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Spallation Materials Technology
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Present status of JSNS mercury target

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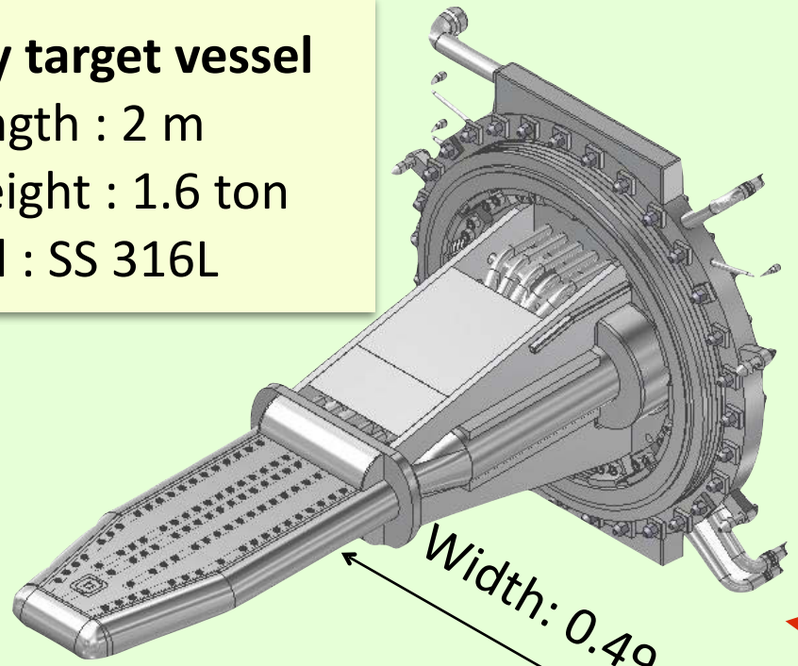
Outline

- Status of JSNS target for the last two years
- Outline of the target troubles in 5th and 7th targets
- Strategy of design and fabrication improvements
- Improved design and inspection of 8th target
- Summary

JSNS 1MW spallation neutron source

Mercury target vessel
Total length : 2 m
Total weight : 1.6 ton
Material : SS 316L



Materials and Life science Facility (MLF)

Cryogenic hydrogen system

Mercury target vessel

Helium vessel

Moderators

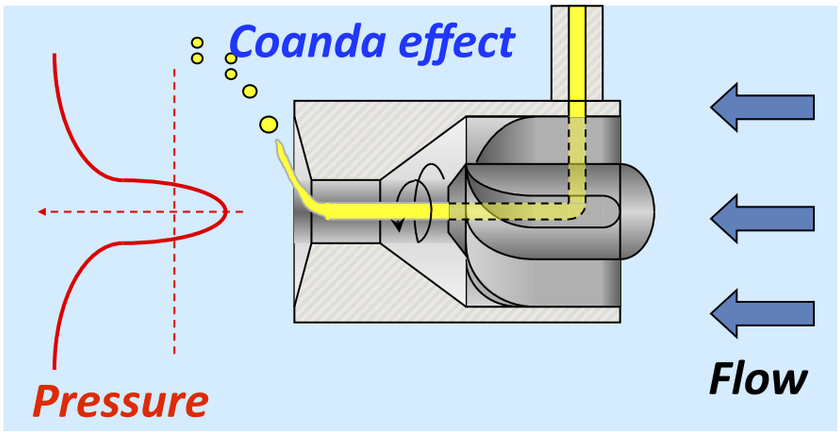
Target trolley

Mercury circulation system

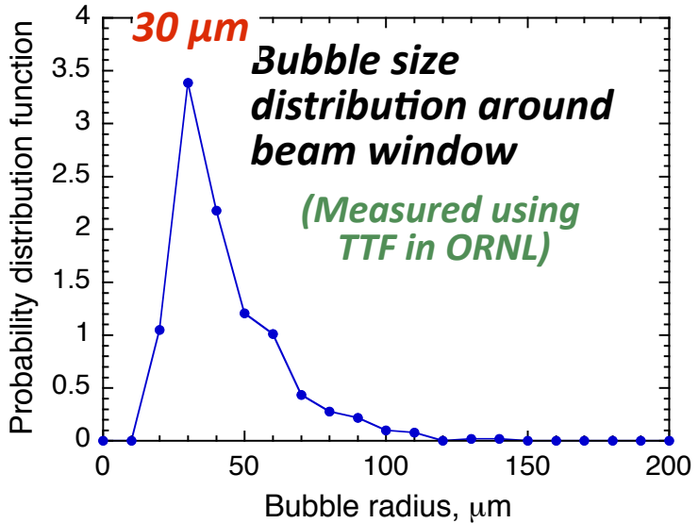
3 GeV 25 Hz
proton beams

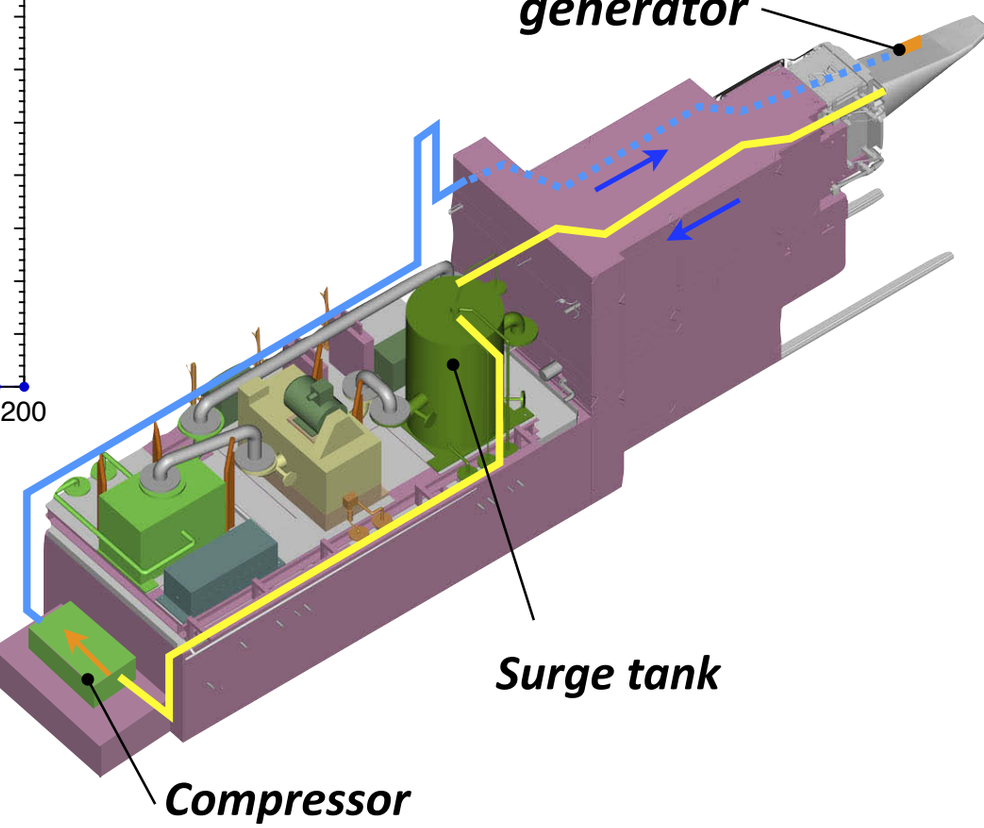
Neutron beam lines (23)

JSNS bubbling system

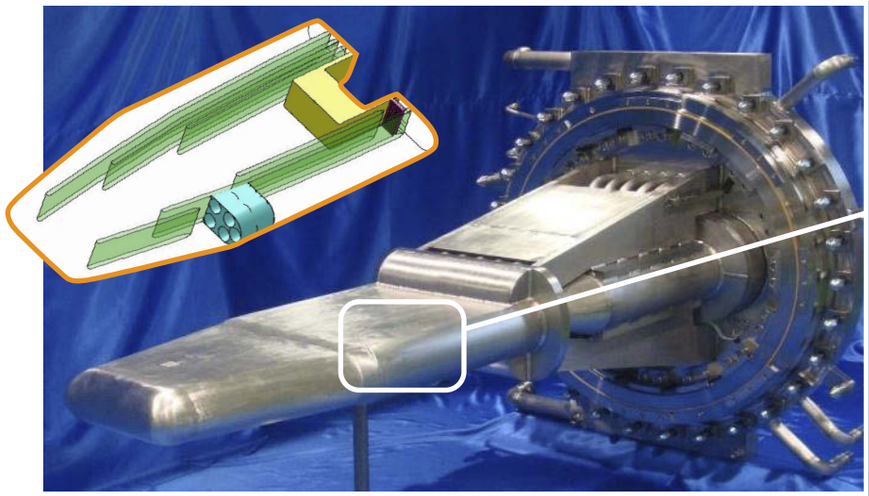


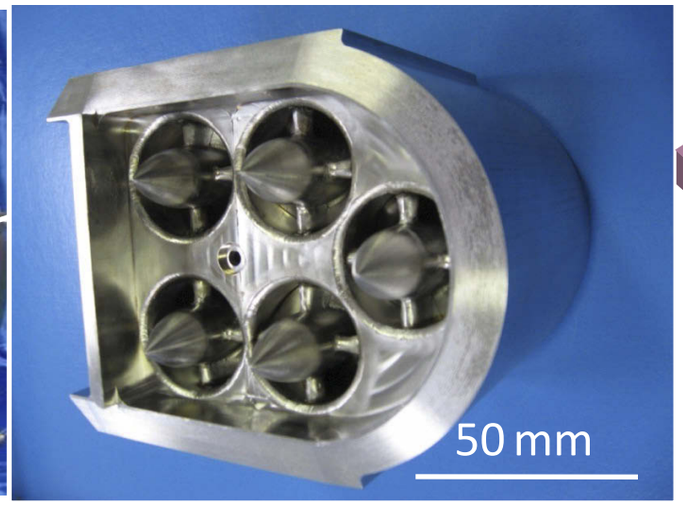
Swirl type bubble generator





JSNS mercury circulation system
(Closed helium gas loop)

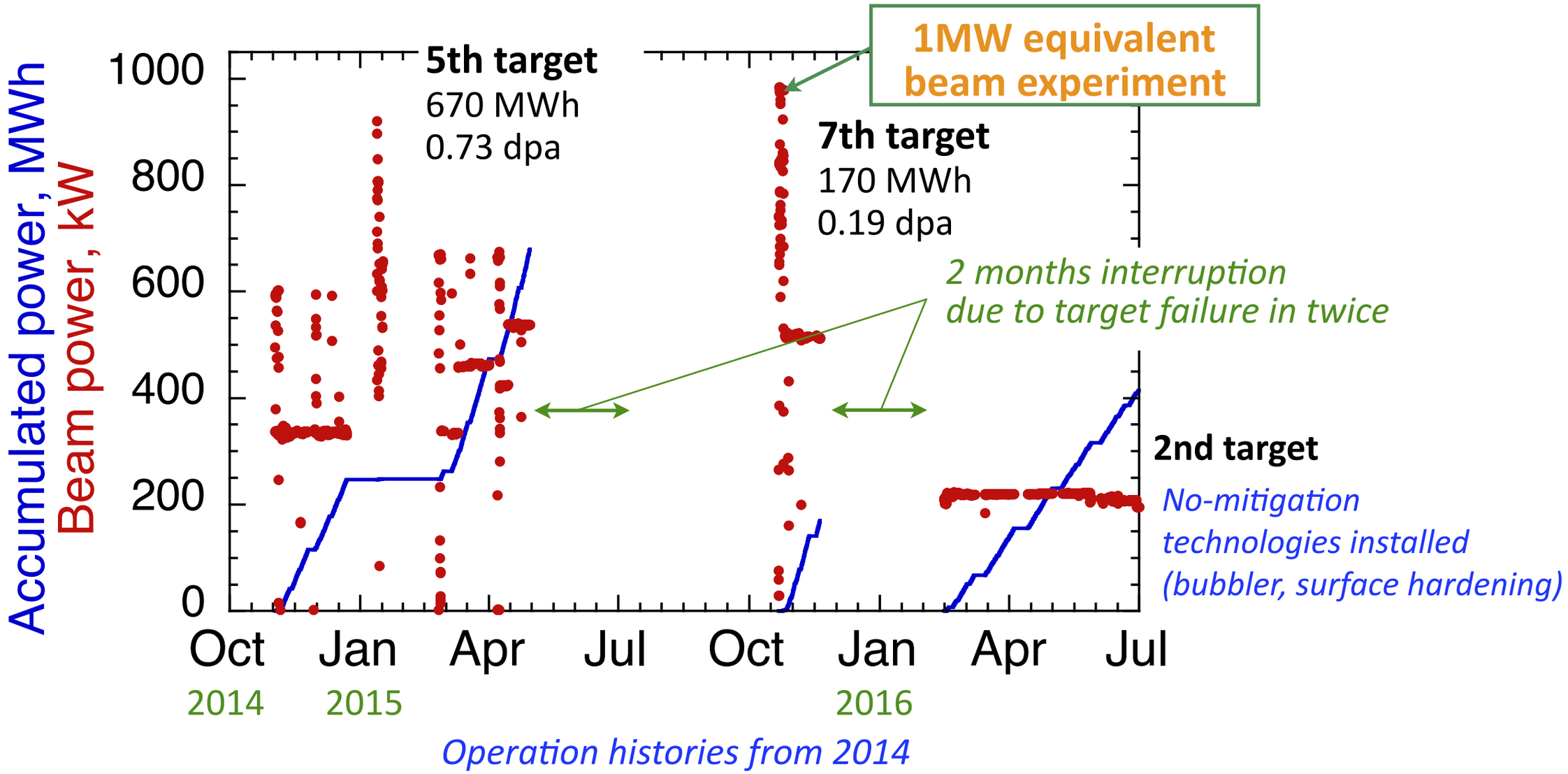




#3 target vessel with bubble generator

- Swirl type microbubble generator was installed from 3rd target vessel with gas circulation system to mitigate proton beam-induced pressure waves
- Peak bubble radius is 30 μm, void fraction (He/Hg flow ratio) is 10^{-2} at bubble generator

Operation status for the last two years

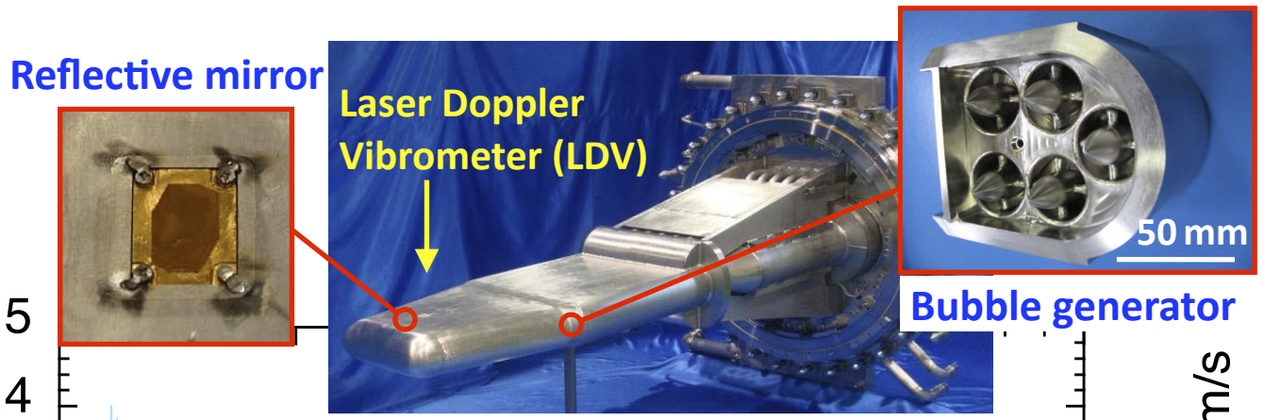


- 5ht target was failed a month after ramping up power to 500 kW
- 7th target (repaired) was failed two weeks after restarting operation at 500 kW

