Workshop on Advanced Neutron
Source and its Application
4 - 5 Nov. 2017

Present status of neutron target on J-PARC

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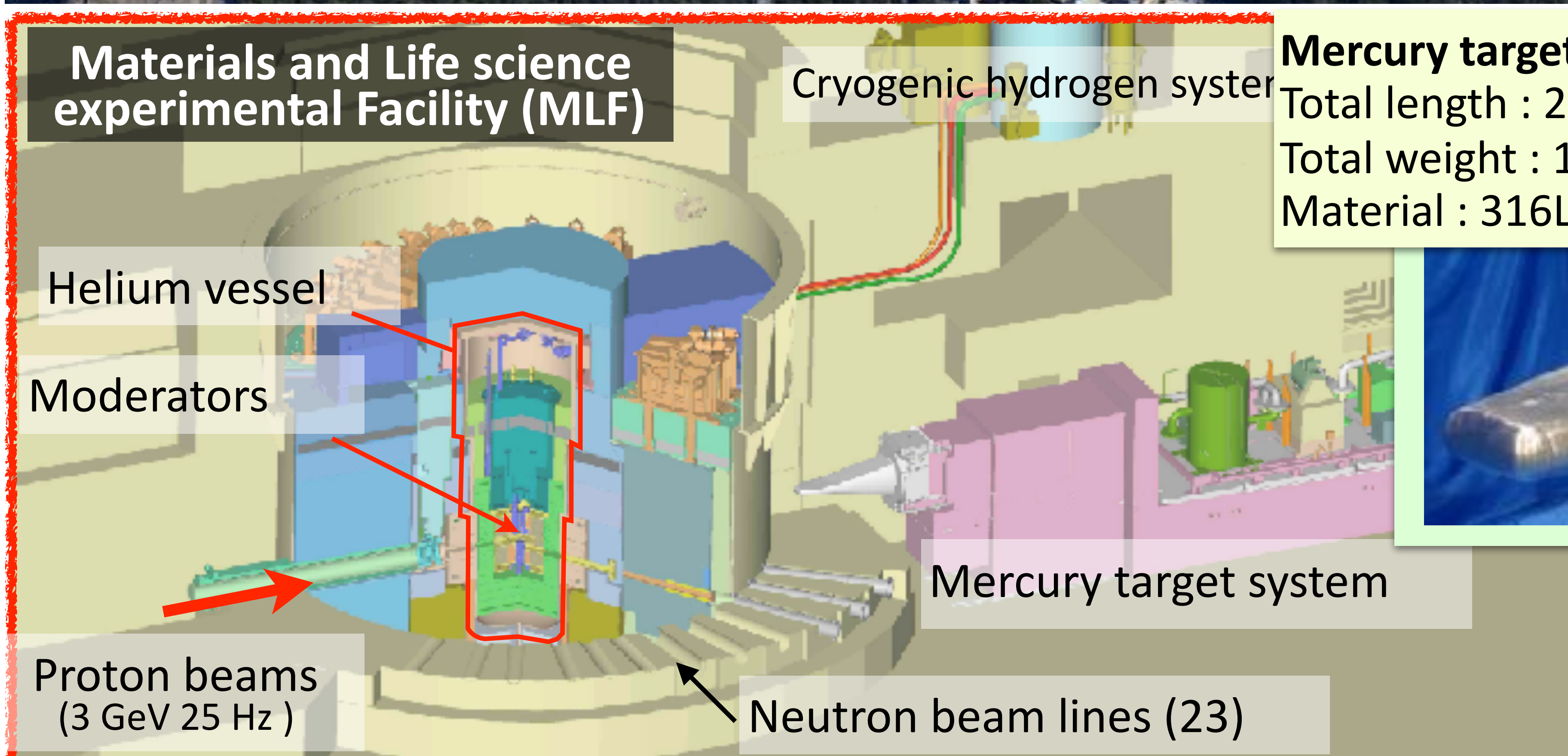
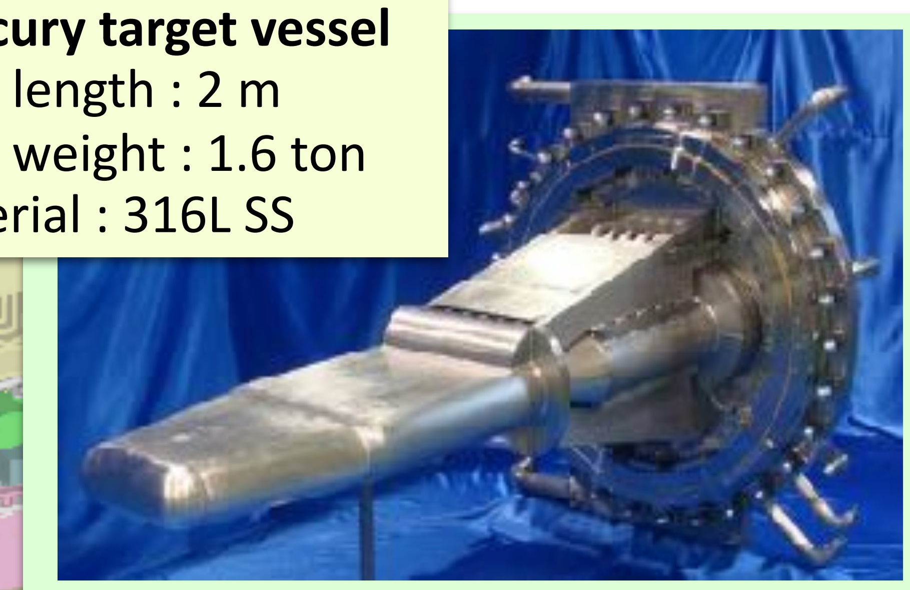
- **Summary**

