平成26年度PWI合同会合
筑波大学 2014 7/31-8/1

LHD長時間放電におけるプラズマ壁相互作用

~ Microscopic modification of wall surface and its impact on particle balance and impurity generation ~

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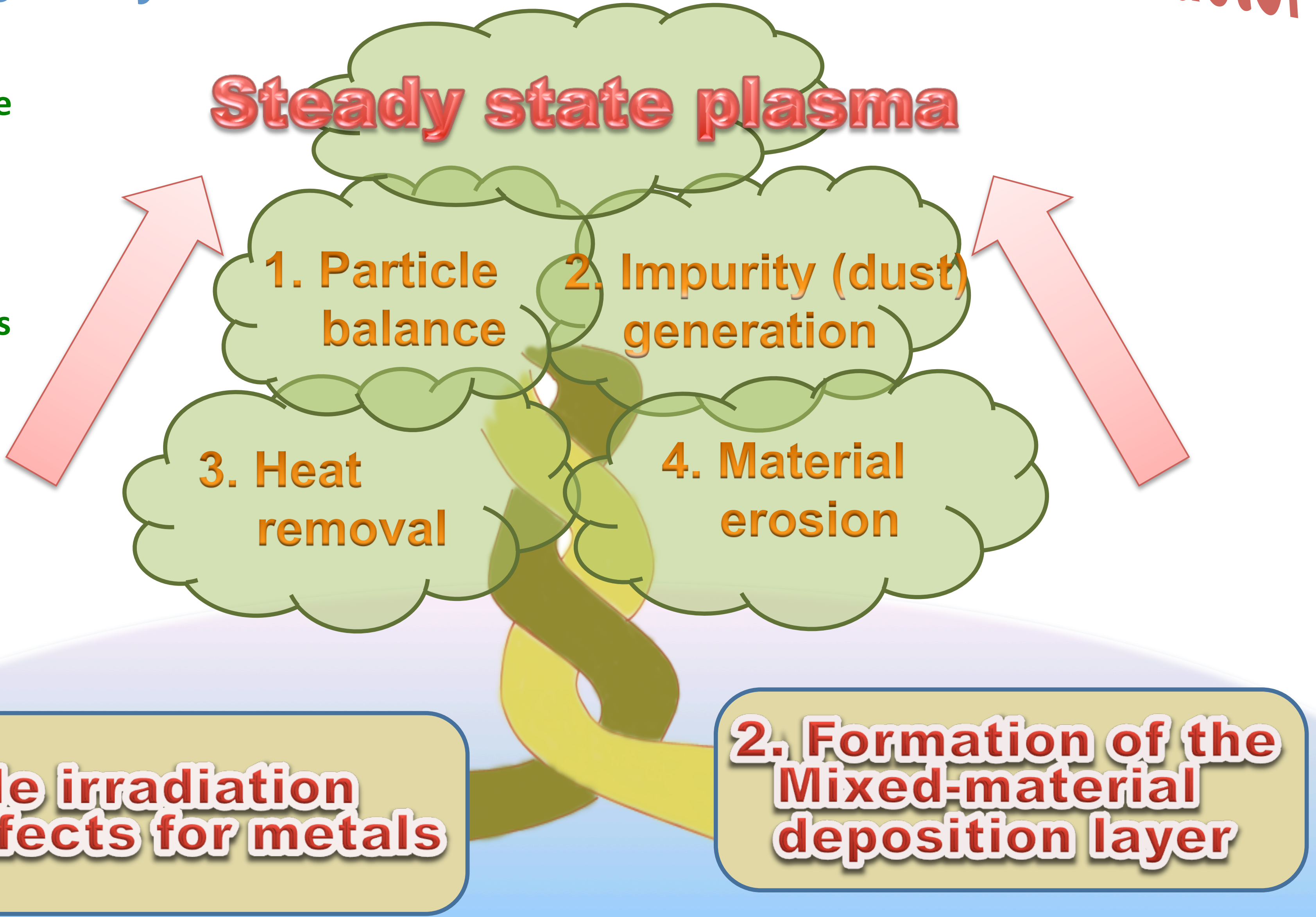
第18サイクル実験テーマグループ体制（平成26年度）

	実験テーマグループ	課題・役割	所内リーダーG
1	高性能化 （コアチーム）	・パラメータ領域の拡大実験 （高温度、高ベータ） ・重水素実験へ向けた予備実験 ・重水素実験シナリオの検討 ・重水素実験の研究計画策定	長壁（リーダー） 森崎・横山・磯部 （シナリオ・計画担当） 秋山（幹事） 榊原・永岡・高橋 （実験担当）
2	プラズマ物理工学 （周辺・PWI・定常・加熱物理・原子分子）	・周辺プラズマ ・定常プラズマ／壁との相互作用 ・原子分子過程 ・ECH/ICH加熱物理	坂本（リーダー） 笠原・時谷 後藤基 吉村泰
3	コア物理 （MHD・高エネ粒子・輸送）	・MHD安定性 ・高エネルギー粒子の閉込め/MHD ・輸送 ・摂動磁場/3次元物理	渡辺清（リーダー） 鈴木康 徳沢 田中謙
4	装置工学		濱口真司 力石浩孝

For steady state plasma operation in Fusion Reactor



Objective

Steady state plasma

Problems

1. Particle balance
2. Impurity (dust) generation
3. Heat removal
4. Material erosion

Physics

1. He irradiation effects for metals
2. Formation of the Mixed-material deposition layer

If we can completely understand and control about He and mixed-material effects, we would be able to get the steady state plasma operations.

Contents

1. Progress of Long pulse helium discharge in LHD

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(A) Dynamic change of the wall pumping rate Γ_{wall}