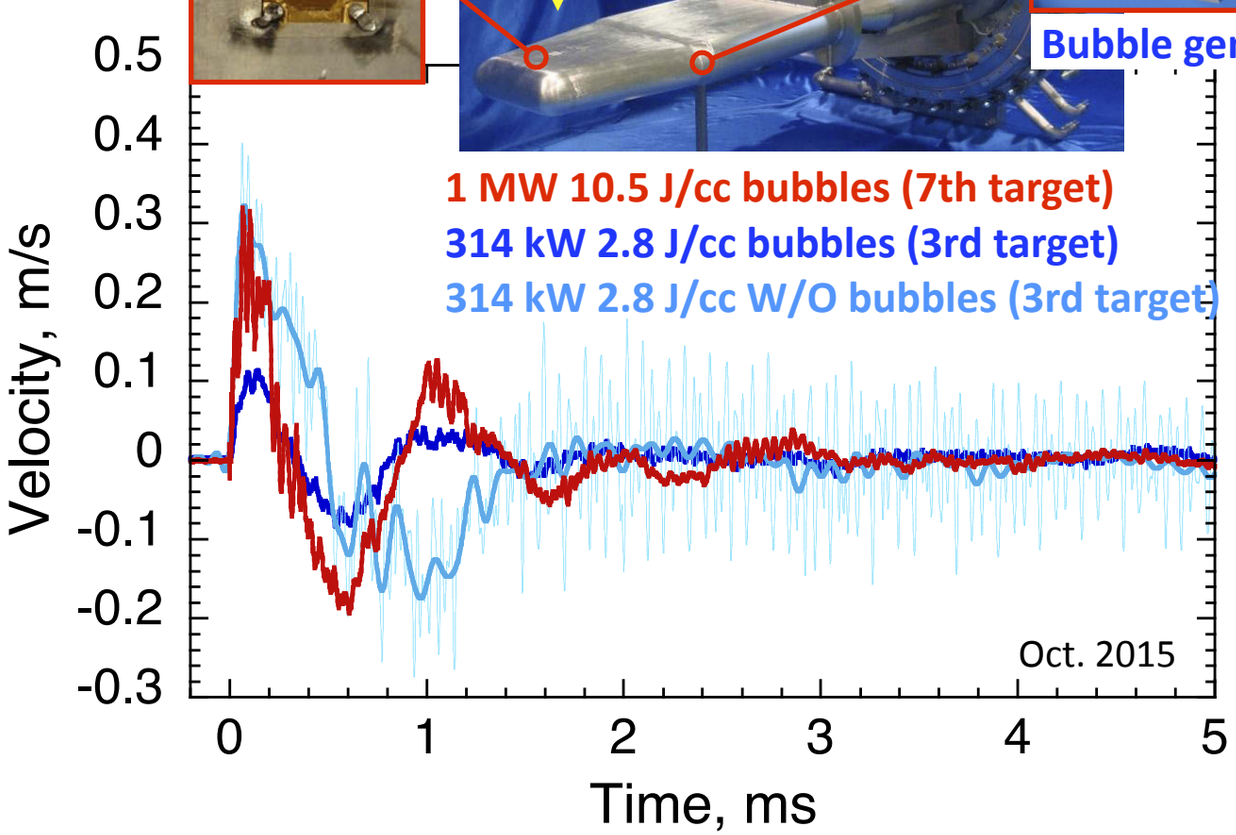
Both targets operation were stopped due to leak of cooling water

- 2nd target should be used till June 2017 (beam power is limited less than 200 kW), because we have no spare target of different structure from the failed targets
- Fabrication of 8th target is now going on and will delivery at next June

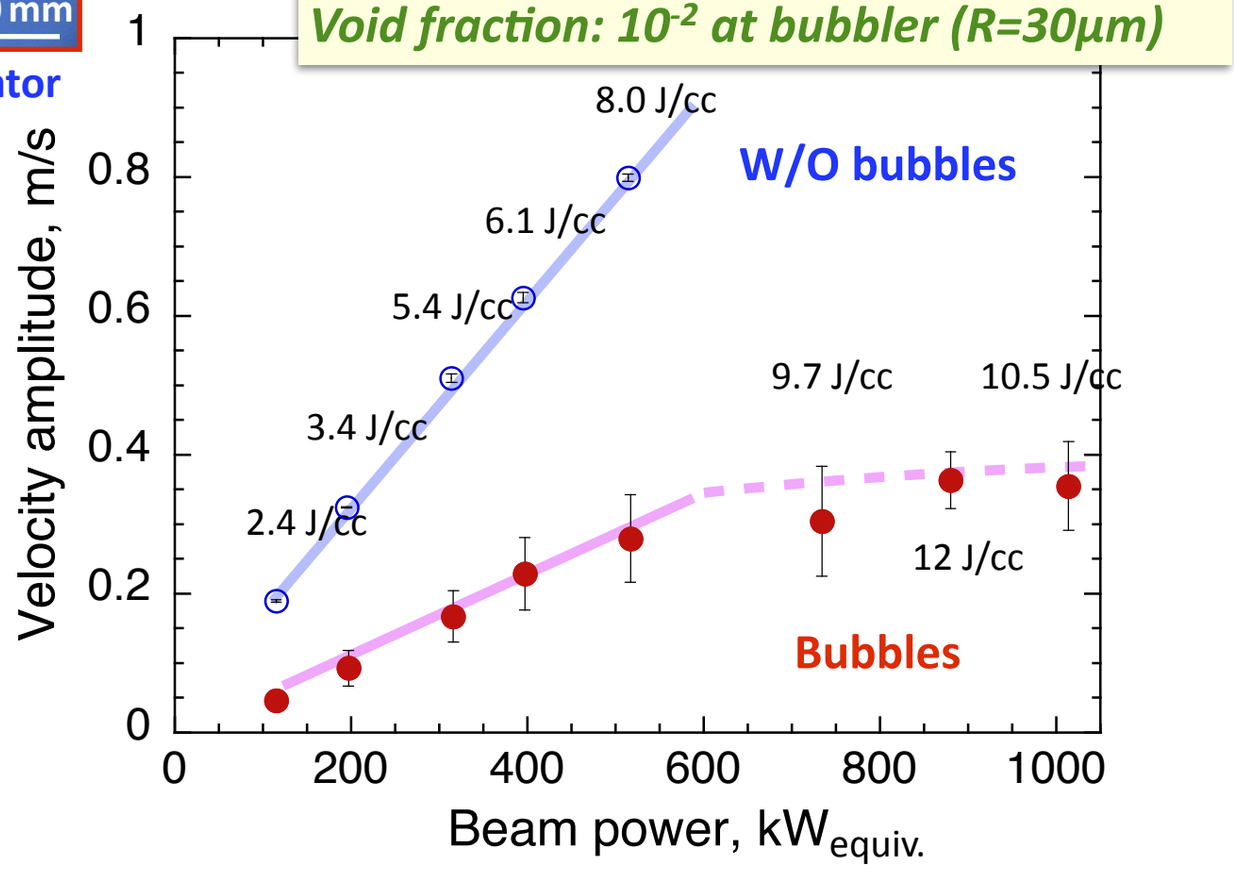
High power beam experiment up to 1MW$_{equiv.}$



Beam conditions
120~520 kW$_{equiv.}$: 0.2 Hz 100 shots
730 kW$_{equiv.}$: 1 Hz 100 shots
880, 1014 kW$_{equiv.}$: single shot x 6
Void fraction: 10^{-2} at bubbler (R=30μm)



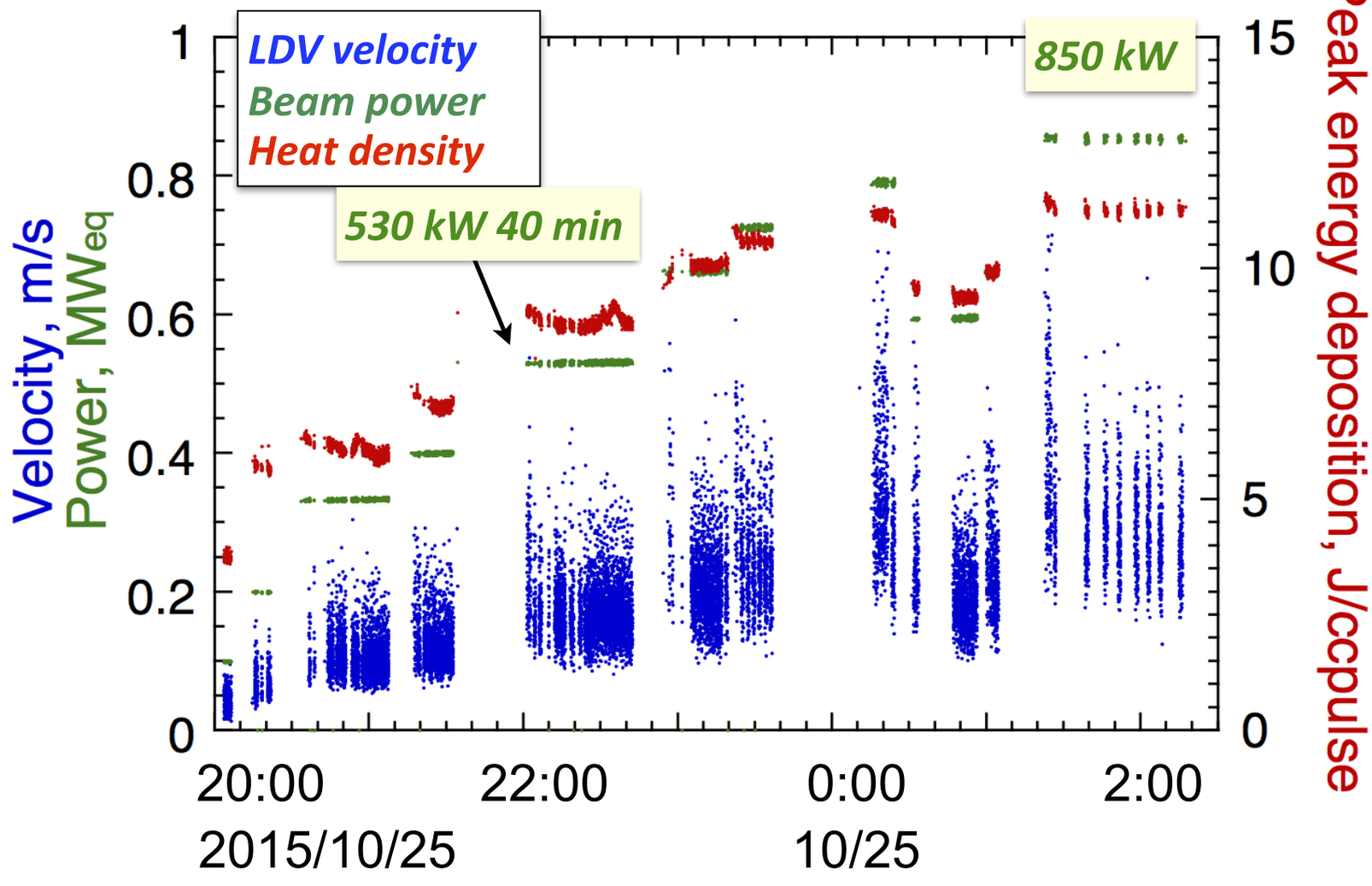
LDV time responses for 3rd and 7th target



LDV peak amplitude obtained from 7th target

- Target system has the LDV diagnostic system (LDV, Mirror)
- Peak amplitude of 1 MW$_{equiv.}$ study (OCT. 2015) showed similar amplitude of 300 kW W/O bubble ➡ **Bubbles extremely mitigates pressure waves**
- Peak amplitude of velocity for bubbles case seems to be 1/4 of W/O bubbles cases

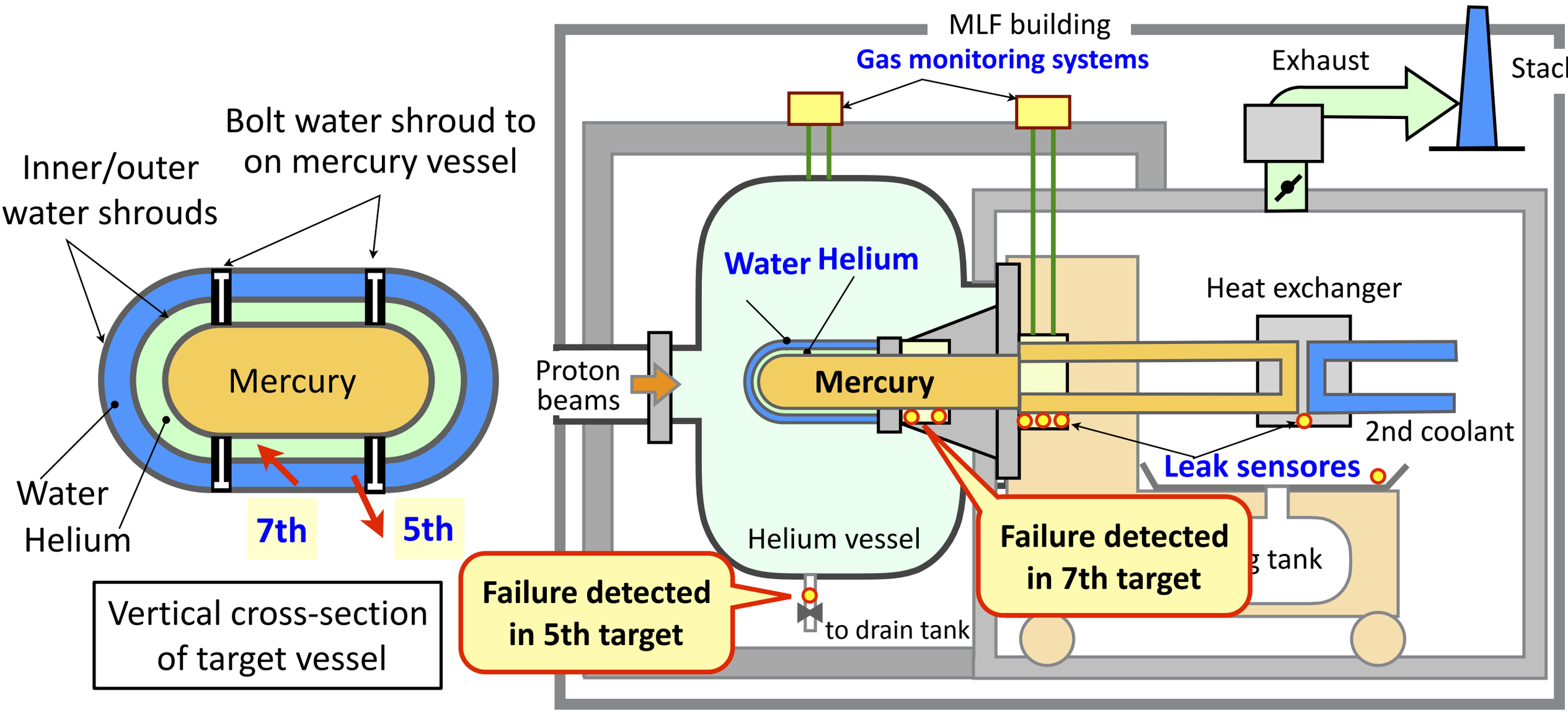
High-power beam experiment at 25 Hz



Beam experiment history of 7th target (25 Hz)

- 25 Hz beam experiment performed under injecting gas microbubbles
- Gas flow ratio is constant but mitigation effect shows large variation
  > bubble distribution at beam window is fluctuating
- In high-power operation, accelerator seems unstable (in my opinion)

Troubles in 2015 — 5th and 7th targets —

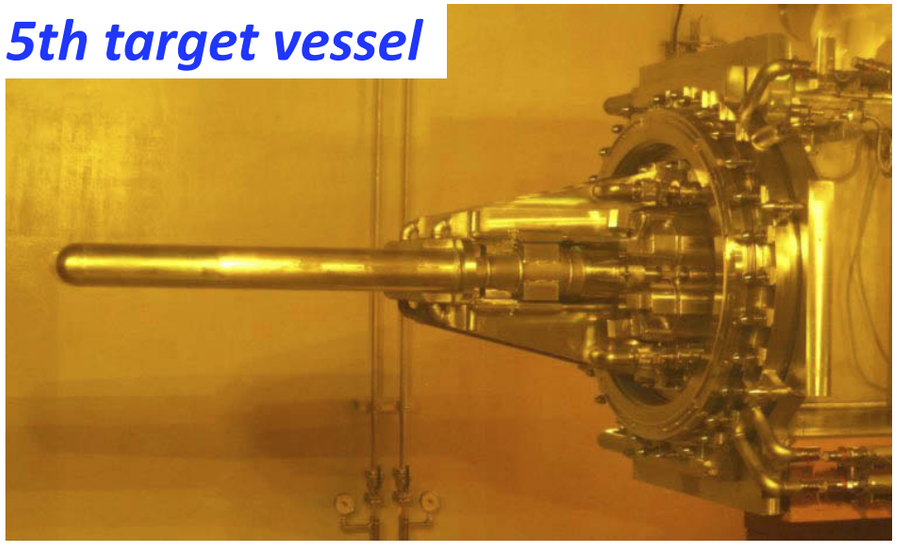


- 5th and 7th targets were failed due to water leak at water shroud
- Leak sensor at the drain tank of helium vessel was detected leak for 5th target
  Water leaked to outside of target vessel
- Leak sensor inside target vessel was detected leak for 7th target
  Water leaked to inside of target vessel

