# Direct measurement of dynamic retention from plasma exposed tungsten & stainless-steel type 316L specimen using Fast Ejecting System of Targeted Sample (FESTA) on QUEST

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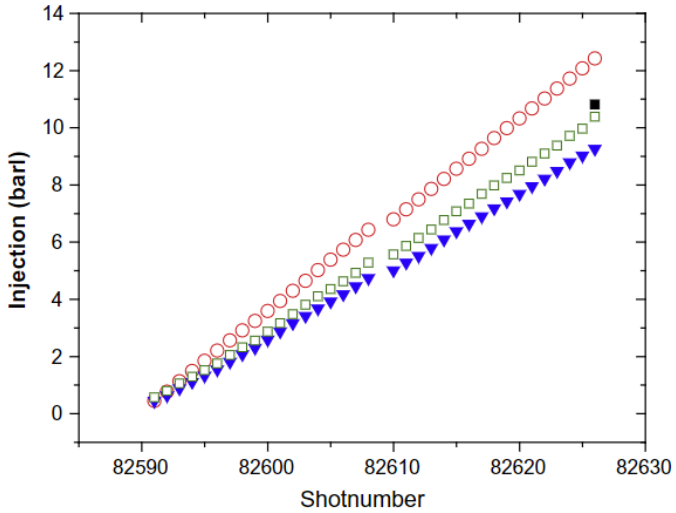
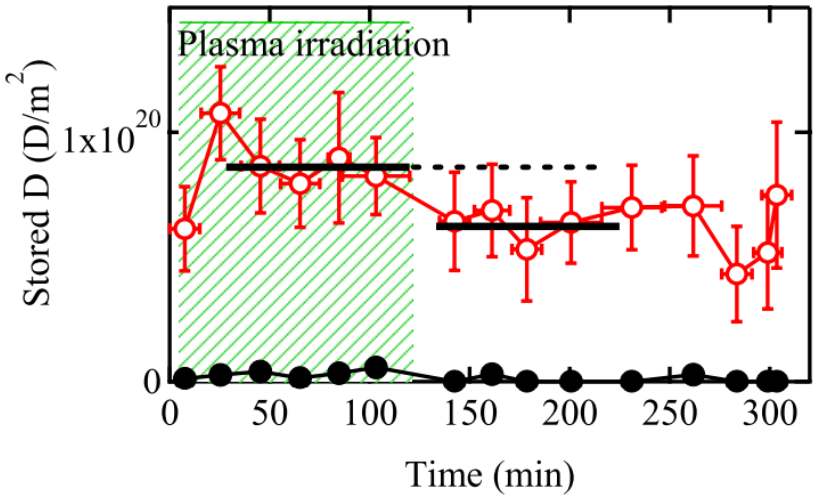
# Motivation

- Steady State Operation (SSO) of plasma is necessary to realize nuclear fusion power generation in the future.
- Adoption of metallic materials (W, Be, etc.) in PFWs is promoted to reduce wall-stored particles but induce an excessive desorption (recycling ratio R >1) of fuel particles.
- Impact on SSO: density runaway, plasma temperature decrease, plasma dilution, even plasma termination.



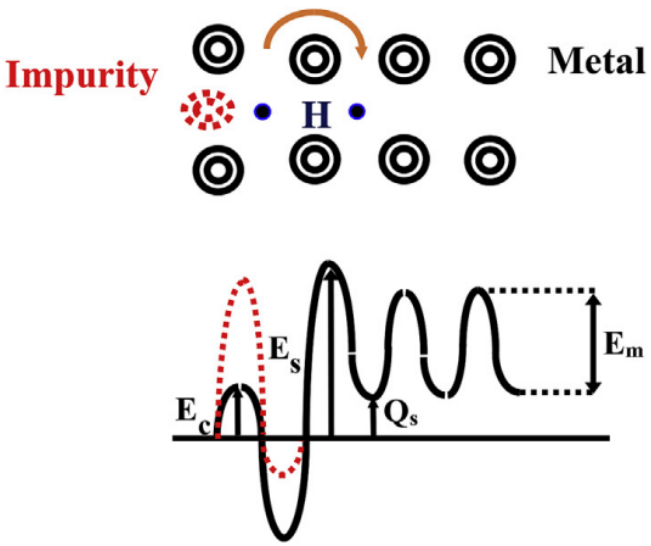

V. Philipps et al., J. Nucl. Matr. 438 (2013) S1067-1071




K. Hanada et al 2019 Nucl. Fusion 59 076007

# Surface conditions of PFWs largely influence particle recycling and FESTA was developed to evaluate them during plasma discharges

- Surface conditions on PFWs closely related to surface barrier $E_C$, especially metal materials such as W are proved to be significant on dynamic retention from PFWs due to surface recombination effect.
- A small change of $E_C$ causes huge changes on the surface recombination of PFWs, the measurement of dynamic retention and the evaluation of $E_C$ <u>during plasma discharges becomes important</u>.
- **F**ast **E**jecting **S**ystem of **T**argeted s**A**mple (FESTA) was developed.

