Experiences of remote maintenance for the mercury target system for the pulsed neutron source

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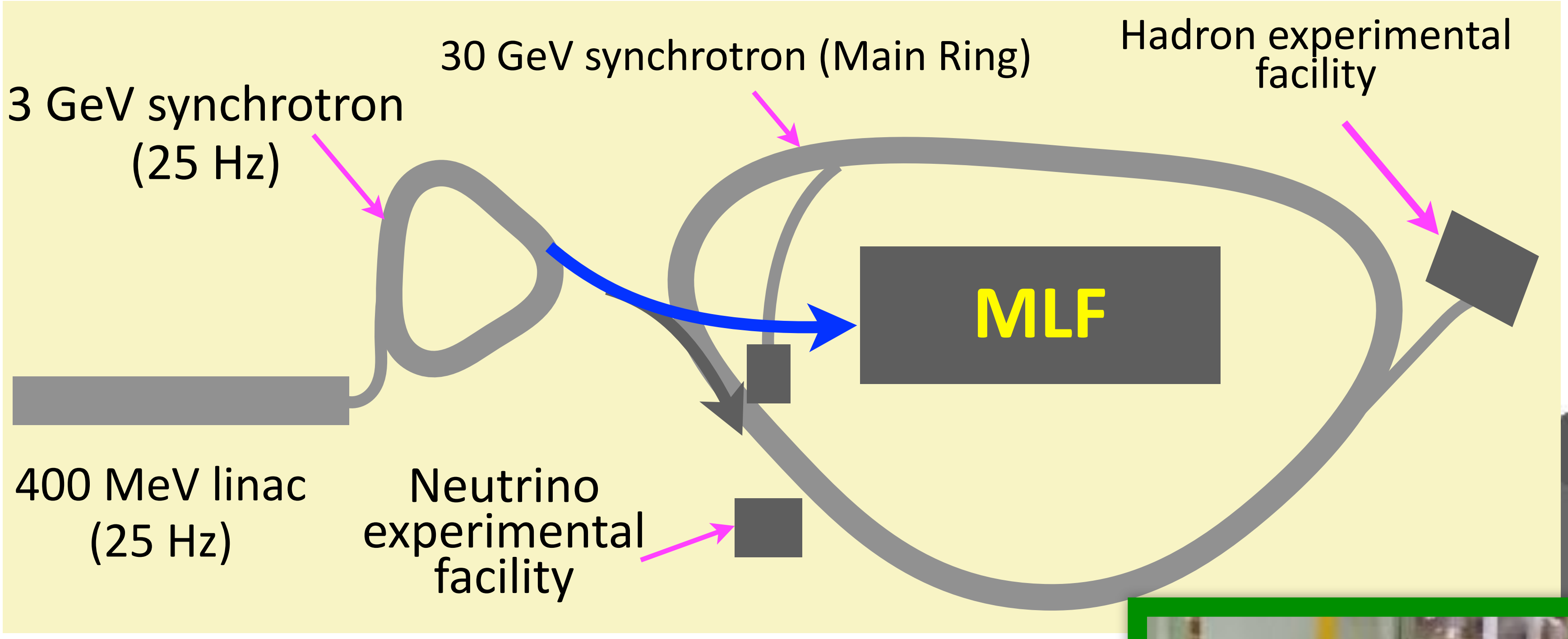
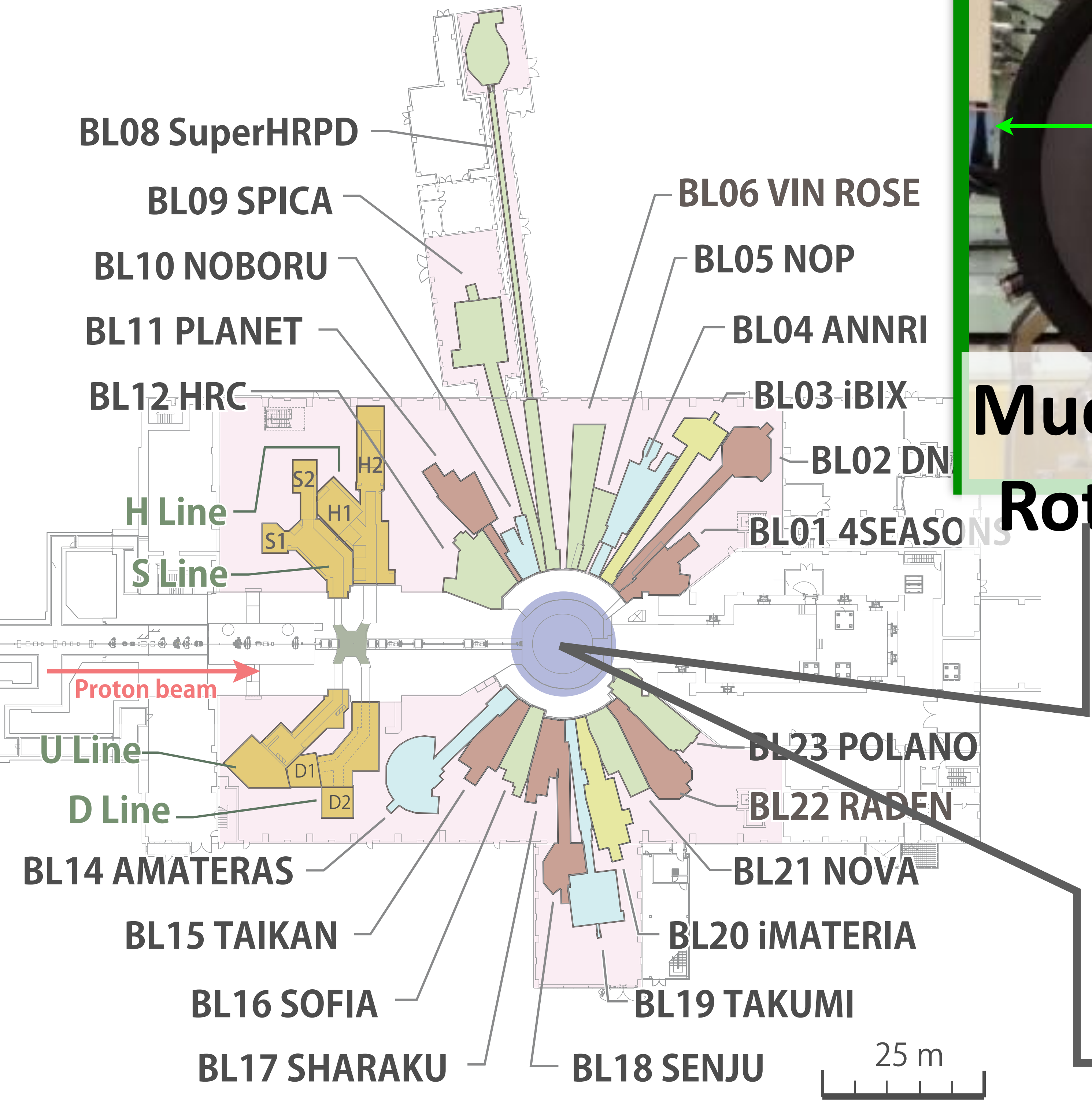
Outline

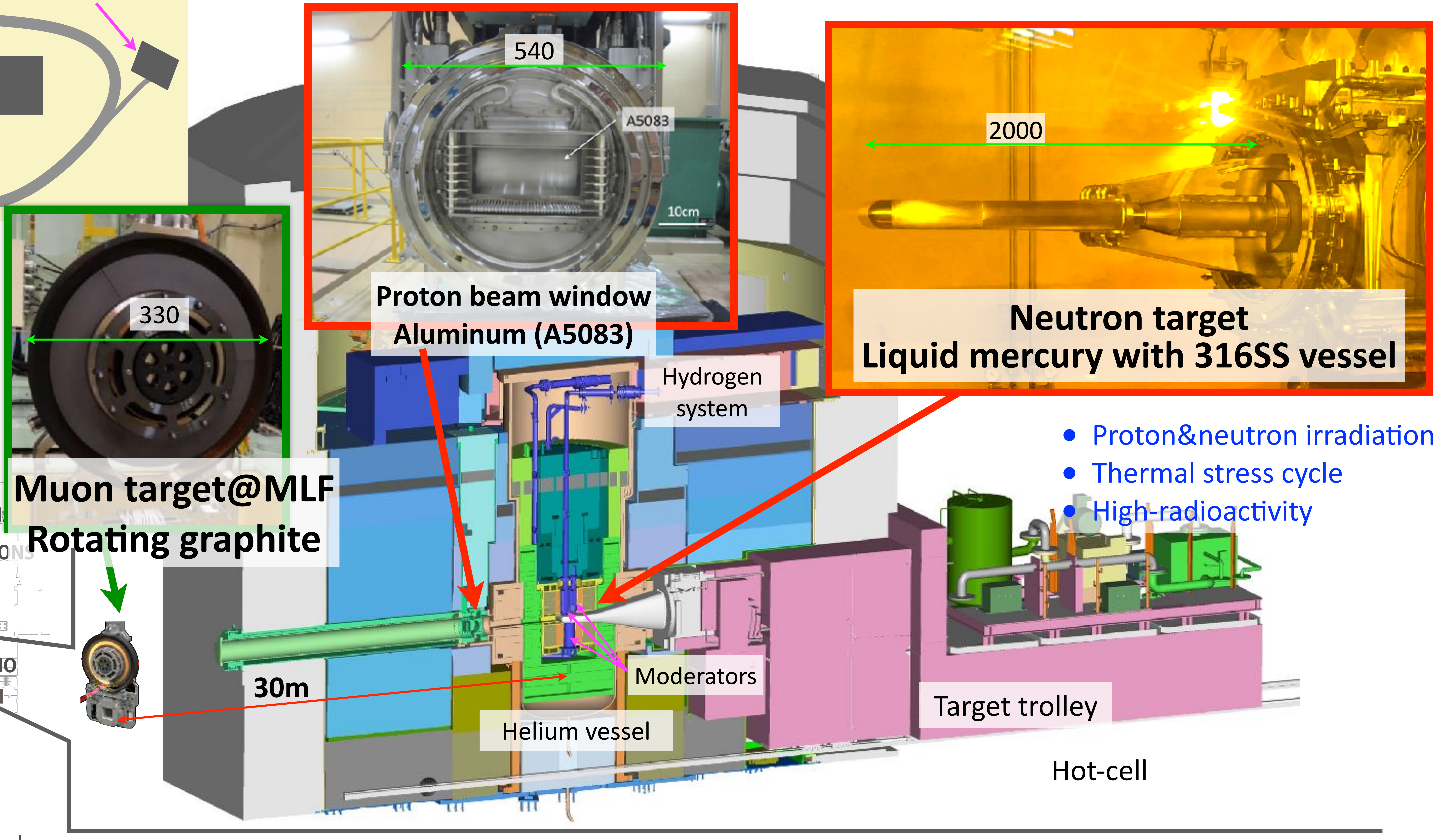
- Mercury target system in MLF/J-PARC
- Mercury pump replacement
- Leak from mercury flange
- Mockup experiment for metal seal replacement
- Metal seal replacement
- Power cables replacement
- Summary

Pulsed neutron source in MLF/J-PARC



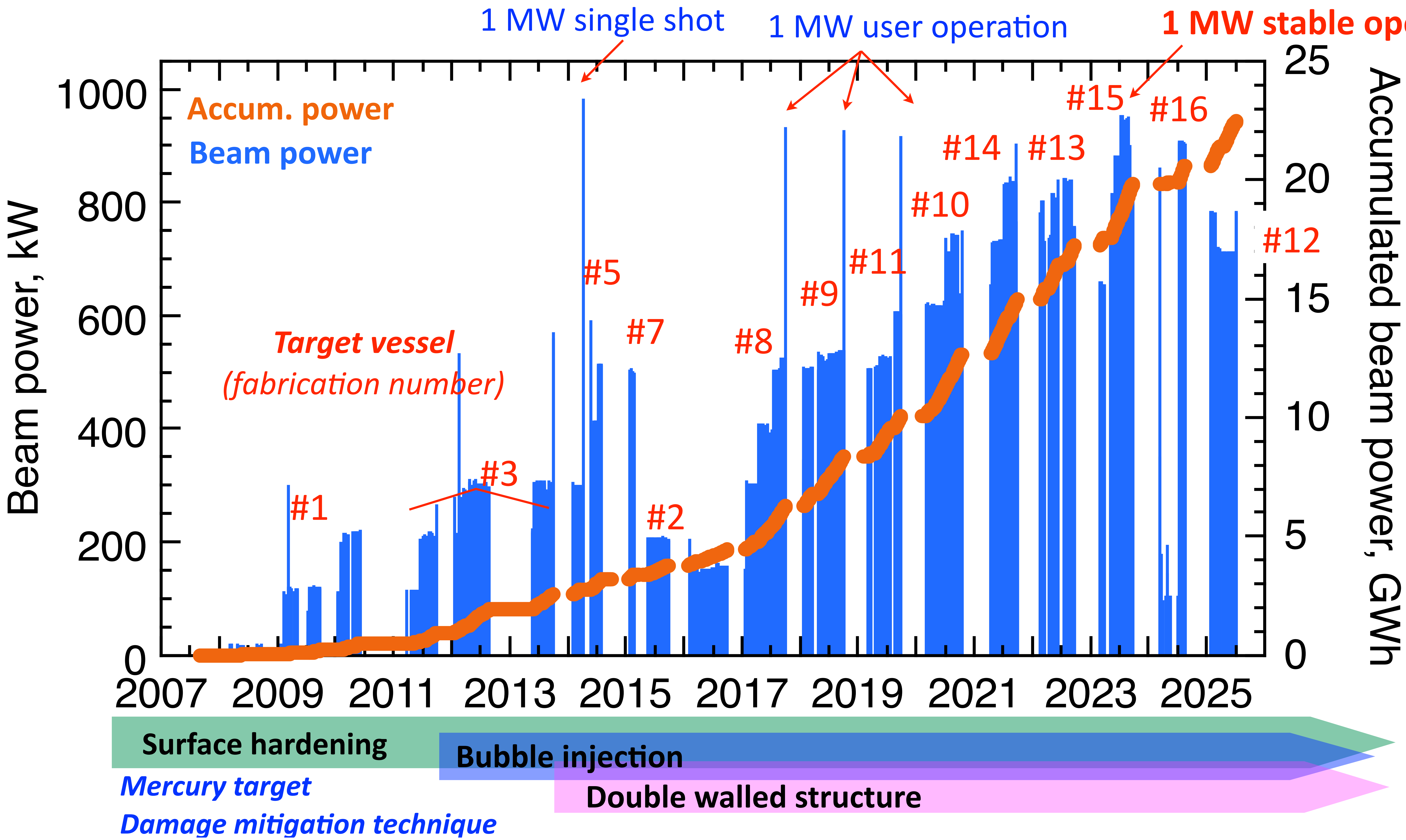


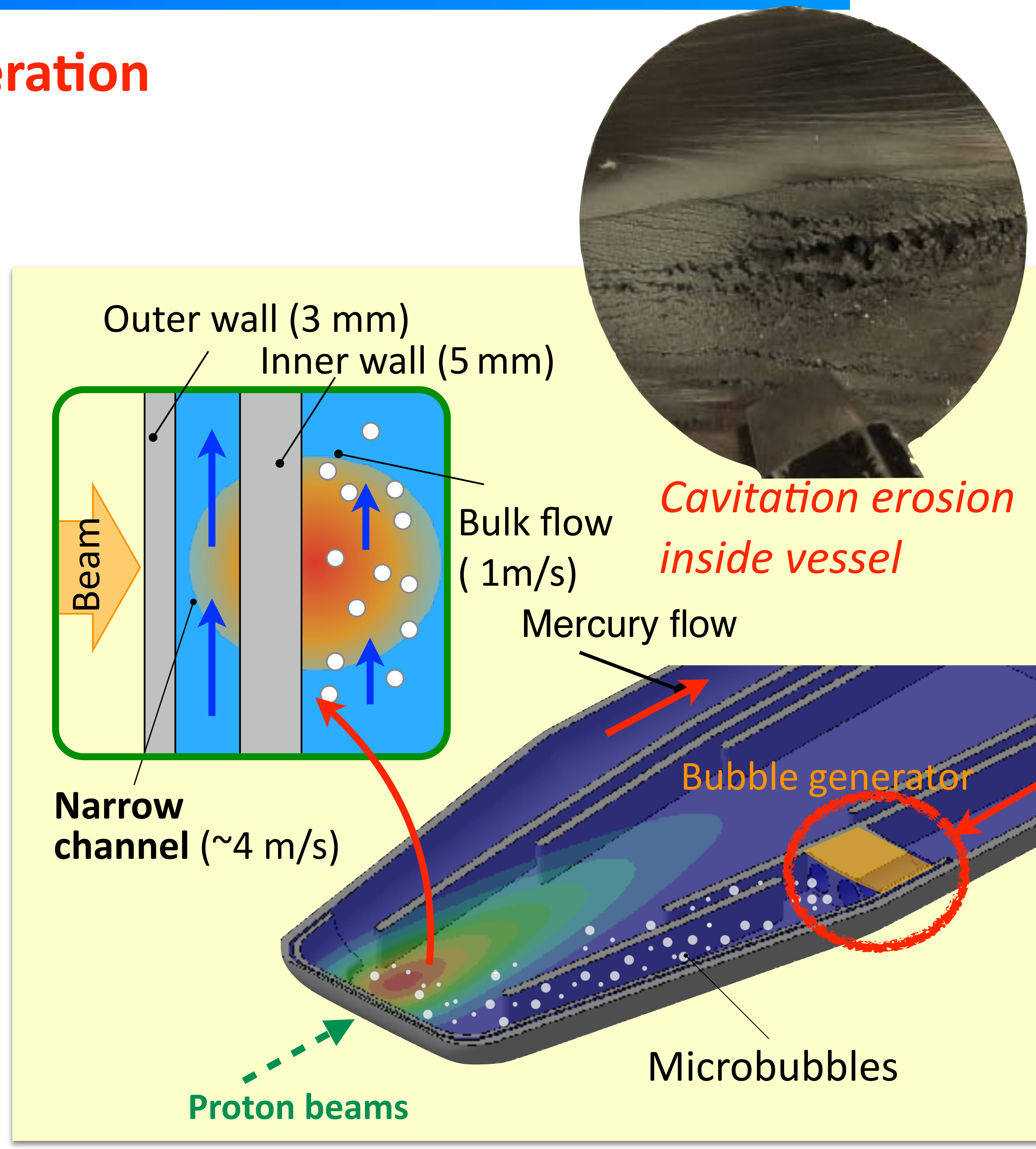
Materials and Life Science Experimental Facility (MLF)