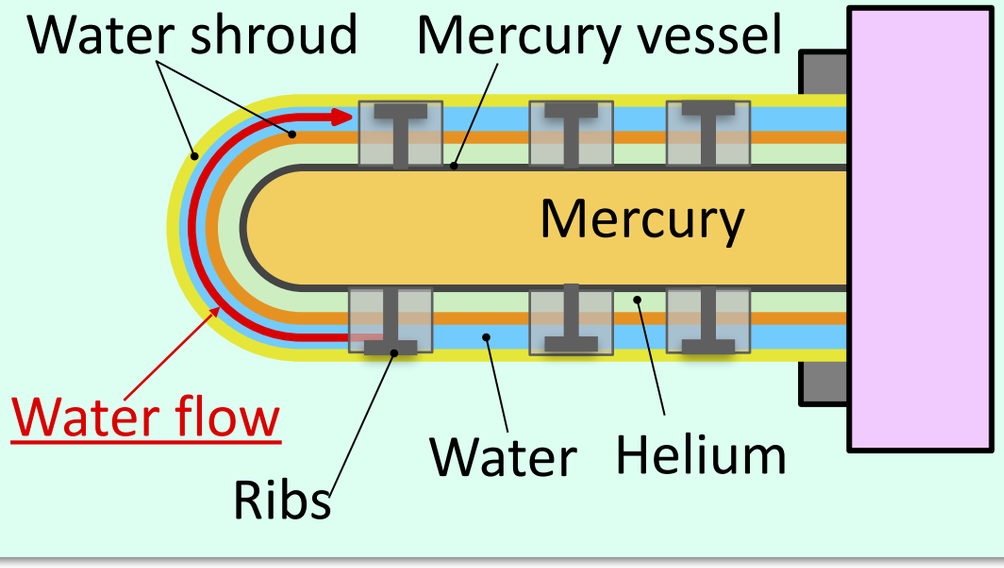
Radioactive gas was not released from stack (Leak occurred in enclosed vessel)

Structure of mercury target vessel

5th target vessel

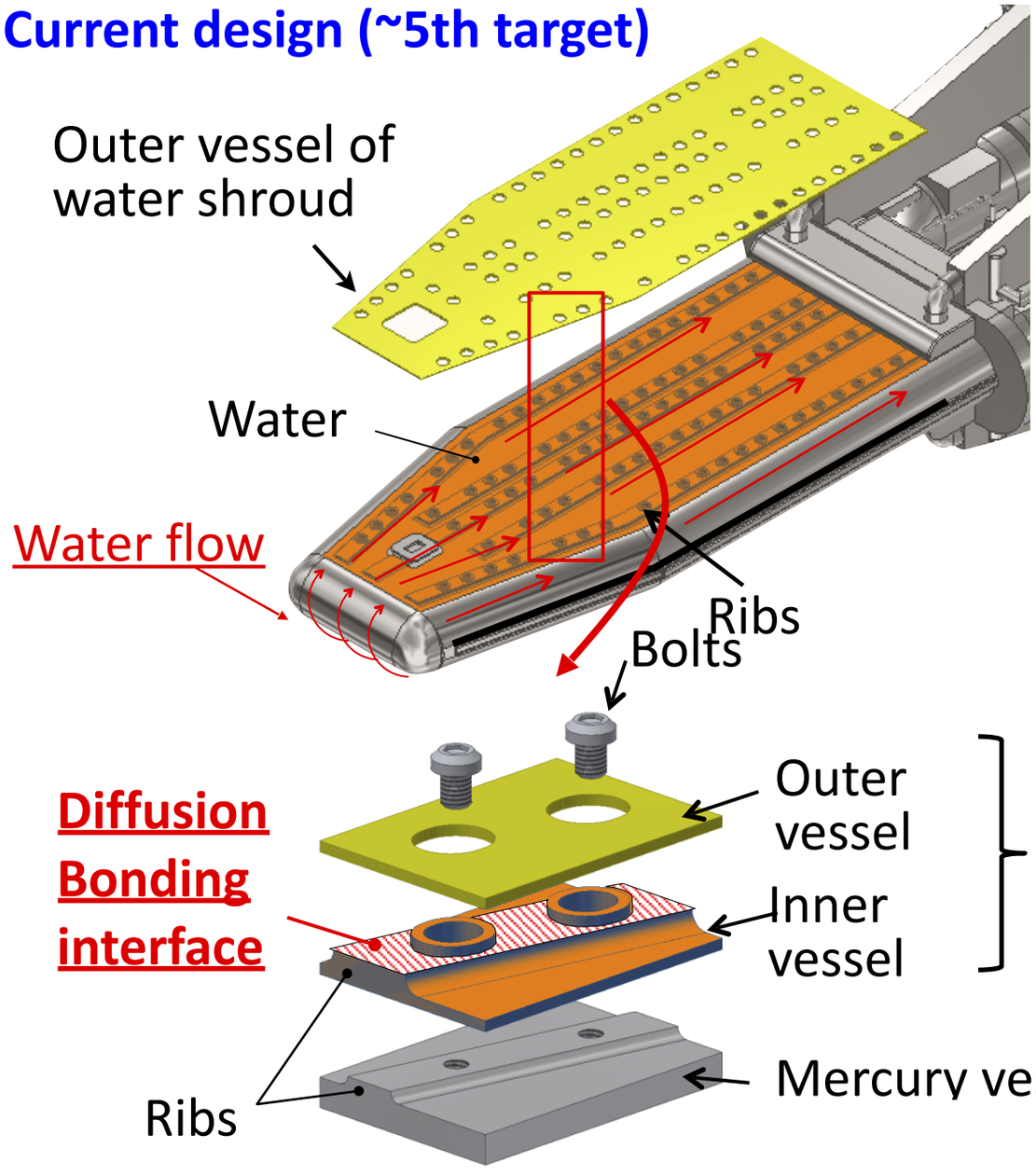


Triple walled structure



Vertical cross section of the target viewed from the taraet side

Current design (~5th target)

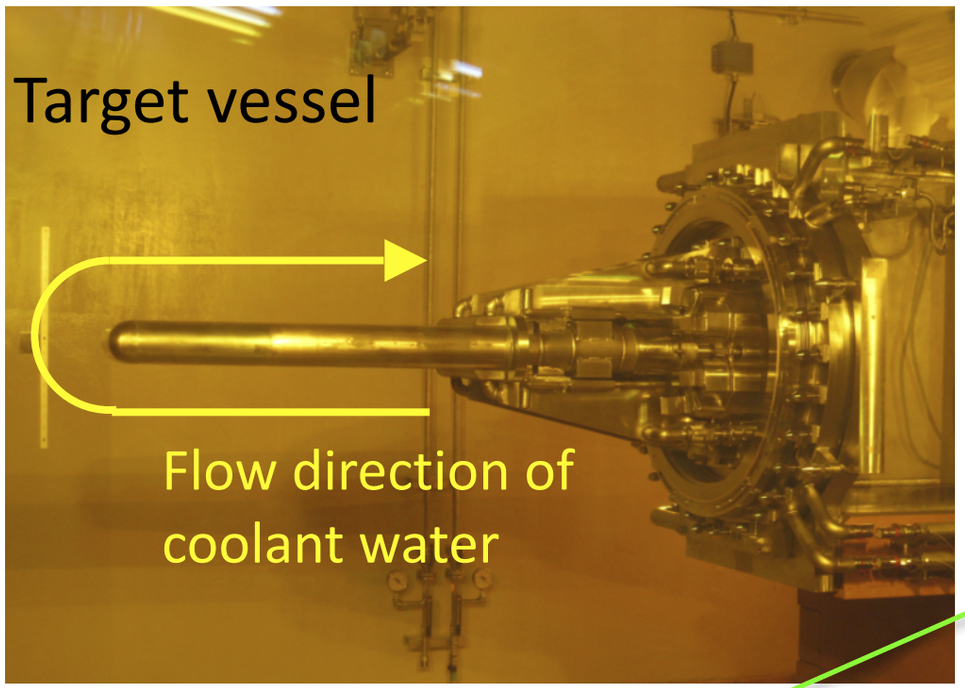


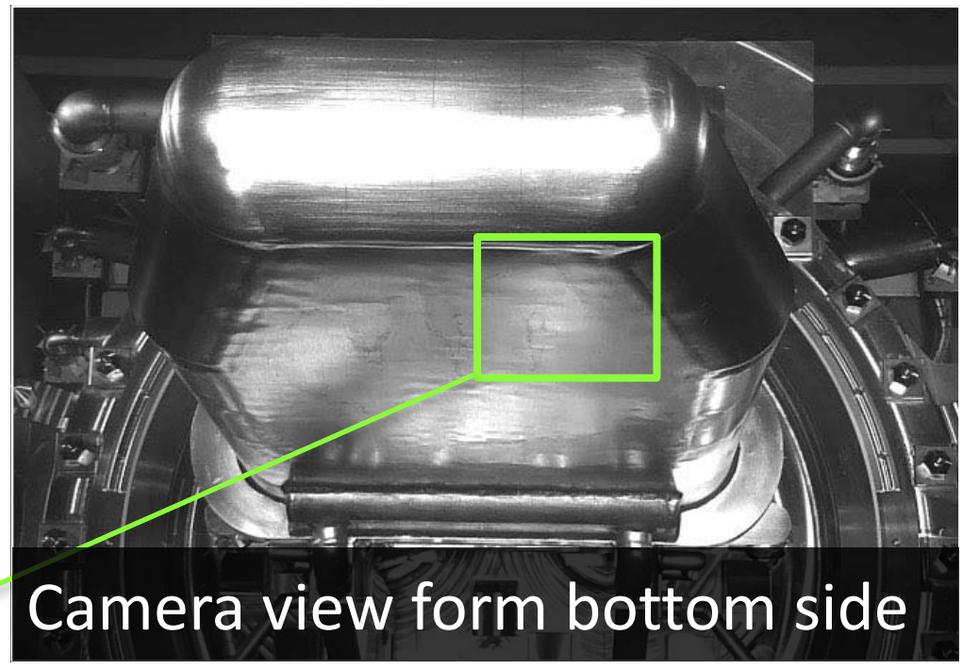
Vertical cross section of the target viewed from the taraet side

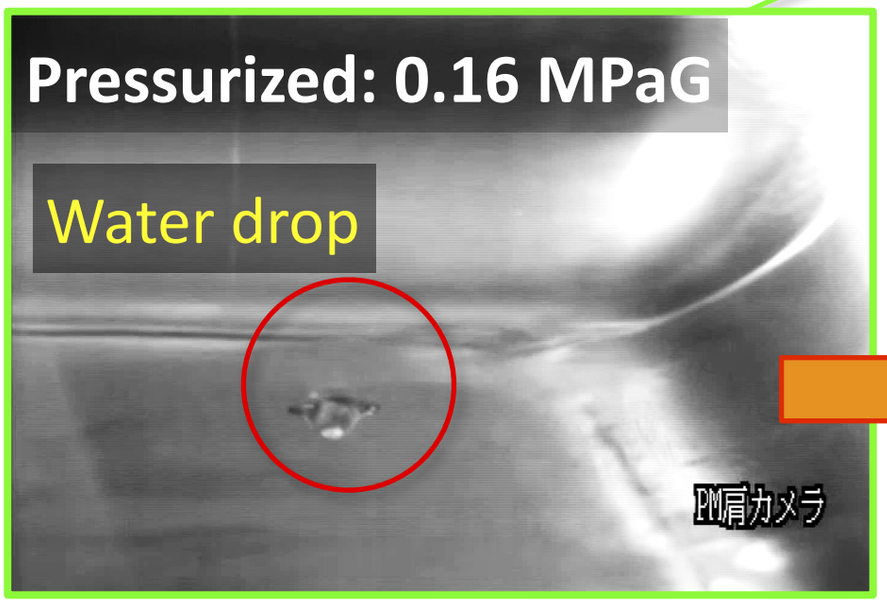
- Target vessel has triple walled structure (Inner/Outer water shroud, Mercury vessel)
- Outer and inner water shroud (diffusion bonded) was bolted to mercury vessel
- Bolt head and outer/inner shroud interface was welded by GTAW

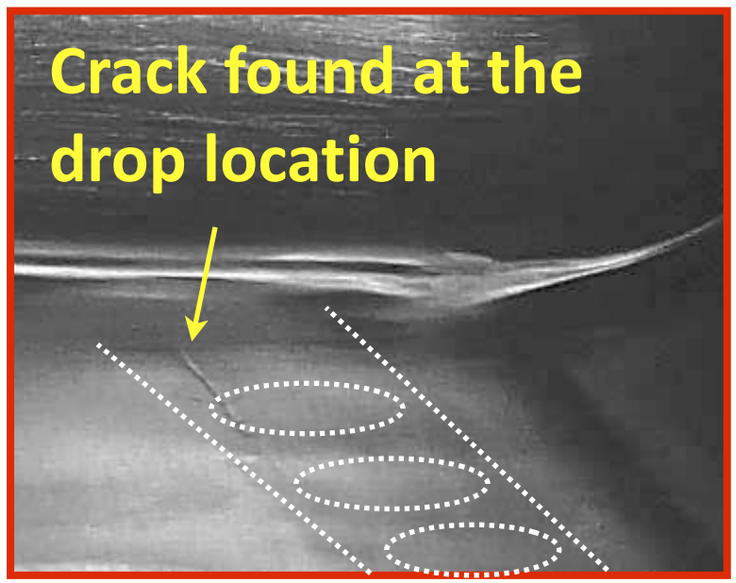
5th target

Visual inspection for detecting leak location









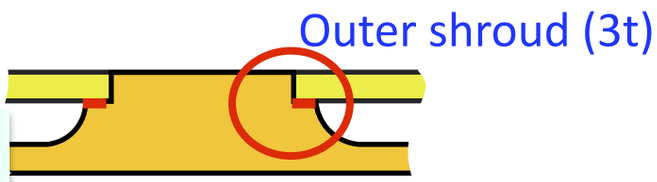
- Observation of target surface by video camera
- Pressurizing water shroud with helium gas (0.16 MPaG)
- A water drop found on the bottom side surface (Determined leak location)
- Crack caused by welding defect was found on leak location