Spallation neutron source in J-PARC

Japan Proton Accelerator Research Complex in JAEA Tokai-site

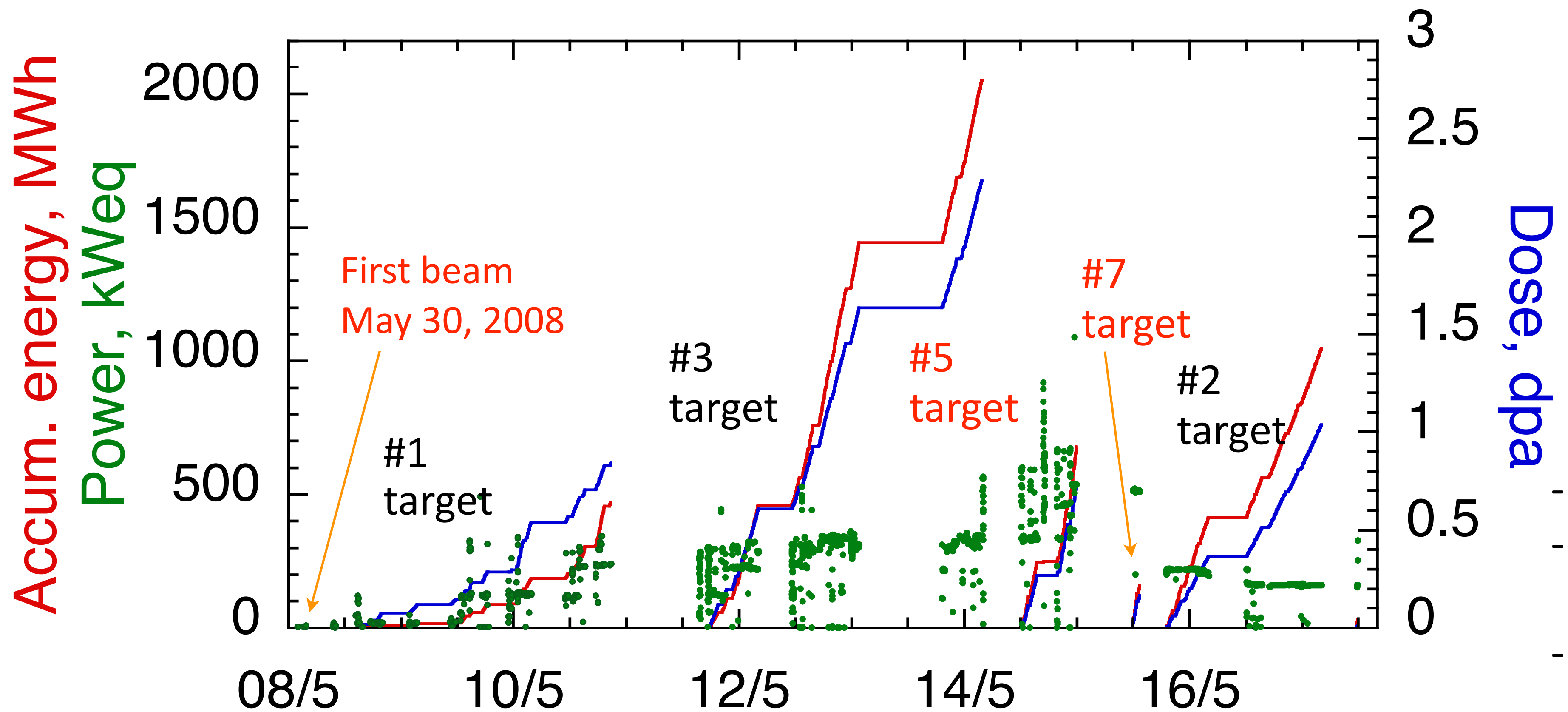


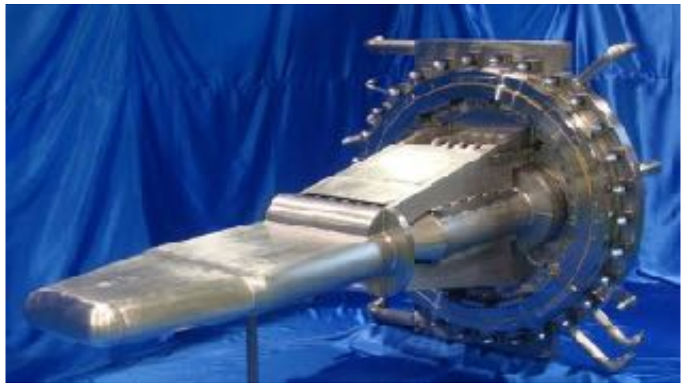
Mercury target vessel
Total length : 2 m
Total weight : 1.6 ton
Material : 316L SS



