Global particle balance investigation using hot wall operation in all-metal plasma facing device, QUEST

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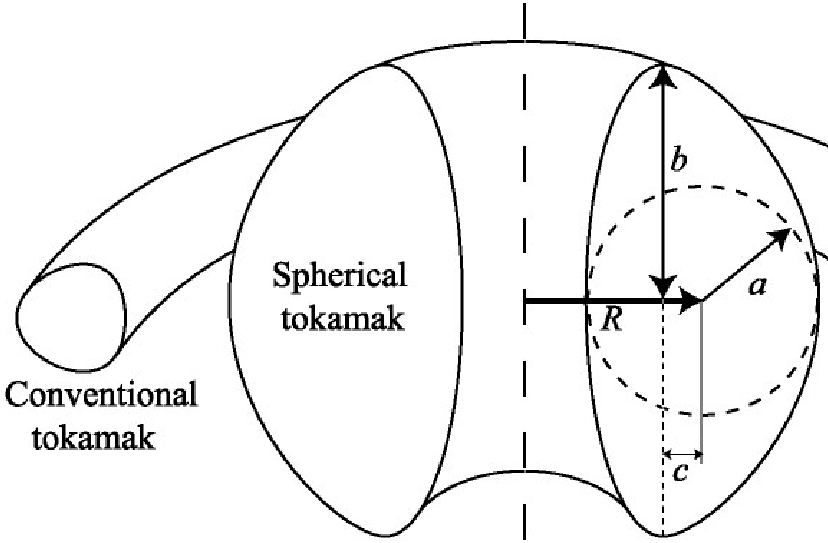
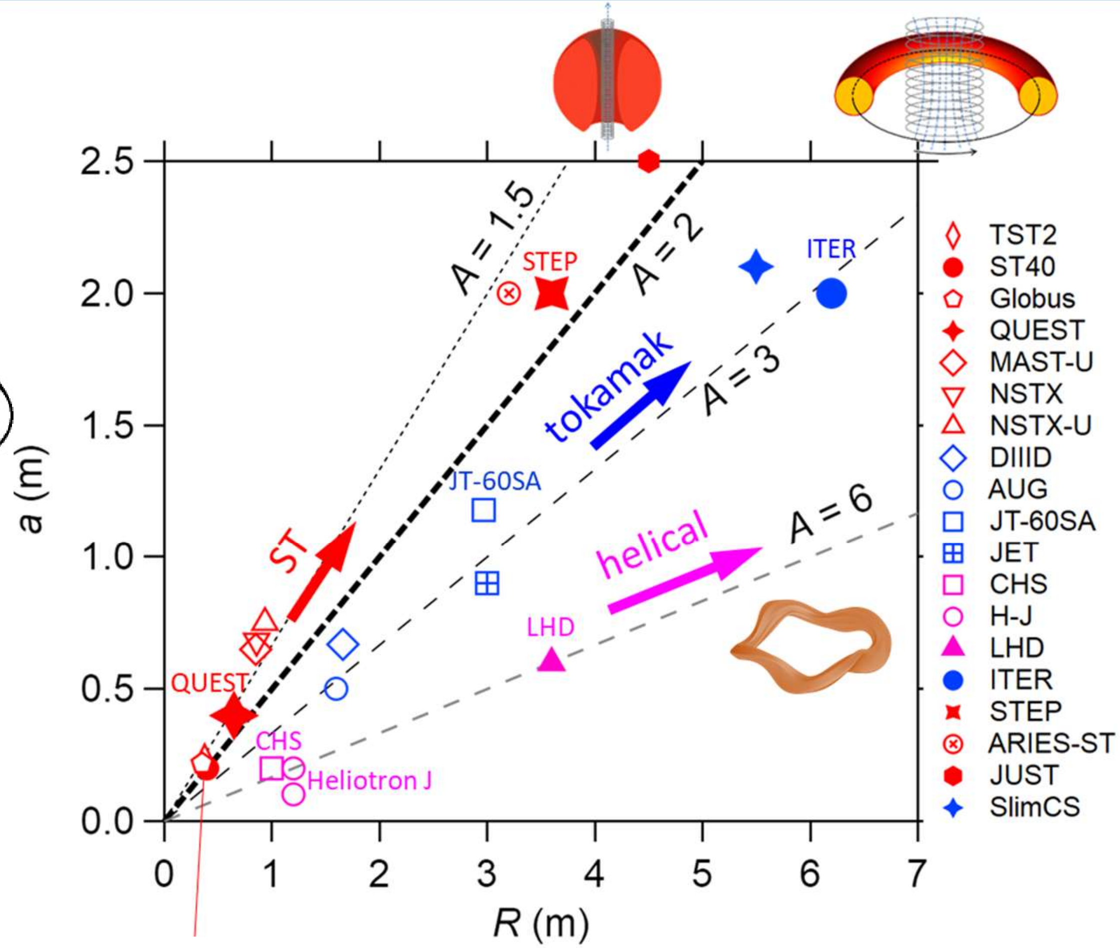
Aspect ratio of various magnetic confinement devices



$$A = R/a \left(A > 1 \right)$$

$$\varepsilon = a/R \left(\varepsilon < 1 \right)$$

$$\kappa = b/a$$

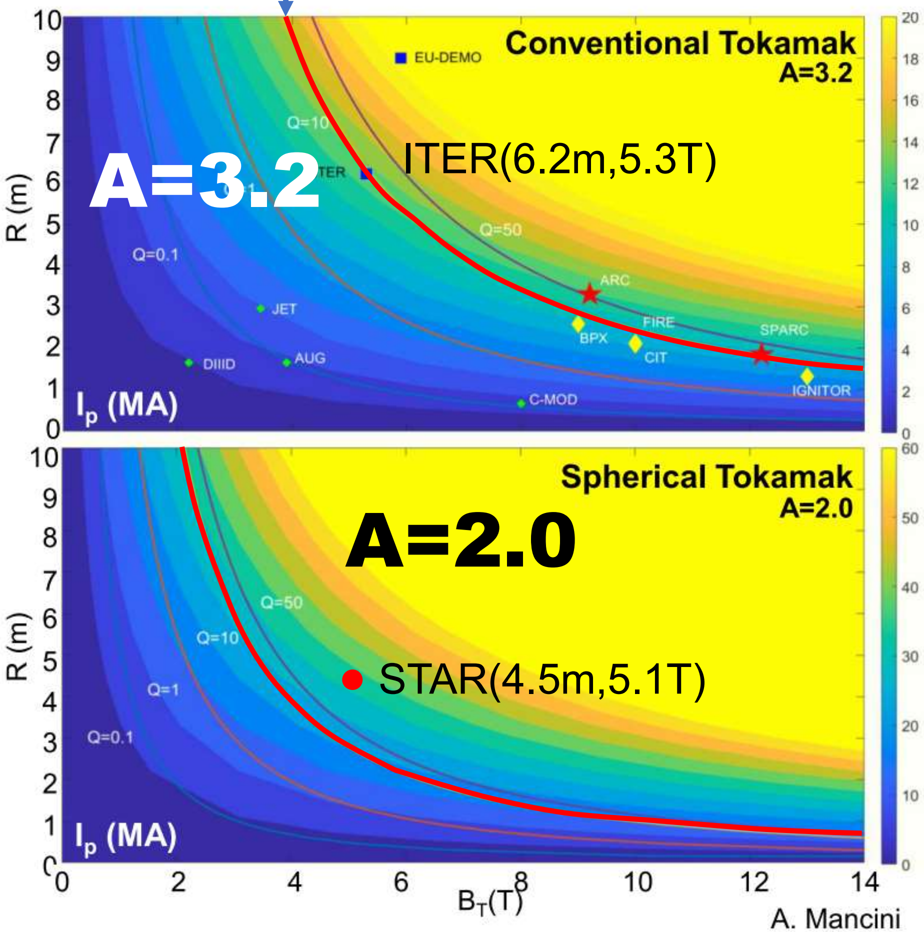


Ti~10^8 K

（ST40）

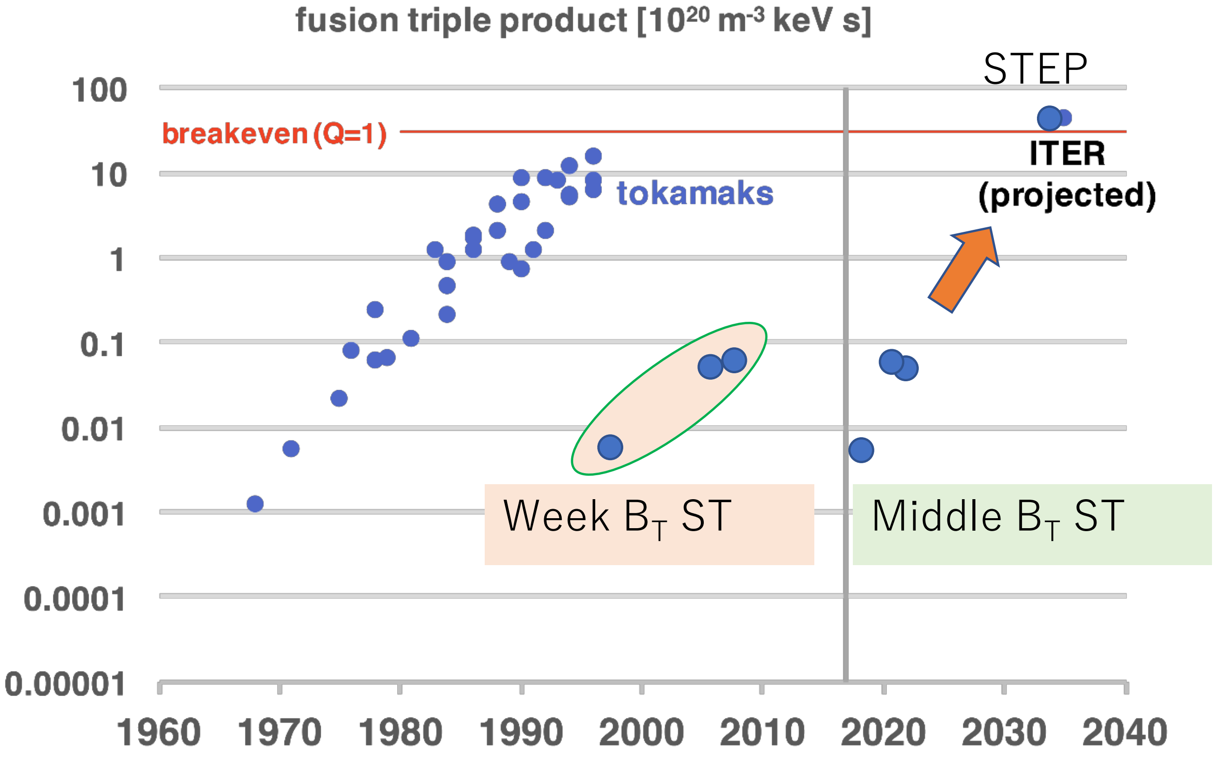
ST has a possibility to realize smaller fusion reactor. Smaller device is much preferable to earlier realization

Q~10: ITER Target



A. Mancini

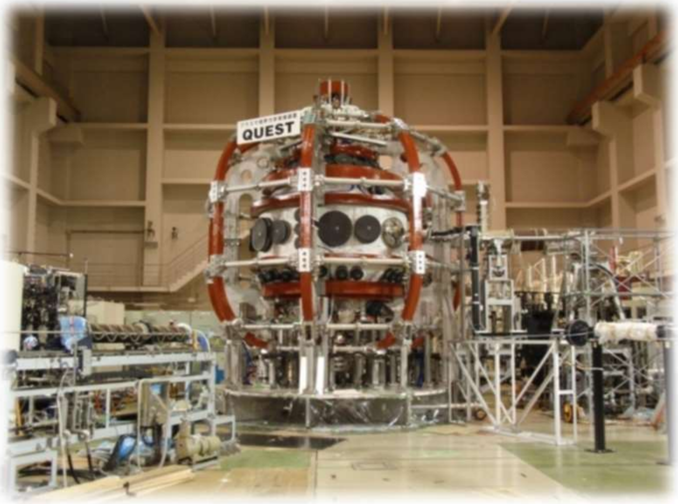
STEP(3.6m,3.2T,A=1.8)

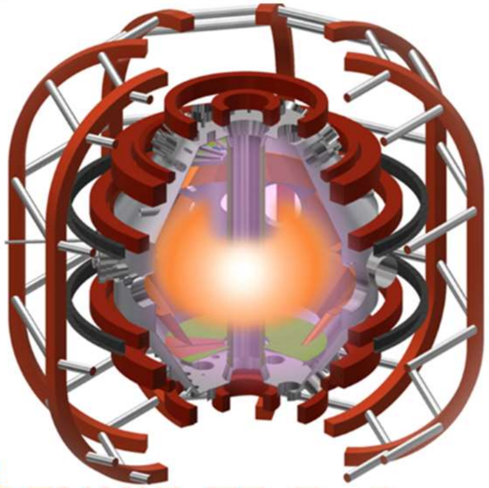


Progress Exceeded Moore's Law for 30 years

Credit: Dr. Greenwald

K.U. has started a ST research QUEST since 2008. QUEST aims at effective plasma start-up and SSO.

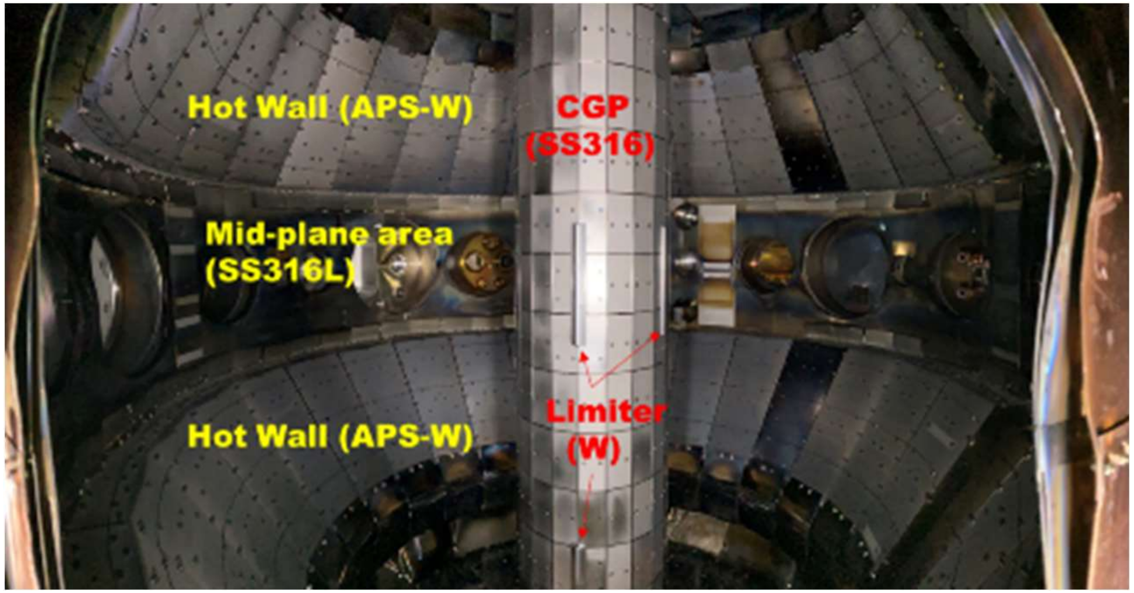


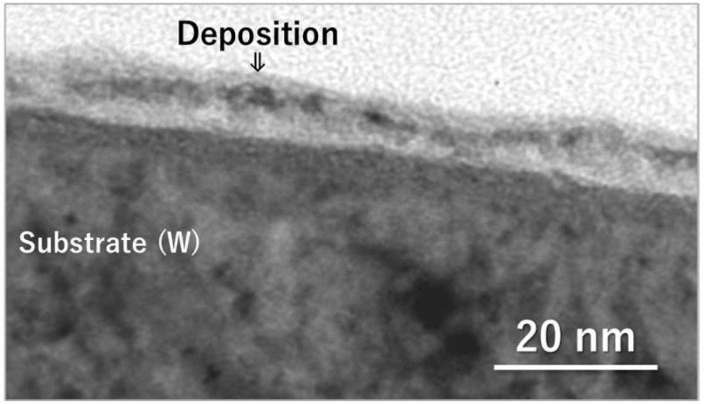


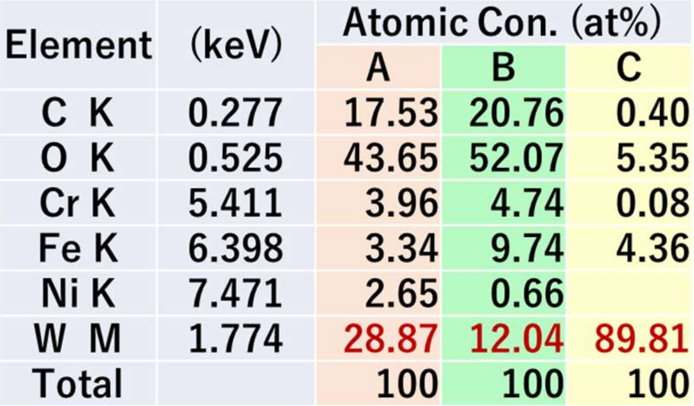
	Design	Achieved
R (m)	0.64	0.64
a(m)	0.4	0.4
B_T (T)	0.25 CW 0.5 SP	0.25 CW Plan 0.5 2s
I_P (kA)	100 (300)	100
Power (MW)	1 (RF) 2 (NBI)	0.1 (RF CW) 0.3 (RF 1s)
OH (Vs)	0.2	0.2

The major component of PFW on QUEST is APS-W and the surface is covered with a deposition layer.

SSO has been conducted in an inner limiter configuration.

