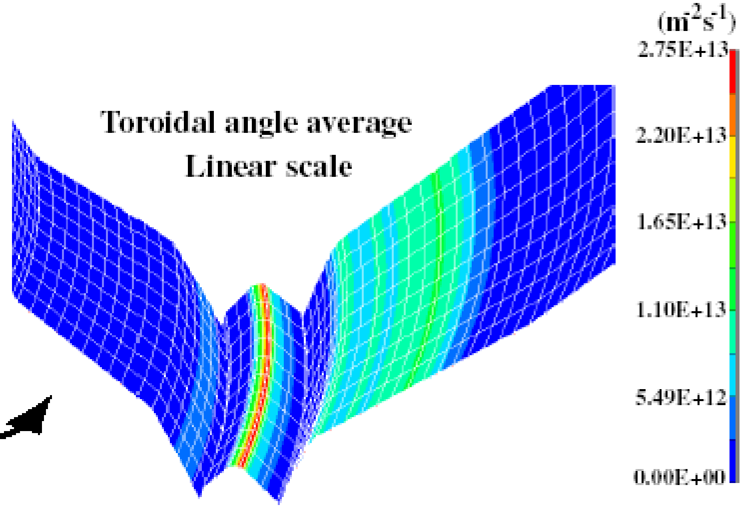
In a case of neutron production of $\sim 10^{14} s^{-1}$

$\sim 10^{11}$ $m^{-2}s^{-1}$: inner and outer midplane first wall

$\sim 10^{12}$ $m^{-2}s^{-1}$: inner divertor target and inner baffle plate

$\sim 10^{13}$ $m^{-2}s^{-1}$: dome top and the outer baffle plate





Masaki et al. 15th PSI

Nagoya University

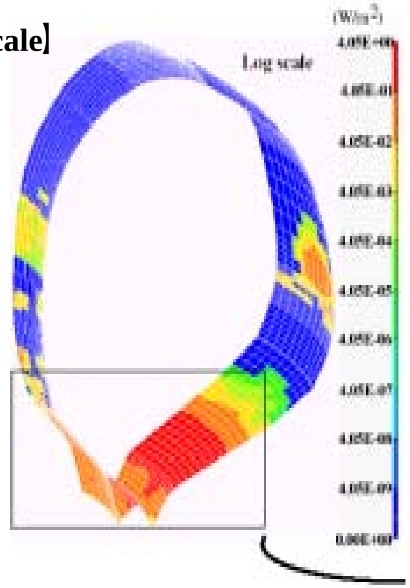
Tritium - Ploidal distribution -

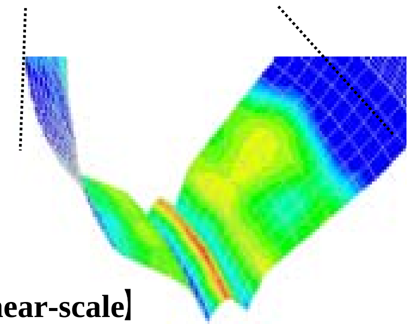
Higher tritium on bottom tiles

Higher tritium on outer wall

Very high tritium on midplane of outer wall

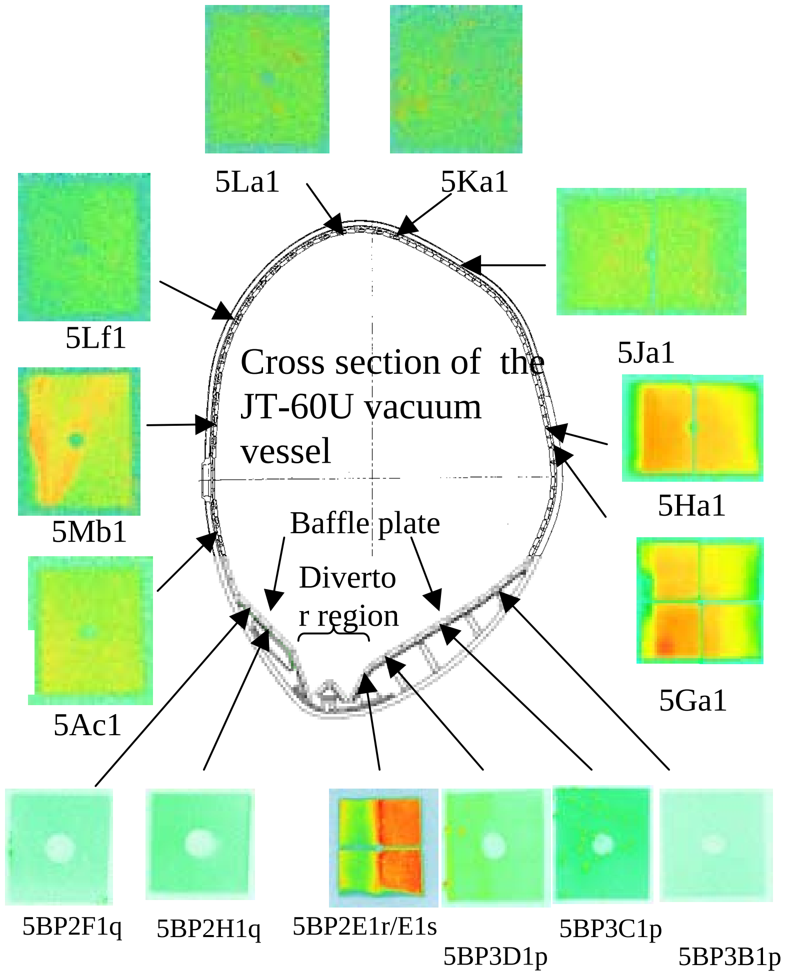
[Log-scale]

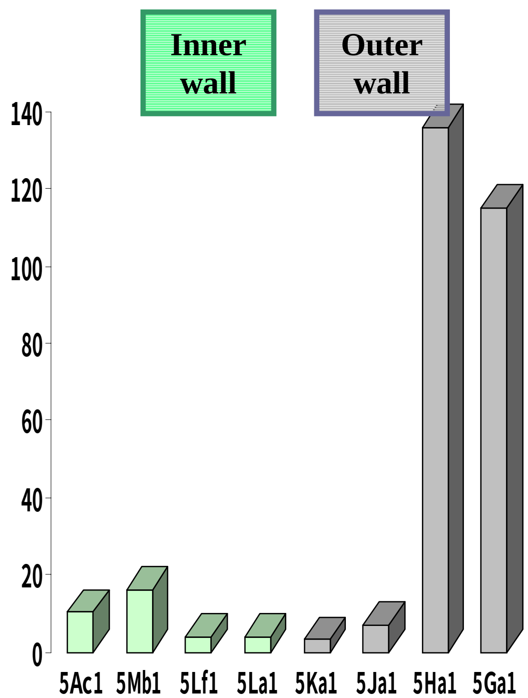




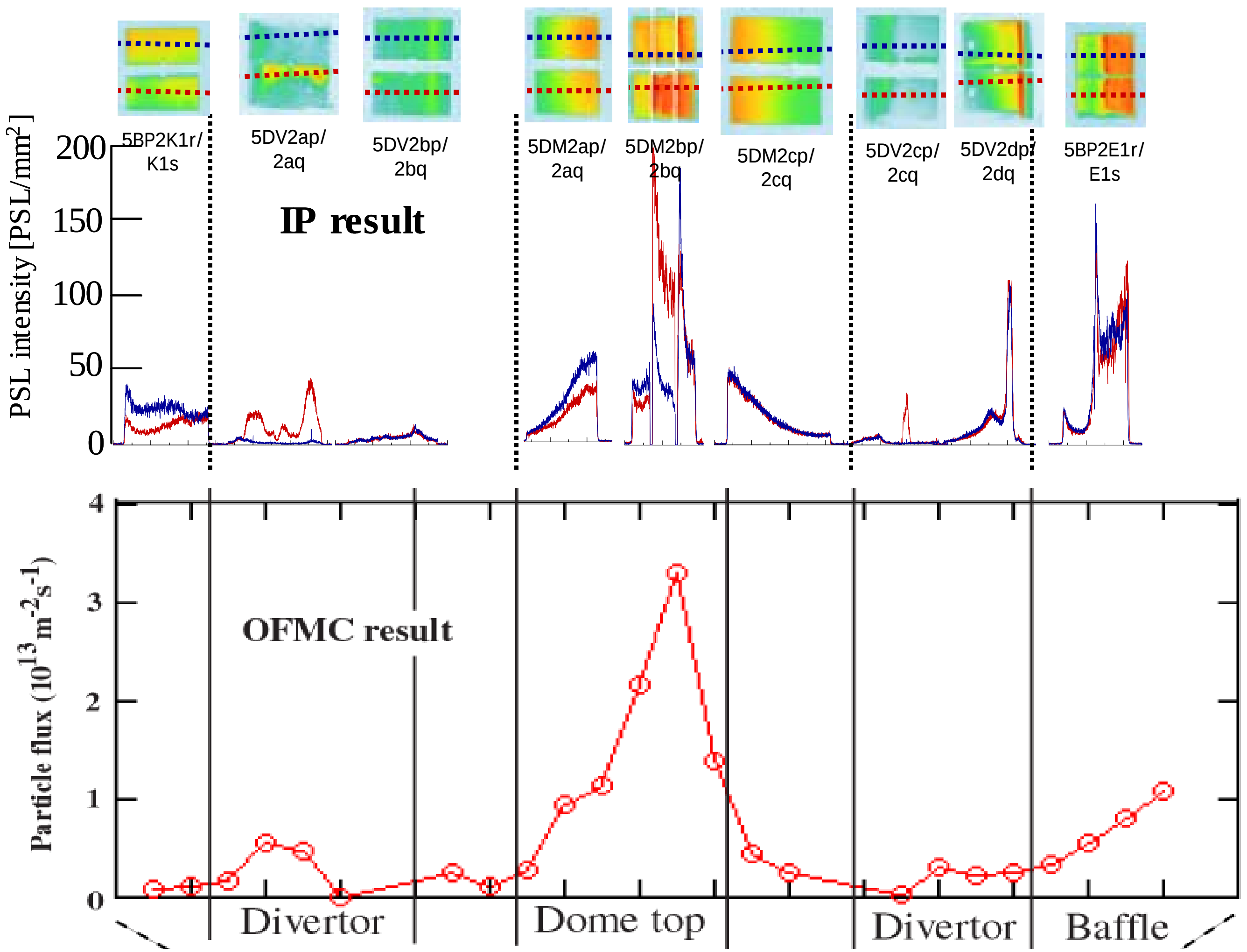
[Linear-scale]