- Proton&neutron irradiation
- Thermal stress cycle
- High-radioactivity

Power upgrade histories of muon and neutron target

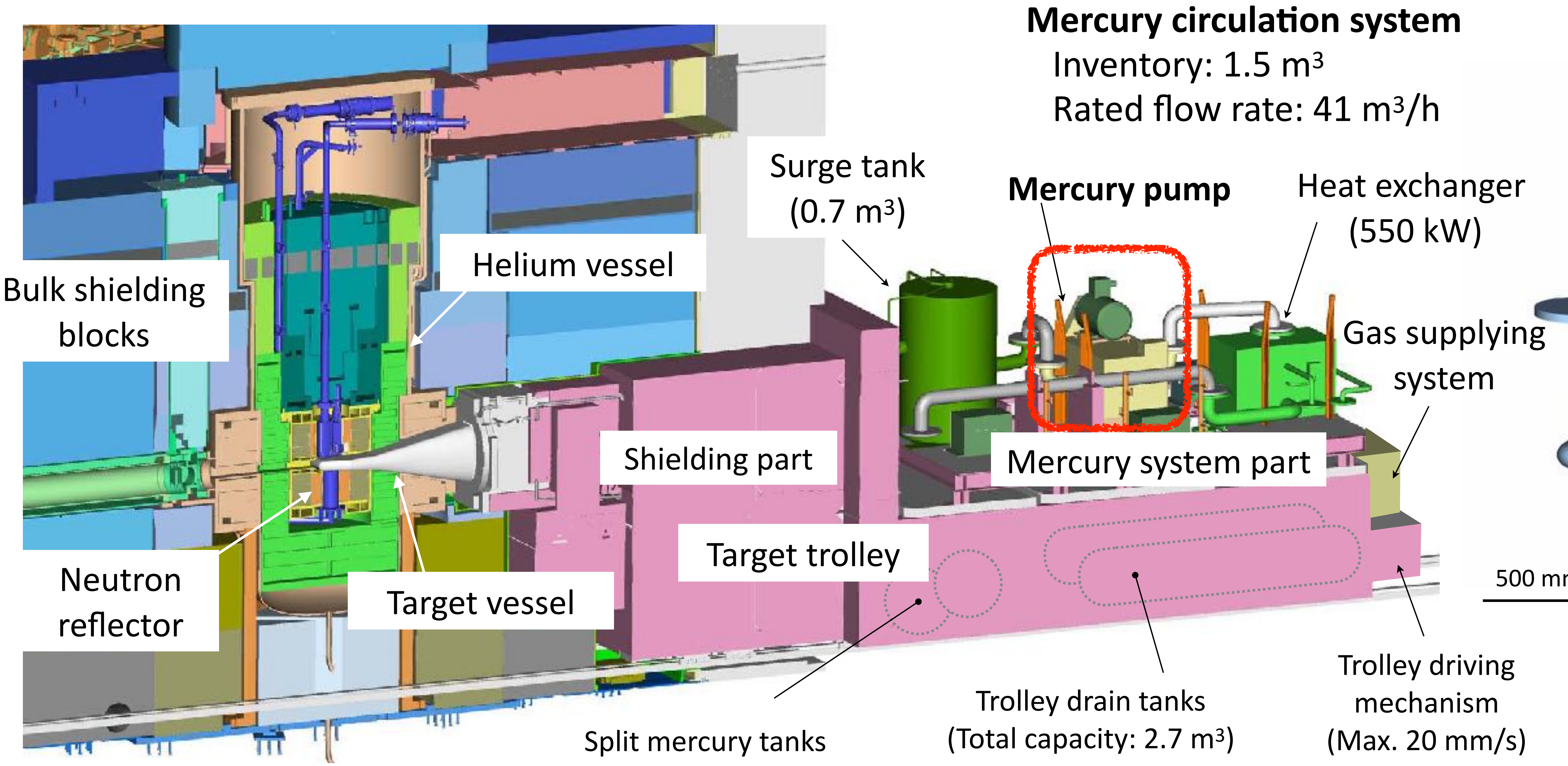


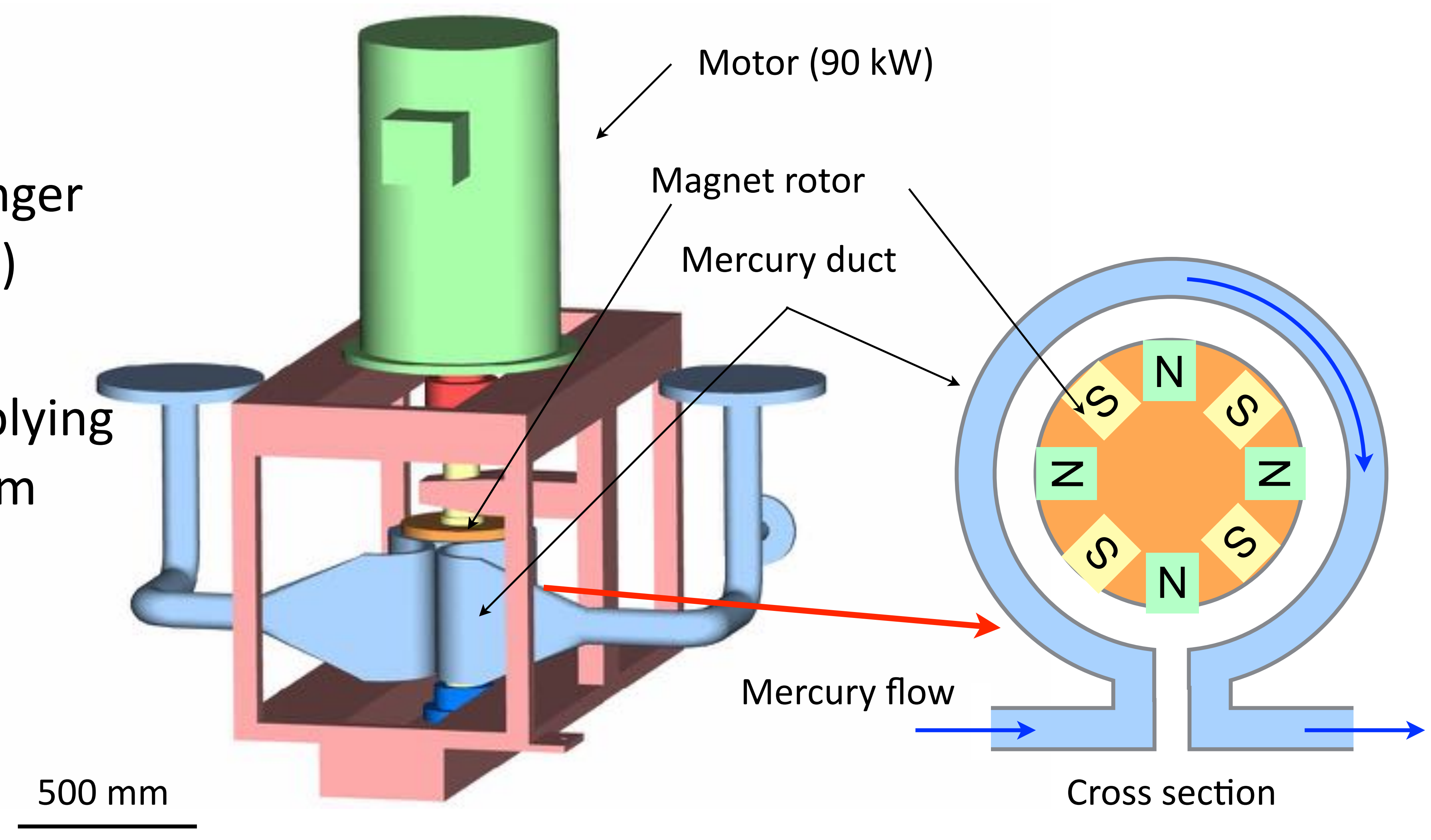


Damage mitigation techniques

- Successfully achieved stable 1 MW operation (MLF goal) for two months in April 2024 using Target #15
- Experienced issues: reduction of insulation resistance pump & cables, flange leak etc….

Mercury target system

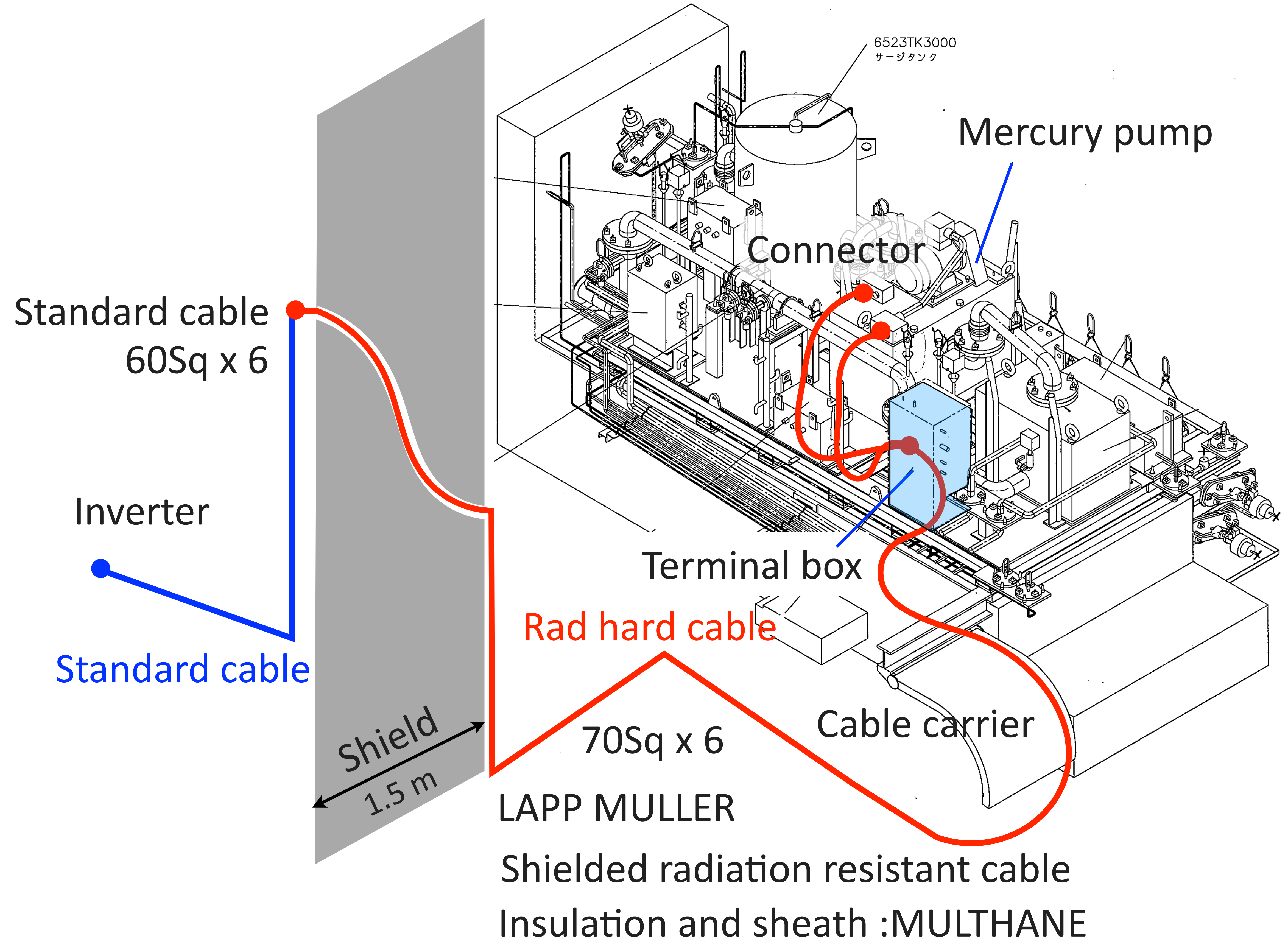


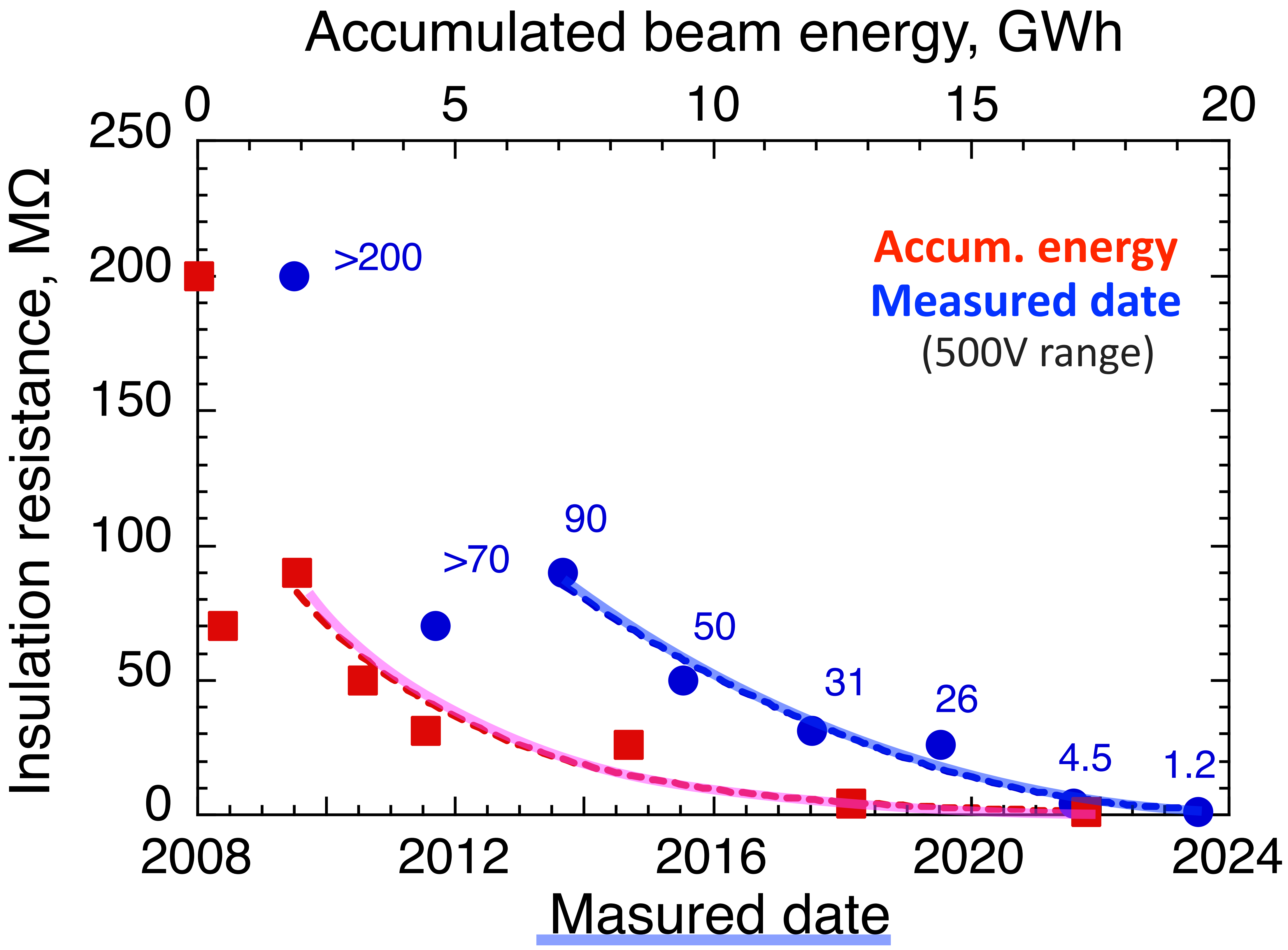


Permanent Magnet Pump Unit

- Permanent magnet rotating mercury pump, drives mercury by Lorentz force and completely enclosed structure, was adopted to eliminate the leak from motor rotating shaft
- To reduce the loss of magnetic force inner/outer duct thickness were designed to 3mm/5mm
- Annual inspections of vibration and duct thickness measurement for erosion inspection in every year, bearing grease-up and insulation resistance measurement in every two years

Insulation resistance of pump motor

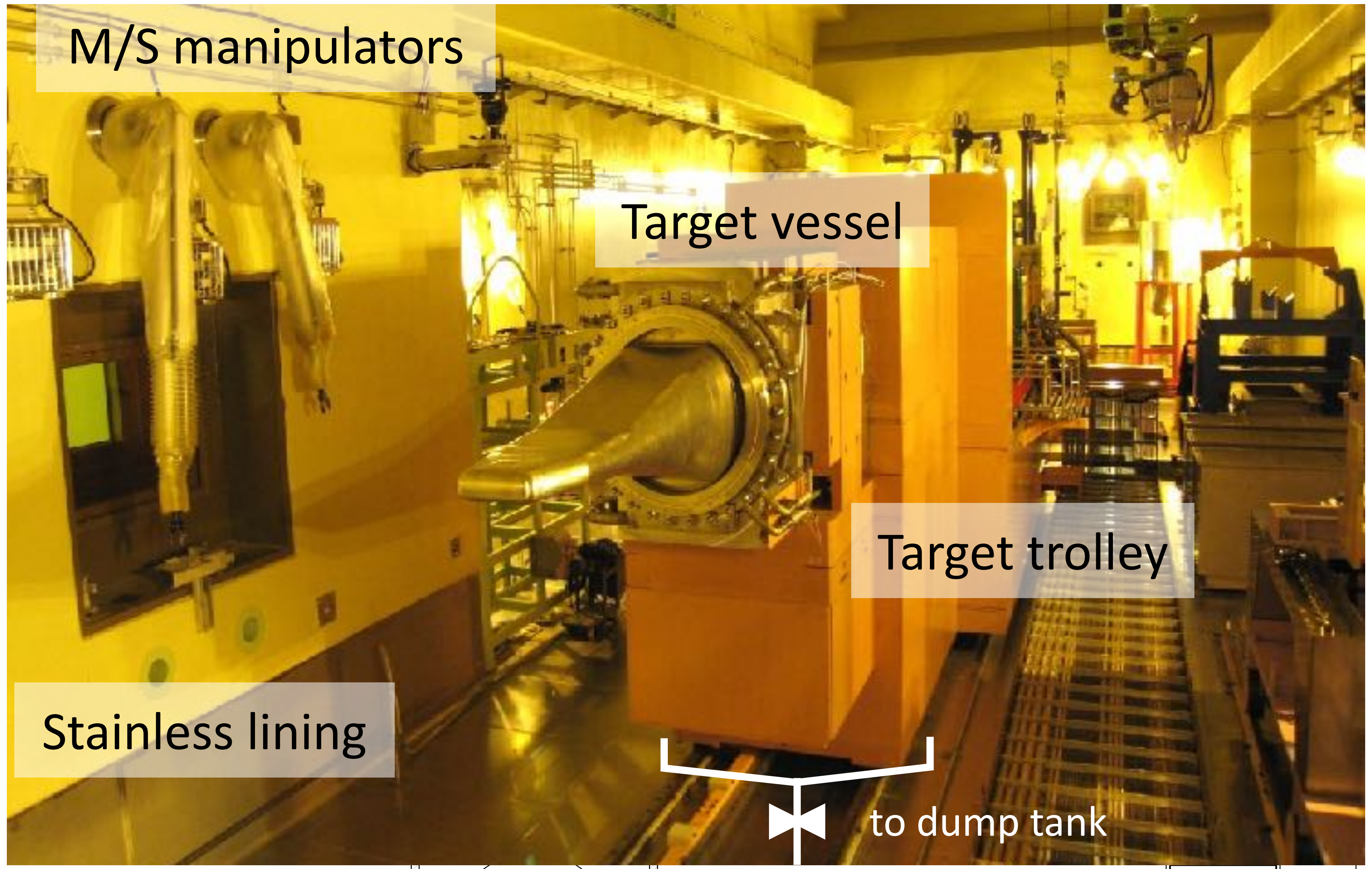


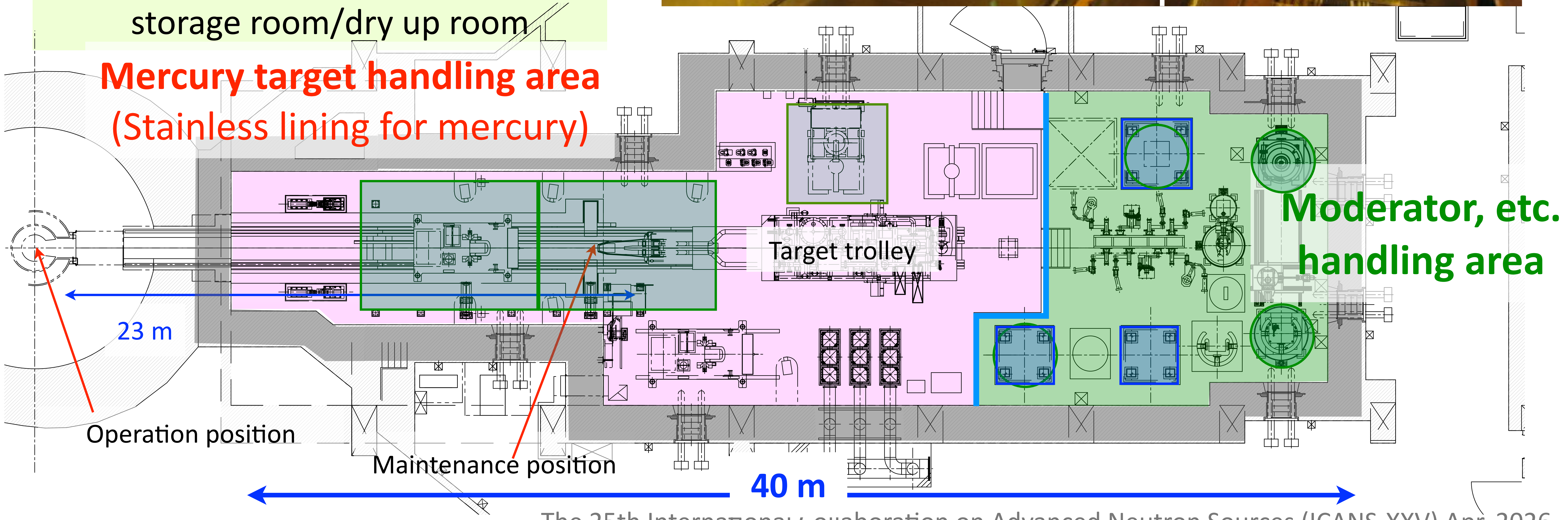


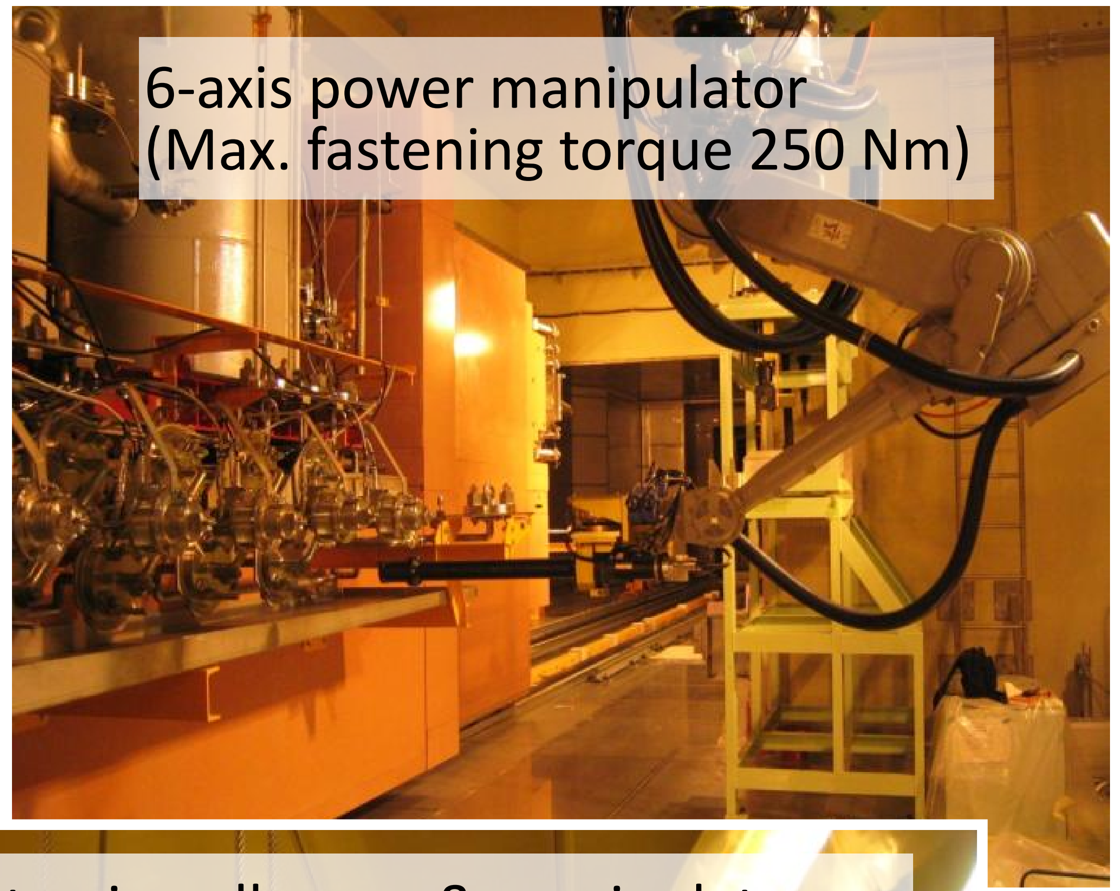
- Insulation resistance between each phase and earth are measured at the outside of hot-cell
- Results including the effects of motor (class F insulation), connector, rad-hard cables (~40 m)
- Replacement was decided resistance showed near the acceptable value of 1.0 MΩ in 2024