Failure mechanism of 5th target

Fabrication process

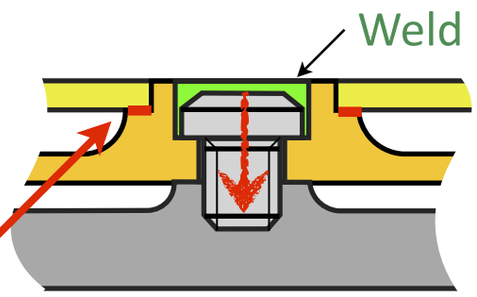
Diffusion bonding

Ultrasonic inspection was passed



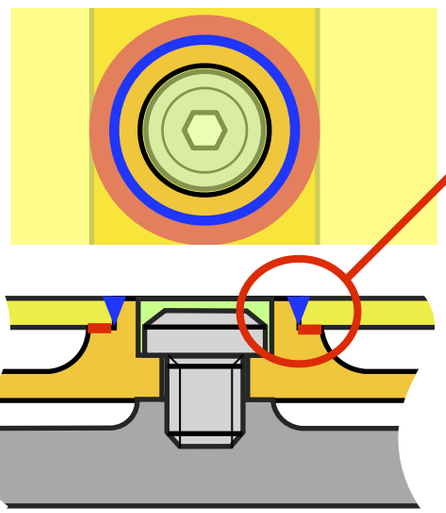
Bolt water shroud to on mercury vessel

Plug bolt head with weld metal



Diffusion bonded interface was detached by thermal deformation

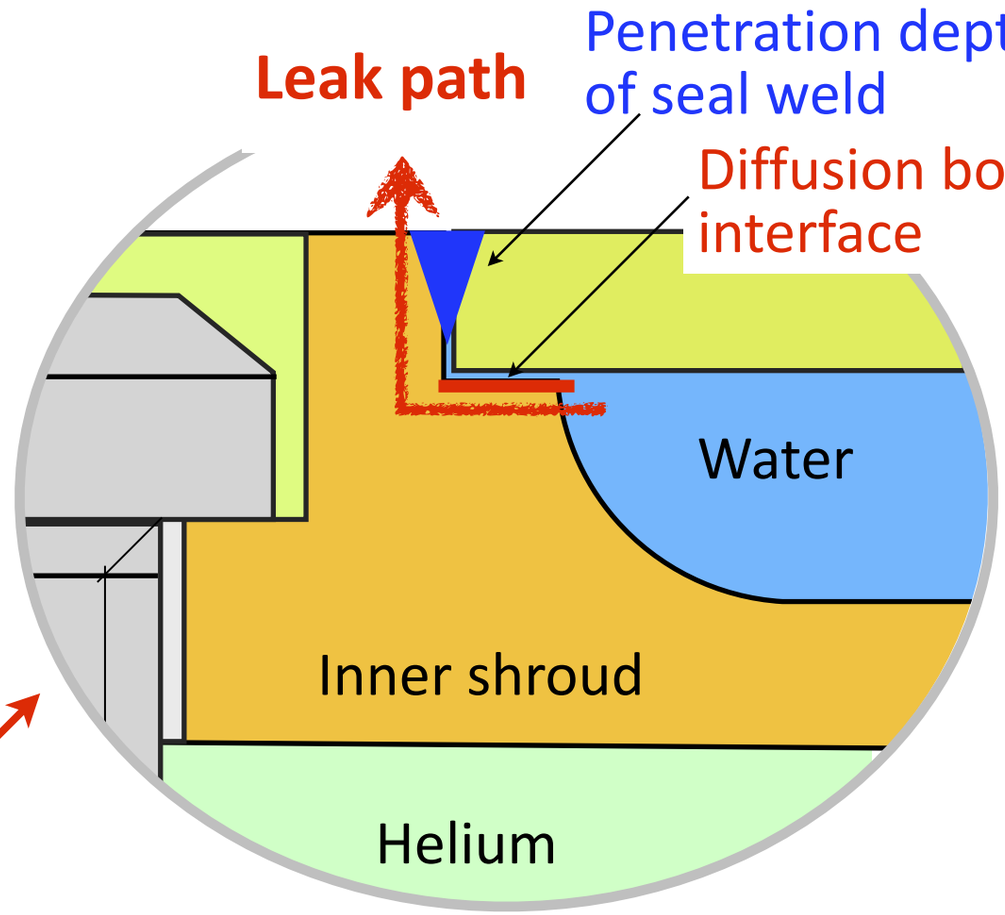
Seal welding w/o groove to ensure airtightness in water shroud



Leak tight test was passed

Beam operation

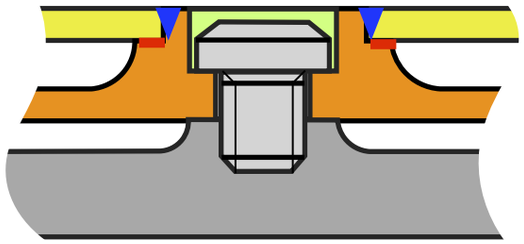
Seal welding of thin penetration depth (<1.5 mm) was failed by repeated thermal stress



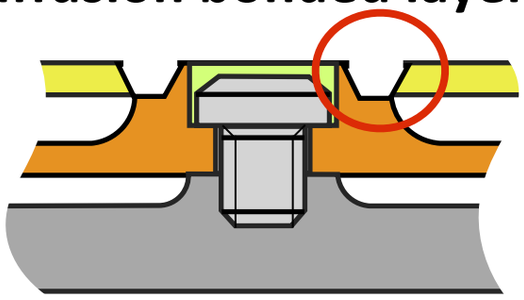
- Crack propagated through the seal welded part between inner and outer shroud
- Total number of thermal cycles due to beam trip for 5th target is ca. 2500
- Structural design, that allowed the seal welding without groove, was attributed to the water leak

Reinforced structure of 7th target

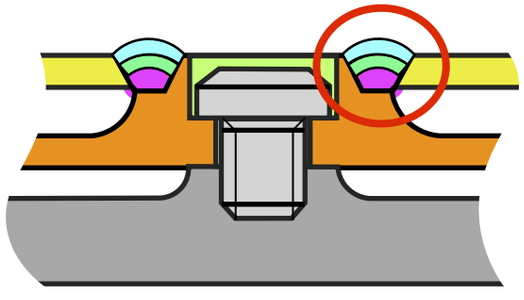
Original design

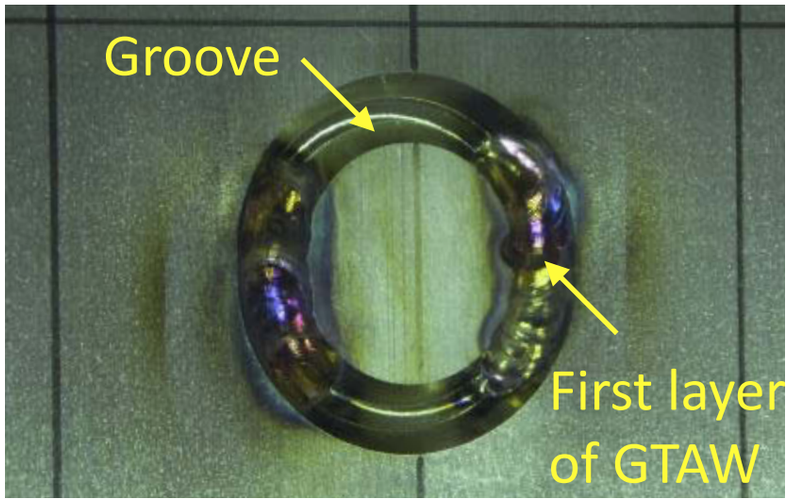


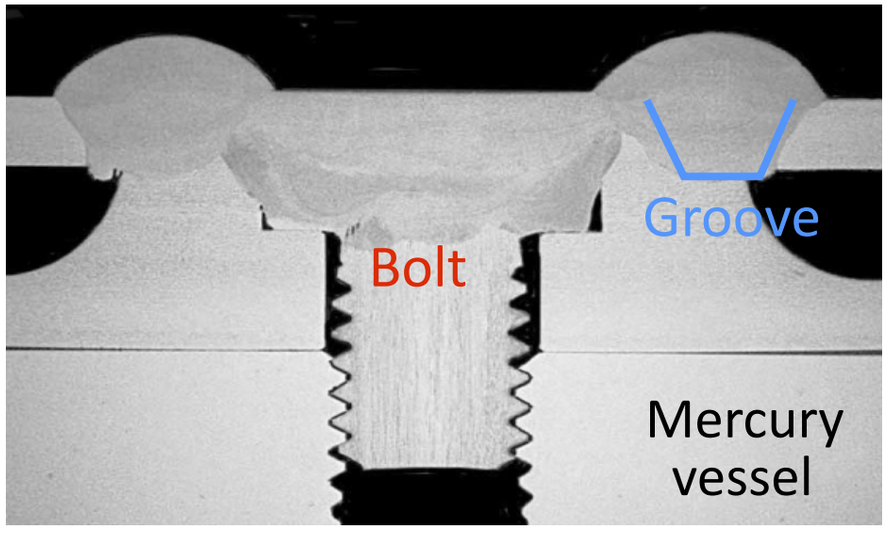
Remove seal welding and diffusion bonded layer



Repair welding (leave a weld bead) 3 path







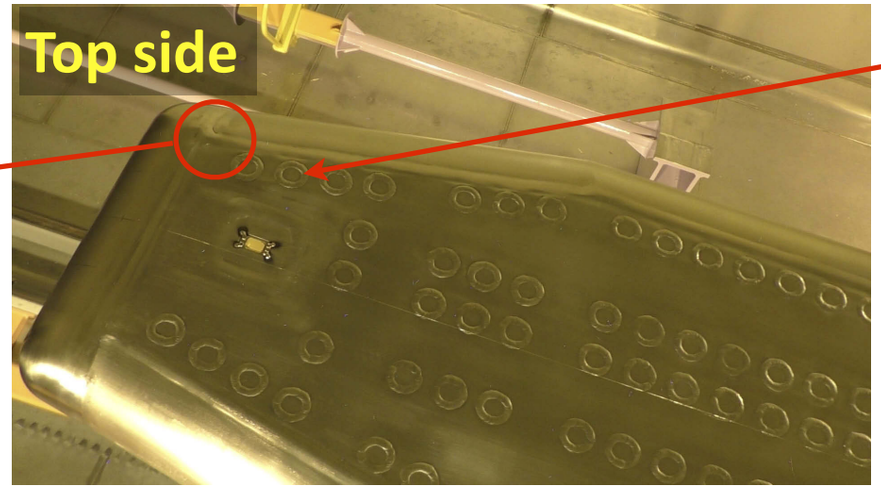
Cross section of mock-up specimen

Repaired 7th target vessel

- Spare target (7th target) which is the same design with 5th target was repaired to eliminate seal welding without groove
- 167 portion of around bolts were repaired and beam operation with repaired 7th target was started from Oct. 2015
- **7th target was failed two weeks after restarting operation at 500 kW**

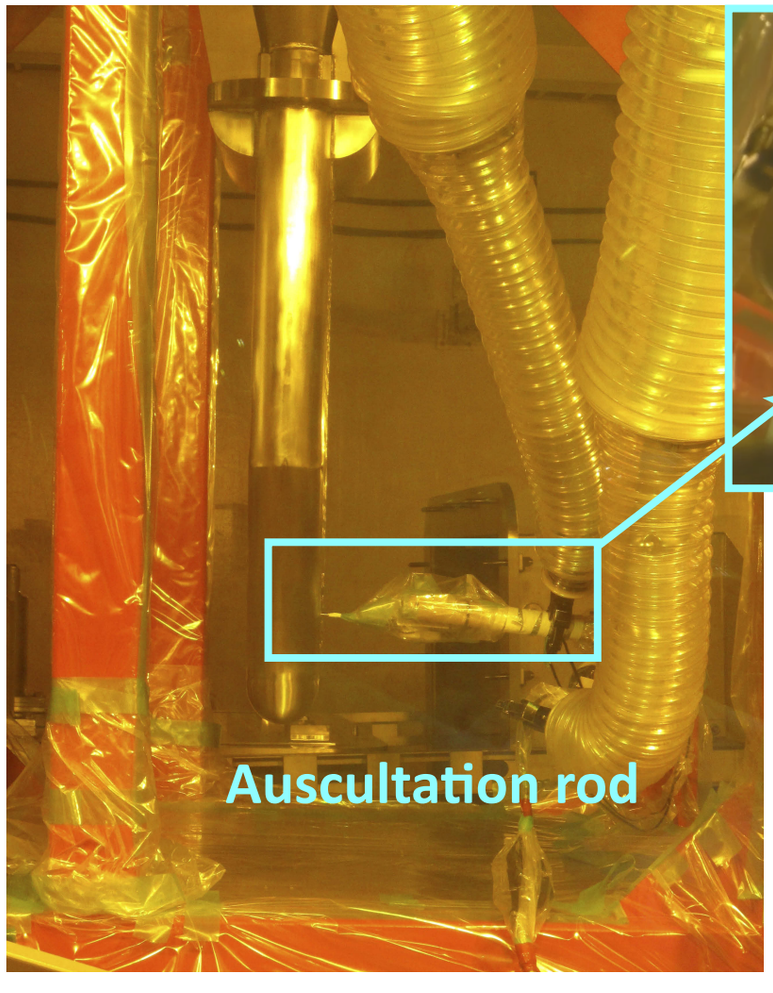
Sound measurement for detecting leak location

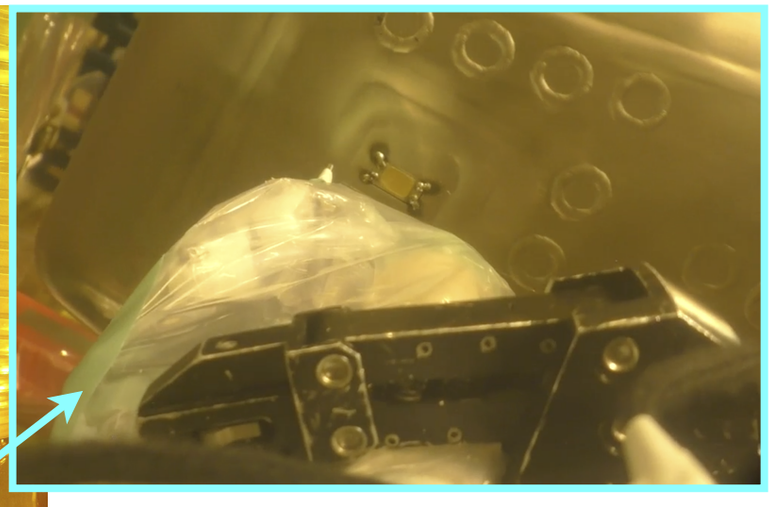
Triple point of welding

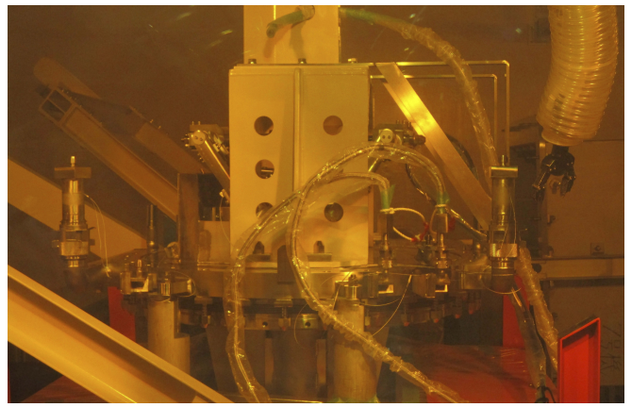


Repaired point of around bolt

No-visible change was found from outside inspection





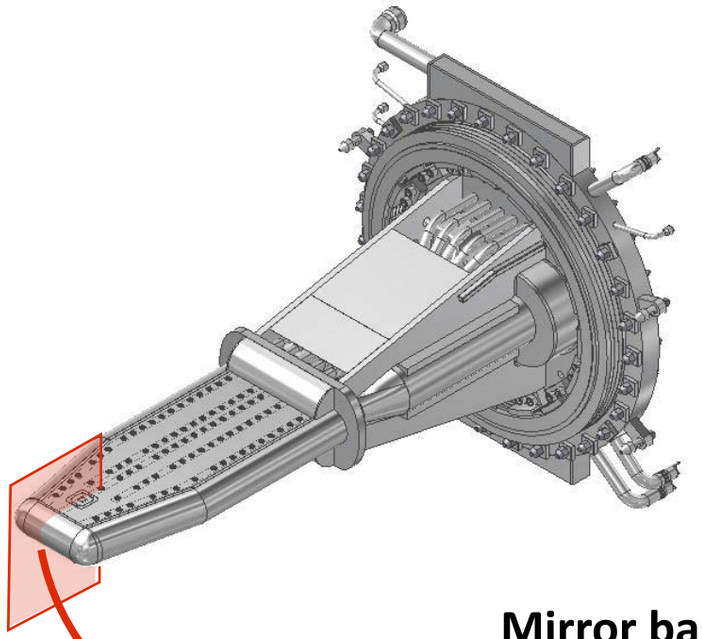


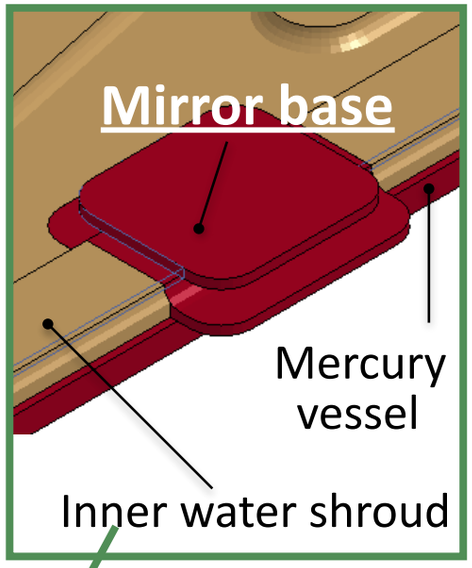
Pressurize water shroud (0.5 MPa)

