Control of fuel particle recycling using the hot wall on all-metal plasma facing wall in QUEST

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Acknowledgement

Thanks to the collaborators of QUEST project

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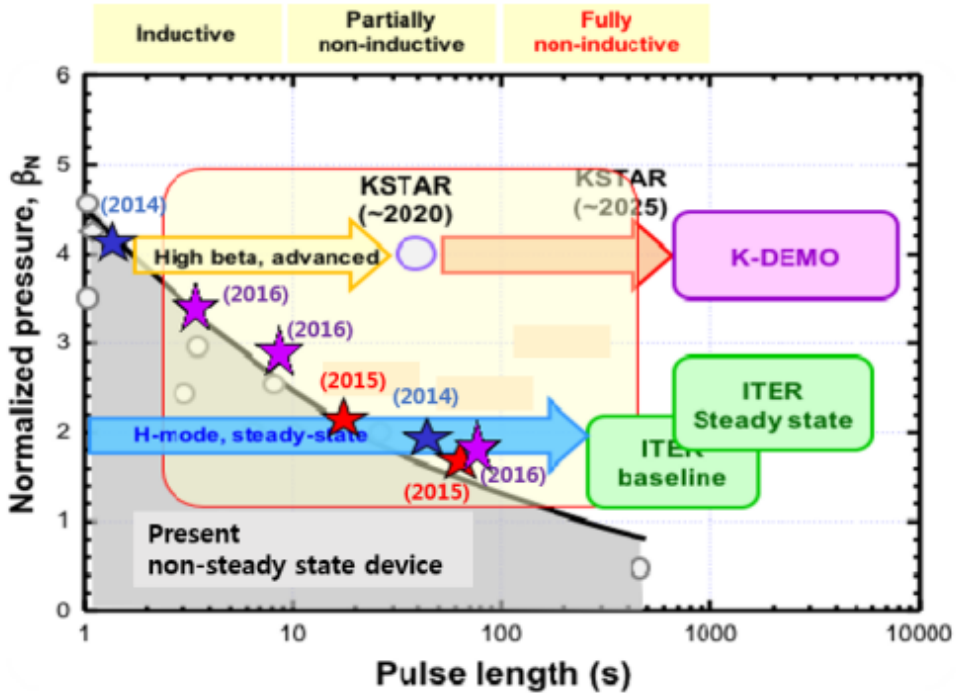
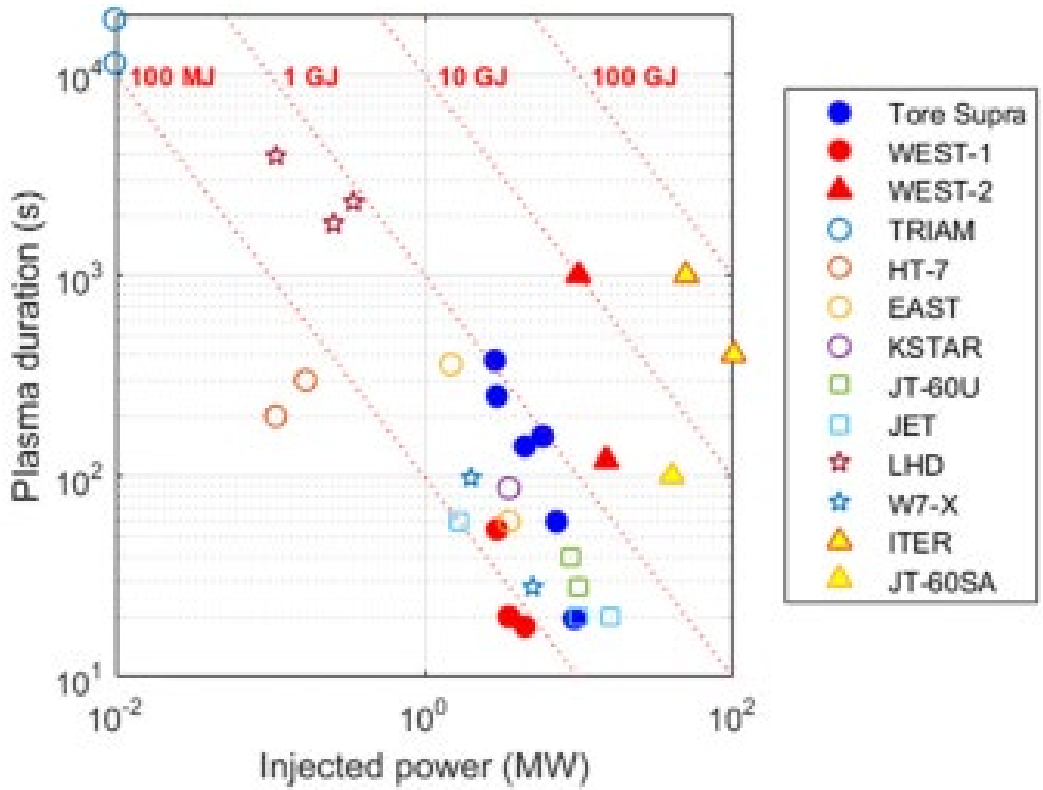
Motivation

- Steady State operation （SSO）of high performance plasma is one of the most important issues for fusion power plant.
- High power injection (α heating in future) leads to high impact on PFWs.
- To reduce T retention in carbon, PFWs would be composed of a low activation and low sputtering metal such as tungsten.



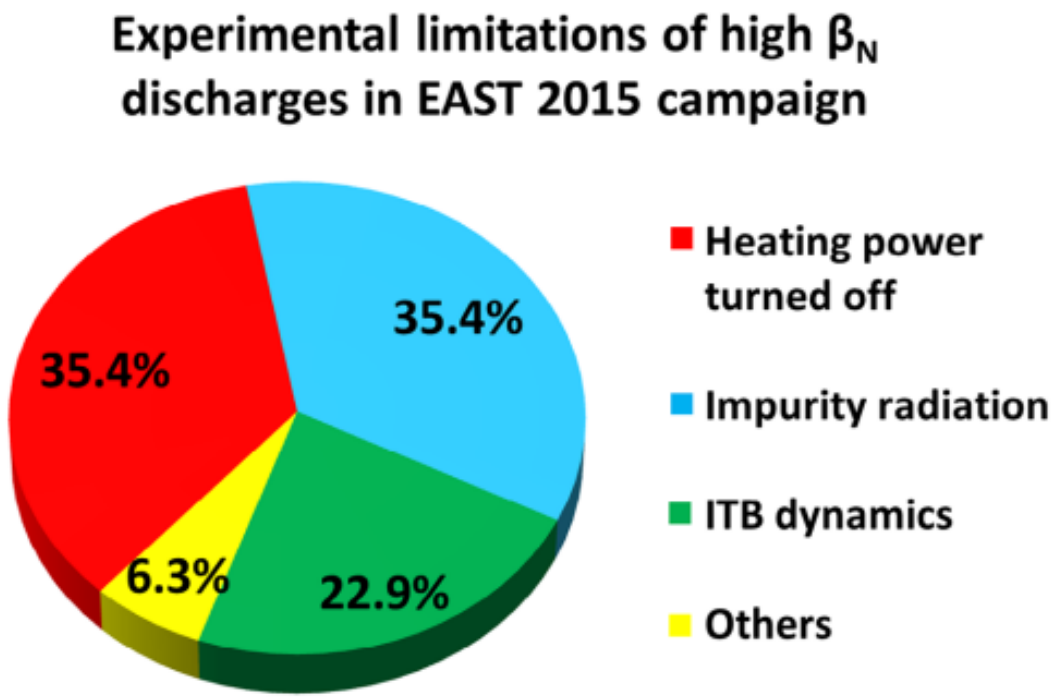
Park_2019_Nucl._Fusion_59_112020



Bucalossi_2022_Nucl._Fusion_62_042007

What is the key to overcome the difficulties

- Control of plasma parameters to obtain high performance has been addressed.
- Lithium dropper has been shown to lower fuel recycling on EAST, and an advanced confinement mode (the I-mode) could be maintained for more than 1000s.
- -> Recycling control is the key to overcome the difficulties.