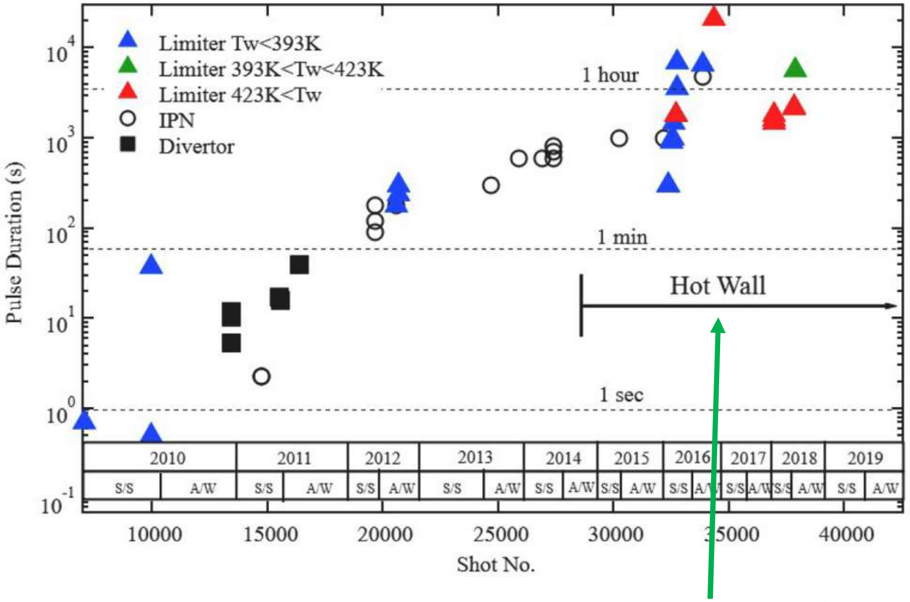




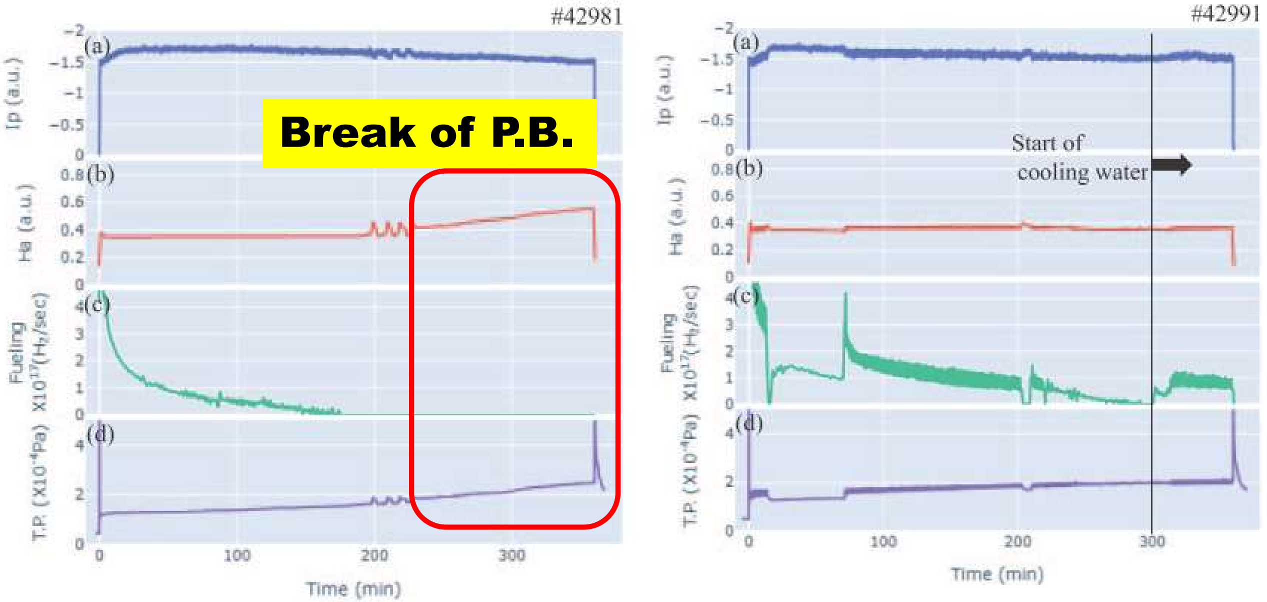


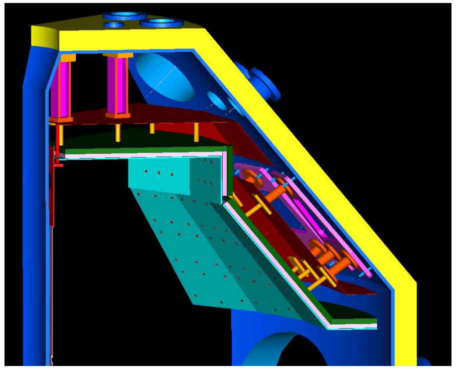
Element	(keV)	Atomic Con. (at%)		
		A	B	C
C K	0.277	17.53	20.76	0.40
O K	0.525	43.65	52.07	5.35
Cr K	5.411	3.96	4.74	0.08
Fe K	6.398	3.34	9.74	4.36
Ni K	7.471	2.65	0.66	
W M	1.774	28.87	12.04	89.81
Total		100	100	100

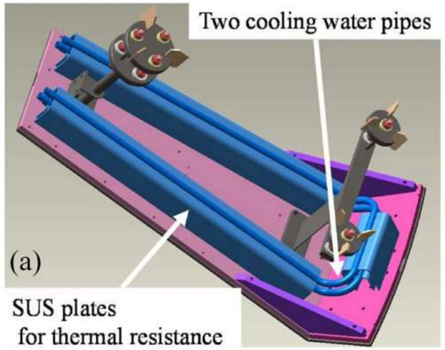
QUEST is making a good progress in researching SSO.
6 hour discharges could be achieved with the hot wall.

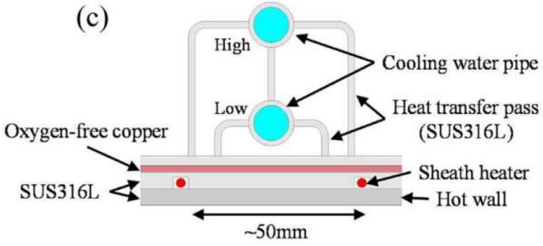


6 hours discharges on QUEST in 2021









K.Hanada et. al, NME 27 (2021) 101013
M.Hasegawa et. al, PFR 16 (2021) 2402034

Advanced Fusion Research Center

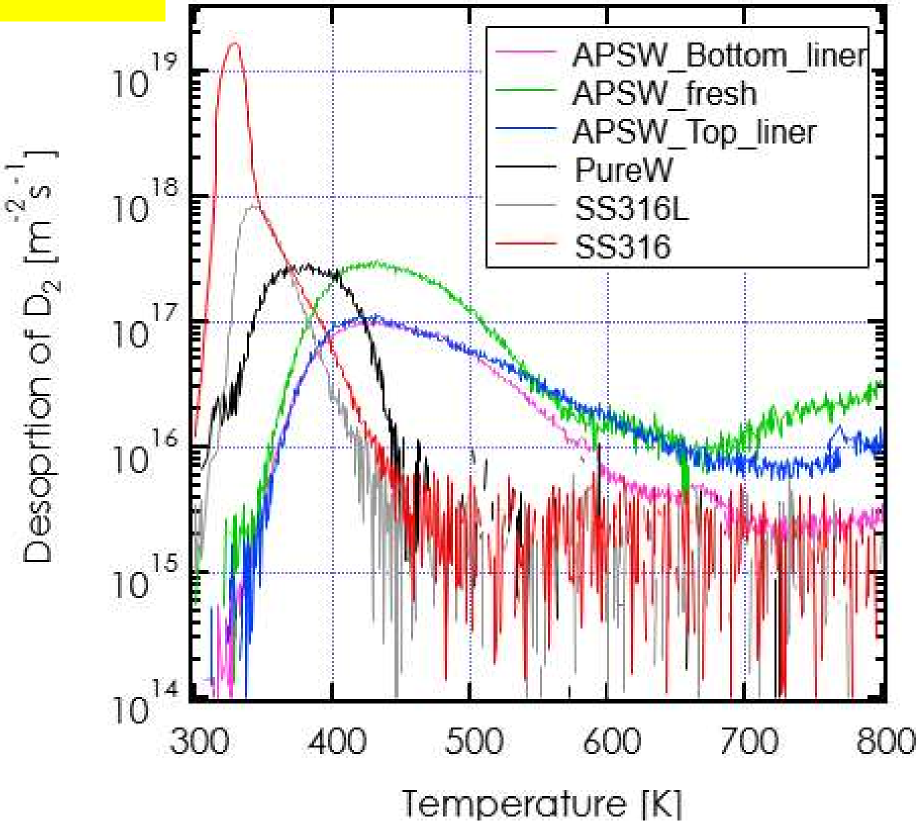
Feature of Materials to understand particle balance. QUEST is basically equipped all-metal PFW.

	W	SS 316L	SS 316L coated with APS-W	Deposition layer
Method	FESTA	TDS	TDS	NRA
$D_0[m^2/s]$	1.5×10^{-10} *1	4.7×10^{-7}	4.3×10^{-10}	1.5×10^{-7}
$E_D[eV]$	0.25 *1	0.57	0.48	0.41
$k_0[m^4/s]$	3.0×10^{-25}	3.8×10^{-28}	1.0×10^{-15}	4.0×10^{-36}
$E_k[eV]$	0.47	0.55	1.08	0.17
$E\ [eV]$	0.85 *1	0.7	1.10	0.5
$C_{T0}[m^{-3}]$	6×10^{26}	1×10^{29}	3.0×10^{27}	1×10^{29}
$d_{surface}[nm]$	10	20	30	-
W_{Doyle}@T_w=R.T.	6.5×10^{-2}	3.7×10^{-2}	72	8.2×10^{-6}
W_{Doyle}@T_w=500K	2.5	3.8×10^{-4}	183	9.9×10^{-8}

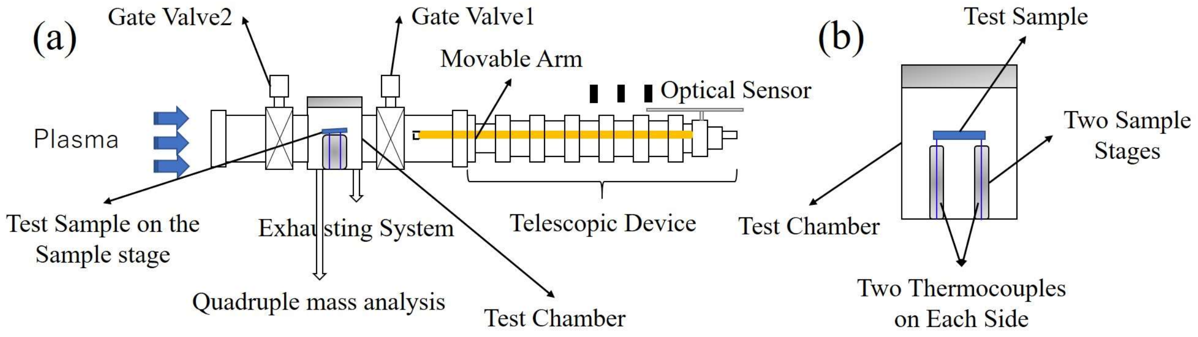
$$W_{Doyle} = d_p \sqrt{\gamma_{in} k_{rec}} / D$$

How to decide the Feature of Materials.
TDS, NRA, Transmittance and FESTA are useful to decide.

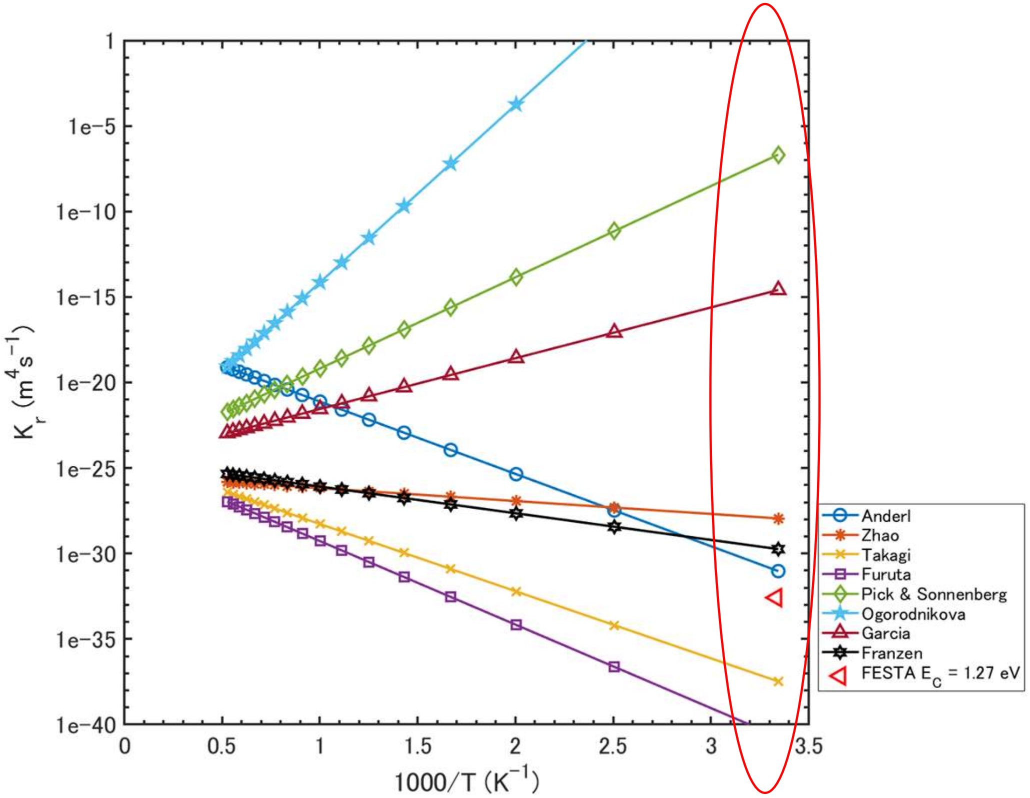
TDS



	Diffusion	Recombination	Trap
TDS	✕	✕	○
NRA	✕	○	✕
Trans.	○	△	✕
FESTA	✕	○	○



The values of W recombination coef. had a large scattering, especially aroud room temperature.



R.A. Anderl: $K_r = 1.3 \times 10^{-17} \exp(-\frac{0.84\,[eV]}{kT})$ [1]

M. Zhao: $K_r = 3.8 \times 10^{-26} \exp(-\frac{0.15\,[eV]}{kT})$ [2]

I. Takagi: $K_r = 4.5 \times 10^{-25} \exp(-\frac{0.78\,[eV]}{kT})$ [3]

W. Furuta: $K_r = 4.1 \times 10^{-25} \exp(-\frac{0.97\,[eV]}{kT})$ [4]

Pick & Sonnenberg: $K_r = \frac{3.0\times10^{-25}}{\sqrt{T}} \exp(\frac{1.06\,[eV]}{kT})$ [5]

O.V. Ogorodnikova: $K_r = \frac{3.0\times10^{-25}}{\sqrt{T}} \exp(\frac{2.06\,[eV]}{kT})$ [6]

C. Garcia: $K_r = \frac{3.0\times10^{-25}}{\sqrt{T}} \exp(\frac{0.59\,[eV]}{kT})$ [7]

Franzen: $K_r = \frac{3.0\times10^{-25}}{\sqrt{T}} \exp(-\frac{0.31\,[eV]}{kT})$ [8]

[1] R. A. Anderl et al. 1992 Fusion Tech. 21:2P2, 745-752
[2] M. Zhao et al 2020 Fusion Eng. and Des. 160, 111853
[3] I. Takagi et al 2011 J. Nucl. Mater. 417, 564-567
[4]古田美博, “タングステンに注入した重水素の再結合と捕捉,” 京都大学工学研究科原子核工学専攻修士学位論文, 2013
[5] M.A. Pick and K. Sonnenberg 1985 J. Nucl. and Mater. 131 208-220
[6] O.V. Ogorodnikova 2019 J. Nucl. Mater. 522 74-79
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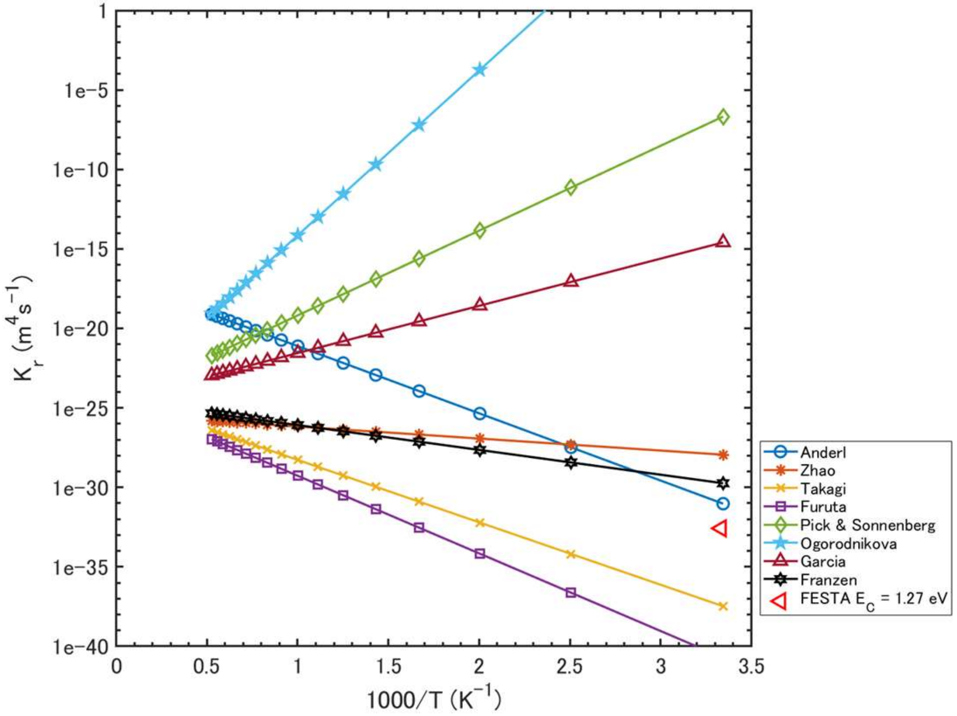

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Doyle's W parameter is a good candidate to identify the material feature for fuel recycling.

$$W_{Doyle} = R\sqrt{\gamma_{in}K}/D$$

B.L. DOYLE Journal of Nuclear Materials 111 & 112 (1982) 628–635

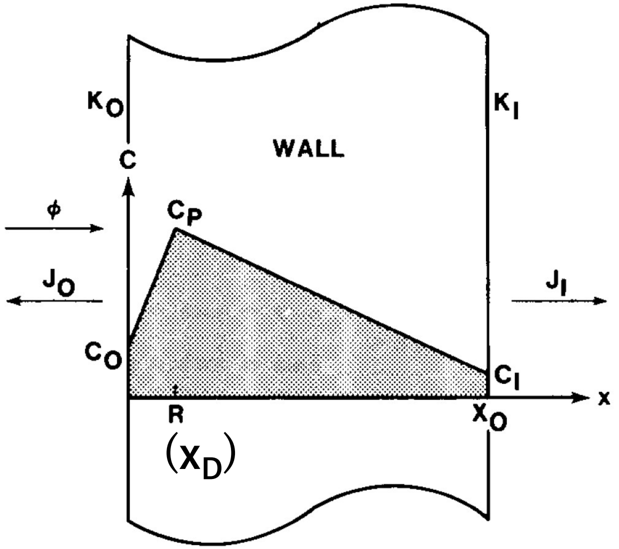


Fig. 1. Schematic of H concentration in a wall membrane. The various parameters listed are defined in the text.