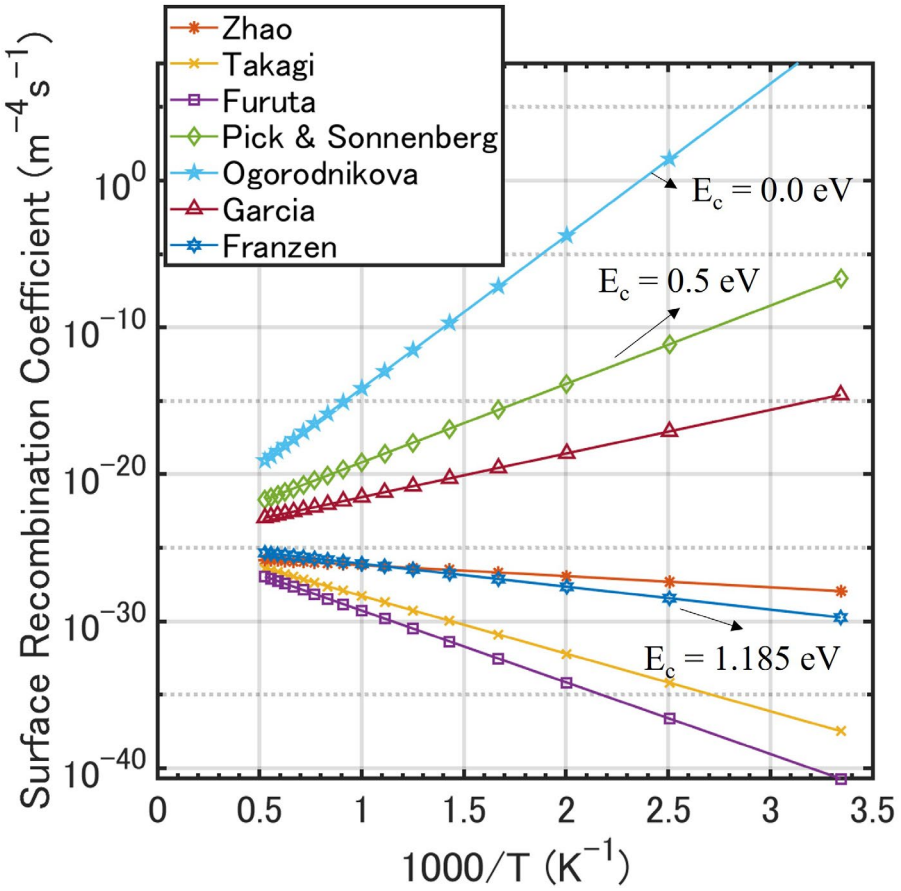



surface recombination coefficient $K_r = \frac{s\mu}{K_s^2}$

solubility $K_s = K_{s0}\exp(-\frac{Q_s}{kT})$

sticking coefficient $s = s_0\exp(-\frac{2E_c}{kT})$

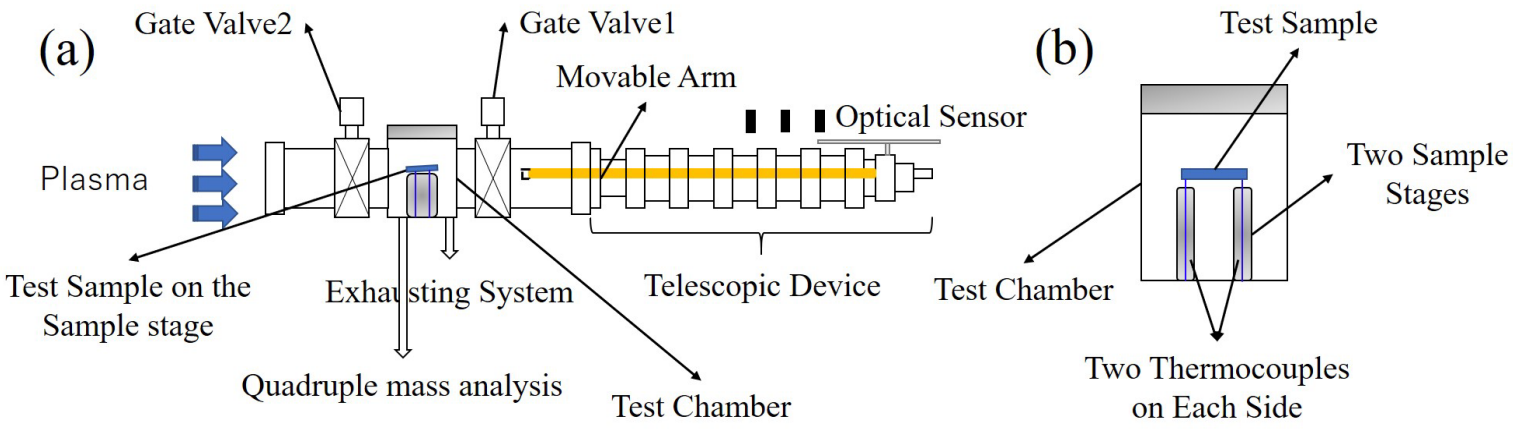
$\Rightarrow K_r = \frac{s_0\mu}{K_0^2}\exp(-\frac{2E_c-2Q_s}{kT})$





O.V. Ogorodnikova 2019 J. Nucl. Mater.
J. Roth and K. Schmid 2011 Phys. Scr.
M.A. Pick and K. Sonnenberg 1985 J. Nucl. Mater.