Hot-cell for target maintenance

Hot cell (MLF 1F)
L : 40 m × W : 13 m × H : 12 m
Ventilation
14,500m³/h (2 x volumes/hour)
Separate two area
Mercury area, moderator area
Ceiling hatch : 12×5 (2), 4×4 (1), 2.4×2.4 (5) m
Carry equipments into hot cell from high-bay
Floor hatch : 2.4×2.4 (3)
Carry used components into storage room/dry up room

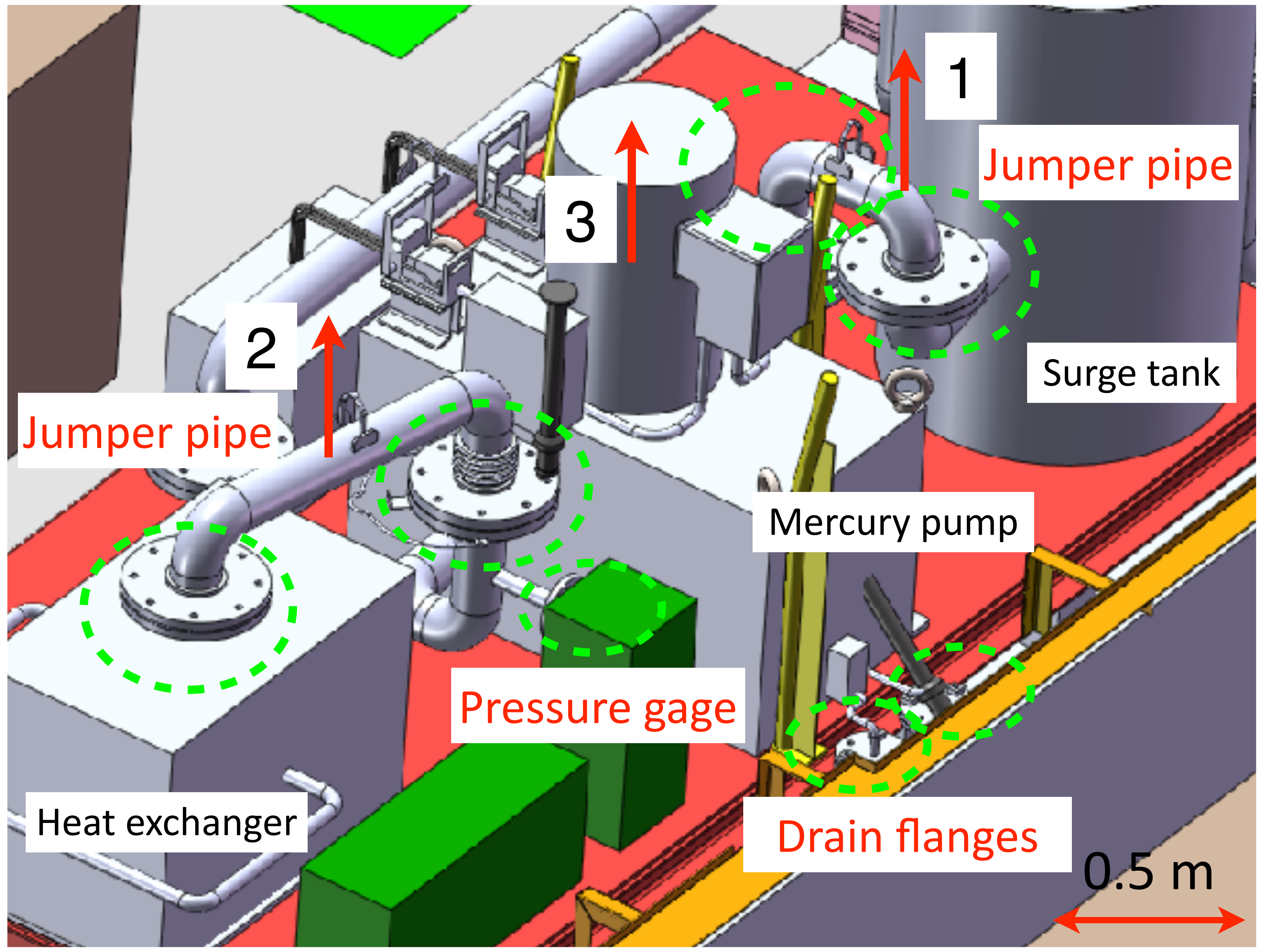


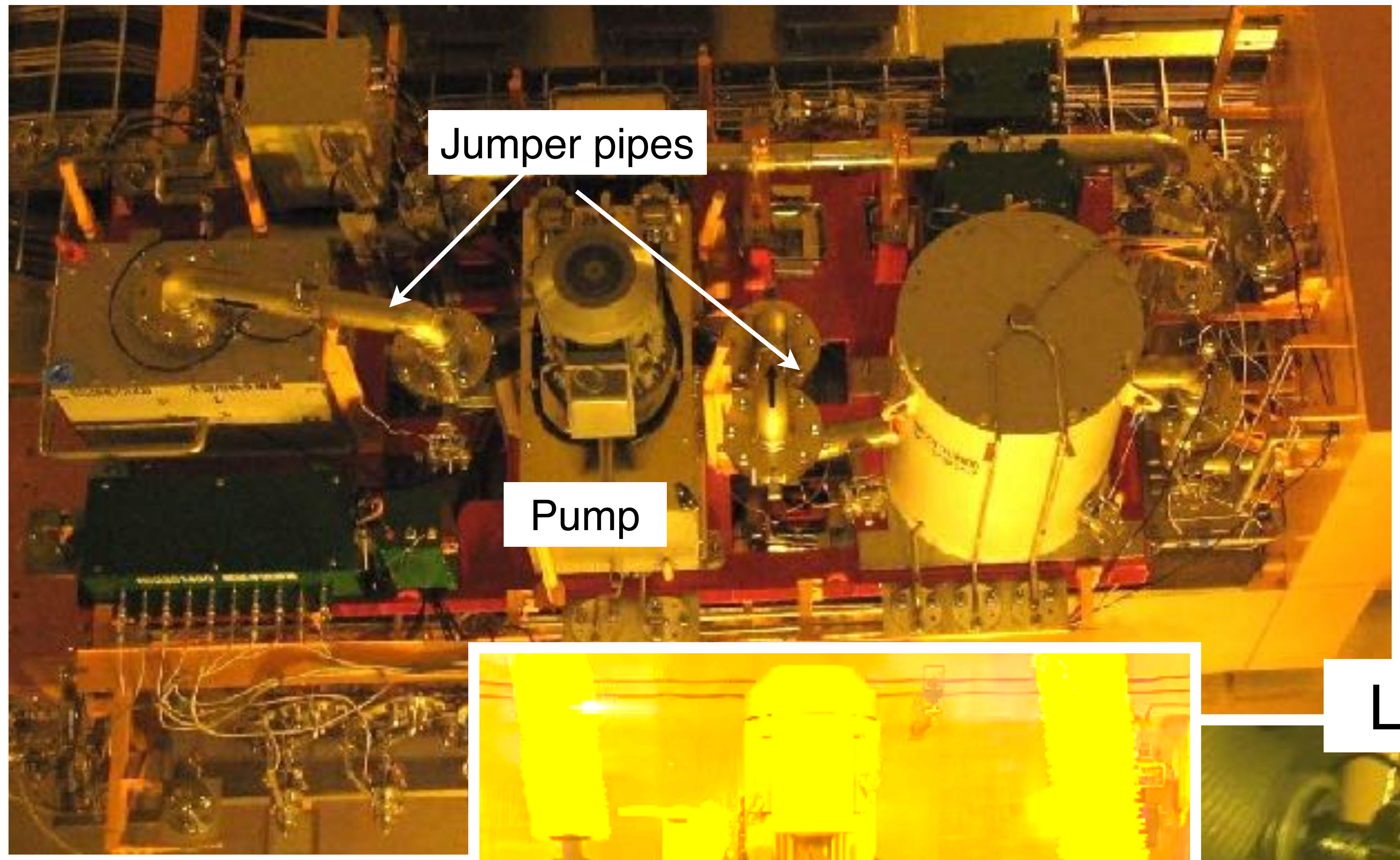


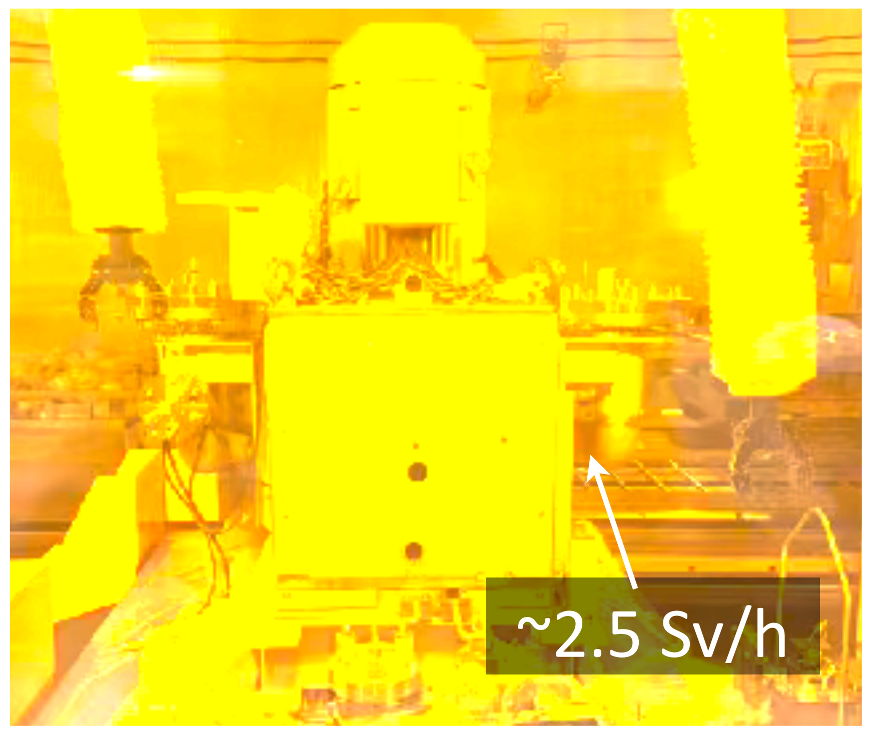


In cell cameras
(11 wall, 2 crane, 2 power manipulator)

Pump replacement by remote handling







Mercury pump (weight: 3 ton)

Loosing bolt by wrench

Removing jumper pipe

Rubber plug insertion

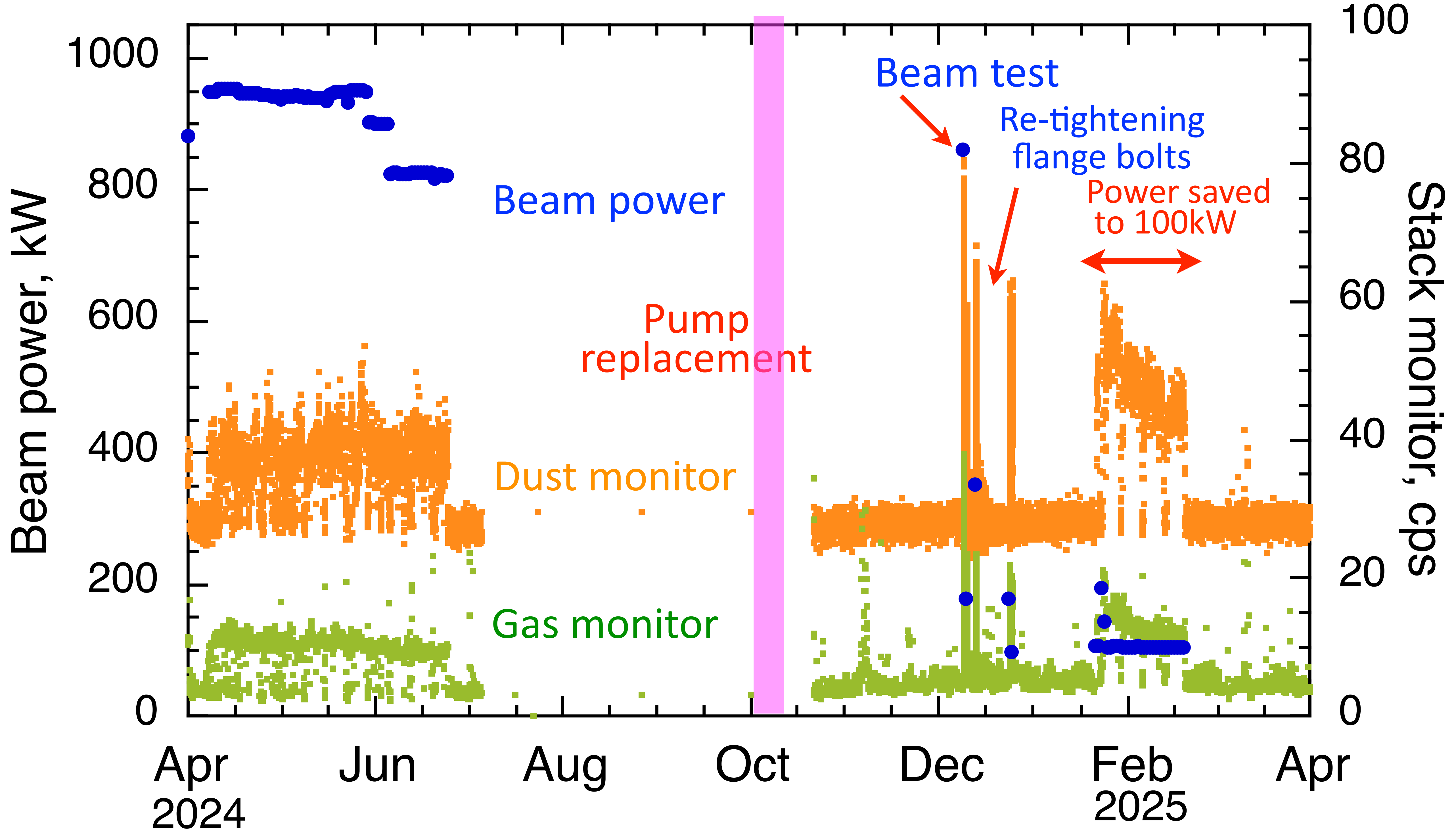
Helium leak test

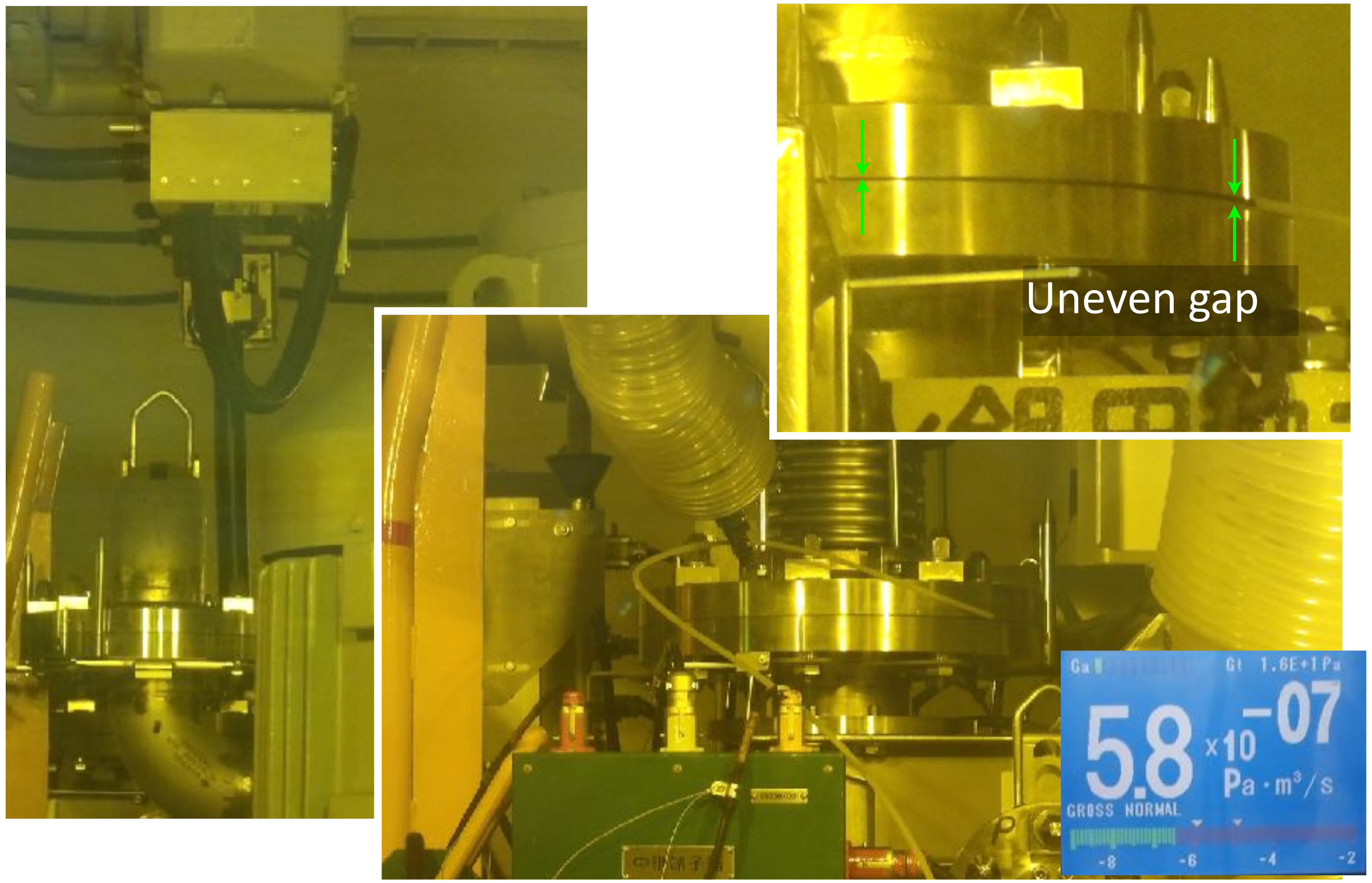
- Remote handling test and training were conducted carefully for rubber plug insertion and metal seal replacement using mockup target trolley
- 7 flanges should be opened for pump replacement, and insert rubber plugs to prevent tritium release from opening parts
- Replacement work and leak test were successful but amount of tritium release was slightly larger than expected

