

Improvement of vacuum and wall conditioning systems in Versatile Experiment Spherical Torus

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Improvement of vacuum and wall conditioning systems in VEST

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Improvement of vacuum and wall conditioning systems in VEST

Motivation

Fig.1 Radiation parameter R of various plasma impurities as a function of electron temperature.

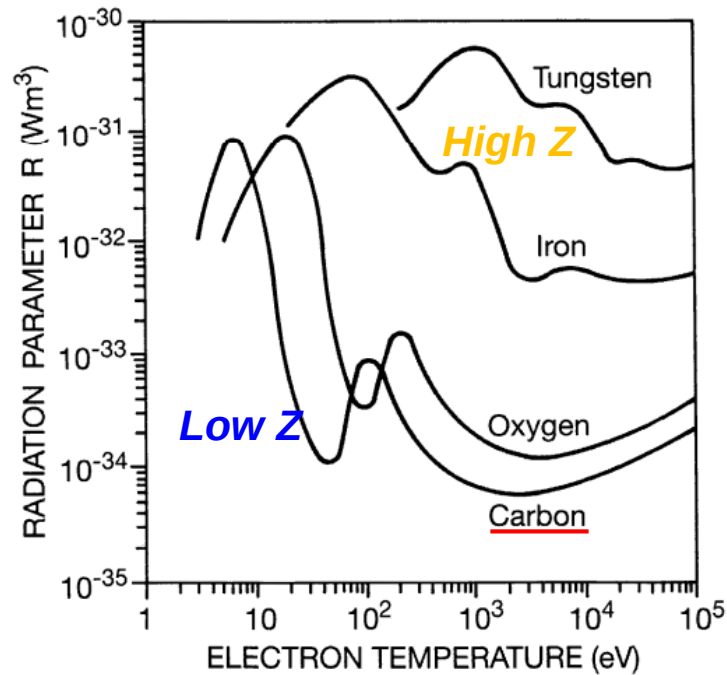
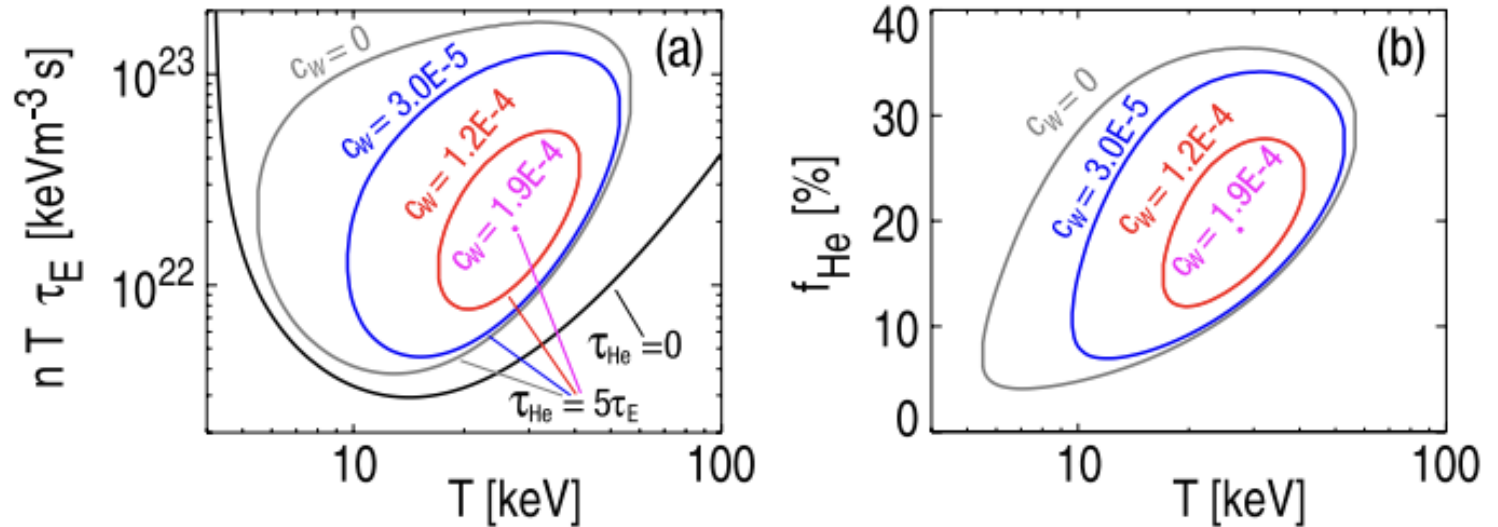


Fig.2 a) Ignition curves in the presence of different W concentration and with the curves[4],
b) Equilibrium He concentrations corresponding to burn curves from part (a).



- ❖ The hydrogen retention effect lowered the fueling efficiency and inherently limits the density control in magnetic fusion device[1],[3].
- ❖ Plasma impurities cause two main effects related to high performance: the radiation of power and the dilution of the hydrogenic species[2].
- ❖ Both dilution and radiation can be taken into account in determining the size of operational space for fusion burn through the “Lawson criterion”[4].

[1] Juhn, J., et al. "Particle balance study for the fueling efficiency in KSTAR experiments 2013." *Journal of the Korean Physical Society* 65.8 (2014): 1304-1311.

[2] Winter, Jörg. "Wall conditioning in fusion devices and its influence on plasma performance." *Plasma Physics and Controlled Fusion* 38.9 (1996): 1503.

[3] Yu, Yaowei, et al. "First comprehensive particle balance study in KSTAR with a full graphite first wall and diverted plasmas." *Plasma Physics and Controlled Fusion* 54.10 (2012): 105006.

[4] Pütterich, Th, et al. "Calculation and experimental test of the cooling factor of tungsten." *Nuclear Fusion* 50.2 (2010): 025012.

Improvement of VEST vacuum system

Introduction of VEST vacuum system

Fig.3 3D schematic drawing of the VEST

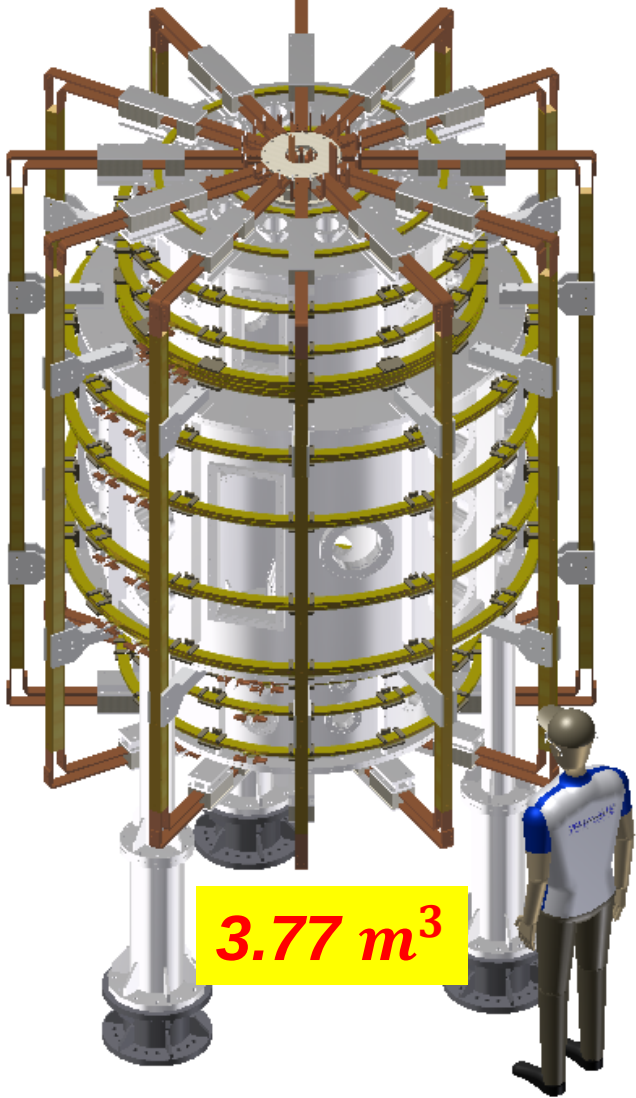


Fig.4 conductance and effective pumping speed by molecular mass in VEST

Gas		Hydrogen	water	Air	Argon
Molecular Mass [amu]		2	18	28	40
C (l/s)	TMP	1490	497	398	333
	main CRYO	705	235	188	158
	NBI CRYO	3330	1110	890	745
S _{eff} (l/s)	TMP	633	411	336	286
	main CRYO	578	227	174	145
	NBI CRYO	2430	1010	714	597
Total S _{eff} [L/s]		3640	1650	1220	1030

- ❖ The VEST pumping system consists of one turbo molecular pump, effective pumping speed is 3640 l/s for hydrogen and two CRYO pumps and nominal VEST volume calculated from the schematic drawing is 3770 l.