Provides neutron beams for materials and life science and industrial use

Operation histories for J-PARC mercury targets

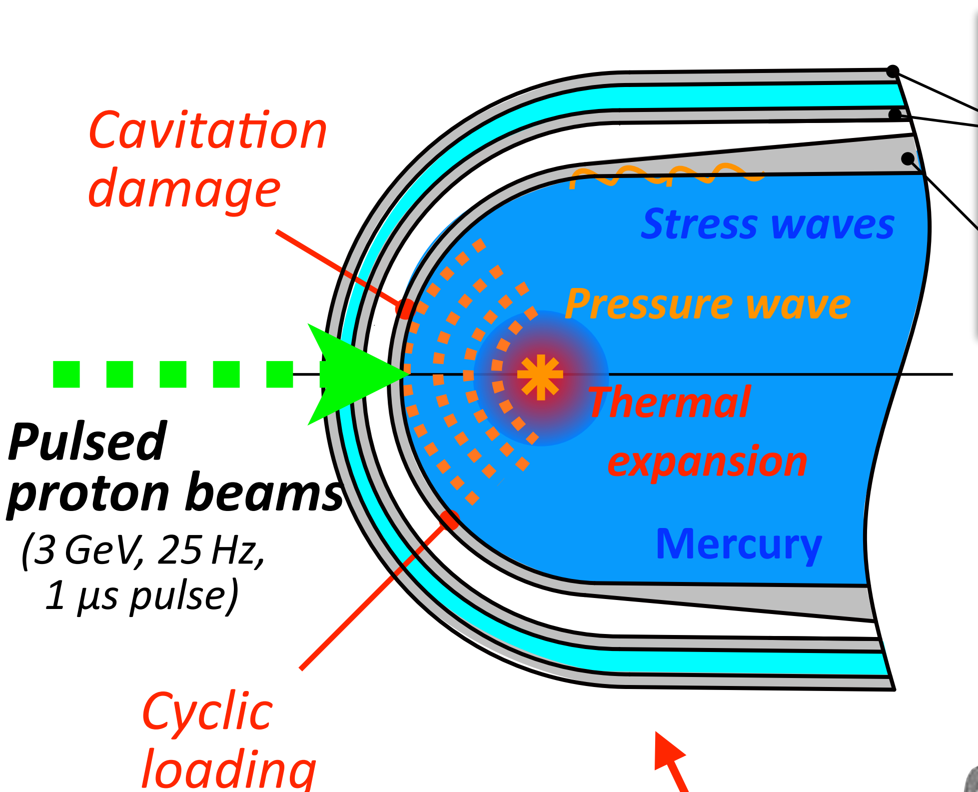




- Target ID is fabrication number
- Operation time calculated from the number of pulses at 25 Hz
- kWqq denotes power/pulse