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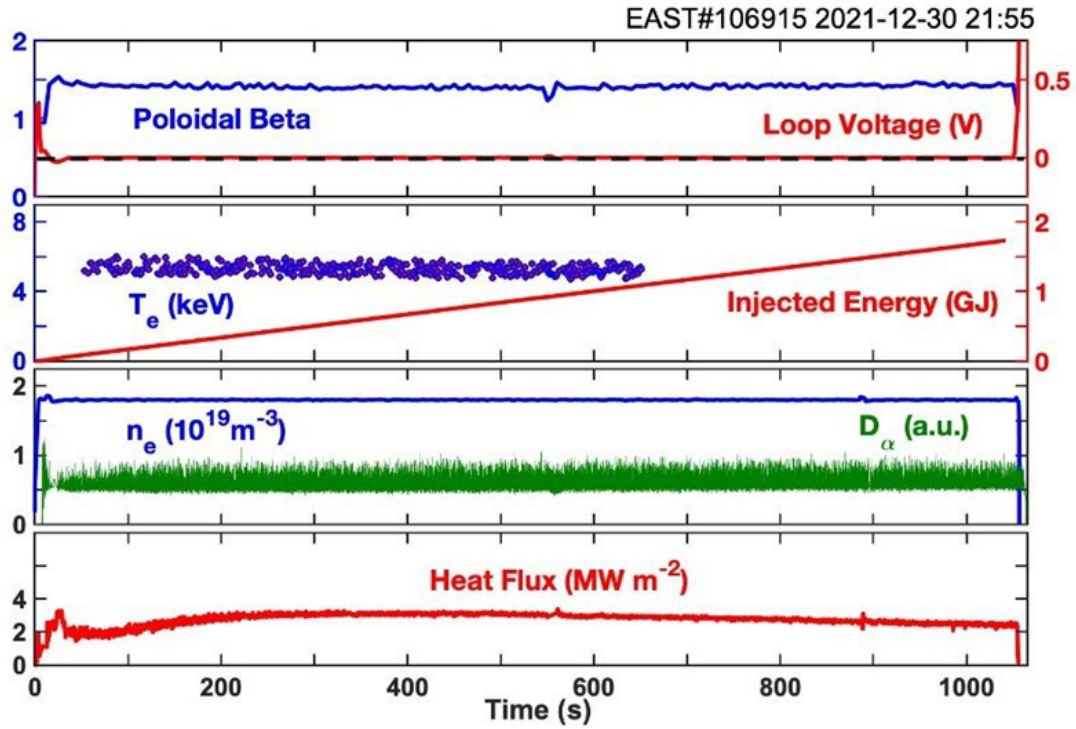
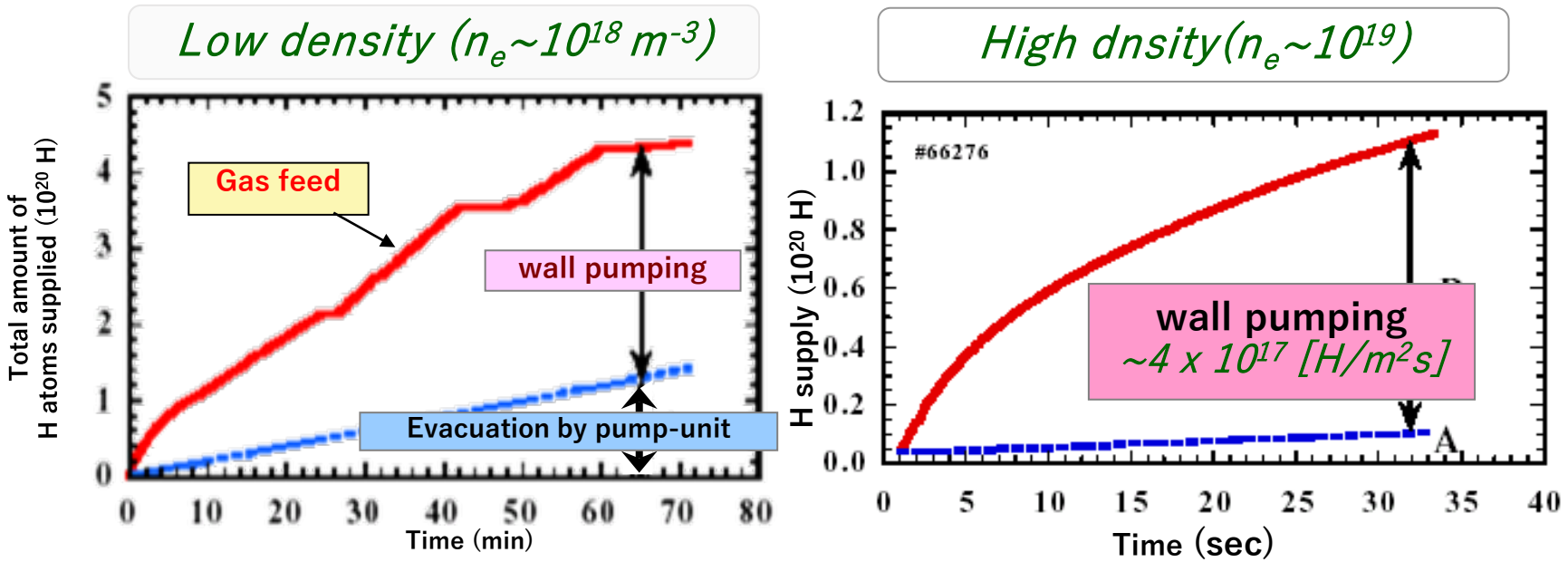


Parameters of shot 106915 (EAST)

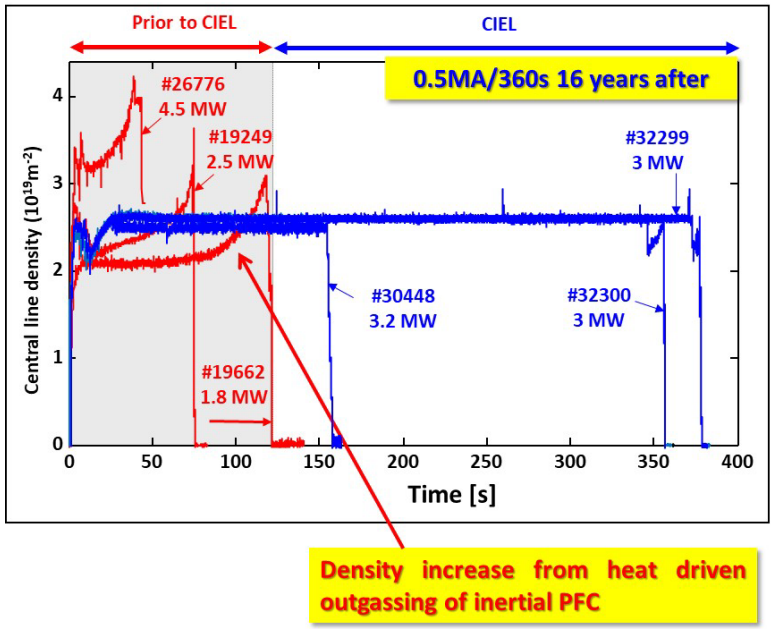
https://www.iter.org/newsline/-/3740

Control of fuel recycling is the key to SSO

- Actually, fuel particle balance is a reason why the longest discharge was terminated.
- Fuel particles could be stored in PFCs and the amount is frequently more than 100 times larger than particle inventory in the plasma -> Wall pumping is significantly higher than the capability of the vacuum pumping system.
- Control of fuel recycling is the key to SSO of high performance plasmas.

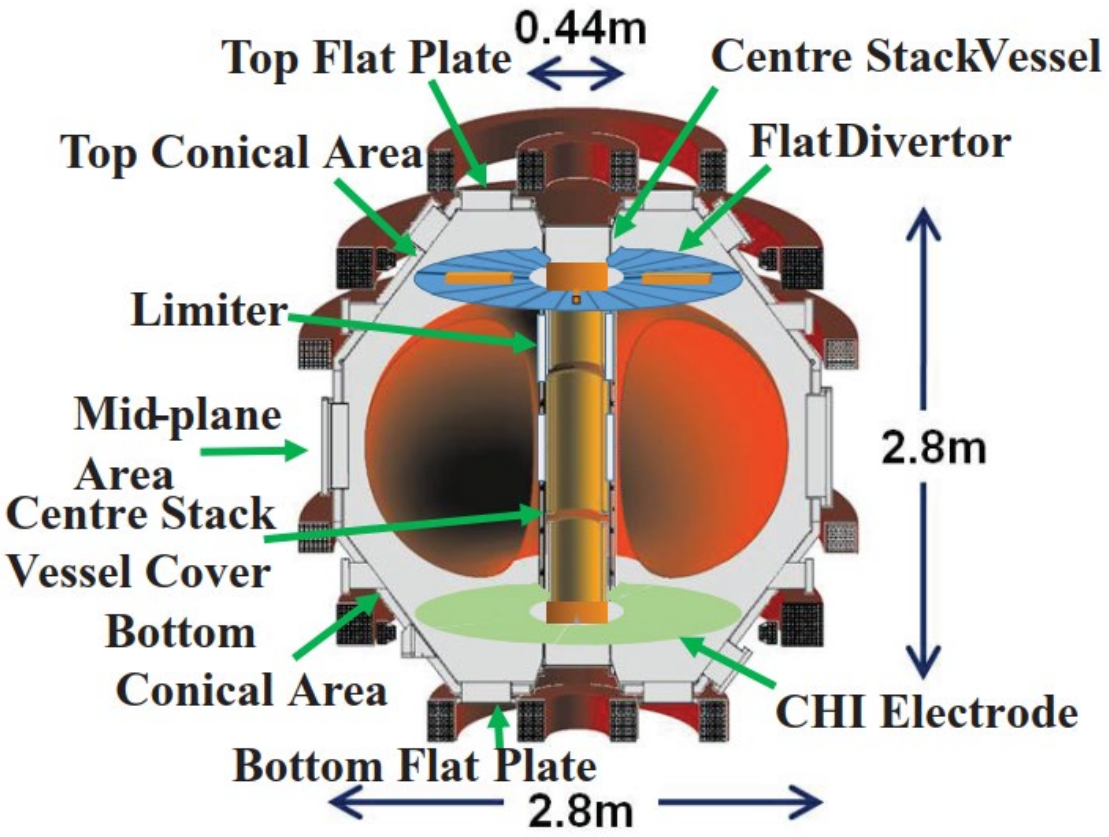


TRIAM-1M(All metal PFCs)