Improvement of VEST vacuum system

Components replacement: the O-ring junction

Fig 5. Bird's eye view of VEST site and main outgassing source detection

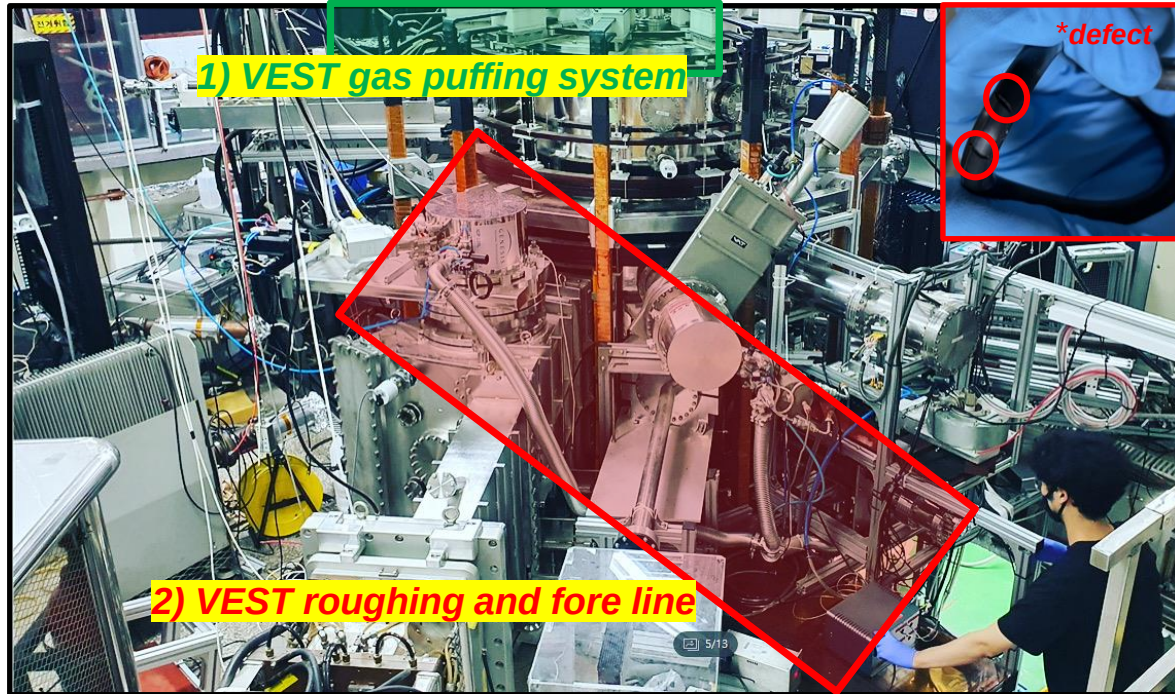
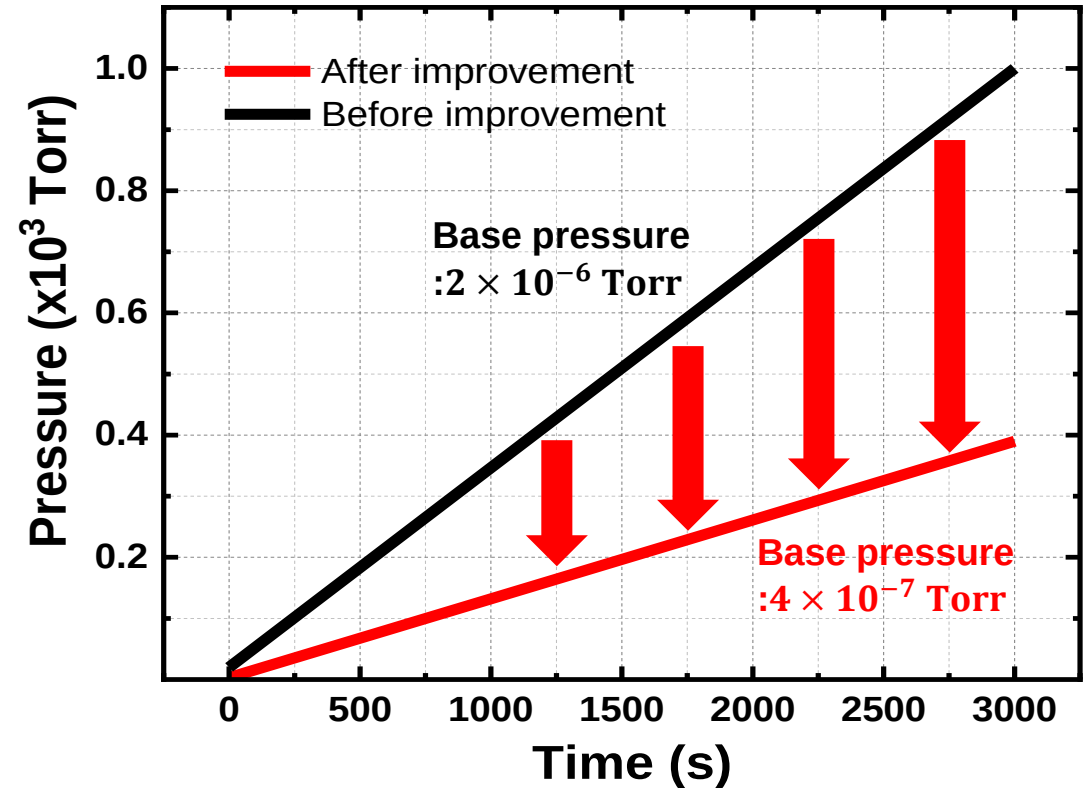


Fig 6. Reduction in outgassing rate before vs after the vacuum improvement



- ❖ First of the improvements of VEST vacuum system is the air leak suppression by replacement of defected o-ring.
- ❖ After the air leakage improvement, the base pressure in VEST is about 70% decreased from 2×10^{-6} torr to 4×10^{-7} torr.

Improvement of VEST wall conditioning system

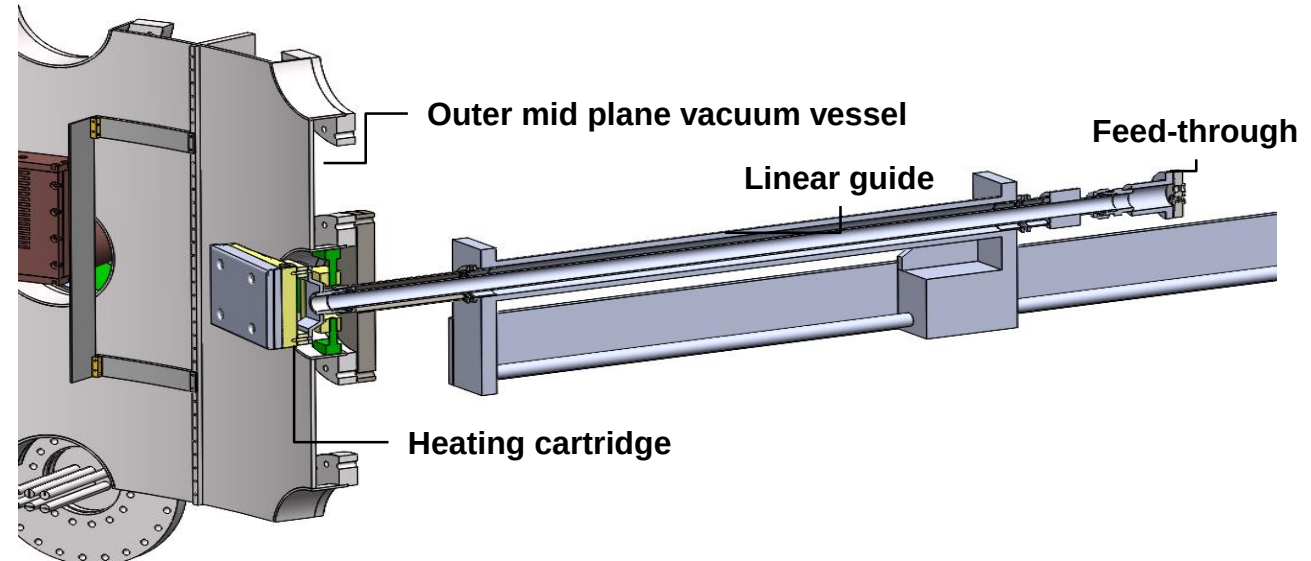
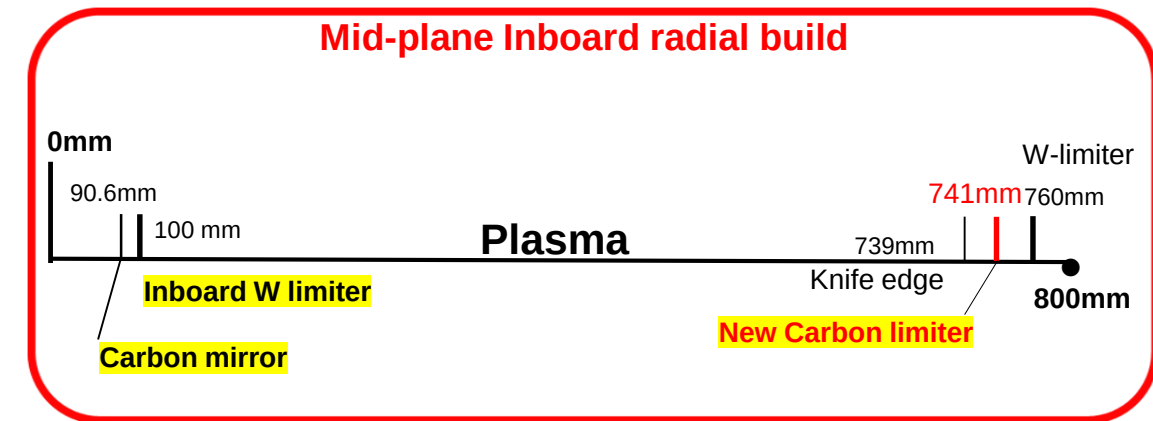
RGA and baking system including bake-able carbon limiter