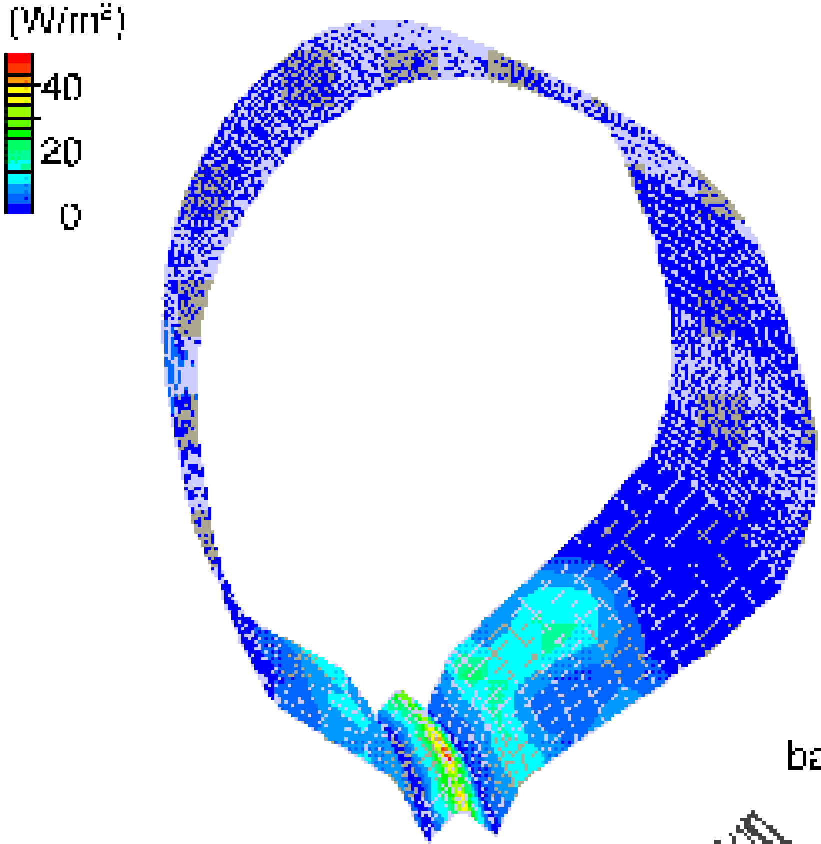
Particle flux by OFMC



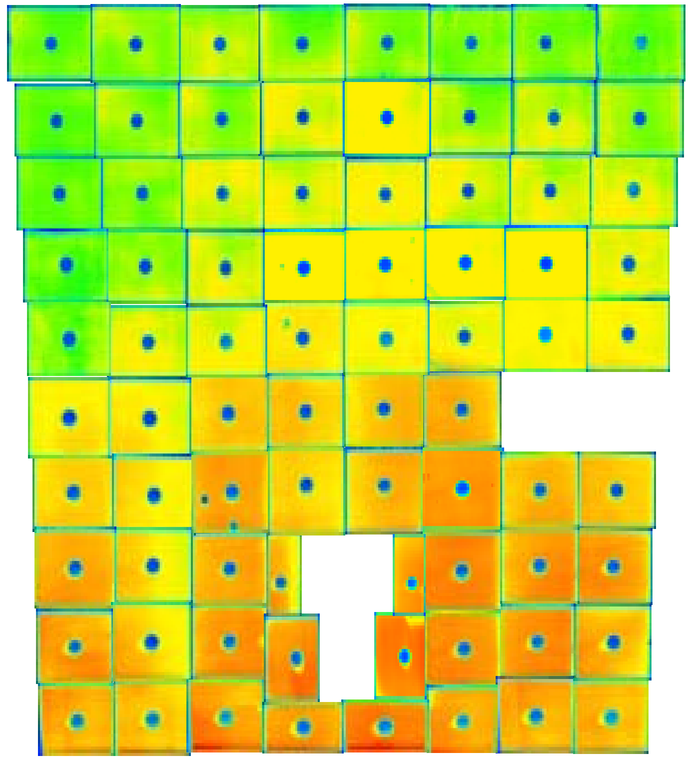


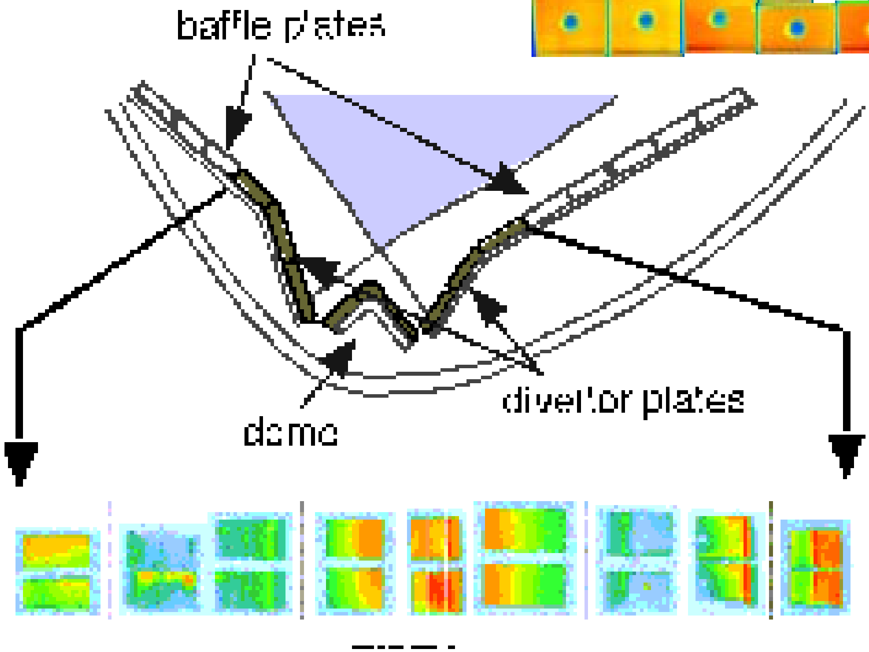
Comparison of IP results and OFMC calculation



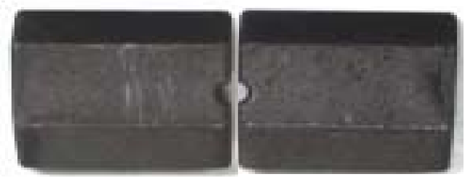


OFMC calculation

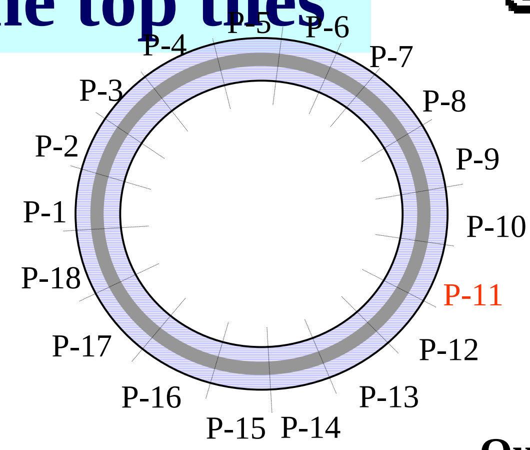


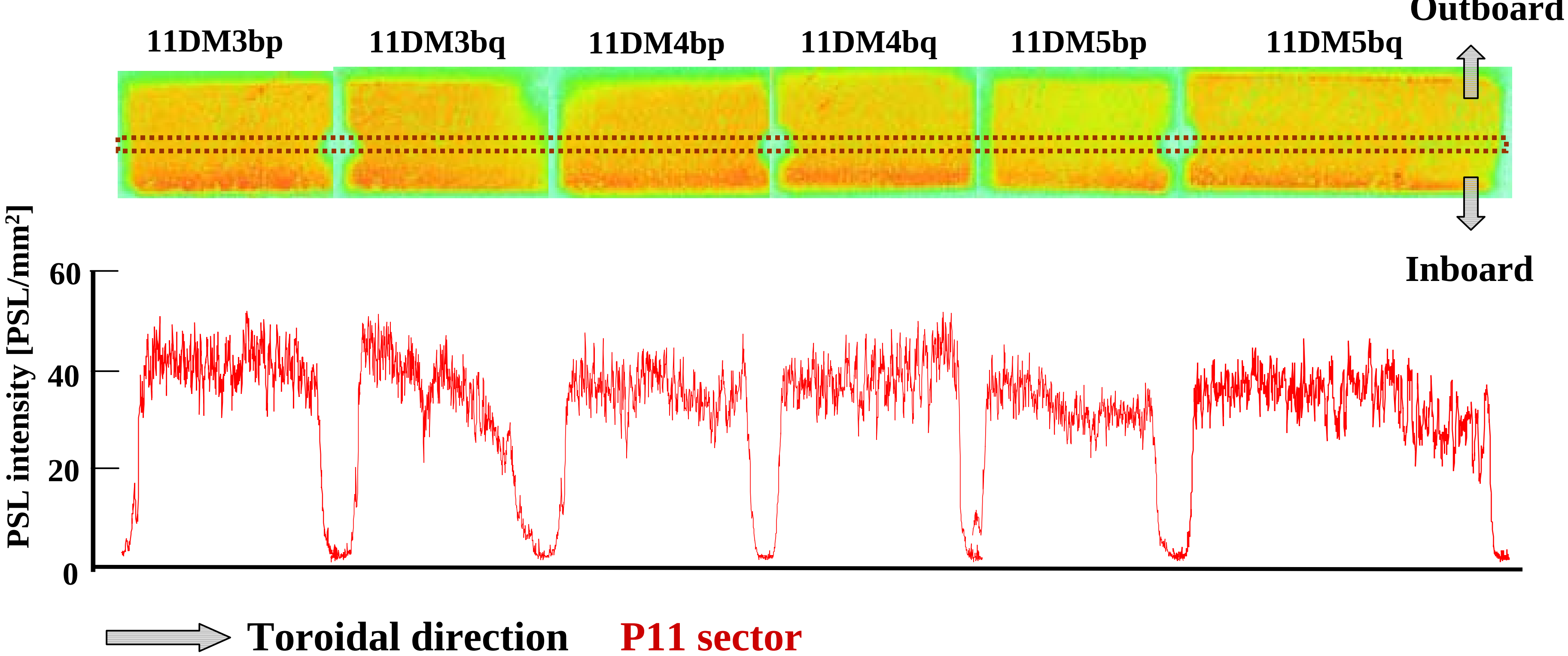


5.Toroidal distribution on dome top tiles



【Photograph of dome top tiles】





Tritium retention: comparison between observation and calculation

Observation

Long term tritium retention : Roughly 40% of produced tritium (18GBq)