(B) Termination of the discharge with impurity mixing

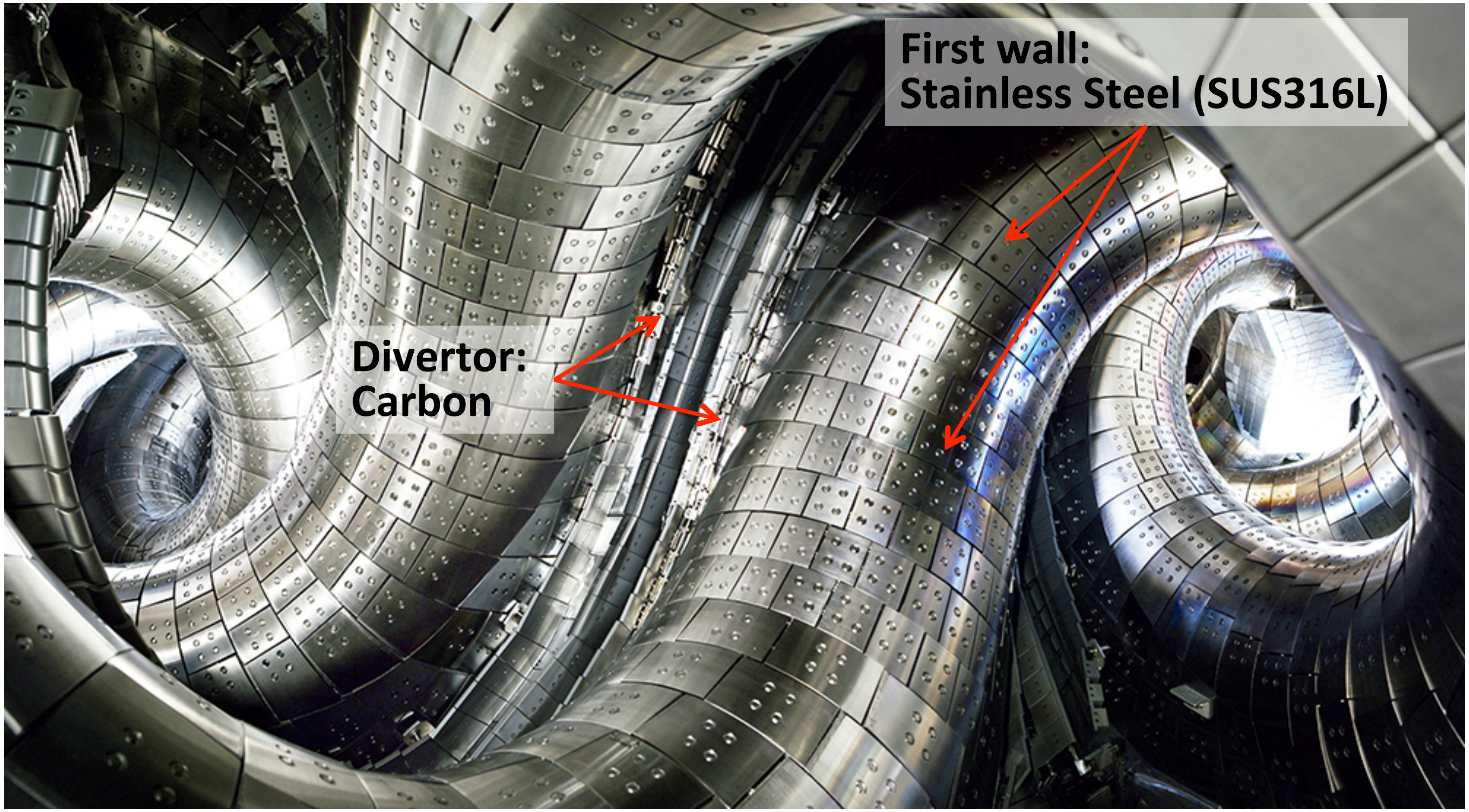
3. Highlight data

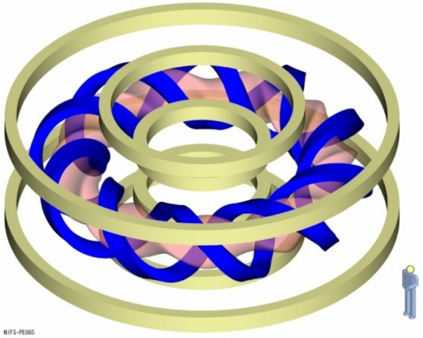
(A) Main mechanism of the continuous wall pumping capability Γ_{wall} during the long pulse discharges

(B) Exfoliation mechanism of the mixed-material deposition layer by nano-material characterization

4. Summary

Large Helical Device; LHD





- **Plasma facing components**
  - **Total area of PFCs: 780m^2**
  - **First wall panels: SUS316L (~730m^2)**
  - **Divertor plates: Graphite (~50m^2)**

External diameter: 13.5 m
Plasma major radius: 3.9 m
Plasma minor radius: 0.6 m
Plasma volume 30 m^3
Magnetic field: 3 T

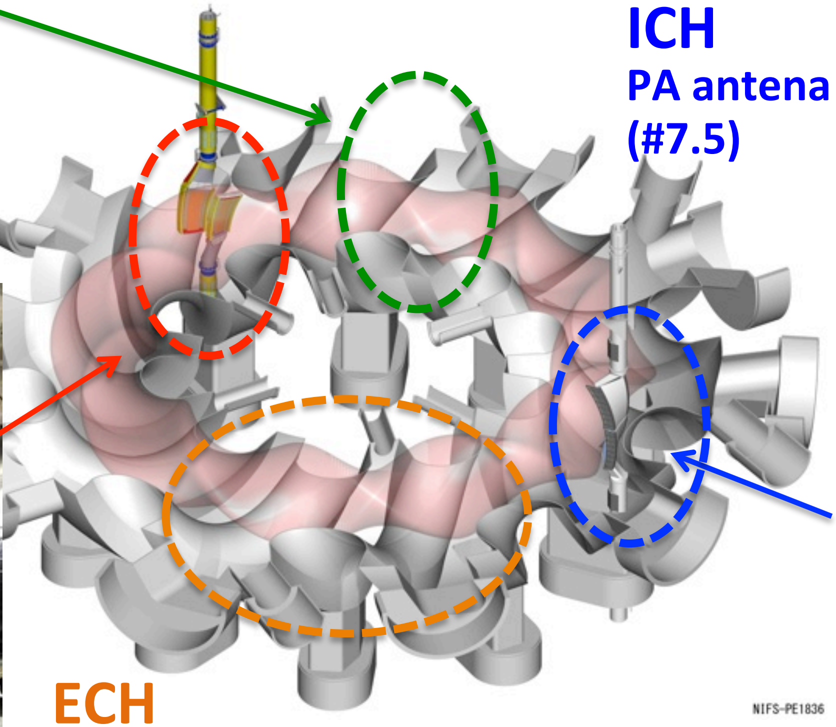
RF heating system for long pulse discharge

◆ For a long pulse discharge experiment

- ◆ H minority ICH+ECH He discharge is the main process
- ◆ Total RF power for a “long pulse” discharge
  - ICH: 3MW in total
  - ECH: 0.54MW in total

ICH
FAIT antenna
(#4.5)

ICH
HAS antenna
(#3.5)

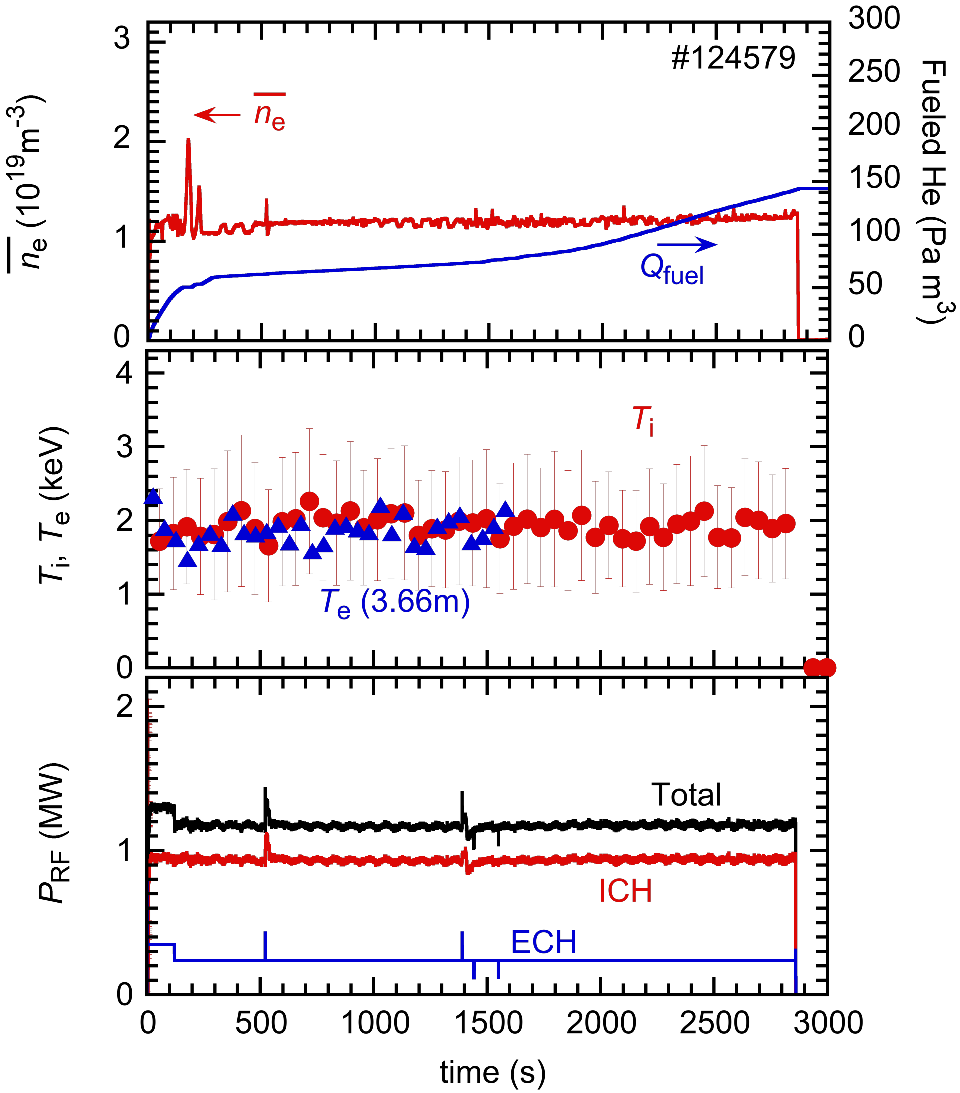


ICH
PA antena
(#7.5)