Fig 5. Movable halogen lamp for the center stack and the local outer mid plane wall baking



- ❖ As an additional wall baking system (shown in fig.5), halogen lamp is newly installed in the VEST to effectively reduce the main oxygen source from the center stack.
- ❖ A new bake-able pure carbon limiter is installed to investigate the possibility of removing water vapor from the outer limiter and vacuum vessel by replacing the entire outboard tungsten limiter (fig.6).

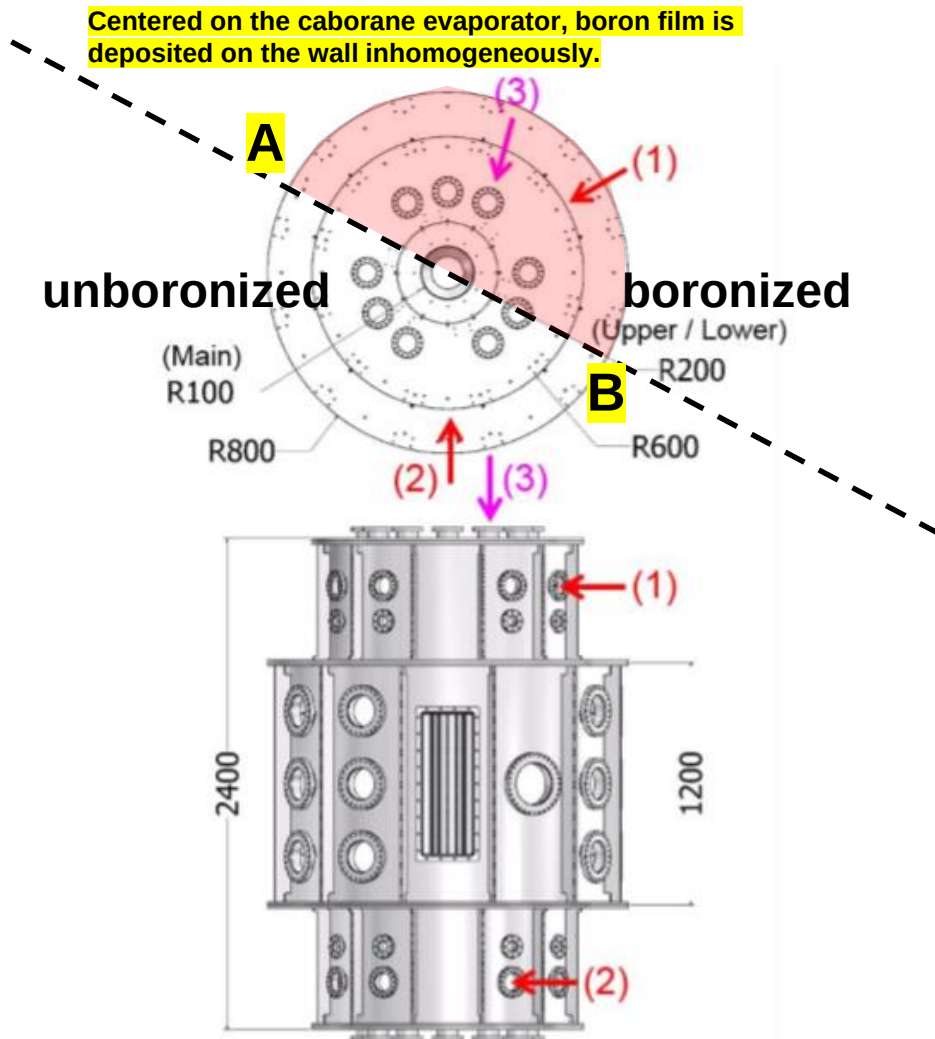
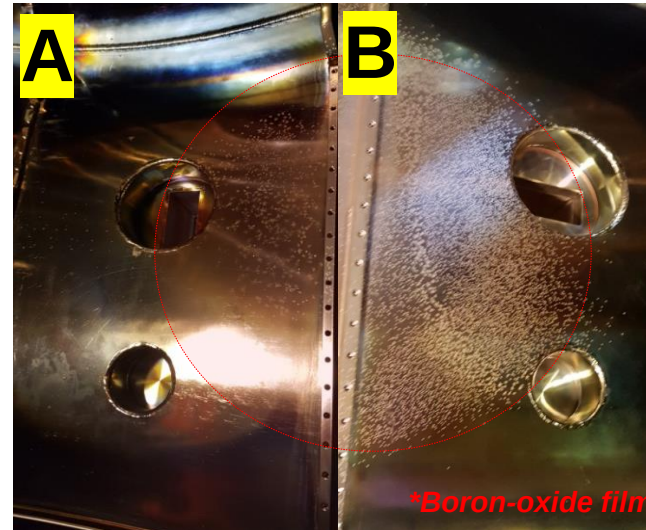
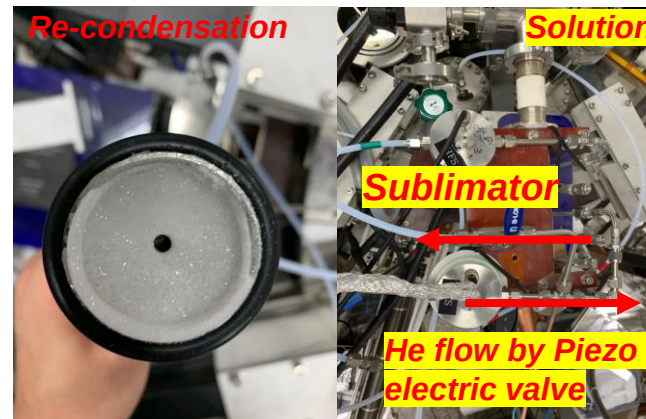
Fig 6. 3D figure of movable and bake-able pure carbon tile and mid plane inboard radial build in VEST



Improvement of VEST wall conditioning system

Improvement of boronization system in VEST

Fig 7. The location of VEST glow discharge anodes (1 and 2) and the carborane sublimator (3). And inhomogeneity of boron-oxide thin film with re-condensation problem and a solution at carborane sublimator.



- ❖ A helium glow discharge is used for boronization in typical tokamaks, also in VEST. And the anodes are equipped at the upper and lower ports of VEST.
- ❖ The carborane sublimator is designed, installed at the top of the chamber.
- ❖ But centered on the sublimator, boron film is deposited on outer wall inhomogeneously.
- ❖ Also re-condensation crystal was found at the end of the sublimator.
- ❖ These boron vapor transport problem can be solved with additional He flow to the VEST through the sublimator[5].