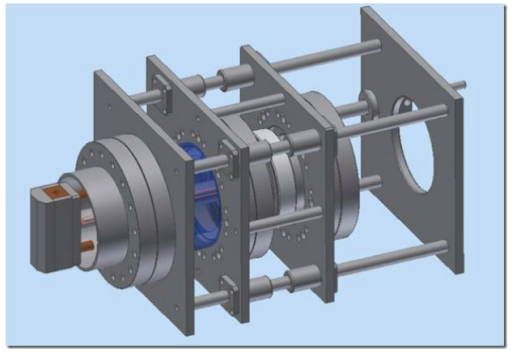


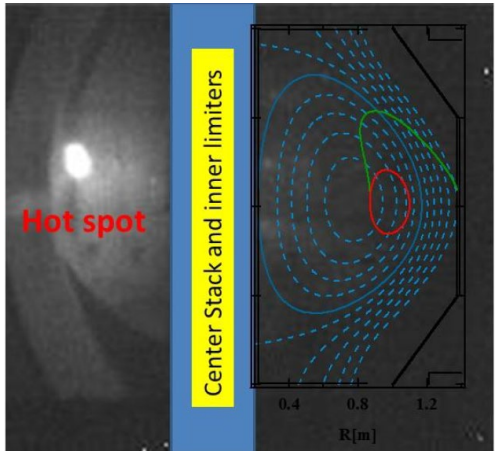
Tore Supra
(C-based PFCs)

QUEST has been equipped with a hot wall since 2014
The hot wall is capable to be at R.T.<Tw<773K

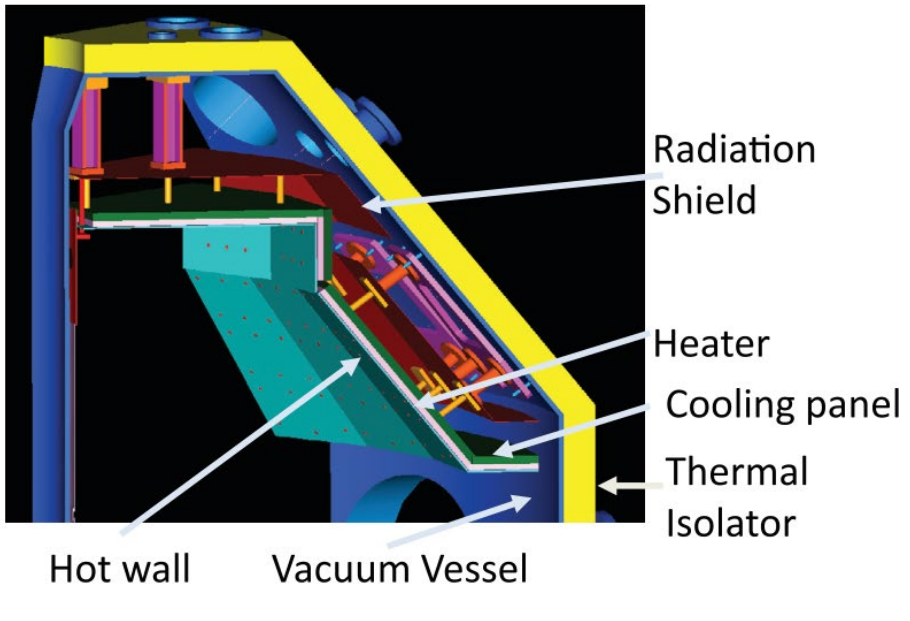


Water cooled limiter





Hot wall



K. Hanada et al Nucl. Fusion 57 (2017) 126061
Y. Takase et al. Nucl. Fusion 57 (2017) 102005

Control knobs for particle balance

Hasegawa_2018_FED
Hasegawa_2022_FED

- The temperature of the hot wall has been controlled by heaters and water flows.
- The water flow is remotely switched during the discharge and the fueling rate is feedback controlled by a calibrated gas-flow controller to a pre-programed target value.

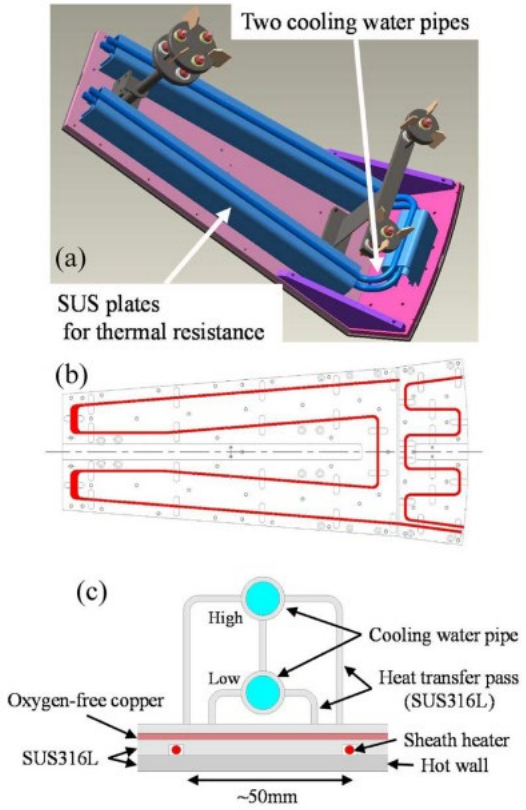


Fig. 2. (a) Schematic 3D view of one section hot wall, (b) sheath heater profile (thick lines), and (c) schematic cross-sectional view of hot wall with water cooling channels.

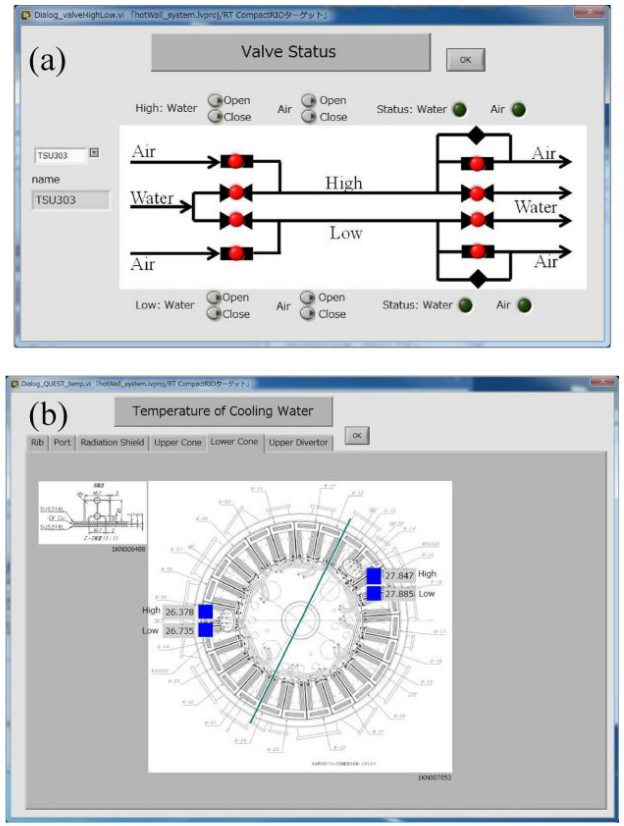


Fig. 3. Example interfaces for controlling hot-wall cooling system: (a) status of motor valves and (b) cooling-water temperature.

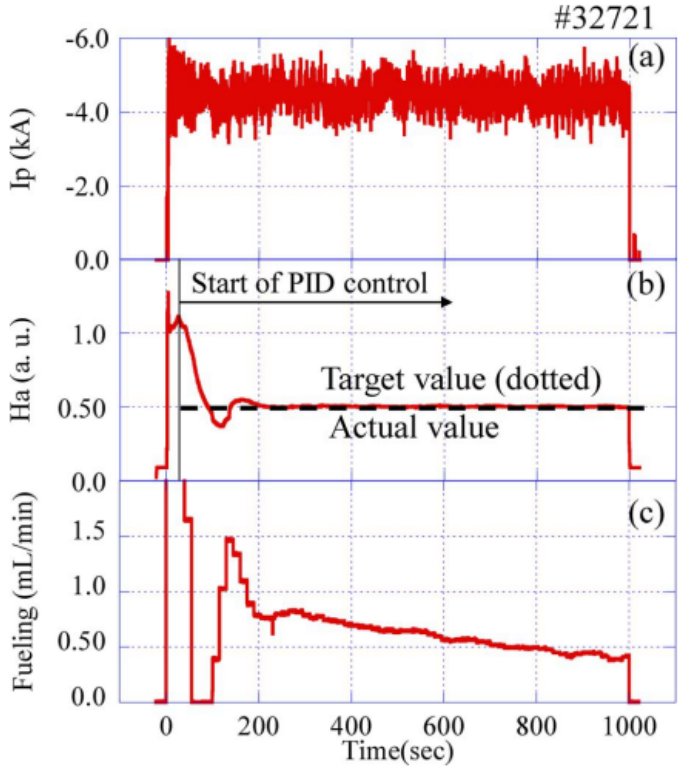


Fig. 5. Waveforms for 1,000 s plasma discharge with gas fueling feedback control: (a) plasma current, (b) plasma Hα emission and (c) fueling rate induced by mass flow controller.