Transmittance $v^2 = C_1 k_{rec}^2/\gamma_{in}$

$$\gamma = \sqrt{\frac{K_0}{K_1}}, \alpha = \frac{R}{x_0}$$

Recombination limit

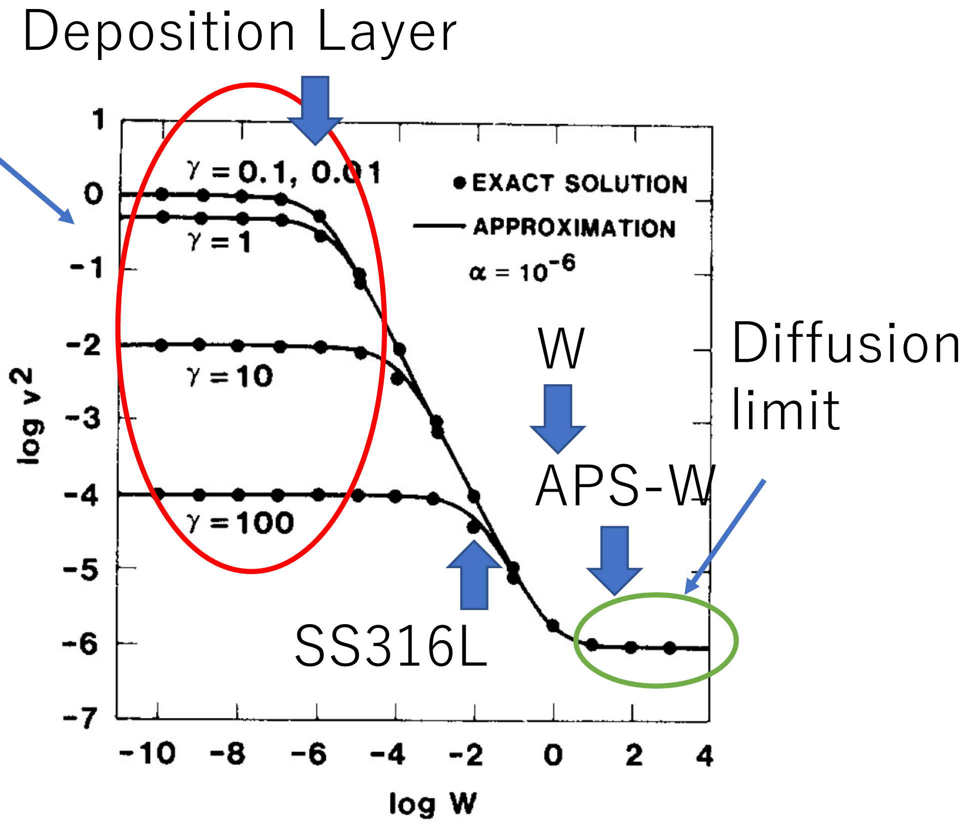
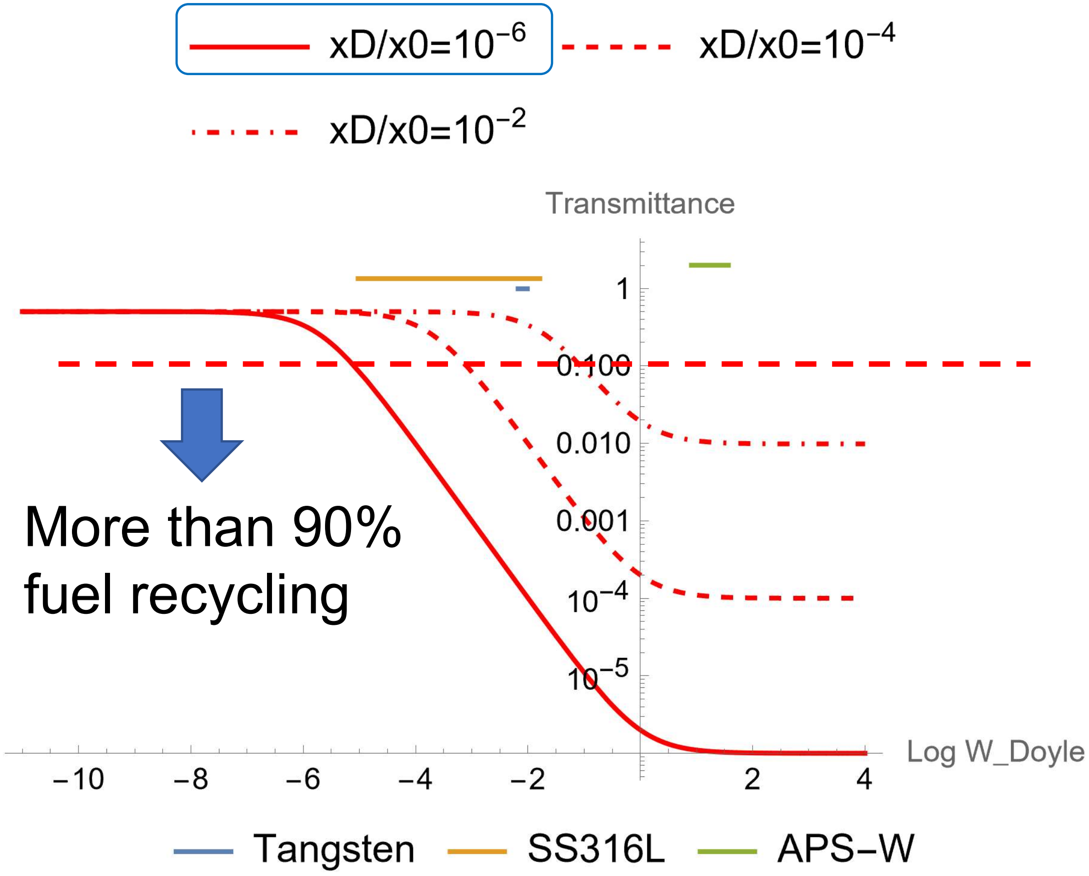
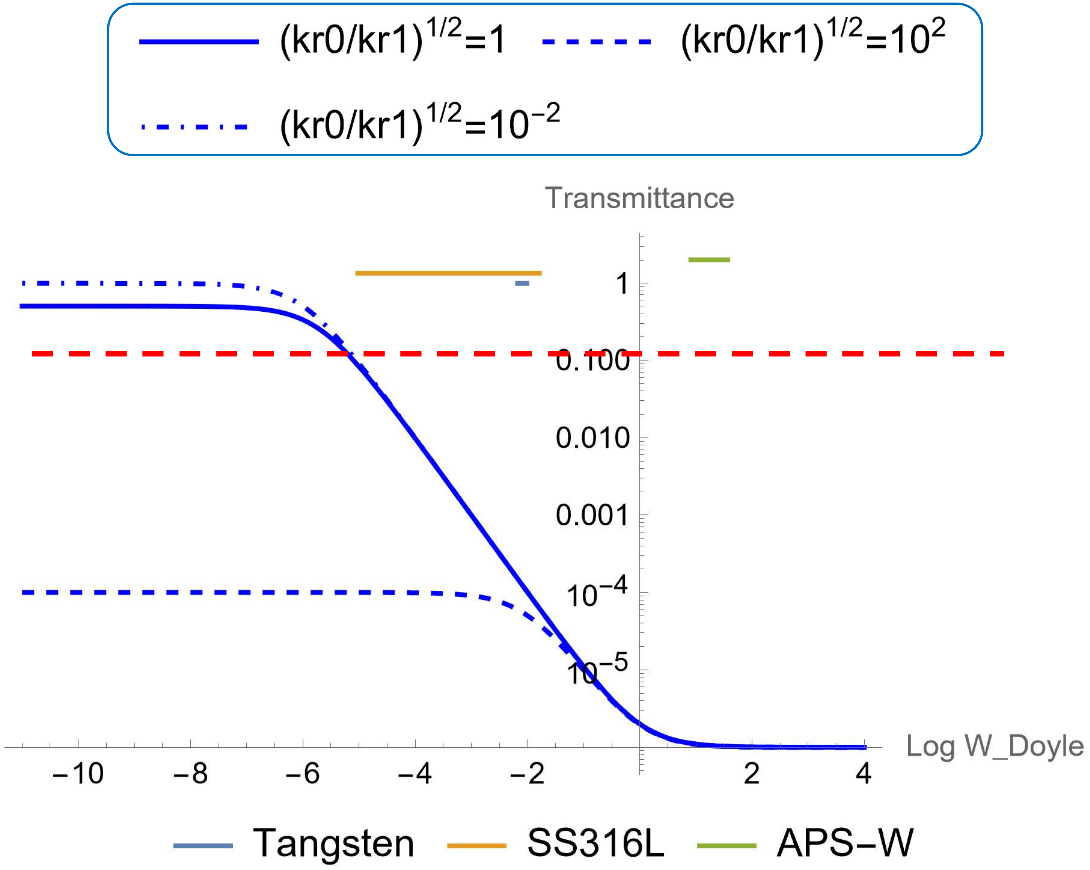


Fig. 3. Same plot as for fig. 2 except for different values of $\gamma((K_0/K_1)^{1/2})$.

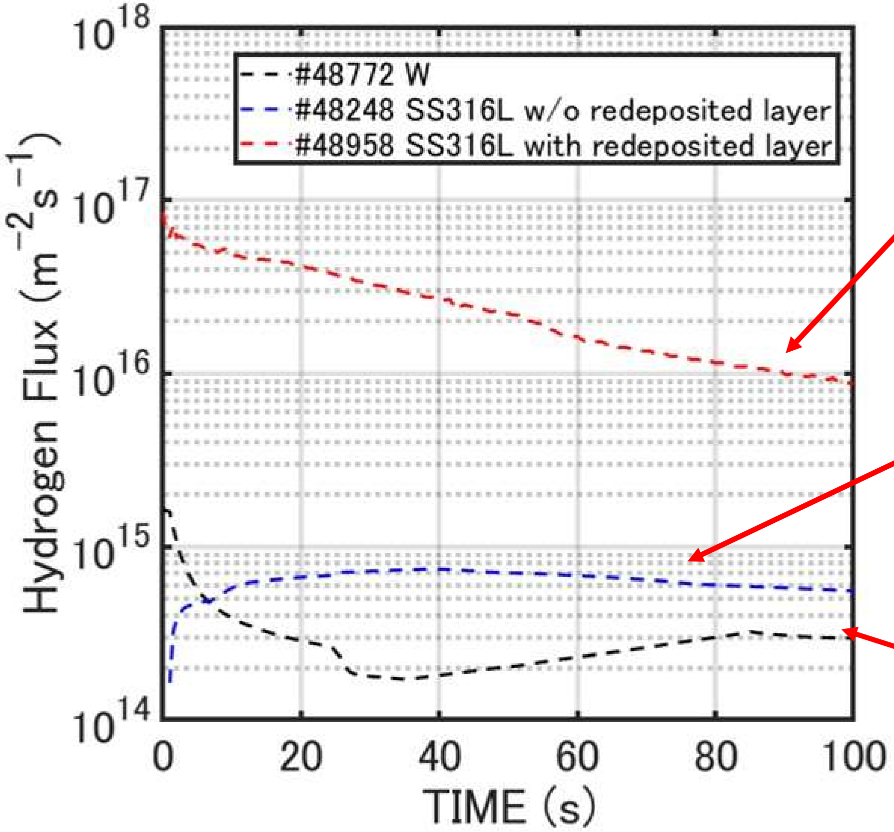
Thickness and kr modification has little effect , because more than 90% of wall injected hydrogen will recycle in SSO.

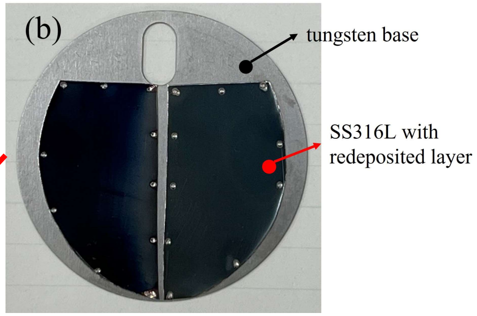


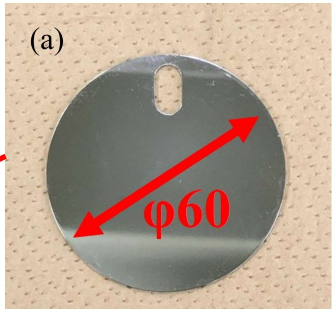
More than 90% fuel recycling

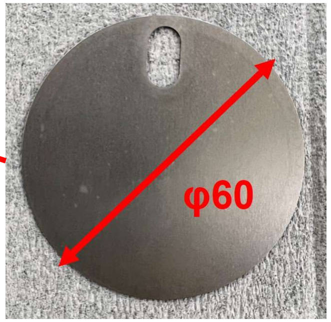


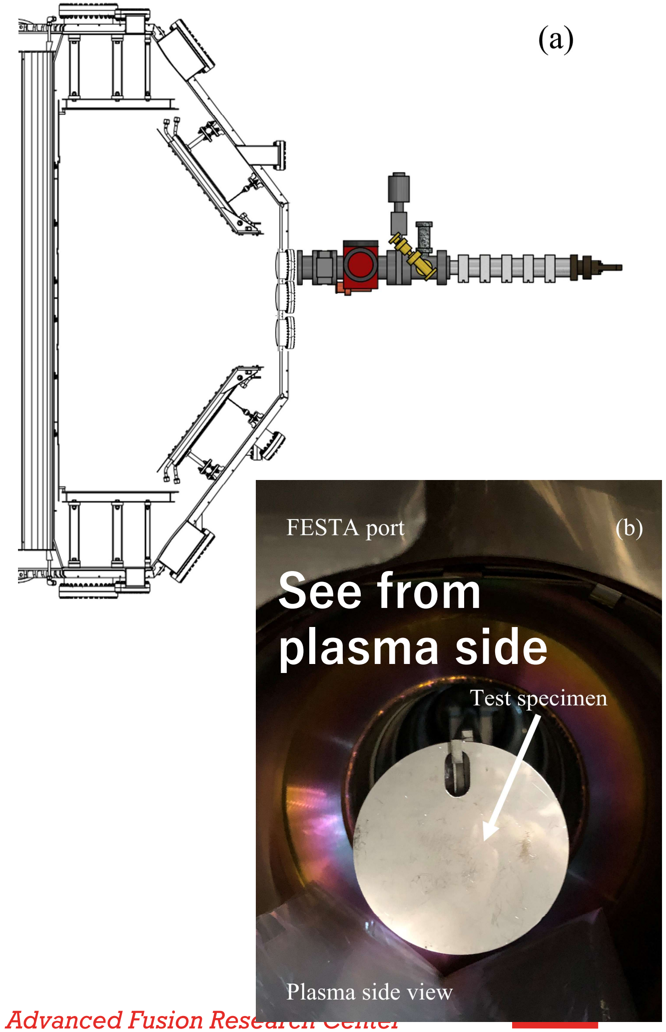
FESTA observation clearly indicated fuel recycling with the deposition layer is much higher.



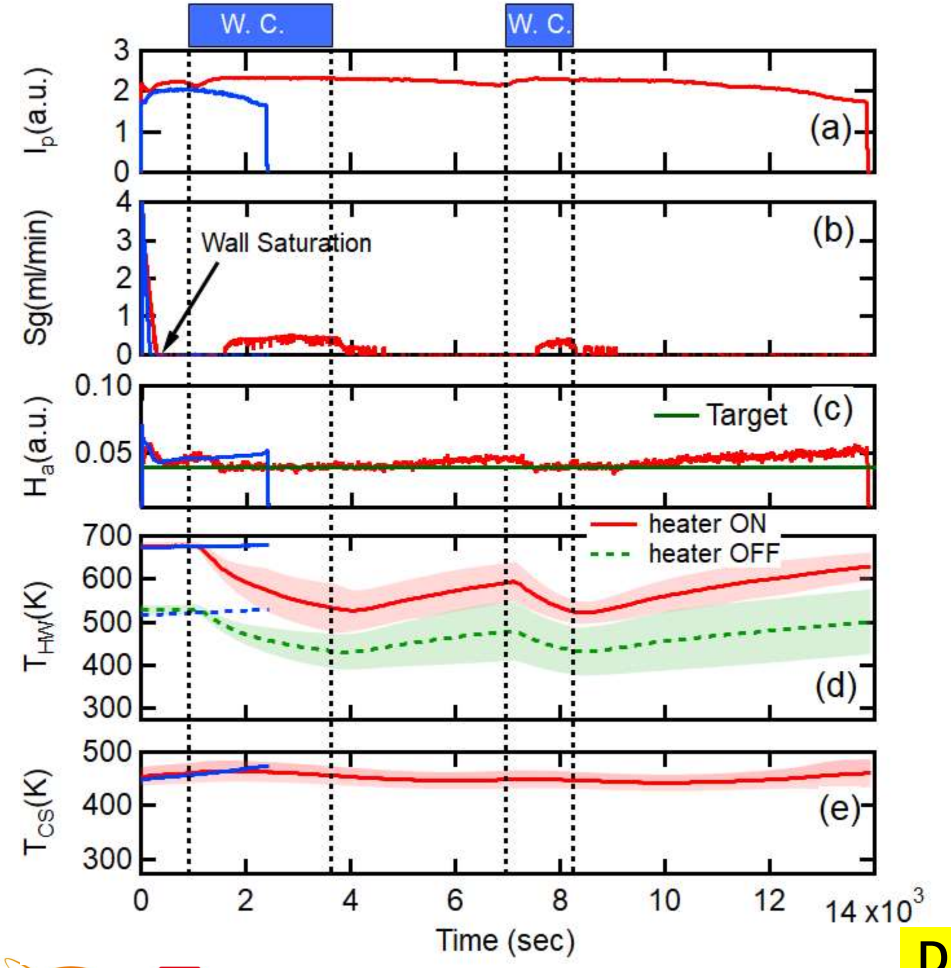


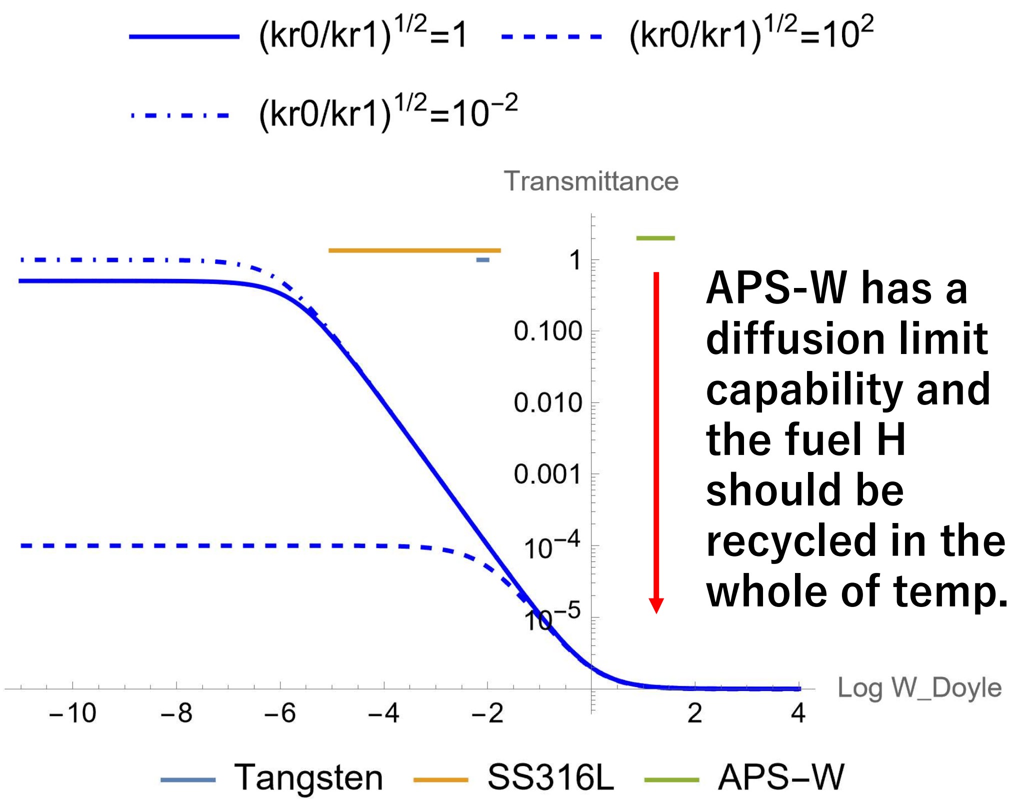






Hot wall covered with APS-W could modify recycling of H, but the APS-W has a diffusion limit capability in the whole temp.



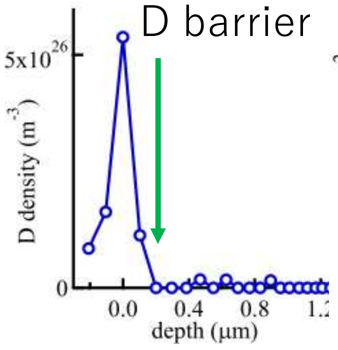


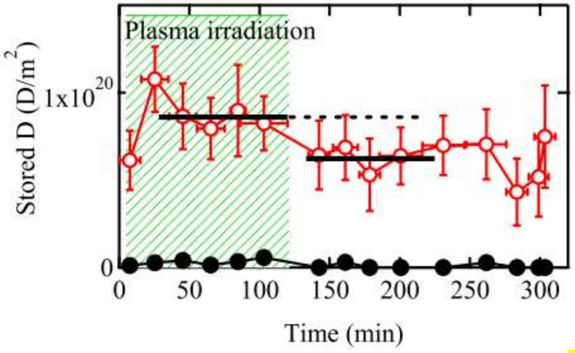
APS-W has a diffusion limit capability and the fuel H should be recycled in the whole of temp.

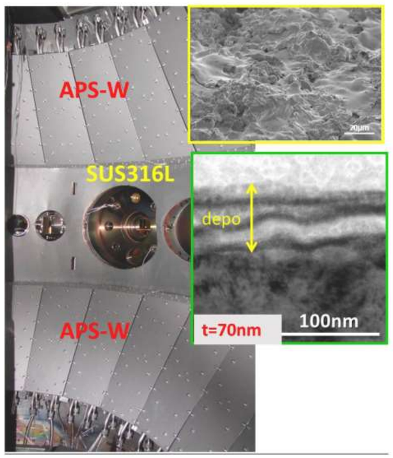
Do not forget the surface of the HW is covered with D.L.

A H barrier between dep. layer and substrate is observed. The dep. layer is considered as a thin PFW material.