Improvement of VEST neutral monitoring system

Development of Penning type fast response neutral pressure gauge

Fig.8 Picture of a Penning type fast neutral pressure gauge head with energetic particle shielding structure

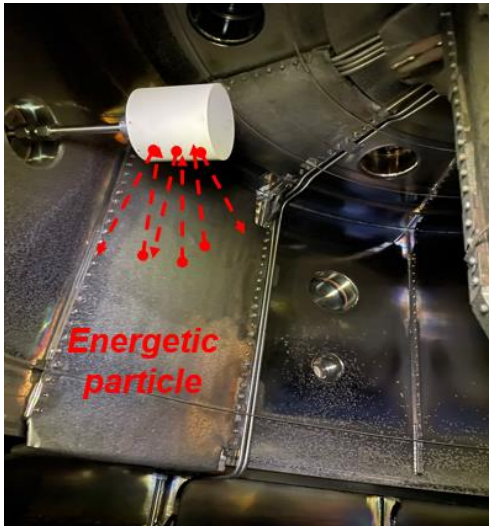


Fig.9 Ignition point at VEST in-situ PIG with Toroidal field

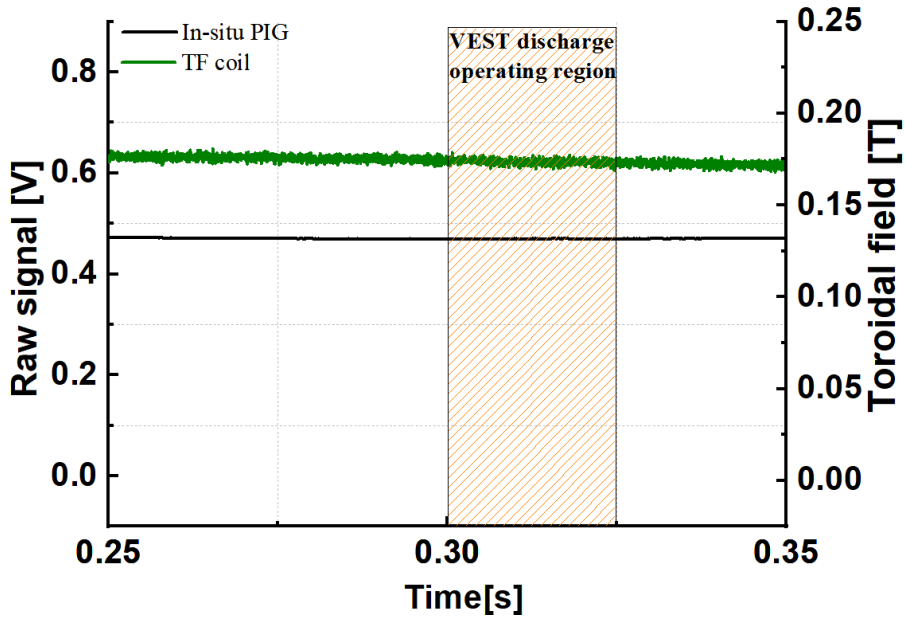
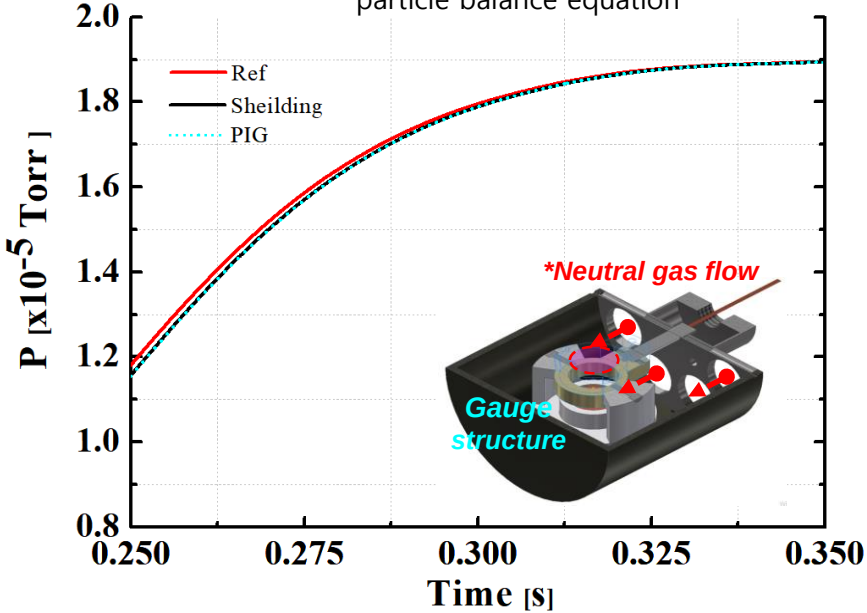


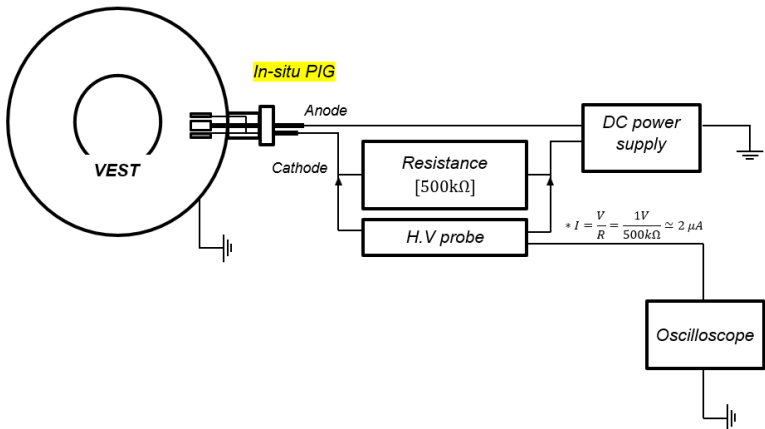
Fig.10 The neutral diffusion time calculated by neutral particle balance equation



❖ Gauge response time [6]

- ✓ Typical gauge response time is defined as ignition delay, diffusion delay and circuit delay.
- ✓ As shown in Fig.9, VEST in-situ Penning gauge discharged around 100 ms earlier than VEST plasma ramp-up, and as shown Fig 10. Penning structure serves the neutral pressure in under ms order.
- ✓ There are no signal processing delay through direct voltage measurement by OSC. – Fig.11.
- ✓ As a result, newly installed neutral monitoring system provides under ms time response of neural measurement.

Fig.11 The current measurement circuit of in-situ PIG in VEST



[6] Kremeyer, T., et al. "Wisconsin In Situ Penning (WISP) gauge: A versatile neutral pressure gauge to measure partial pressures in strong magnetic fields." *Review of Scientific Instruments* 91.4 (2020): 043504.