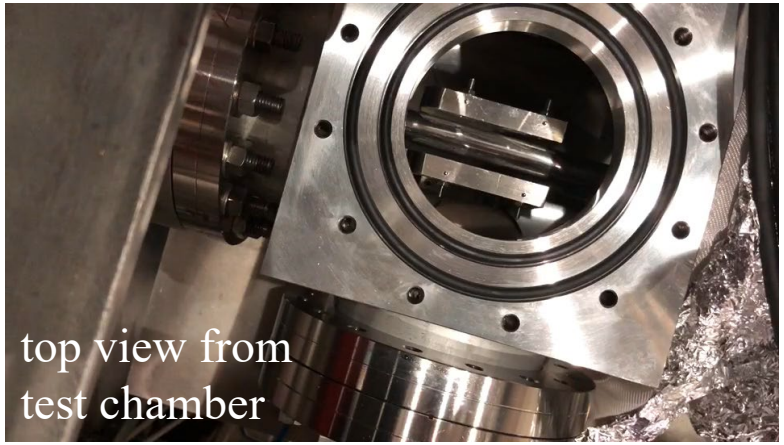
# FESTA [Q. Yue et al. 2020 Plasma Fusion Res. 15 240201] was developed to measure the particle recycling and to be able to decide $E_C$ during the plasma discharge.




(a) The structure of FESTA

(b) the profile of the test chamber from the plasma side. Two thermocouples on each side of the specimen stage, four in total.