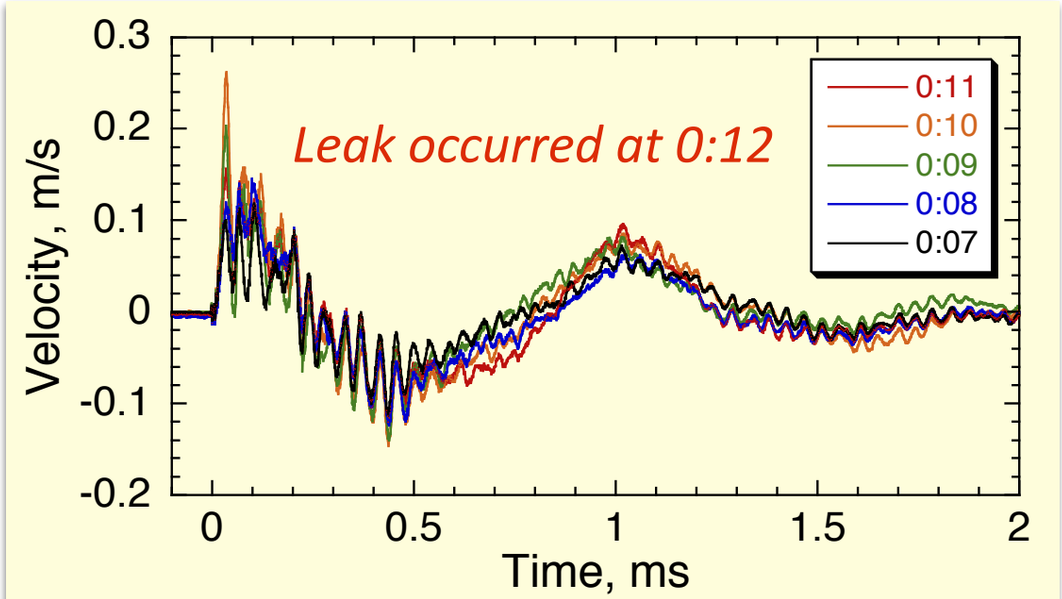
- Prepared microphones to detect the sound of gas ejecting from inner water shroud
- However, passage of gas between helium layer and water layer was closed when we tried to measure sound

We retried sound measurement in this October, but still unclear the leak location

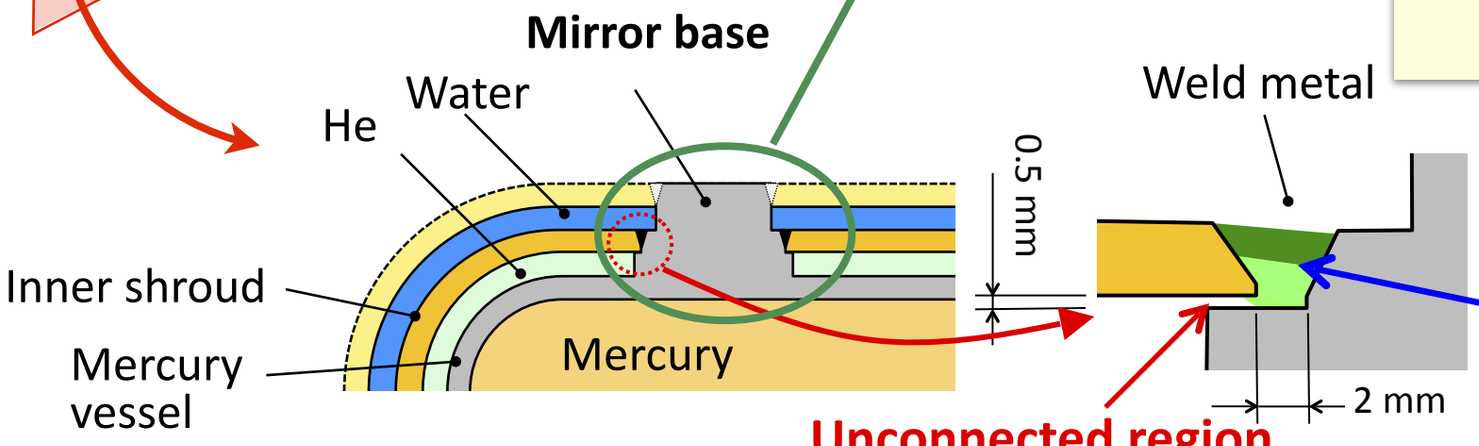
A possible reason for leak of 7th target







LDV time responses just before failure



Vertical section of target vessel

152MPa stress range by pressure wave at the weld between the base & int. vessel

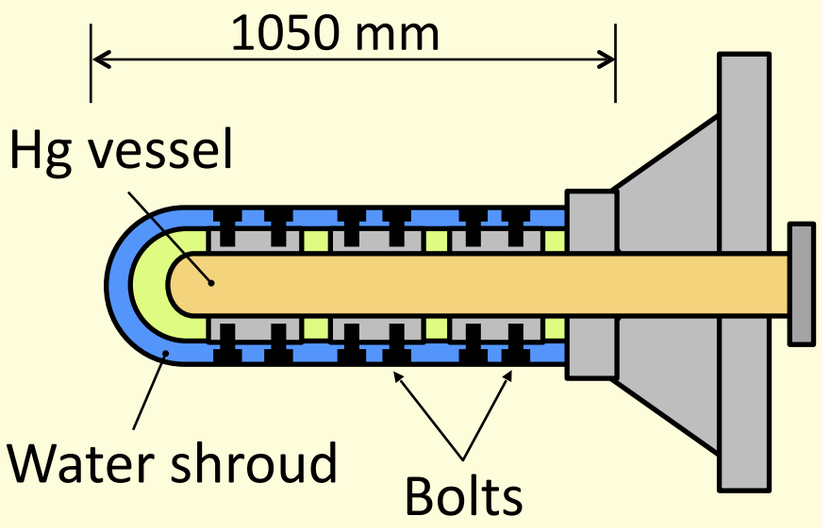
Welded with 0.5 mm step & 2 mm gap (identified during the interview with engineers)

Details of failure analysis for 7th target will be shown in Wakui's talk on Wednesday

- Monolithic structure around mirror for LDV system seems to be leak location
- Welding defect (unconnected region) acts as notch for propagating fatigue crack by pressure waves and thermal stress
- But we did not find any change in LDV signals just before failure

Strategy of design & fabrication improvements

Failed at 500kW operation

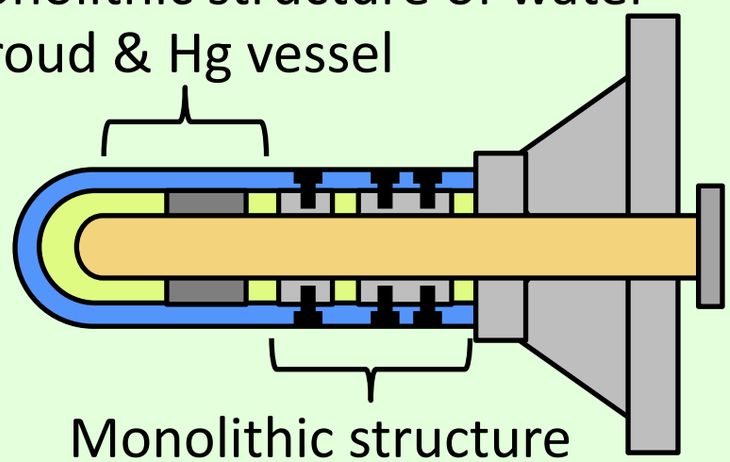


Many welds incl. diffusion bonding with constraints between vessels

1st～7th (previous)

Improved structure

Monolithic structure of water shroud & Hg vessel



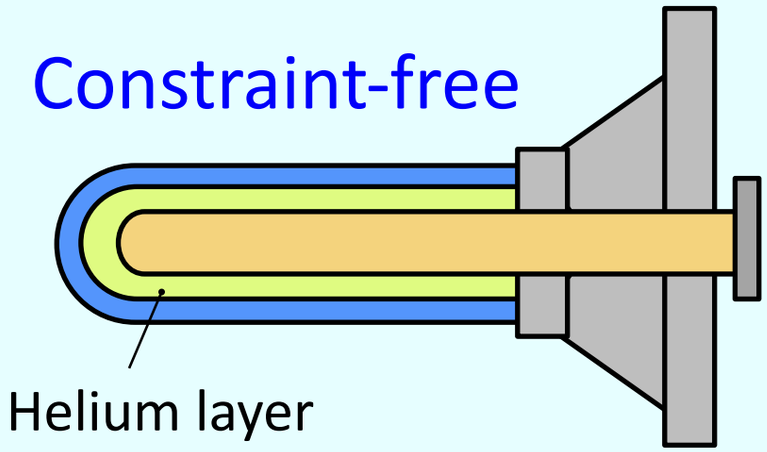
Monolithic structure of water shroud

Much fewer welds with constraints

8th(next)

Future plan for high power operation

Constraint-free



Few welds with no constraints

10th or later

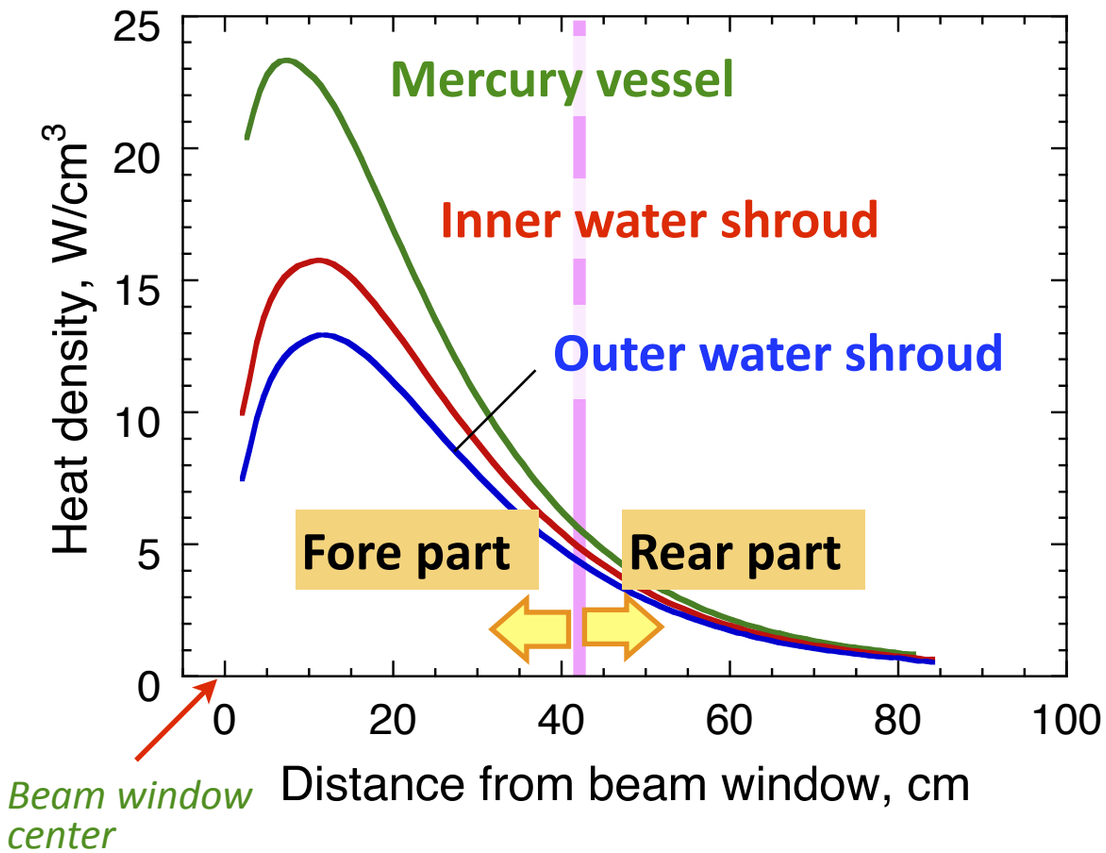
For 8th target

- Reducing welding parts as few as possible (reduced to 70%)
- Adopting fabrication processes which makes inspections of welding lines easier

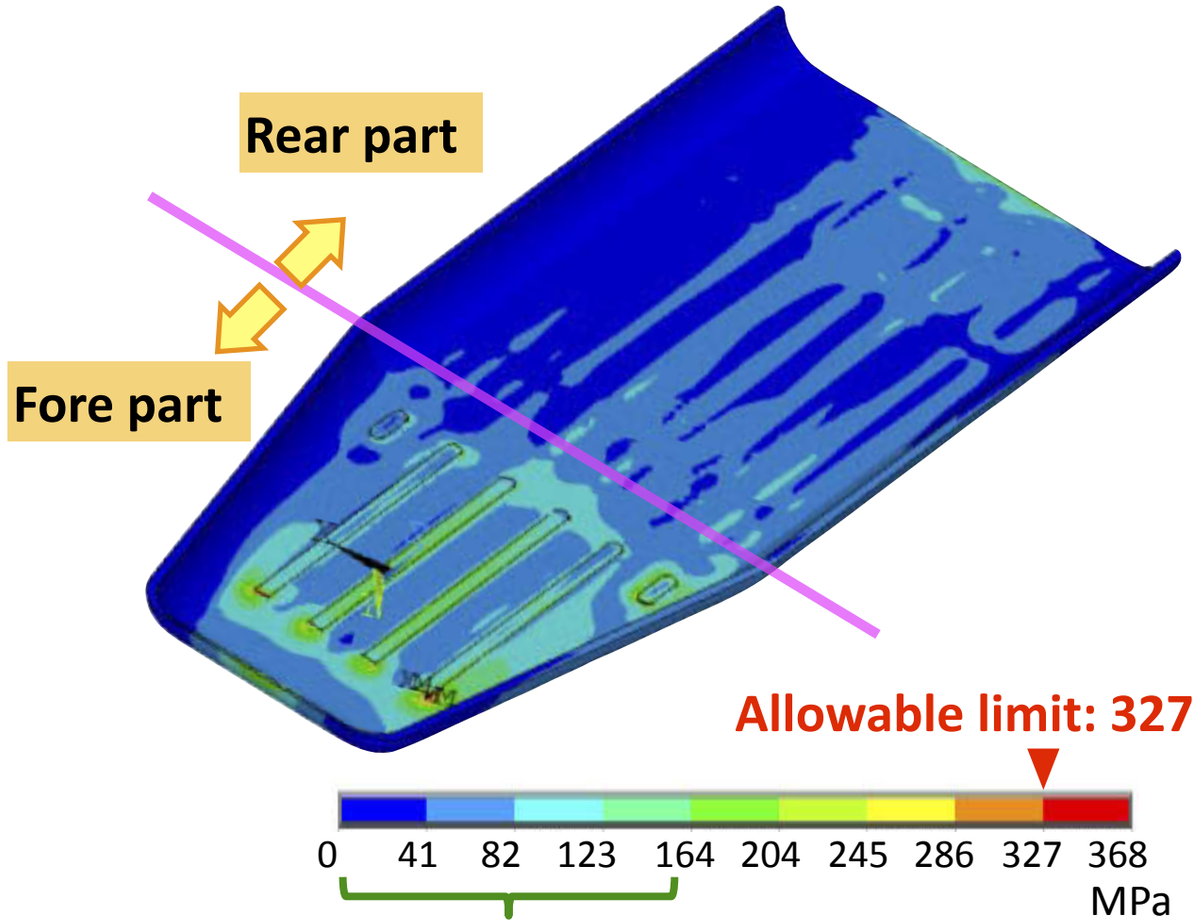
Added for 10th or later targets

- Minimizing the constraints between water shroud and mercury vessel to reduce thermal stress

Heat density and thermal stress



Heat density distribution at 1MW



Stress range in rear part

Thermal stress distribution for inner water shroud at 1 MW

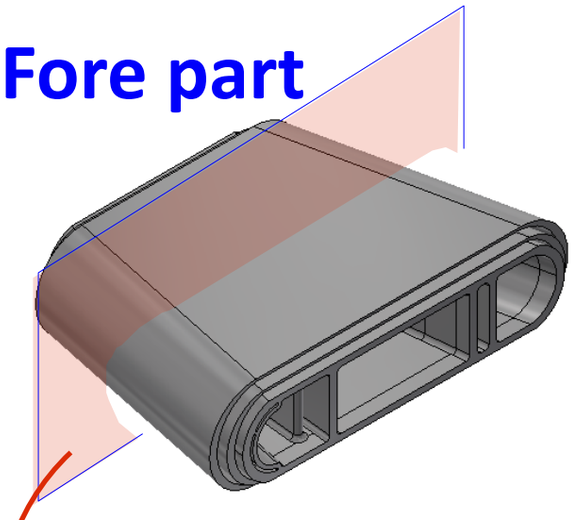
- Heat density in rear part is less than 1/4 of fore part
- Thermal stress is less than half of allowable stress