Experimental results

Components replacement: the O-ring junction

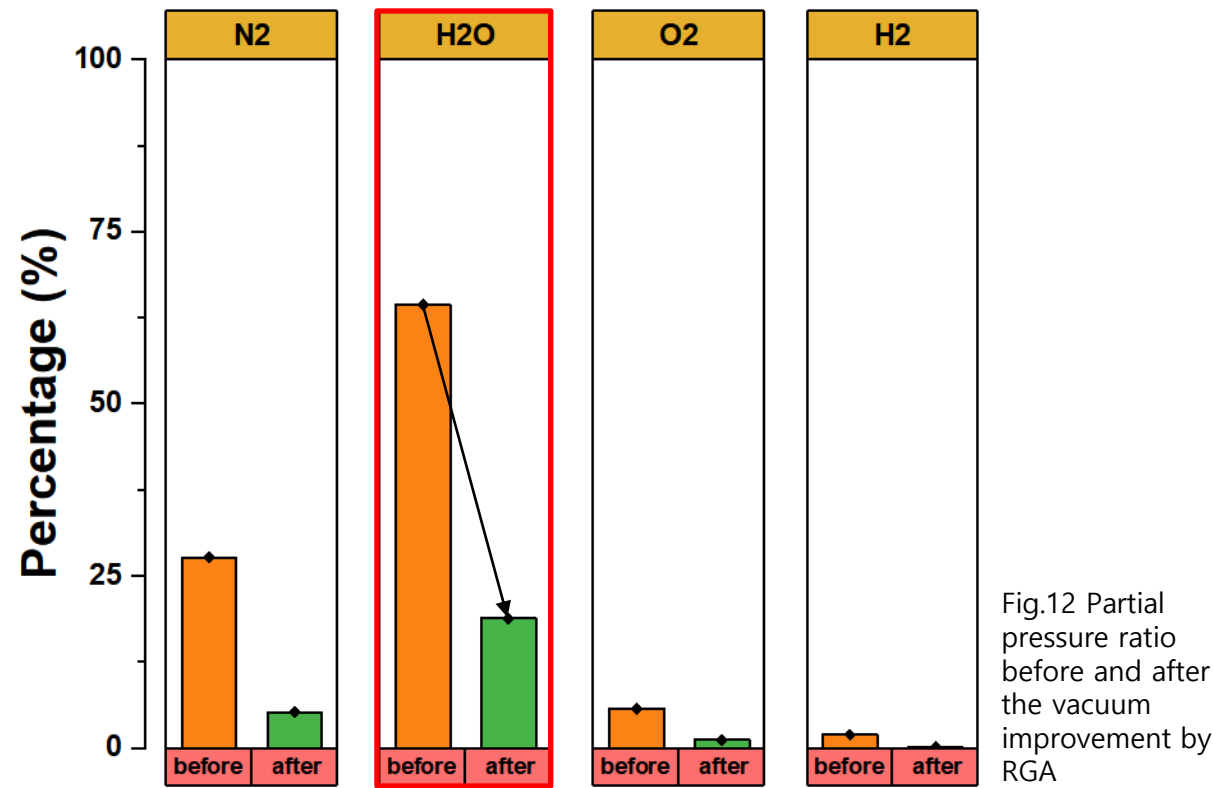
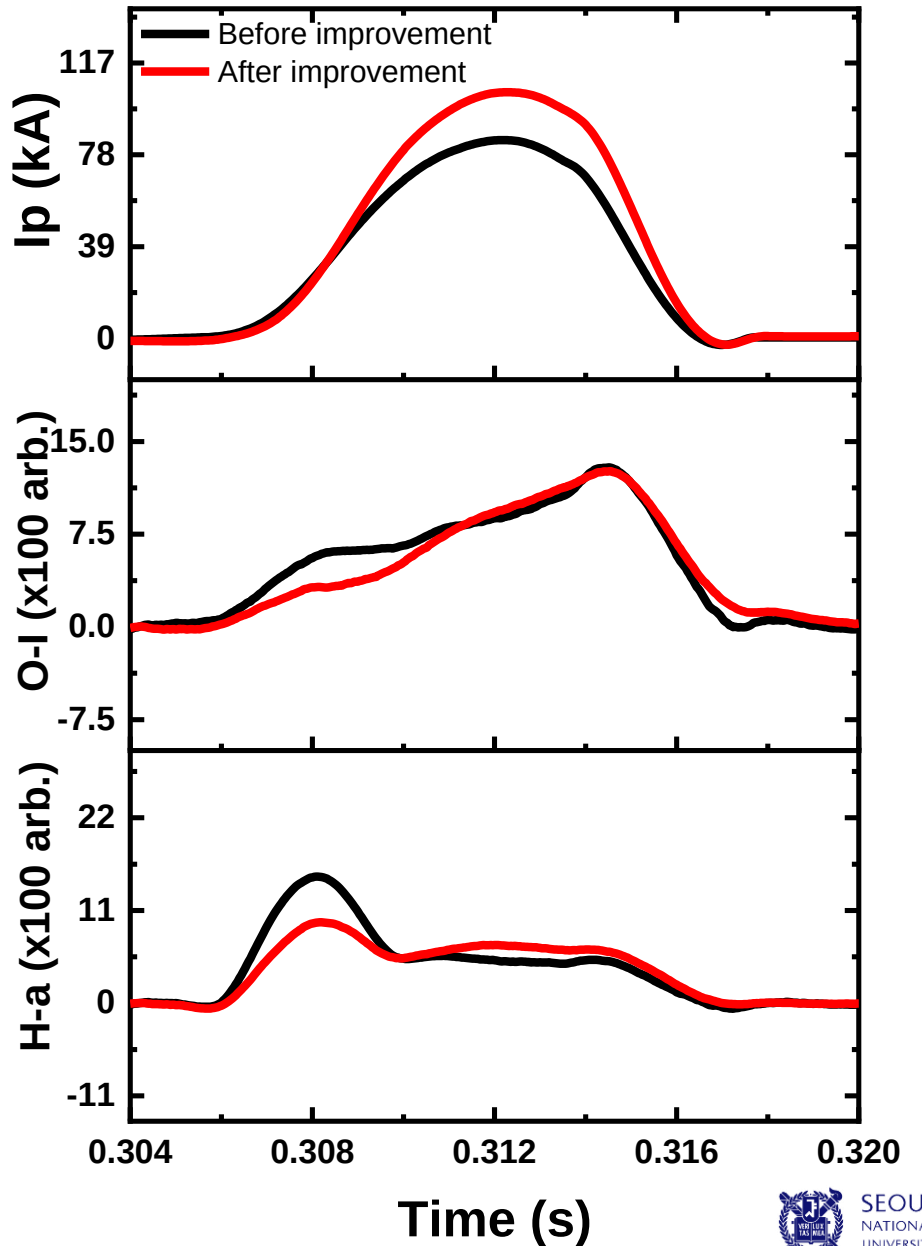


Fig 13. Plasma performance enhancement before vs after the vacuum improvement



❖ Plasma performance enhancement after the vacuum improvement

- ✓ In VEST, due to the vacuum components such as O-ring ($T < 200^{\circ}\text{C}$), effective chamber baking system is limited and should be localized [7].
- ✓ As shown in fig.13, improved vacuum system lead to a high performance plasma shot. At the plasma start-up phase, both oxygen and hydrogen neutral emission line decreased by about 40% and it turns out to increase the plasma maximum current by 25%.
- ✓ Fig.12 and 13 shows the correlation between main outgassing source in metal based wall and the plasma performance.

[7] Lee, H. Y., et al. "Development of wall conditioning and impurity monitoring systems in Versatile Experiment Spherical Torus (VEST)." *Fusion Engineering and Design* 109 (2016): 1082-1086.

Experimental results

RGA and baking system including bake-able carbon limiter

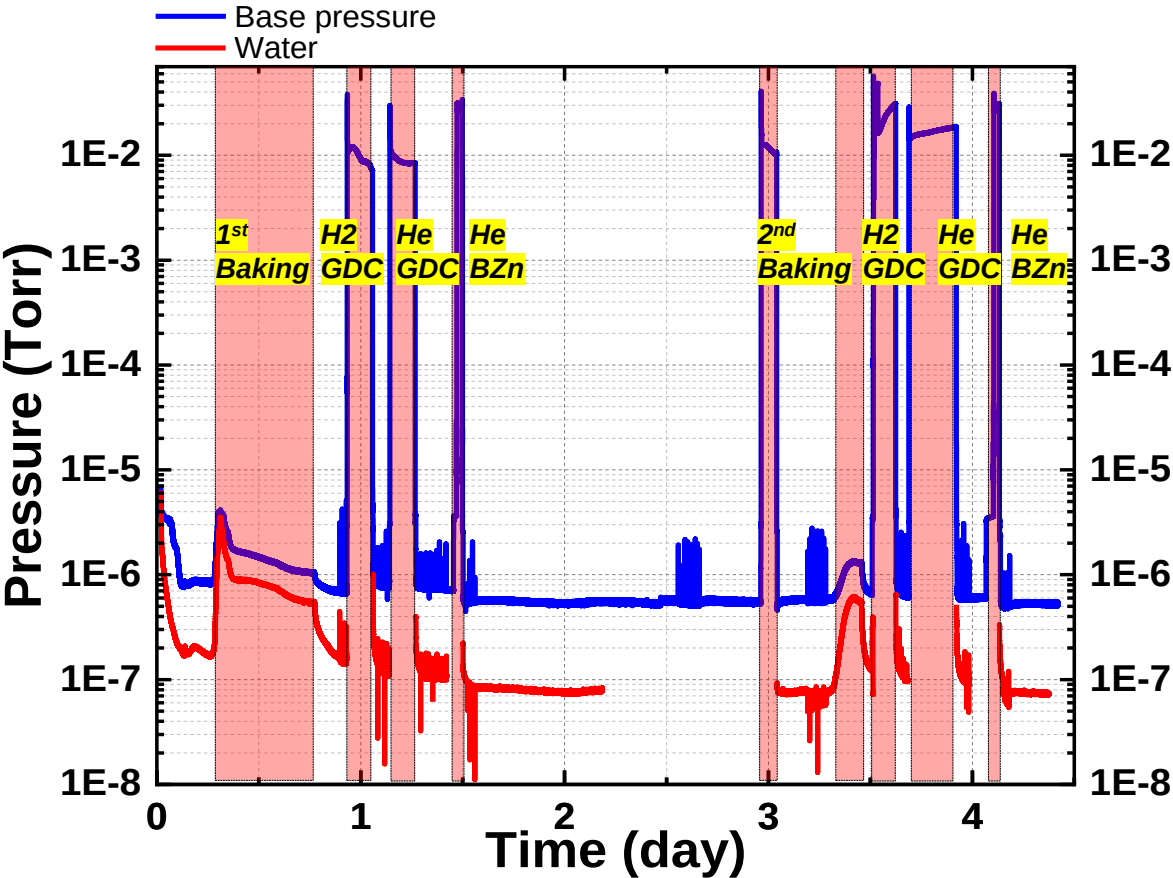


Fig 14. Reduction in outgassing rate before vs after the vacuum improvement

No treatment (Torr)	Base P	Water P
	9e-7	2e-7

↓

1st sequence (Torr)	Base P	Water P
	6e-7	8e-8

↓

2nd sequence (Torr)	Base P	Water P
	5e-7	6e-8

Fig 15. Base and water partial pressure decrease after the wall conditioning sequences.

❖ Wall condition effect on Vacuum parameters

- ✓ Wall conditioning sequences are proceeded with halogen lamp baking, H2 GDC, He GDC and He boronization.
- ✓ In case of the halogen lamp baking phase, CRYO pumps are turned on to increase the water pumping speed. And hydrogen and helium glow discharge cleaning are conducted about 3hours each.
- ✓ After the first and second wall condition sequence, base pressure and proportion of water vapor decreases by 44%, 10% respectively.

Experimental results

Improvement of boronization system in VEST

Fig.16 The Emission line measurement of the VEST shot (Red: Boronization, Black: GDC).