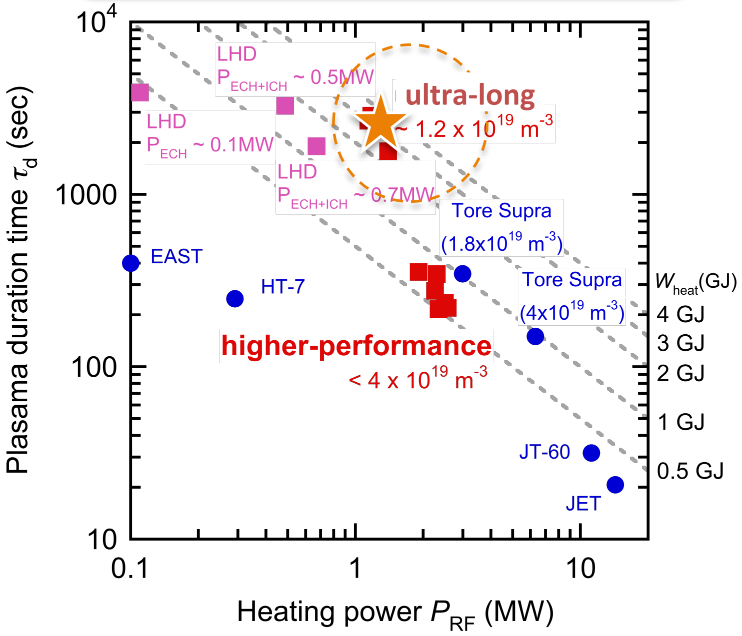
ECH
77GHz(×3), 82.7GHz,
84GHz, 154GHz (6 set in total)

Progress of long pulse helium discharge in LHD

- **n_e~1.2×10^{19} m^{-3}, $T_{i,e}$~2 keV, τ_d~48 min. with $P_{ICH+ECH}$~1.2 MW**
  W_{heat}~3.6 GJ (world record)



Outstanding achievement for a new operation regime

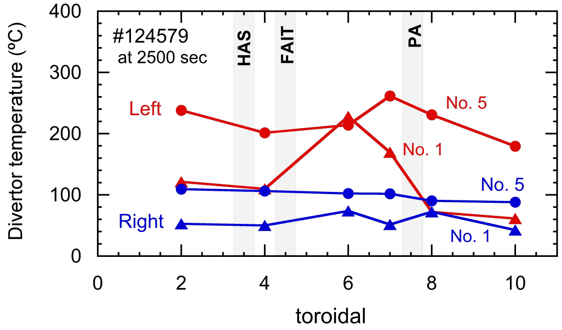


Robust plasma by higher power input

◆ Contributed tools for **the ~48 min** long pulse

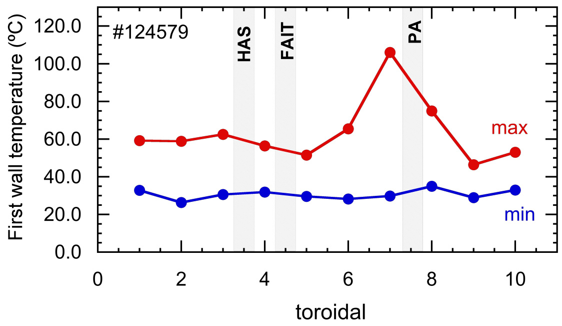
1. **Feedback controlled gas feed system**
2. **Efficient minority gas (H) ratio control system (SSGP, gas-puff)**
3. **Effective heat flux distribution by three sets of ICH antennas**

Divertor heat loading



$P_{div\ avg}$ ~ 0.8 MW/m²

First wall



~ 60℃

High temperature plasma ($T_{i,e}$~2 keV) with high input power $P_{ICH+ECH}$~1.2 MW

Plasma was changed to the robust conditions against the small fluctuation event

High performance ultra-long pulse discharges

Contents

1. Progress of Long pulse helium discharge in LHD

2. Objective

: Two uncontrollable issues against the steady state ultra-long pulse discharge in LHD

(A) Dynamic change of the wall pumping Γ_{wall}

(B) Termination of the discharge with spark (impurity mixing)

3. Highlight data

(A) Main mechanism of the continuous wall pumping capability Γ_{wall} during the long pulse discharges

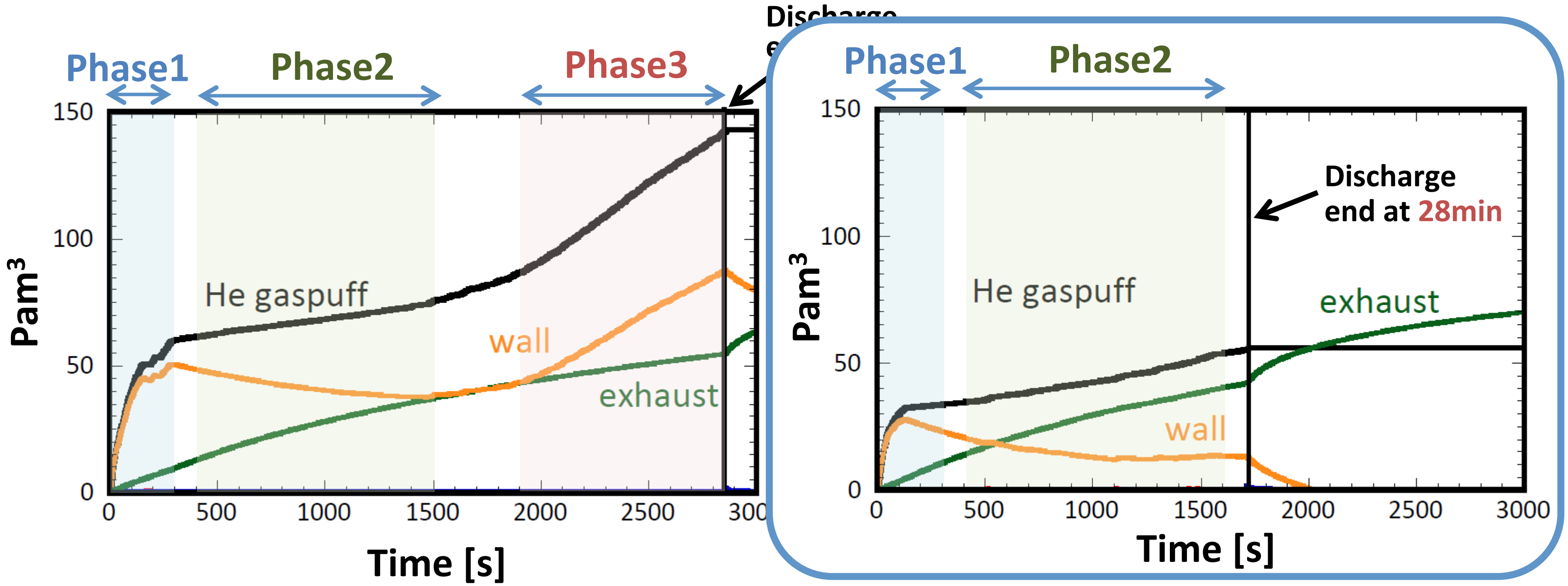
(B) Exfoliation mechanism of the mixed-material deposition layer by nano-material characterization

4. Summary

(A) Dynamic change of the wall pumping rate

G. Motojima

Time evolution of a total amount of the evacuated He by pump and the retained He on the wall estimated by global particle balance



	Phase 1	Phase 2	Phase 3
Γ_{wall}	~1.0×10^{20}He/s	~-3.5×10^{18} He/s	~1.4×10^{19}He/s