	From	Due	Operation time, h	Average beam power, kW	Accumulated energy, MWh	Accumulated dose, dpa	Remaks
#1	2008/5	~2011/11	3713	127	471	0.84	Pneumatic bellows failed by earhquale
#3	2011/12	~2014/6	7537	272	2050	2.28	
#5	2014/10	~2015/4	1672	400	670	0.73	Water leak from outer water shroud
#7	2015/10	~2015/11	308	516	159	0.17	Water leak from inner water shroud
#2	2016/2	2017/7	5801	181	1048	1.04	
#8	2017/10~	in service		300			

Proton beam-induced pressure waves in mercury



Mercury target vessel
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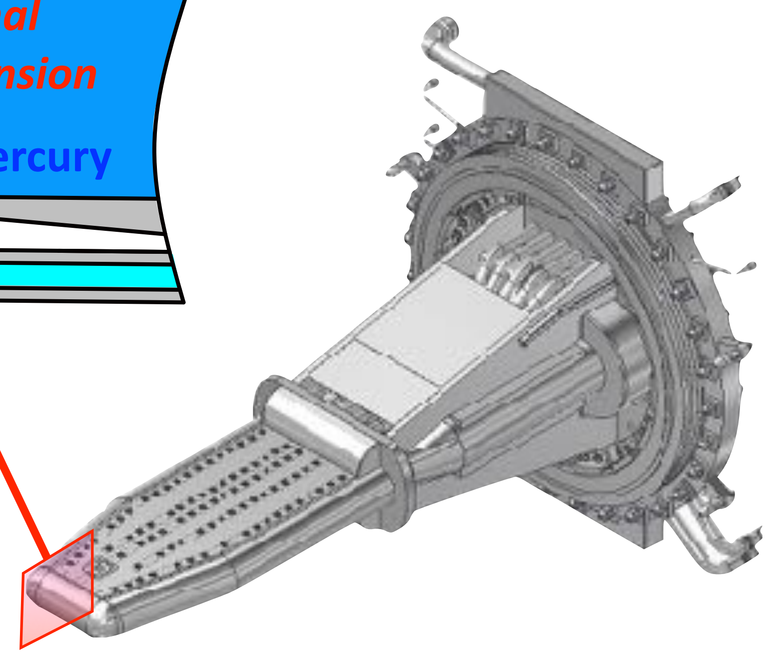
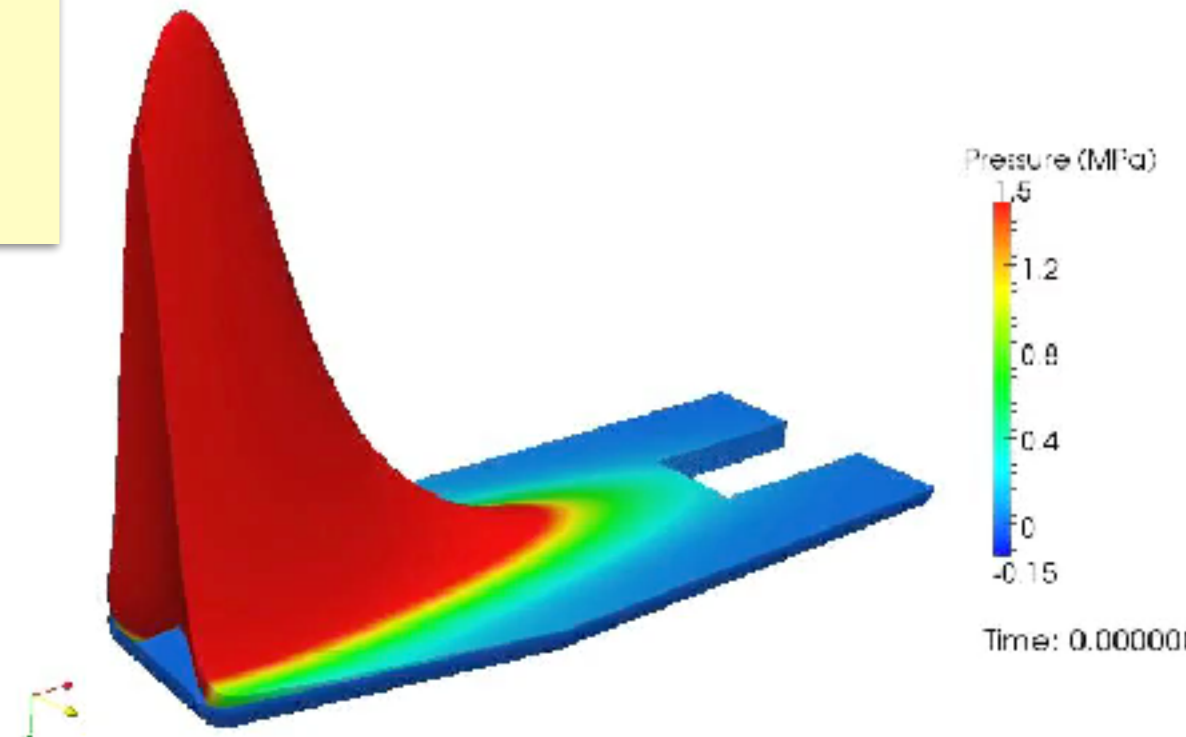