<Tritium concentration>
Inner divertor: 2 kBq/cm^2
2 Dome top: 60 kBq/cm^2
Outer divertor: 250 Bq/cm^2

<Tritium retention>
Divertor region
10% of produced tritium

OFMC calculation

31% of tritons produced by nuclear reaction are lost from plasma

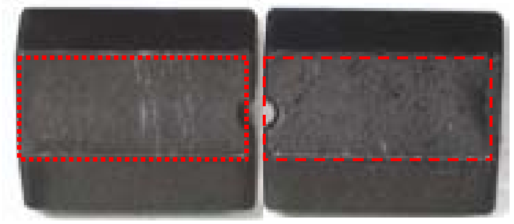
Dome :	6% of the produced tritons,	~0.7 MeV
First wall:	1%,	~1 MeV
Divertor:	3%,	~0.5 MeV
Inner baffle plate:	1%,	~1 MeV
Outer baffle plate:	20%,	~0.6 MeV

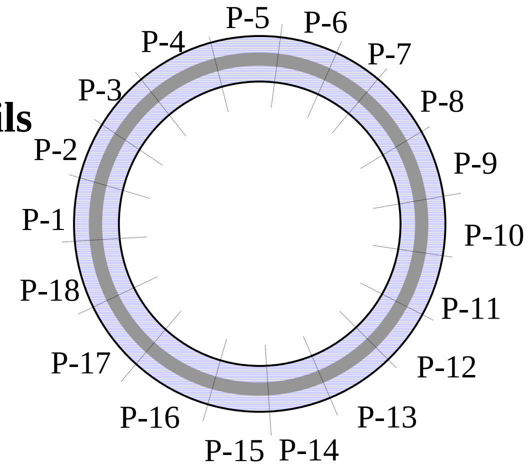
<Tritium retention>
Divertor region
12% of produced triton

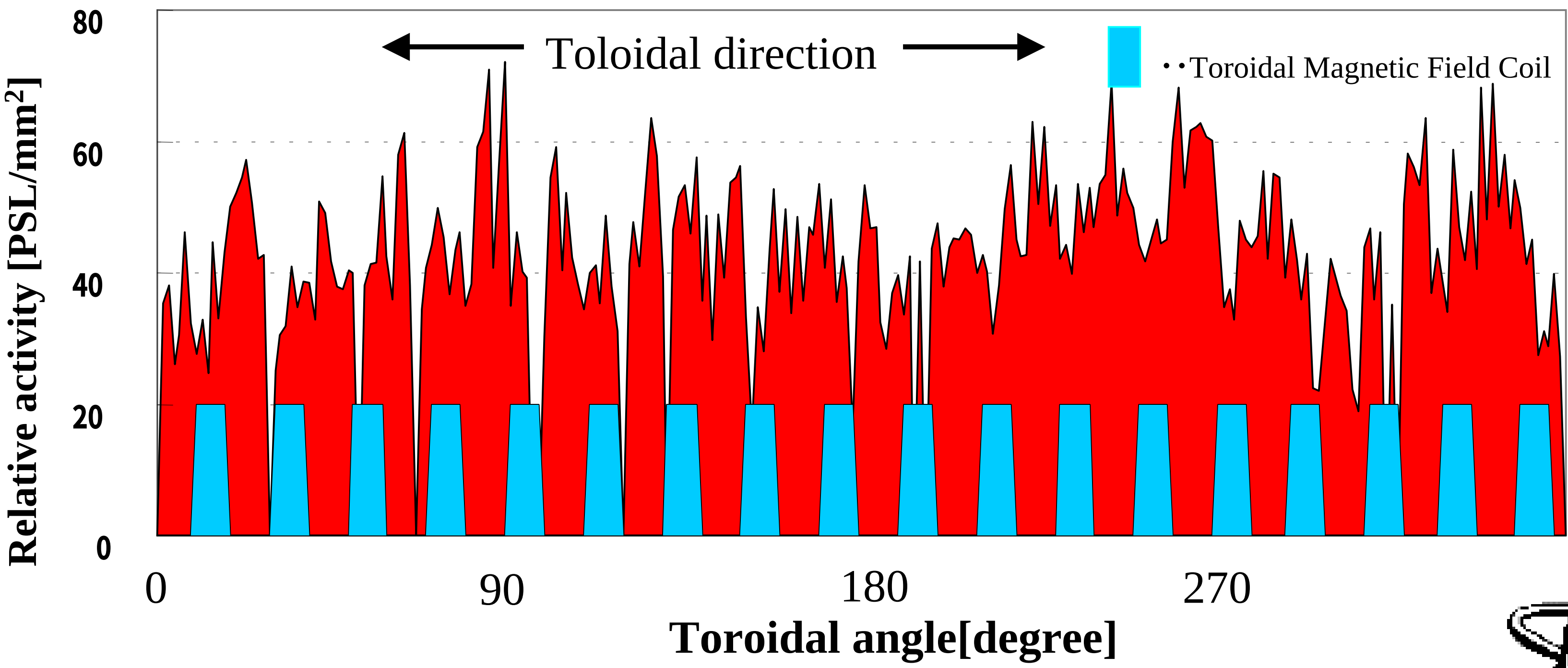
Tritium –Full toroidal distribution-

240 peaces of tiles

relation between tritium distribution and toroidal magnetic coils







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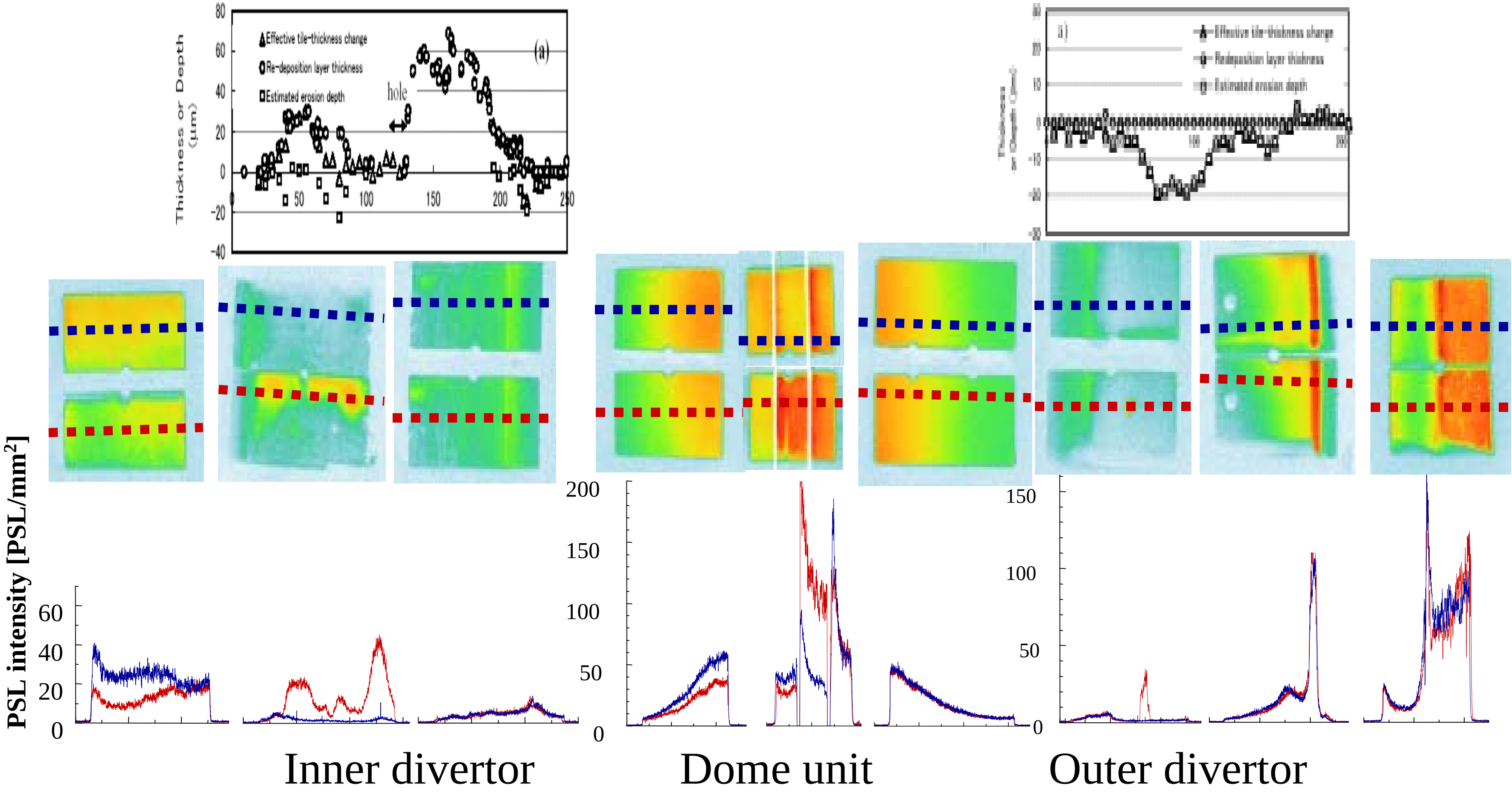
No relation between tritium distribution and deposition

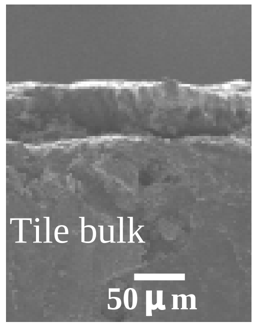


Nearly half of triton produced by D-D reaction is implanted into more than 1 μm in depth