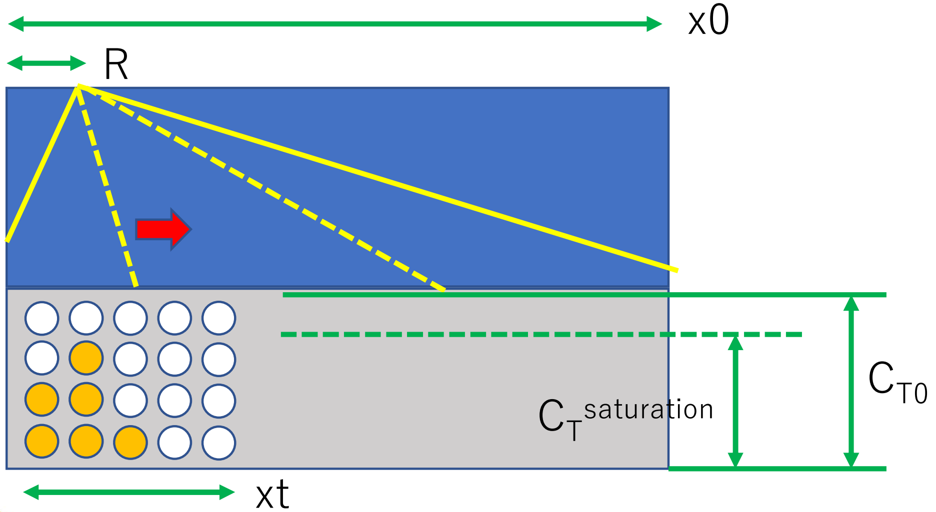
NRA measurement



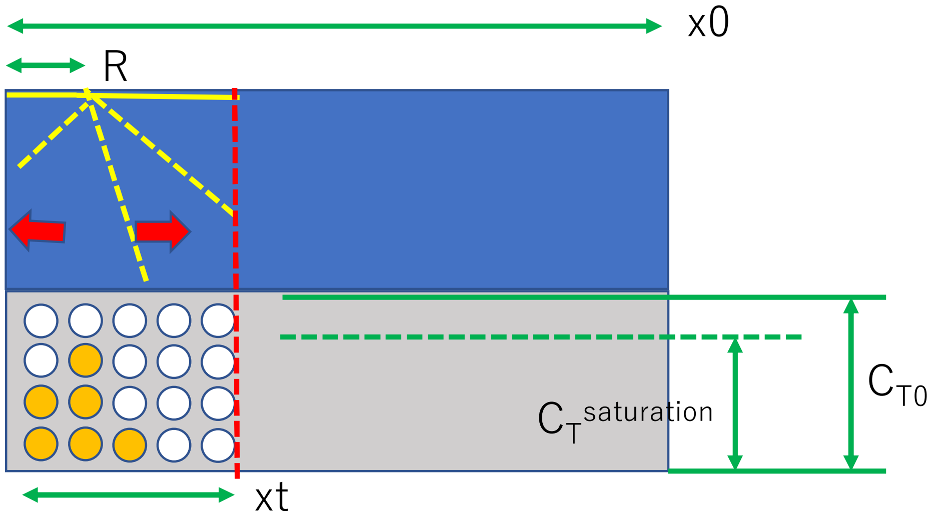




Diffusion- Trap model



H barrier model



Consideration of trapping site provides us the quantitative estimation of wall pumping and its temp. dependence.

The amount of SS uptake in the trapping site.

$$\frac{\partial C_T}{\partial t} = \frac{D}{\lambda^2} C \left(1 - \frac{C_T}{C_{T0}}\right) - C_T \nu_0 Exp\left(-\frac{E_0}{k_B T}\right)$$

$$\boxed{C_T^{Sat} = \frac{C_{T0}}{\left(1 + \alpha\beta Exp\left(-\frac{E_0}{k_B T}\right)\right)}}$$

$$\alpha = \frac{\lambda^2 \nu_0}{D} \qquad \beta = \frac{C_{T0}}{\sqrt{\Gamma / k_{rec}}}$$

Original feature of Material

Depending on Experimental condition.

The time constant of balance between trapping and de-trapping

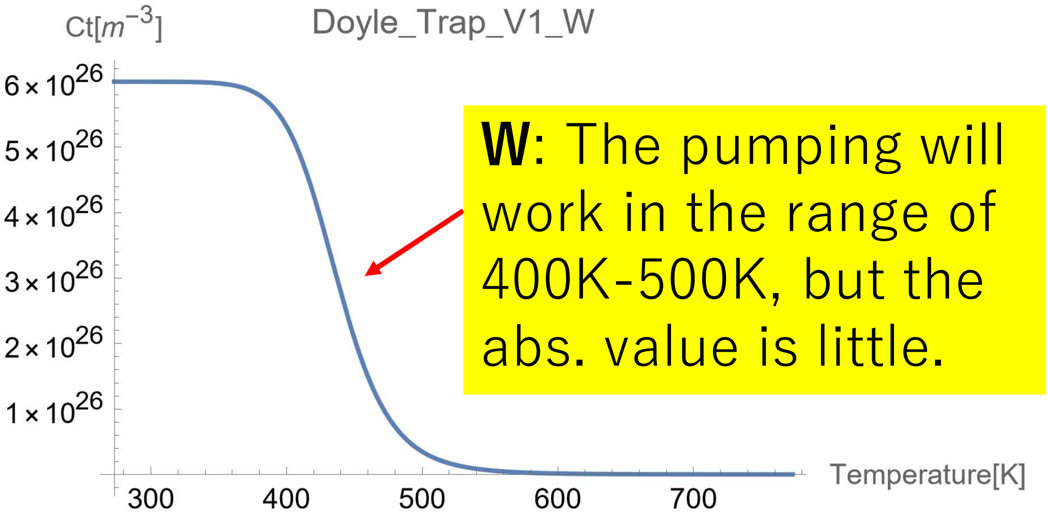
$$\frac{\partial C_T}{\partial t} = \frac{D}{\lambda^2} C \left(1 - \frac{C_T}{C_{T0}}\right) - C_T \nu_0 Exp\left(-\frac{E_0}{k_B T}\right)$$

$$\frac{\partial \rho_T}{\partial t} = -\nu_0 \left(\frac{1}{\alpha\beta} + Exp\left(-\frac{E_0}{k_B T}\right)\right) \rho_T = -\frac{\rho_T}{\tau_0}$$

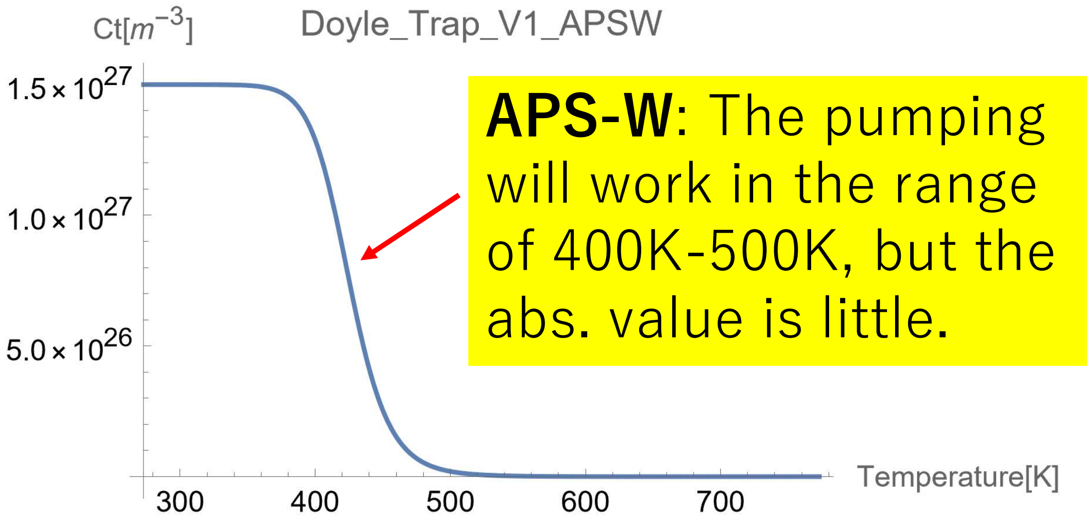
$$\rho_T = \frac{C_T}{C_{T0}} \frac{1}{\tau_0 \nu_0} - \frac{1}{\alpha\beta} \qquad \boxed{\tau_0 = \nu_0^{-1} \left(\frac{1}{\alpha\beta} + Exp\left(-\frac{E_0}{k_B T}\right)\right)^{-1}}$$

The time constant is very quick rather than the time constant of wall saturation.

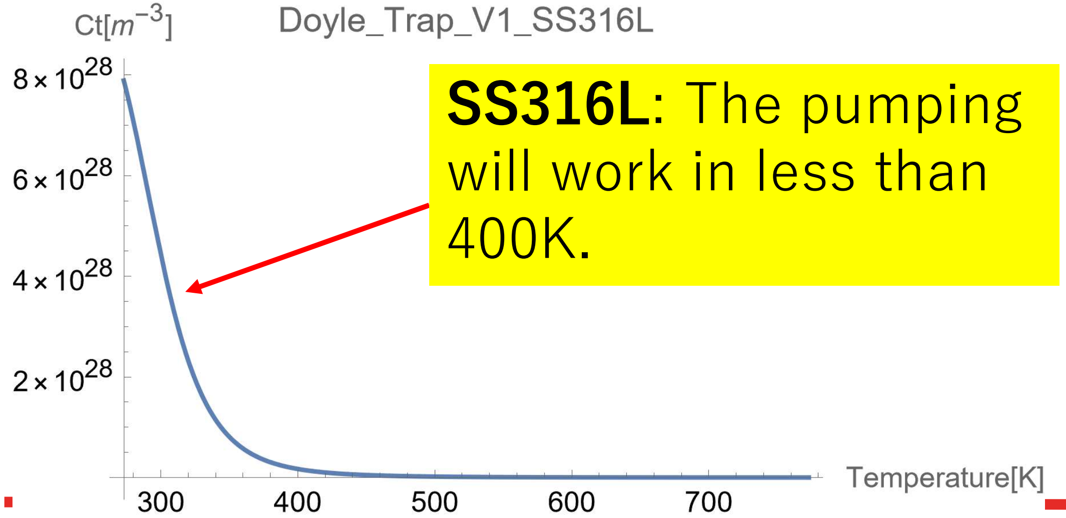
Trapping effect is included in the model. Wall pumping capability and the temp. dependence could be obtained.



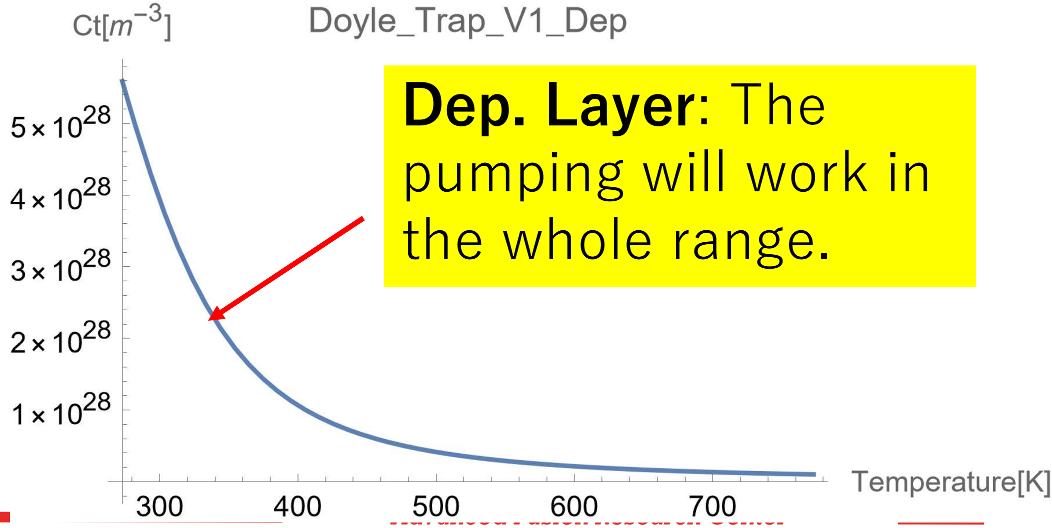
W: The pumping will work in the range of 400K-500K, but the abs. value is little.



APS-W: The pumping will work in the range of 400K-500K, but the abs. value is little.



SS316L: The pumping will work in less than 400K.



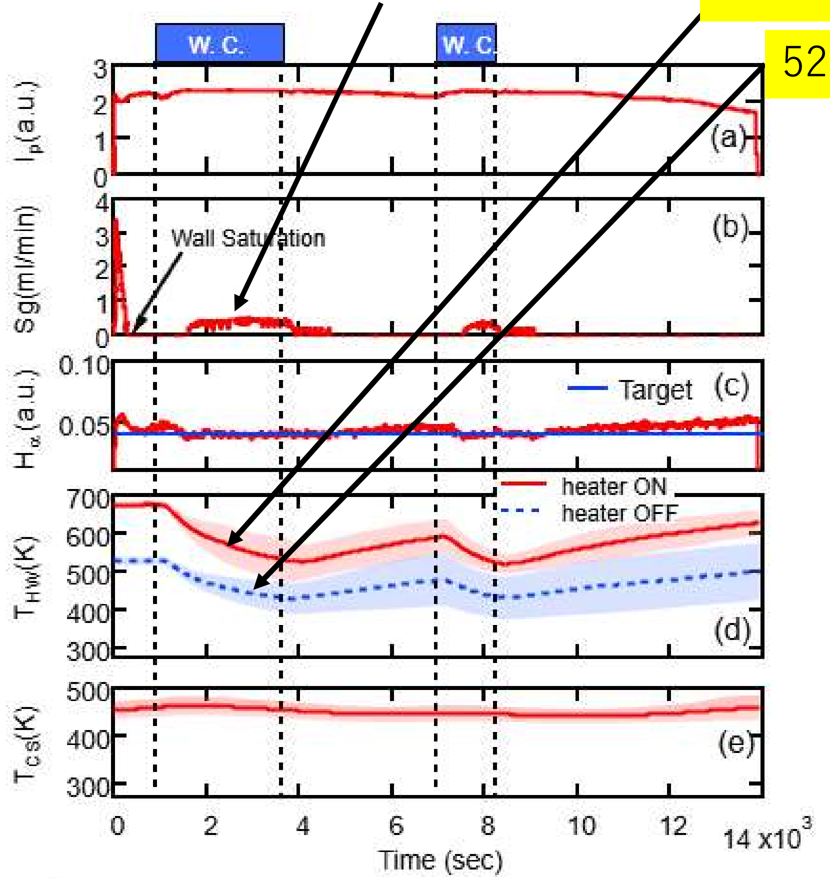
Dep. Layer: The pumping will work in the whole range.

QUEST experiment could be quantitively explained by the effect of the deposition later.

~10ml=2.7×10^{20} H_2

673K->530K

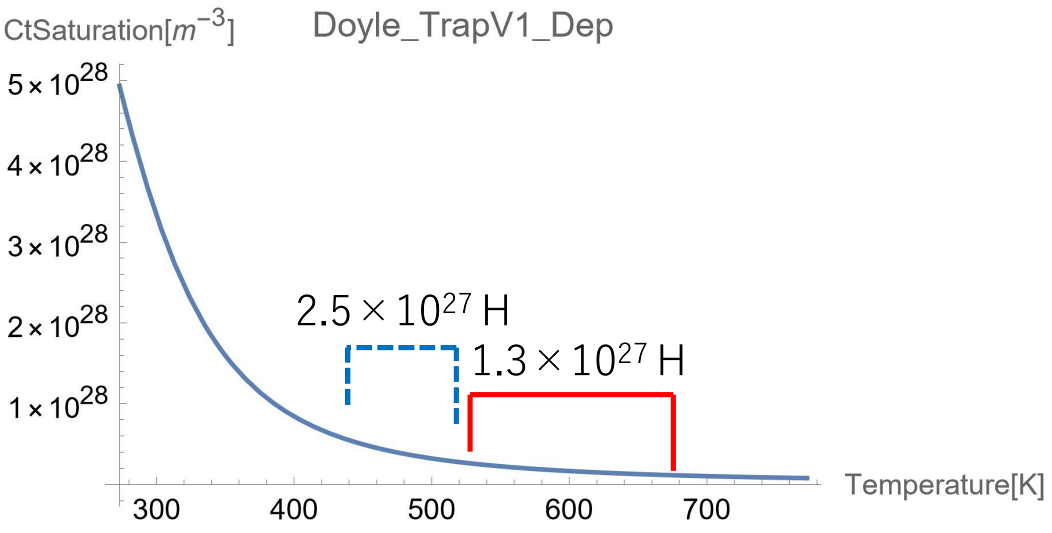
520K->440K



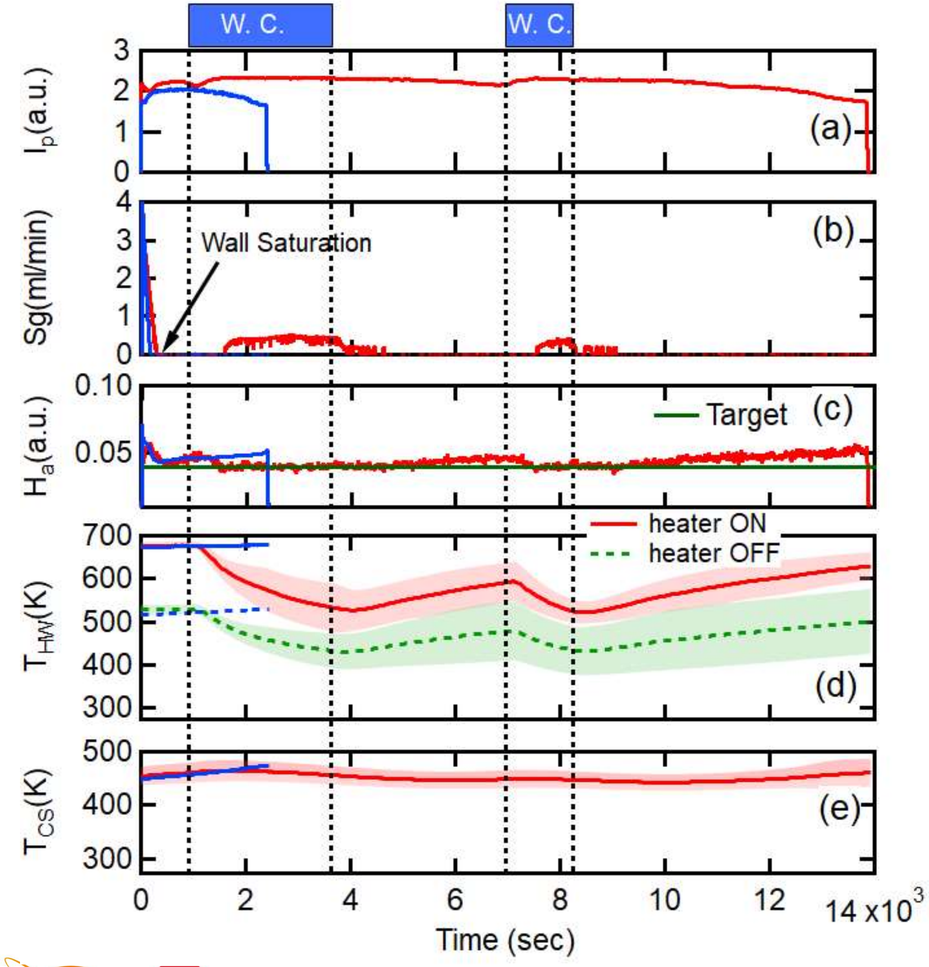
$1.3\times10^{27}\times40\text{nm}\times9.1\text{m}^2\times21/32\times0.5=1.6\times10^{20}$ H

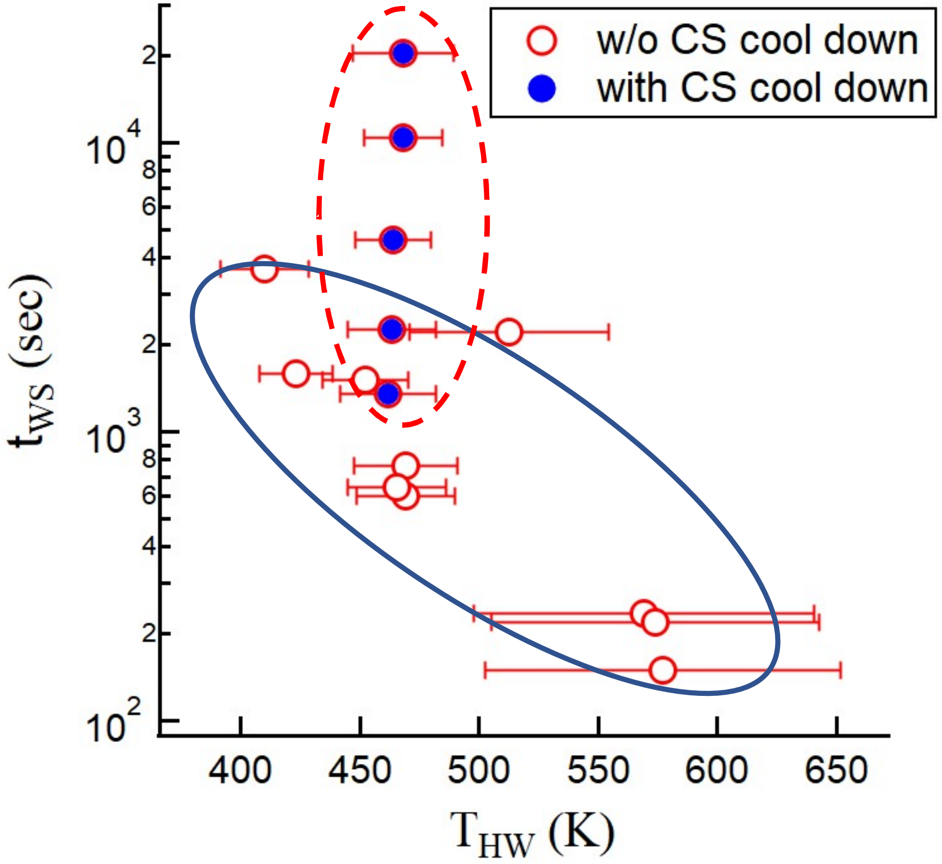
$2.5\times10^{27}\times40\text{nm}\times9.1\text{m}^2\times11/32\times0.5=1.6\times10^{20}$ H

1.6×10^{20} H_2



Wall saturation time has been decided by the stopping time of fueling to keep plasma density constant.