## movement of FESTA

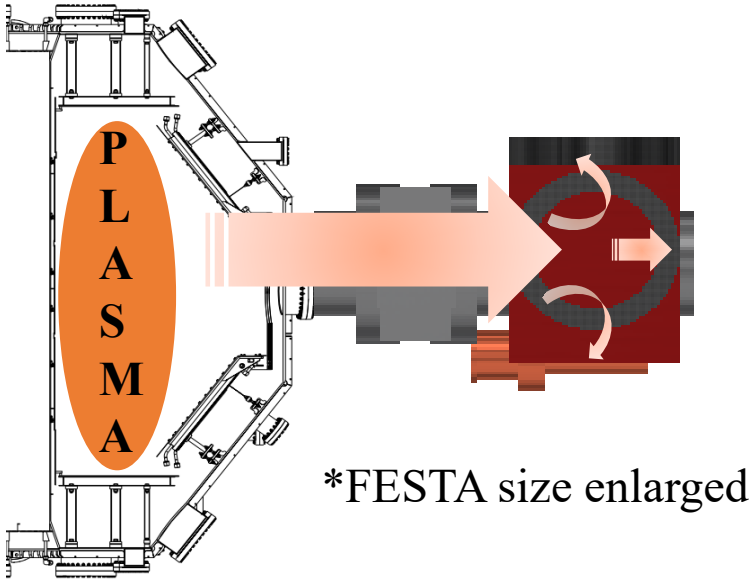




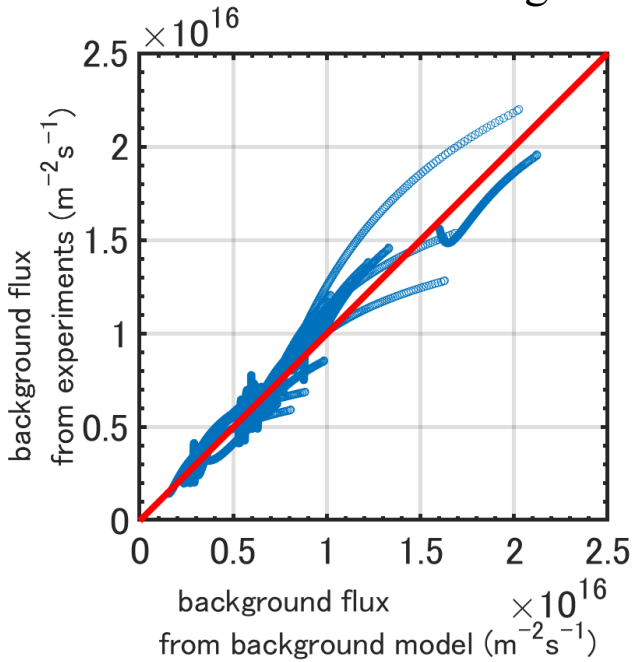
## Time scale of operating FESTA

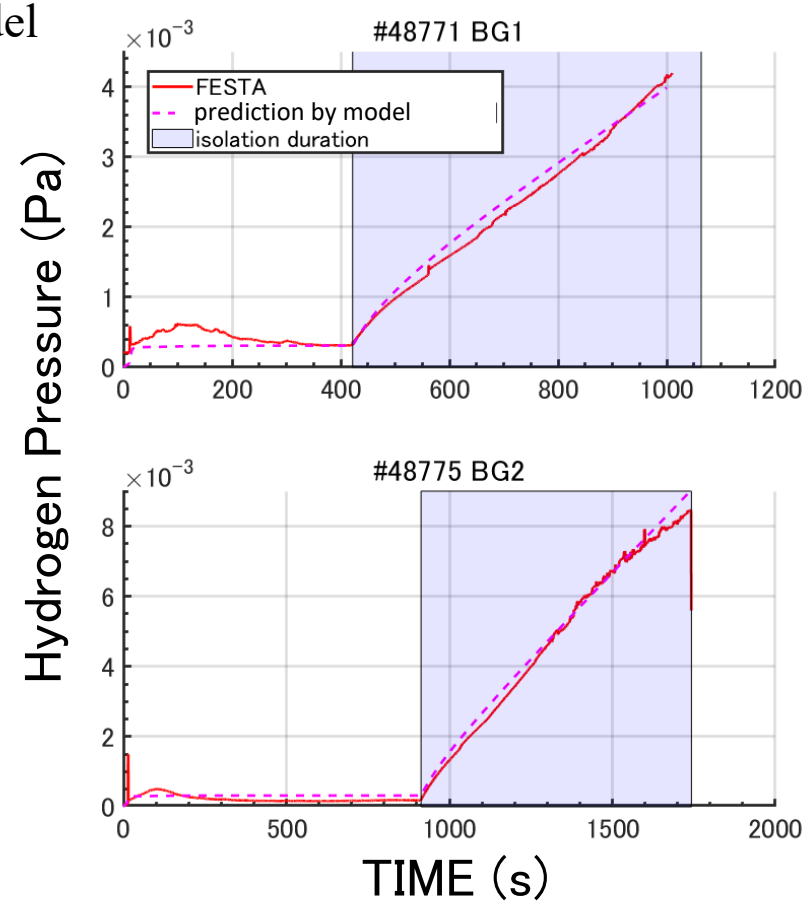
| FESTA operations | Required time (s) |
|---|---|
| End of specimen exposure | 0 |
| Closing gate valve 2 | 8 |
| Closing gate valve 1 | 2.8 |
| Measurement | Continuation |

# Background model was constructed [Q. Yue et al. 2020 PFR. 15 240201] to eliminate the influence from plasma-induced background




tolerance –error from background model



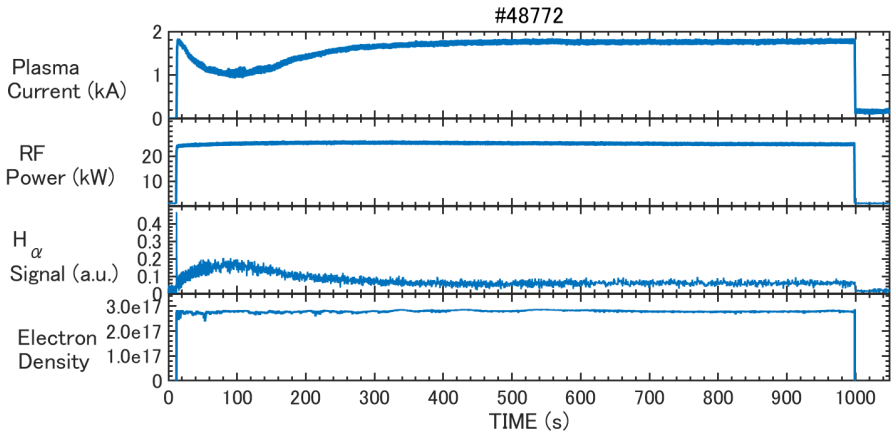

Measurement will be influenced by

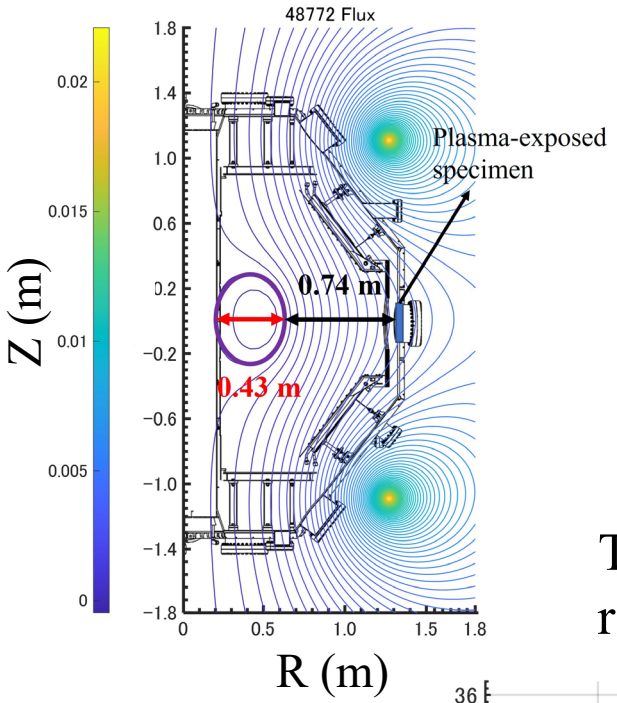
- High energy charge-exchange hydrogen atoms come into the test chamber and are adsorbed・stored by the test chamber wall, which is called plasma induced background.
- Low-speed neutral particles move back and forth due to the connection of QUEST vacuum chamber and FESTA test chamber.
- Outgas from the vacuum vessel wall is being released.