How to control particle balance

Oya_2019_FED
Koike_2021_NME
Koike_2022_FED

Hanada_2015_JNM
Hanada_2019_NF

Monitoring of PFC surface condition.

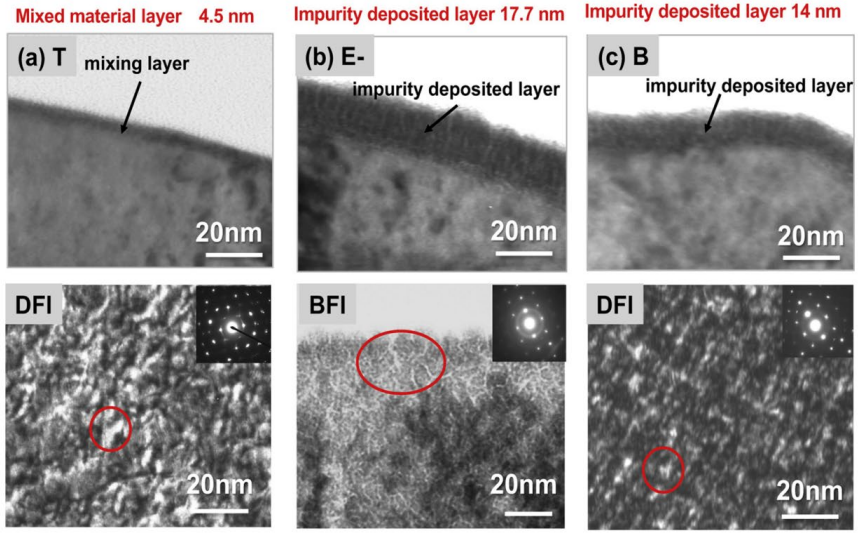
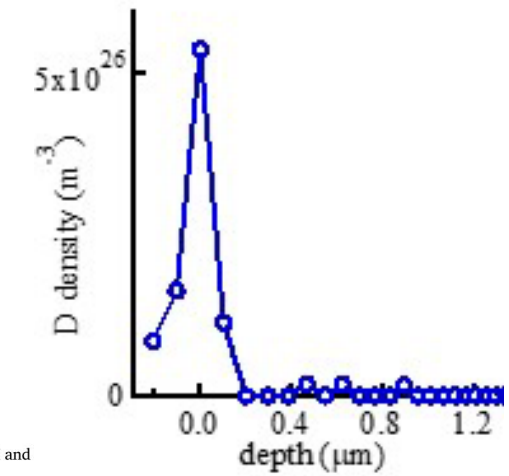
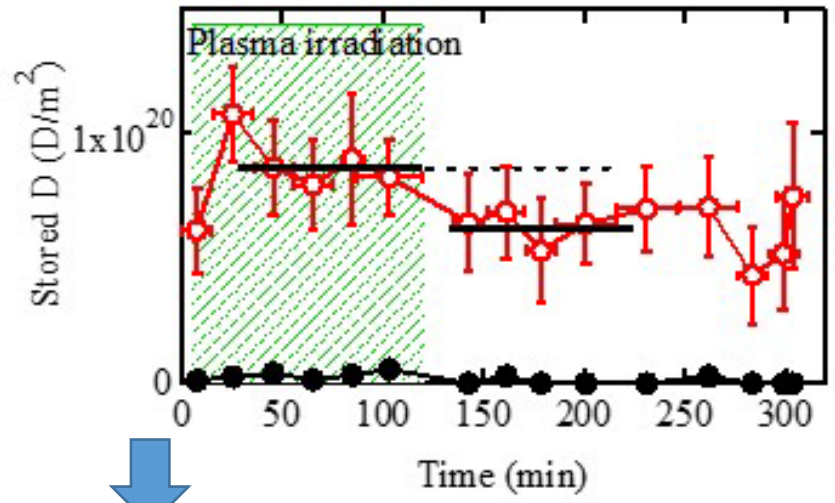


Fig. 4. Cross-sectional view using FIB (Upper row) and microstructure images (Lower row) for W samples placed in QUEST during 2016A/W campaign. DFI and indicate dark field image and bright field image, respectively.

H barrier was discovered between deposition layer and metal substrate.





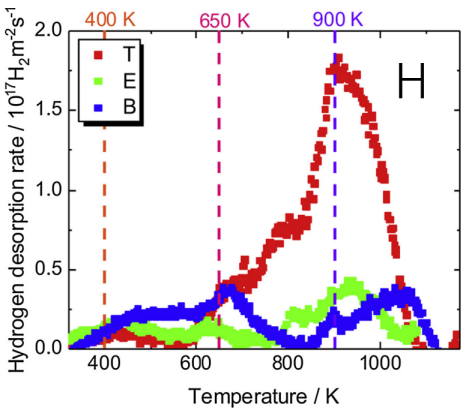


Fig. 7. Hydrogen TDS spectra for W samples exposed to QUEST H plasma.

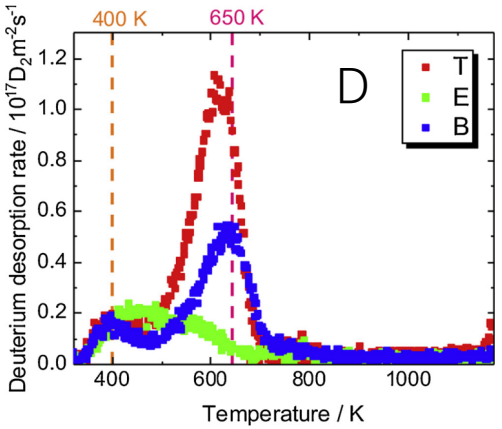
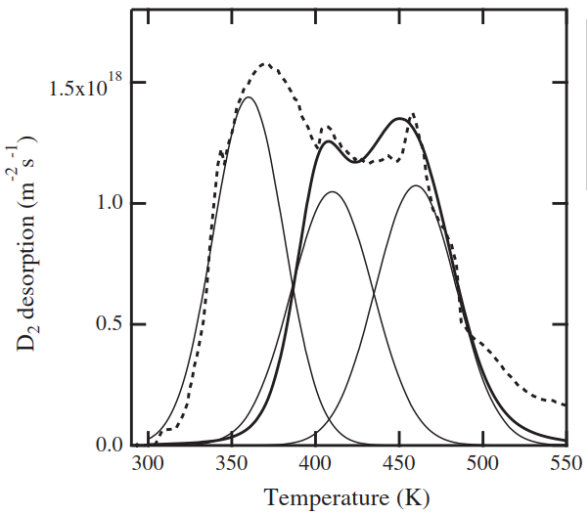


Fig. 8. Deuterium TDS spectra for W samples exposed to QUEST H plasma with additional 1 keV D_2^+ implantation.