Time constant is an important parameter in particle balance. Trapping effect is not considered in Doyle's model.

	W	SS 316L	SS 316L coated with APS-W	Deposition layer
τ T=R.T.	0.012	571.6	26.7	$7.7\text{X}10^7$
τ T=500K	0.0012	777.7	0.016	$9.16\text{X}10^8$

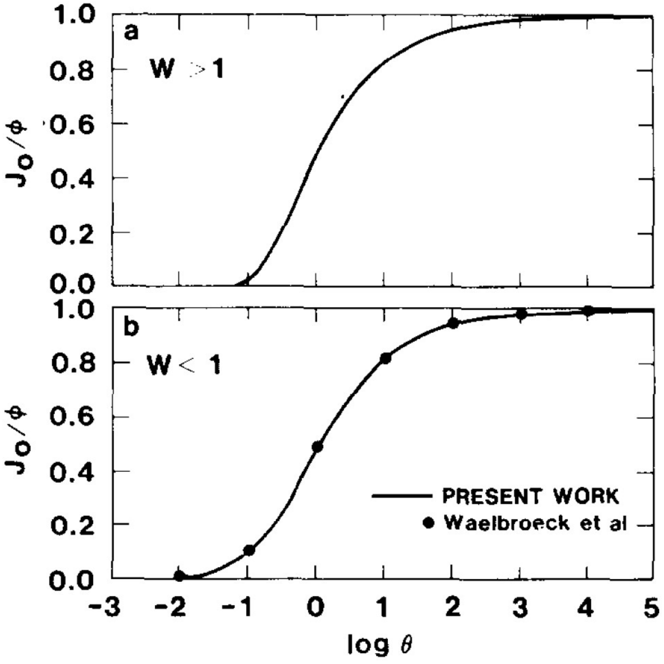
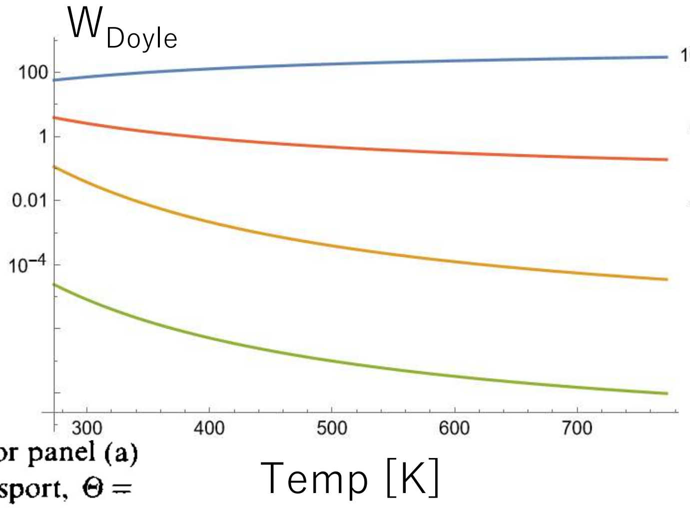
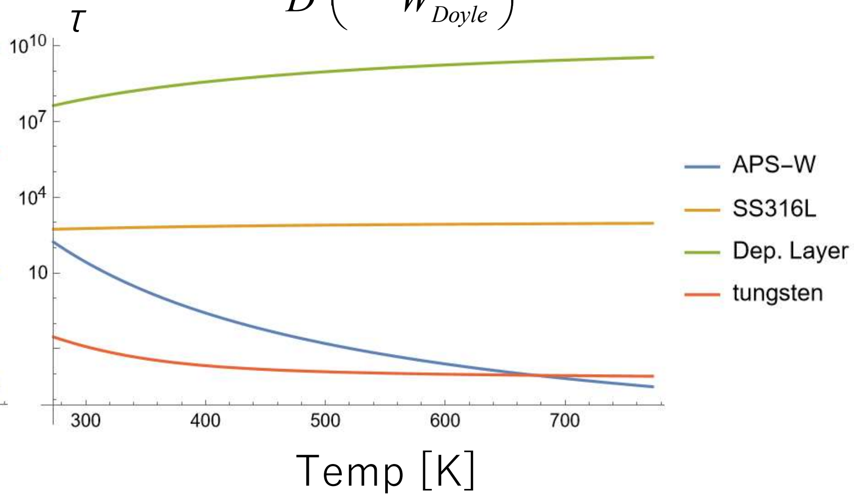


Fig. 6. Recycle flux, J_0, normalized to ϕ versus Θ. For panel (a) ($W>1$), which represents diffusion limited-H transport, $\Theta = Dt/R^2$ whereas for panel (b) ($W<1$), in which case H transport is recombination-limited, $\Theta = K_0\phi t/D$. The solid circles in panel (b) are taken from [9]; similar calculations were not available for $W>1$.

$$W_{Doyle} = R\sqrt{\gamma_{in}K}/D$$

$$\tau = \frac{R^2}{D}\left(1+\frac{1}{W_{Doyle}^2}\right)$$





Analytic solution including trapping effect could be obtained in the modified H barrier model.

New time constant including trapping effect could be obtained.

$$\frac{\partial H_W}{\partial t} = \Gamma_{in} - \frac{k_{rec}}{d^2} H_W^2$$

$$H_W = d\sqrt{\frac{\Gamma_{in}}{k_{rec}}}\, Tanh\left[\frac{\sqrt{\Gamma_{in} k_{rec}}}{d} t\right]$$

$$\frac{\partial H_W}{\partial t} = \Gamma_{in} - \frac{k_{rec}}{d^2} H_W^2 - \frac{\partial H_T}{\partial t}$$

$$\frac{\partial H_T}{\partial t} = \frac{D}{\lambda^2} H_W \left(1 - \frac{H_T}{H_{T0}}\right) - \nu_0 H_T\, Exp\left[-\frac{E_0}{k_B T}\right]$$

$$\frac{\partial H_T}{\partial t} = \frac{D}{\lambda^2} H_W \left(1 - \frac{H_T}{H_{T0}}\right) - H_T \nu_0\, Exp\left[-\frac{E_0}{k_B T}\right]$$

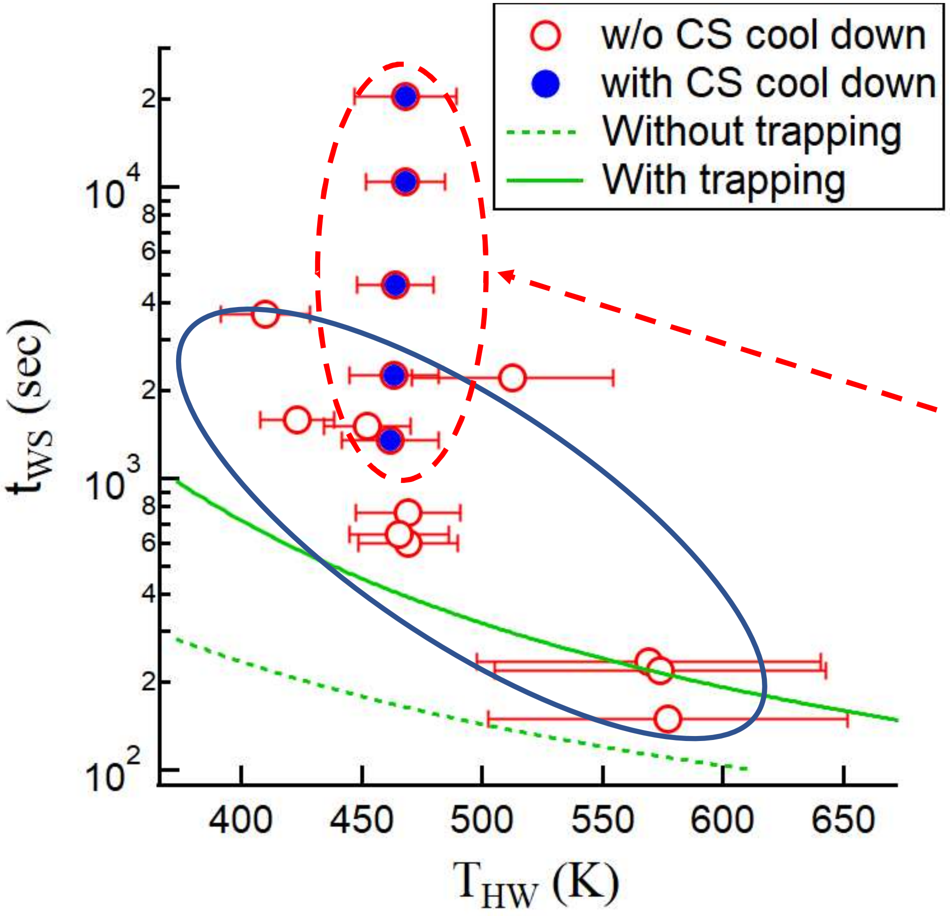
$$\boxed{\frac{H_T}{H_{T0}} \ll 1}$$

$$H_T \approx \frac{D}{\lambda^2 \nu_0} Exp\left[\frac{E_0}{k_B T}\right] H_W$$

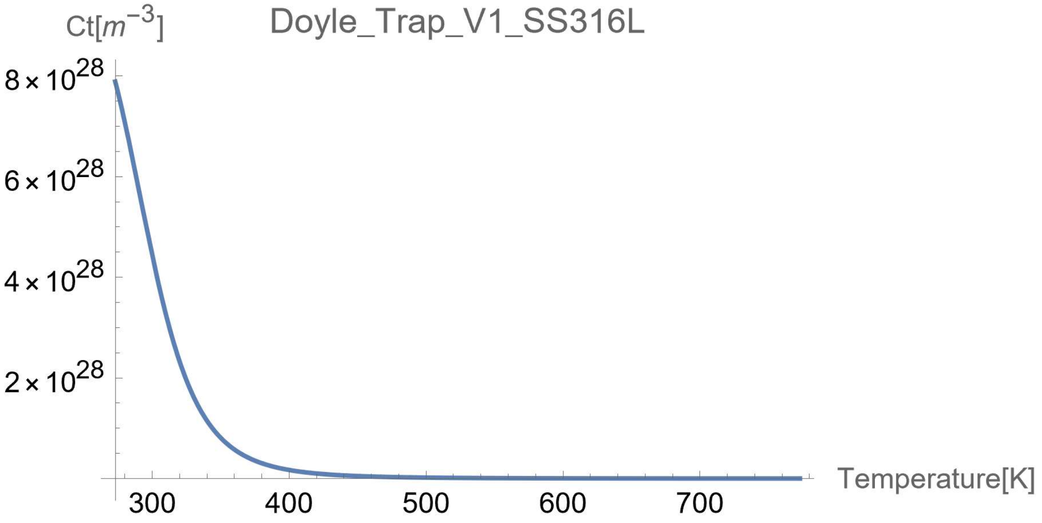
$$\left[1 + \frac{D}{\lambda^2 \nu_0} Exp\left[\frac{E_0}{k_B T}\right]\right] \frac{\partial H_W}{\partial t} = \Gamma_{in} - k_{rec}\left(\frac{H_W}{d}\right)^2$$

$$H_W = d\sqrt{\frac{\Gamma_{in}}{k_{rec}}}\, Tanh\left[\boxed{\frac{\sqrt{\Gamma_{in} k_{rec}}}{d\left(1 + \frac{D}{\lambda^2 \nu_0} Exp\left[\frac{E_0}{k_B T}\right]\right)}}\, t\right]$$

Time constant for wall saturation could be explained by the deposition layer parameters.



SS316L

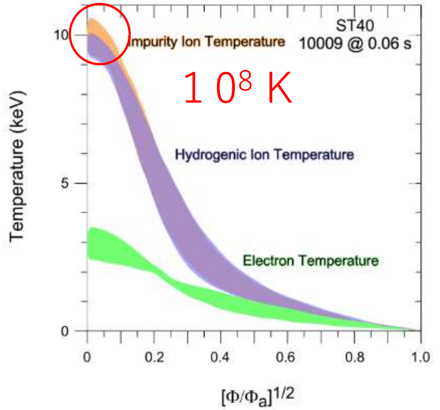


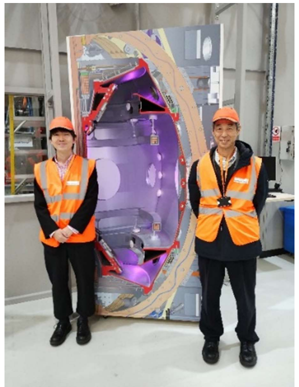
The tendency can be expressed by the feature of SS316L which is used for center stack cover.

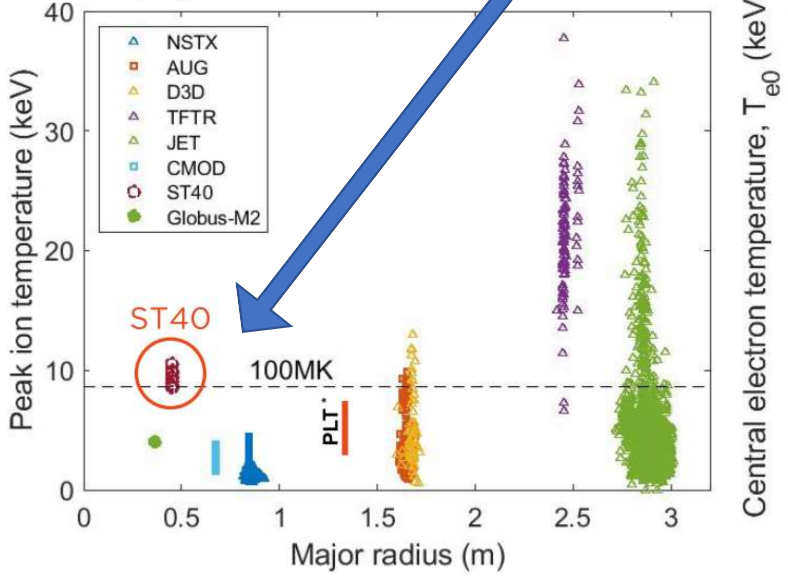
Summary

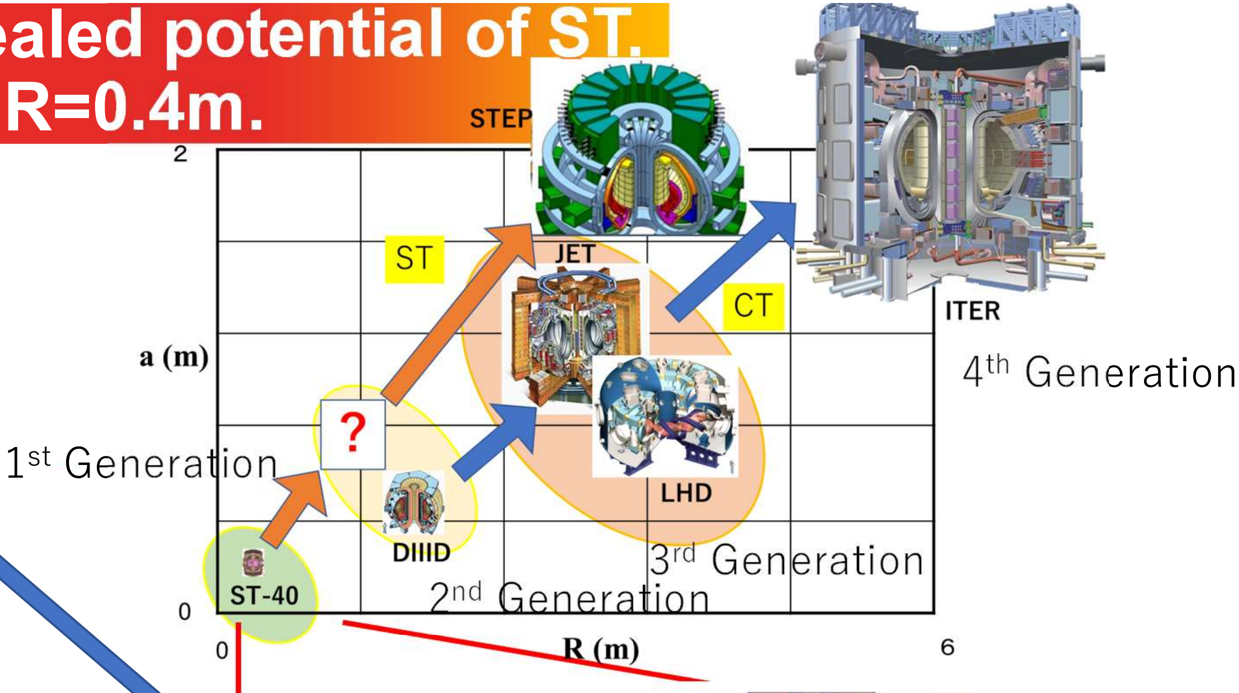
- Spherical tokamak is a good candidate for compact fusion power plant. But it has a little achievement in SSO.
- QUEST has a capability to conduct SSO. And 6 h discharges could be achieved.
- QUEST equips all-metal PFW, but the feature of the deposition layer play an essential role in particle balance on SSO.
- The wall pumping capability is quantitively explained by the feature of the deposition layer.
- The H barrier model is applicable to the deposition layer including trapping site and it predict the time constant for wall saturation on QUEST.

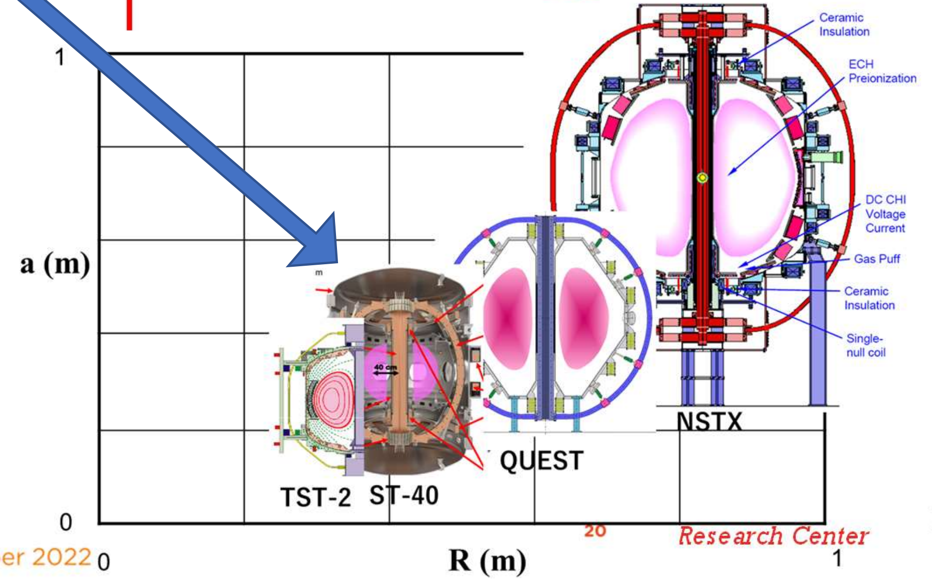
Various experiments have revealed potential of ST. ST40 could achieve 10^8 K with R=0.4m.











But, ST had little achievement on steady state operation. TRIAM-1M (K.U.) could obtain more than 5 h. in 2003.