Tritium depth profile

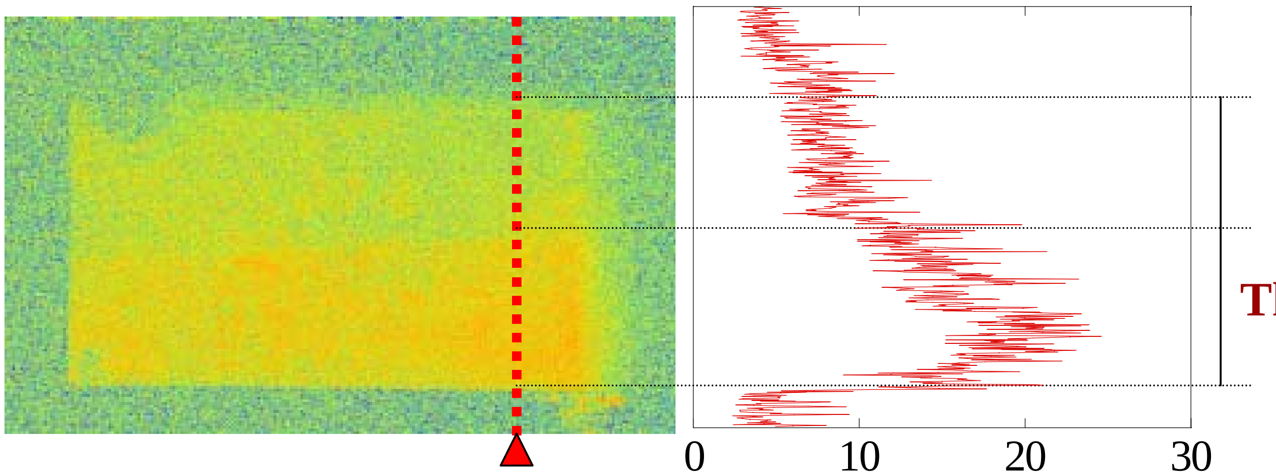
Tritium beneath the deposited layer (Inner divertor tile)

- **Exfoliate some redeposited area on inner diverot tile 5DV2ap**
- Redeposited layer with thickness of 20m (Max 60m)



Redeposited layer

[SEM photograph]
Near the top surface
of the inner divertor tile



Surface of the redeposited layer

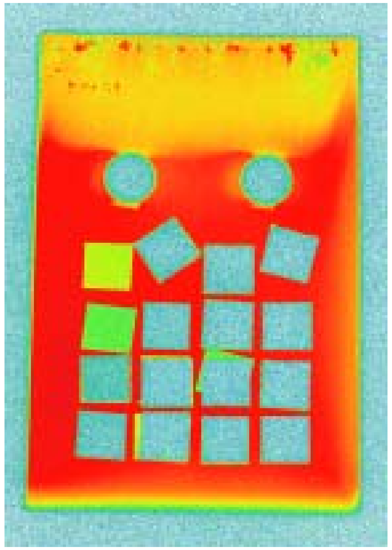
The exfoliated region

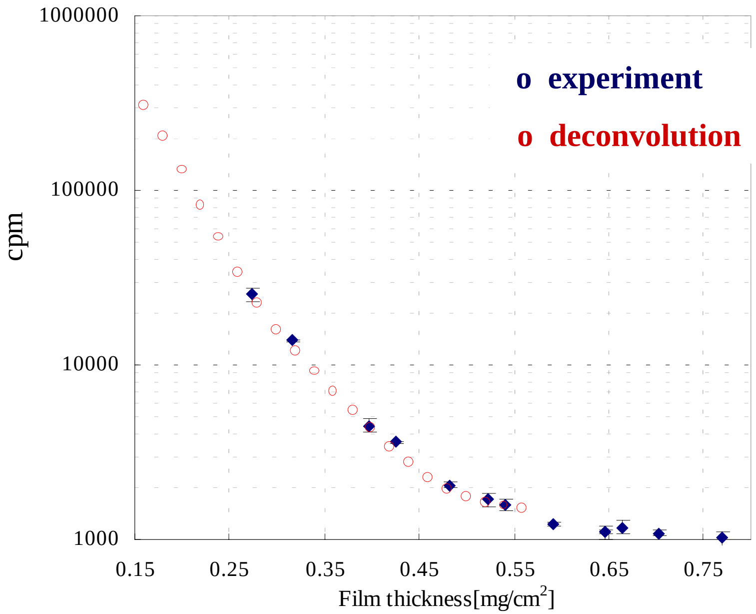
PSL intensity (tritium level) [PSL/mm^2]

Depth profile of tritium (Implanted more than 1μm in depth)

Inserted film thickness / micrometers

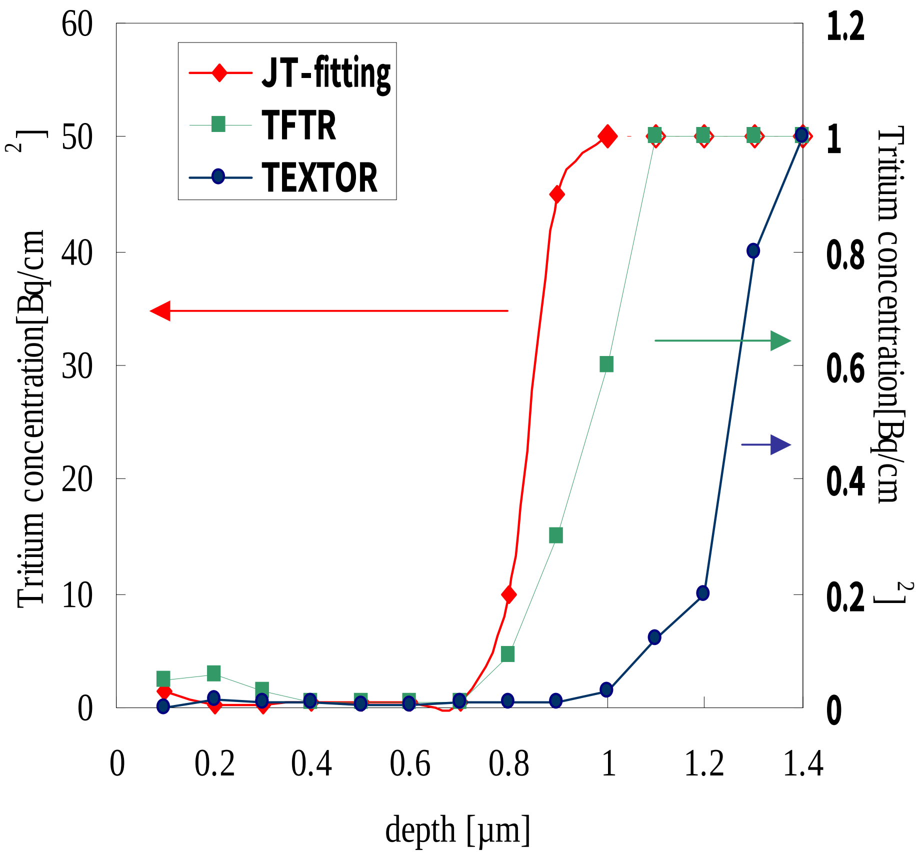
1.2	3.6	6.0	5.2
2.0	4.0	6.0	5.6
2.4	4.4	6.0	8.0
3.2	4.8	6.0	10