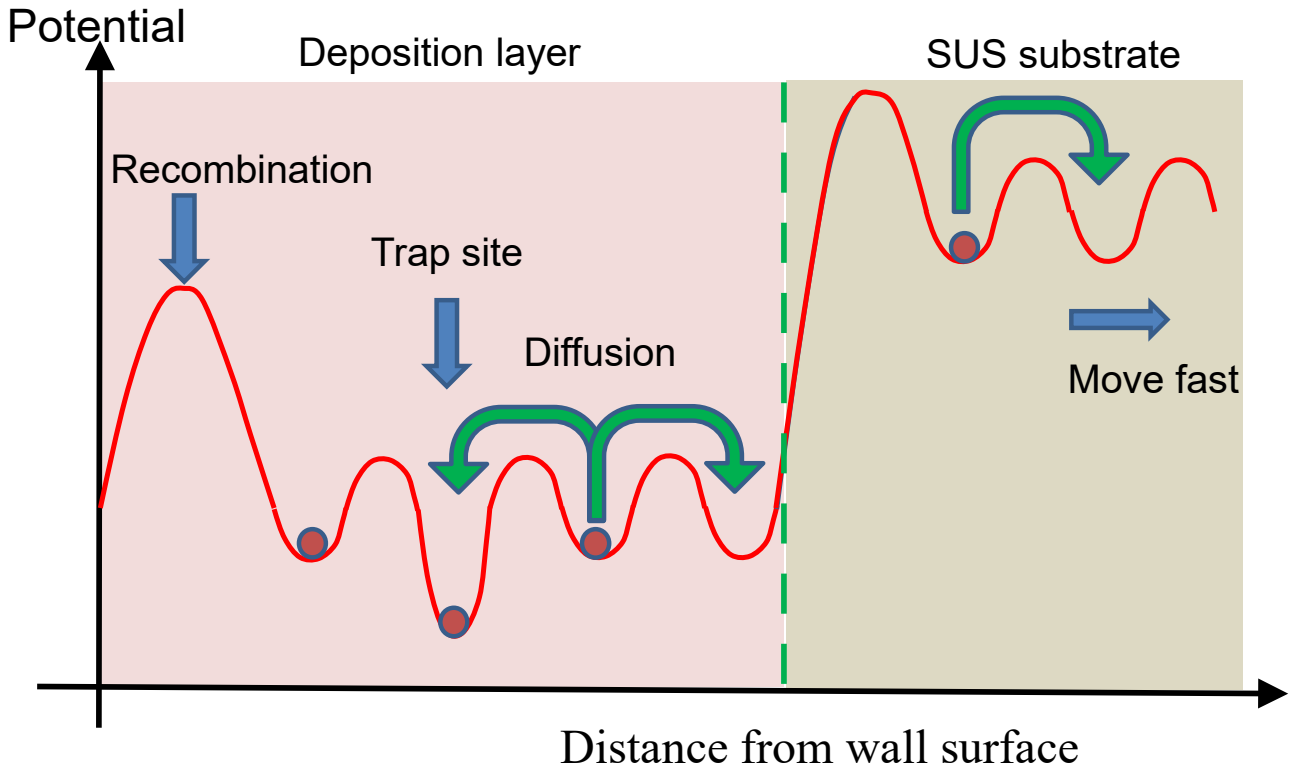


$$N_w(t) = \frac{\sqrt{\Gamma_{in}}}{\sqrt{k}} \tanh \sqrt{\Gamma_{in} k t}$$

A wall model with hydrogen barrier (HB) is proposed

Hanada_2019_NF

In this model, H atoms basically move diffusively and don't transport across the boundary between the deposition layer and the SUS substrate due to high transport potential.
H_w and H_T are total numbers of H atoms in deposition layer.



$$\frac{d(H_W + H_T)}{dt} = \Gamma_{in}\, S - \frac{k}{S\, d_R^2} H_W^2$$

Influx to the deposition layer

Release due to recombination

$$\frac{dH_T}{dt} = \alpha H_W \left(1 - \frac{H_T}{H_T^0}\right) - \gamma H_T$$

Trapping

De-trapping

H_W :the number of H dissolved in wall material

H_T :the number of H trapped in defects

H_T^0 :the upper-limit number of H_T

Γ_{in} :net influx per unit area into wall material

S : surface area

k : surface recombination coefficient of H atoms

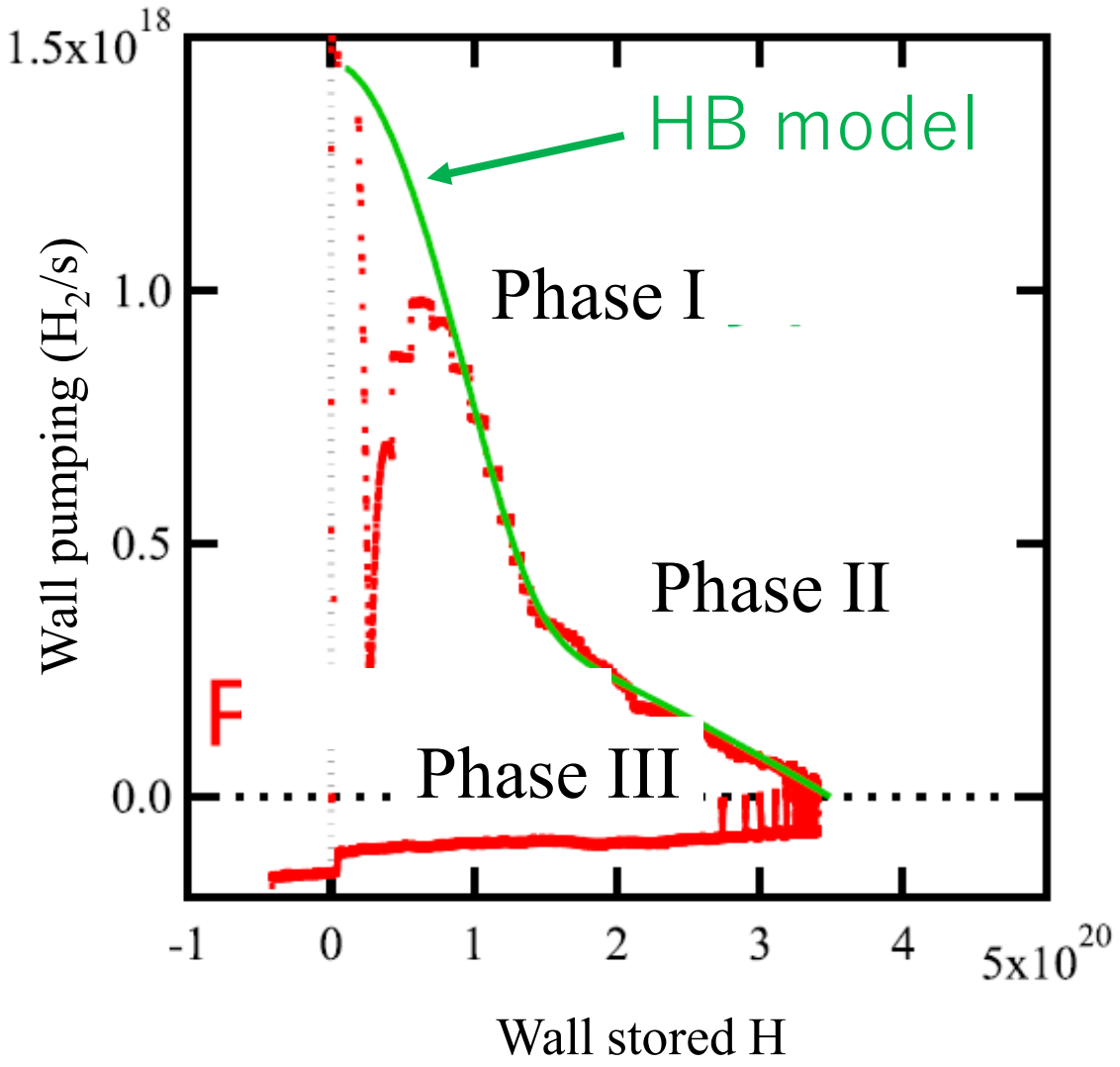
d_R : thickness of deposition layer

α : H trapping rate γ : H de-trapping rate

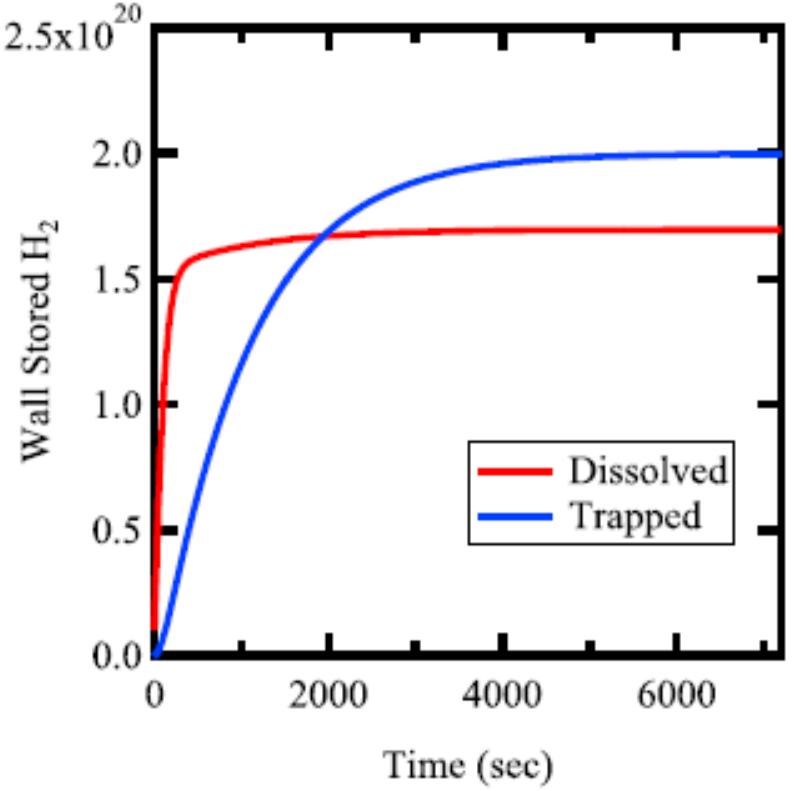
Advanced Fusion Research Center

The H barrier model well-estimates particle balance

Hanada_2017_NF



	Wall pumping rate (H/sec)	Wall stored H
HB model	$\frac{d(H_W + H_T)}{dt}$	$H_W + H_T$ (0 @t=0)
Experimental	$q_{fuel} - q_{pump}$	$\int_0^t (q_{fuel} - q_{pump}) d\tau$



- The wall-stored H gradually increase with the decrease of wall pumping rate.
- The Phase I is explained by HB model and The Phase II can be expressed by trap-detrap effect.
- In phase III, it is difficult to explain. It is a future work.