Predicted/ Result :141GBq / 160 GBq

Replacement procedure

Increase of stack radiation monitor during operation

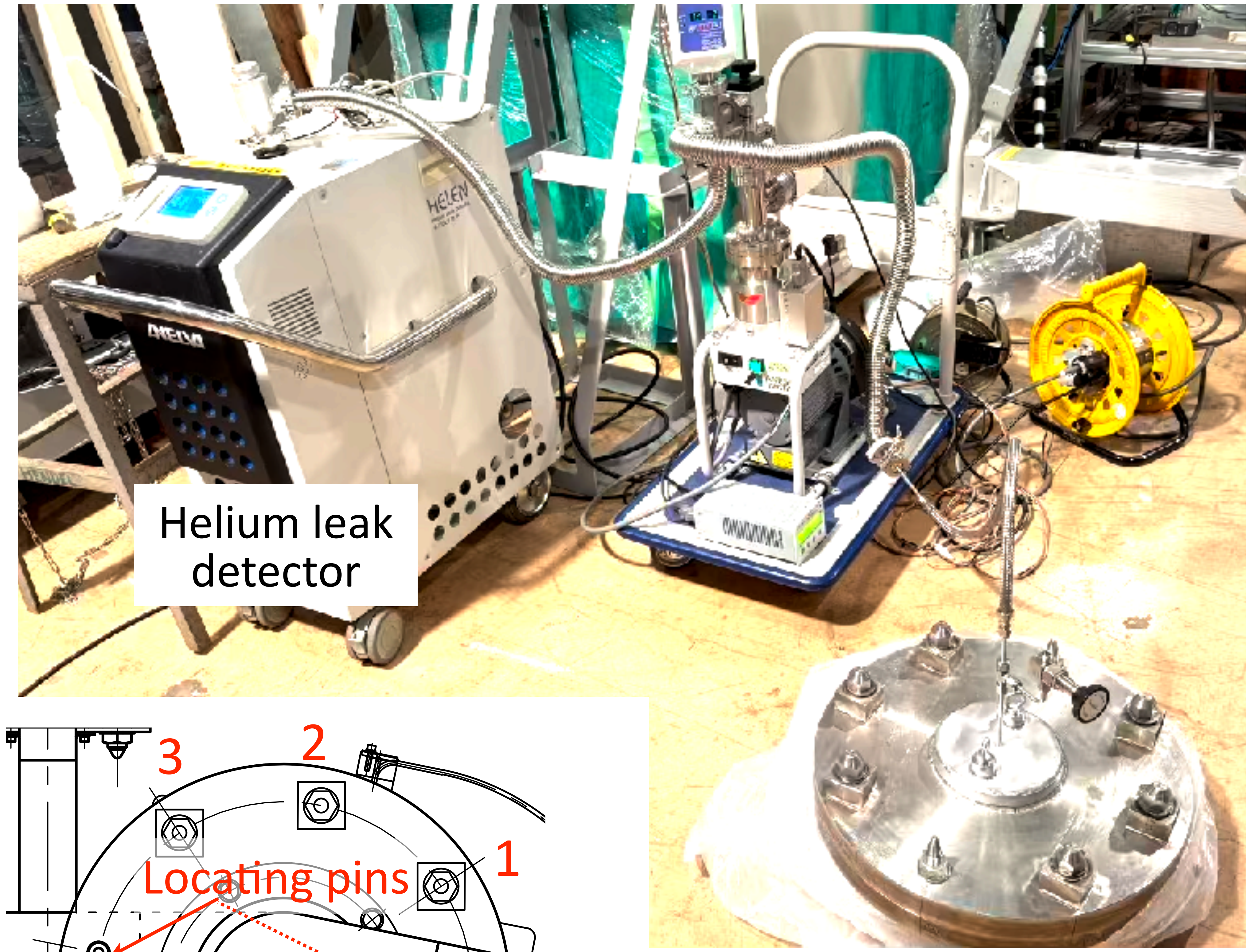


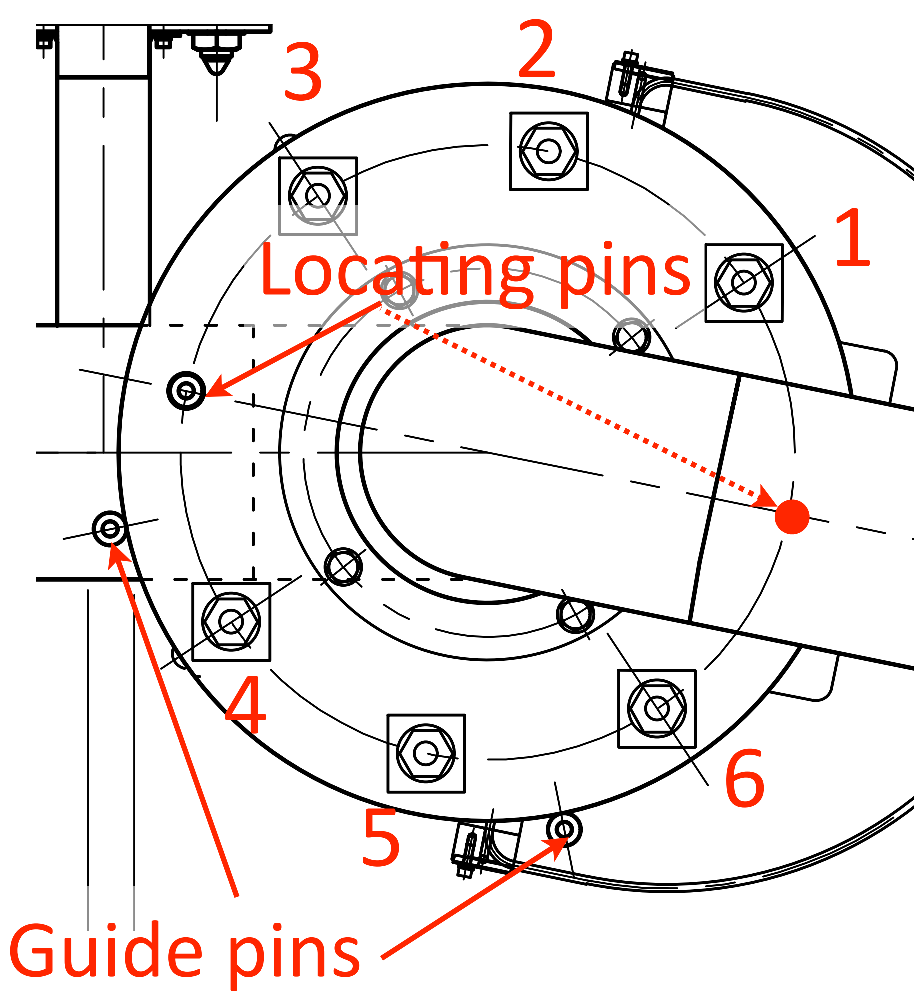


Sniffer helium leak test using manipulator

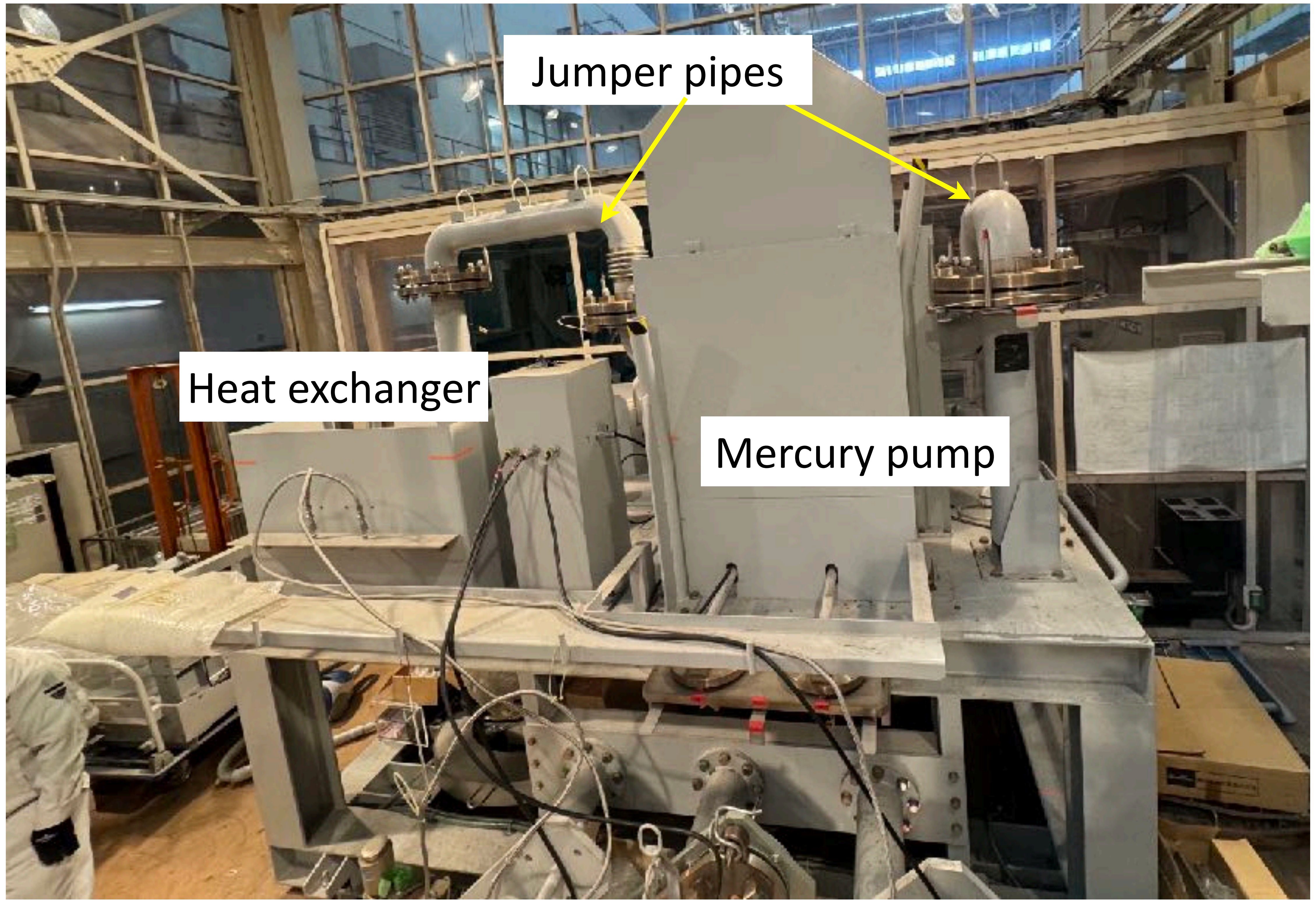
- Helium leak test was passed but rise of stack monitors counts were detected during beam test before user operation
- Inspection criteria was set to 1E-6 Pam^3/s by focusing on to prevent mercury leakage at that time
- Re-inspection after beam test, tiny gas leak was detected on pump flange 5.8E-7 Pam^3/s
- Retightening of flange bolts was not effective to reduce leak, and decided to reduce beam power to 100 kW and to replace flange seal in March

Mockup tests for metal seal replacement





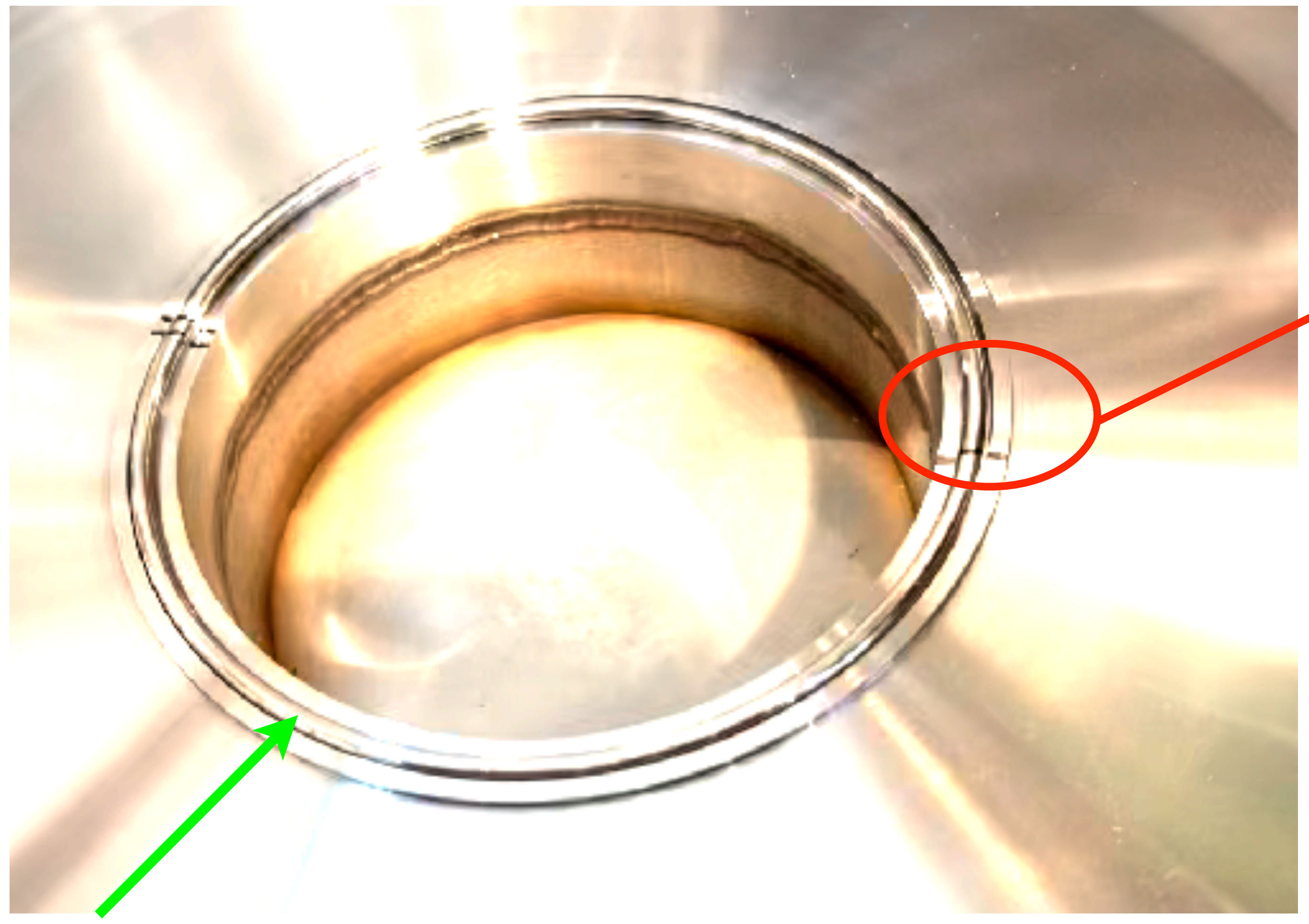
150A flange mockup (ϕ480x40t)



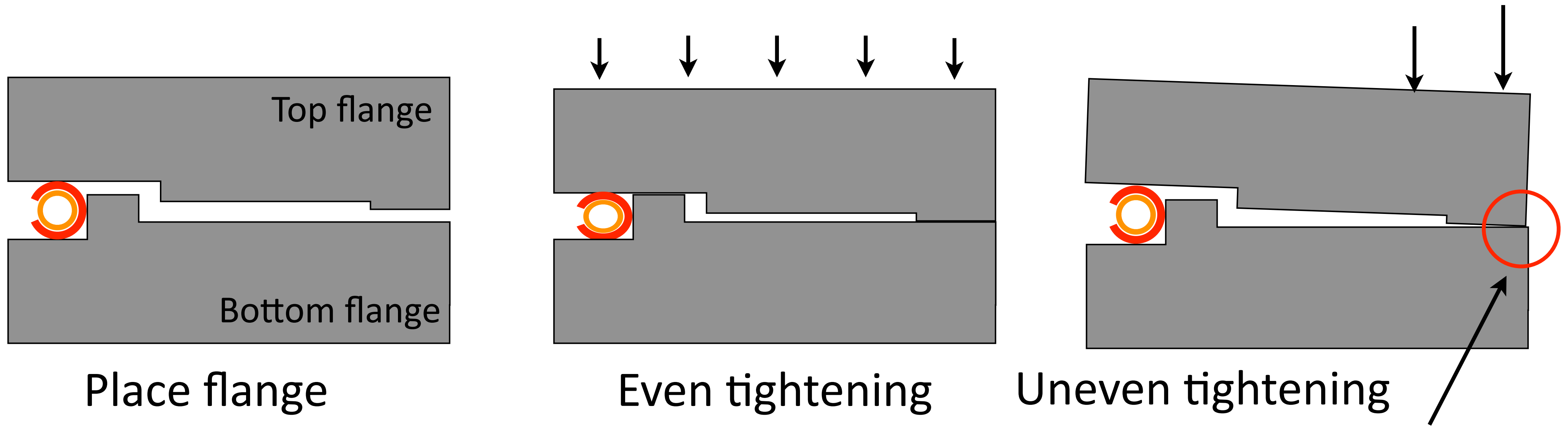
Target trolley mockup

- To investigate the reason of flange leak and improve the seal replacement procedures by remote handling, mockup tests using flange element and jumper pipe were conducted
- Vacuuming leak test was selected to detect leak in high-precision, although the actual target system is available only sniffer test

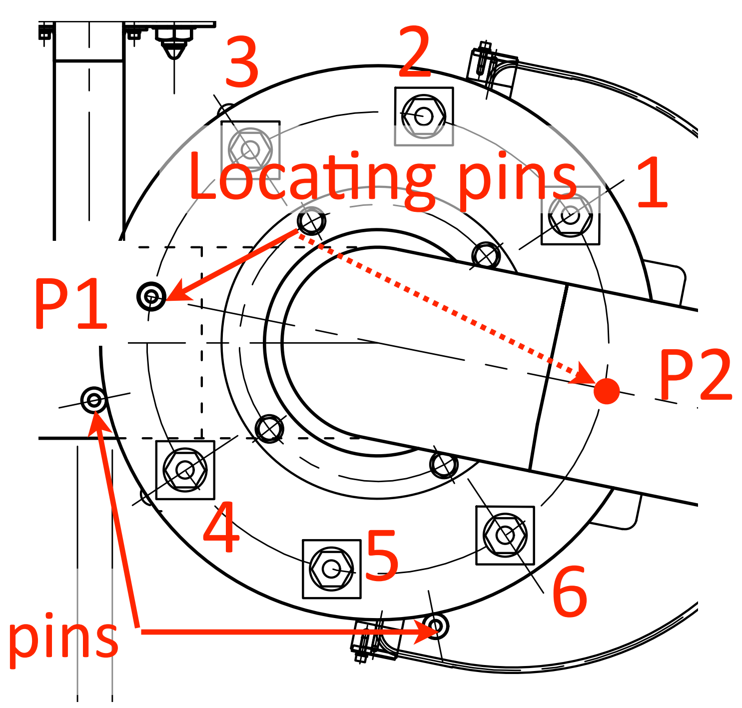
Flange structure and cause analysis of flange leak



VALCUA 3645 TRYPACK
Metal c-ring with coil spring
Ni-ring, SUS spring



Torque and axial force



Contact at flange edge

Loose 1 rotation did not affected for even gap

Torque	He leak	Flange gap at each bolt[mm]								
Nm	[Pam³/s]	P1	1	2	3	P2	4	5	6	note
0		0.6	0.6	0.65	0.65	0.6	0.6	0.6	0.65	Placeflange
60		1.45	0.85	0.19	<0.04	0.19	0.75	1.35	1.65	Tighten #3 60 Nm
60		0.6	0.6	0.6	0.65	0.65	0.6	0.6	0.6	Loosen #3 1 rotation
60		0.21	0.75	1.35	1.65	1.45	0.8	0.18	<0.04	Tighten #6 60 Nm
60		0.15	0.08	0.19	0.3	0.55	0.32	<0.04	<0.04	All bolts 60 Nm
120	Vacuum test	0.12	<0.04	<0.04	<0.04	0.17	<0.04	<0.04	<0.04	Turbo pump start
200	5.0E-09	0.07	<0.04	<0.04	<0.04	0.09	<0.04	<0.04	<0.04	

Required line load
490 kN/m for metal seal

$\pi D=0.487$ m
F=240kN
=40 kN/bolt

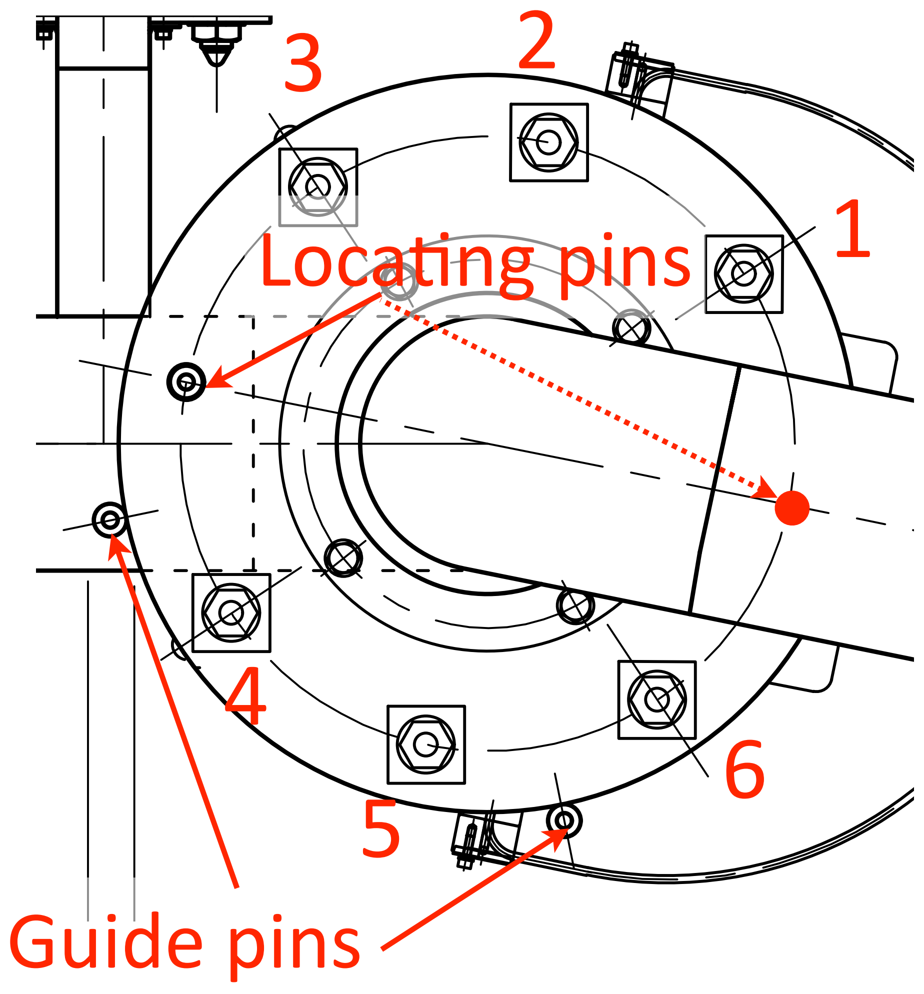
$F=T/(kd)$
$= 200\text{Nm}/(0.02\text{m}*0.2)$
$= 50\text{kN}$
Satisfy required force