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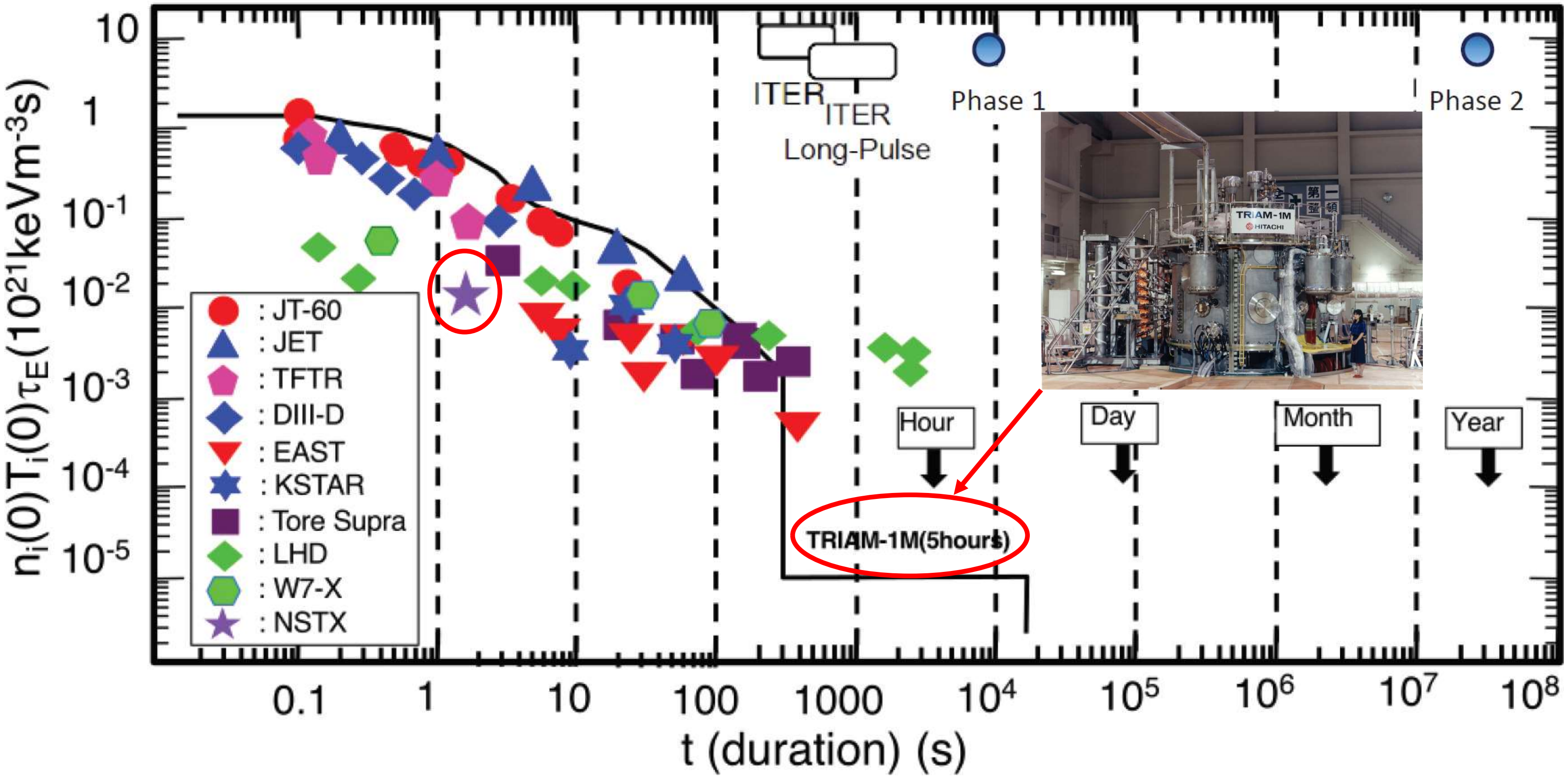
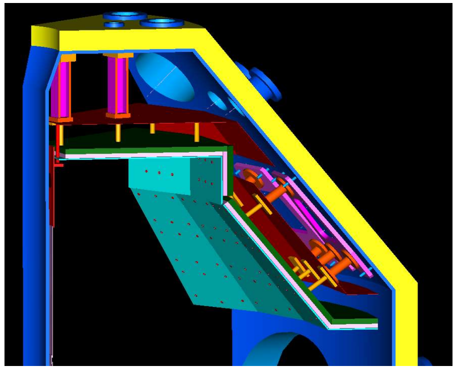
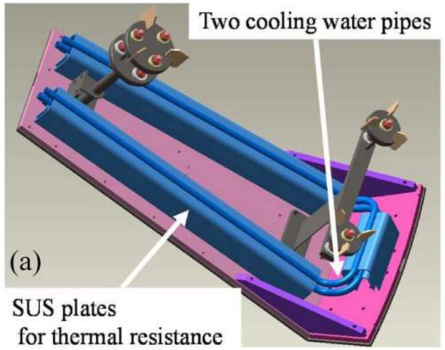
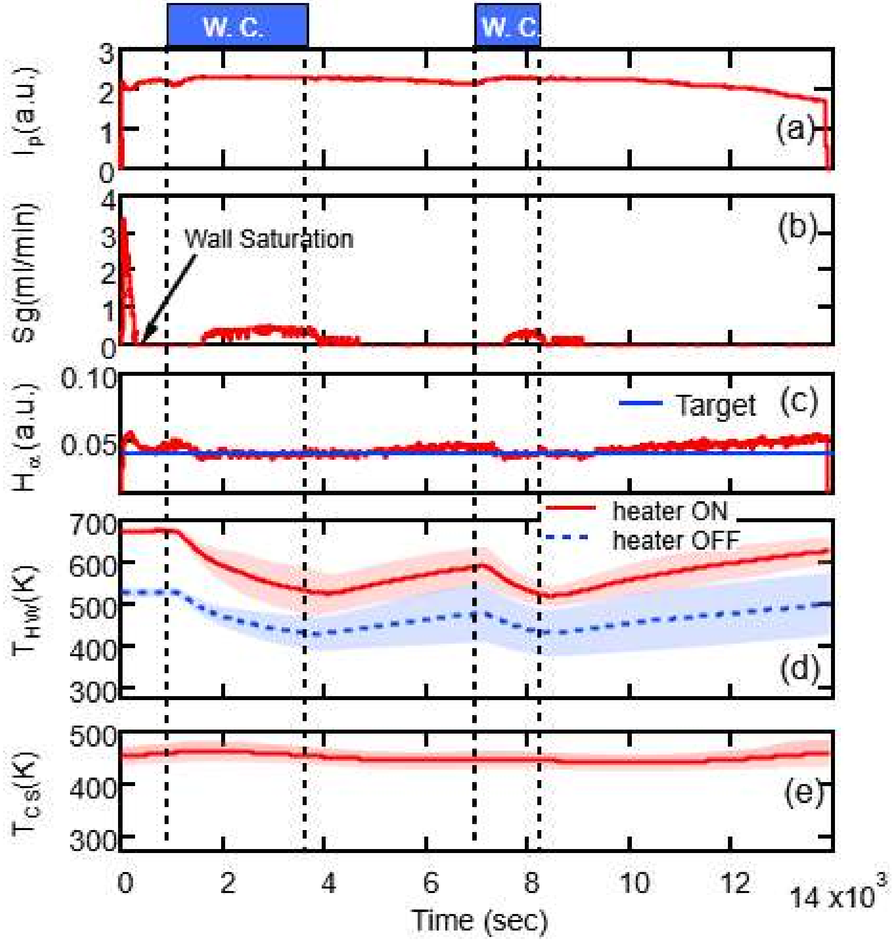


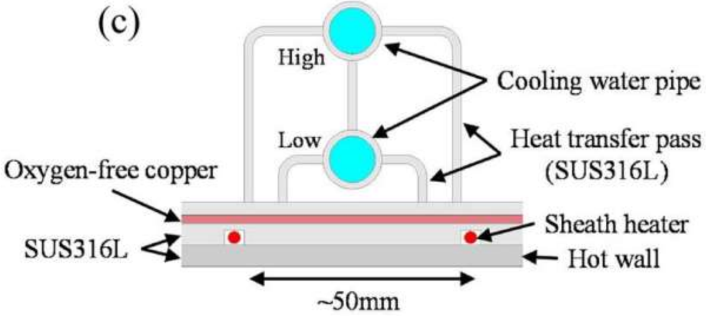
[Bringing Fusion to the U.S. Grid | The National Academies Press]

Wall temperature control on QUEST indicated the fuel recycling could be modified.

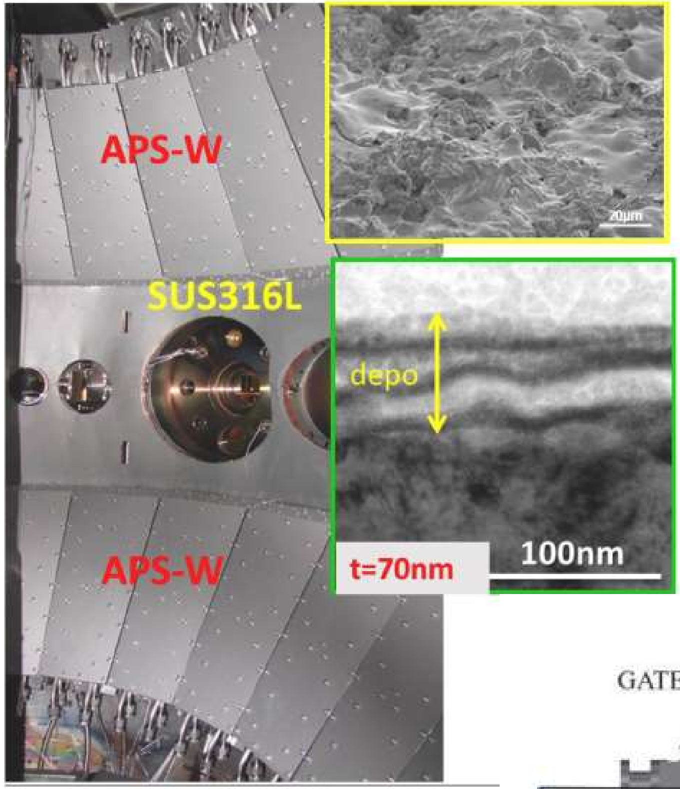


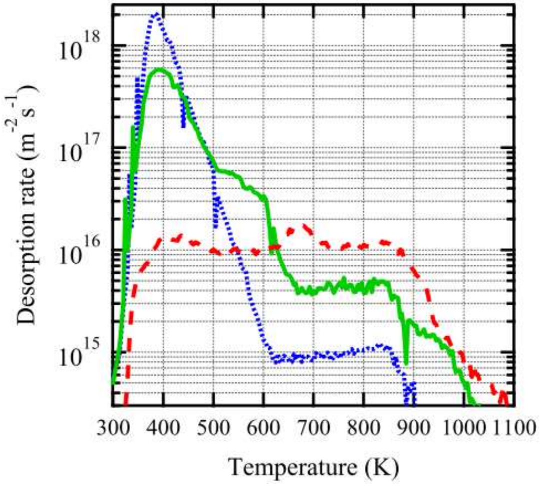


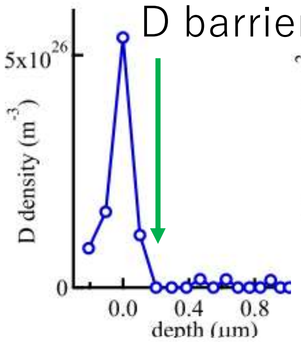


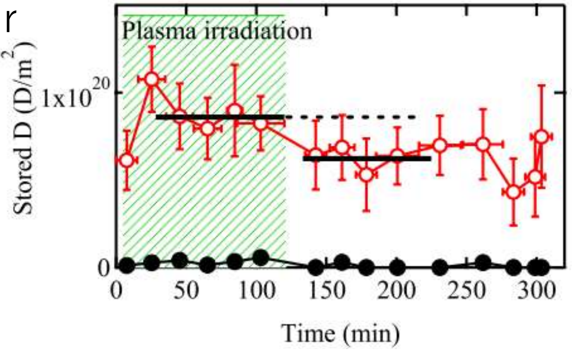


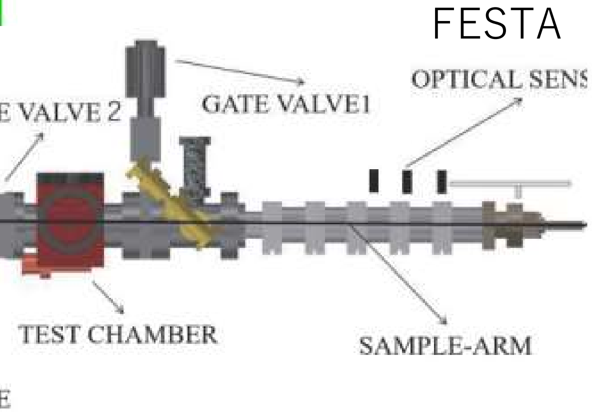
Plasma induced deposition layer play an essential role. Hydrogen barrier and enhanced recycling are induced by D.L.

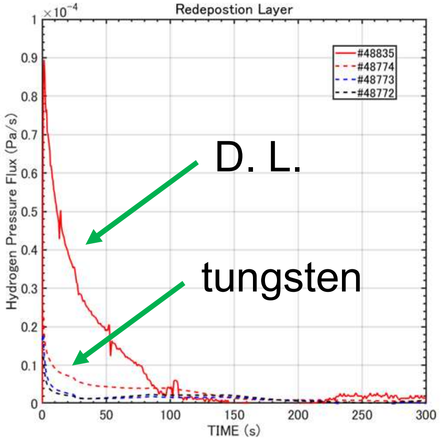


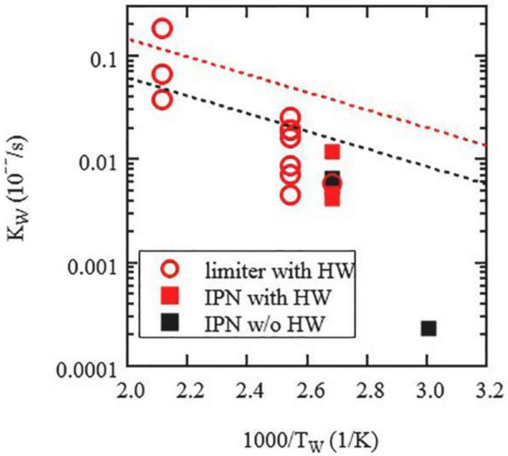






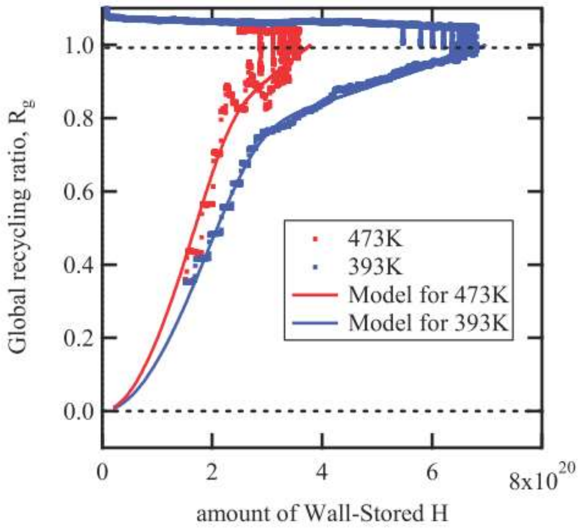


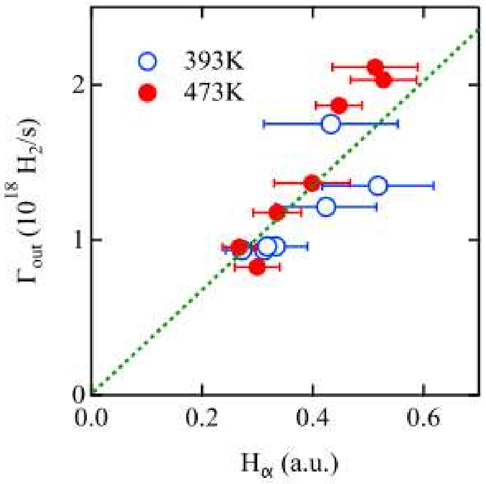


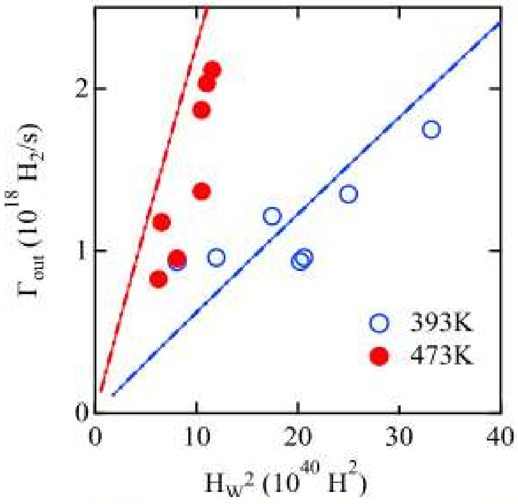


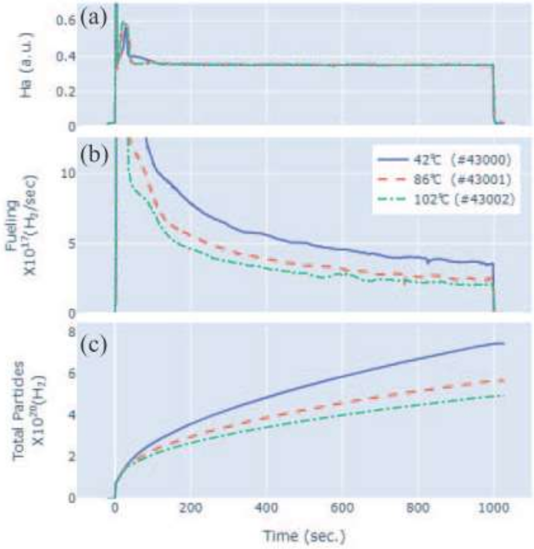
K.Hanada et. al, NME 19 (2019) 544–549
K.Hanada et. al, NME 27 (2021) 101013
K.Hanada et. al, NF 57 (2017) 126061
Q.Yue et. al, PFR 15 (2020) 2402013
Q.Yue Dr. Thesis in Kyushu University

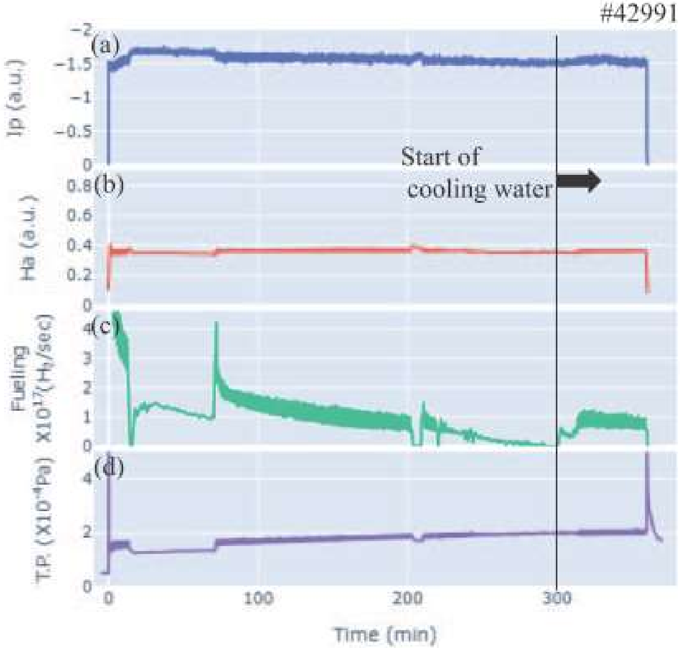
Plasma facing Temp. is able to control P.B. and fuel recycling. Its control is effective to achieve SSO on QUEST.