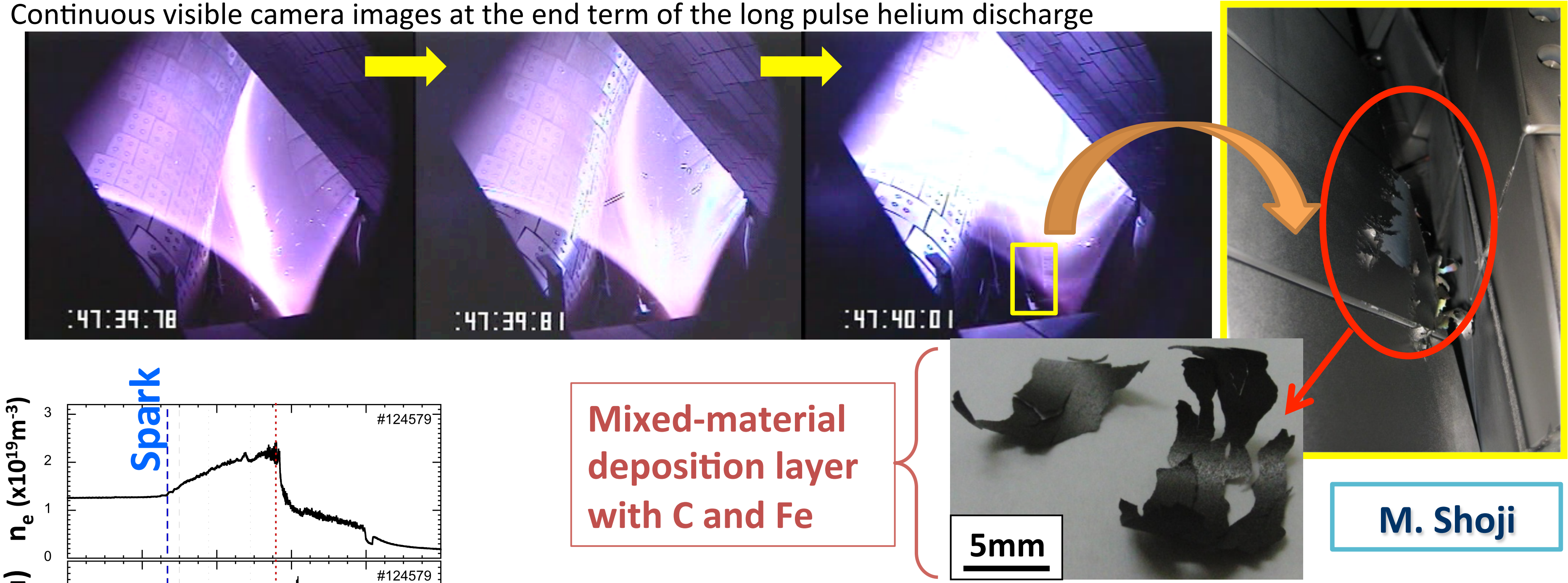
☐ The electron density (n_e) was well controlled by gas feedback system during the discharge, however, Γ_{wall} changed differently in the three phases (not static).

☐ Such a dynamical change of Γ_{wall} disturbs the stable particle control.

Neutral He (P_{vv} x 245 m^3) and Plasma particle (n_e x 30 m^3) are negligible small

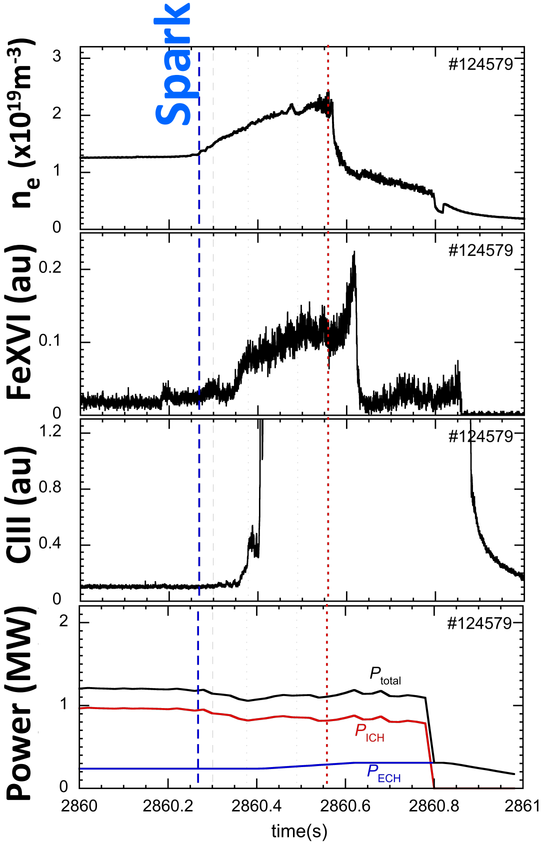
(B) Termination of discharge with impurity mixing

Continuous visible camera images at the end term of the long pulse helium discharge



Mixed-material deposition layer with C and Fe

M. Shoji



◆ Termination process

1. **Intensive sparks were observed at the divertor region.**
2. **C and Fe emission suddenly increased at the same timing of the spark.**
3. **Accumulated deposition layer was likely exfoliated and mixed into the plasma with sparks.**

Two uncontrollable issues

◆ For achievement of the steady state ultra-long pulse discharge

(A)

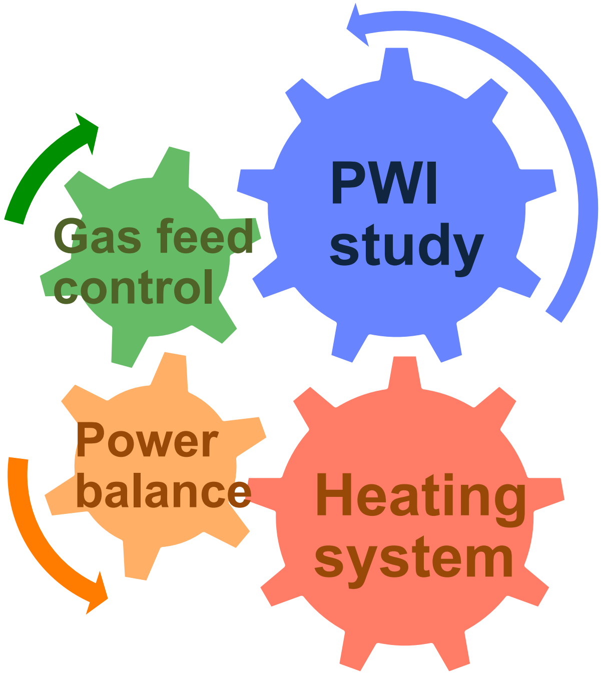
Dynamic change of the wall pumping Γ_{wall}

Dynamic change of Γ_{wall}

↓

Disturbs the stable particle control.

1. Particle balance



(B)

Termination of the discharge with impurity mixing

C and Fe mixing by exfoliated flakes.

↓

Termination of plasma

2. Impurity (dust) generation

◆ Microscopic modification of wall surface would affect **Particle balance** and **Impurity (dust) generation**

A) Main mechanism of the continuous wall pumping capability Γ_{wall} during the long pulse discharges.

B) Exfoliation mechanism of the mixed-material deposition layer by nano-material characterization.

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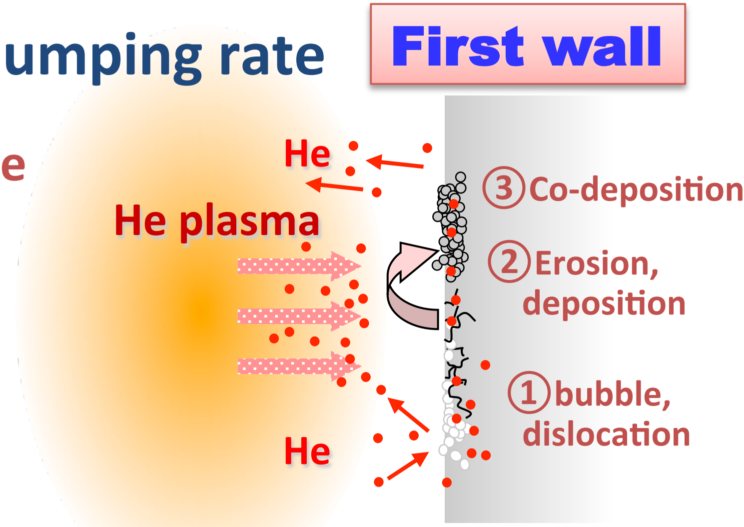
(A) Dynamic change of the wall pumping rate

☐ Possible scenario for change of the wall pumping rate



Microscopic modification of the first-wall surface
(He radiation damage, Deposition layer)

He was retained on the modified surface

He sink and He source change dynamically

Affects the wall pumping rate

Which types of a surface modification affects the dynamic change of the wall pumping rate?