316L welded structure



Pressure wave propagation in mercury (ca.40 MPa@ 1MW)

Irradiation damage	3 Gev proton and neutron irradiation
Cavitation damage	Proton beam-induced pressure waves in mercury causes cavitation
Fatigue damage	Loading cyclic with high strain rate stress in service life (~4.5x10^8) TIG welded multi-walled structure (back bead)

Factors to decide lifetime of target

Radiation damage (incl. water shroud)

- Depending on beam power and operation time (8 dpa@5000MWh)
- Designed lifetime:1 MW 2500 h

  Tentative dose : 5 dpa (10 dpa allowable)

Damage inside mercury vessel

- **Cavitation damage**

  Depending on beam power & operation time
- **Measures**

  1st : Surface modification

  3rd: Gas microbubbles injection

  5th: Bubbling and double walled structure

  Prediction and measurement of damages for lifetime estimation

Fatigue by pressure waves

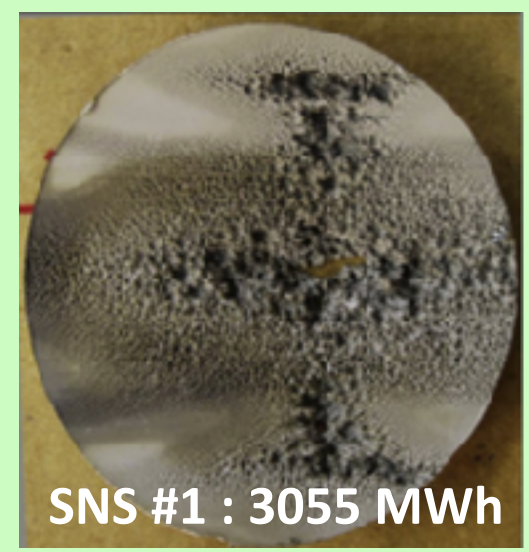
- Very high-cycle fatigue
- Induced by beam injection

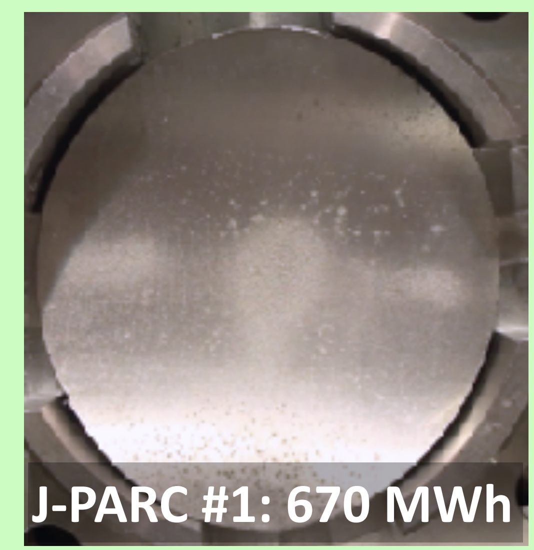
  4.5×10^8 cycles for 5000 hours (1Y)

Fatigue by thermal stress

- Low cycle fatigue
- caused by beam trip

  ca.10^4 cycles for 5000 hours





SNS mercury target vessel (ORNL)