Bolt structure in rear part is enough to withstand thermal stress at 1 MW

Lesson and improvement from failures

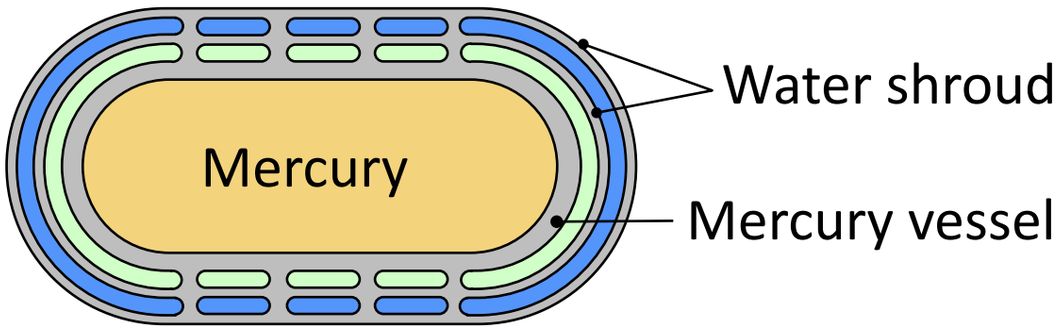
Improvement for 8th target

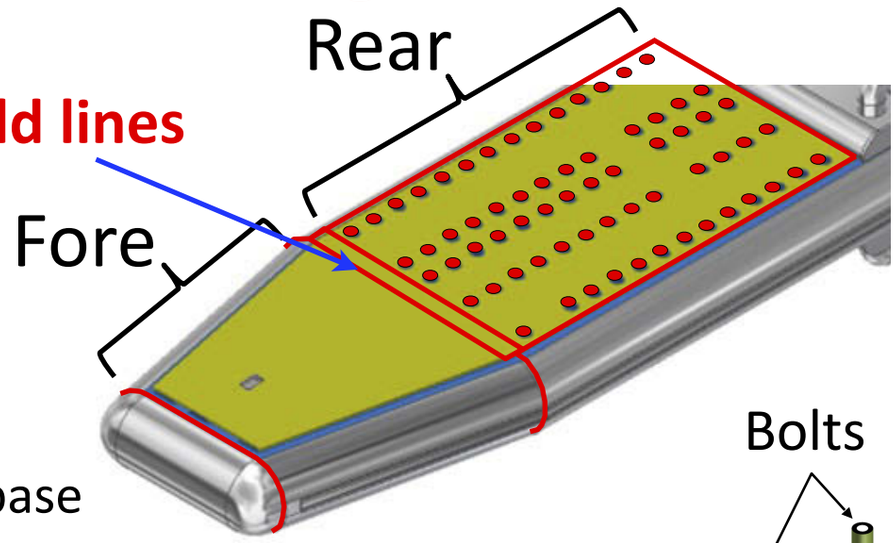
Fore part



The monolithic structure has the function of mirror base in itself.

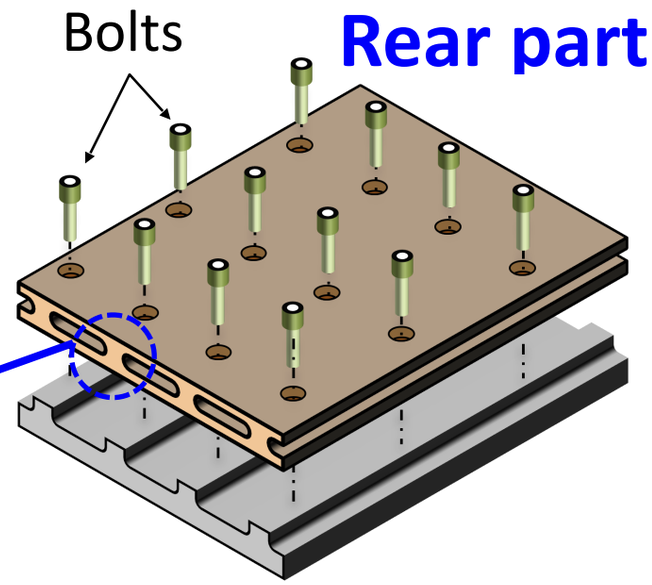
Vertical cross- section





Plug bolt-hole by welding after bolting water shroud on mercury vessel

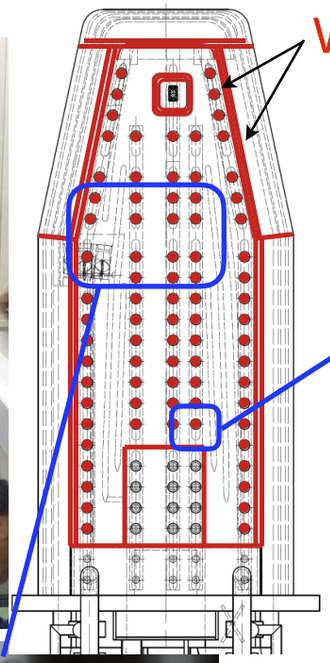
Rear part

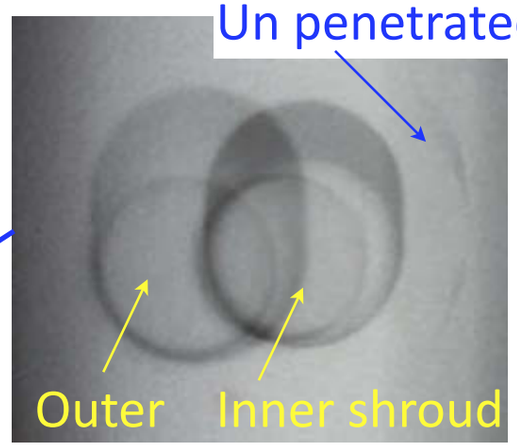


Wire EDM was applied to reduce welding line and to eliminate diffusion bonding

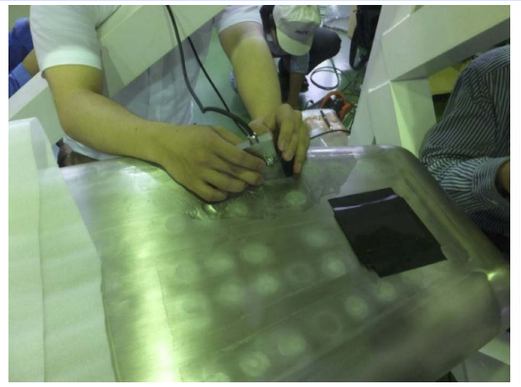
- Lack of penetration depth for seal welding led leakage of water (5th target)
  Fatigue crack was propagated thermal cycles by beam trip from weld defect
- Monolithic structure of LDV mirror base seemed to be induce un-welded region which acts as notch, and fatigue crack propagated by pressure waves

Improvement of inspection

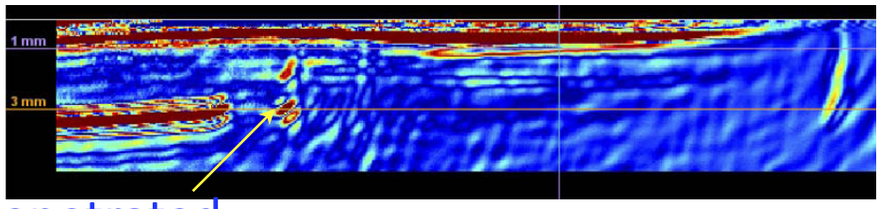


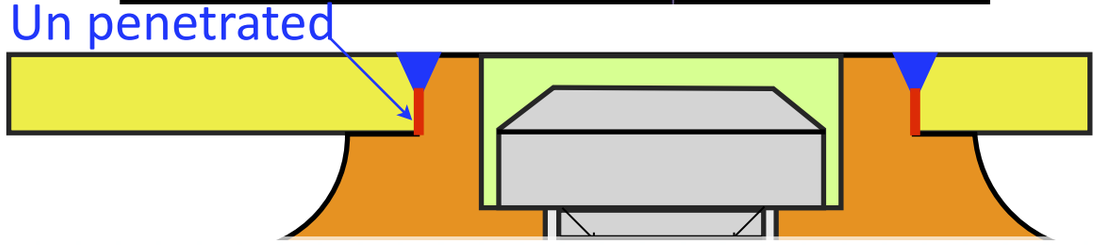


6th target vessel was inspected to investigate inspection processes of RT and UT



Inspection of mock-up specimen by phased array & Full Matrix Capture (FMC) / Total Focusing Method (TFM)





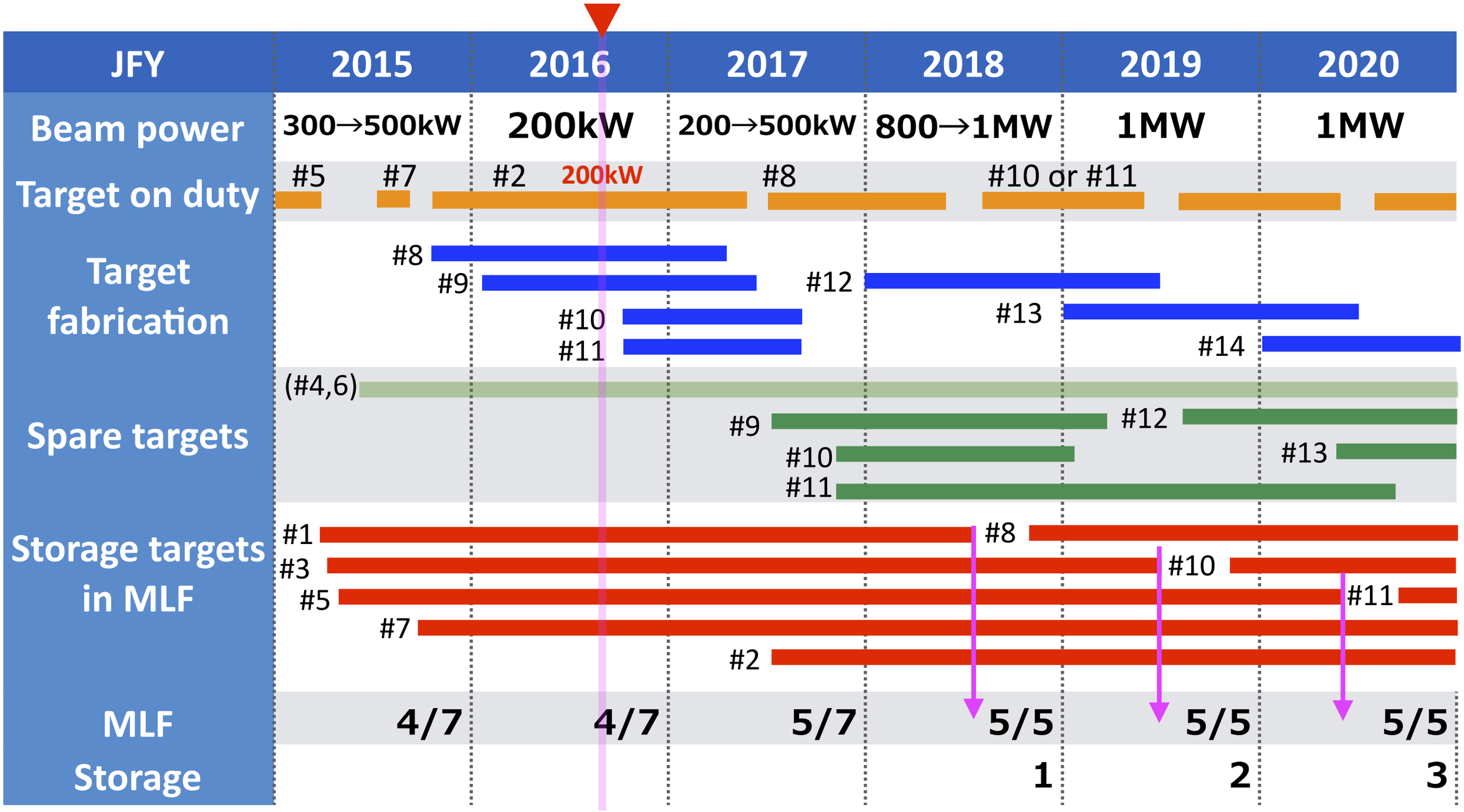
Radiographic Testing (RT)

Ultrasonic Testing (UT)

Details of nondestructive inspection for target vessel will be shown in Wakui's poster

- Based on the experiences of target failure, we revised the inspection procedure
  RT : Front part of mercury vessel only (~7th) —> All part including water shroud (8th~)
- UT inspection will be added :
  Nondestructive inspection method: phased alley &FMC/TFM method (GEKKO, Insight)

Power upgrade scheme towards 1 MW



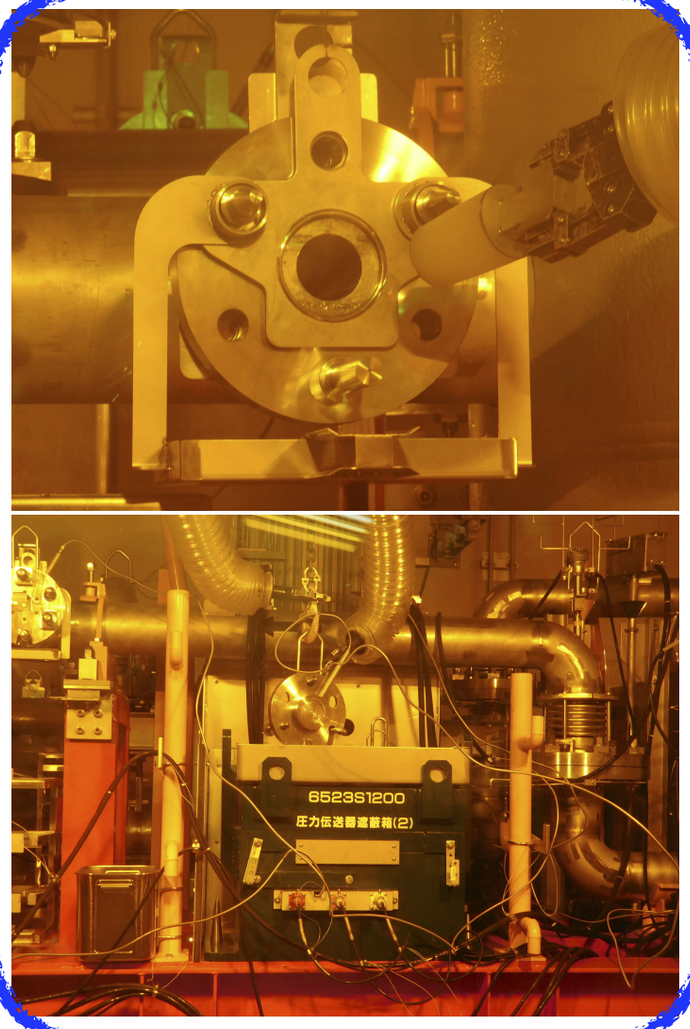
- Ramp up proton beam power step by step with ~100 kW
- We should keep 200 kW operation due to delay of delivery of 8th target until June, 2017
- Storage building is under construction, and operation will start from 2018