Material probe experiment

- Surface modification
- Retention properties of He

Compare

0-D global particle balance

G. Motojima
P3-042 (Thu.)

Material probe experiment

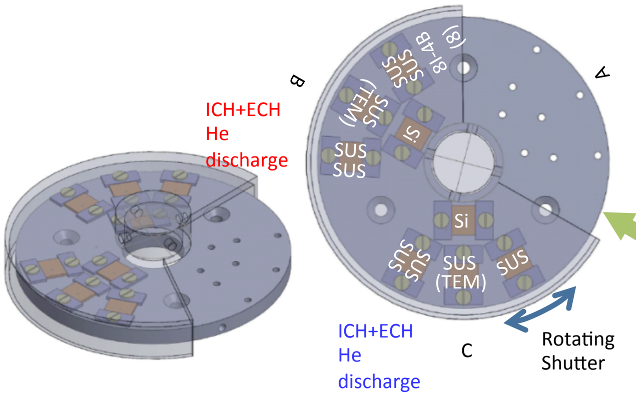
☐ Experimental set up for material irradiation

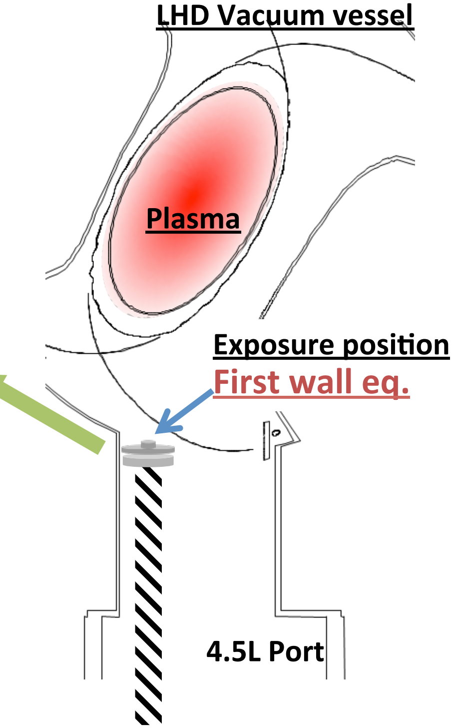
- Stainless steel (SUS316L) specimens were mounted on the probe head
- They were inserted into a first-wall eq. position.
- Exposed to the preference plasma by using the rotating shutter

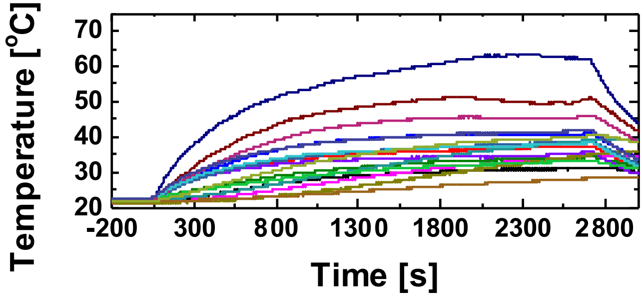
Target plasma parameter:

- $n_e \sim 1.2 \times 10^{19}\ m^{-3}$,
- $T_{i,e} \sim 2$ keV,
- $P_{ICH+ECH} \sim 1.2$ MW

Three cases of target exposure time: [1000s], [3000s], [10000s] in total







Time evolution of temperature of typical first wall positions during a long pulse discharge.

☐ Material analysis

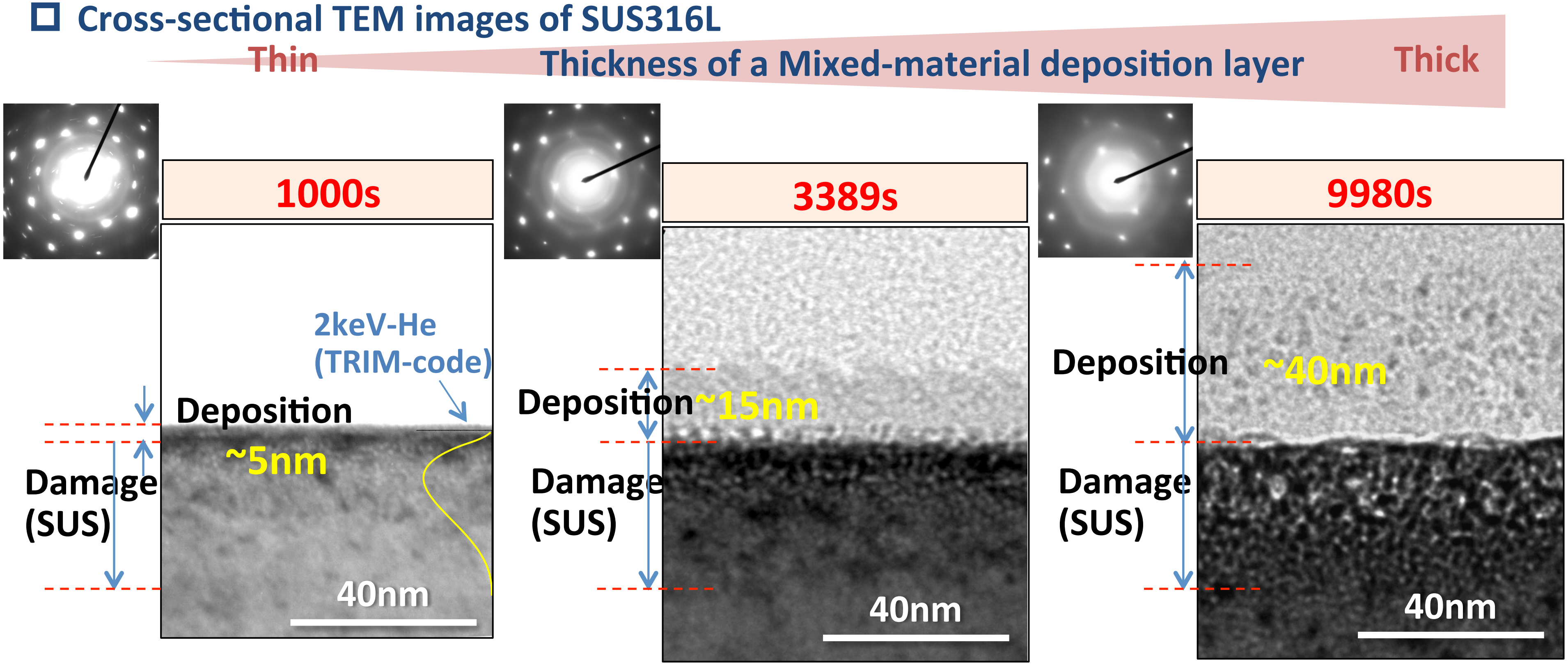
- Transmission electron microscope (TEM)
- Thermal desorption spectroscopy (TDS)
- Rutherford backscattering spectrometry (RBS)

☐ From analysis data

- Average wall pumping rate was estimated

Characteristics of the deposition layer

☐ Cross-sectional TEM images of SUS316L



Thickness of the deposition layer was increased with increasing the exposure time