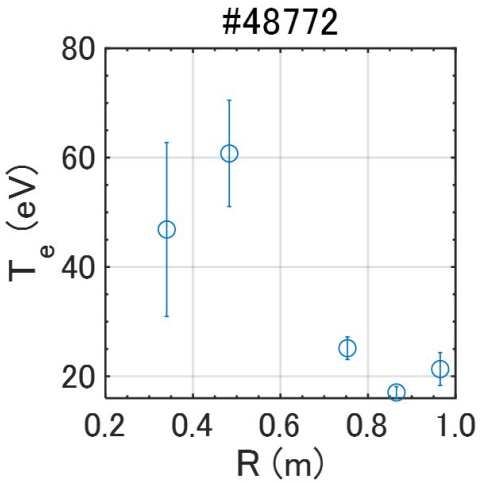
Without plasma-exposed specimen, the hydrogen pressure predicted from background model has an agreement with the experiment data.

# With the help of FESTA, a W specimen was exposed to QUEST hydrogen plasma for 3 times shot by shot in 2022S/S campaign.

## plasma condition

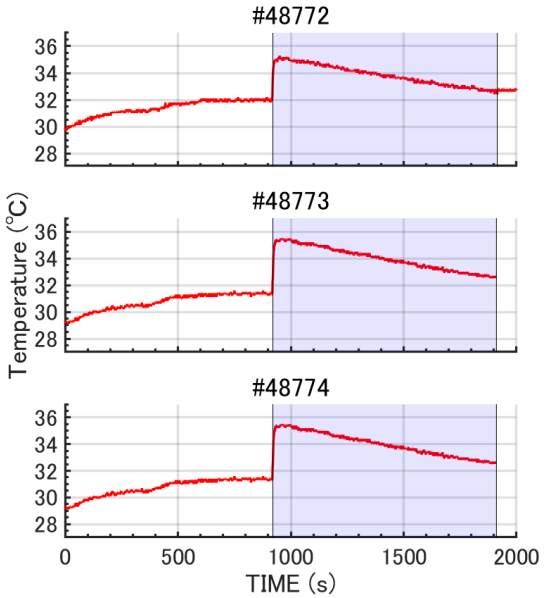


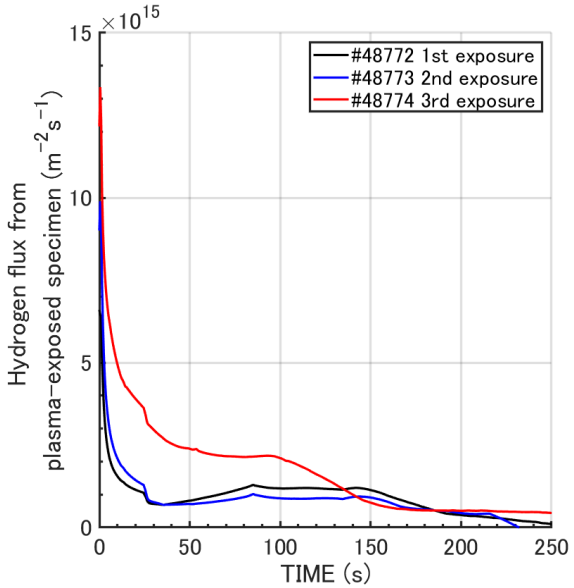



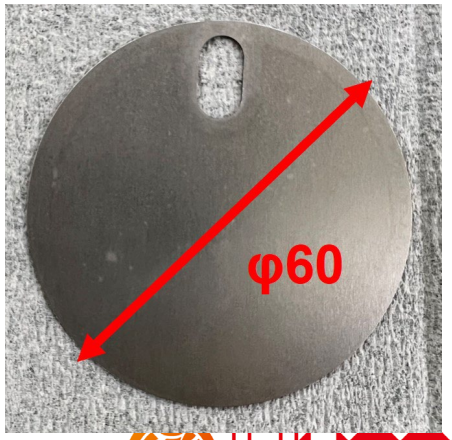

W specimen was exposed to the same plasma lasting 910 seconds three times with a fixed interval of 70 minutes at room temperature.