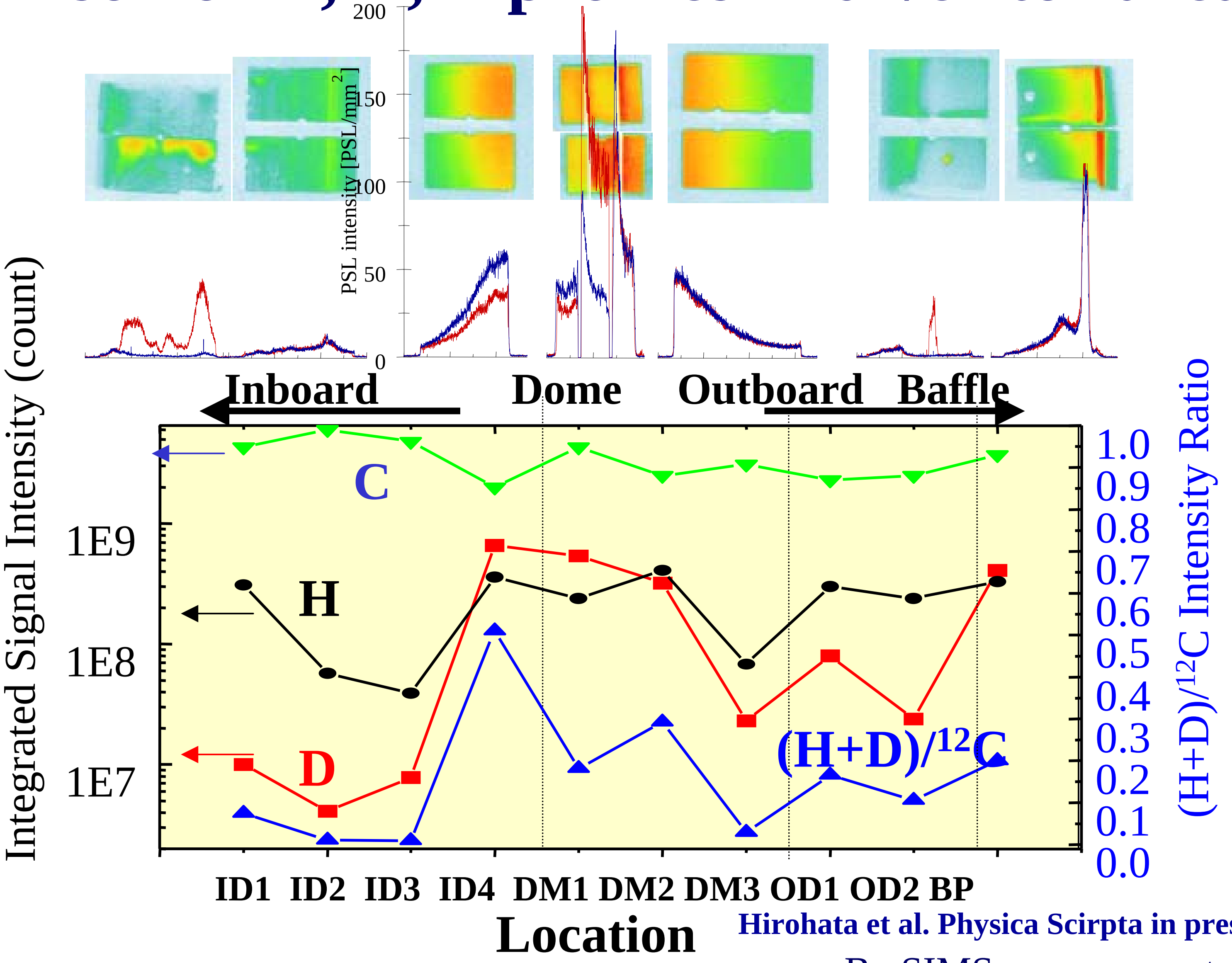
Deconvolution of depth profile

convolution



Comparison of tritium depth profile of D-D tiles

Comparison of H, D, T profiles in diveritor area



Hirohata et al. Physica Scirpta in press

By SIMS measurement

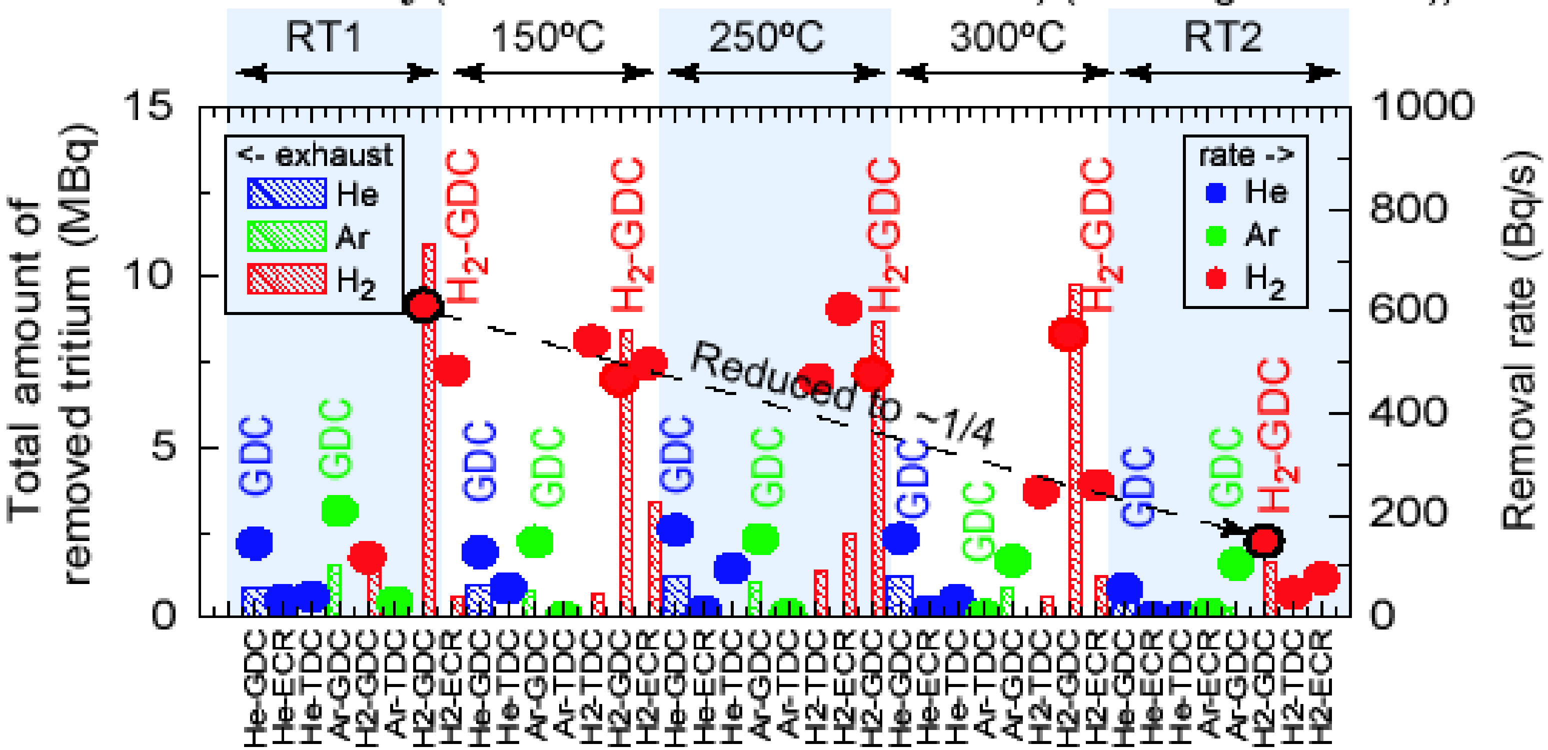
H, D, T profiles are very similar in JT-60U → High Temperature

3. Tritium removal by discharge technique

H_2 gas: Large removal rate, Similar effectiveness in glow, ECR and Taylor discharges
Noble gas: Small removal rate, Effectiveness(Glow)>Effectiveness(ECR) ~Effectiveness(Taylor)

- Total amount of removed tritium: ~73 MBq (smaller than predicted retained tritium (~ several 100 GBq) in first wall).

Removal rate (∫ (total amount of removed tritium)/(discharge duration))



- Effect of wall conditioning discharges on tritium removal: Confirmed

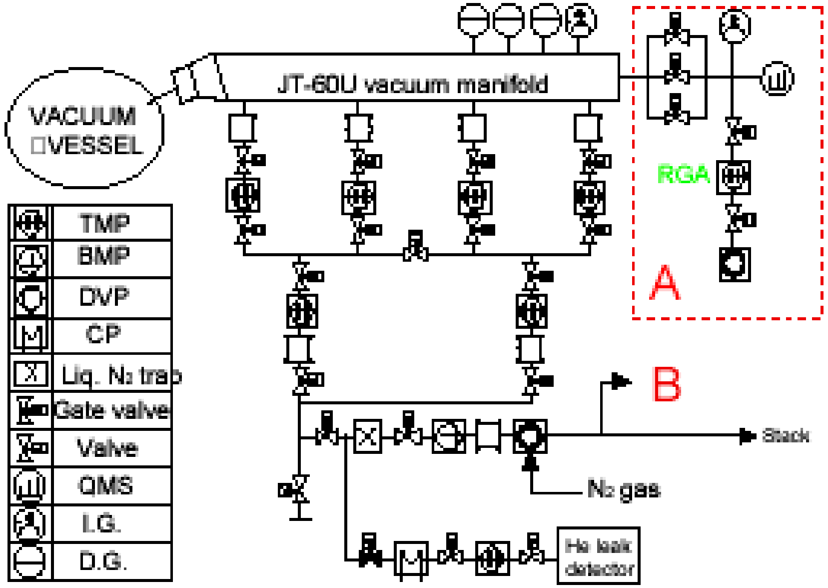
In glow discharge, by RT1->RT2

H_2 gas: reduced to ~1/4, Noble gas: reduced to ~1/2

Diagnostics for tritium concentration and residual gas

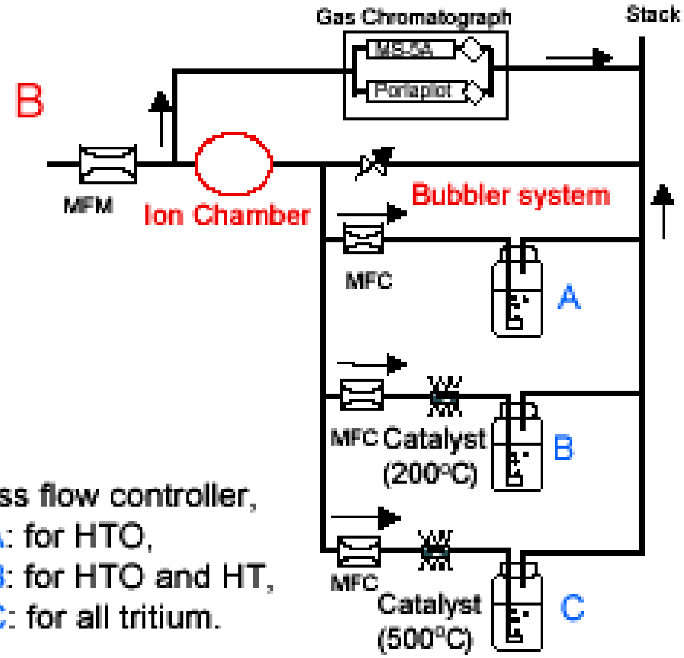
Ion chamber: Tritium concentration
Bubblers with heated catalysts (200ºC,500ºC): Tritium chemical form
RGA, Gas Chromatography(GC): Gas species

Measurement system (sampling points)



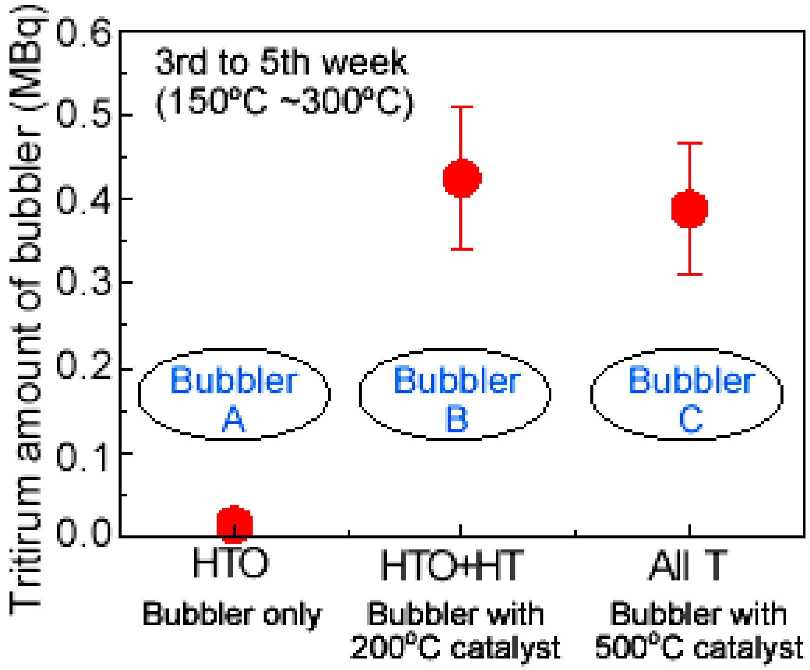
Flow diagram of JT-60U vacuum pump system

MFC: Mass flow controller,
Bubbler A: for HTO,
Bubbler B: for HTO and HT,
Bubbler C: for all tritium.



Flow diagram of tritium and gas species measurement system

Chemical form of removed tritium of JT-60U: Elemental (hydrogen) form



Results of bubbler measurement. Tritium amount collected by bubbler A~C during series of conditioning discharge at 150°C ~300°C.

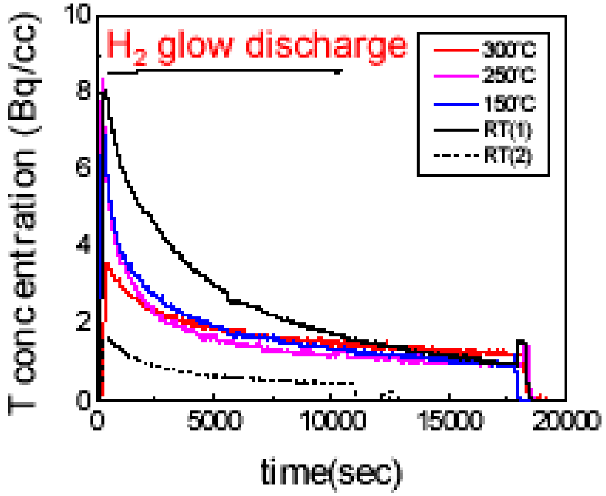
RGA and GC showed that hydrocarbon was generated during baking. However, the content of water vapor and hydrocarbon with tritium was small.