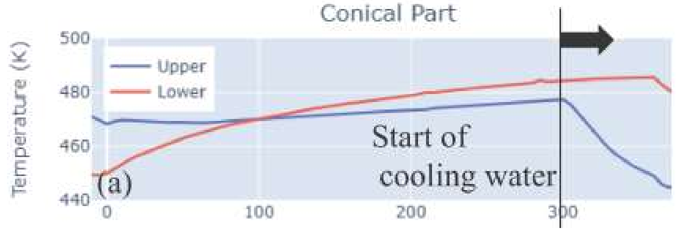






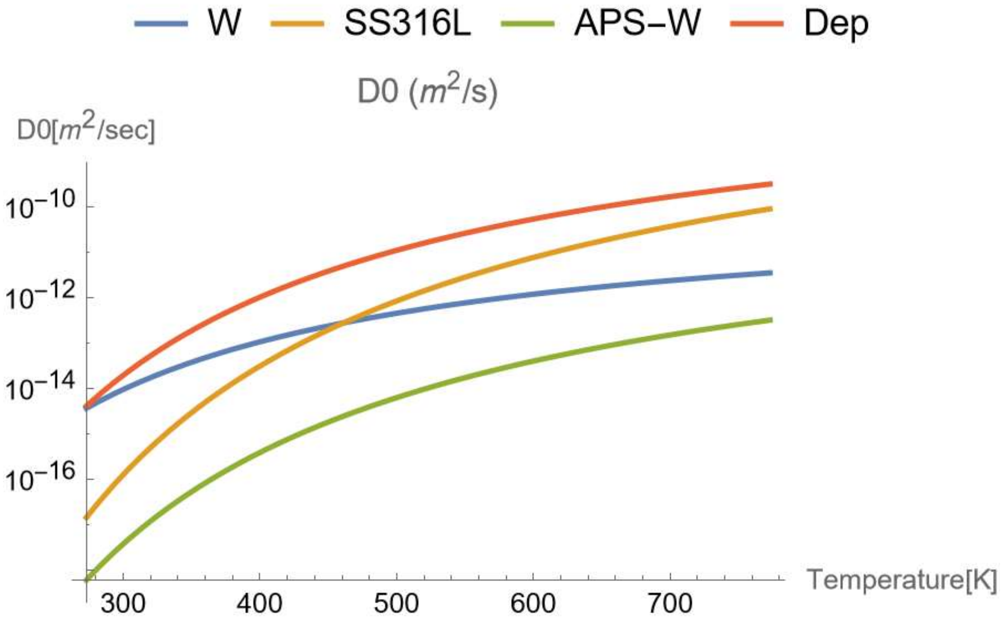


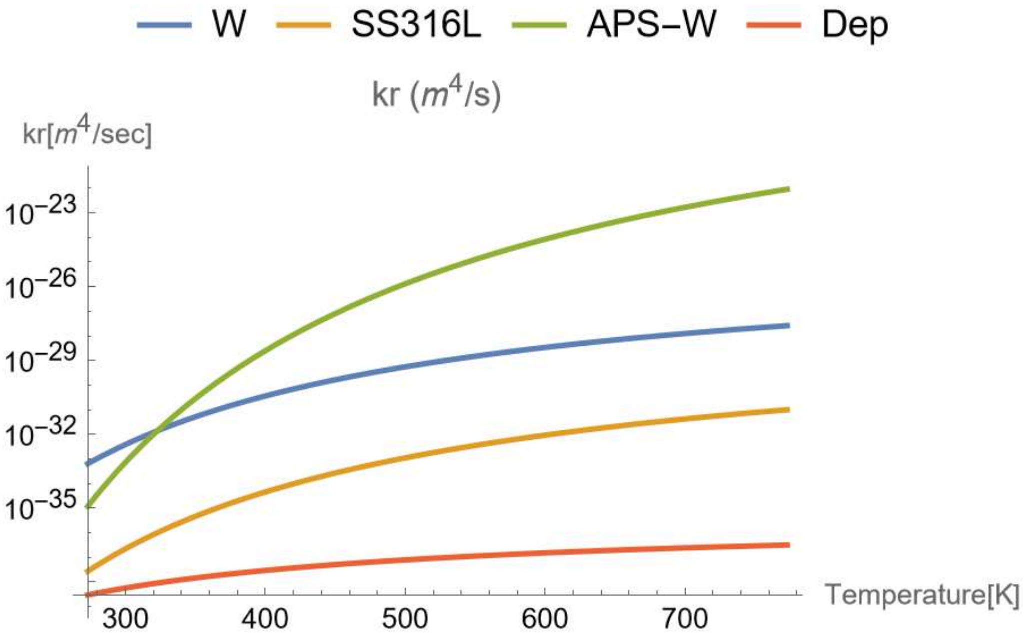




K.Hanada et. al, NF 57 (2017) 126061
K.Hanada et. al, NF 59 (2019) 076007
M.Hasegawa et. al, PFR 16 (2021) 2402034

Parameters of Material





立ち下げ時

Trap siteなし

$$\frac{\partial H_W}{\partial t} = -k_{rec} H_W^2$$

$$H_W\Big|_{t=t_{End}} = \sqrt{\frac{\Gamma_{in}}{k_{rec}}}\,\mathrm{Tanh}\left(\sqrt{\Gamma_{in}k_{rec}}\,t_{end}\right) = H_W^{End}$$

$$H_W\left[t\right] = \frac{H_W^{End}}{1+k_{rec}H_W^{End}\left(t-t_{End}\right)}$$

Trap siteあり

$$\frac{\partial H_{WT}}{\partial t}\left(1+\frac{D}{\lambda^2\nu_0}Exp\left(\frac{E_0}{k_BT}\right)\right) = -k_{rec}H_{WT}^2$$

$$H_W\Big|_{t=t_{End}} = \sqrt{\frac{\Gamma_{in}}{k_{rec}}}\,\mathrm{Tanh}\left(\frac{\sqrt{\Gamma_{in}k_{rec}}}{\left(1+\frac{D}{\lambda^2\nu_0}Exp\left(\frac{E_0}{k_BT}\right)\right)}t_{END}\right) = H_{WT}^{End}$$

$$H_{WT}[t] = \frac{H_{WT}^{End}}{1+k_{rec}H_{WT}^{End}\dfrac{t}{\left(1+\frac{D}{\lambda^2\nu_0}Exp\left(\frac{E_0}{k_BT}\right)\right)}}$$

壁飽和からの放出束が1/eになるまでの時間

$$\frac{\partial H_{WT}}{\partial t}\left(1+\frac{D}{\lambda^2\nu_0}Exp\left(\frac{E_0}{k_BT}\right)\right)=-k_{rec}H_{WT}^2$$

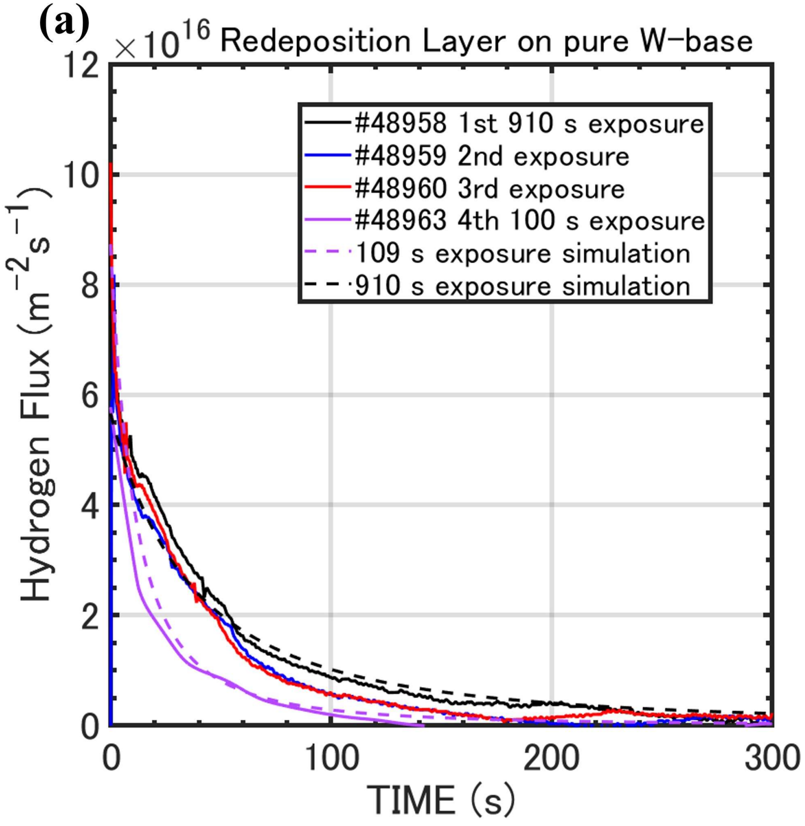
$$H_W\Big|_{t=t_{End}}=\sqrt{\frac{\Gamma_{in}}{k_{rec}}}\,\mathrm{Tanh}\left(\frac{\sqrt{\Gamma_{in}k_{rec}}}{\left(1+\frac{D}{\lambda^2\nu_0}Exp\left(\frac{E_0}{k_BT}\right)\right)}t_{END}\right)=H_{WT}^{End}$$

$$H_{WT}[t]=\frac{H_{WT}^{End}}{1+k_{rec}H_{WT}^{End}\dfrac{t}{\left(1+\frac{D}{\lambda^2\nu_0}Exp\left(\frac{E_0}{k_BT}\right)\right)}}$$

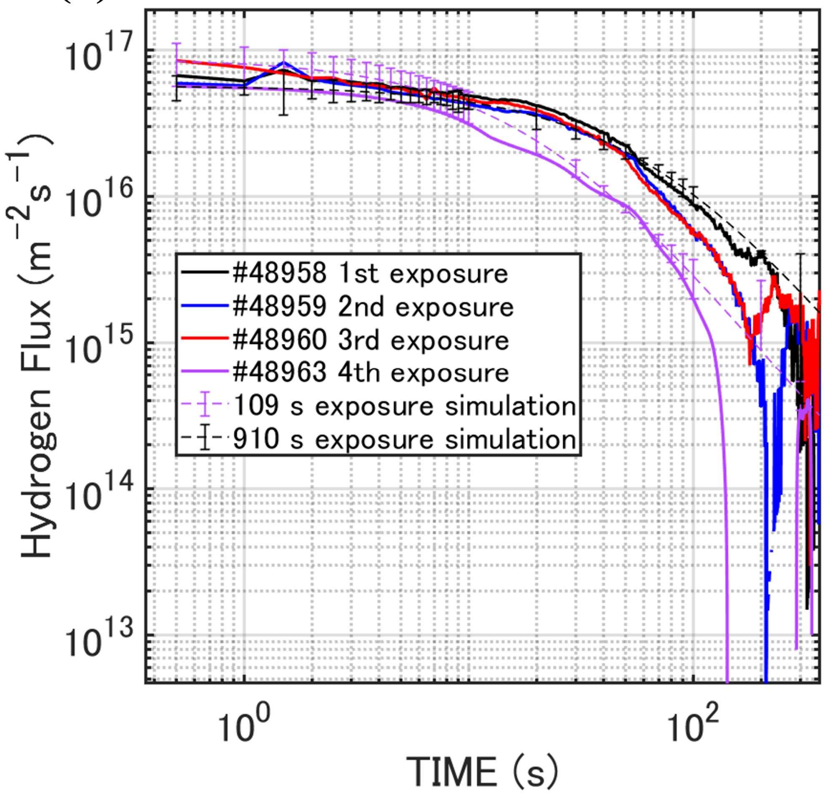
壁飽和している場合にはTanh[]=1と近似

FESTA result for W could be reconstructed with the published parameters of W.

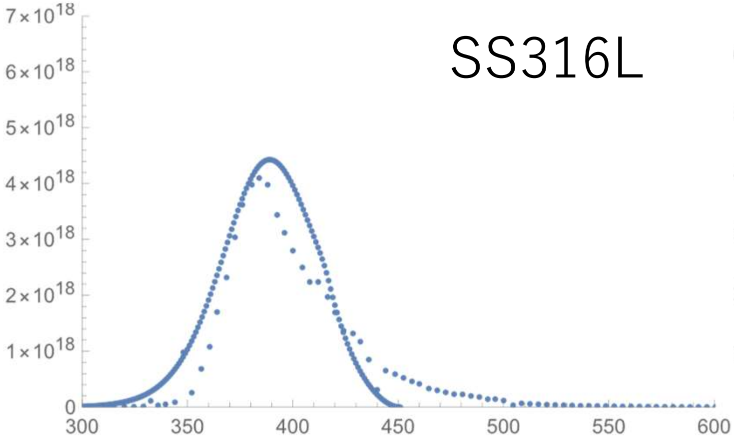
(a)

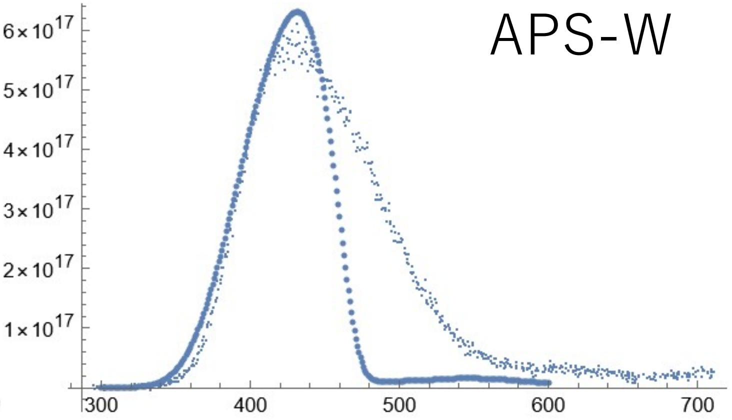


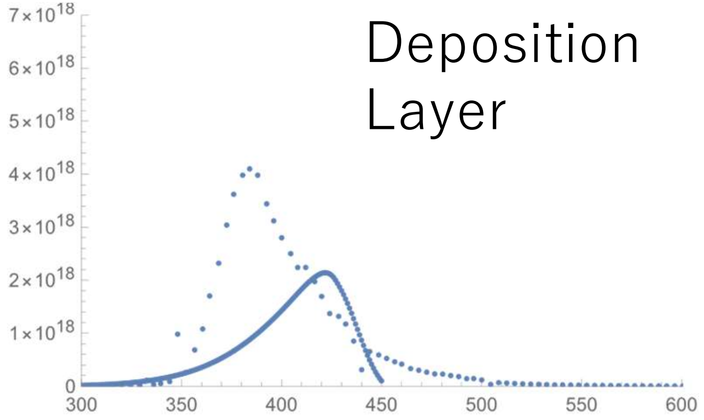
(b)



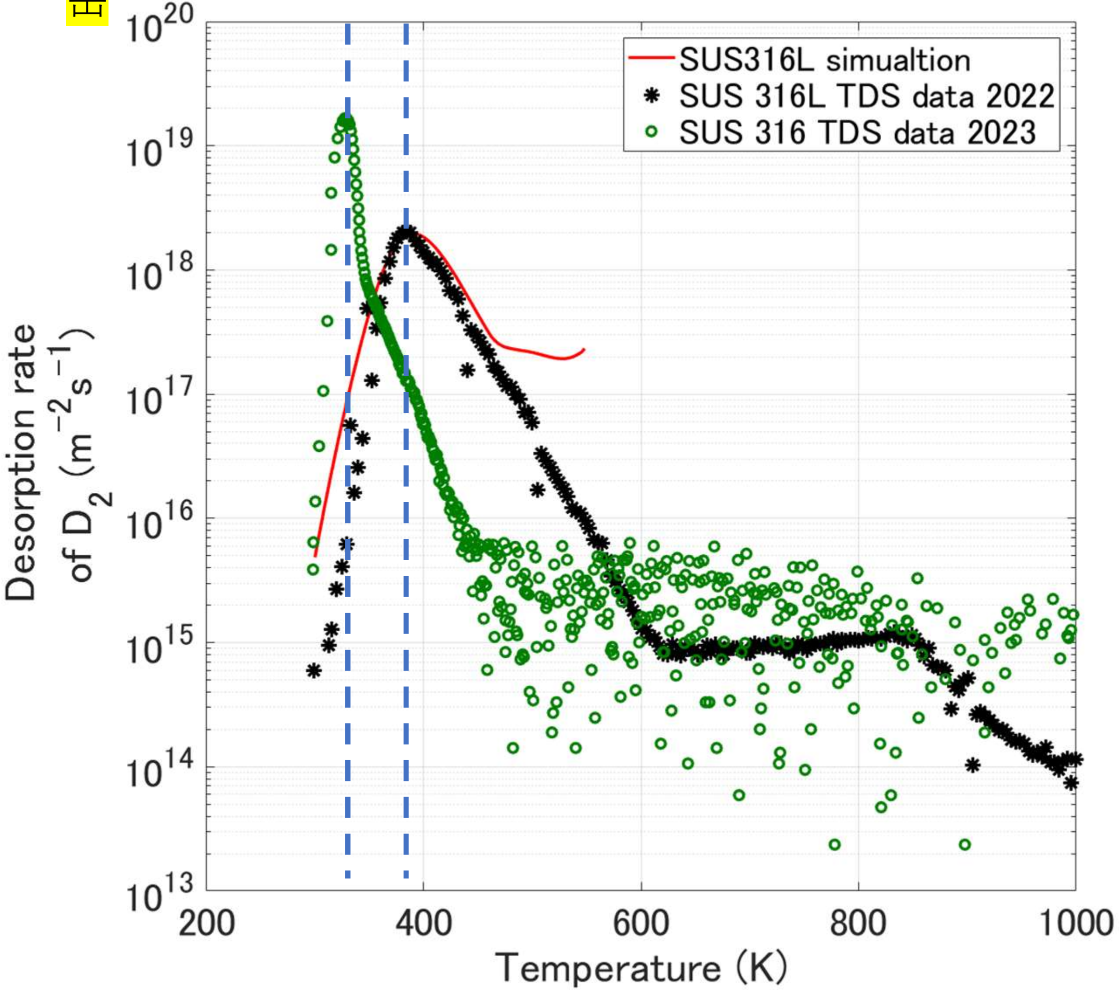
Thermal desorption spectrum provides the parameters of material



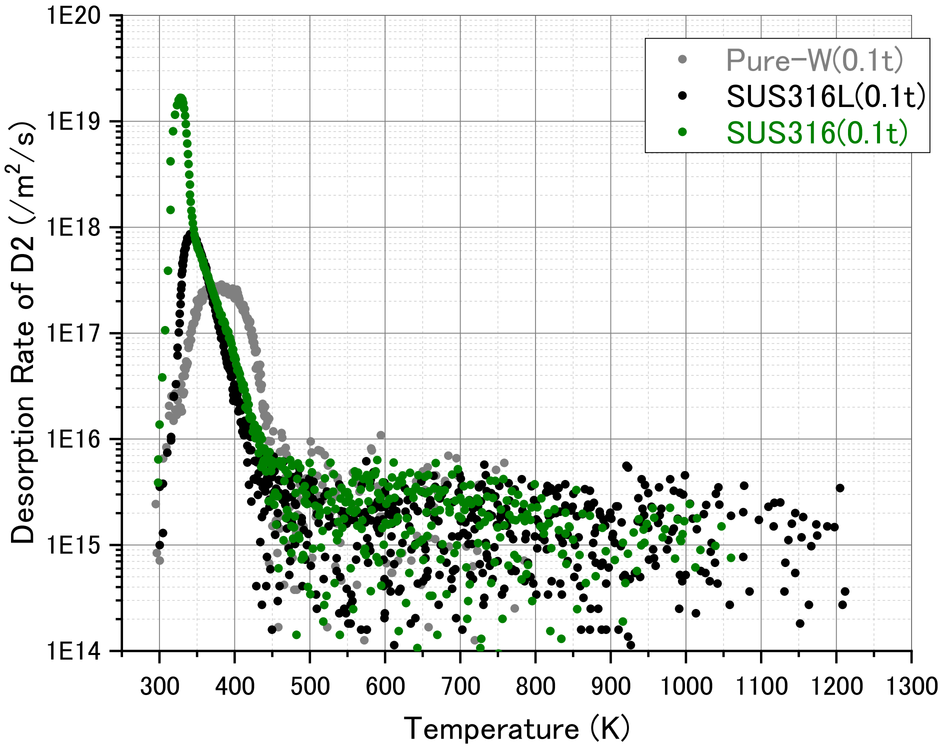




岳



島袋さん



① 316と316Lのピーク（desorption rate & T）に差がある（左右図）。
② 以前貰って316Lデータとも少し差（ピークの温度）がある。（試料が違うため、許容範囲内？）
③ SUS316のデータを再現するために、デトラップエネルギー（表のE=0.7 eV）また再結合係数を再評価？