How to estimate particle balance

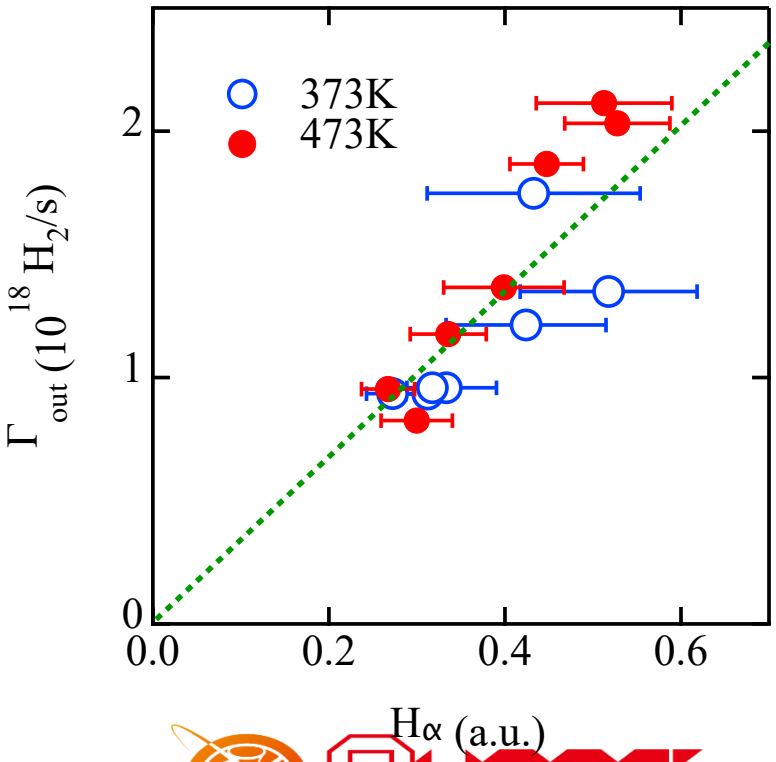
Hanada_2019_NME
Hanada_2019_NF
Hanada_2022_NME

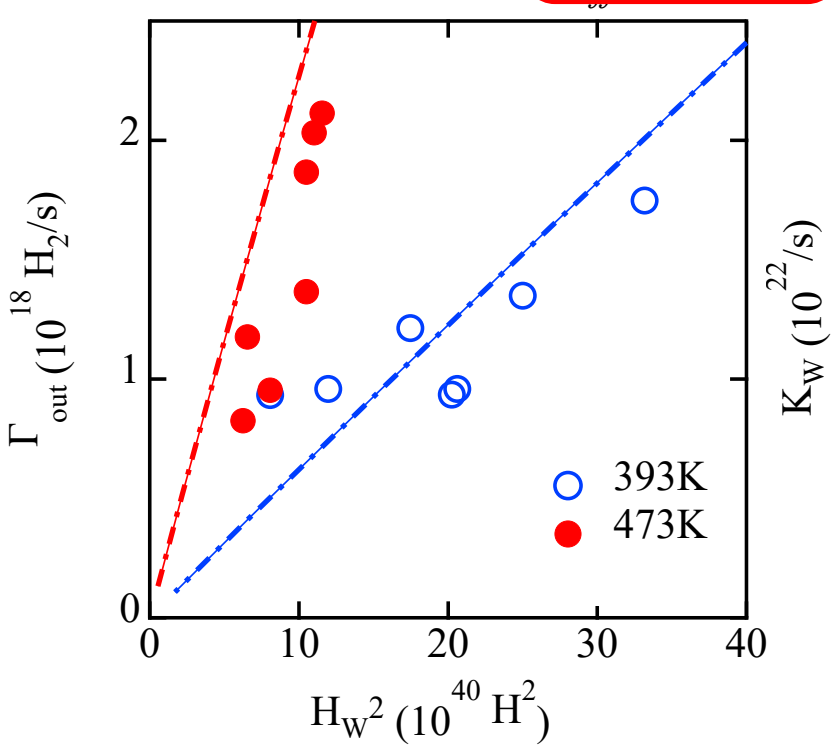
- Γ_{in} can be monitored by fuel released just after wall-saturated discharge.
- T_W dependence of surface recombination coefficient has been measured on QUEST.
- Measured surface recombination coefficient has positive tendency of T_W on QUEST.

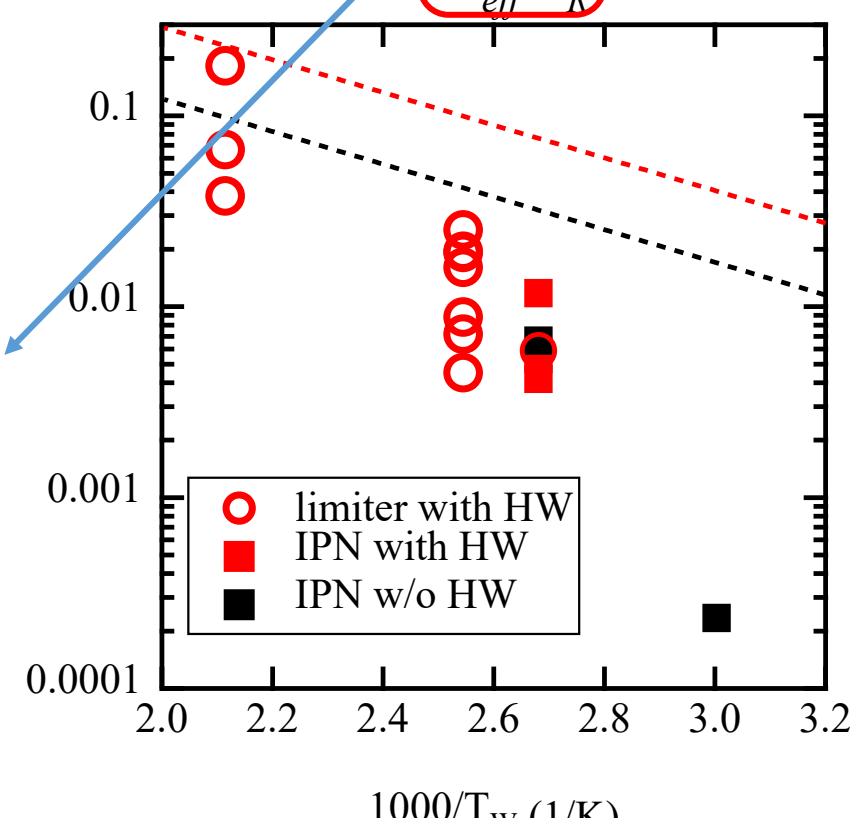
$$\frac{dH_W}{dt} = -\Gamma_{in} + kC_W^2 S_{eff} = 0$$