In H_2 glow discharges, Tritium and HD: monotonically decay, Methane: almost constant

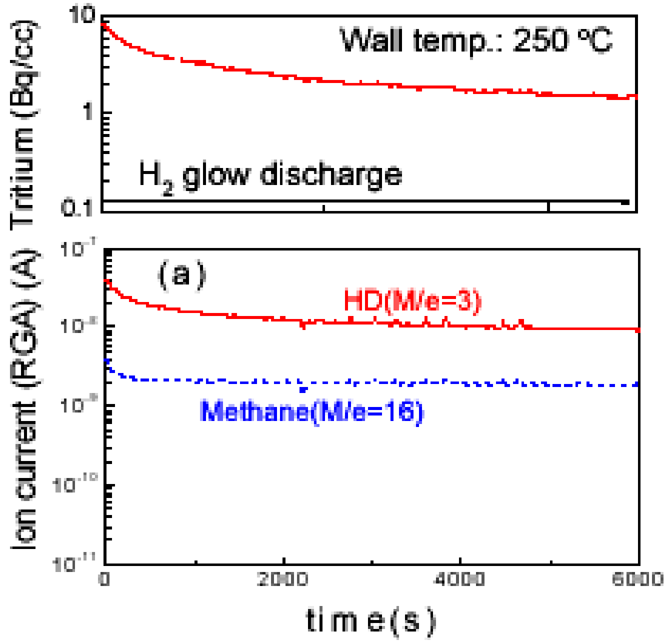
Removal behavior of hydrogen isotopes and hydrocarbon in glow discharges

Tritium and HD: monotonically decay

Methane: almost constant



Time evolution of tritium concentration in exhausted gas during H_2 glow discharges.



Time evolution of HD and methane intensity during H_2 glow discharges in comparison with tritium.

Removal of carbon codeposit using wall conditioning discharge

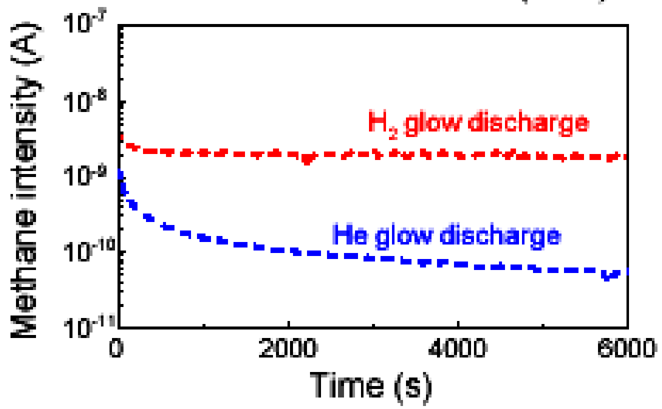
Problems: Tritium removal from co-deposition in DT machine

-> Can we remove co-deposit by wall conditioning discharges?

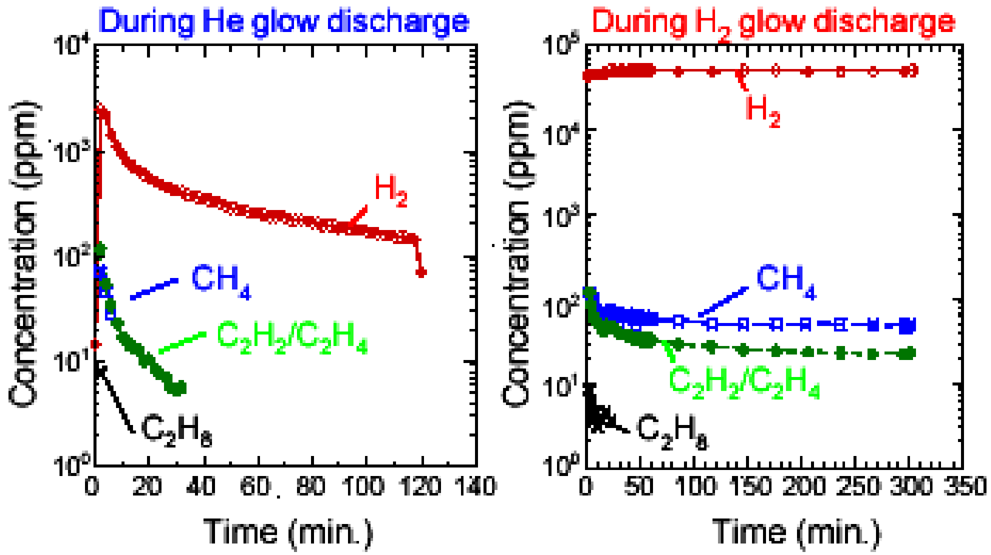
H_2 glow discharge can remove much carbon atoms from the first wall (co-deposit layer?) than He glow discharge.

-> Qualitative evaluation of carbon removal rate is necessary.

Time evolution of methane (RGA)



Time evolution of hydrogen/hydrocarbon concentrations (GC)



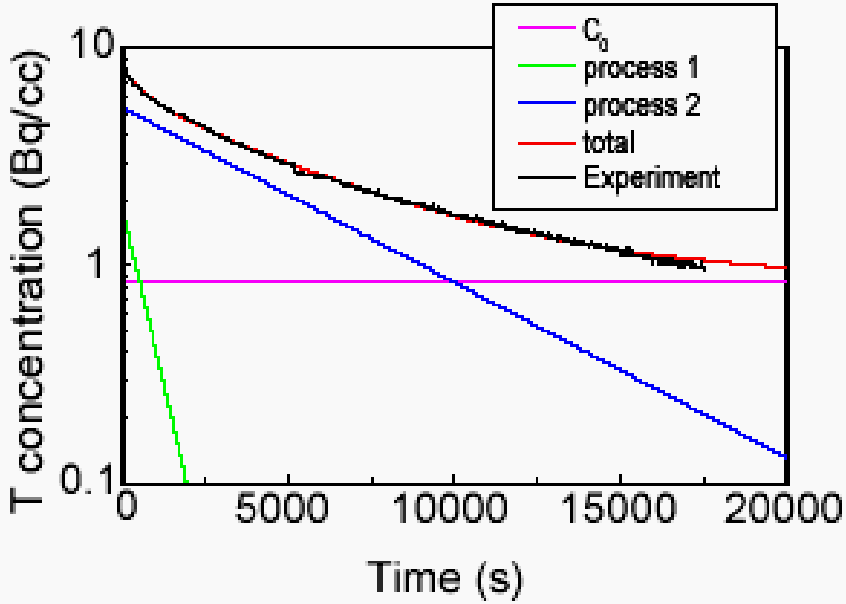
Time behavior of hydrogen isotope removal: by exponential fitting

Hydrogen isotope transport by diffusion and trapping below 300°C: negligible
(Small diffusivity (~$10^{-25}$$m^2$/s), Higher trap energy (2~4eV))

•For analysis of hydrogen isotope removal by glow discharges,
Exponential fitting: Combination of multiple removal processes

$$C(t) = C_0 + \sum_j^n \frac{A_j}{\tau_j} \exp\left(-\frac{t}{\tau_j}\right)$$

$C(t)$: T concentration in exhausted gas
C_0: Constant T concentration
A_j: Pre-exponential factor for process j (Max. of removal amount)
τ_j: Time constant for process j



Fitting result of decay curve of tritium concentration in H_2 glow discharge at RT1.

-> Experiment could be reproduced by two exponential functions.
Process 0: constant
Process 1: fast decay
Process 2: slow decay

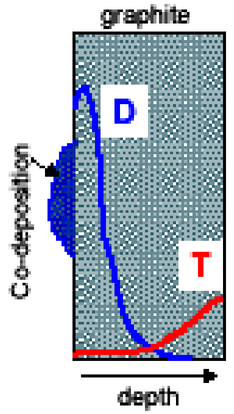
Tritium of DT-machine: recycle particle -> existing in near-surface region -> Deuterium behavior of JT-60U: Good reference

- Different distribution in the first wall in JT-60U
  - D: surface area and co-deposit layer
  - T: deeper area (~μm)
- Removal process of D and T: similar, independent on depth profiles

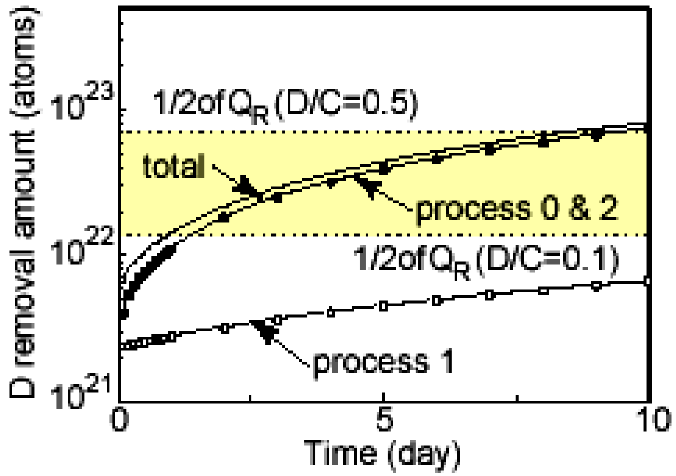
How much tritium can be removed by glow discharge?
How long does it take to remove ?

Removed amount(Q)
Initial conditions:
(1) Incident energy of D ions in H_2 glow discharge: ~300 eV
-> Incident depth <15 nm (by TRIM98)
(2) D/C ratio measured in JT-60U carbon surface: 0.1 ~ 0.5.

According to C_0, τ_1, τ_2, A_1 and A_2,
Half-life of D retention amount by continuous H_2 glow discharge: 1 ~ 10 days



Conceptual diagram of depth profile of D and T



Estimated deuterium removal amount by continuous H_2 glow discharge at 300°C. Q_R: deuterium retention amount within 15 nm depth of graphite first wall.

4. In vessel PMI studies

T. Nakano and others
(Spectroscopy group)

JAERI, Naka

1. **CD_4/CH_4, C_2D_x/C_2H_x sputtering yields**
   (T.Nakano et al., Nucl. Fusion 42 (2002) 689)
2. **Reduction of carbon content by lowering wall temperature**
   T. Nakano et al., unpublished
3. **Effects of boronization**
   T. Nakano et al., J. Nucl. Mater. 313-316 (2003) 149.