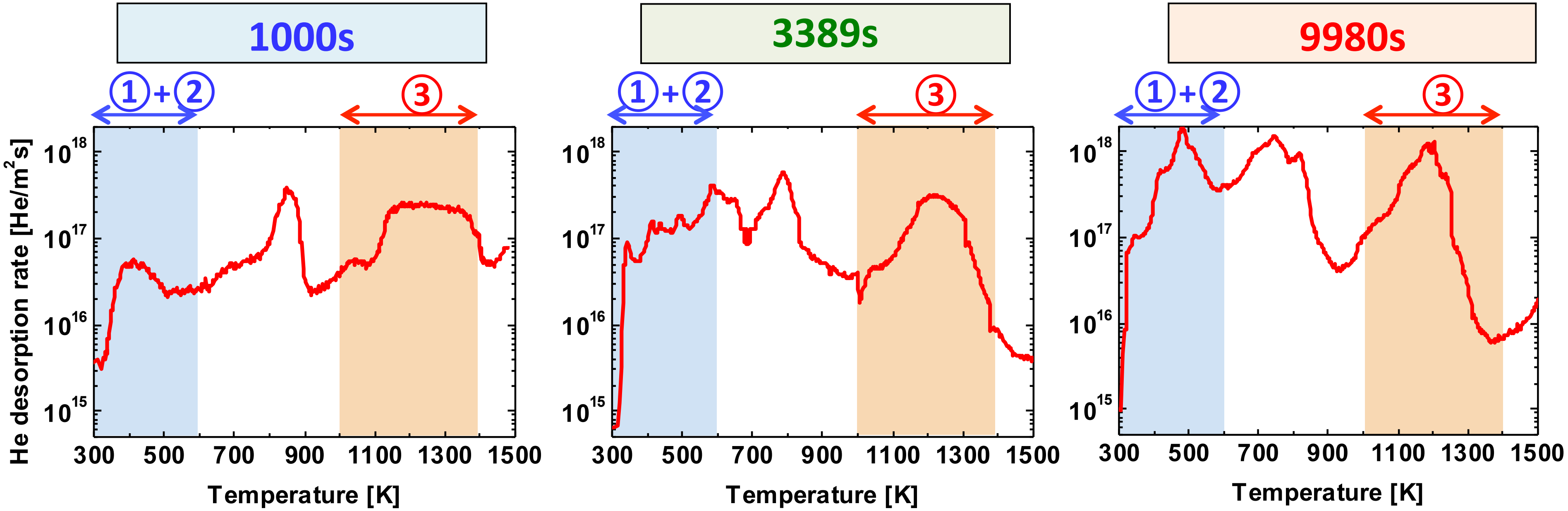
☐ Atomic concentration of the deposition layer (by RBS)

Main component is C→

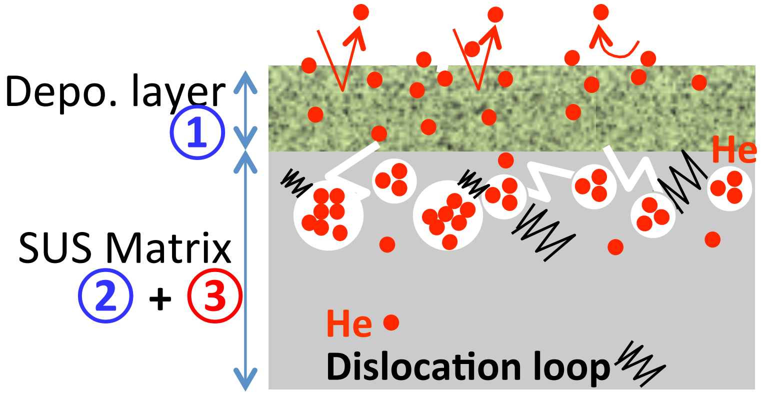
	3389s	9980s
C [atoms/m^2]	2.6×10^{21}	3.7×10^{21}
Fe [atoms/m^2]	3.0×10^{19}	3.8×10^{19}
Mo [atoms/m^2]	7.0×10^{17}	2.3×10^{18}

C : 98%,
Fe : 1 ~2%

Thermal desorption spectra of He



- **Low temperature: ~ 300-600K**
  - **① Mixed-material deposition layer**
  - **② Weak trapping site in the SUS matrix**
- **High temperature: ~ 1000-1400K**
  - **③ Inside of the He bubble**

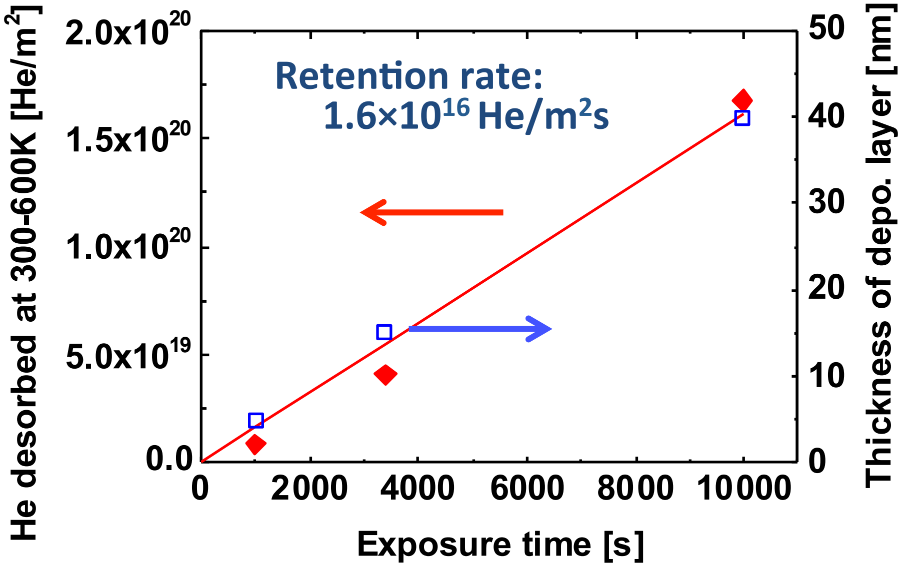


Helium trapped in the helium bubbles would not make any serious effect for long pulse discharge.

Helium trapped in the mixed-material deposition layer (**300-600K**) could affect the dynamic change of the wall pumping rate.

Wall pumping rate by mixed-material

☐ **Relationship of total retention of He desorbed at 300-600K and thickness of the mixed-material depo. Layer as a function of an exposure time**



- Amount of He retention is linearly proportional to the thickness of the Mixed-material deposition layers.
- Saturation of a He retention cannot be seen even at around 10000s

Total amount of an average retention rate in whole LHD first wall:

1.6×10^{16} He/m^2s x 730 m^2= **1.2×10^{19} He/s**

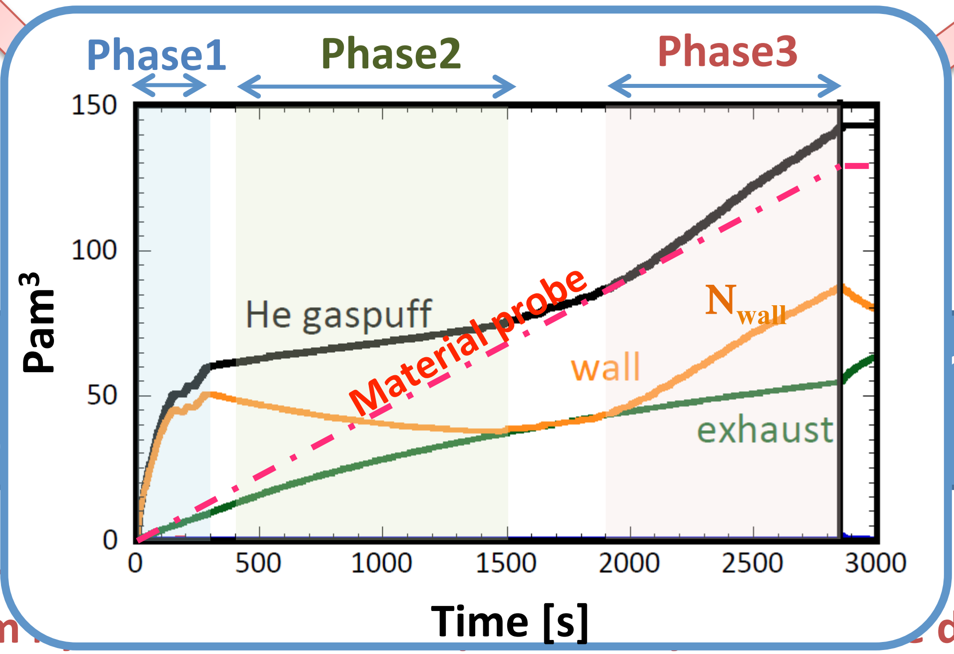
Comparison of the wall pumping rate

Material probe experiment ⇔ Compare ⇔ **0-D global particle balance**

[G. Motojima P3-042 (Thu.)]

1.2×10^{19} He/s

	Phase 1	Phase 2	Phase 3
Γ_{wall} [He/s]	~1.0×10^{20}	~-3.5×10^{18}	~1.4×10^{19}



Even at a C ba
play a major r

In ITER case, since ma
characteristics of helium
different
with LHD case. However, dynamic change of the wall pumping rate might be induced and influenced for a steady state plasma control.