$$\frac{dH_W}{dt} = -\Gamma_{in} + S_{eff} + \frac{2k}{S_{eff} d_R^2} H_W^2$$

$$\frac{2k}{S_{eff} d_R^2} H_W^2$$

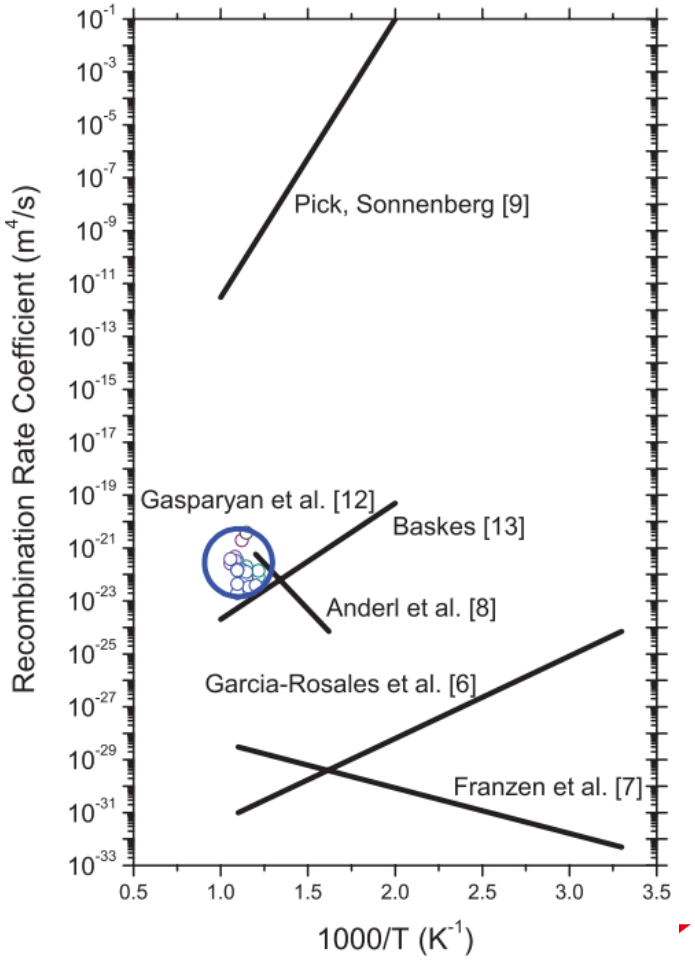


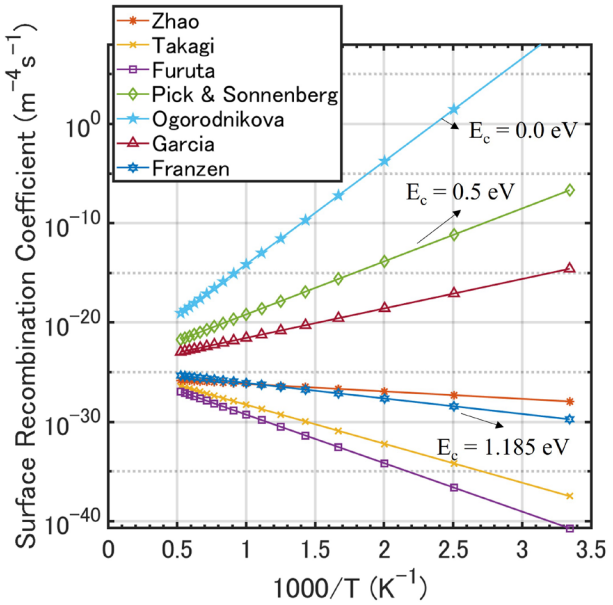




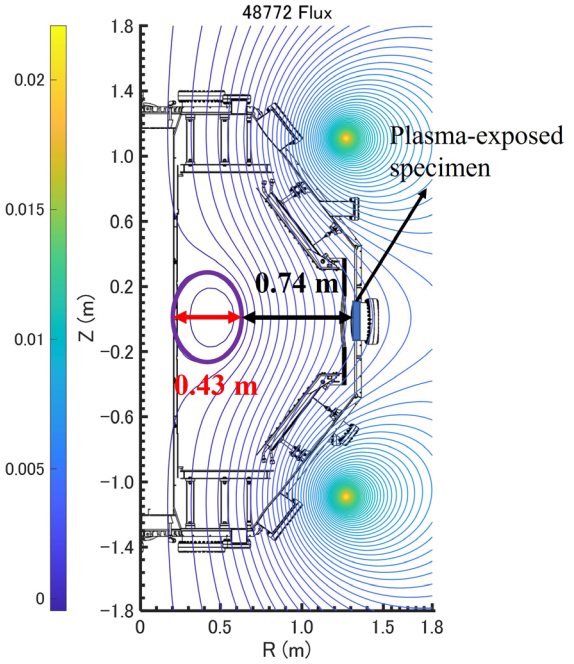
Surface recombination is significantly affected by sticking potential due to surface conditions

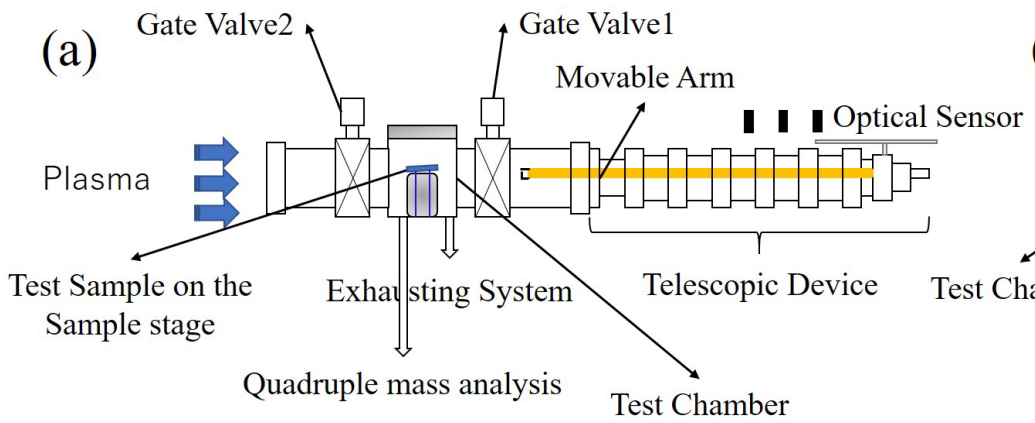
- Sticking potential, E_C, is measured with FESTA for the specimen exposed QUEST plasmas without exposure to the air.
- Wall temperature, T_W, is a key to controlling fuel recycling.

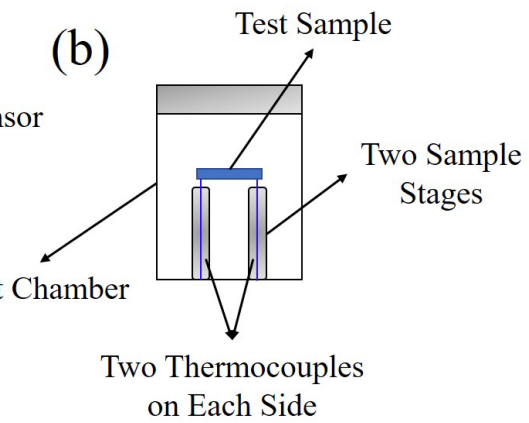




You can hear Mr. Yue's presentation in this conference.



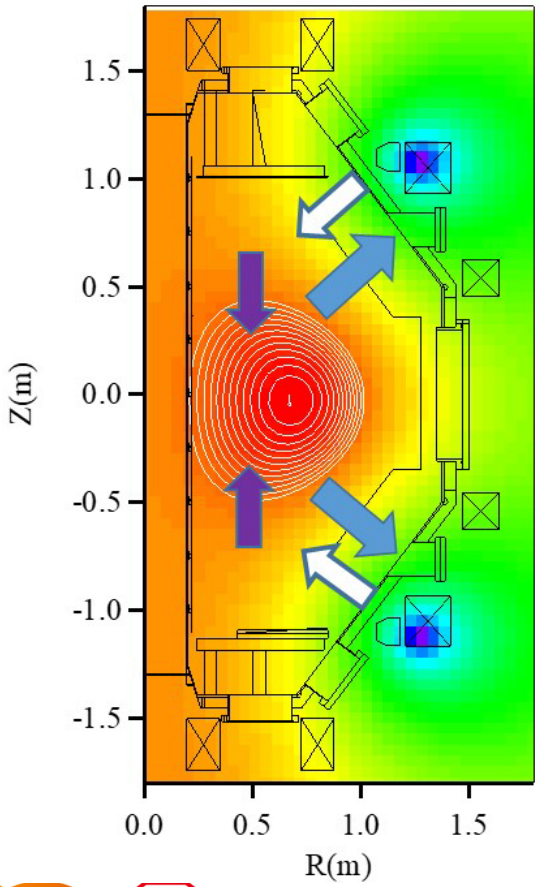


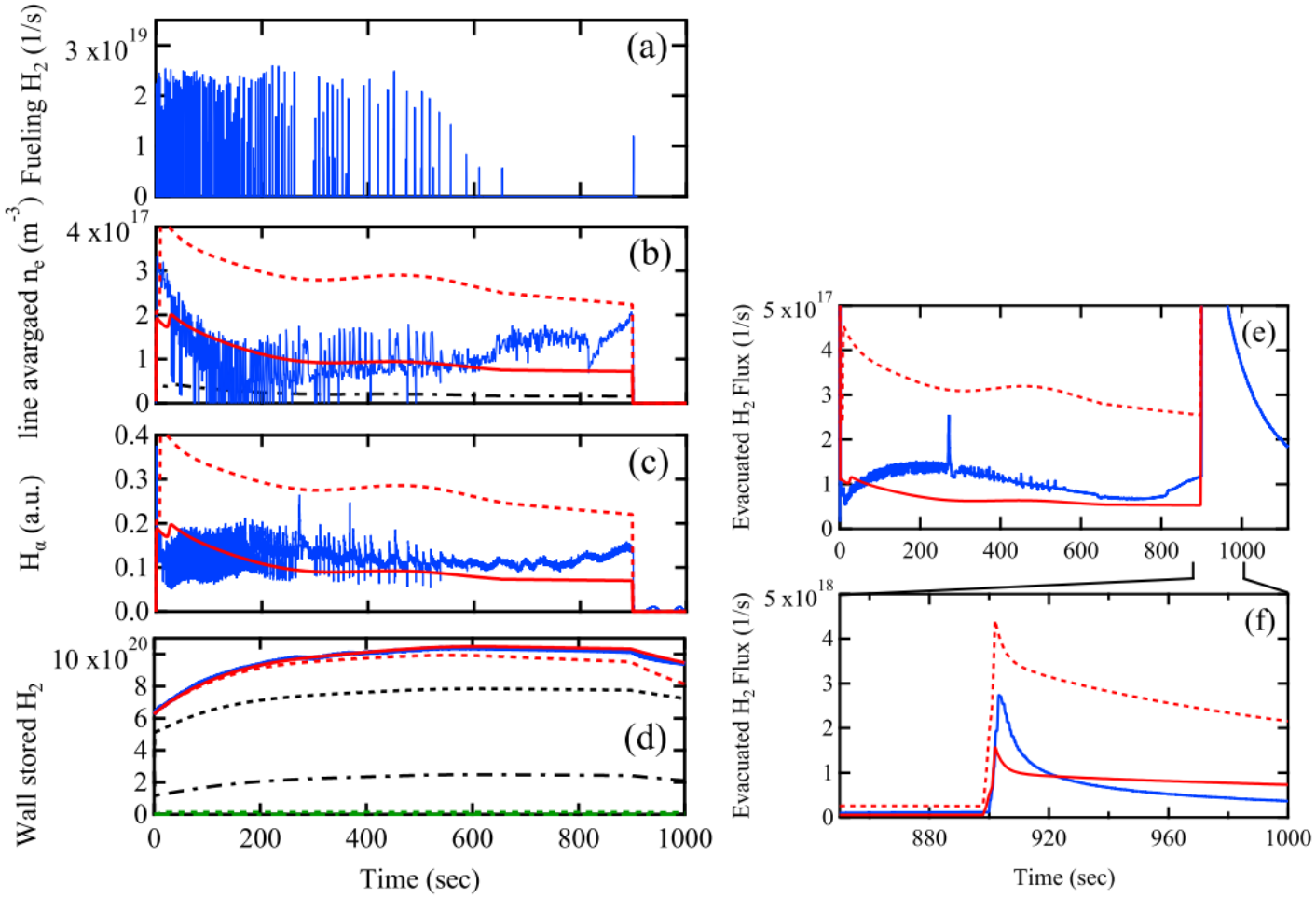


Global fuel recycling on QUEST is predicted

Hanada_2021_NME

- Global model has been developed to check fuel particle balance quantitatively.
- The global model could reconstruct fuel particle balance and quantitatively clarify the effect of wall pumping on particle balance.