Time evolution of temperature and dynamic retention from plasma-exposed W specimen



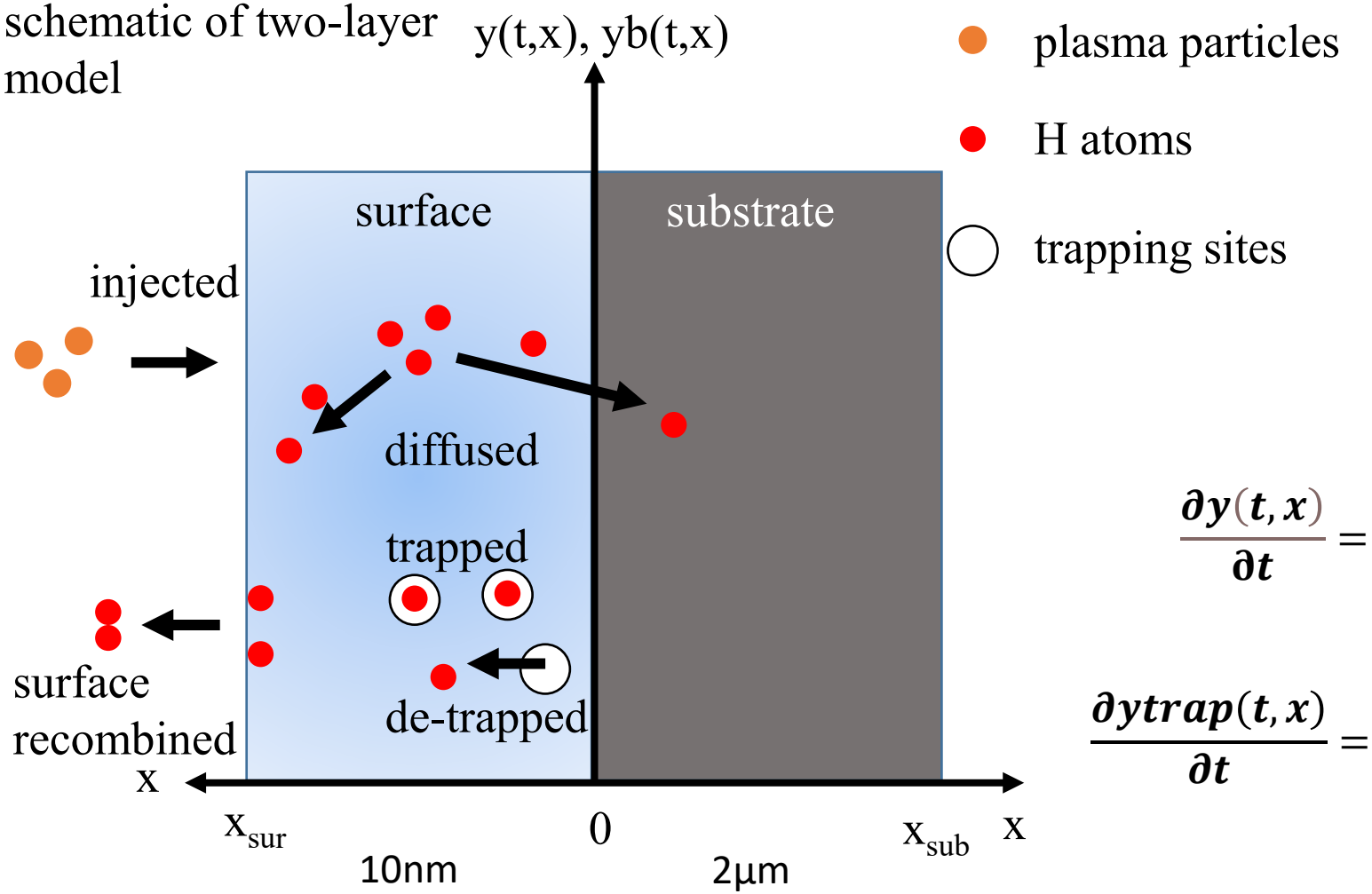

## plasma-exposed specimen




- Material: tungsten (99.99%)
- Size: Φ 60 mm
  d 0.5 mm
- Surface Treatment: ultrasonic cleaning

# Using two-layer model to verify the experimental data and to decide the surface barrier $E_C$.

schematic of two-layer model




y(t,x) – surface hydrogen concentration
$k_D$ - diffusion coefficient
SRC(t,x) - distribution of injected hydrogen atoms
ytrap(t, x) - concentration of hydrogen atoms
yb(t,x) - substrate hydrogen concentration
$a_{tk}$ - trapping coefficient
$a_{dk}$ – de-trapping coefficient
$k_{traprate}$ – trapped rate of hydrogen atoms

$$\frac{\partial y(t,x)}{\partial t} = k_D \frac{\partial^2 y(t,x)}{\partial x^2} + SRC(t,x) - \frac{\partial ytrap(t,x)}{\partial t}$$

$$\frac{\partial yb(t,x)}{\partial t} = k_D \frac{\partial^2 yb(t,x)}{\partial x^2}$$

$$\frac{\partial ytrap(t,x)}{\partial t} = a_{tk} \cdot y(t,x) k_{traprate}(t,x) - a_{dk} \cdot ytrap(t,x)$$