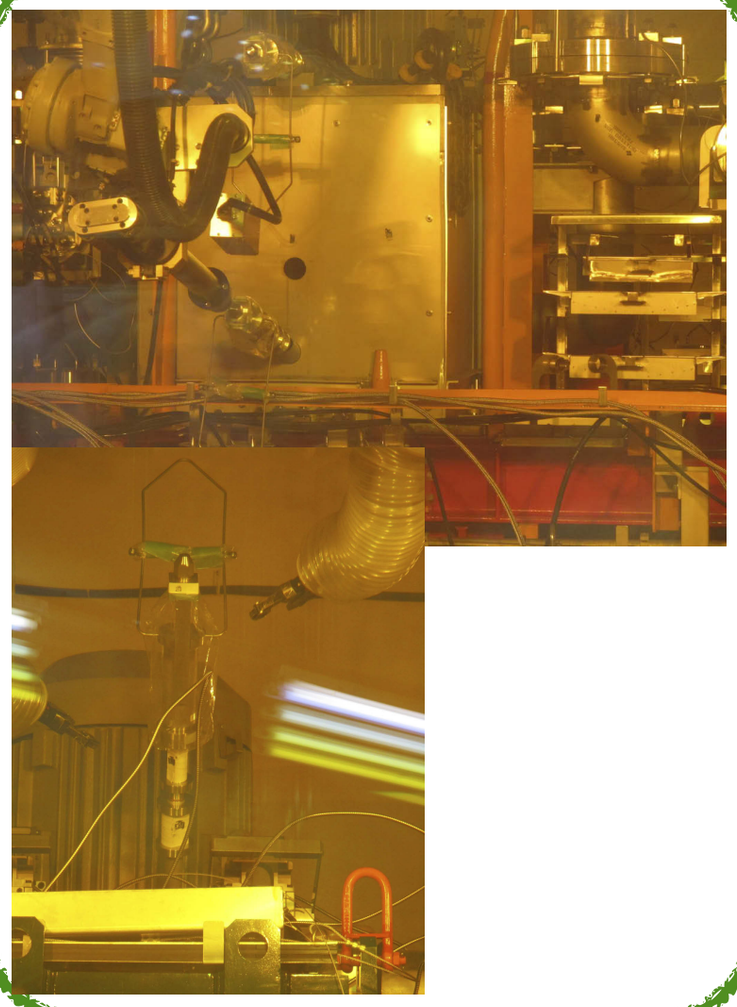
Summary

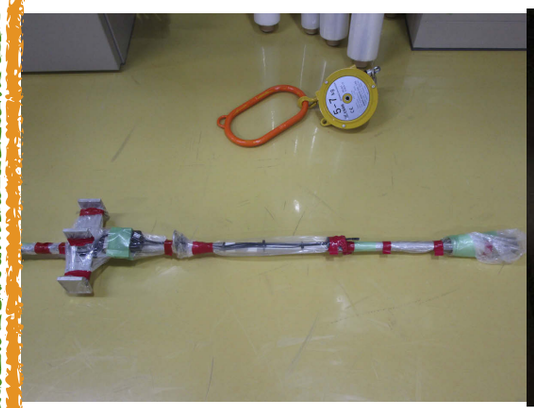
- 1 $MW_{equiv.}$ beam experiment was achieved in 2015, and confirmed excellent effect of injecting gas microbbules on pressure wave mitigation by LDV measurement
- Current beam power of JSNS is 200 kW, 2nd target (w/o bubble injection system) is under operation
- The causes of water leak for 5th and 7th targets are welding defect and structural design
- Design, fabrication, and inspection were improved based on the lessons learned from the target failures (reduce of welding lines to 70% by adopting monolithic structure using wire-EDM)
- The constraint-free type structure will be adopted for 10th or later targets aiming for the 1MW stable beam operation

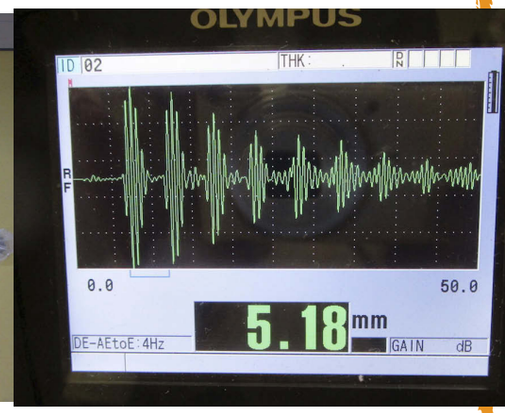
Backup slides

Maintenance work in 2016 Related to target system





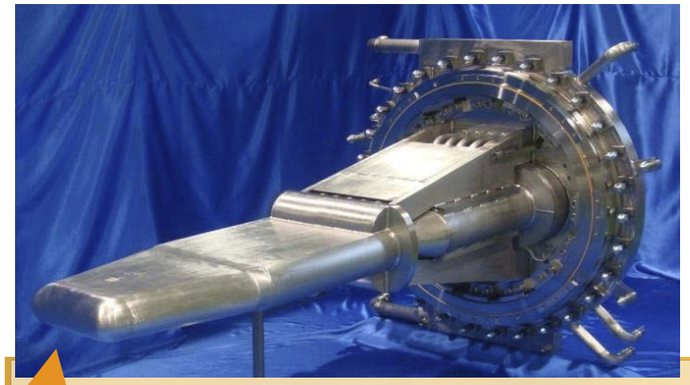


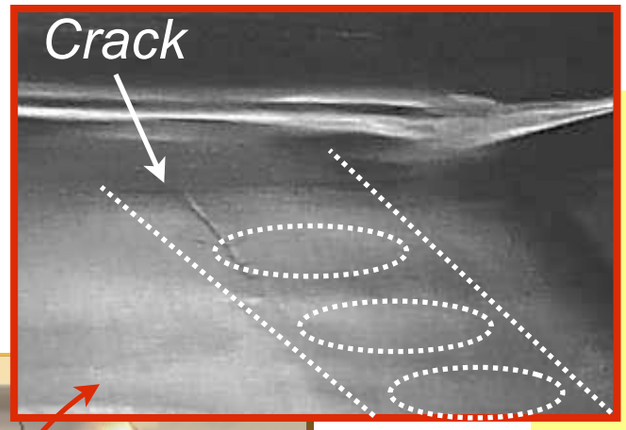


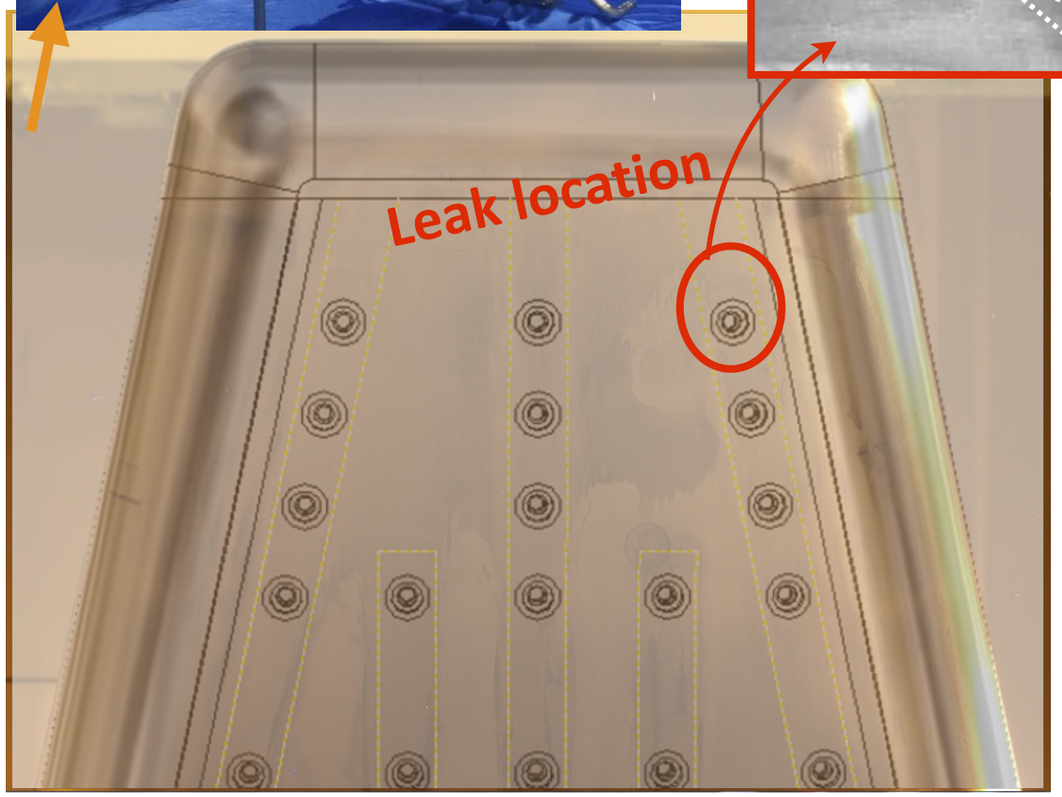
- Pressure sensors, which were damaged by neutron irradiation and showed strange value, were replaced new type sensors (Rosemount sensor)
- Grease the bearing and motor for mercury pump by remote handling
  - Design life of motor for mercury pump is 10 years (8y /10y now)
- Erosion of mercury channel for mercury pump in which thickness is 5 mm was measured using ultrasonic thickness gage by remote handling
  - No-obvious erosions were detected after about 8 years operation

5th target

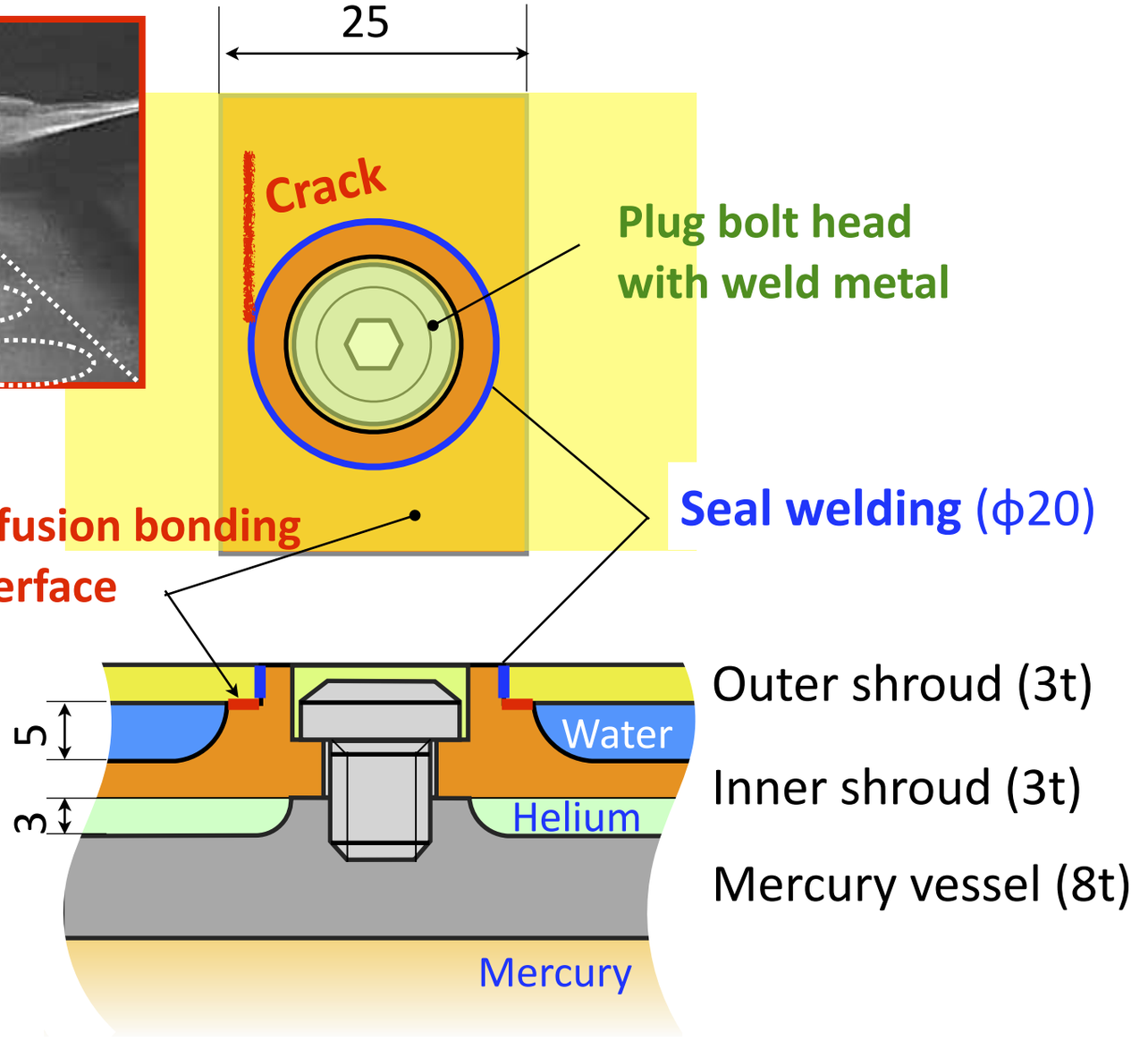
Water leak from welding defect







Bottom view



- Crack propagated through the seal welded part between inner and outer shroud
- Seal welding without groove was performed by GTAW to satisfy only seal performance
- Penetration depth is less than 1.5 mm (Structural strength is not expected)

Failure mechanism of 5th target

Fabrication process

Diffusion bonding

Ultrasonic inspection was passed

Bolt water shroud to on mercury vessel

Plug bolt head with weld metal

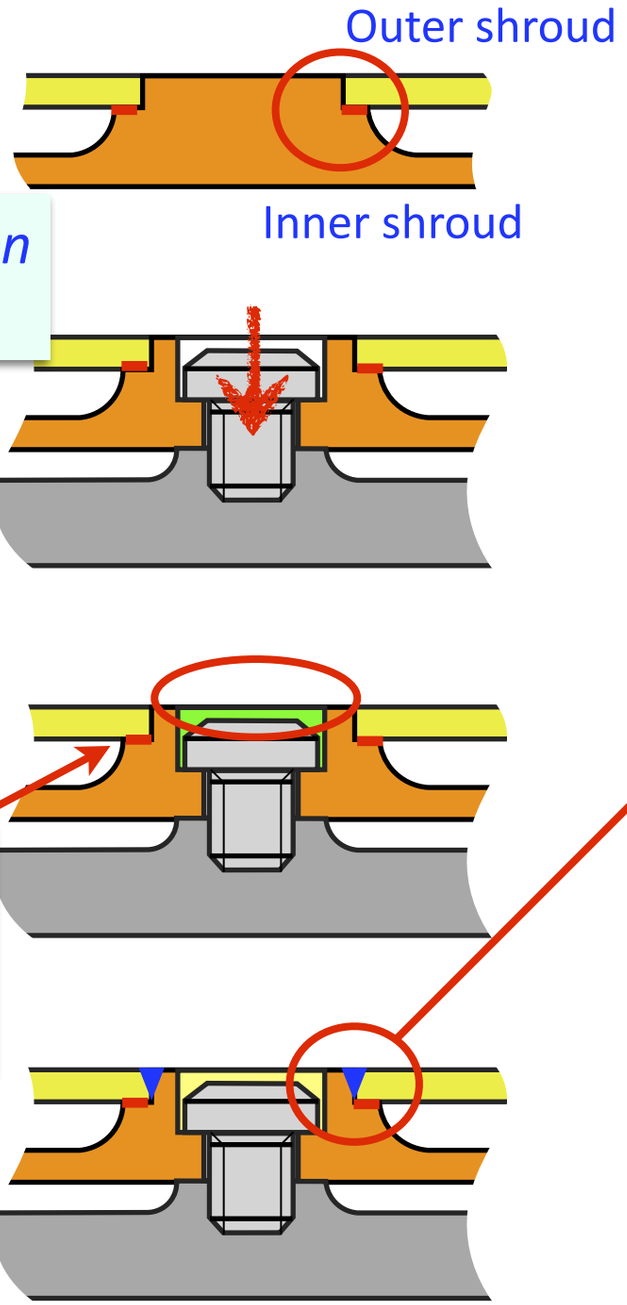
Diffusion bonded interface was detached by thermal deformation

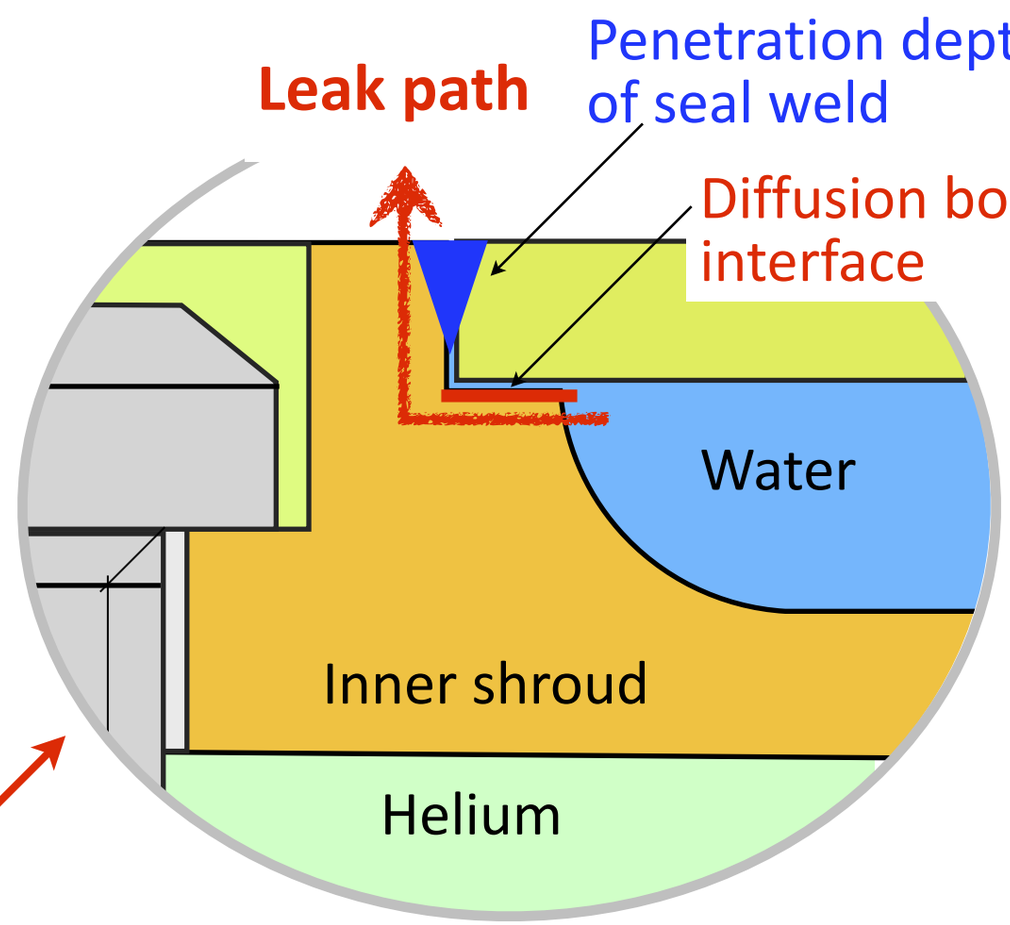
Seal welding to ensure airtightness in water shroud