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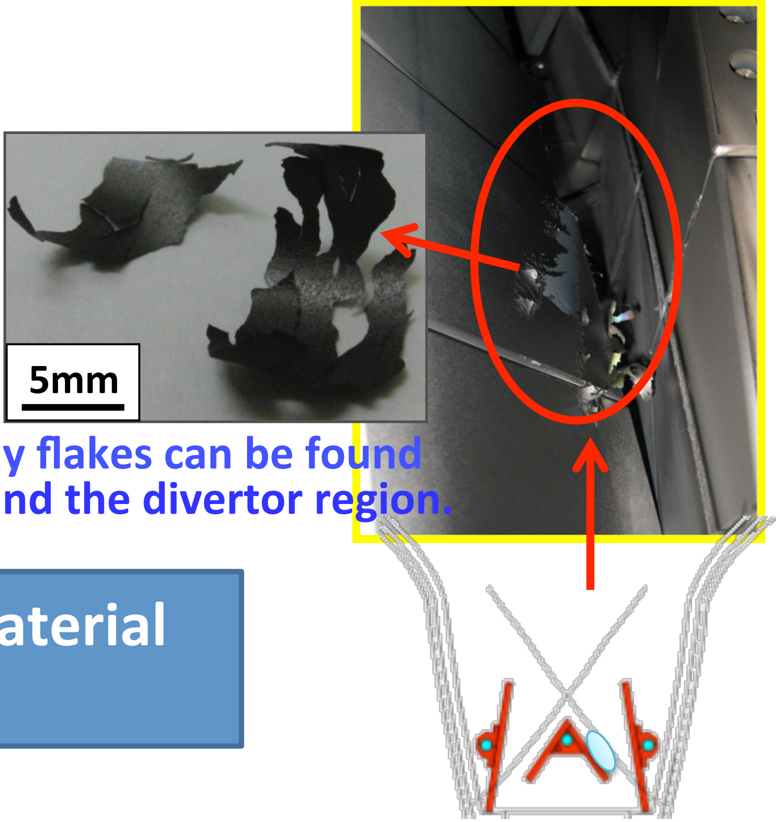
(B) Termination of the discharge with impurity mixing

☐ Possible scenario of impurity mixing

Mixed-material deposition layer with C and Fe is formed on the PFMs

⬇

Exfoliate from the substrate and mix to the plasma



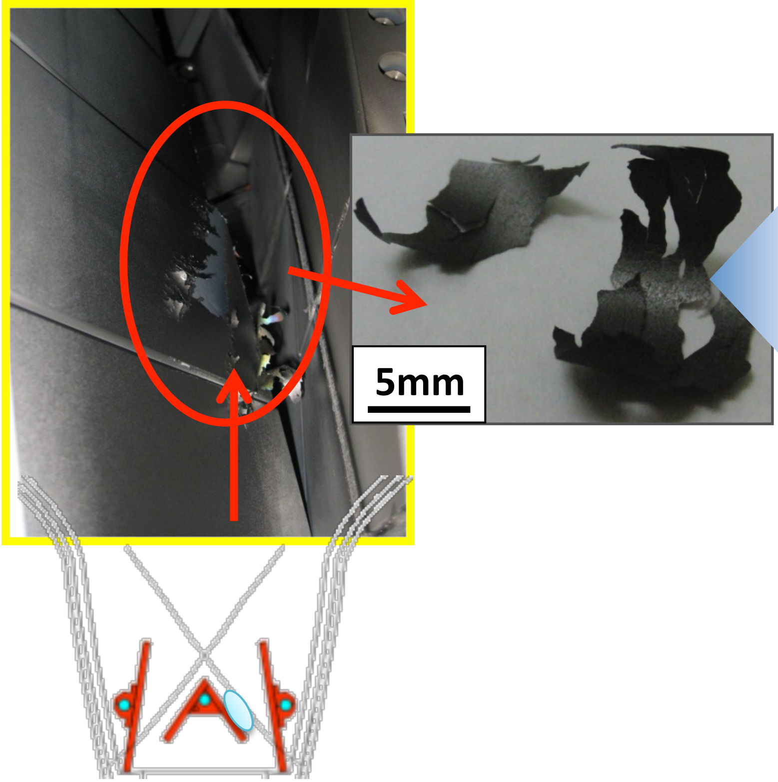
- Many flakes can be found around the divertor region.

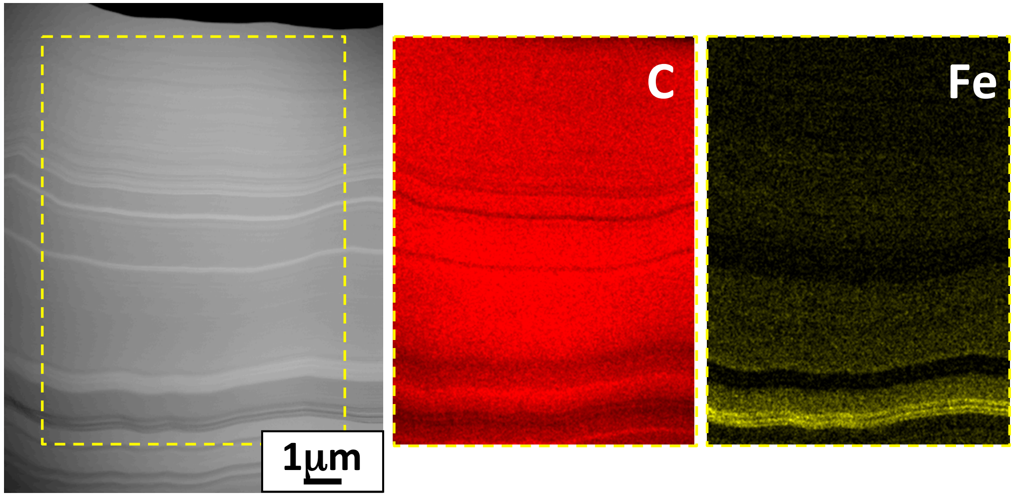
Exfoliation mechanism of the mixed-material deposition layer should be clarified.

1. Microstructural characterization
2. Evaluation of mechanical properties
3. Possible scenario of the exfoliation of the mixed-material deposition layer

Microstructural characterization by TEM

Cross-sectional TEM images and EDS mapping of the exfoliated mixed-material deposition layer formed on the divertor region



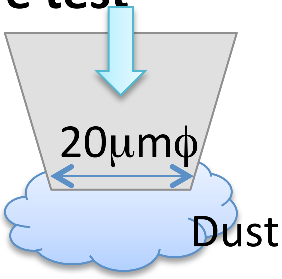


- Very fine stratified layer structure [1].
- Main component is C (~90%).
- It was created by erosion and re-deposition of a carbon divertor tiles through a short range transport of C.

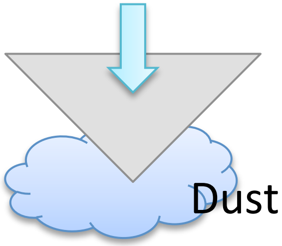
[1] M. Tokitani et al., J. Nucl. Mater. 417 (2011) 668

Evaluation of mechanical properties

☐ **Nano-scale compression fracture test**

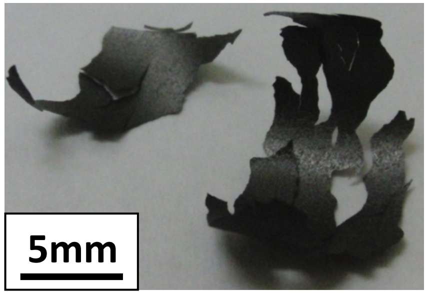


☐ **Nano-scale hardness test**

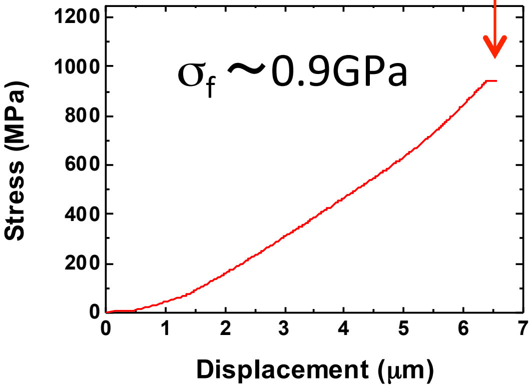


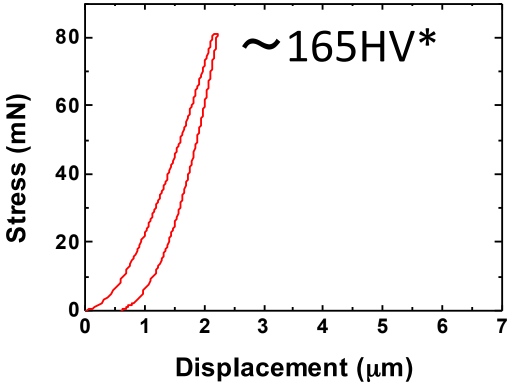
Triangular Pyramid Indenters
Apex angles: 115˚
Radius of curvature of tip : less than 0.1μm