F: Axial force
D: Seal diameter
6 bolts

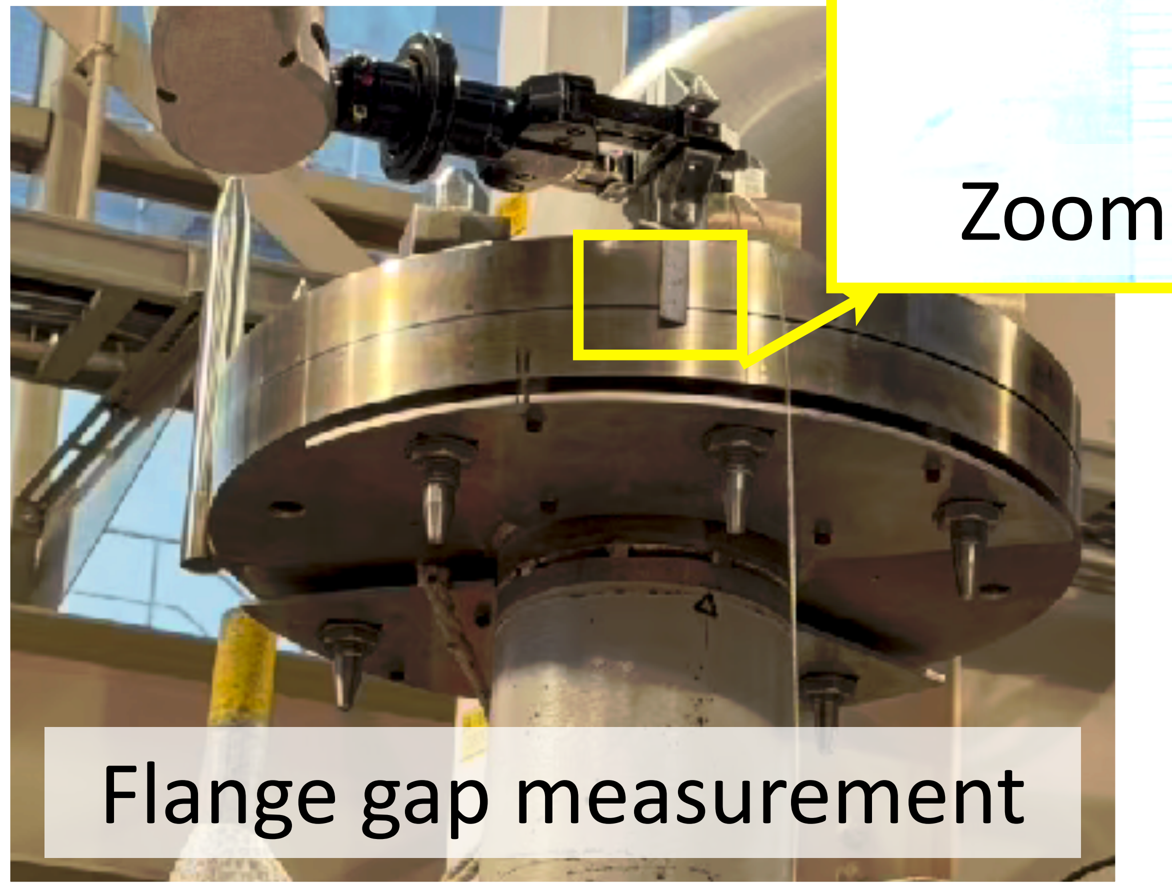
T: Tightening torque
k: Torque coefficient (0.1~0.2)
d: bolt diameter

- Leak was reproduced (5E-8 Pam³/s in vacuum helium leak test) traced scenario at pump replacement bolts tightened 60 Nm (1) → loose 1 rotation → 60 Nm (1,4,6,3,5,2)→ 120 Nm(1,4,6,3,5,2) → 200 Nm (1,4,6,3,5,2)
- No leak occurred (<10E-11 Pam³/s) when the bolts were tightened evenly, as an ideal hands tightening procedure

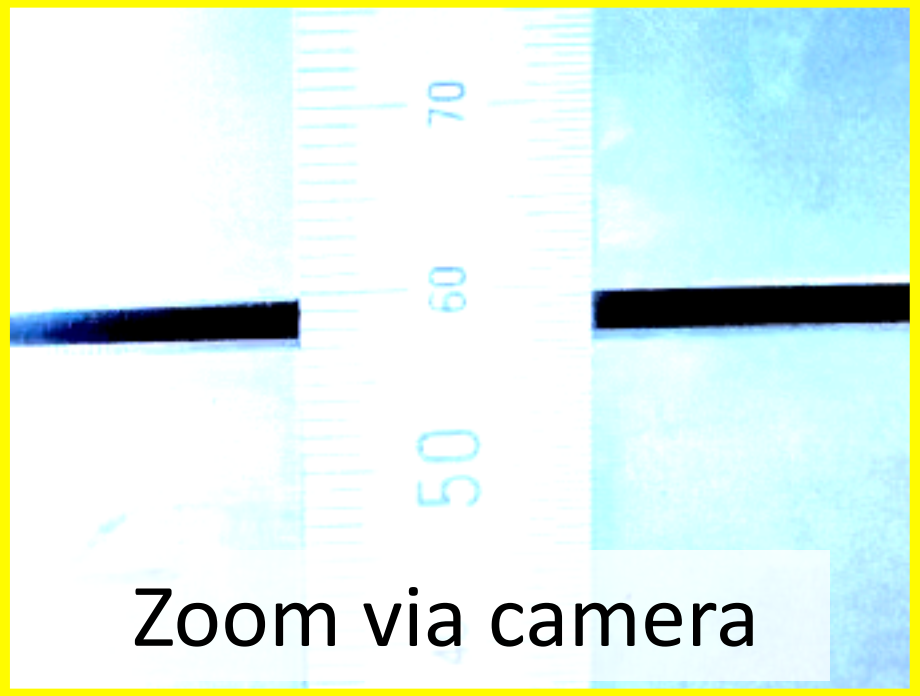
Optimization of procedure for remote handling



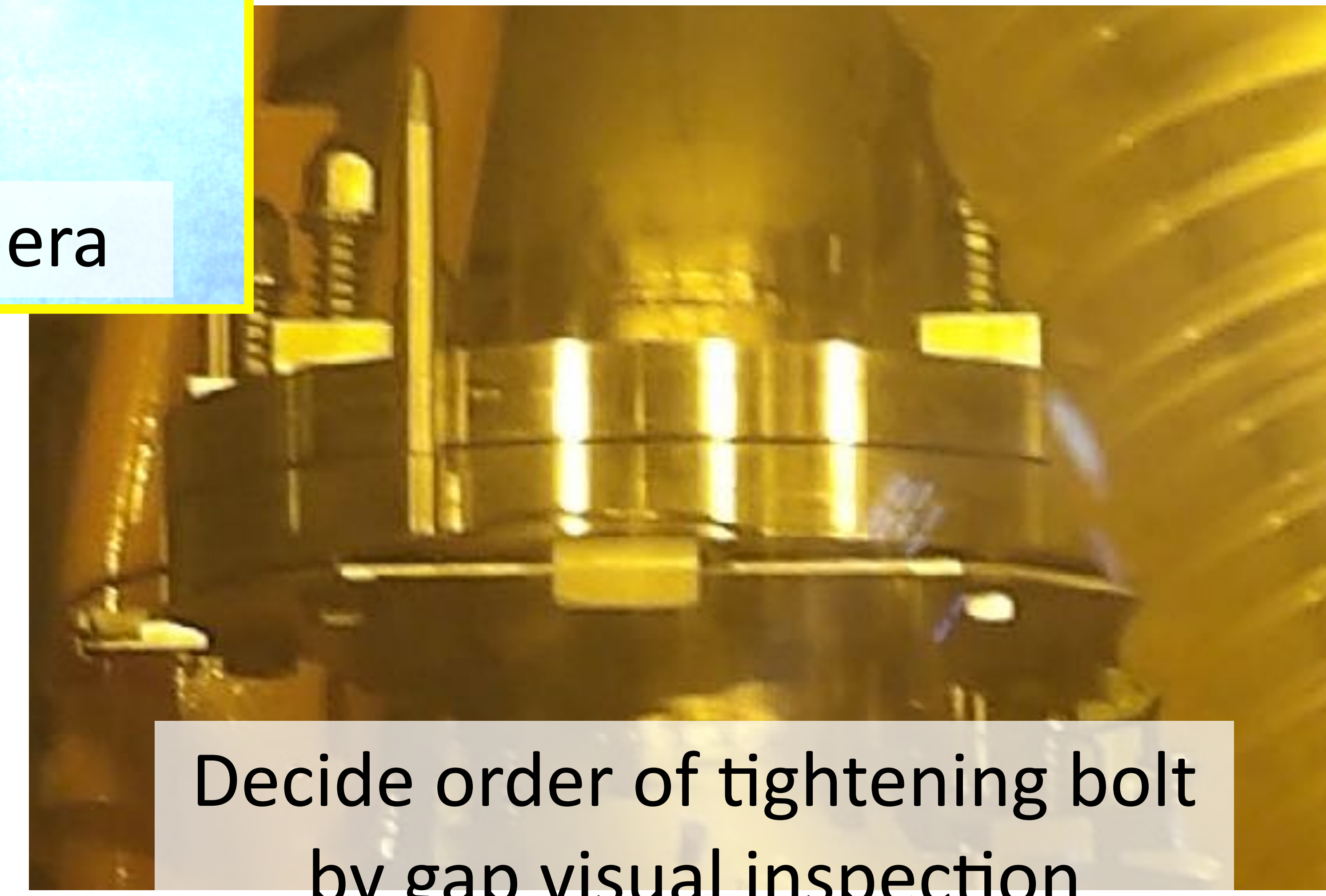
Jumper pipe setup by crane and manipulator



Flange gap measurement



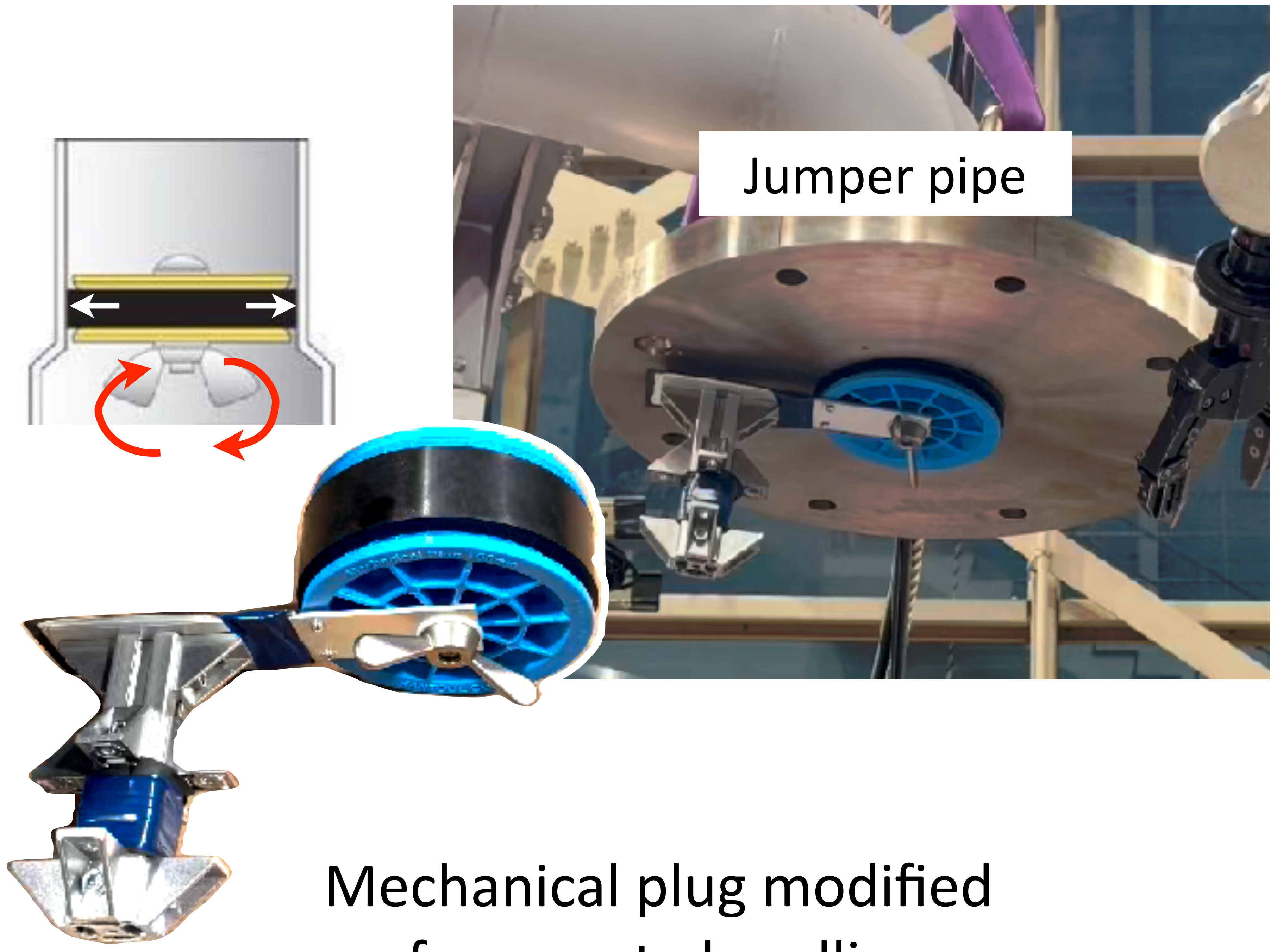
Zoom via camera



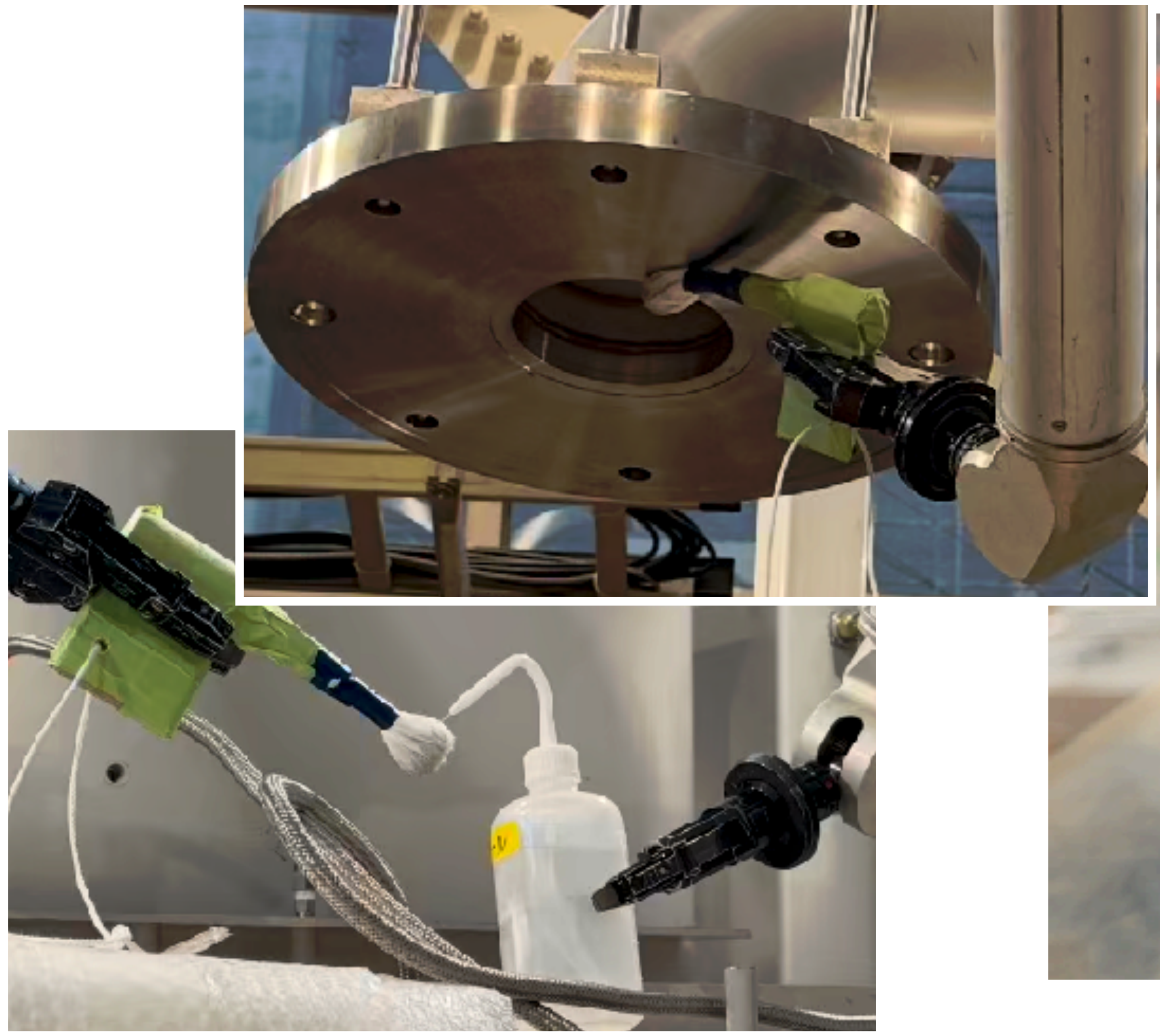
Decide order of tightening bolt by gap visual inspection

- We learned that the ideal fine-torque management (5–10 Nm steps) is effective for securing leak tightness, but it is not feasible for a power manipulator
- To reproduce the even tightening achieved by manual work using the power manipulator, we conducted 10 flange mock-up tests and 6 jumper-pipe mock-up tests, varying the bolt-tightening procedures to confirm reproducibility
- Based on these results, we decided to focus on achieving even flange gap, rather than managing tightening torque
- The final procedure is: Initial tightening at 20 Nm (sequence: 1, 2, 3, 6, 5, 4), Adjust as needed to achieve an even flange gap at 40–120 Nm, Apply final star-pattern tightening at 160 Nm and 200 Nm