Leak tightness test was passed

Seal welding of thin penetration depth was failed by repeated thermal stress

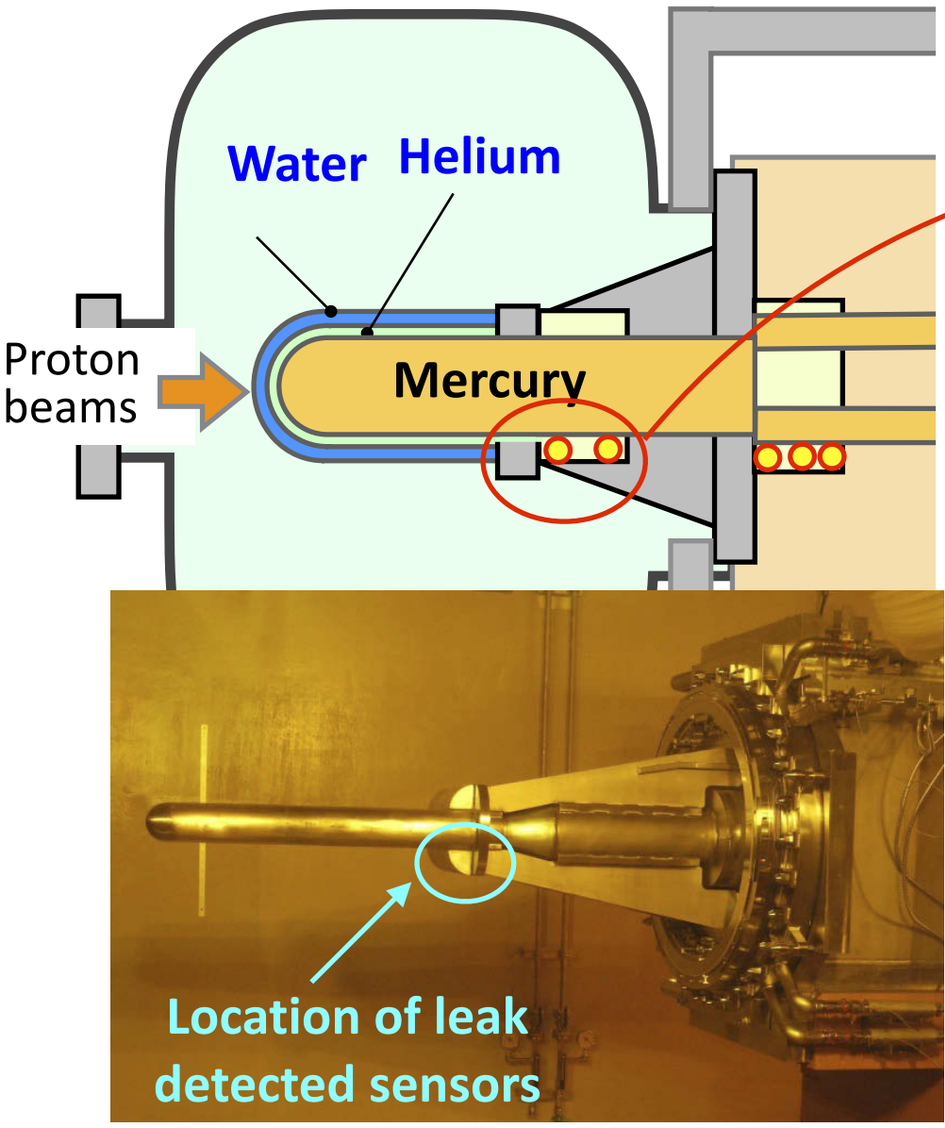
Beam operation

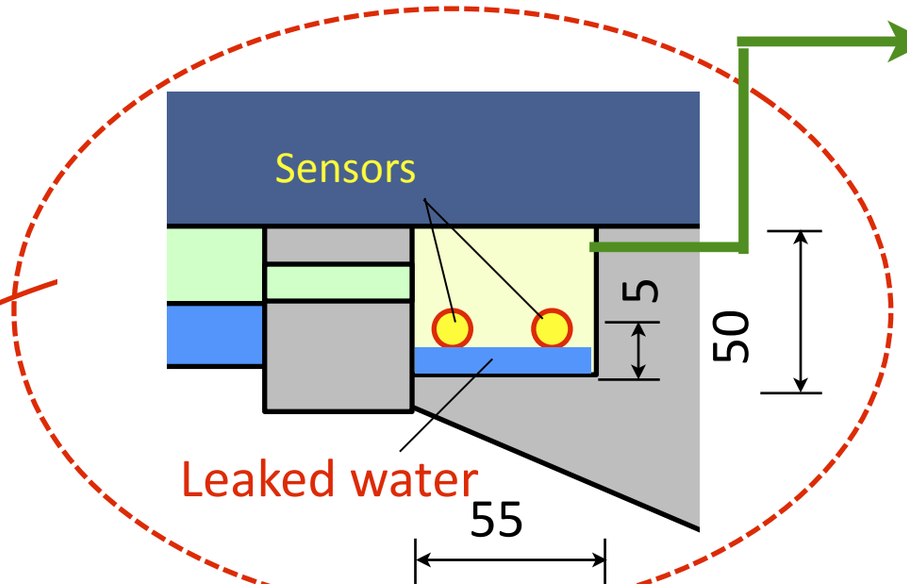




- Total number of thermal cycles due to beam trip for 5th target is ca. 2500
- Structural design, that allowed the seal welding without groove, was attributed to the water leak

Water leak of 7th target





Leak sensor layout

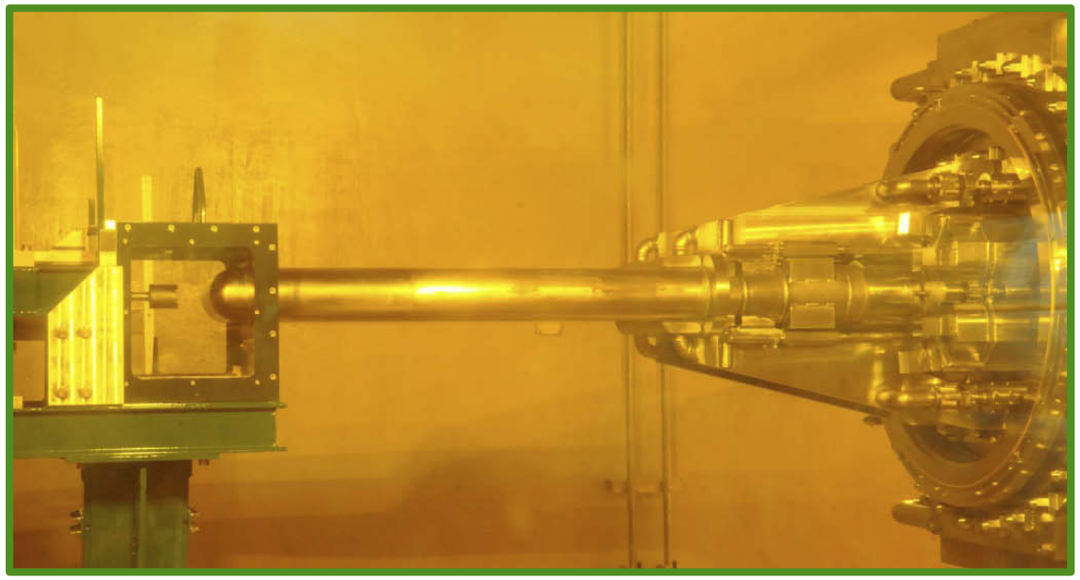
How we judged the water leakage

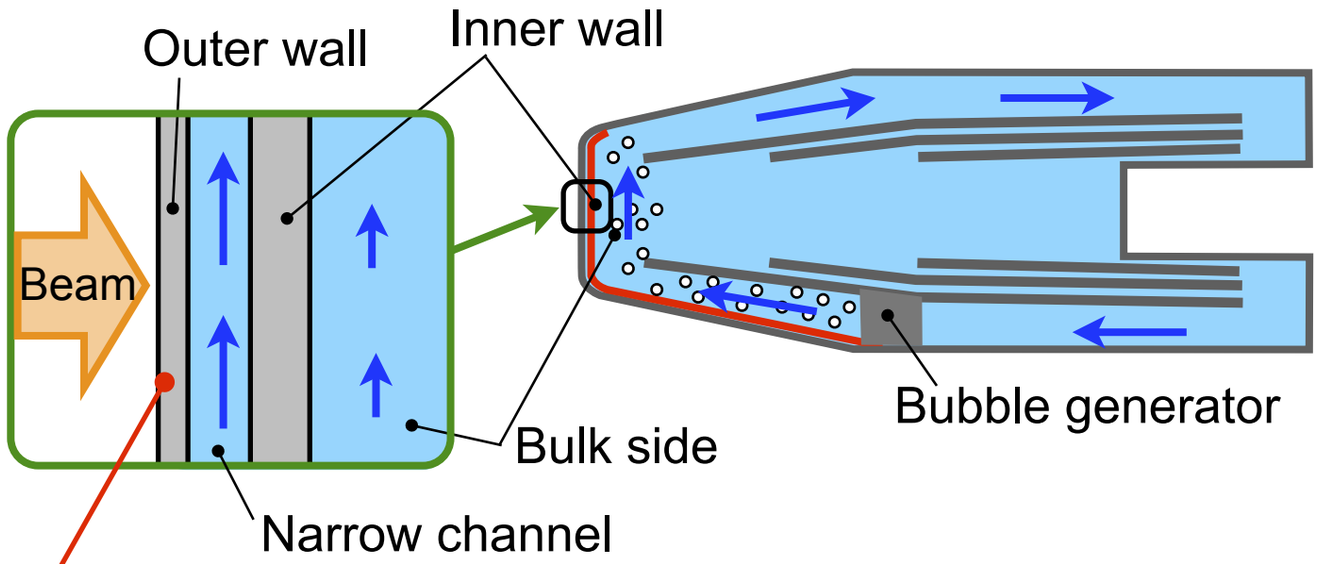
- No-mercury related radio active gas was detected by gas monitoring system
- Electric resistance of sensor showed 5~6 kΩ (same as water)
- Pressure of helium layer correlated closely with pressure change in water layer

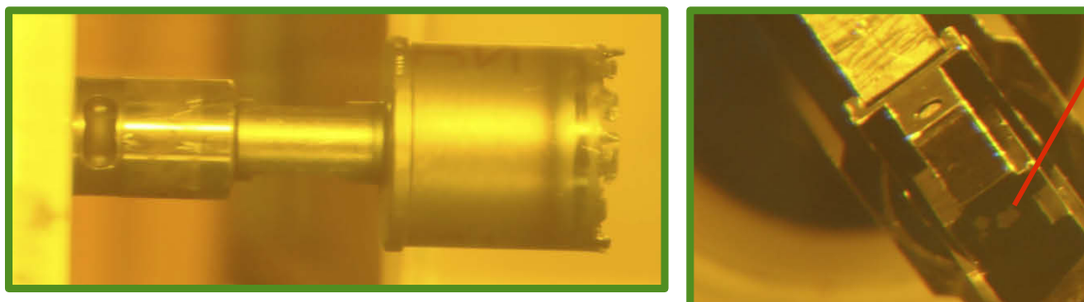
- 7th target was failed by water leak two weeks after staring 500 kW operation
- Two leak sensors detected leak in operation Nov 20th, 2015
- **Leak location was inner water shroud, but not yet found pinpoint location**

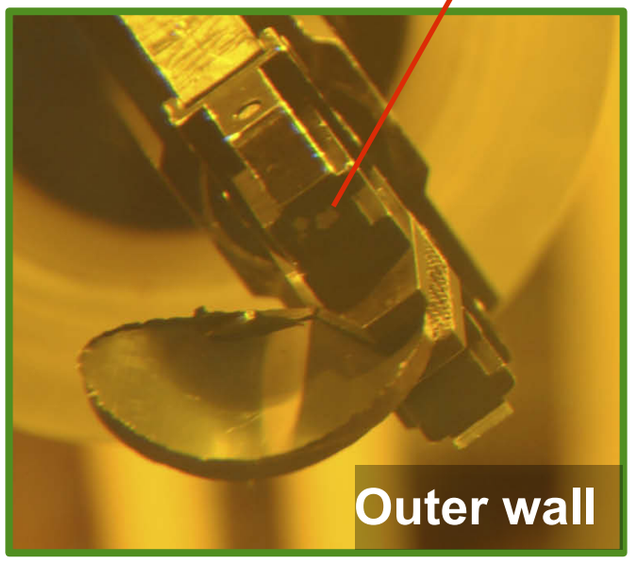
5th target

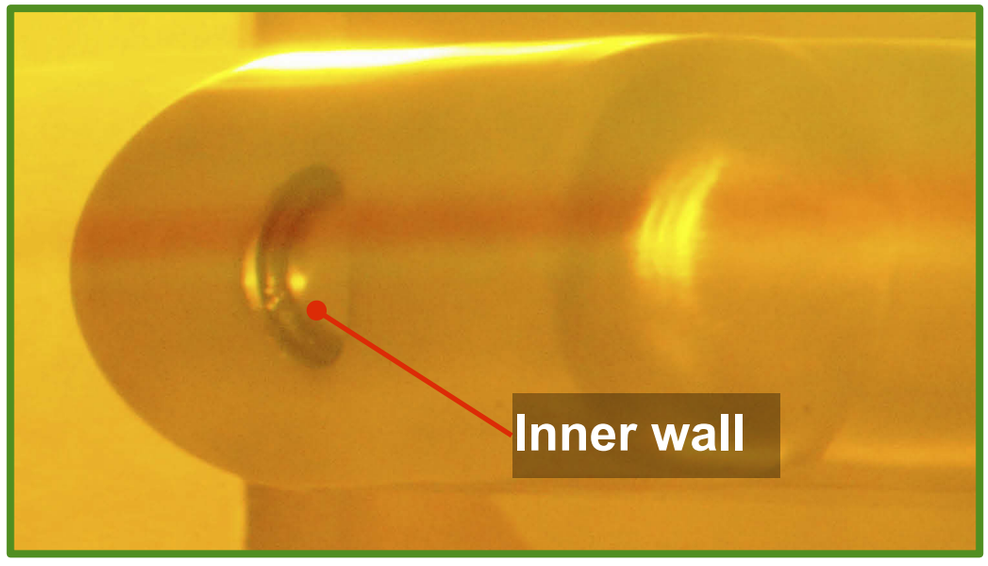
Inspection of specimen cut out from 5th target











- Beam window of failed target vessel was cut to observe cavitation damage inside mercury vessel
- Cavitation damage on narrow channel was measured by replica method
- Innermost surface of beam window could not cut due to broken of cutter

Details of damage inspection will be shown on Thursday

Operational histories of JSNS targets

Damage mitigation technologies	2008	2009	2010	2011	2012	2013	2014	2015	2016
Surface hardening	1st target Max. 220 kW 471 MWh							2nd target Max. 220 kW	In operation
Surface hardening + Injecting microbubbles				3rd target Max. 310 kW 2050 MWh					
Surface hardening + Injecting microbubbles + Double wall				5th target Max. 513 kW 670 MWh			Water shroud failed	7th target Max. 505 kW 170 MWh	

- 1st operation was stopped due to the earthquake
- 4th & 6th targets (spare) has the same structure with 5th target
- 5th & 7th targets operation were stopped by trouble of water shroud
- Fabrication 8th target is now going on and will delivery at next June