C_2H_y/C_2D_y Should Be Taken into Account in Cold and Dense Divertor

JT-60U

Usual measurement of chemical yield

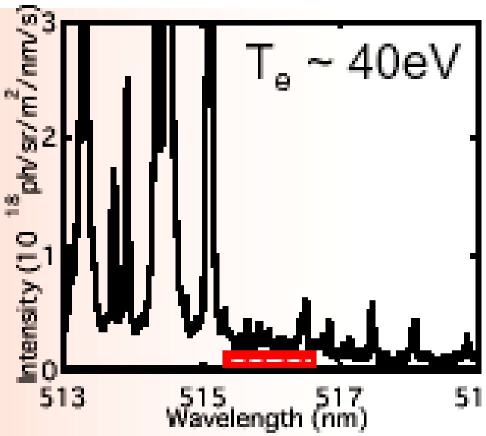
$$Y_{total} = Y_{CD4}$$

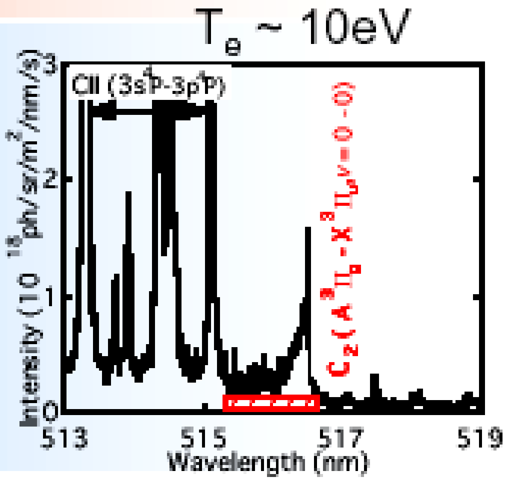
$$= I^{CD} \times (D/XB^{CD}) / \Gamma_{ion}$$

D:Dissociation rate coefficient

X:eXcitation rate coefficient

B:Brancing ratio





In this study,

Simultaneous measurement of CD & C_2

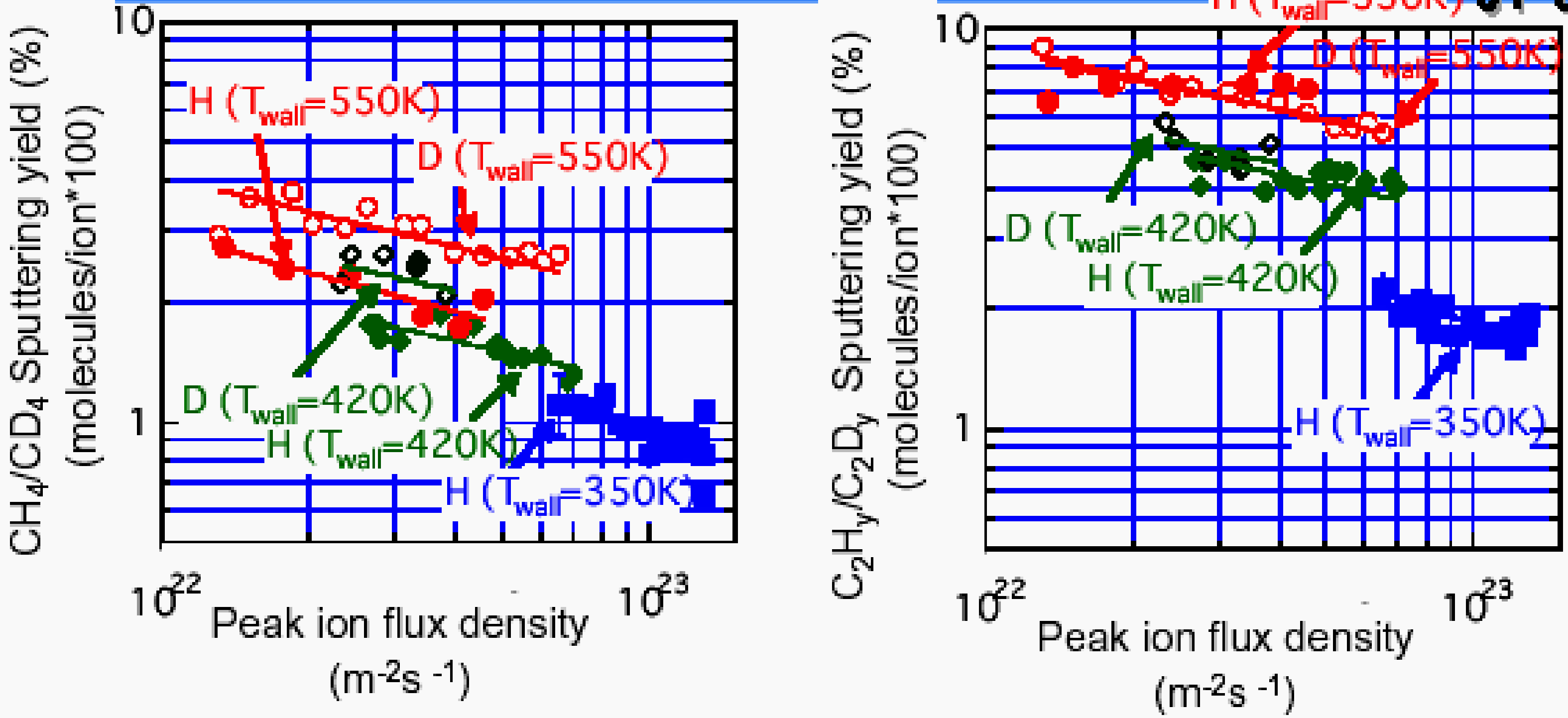
$$Y_{total} = Y_{CD4} + Y_{C2Dy} \times 2$$

$$= I^{CD}_{CD4} \times (D/XB^{CD}) / \Gamma_{ion}$$

$$+ I^{C2}_{C2Dy} \times (D/XB^{C2}) / \Gamma_{ion} \times 2$$

Result : Chemical Sputtering Yield

JT-60U



Dependence on T_{wall} $Y^{550K}:Y^{420K}:Y^{350k} = 1:\sim0.6:\sim0.4$

Dependence on isotope $Y^{D} \sim 1.3 \times Y^{H}$

Dependence on ion flux $Y \propto \Gamma^{-0.1\sim-0.3}$

Summary 1

JT-60U

1. Temperature effect; $Y^{550K}:Y^{420K}:Y^{350k}$ = 1:~0.6:~0.4
   The ratio depends on neither H/D nor C_xH_y.

2. Isotope effect; $Y^D \sim 1.3 \times Y^H$

   The coefficient depends on neither T_{wall} nor C_xH_y.

3. Ion flux & incident ion energy; $Y \propto \Gamma^a$ a~-0.1~-0.3

   $Y_{chem}/T_e^{0.37}$ does not depend on ion flux.

4. C_2H_x contributions ~ 80% to total sputtered carbon atoms.

Summary 2

JT-60U

In order to investigate effects of low T_{wall} & boronization, the discharges with identical discharge conditions have been repeated ~ 100 times in 2 years.

The database is based on data from,

deuterium discharges at T_{wall} ~ 420 and 540K (13 boronization sessions)

& hydrogen discharges at T_{wall} ~ 350, 420 and 540K.

The database indicates,

1. n_C/n_e decreases at low T_{wall} because of reduction of Y_{chem}.
2. Γ_{chem} contributes 5-15% of Γ_{C+} in the divertor.
3. Γ_{chem} contributes 30-80% of N_C^{core}. The contribution depends on confinement modes and woking gases. (Preliminary)

Summary 3

JT-60U

In 50 shots after boronization, suppression of sputtering at carbon plates resulted in low core carbon content. After that, the carbon content became constant ~ 2.5%.

In 50 shots after boronization, the boron content decreased to ~ 0.5%.

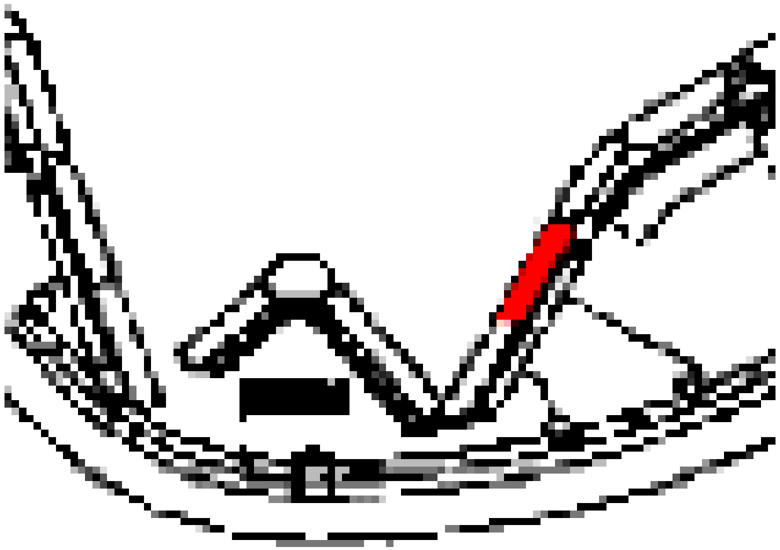
Boronization using 70 g of $B_{10}D_{14}$ suppressed the core oxygen content $\leq$ ~ 1.0% in 400 - 500 shots. The durability of boronization using 20 g is much shorter.

Continual boronization every 200 shots using 10 - 20 g of $B_{10}D_{14}$ successfully kept the core oxygen content $\leq$ ~ 1.0%.