Feature of Materials to understand wall saturation

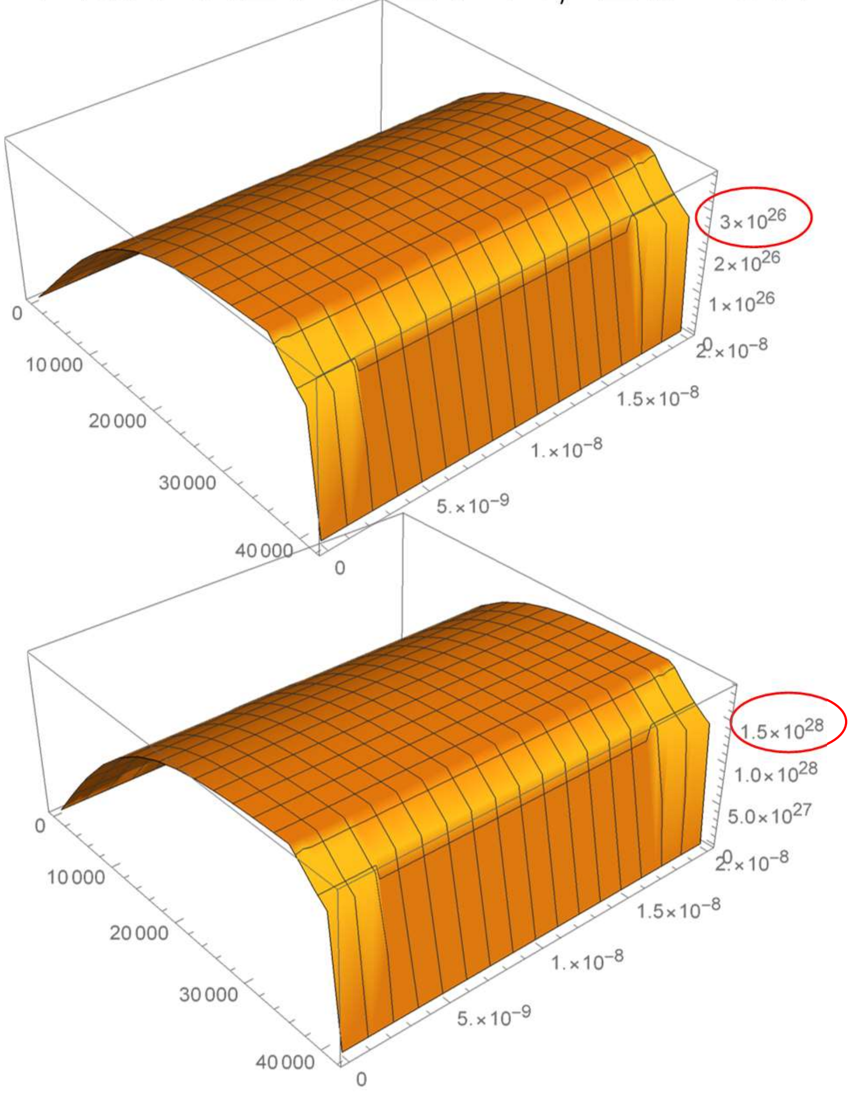
	W	SS 316L	SS 316L coated with APS-W	Deposition layer
Method	FESTA, TDS	TDS	TDS	NRA
$D_0[m^2/s]$	1.5 x 10^{-10} [*1]	4.7 x 10^{-7}	4.3 x 10^{-10}	1.5 x 10^{-7}
$E_D[eV]$	0.25 [*1]	0.57	0.48	0.41
$k_0[m^4/s]$	3.0 x 10^{-25}	3.8 x 10^{-28}	1.0 x 10^{-15}	4.0 x 10^{-36}
$E_k[eV]$	0.47	0.55	1.08	0.17
E [eV]	0.85 [*1]	0.7	1.05	0.5
$C_{T0}[m^{-3}]$	6 x 10^{26}	1 x 10^{29}	1.5 x 10^{27}	1x 10^{29}
$d_{surface}[nm]$	10	20	30	10
W_{Doyle}@T_w=R.T.	6.5 x 10^{-2}	3.7 x 10^{-2}	72	8.2 x 10^{-6}
W_{Doyle}@T_w=500K	2.5	3.8 x 10^{-4}	183	9.9 x 10^{-8}

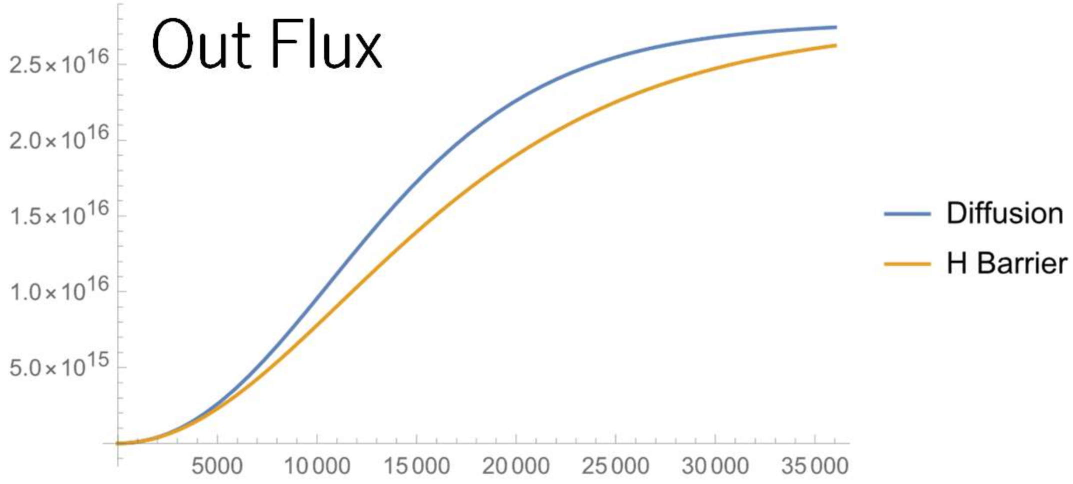
$$W_{Doyle} = d_p \sqrt{\gamma_{in} k_{rec}} \big/ D$$

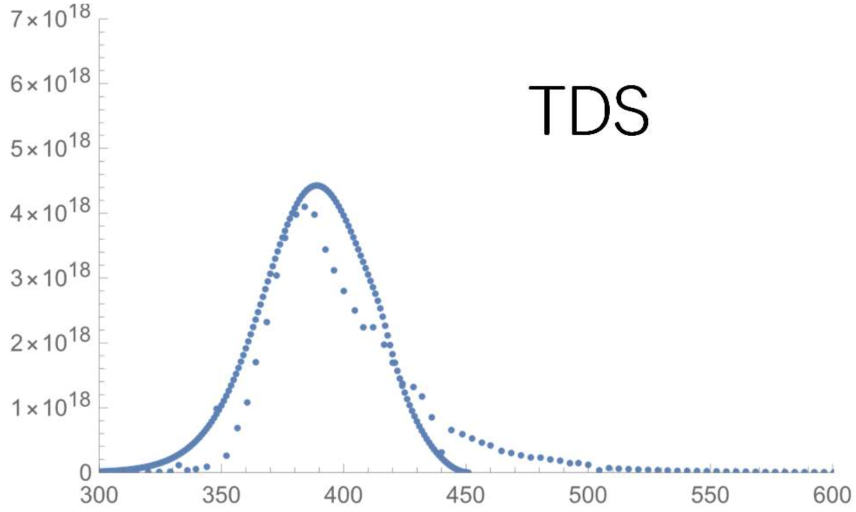
SUS316Lのモデリング

SUS316L_TDS_Analysis_Fit_2Layer_Check1_gakuV1_9

Flux 0.278e17 H, Ed=0.7eV, ddep=20, yTa0=1, R x 1/20 Mod







APS-W（２層モデル）でのバリアモデルとの比較

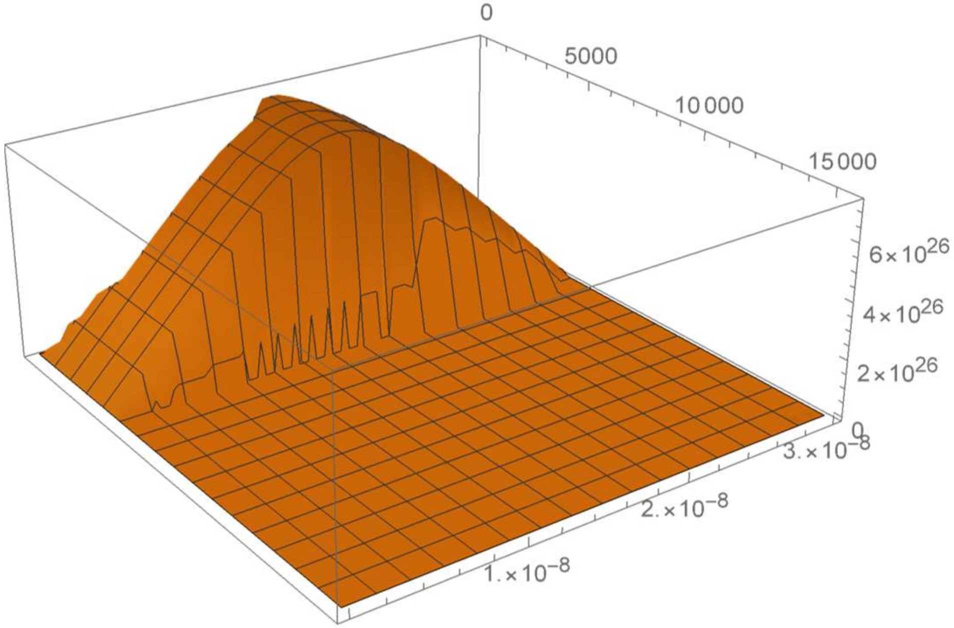
APSW_TDS_Analysis_Fit_2LayerV1_final

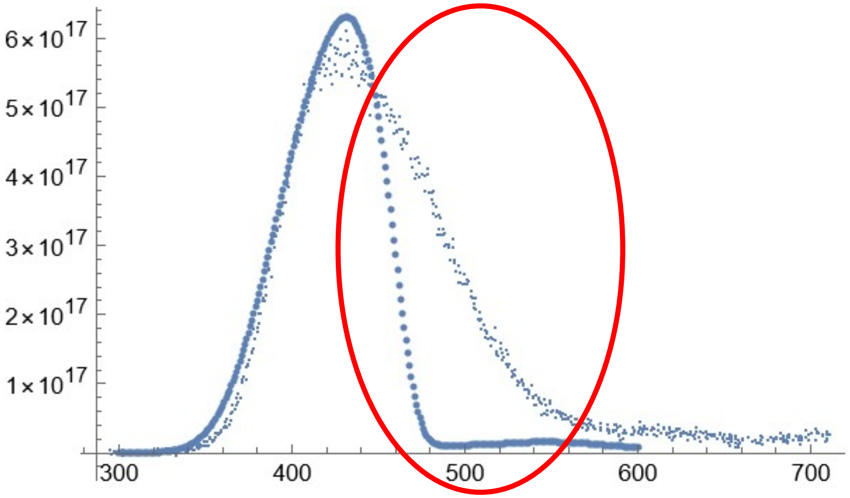
時間変化は一致しない。

拡散係数が小さく、バリアモデルで必要とされる早い拡散が満たされていないため。

放出は半分

TDSは高温部分で一致しない（計算値は２倍）もう一つtrap siteが存在する可能性

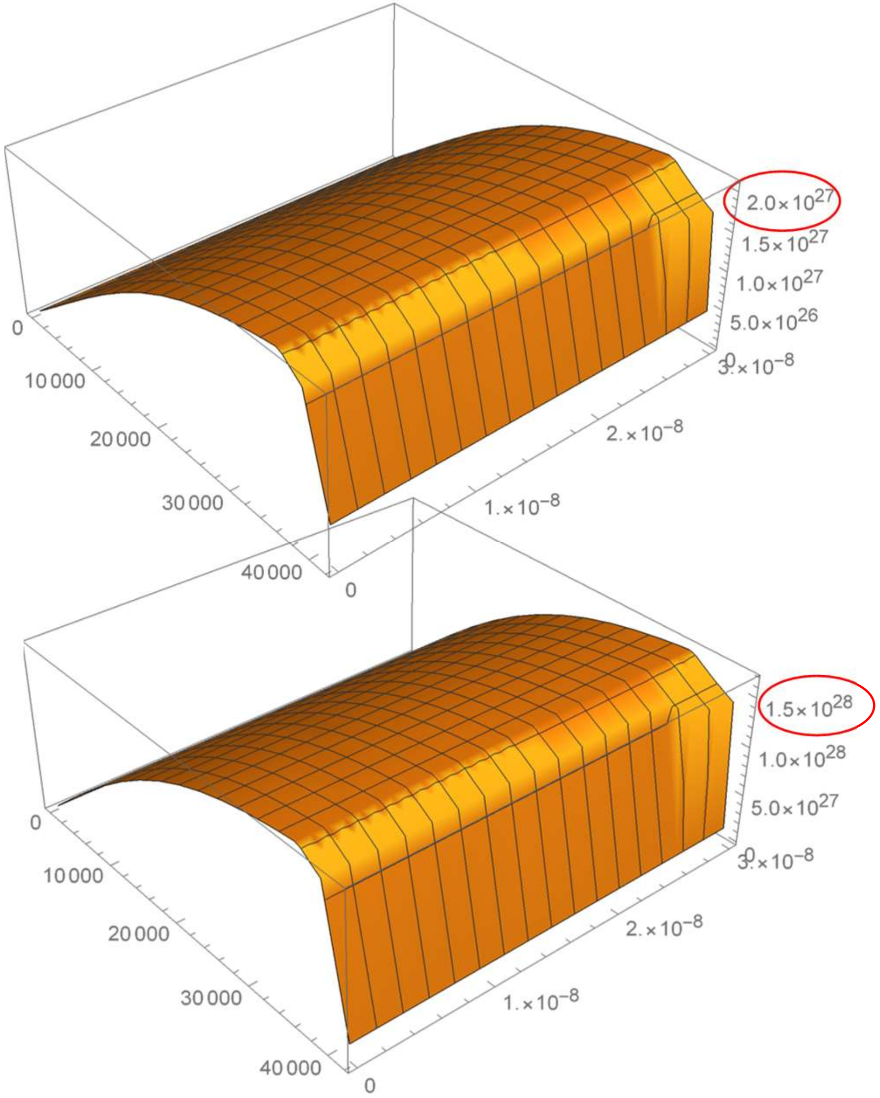


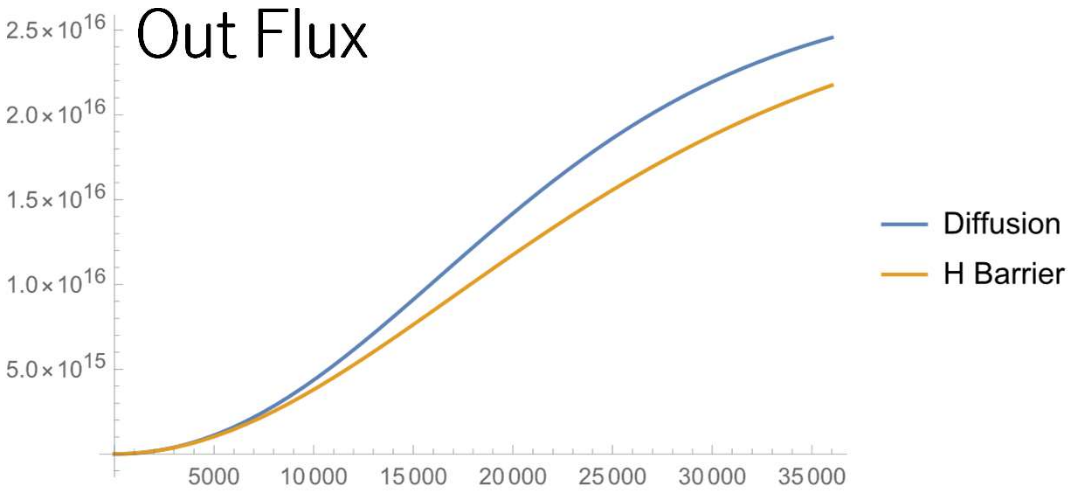


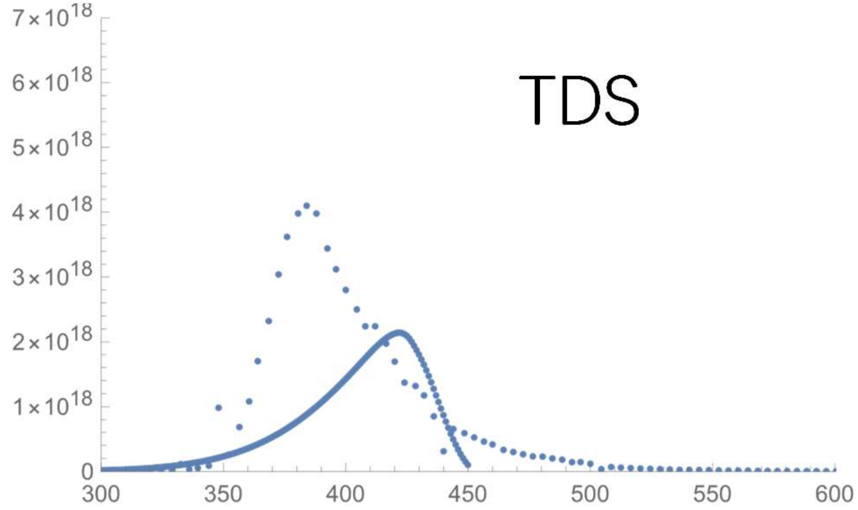
堆積層のモデリング

Deposition_TDS_Analysis_Fit_2Layer_Check0_1

Flux 0.278e17 H, Ed=0.5eV, ddep=30, yTa0=1, R Takagi ERX2




Out Flux


TDS

Trap siteに関する検討　Trap卓越モデル

$$\frac{\partial C_T}{\partial t}=\frac{D(temp)}{\lambda^2}\left(1-\frac{C_T}{C_{T0}}\right)C-\nu_0 Exp\left[-\frac{T_T}{temp}\right]C_T$$

$$\frac{\partial C_T}{\partial t}=\frac{D(temp)}{\lambda^2}C-\left(\frac{D(temp)}{\lambda^2}\frac{C}{C_{T0}}+\nu_0 Exp\left[-\frac{T_T}{temp}\right]\right)C_T$$

ここで、定常状態の解として

$$C(x)=-(C_P-C_1)\frac{x-R}{x_0-R}+C_P\ (x\ge R)$$

を使うと、

$$C_T(x)\Big|_{t\to\infty}=\frac{D\left(C_P(x-x_0)-C_1(x-R)\right)/\lambda^2}{\frac{D}{\lambda^2}\left(\frac{C_P}{C_{T0}}(x-x_0)+\frac{C_1}{C_{T0}}(x-R)\right)+\nu_0(x_0-R)Exp(-T_T/temp)}(x\ge R)$$

をx=R~x0で積分すると、

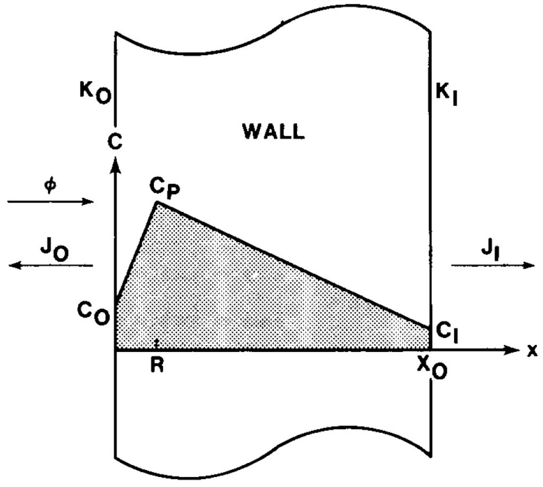


Fig. 1. Schematic of H concentration in a wall membrane. The various parameters listed are defined in the text.

Trap siteに関する検討　Trap卓越モデル

$$\frac{\partial C_T}{\partial t}=\frac{D(temp)}{\lambda^2}\left(1-\frac{C_T}{C_{T0}}\right)C-\nu_0 Exp\left[-\frac{T_T}{temp}\right]C_T$$

$$\frac{\partial C_T}{\partial t}=\frac{D(temp)}{\lambda^2}C-\left(\frac{D(temp)}{\lambda^2}\frac{C}{C_{T0}}+\nu_0 Exp\left[-\frac{T_T}{temp}\right]\right)C_T$$

ここで、定常状態の解として

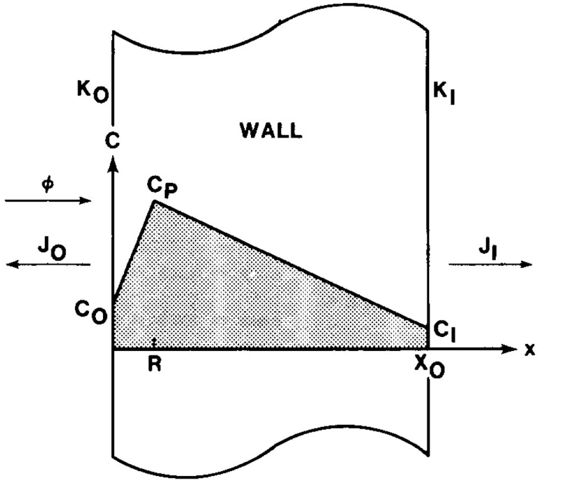
$$C(x)=\frac{C_P-C_0}{R}x+C_0\,(x\le R)$$

を使うと、

$$C_T(x)\Big|_{t\to\infty}=\frac{\dfrac{D}{\lambda^2}\left(\dfrac{C_P-C_0}{R}x+C_0\right)}{\dfrac{D}{\lambda^2}\left(\dfrac{C_P-C_0}{R}x+C_0\right)+\nu_0 Exp\left(-T_T/temp\right)}(x\le R)$$

をx＝０~Rで積分すると、

$$C_T^{total}$$



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