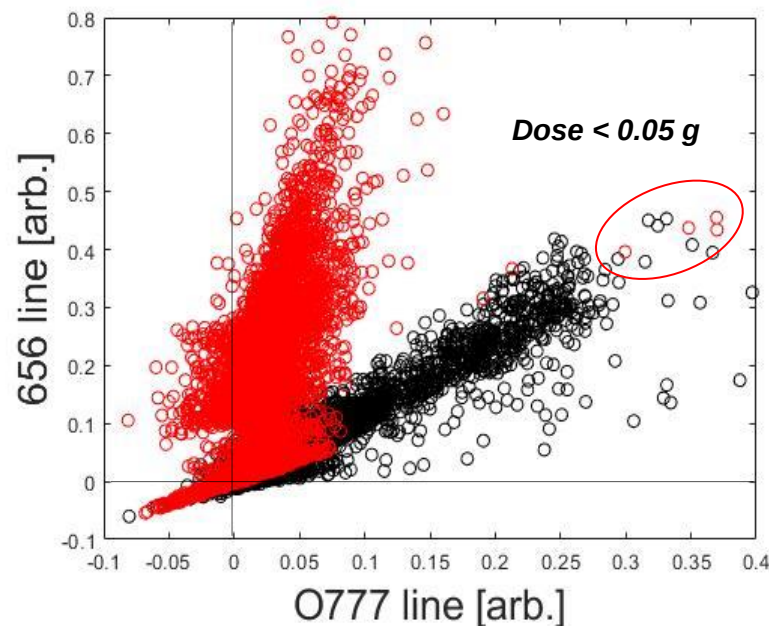
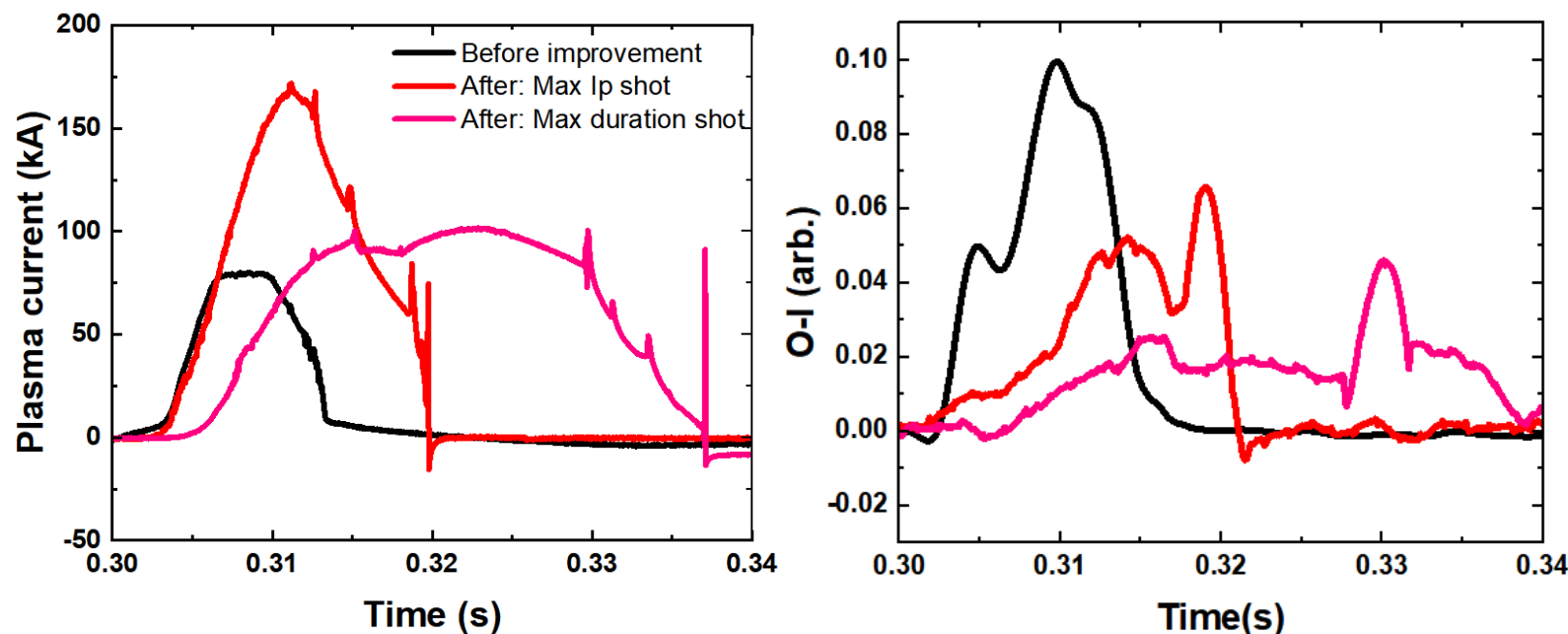


Fig.17 Maximum plasma current and duration shot in VEST with the improved boronization system



❖ Improved boronization effect on plasma

- ✓ Two alternative ways of reduction the oxygen content of the plasma have been explored: 1) GDC 2) metal-gettering are optimized to yield the high performance plasma to prevent the ohmic power consumption.
- ✓ As shown in figure16, black circle, in the case of a shot with GDC-based wall conditioning, a lot of oxygen is detected.
- ✓ On the other hand, red circle, boronization based shots not only decreased the amount of Oxygen detected except for the case less than 0.05g doze rate cases.
- ✓ To improve the toroidal homogeneity and recondensation of boron compound, a boronization system is upgraded by additional helium flow.
- ✓ After the boronization system improvement, fig.17 shows two record plasma shots in VEST, maximum Ip ~ 170kA, maximum dt ~ 30 ms

Experimental results

Development of Penning type fast response neutral pressure gauge

Fig18. Neutral pressure measurements during #37430 by fast response PIG, PKR-251 respectively