5. Future works

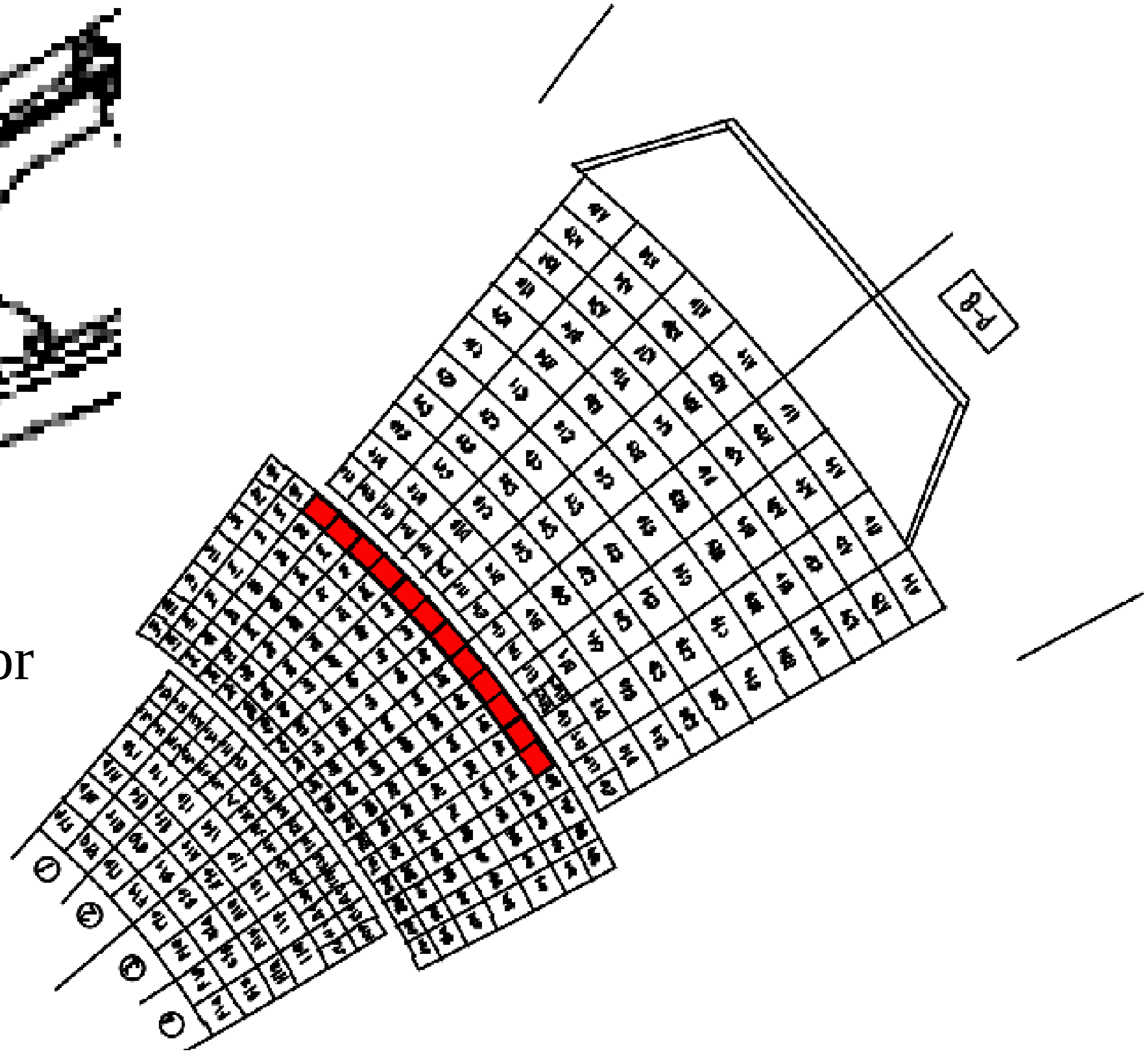
1. Collection of dust and debris in the vessl cooperation with Phil Sharjp (INEEL)
2. Installation of 13 tiles of W(50μm) on C at outer divertor
3. Erosion and deposition measurements with installation of specially designed tiles
4. Collector probe measurement
5. Gas puff from outer divertor

Installation of 13 tiles of W(50µm)on C at outer divertor

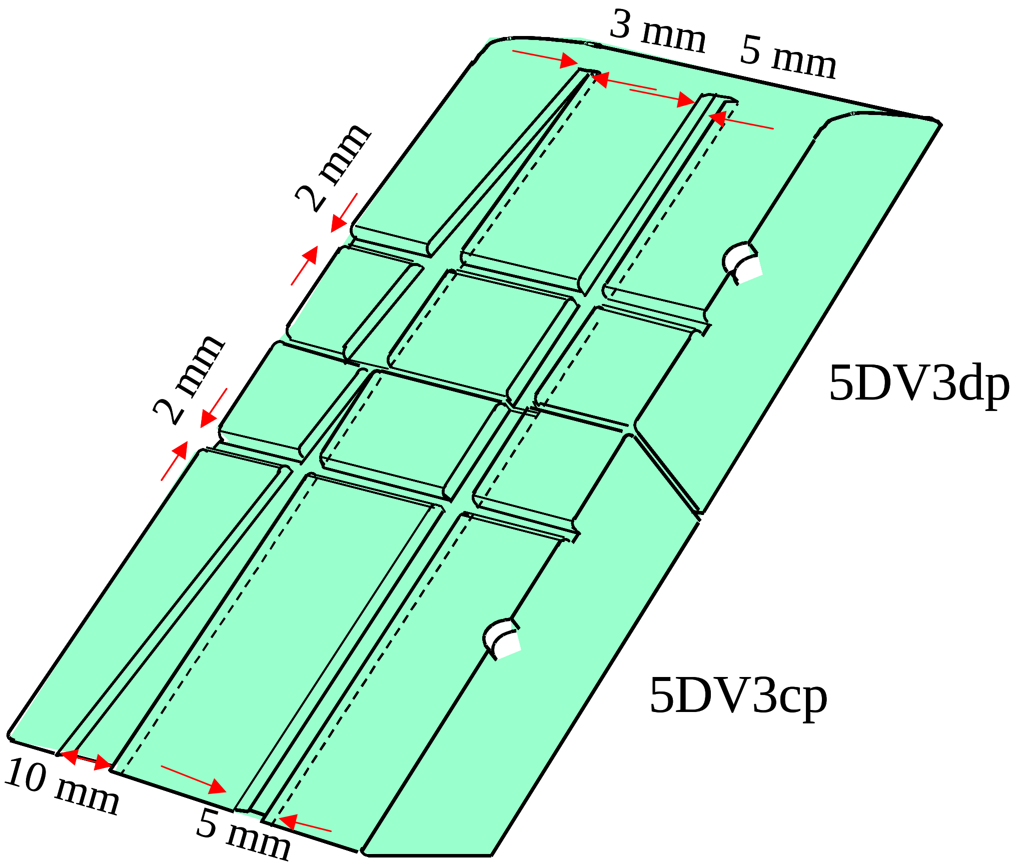


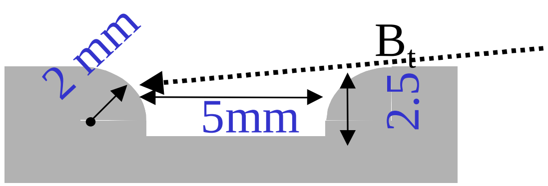
12 pieces at outer divertor

1 piece at inner divertor



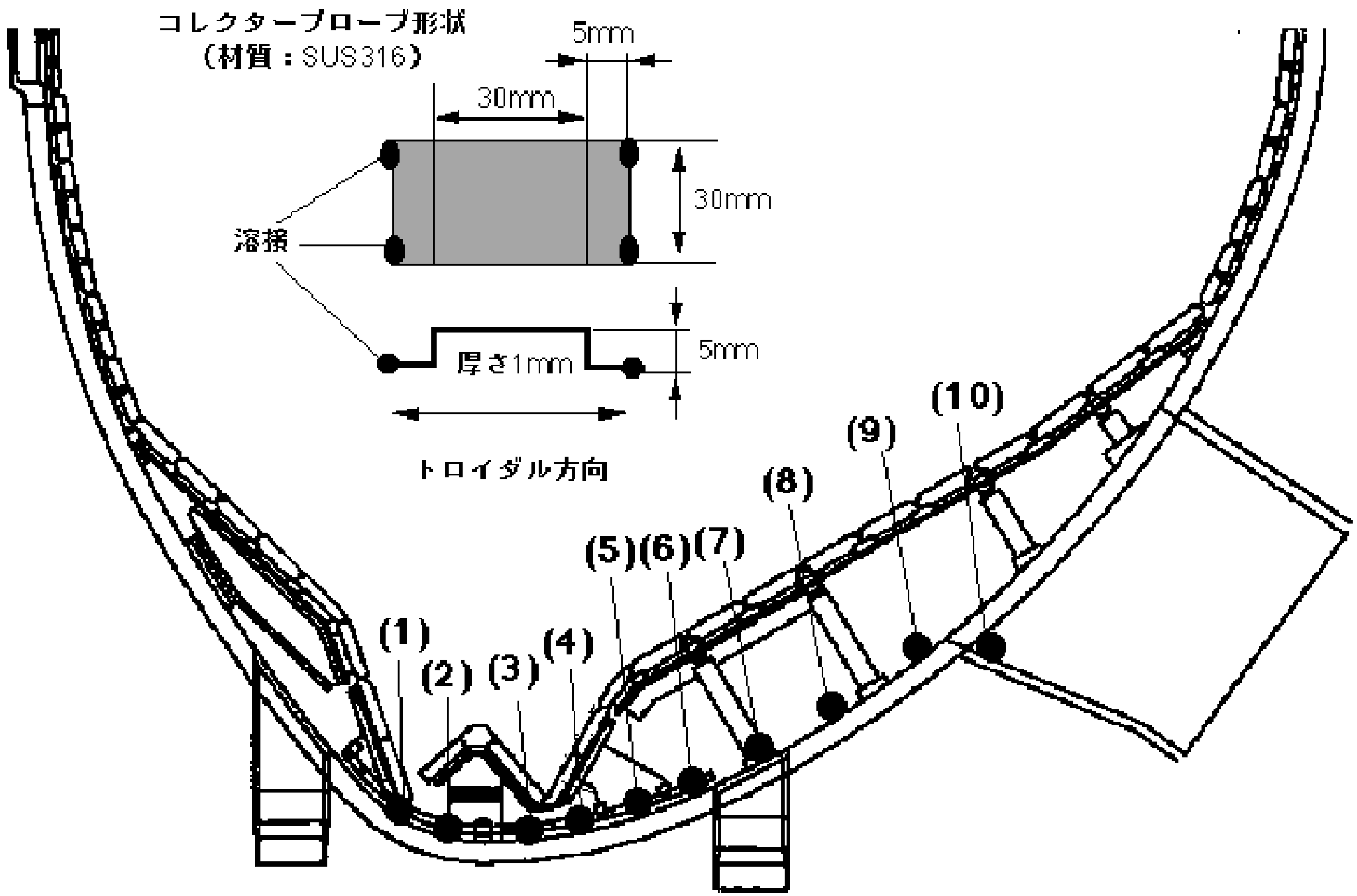
Erosion and deposition measurements with installation of specially designed tiles





Cross section of dip

Collector probe measurement



Gas puff from outer divertor

Planned

→ Introduction of $^{13}CH_4$ or $^{13}CD_4$ for impurity transport by spectroscopy and post mortem analysis)

→ Introduction of D_2 for chemical sputtering and hydrogen recycling by spectroscopy

→ Introduction of High Z gas for physical sputtering, transport, impurity behavior by spectroscopy and post mortem analysis

Workshop Agenda