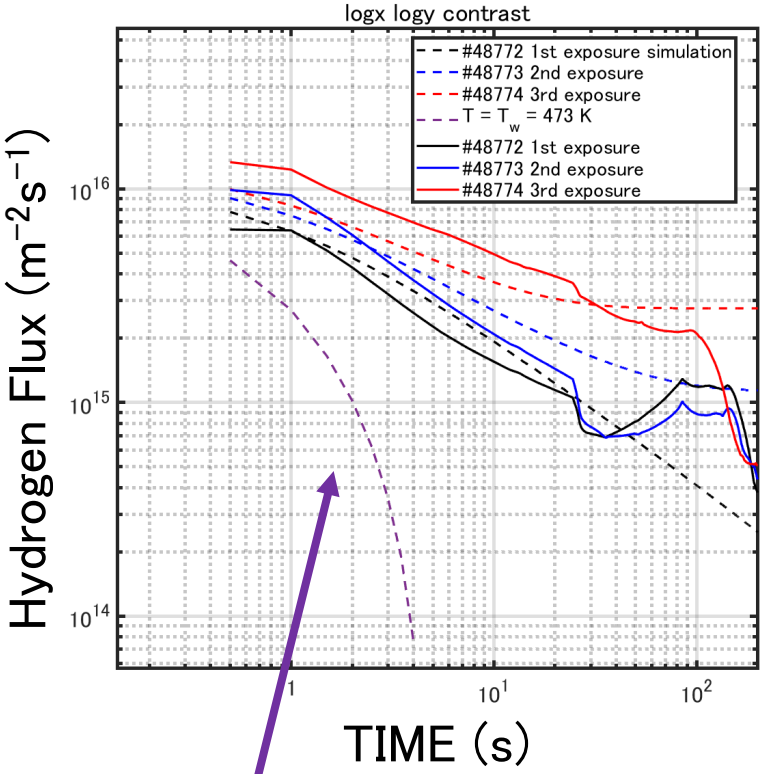
Hydrogen only invades into the surface of W specimen according to TRIM [J. F. Ziegler & J. P. Biersack 1977-1985]

Dynamic Retention from plasma-exposed specimen $\Gamma = K_D c(t)^2$

$K_r$ – surface recombination coefficient
c(t) – hydrogen concentration on surface

# Comparison between model calculation and experimental data

| | |
|---|---|
| $\Gamma_{in}$ [$m^{-2}s^{-1}$] | $2.5 \times 10^{17}$ |
| Exposure time [s] | 910 |
| $D_0$ [$m^2s^{-1}$] [1*] | $1.5 \times 10^{-10}$ |
| $E_D$ [eV] [2*] | 0.25 |
| $k_{r0}$ [$m^4s^{-1}$] [3*] | $3 \times 10^{-25}$ |
| $E_k$ [eV] | 0.33 |
| $E_C$ [eV] | 1.195 |
| de-trap activation energy [eV] [4*] | 0.85 |
| $C_{T0}$ [$m^{-3}$] [5*] | $7 \times 10^{26}$ |



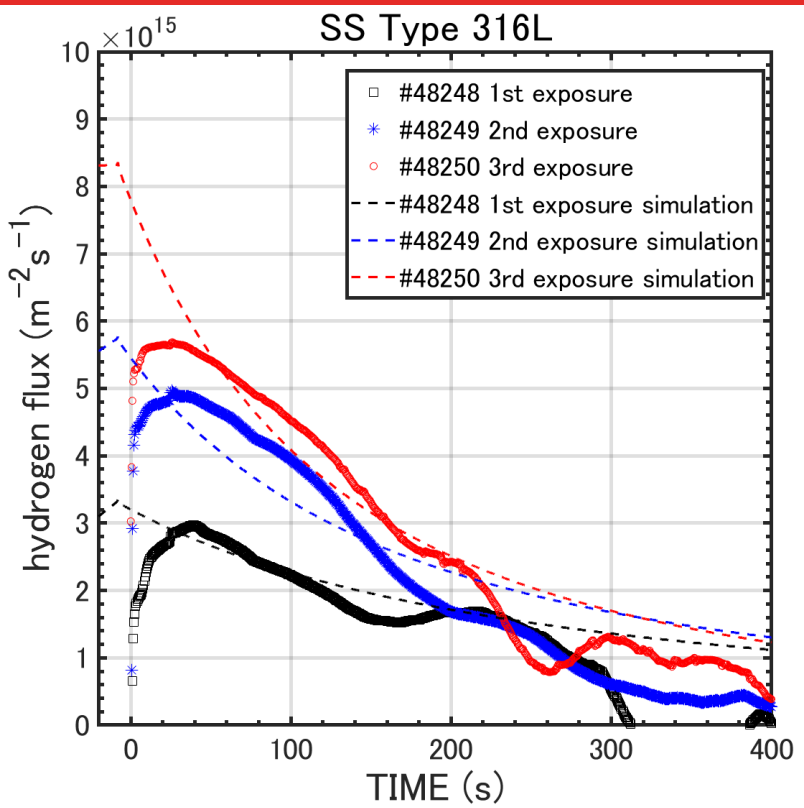

- Hydrogen atoms were trapped into W specimen due to the exposure to hydrogen plasma.
- The dynamic retention from the plasma-exposed specimen became a bit higher, due to the trapped・dissolved hydrogen.
- The surface barrier $E_C$ has been evaluated using two-layer model at room temperature during plasma discharges.
- The adoption of metal walls can reduce the wall-stored particles, but within successive long-duration plasma discharges, the dynamic retention seems to be increased.