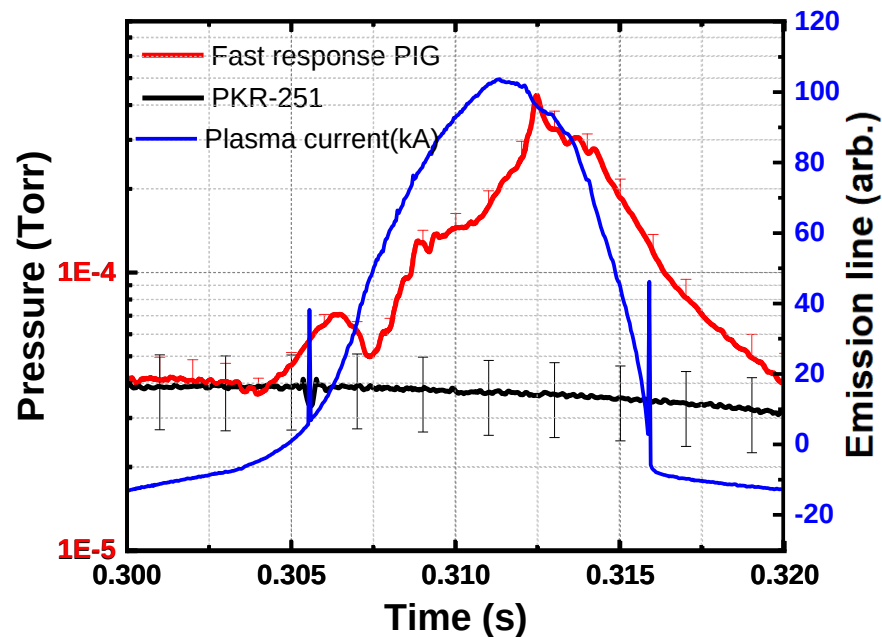


Fig19. H-alpha and O-I emission line at #37430

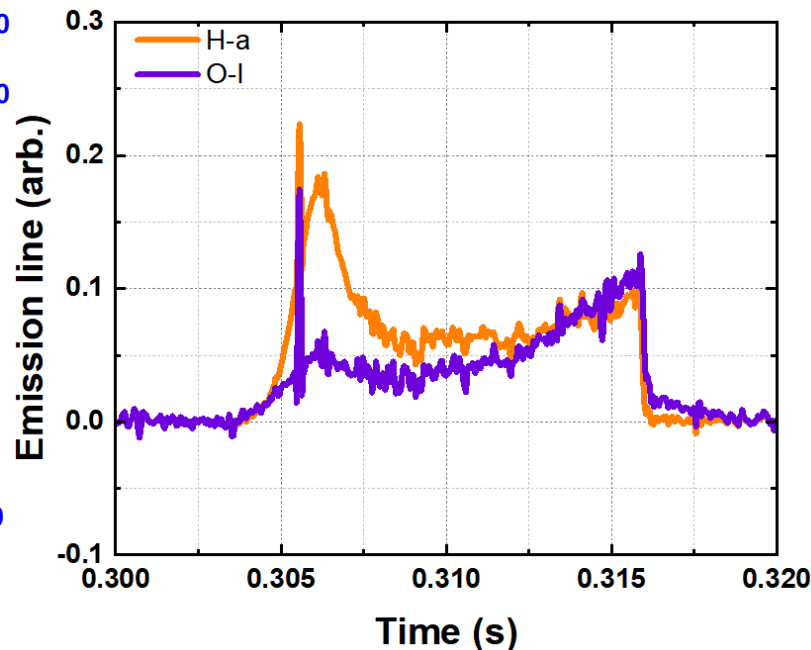
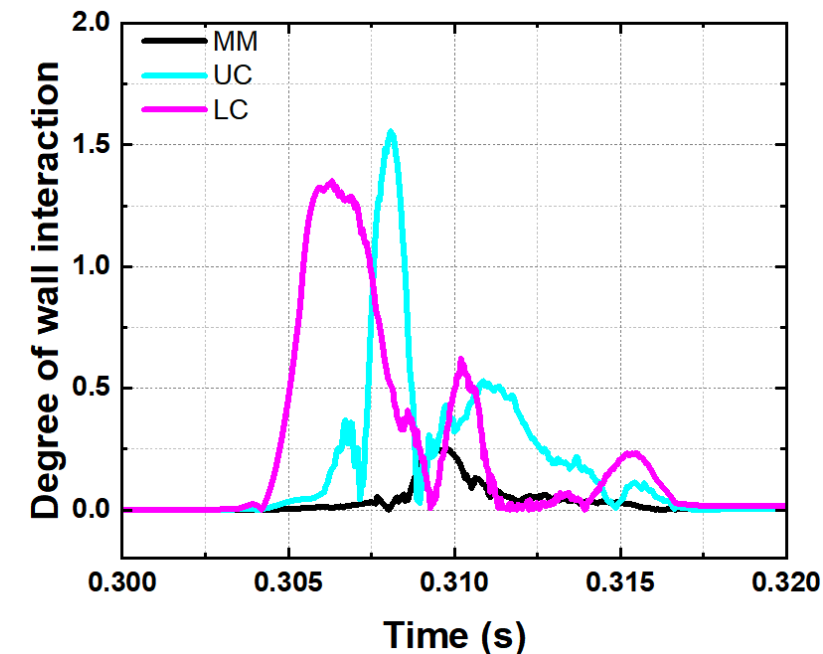


Fig20. RMS value of outboard limiter current signal at #37430



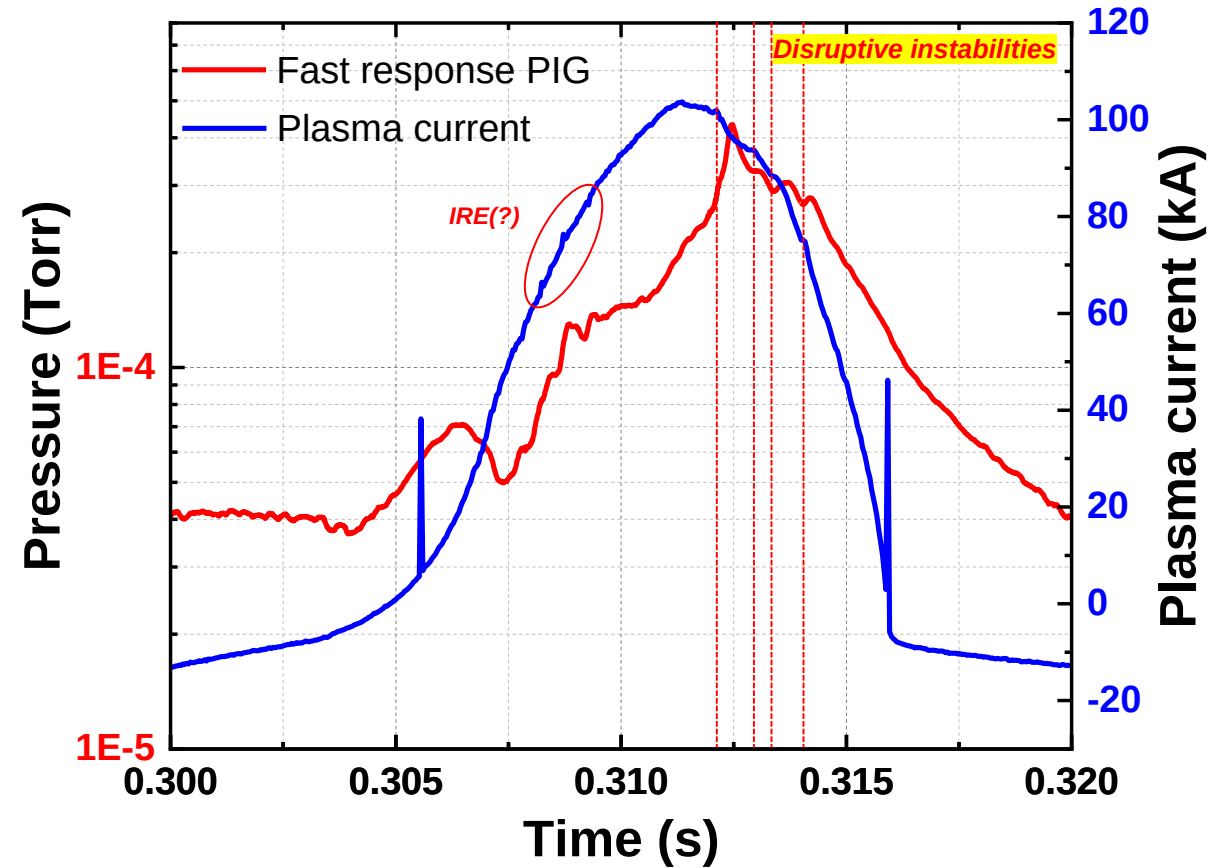
❖ Plasma wall interaction study in VEST

- ✓ Newly developed fast response in-situ gauge measures in-vessel neutral pressure as ms order time response, compare to the commercial pressure gauge.
- ✓ Fig19, H-alpha and O-I neutral emission line shows consistent results with the developed fast response gauge signal at the plasma start-up phase.
- ✓ Additionally, also with the outboard limiter signal rms value, new gauge enables VEST to plasma wall interaction study at limited plasma regime.
- ✓ This is the evidence that limited plasma concept experiment should be conducted with controlled neutral particles including impurities for high performance fusion plasma.

Experimental results

Development of Penning type fast response neutral pressure gauge

Fig21. Fast neutral pressure measurement with plasma current



- 1) In JET, disruptive discharges release approximately two times more particles than non-disruptive discharges[8].
- 2) Disruptive discharges release more particles from the first wall, especially the disruptions with a large plasma energy and a high quench rate[9].
- 3) Far more research will be needed for precise neutral particle modelling for identification of a correlation between plasma density and neutral pressure[10,11].
- 4) Also, rapid neutral pressure increase is observed right after the disruption like instabilities in VEST.

[8] Philipps, V., et al. "Effect of disruptions on fuel release from JET walls." *Journal of nuclear materials* 390 (2009): 478-481.

[9] Yu, Yaowei, et al. "First comprehensive particle balance study in KSTAR with a full graphite first wall and diverted plasmas." *Plasma Physics and Controlled Fusion* 54.10 (2012): 105006.

[10] Juhn, J., et al. "Particle balance study for the fueling efficiency in KSTAR experiments 2013." *Journal of the Korean Physical Society* 65.8 (2014): 1304-1311.

[11] Kim, Hyun-Tae, A. C. C. Sips, and EFDA-JET Contributors. "Physics of plasma burn-through and DYON simulations for the JET ITER-like wall." *Nuclear Fusion* 53.8 (2013): 083024.