C rich (～90%) with Fe



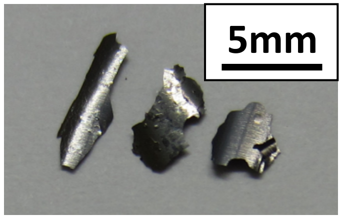
× Fracture



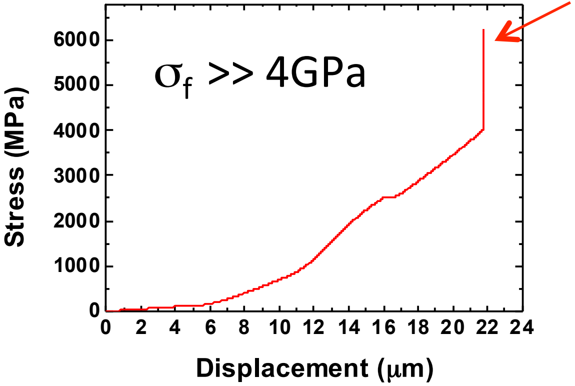


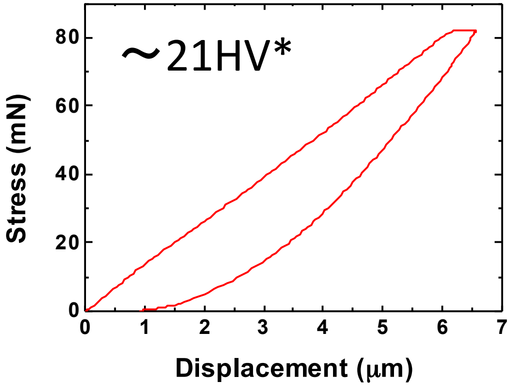
➢**Hard and brittle**

Fe rich (～80%) with C



No fracture



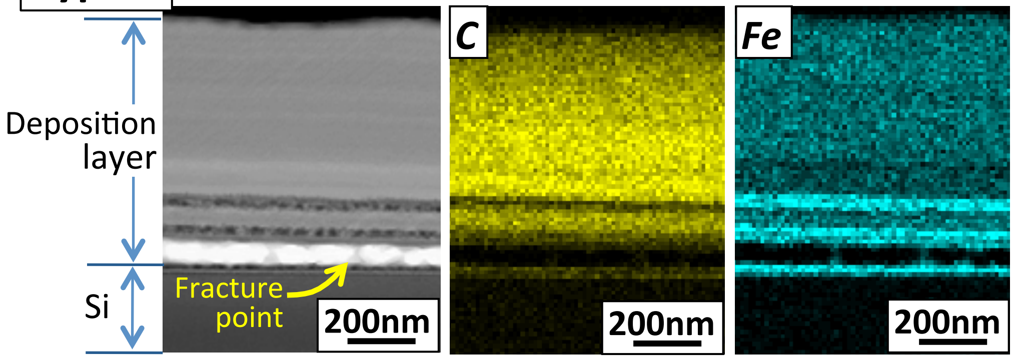


➢**Soft and ductile**

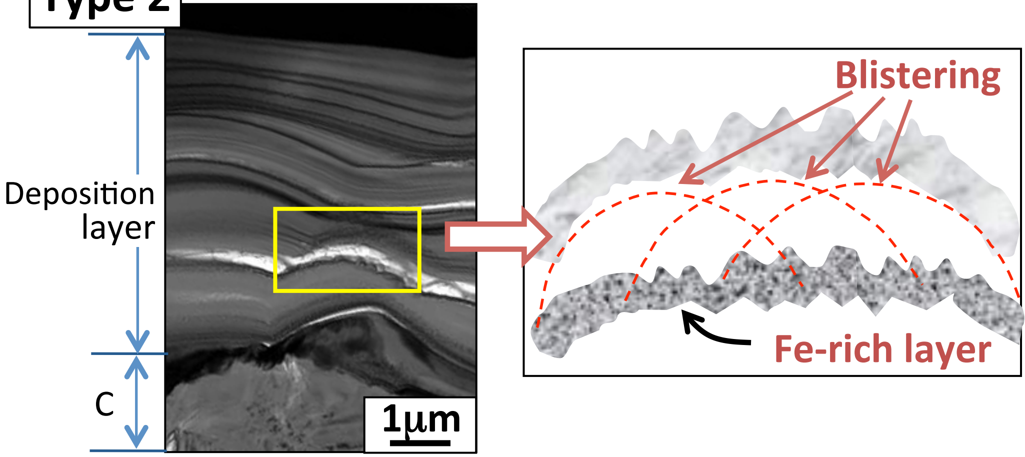
C rich depo. layer is hard and brittle → Easy to exfoliate than Fe rich layer

Two types of an exfoliation pattern

Type 1

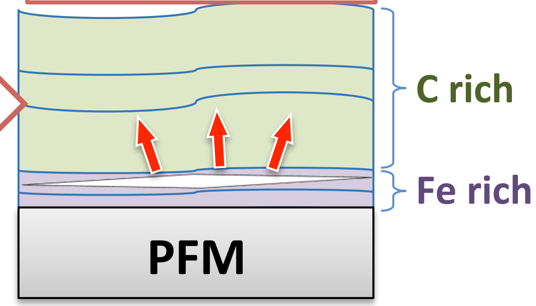


Type 2

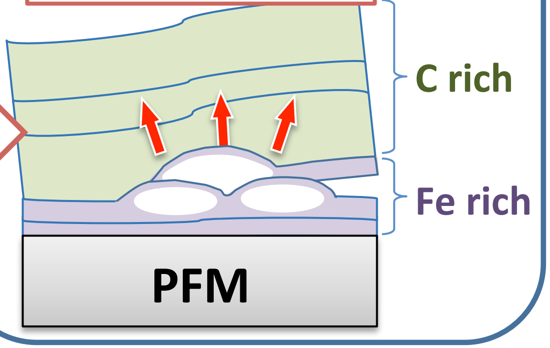


Possible scenarios of exfoliation

Stress release
“Fracture at Fe layer”



Blistering growth
“Fracture at Fe layer”



The possible way for reducing the exfoliation

1. Material use with low sputtering yield
2. PFMs should be composed by a single element

Summary

Two major PWI issues (A) and (B) for achievement of the steady state ultra-long pulse discharge were studied

(A) Dynamic change of the wall pumping rate Γ_{wall}

- The microscopic modification, such as helium radiation damage and mixed-material deposition layers due to the PWI were formed on the first-wall surface.
- The C based mixed-material deposition layer seems to cause the continuous wall pumping capability. However, since the trapping energy of the helium into that deposition layer is weak and trapped helium is dramatically released even at near room temperature (~400 K). Desorbed helium from this trapping site likely causes the "dynamic change of the wall pumping rate“.

(B) Termination of the discharge with impurity mixing

- The C based mixed-material deposition layer was hard and brittle. Such material properties likely affected the exfoliation feature of the mixed-material deposition layer
- Two kinds of exfoliation scenario Type 1 and Type 2 were proposed, and its information is helpful for predicting the mixing scenario of the mixed-material deposition layer to plasmas.

One of the effective candidate methods for controlling the two major issues would be that the materials of the PFMs should be composed by a single element with low sputtering yield.