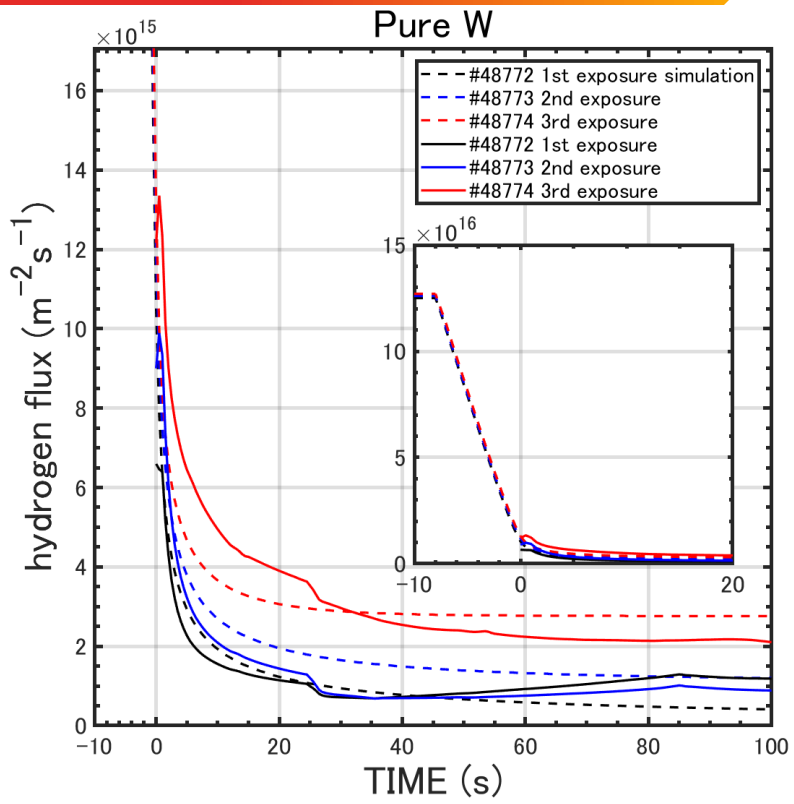
- Within the increase of wall temperature, the released hydrogen flux is predicted to be faster, indicating that Tw is also a key to control fuel recycling and SSO.

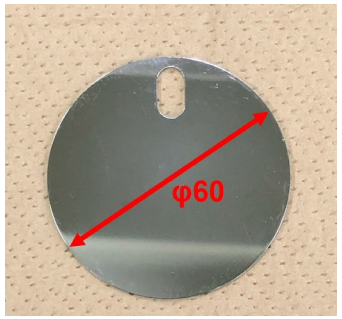

[1-2] P. Franzen 1997 J. Nucl. Mater.
[3] O.V. Ogorodnikova & Franzen
[4-5] P. Franzen 1997 J. Nucl. Mater.
C.Garcia-Rosales 1996 J. Nucl. Mater.

# Comparison between W and SS type 316L

| | |
|---|---|
| $\Gamma_{in}$ [$m^{-2}s^{-1}$] | $1.3 \times 10^{17}$ |
| Exposure time [s] | 910 |
| $D_0$ [$m^2s^{-1}$] [1*] | $1.5 \times 10^{-10}$ |
| $E_D$ [eV] [2*] | 0.25 |
| $k_{r0}$ [$m^4s^{-1}$] [3*] | $3 \times 10^{-28}$ |
| $E_k$ [eV] | 0.55 |
| $E_C$ [eV] | 1.305 |
| de-trap activation energy [eV] | 0.7 |
| $C_{T0}$ [$m^{-3}$] | $6 \times 10^{26}$ |




plasma-exposed specimen

- Material: SS type 316L
- Size: Φ 60 mm d 1 mm
- Surface Treatment: ultrasonic cleaning

- Using the same two-layer model, the surface barrier $E_C$ of stainless-steel type 316L was also evaluated during long-duration plasma discharge.

- The hydrogen flux from SS type 316L was more slow and smaller than that from tungsten but increased more obviously shot by shot.


[1-2] Y. Sakamoto et al. 1982 J. Japan Inst. Metals.
[3] QUEST

# Summary

- A device named FESTA (Fast Ejecting System of Targeted sAmple) has been developed to measure the dynamic retention of hydrogen during plasma discharge in QUEST and its pre-programmed motion was proved successfully.
- A prepared specimen (pure W and SS type 316L) was exposed to QUEST hydrogen plasma using FESTA 3 times with a fixed interval of 70 minutes at room temperature.
- The increase dynamic retention from the plasma-exposed specimen shot by shot was directly measured.
- To understand physical processes, a hydrogen diffusion-desorption model called two-layer model including trap-de-trap effect was constructed.
- By the model calculation, the important surface barrier $E_C$ and surface recombination coefficient can be evaluated during plasma discharge.
- It is indicated that the surface conditions of PFWs are significant, a successive and long-duration plasmas discharge will lead to an increase on dynamic retention from PFWs, which influence SSO to a large extent.