Experimental results

Development of Penning type fast response neutral pressure gauge

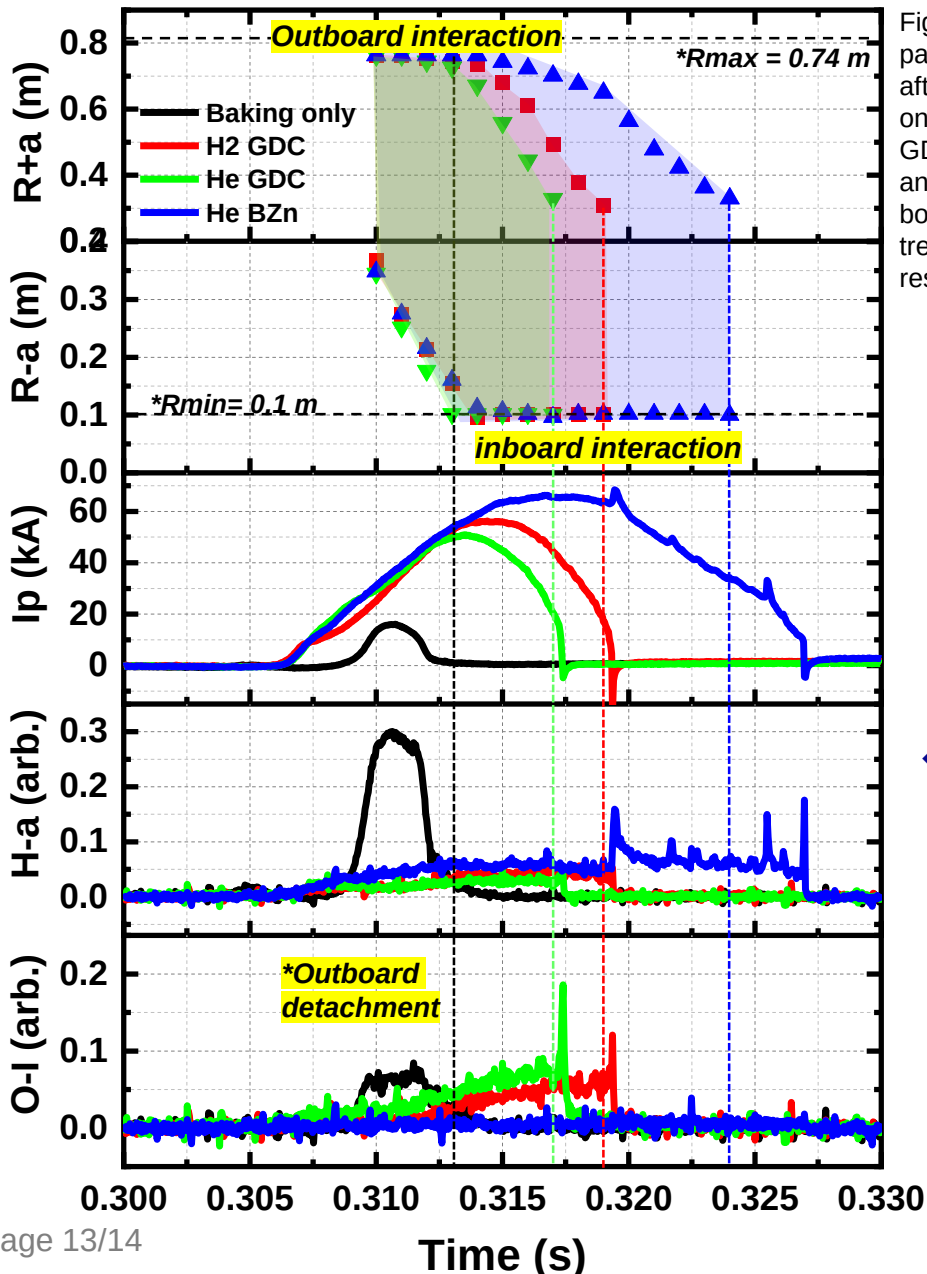


Fig22. Plasma parameters right after the baking only, hydrogen GDC, helium GDC and helium boronization treatment, respectively.

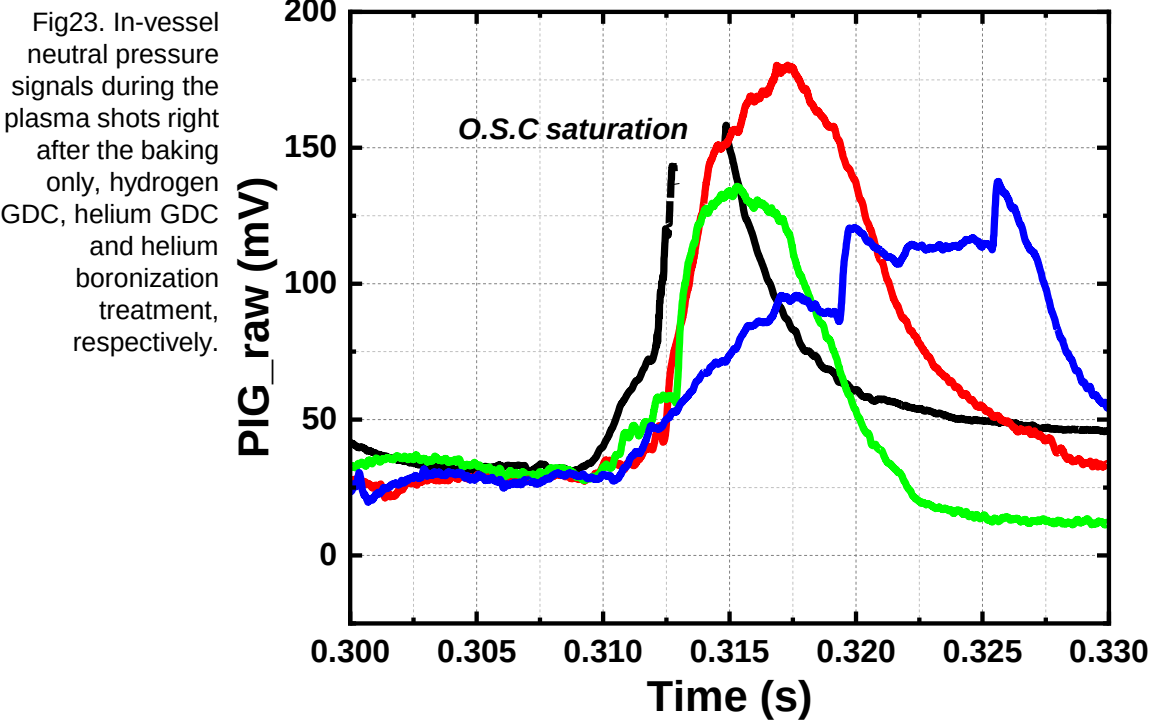


Fig23. In-vessel neutral pressure signals during the plasma shots right after the baking only, hydrogen GDC, helium GDC and helium boronization treatment, respectively.

❖ Plasma wall interaction study with various wall condition techniques

- ✓ Typical VEST plasma initiates the edge of the mid-plane and quenches at the center.
- ✓ In case of the GDC conditioned plasma, neutral oxygen emission line increases more rapidly at inboard interaction dominant phase than the outboard interaction phase (fig.22,23).
- ✓ But after the Boronization, Oxygen impurity suppression is observed entire wall interaction phase with a slight hydrogen concentration increment originated from boron compound dissociation.
- ✓ To improve the plasma performance, boronization technique is an inevitable treatment for the suppression of the water vapor based impurity influx to the plasma with new hydrogen concentration reduction method in VEST.

Conclusion and future works

❖ Conclusion and discussion

- ✓ After improvement of VEST vacuum system, both oxygen and hydrogen neutral emission line decreased by about 40% and it turns out to increase the plasma maximum current by 25%.
- ✓ Wall condition sequences including newly installed halogen lamp baking system reduce the base pressure and proportion of water vapor by 44%, 10% respectively
- ✓ After the boronization system improvement, fig.17 shows two record plasma shots in VEST, maximum $I_p \sim 170\text{kA}$, maximum $dt \sim 30\text{ ms}$
- ✓ To monitor neutral gas behavior, fast response in-situ neutral pressure gauge has been developed in VEST.
- ✓ As shown in fig.22, identified main oxygen source should be removed by various wall condition techniques including the boronization in VEST.

❖ Future works

- ✓ Bake-albe carbon tile effect study will be conducted near future to investigate the possibility of removing water vapor from the outer wall by replacing entire tungsten limiter.
- ✓ New wall condition techniques such as deuterium boronization or in-situ titanium gettering will be tested for achieving high performance plasma in VEST [12].
- ✓ Neutral particle balancing model will be established by interferometry, Thomson scattering system and newly developed fast response neutral pressure gauge for the quantative analysis of wall interactions.

References

- [1] Juhn, J., et al. "Particle balance study for the fueling efficiency in KSTAR experiments 2013." *Journal of the Korean Physical Society* 65.8 (2014): 1304-1311.
- [2] Winter, Jörg. "Wall conditioning in fusion devices and its influence on plasma performance." *Plasma Physics and Controlled Fusion* 38.9 (1996): 1503.
- [3] Yu, Yaowei, et al. "First comprehensive particle balance study in KSTAR with a full graphite first wall and diverted plasmas." *Plasma Physics and Controlled Fusion* 54.10 (2012): 105006.
- [4] Pütterich, Th, et al. "Calculation and experimental test of the cooling factor of tungsten." *Nuclear Fusion* 50.2 (2010): 025012.
- [5] Hong, Suk-Ho, et al. "Initial phase wall conditioning in KSTAR." *Nuclear Fusion* 51.10 (2011): 103027.
- [6] Kremeyer, T., et al. "Wisconsin In Situ Penning (WISP) gauge: A versatile neutral pressure gauge to measure partial pressures in strong magnetic fields." *Review of Scientific Instruments* 91.4 (2020): 043504.
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- [12] Harra, D. J., and T. W. Snouse. "A radiant heated titanium sublimator." *Journal of Vacuum Science and Technology* 9.1 (1972): 552-555.