T_W control assists to extend pulse duration

Takase_2022_NF
Hasegawa_2021_PFR

- 6h discharges could be achieved at TW<473K.
- Higher T_W reduces pulse duration.
- T_W control can assist to extend it.

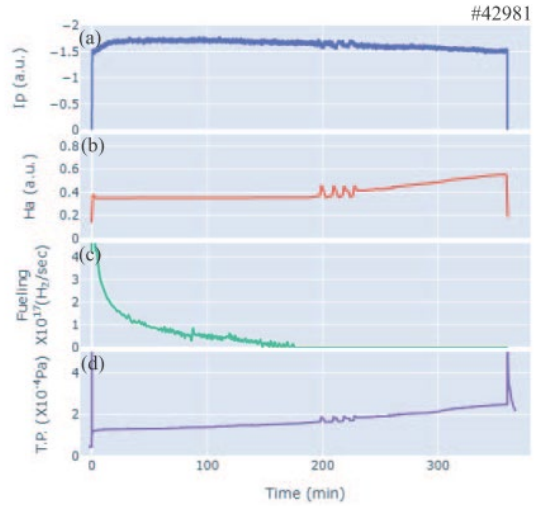


Fig. 8 Wave forms of 6 h long plasma discharge. (a) Plasma current, (b) Hα emission, (c) fueling rate by MFC, and (d) total pressure.

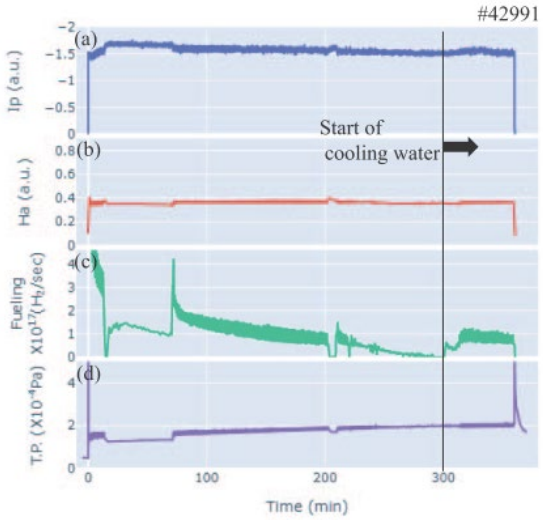
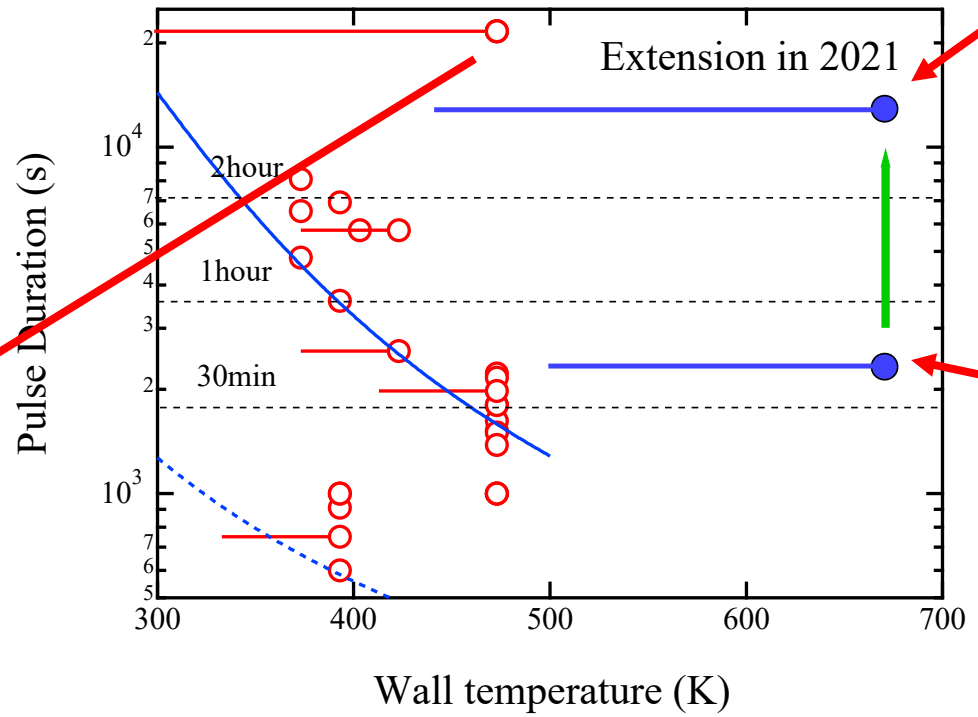
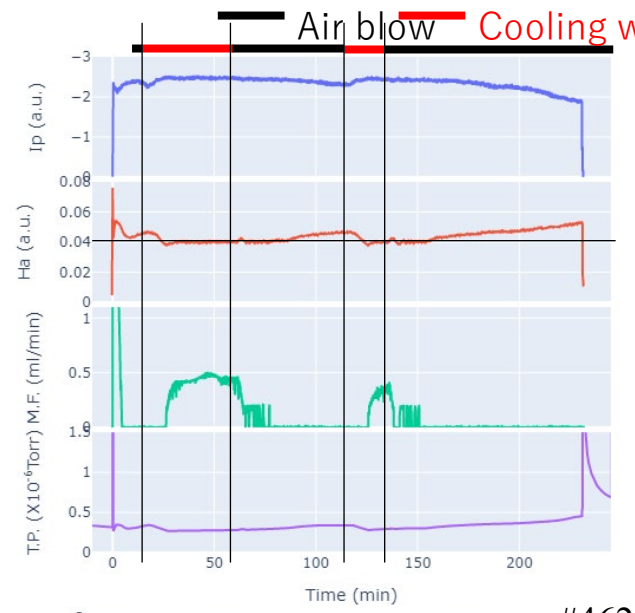
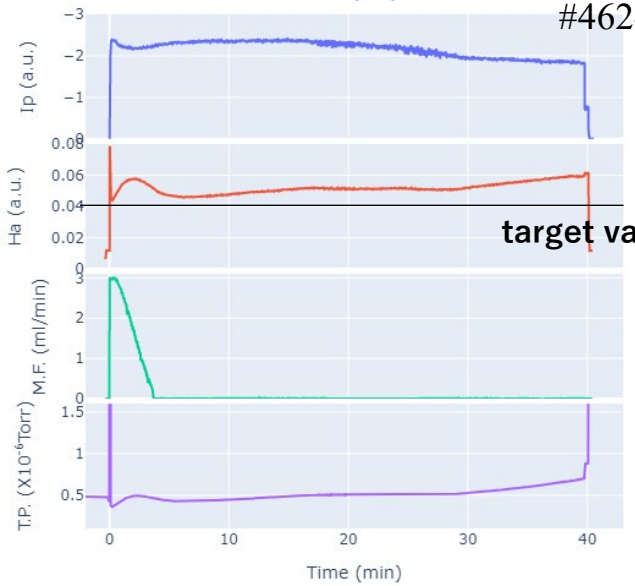


Fig. 11 Wave forms of 6 h long plasma discharge with cooling water. (a) Plasma current, (b) Hα emission, (c) fueling rate by MFC, and (d) total pressure.







Advar

Summary

- Steady State operation （SSO）of high performance (HP) plasma is one of the most important issues for realizing fusion power plant.
- Recycling control is a key to resolve the issue.
- QUEST has been equipped with capability for wall temperature regulation since 2015.
- QUEST wall was partially covered by plasma induced deposition layer and H transport barrier was discovered between the deposition layer and metal substrate.
- The H barrier model was confirmed in QUEST experiments（post-Mortem analysis of plasma-exposed material has been conducted).
- Fast Ejection System for Targeted sAmple (FESTA) has been developed to measure H emission from the sample.
- Global model has been developed to check fuel particle balance quantitatively.
- The global model could reconstruct fuel particle balance and quantitatively clarify the effect of wall pumping on particle balance.
- 6h discharge could be achieved at TW<473K.
- Higher T_W reduces pulse duration, but T_W control can assist to extend it.