Seal replacement training



Mechanical plug modified for remote handling



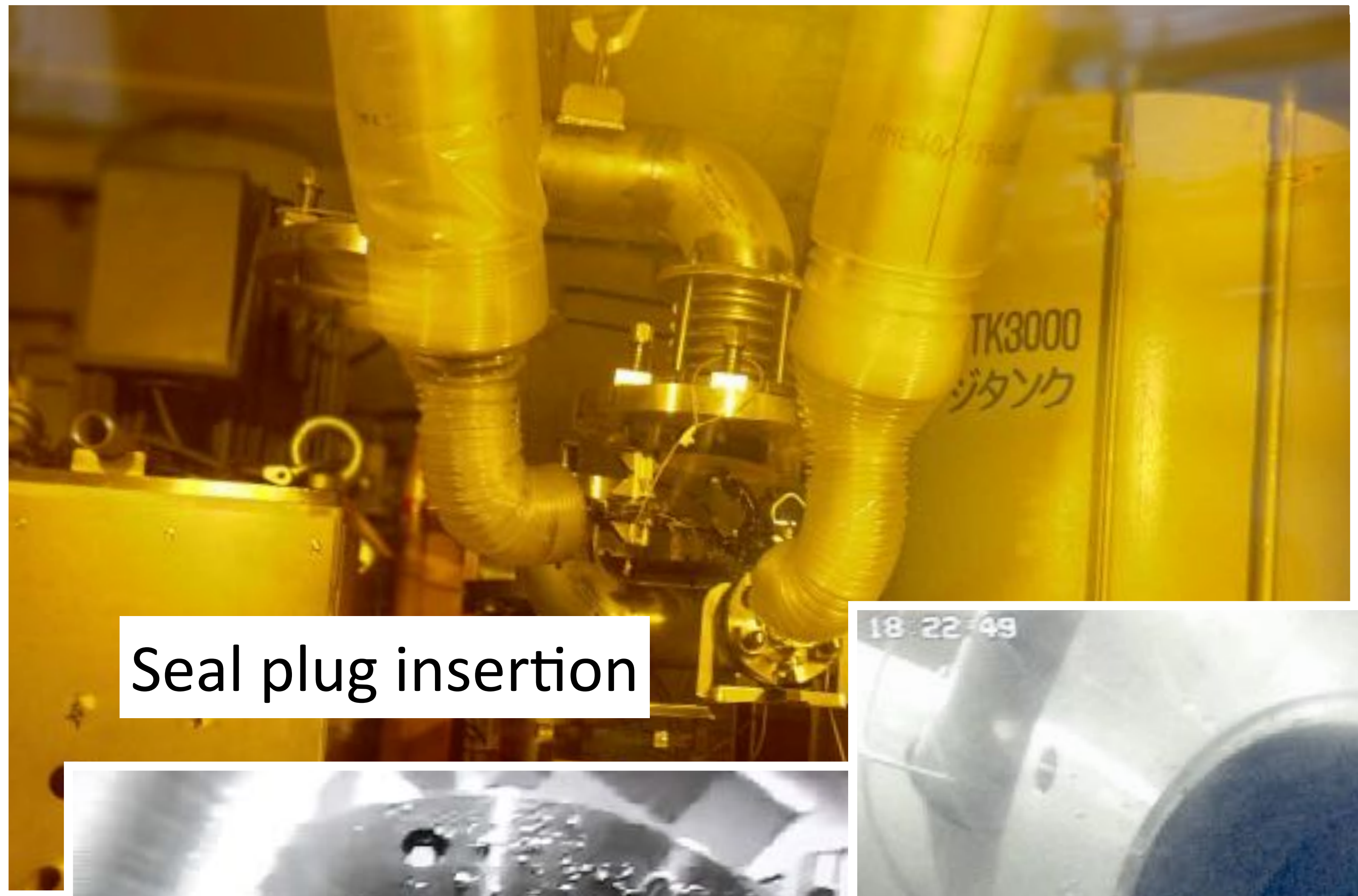
Flange cleaning by manipulator

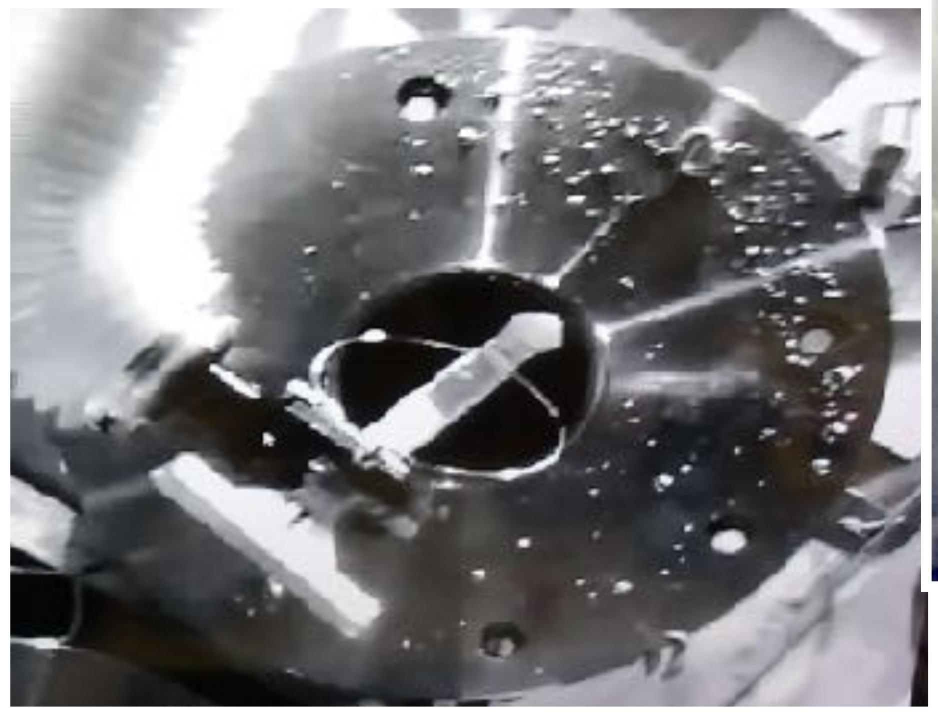
Metal seal replacement

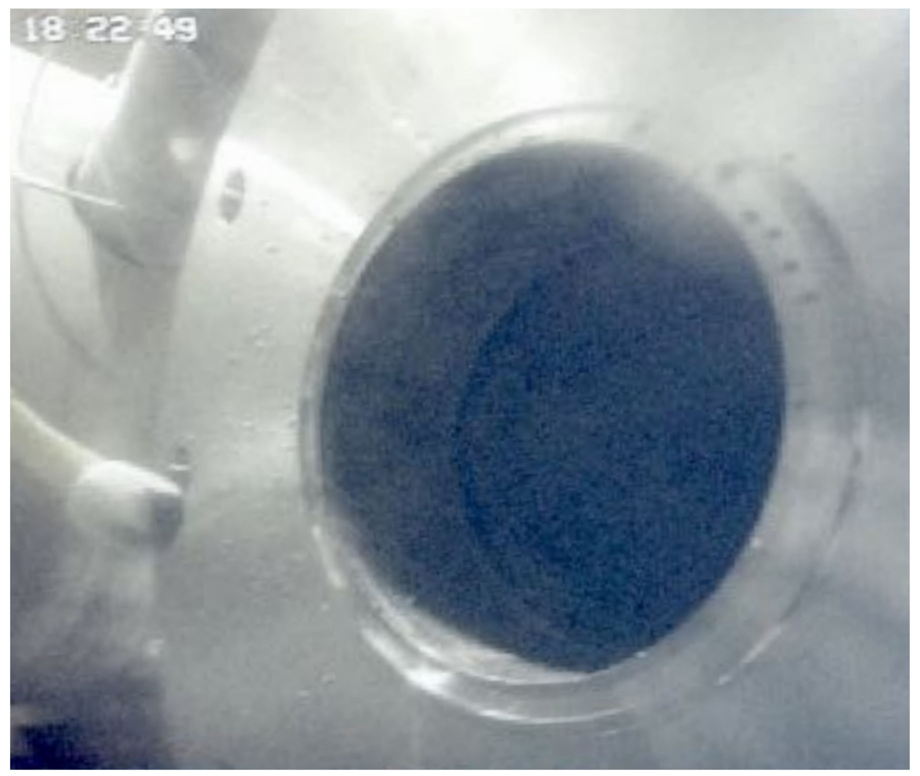
Improvements Based on Pump Replacement Experience

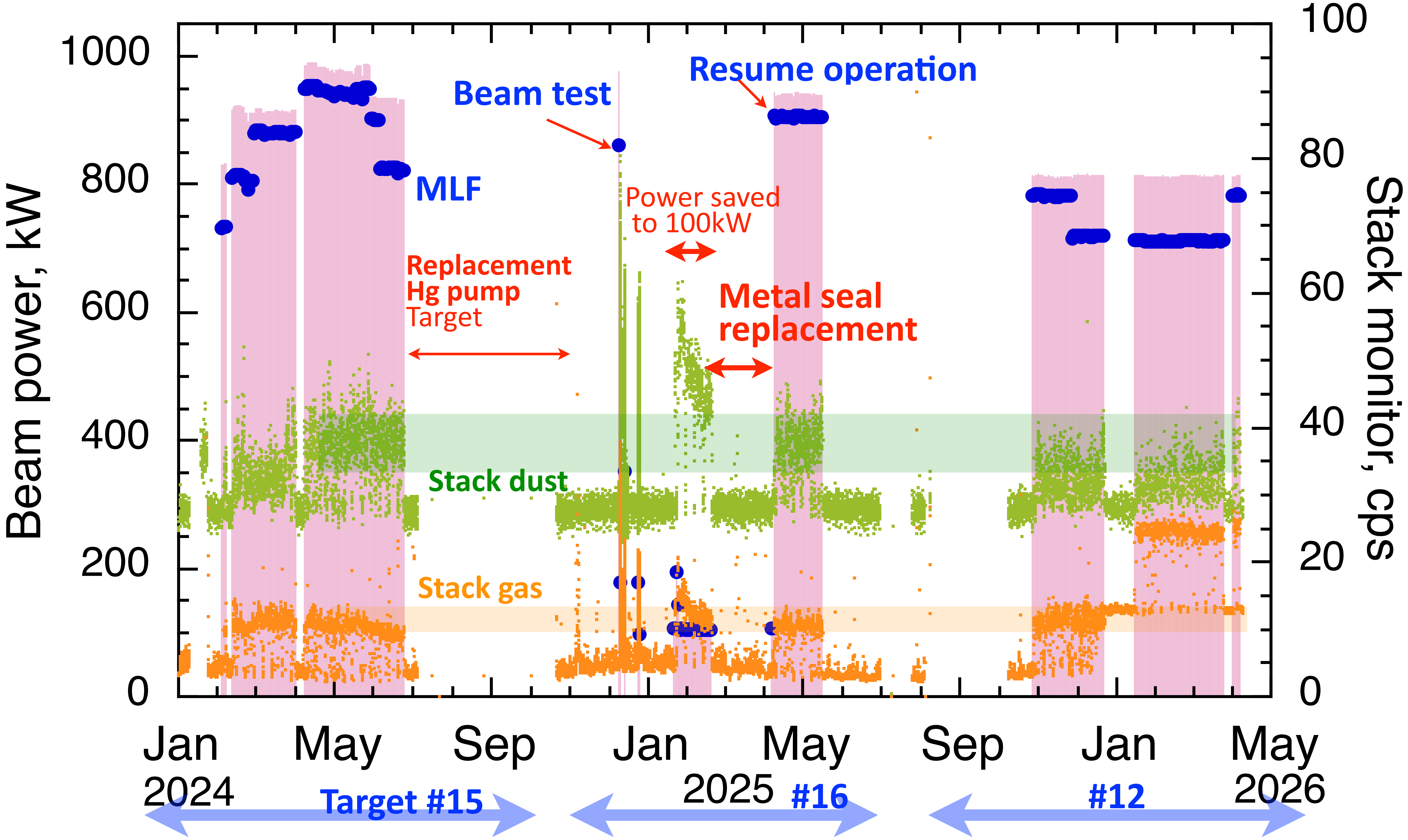
- Based on experience during the pump replacement, we changed seal plug for the jumper pipe
- Due to a risk of damaging the sealing surface of flange, we skipped flange cleaning process in pump replacement, but for seal replacement, we decided to add a flange cleaning process for the seal replacement
- We conducted training for the newly added tools and cleaning procedure

Beam operation after seal replacement


Seal plug insertion

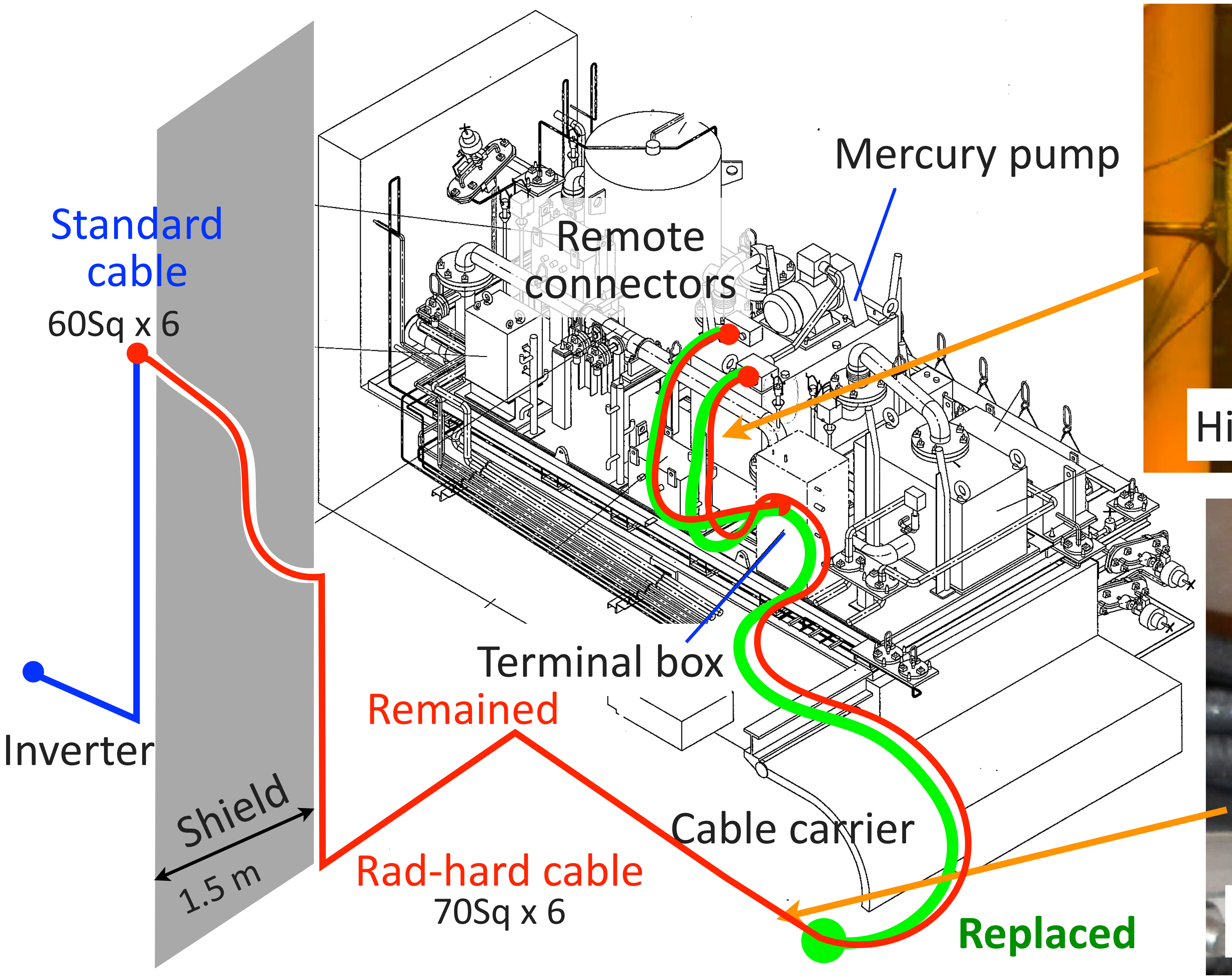

Seal replacement

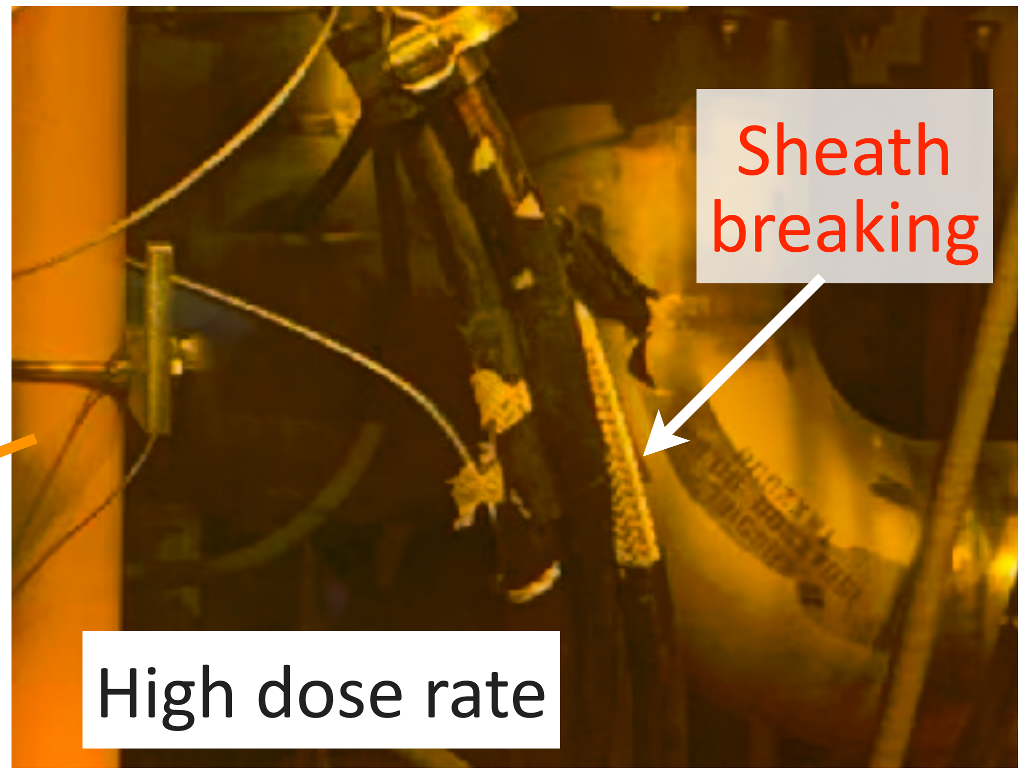

Flange cleaning

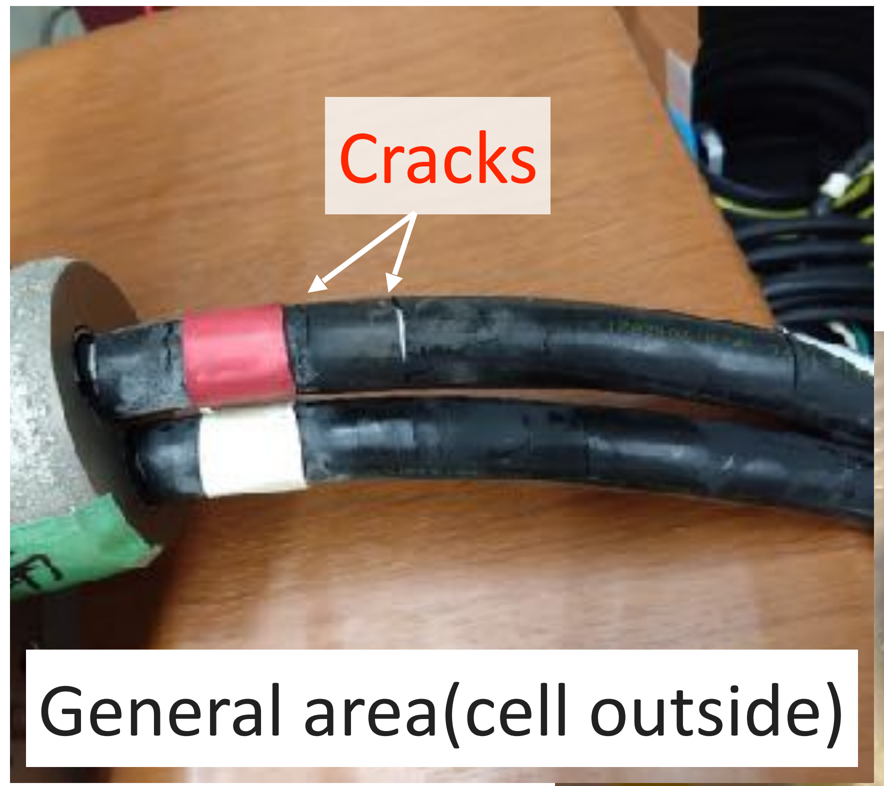


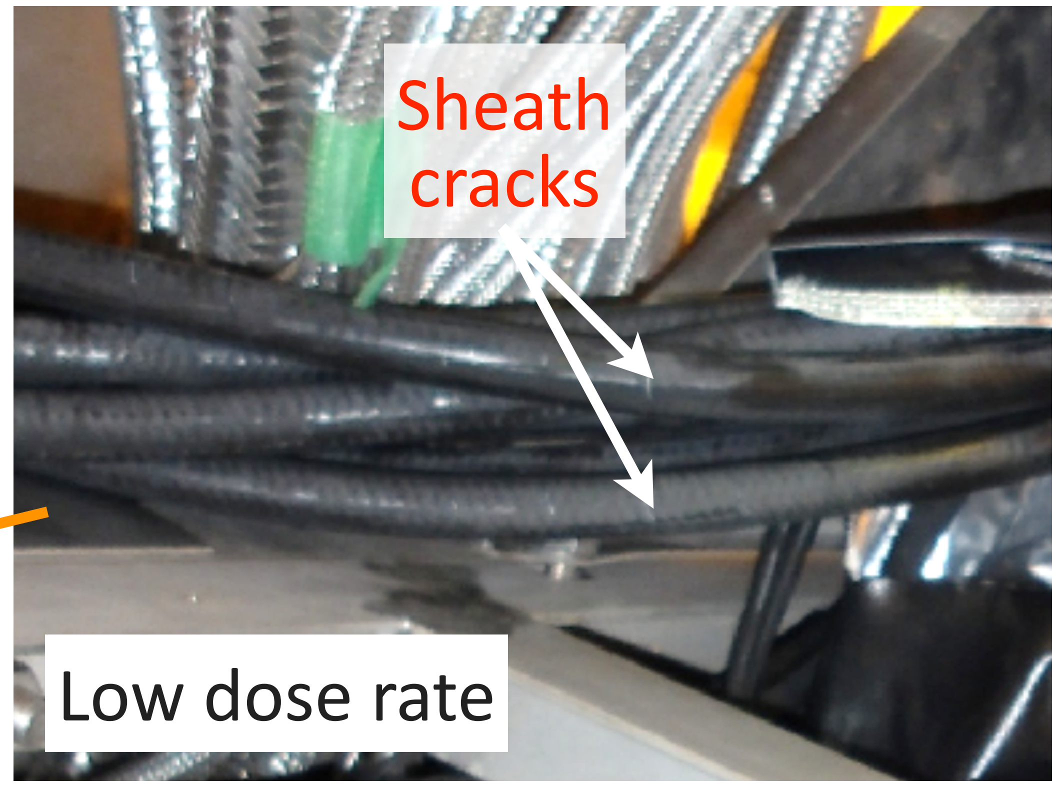
- Helium leak test showed below detectable limit for all flanges after seal replacement
- Stuck monitors are recovered usual value in beam operation

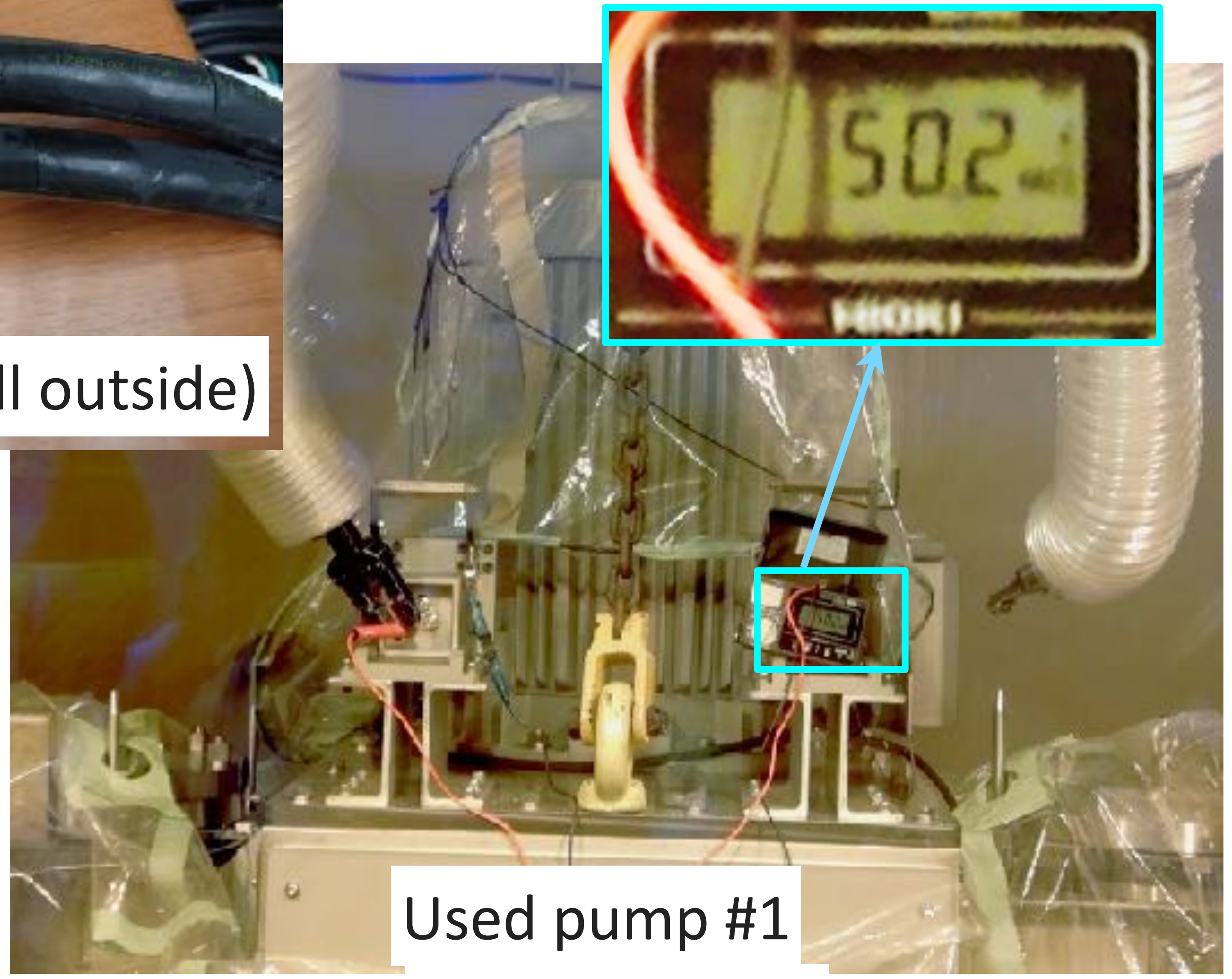
Pump power cables replacement











			Total resistance
Jul. 2024	Before pump replacement	Cable+Connector+Pump#1(50 MΩ)	0.8 MΩ
Nov. 2024	After pump replacement	Cable+Connector+Pump#2	3.8 MΩ
Jul. 2025	After 1 year operation	Cable+Connector (0.72 MΩ)+Pump#2 (75 MΩ)	0.27 MΩ
Nov. 2025	After cable replacement	Cable+Connector (7.4 MΩ)+Pump#2 (75 MΩ)	2.7 MΩ

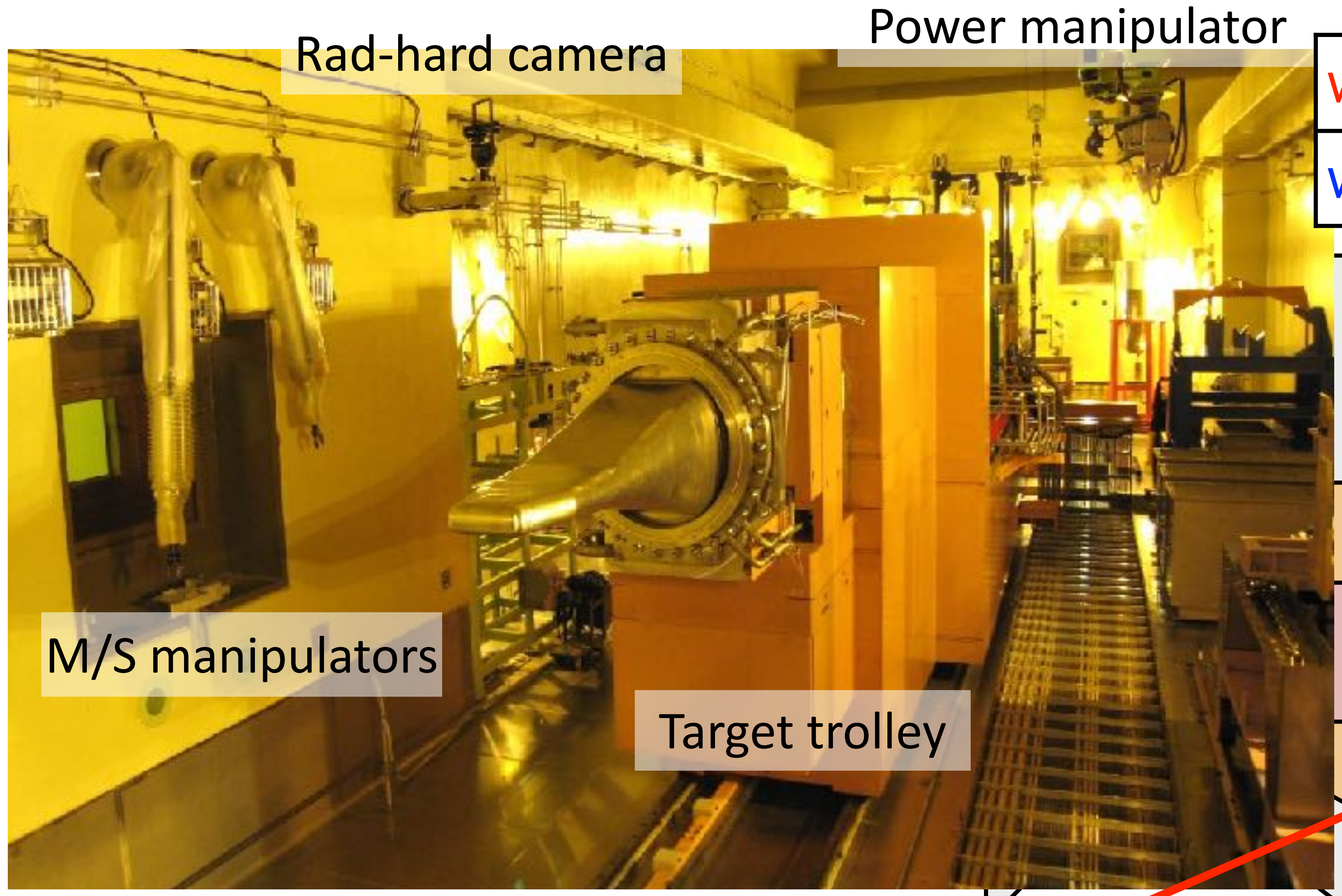
- Rad-hard (5MGy) cable was damaged not only high dose area but also low dose area in 15 years
- Reduction of insulation resistance since cables stored in general area was also damaged

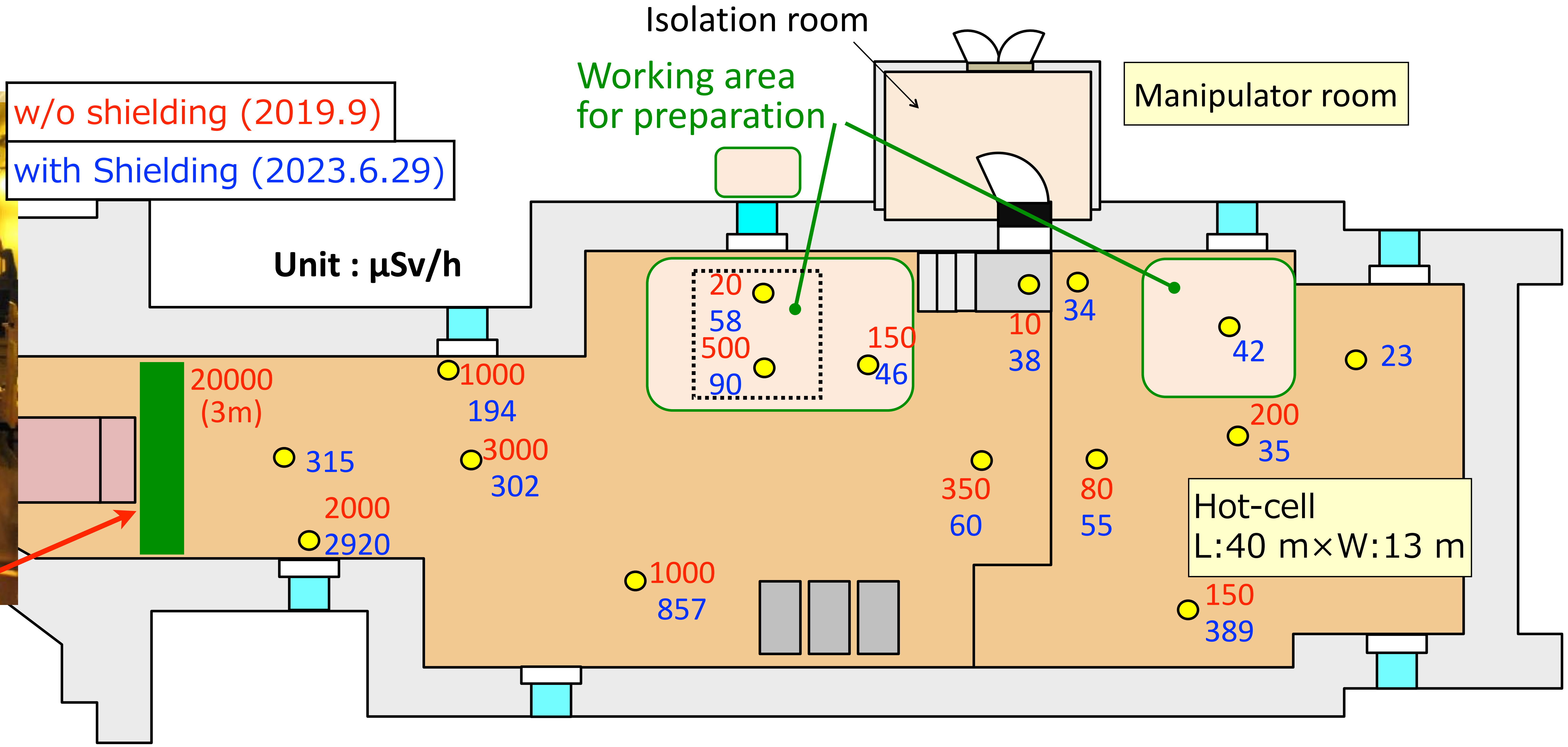
- Full rad-hard cables and connectors replacement are planned in Oct. 2026

Summary

- Degradation of insulation resistance for mercury pump was observed after 15 years of operation
- Mercury pump was replaced in Nov. 2024; however, small leak was detected during operation
- To recover from the leak, flange metal seals were replaced using an improved bolt-tightening procedure based on the mock-up tests
- The pump power cables, which had degraded due to radiation and/or aging, were temporarily replaced; installation of radiation-hard cables is planned for Sep. 2026

Working area and environment



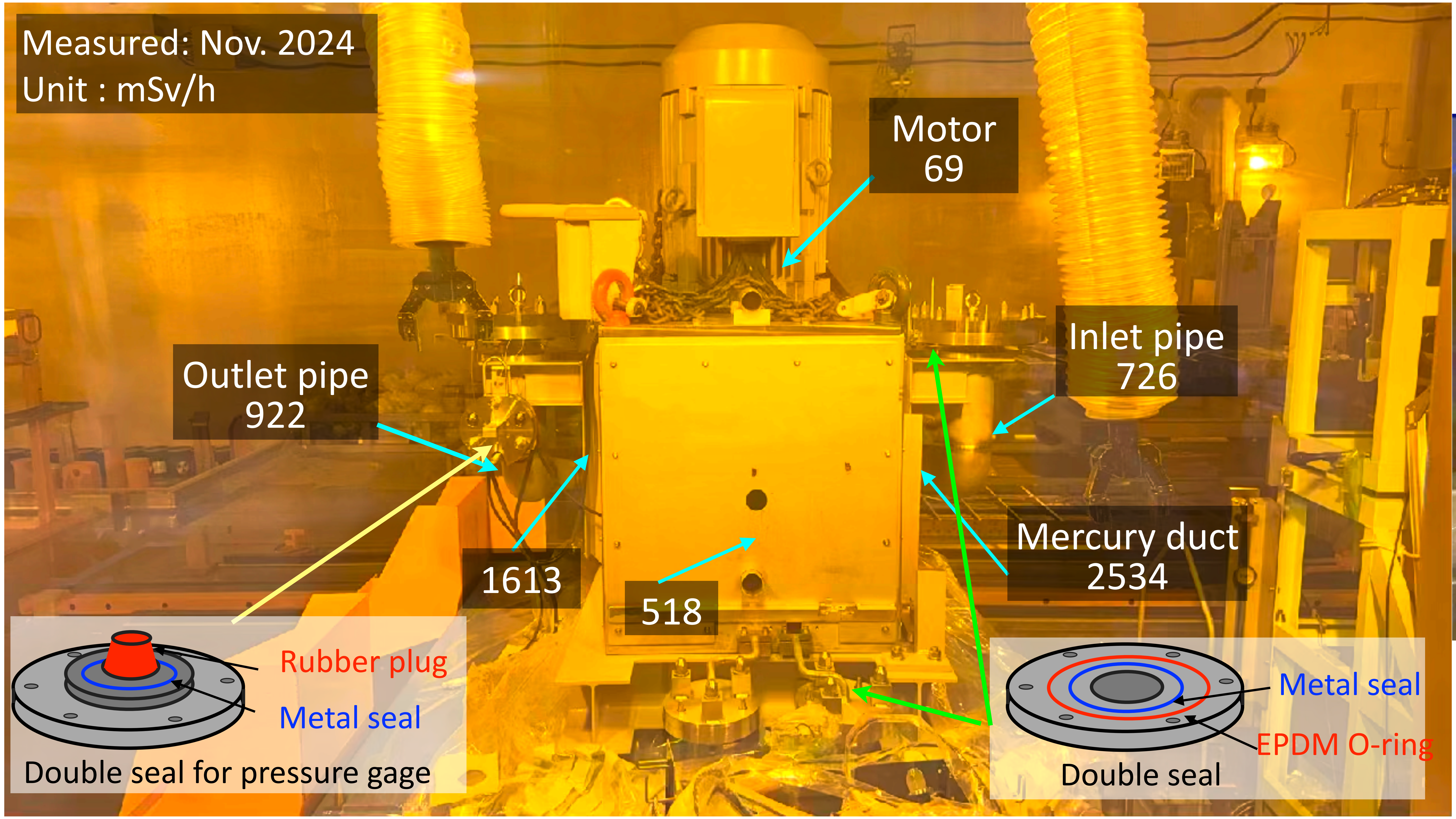


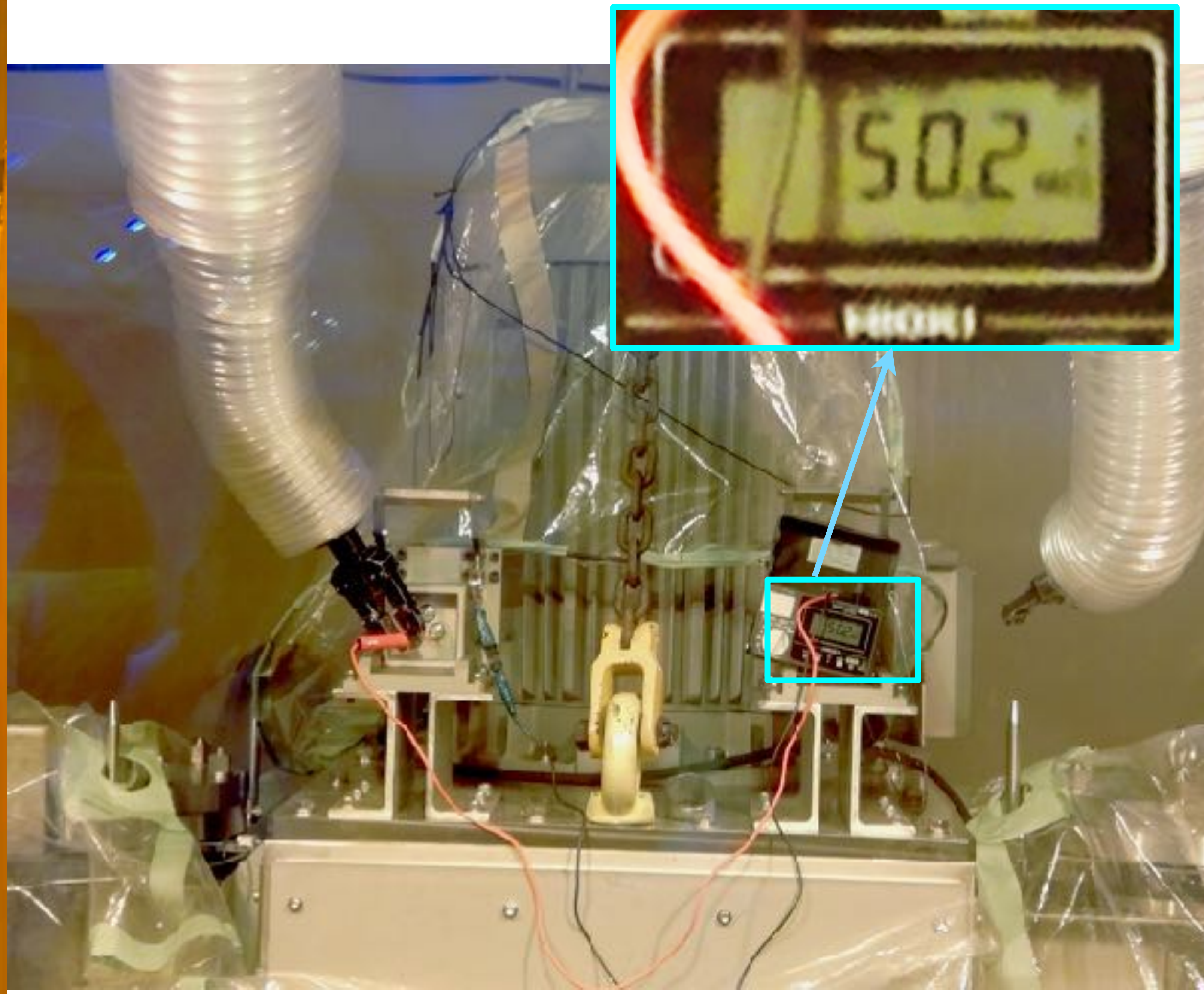
Remote measurement

Additional shielding

- Dose rate map can be measured remotely using crane and ion chamber dosimeter
- Replacement work is performed by full-remote handling, but equipment preparation and cleanup work are done by entering hot-cell with placing additional shielding
- Air contamination is not detected without opening mercury flange
- Tyveck with full-face mask requires for the worker

Storage and disposal for used pump issues



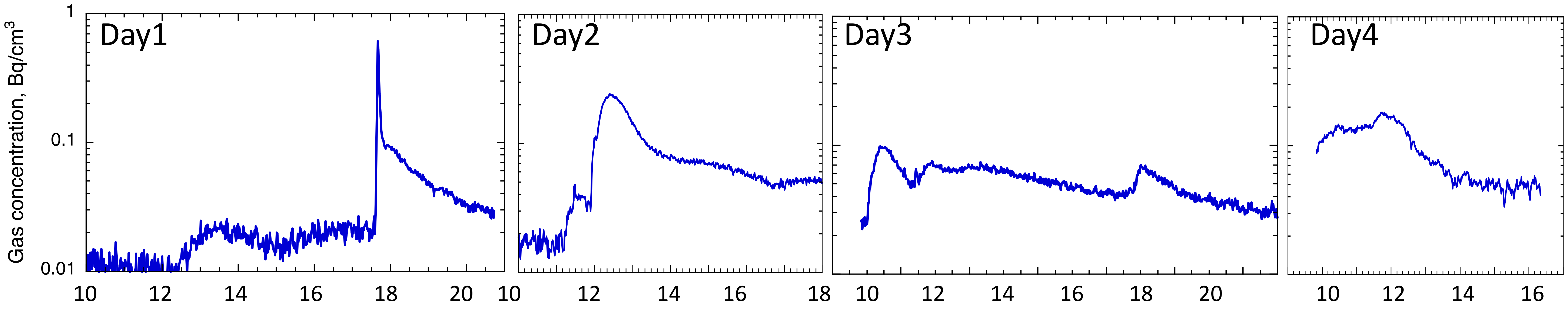


Insulation resistance measurement by manipulator

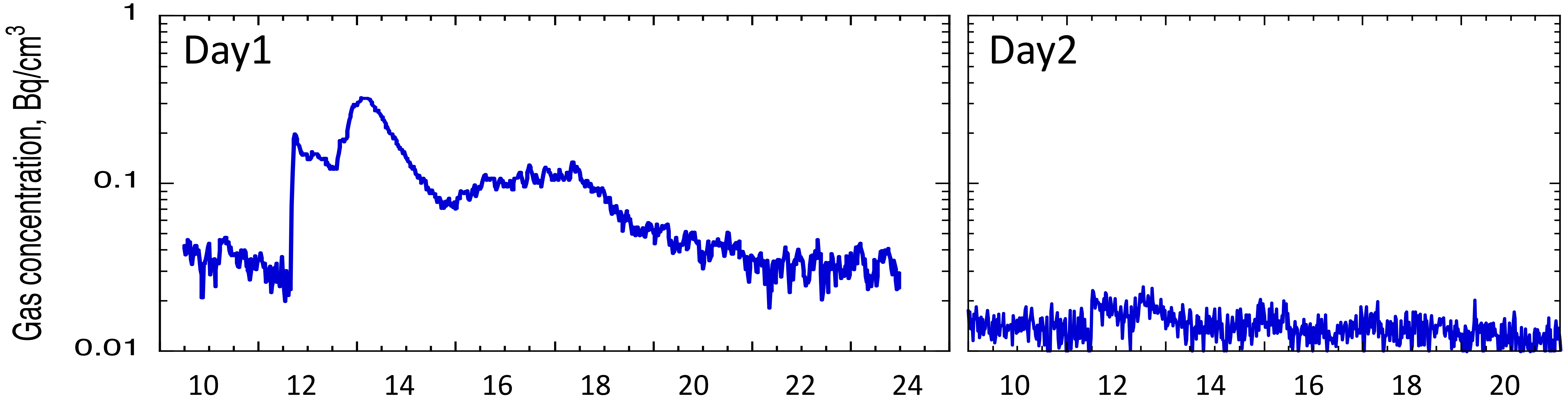
- Opening flanges were closed by blank flange with double seal, and temporary stored in the storage room
- Using remote measurement tool developed after replacement, we confirmed that the pump has sufficient insulation resistance for use
- Due to the size of hatch to the storage room, pump can not stored in the cask and keep as a spare

Tritium release during replacement

Pump replacement



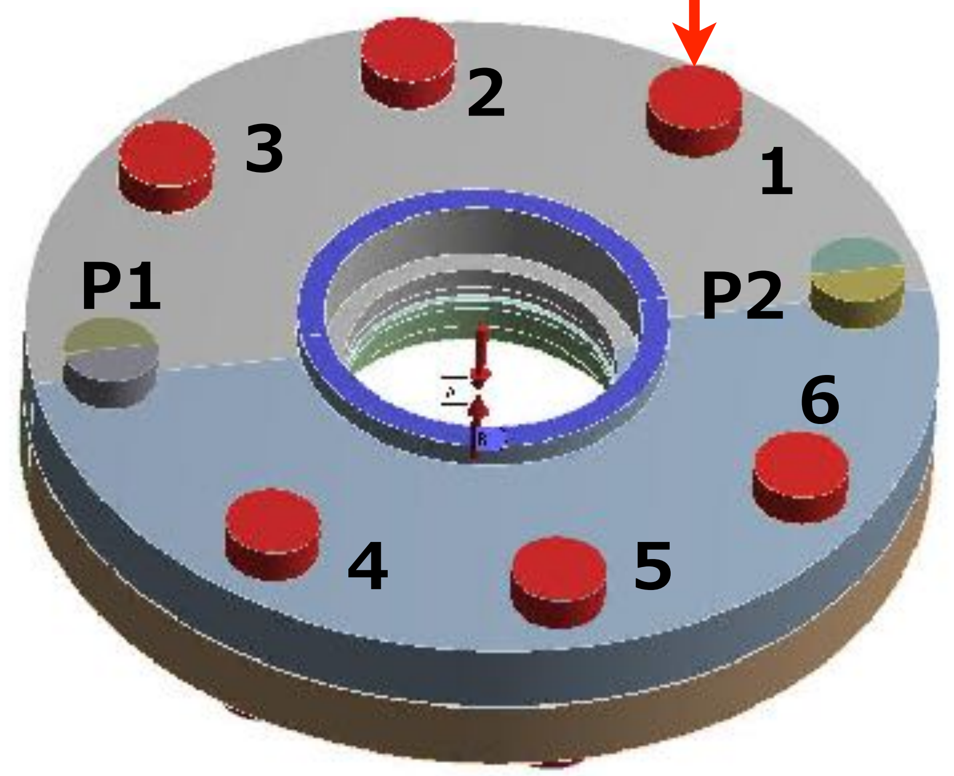
Seal replacement



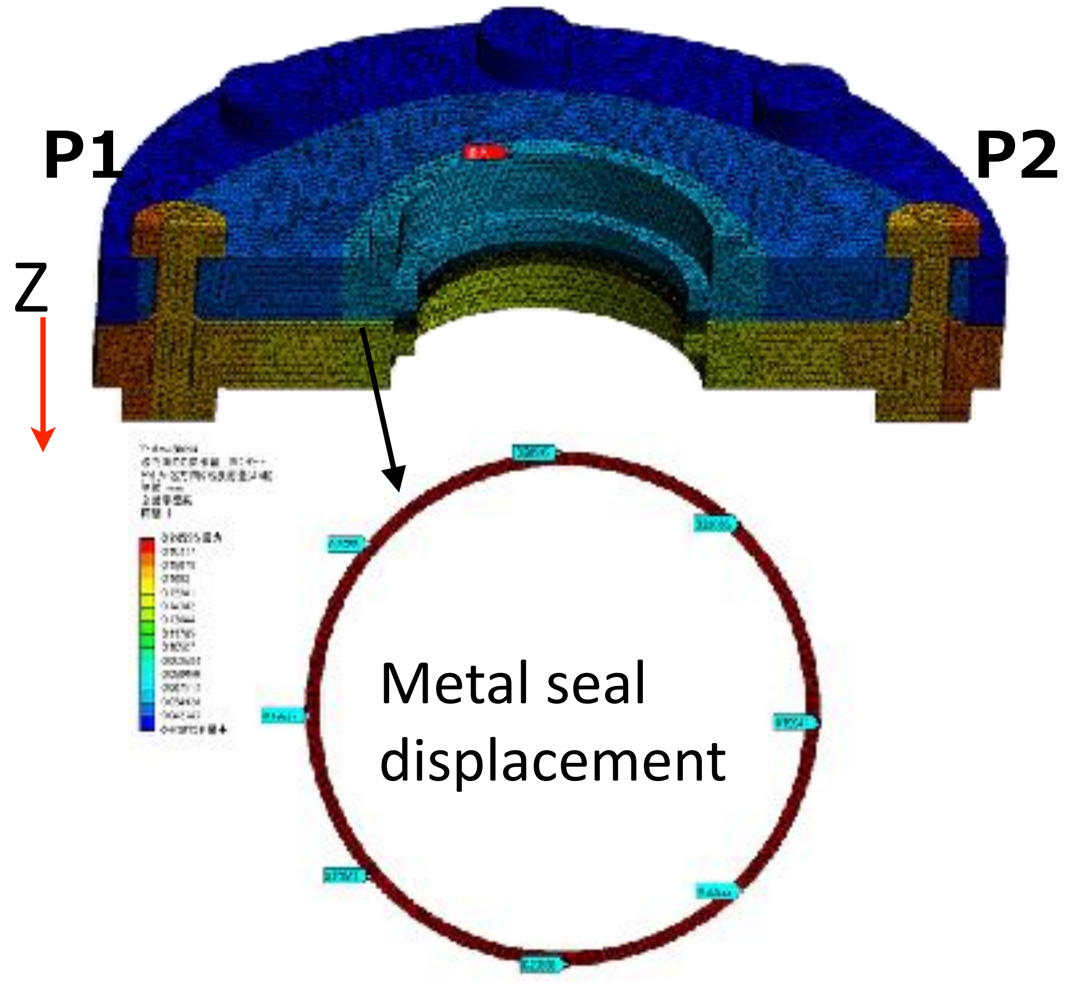
	[GBq]	Total	Day1	Day2	Day3
Pump replacement	Ion chamber	268	32	139	97
	Silica gel	160	18	68	74
Seal replacement	Ion chamber	6	6.0	ND	
	Silica gel	7.4	5.2	2.2	

The main reason why the value of the stack ionization box is higher than that of cell silica when replacing the pump is
This is because the count of rare gas element nuclei is also evaluated as tritium.

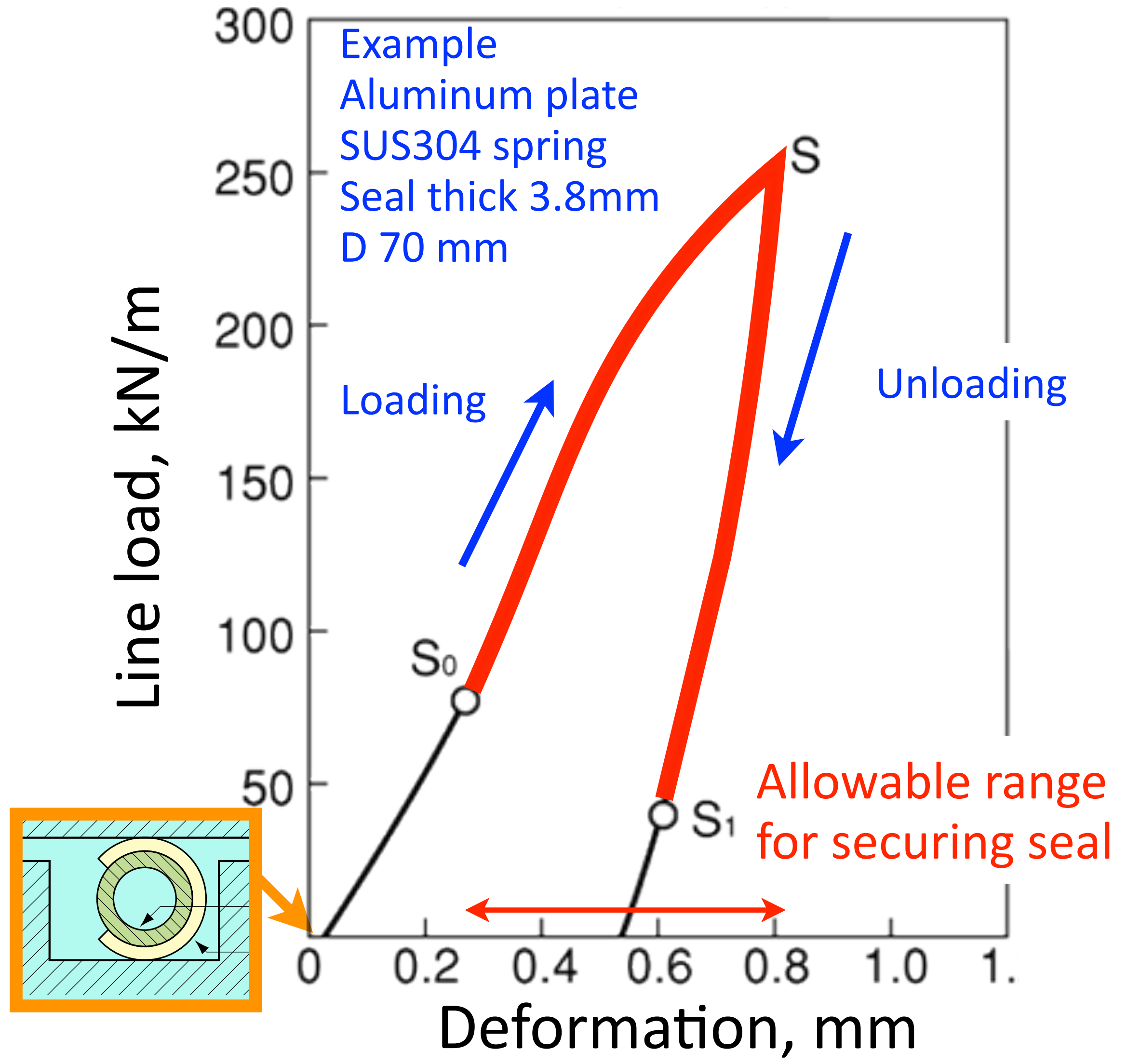
Numerical simulation for metal seal deformation



Pre tension applied to the flange through the bolts



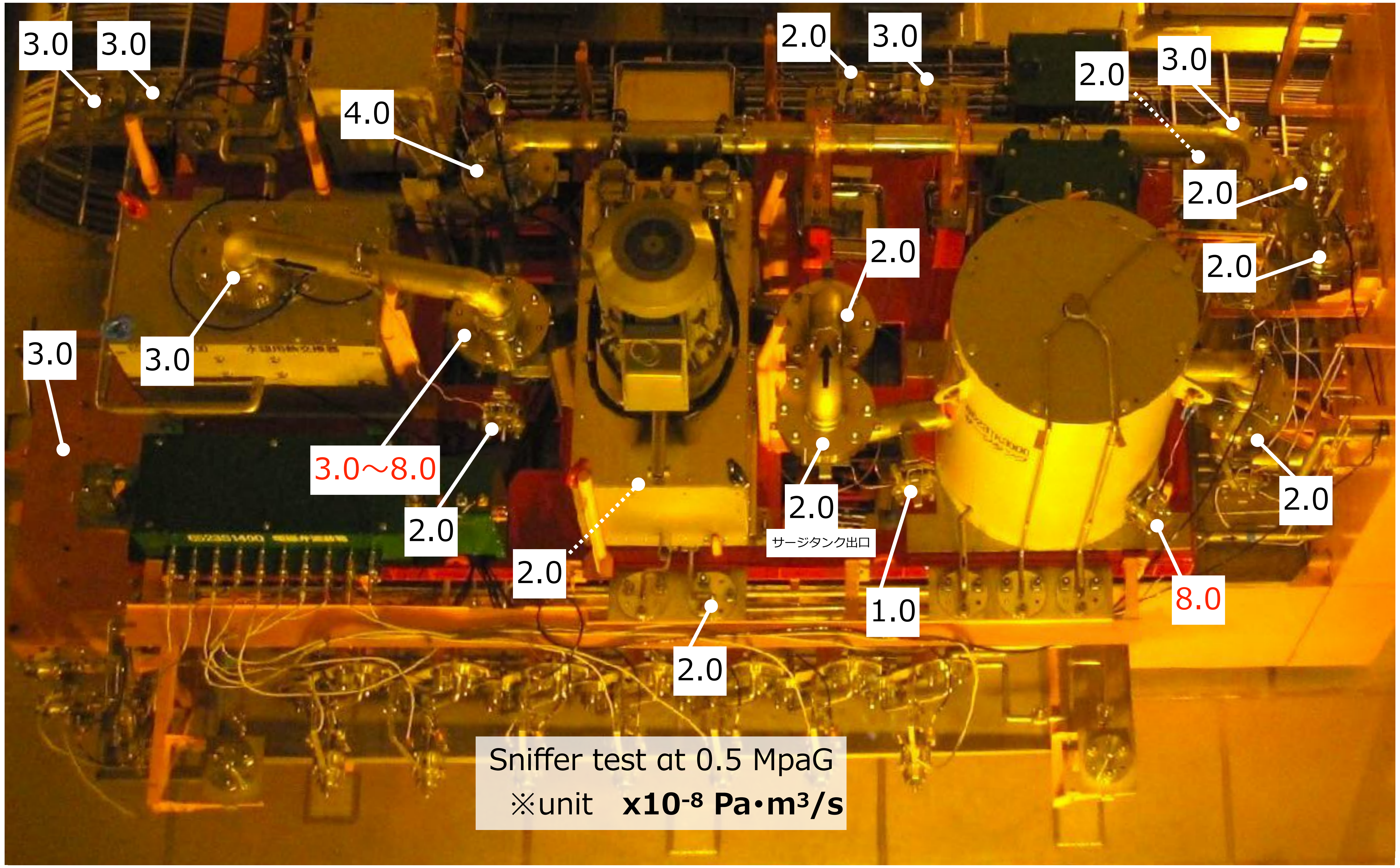
Displacement contour of Z direction

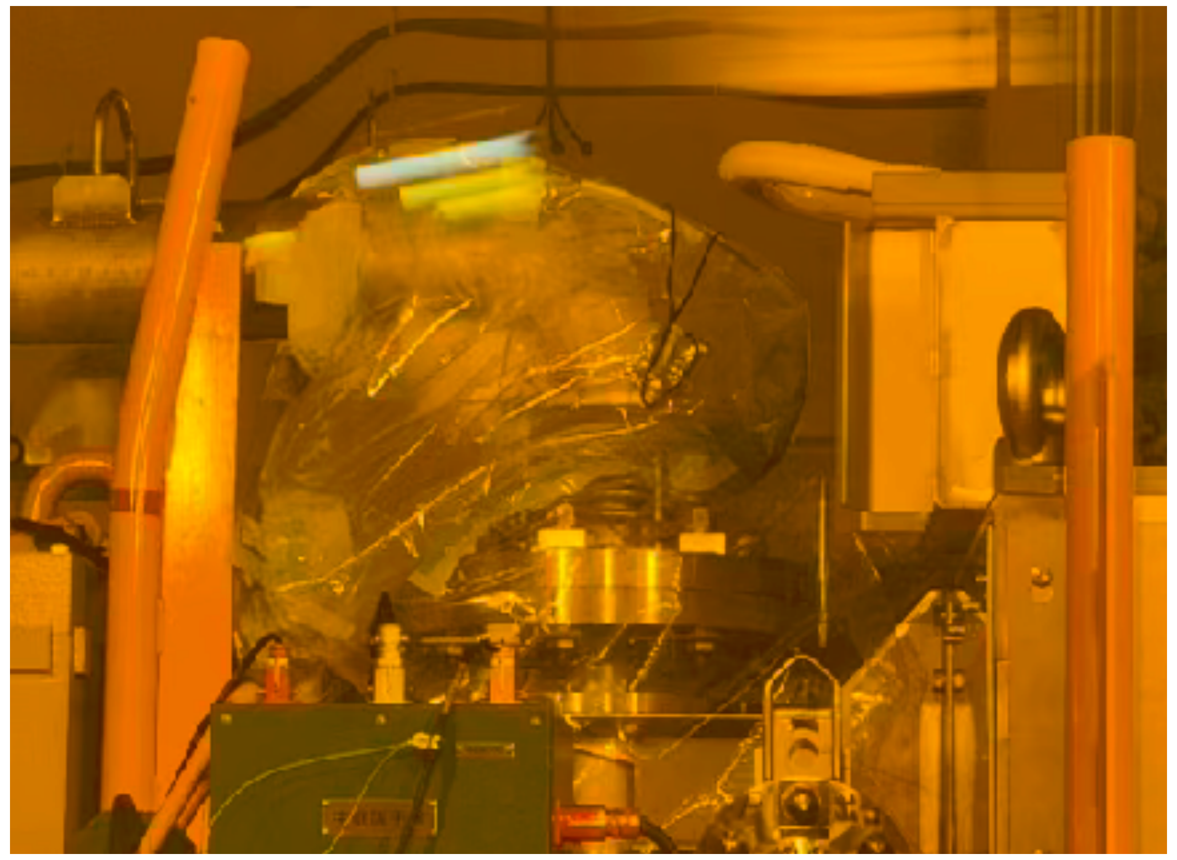


	Torque	Normalized seal deformation (Value / Max)							
Bolts	Nm	P1	1	2	3	P2	4	5	6
6	200	0.97	0.98	1.00	0.98	0.97	0.98	1.00	0.98
8	200	1.00	1.00	1.00	1.00	1.00	1.00	0.99	0.99

- From FEM simulation, current bolt number and layout is enough to deform the metal seal uniformly
- Difference between 6 bolts and 8 bolts are negligible small

Helium leak rate after retightening





Flange cover