D. McClintock, et al., JNM 431(2012)

Cavitation damage is dominant factor to decide lifetime in the present situation

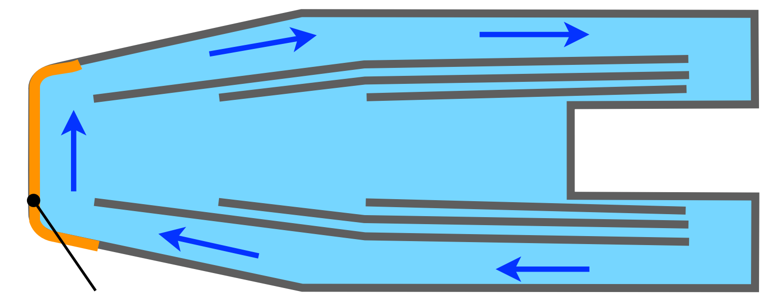
Cavitation damage mitigation technologies

Targets
Fabrication number

1st

Surface hardening

Reduce cavitation damage
Nitriding & Carburizing, Kolsterising®



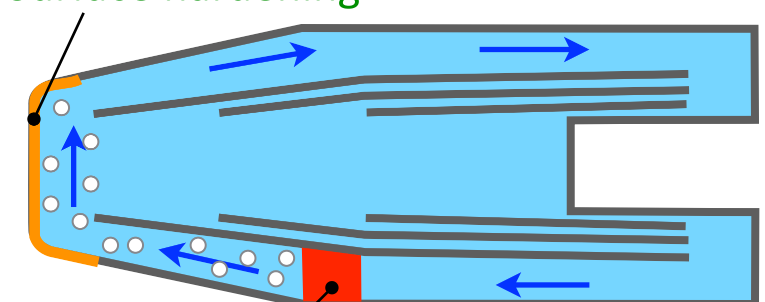
2nd target (Spare) No-bubbling techniques
to mitigate pressure waves and cavitation damage

3rd

4th

Microbubble injection

Reduce pressure wave and cavitation damage
Inject helium gas microbubbles (R<50 μm)
into flowing mercury (VF:10^{-2} in flow ratio)

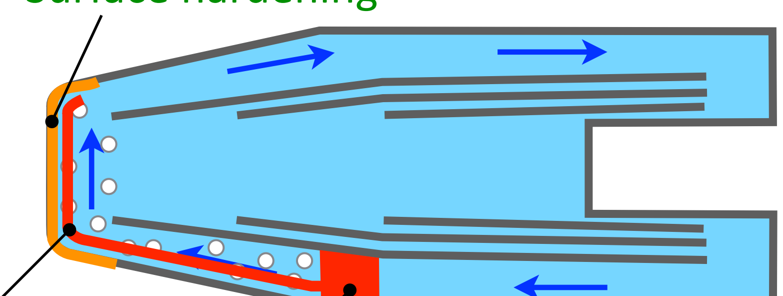


3rd target vessel with bubble generator

5th
|
8th

Double walled structure

Reduce cavitation damage by high-speed
mercury flow and narrow gap

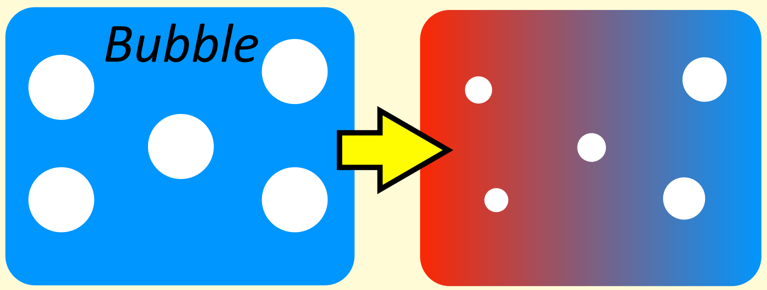


Order of target vessel operation

	1st →	3rd →	5th →	7th →	2nd →	8th
Year	2008	2011	2014	2015	2016	2017

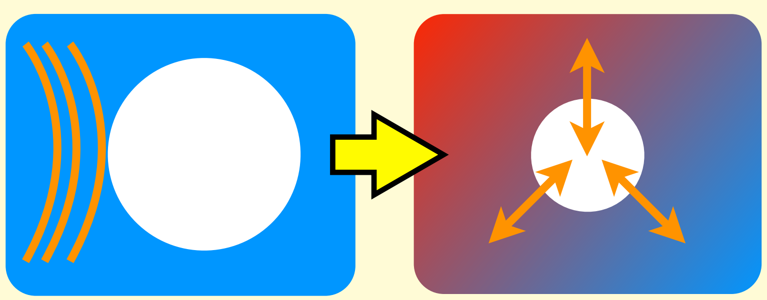
Effect of gas microbubble injection

Absorption



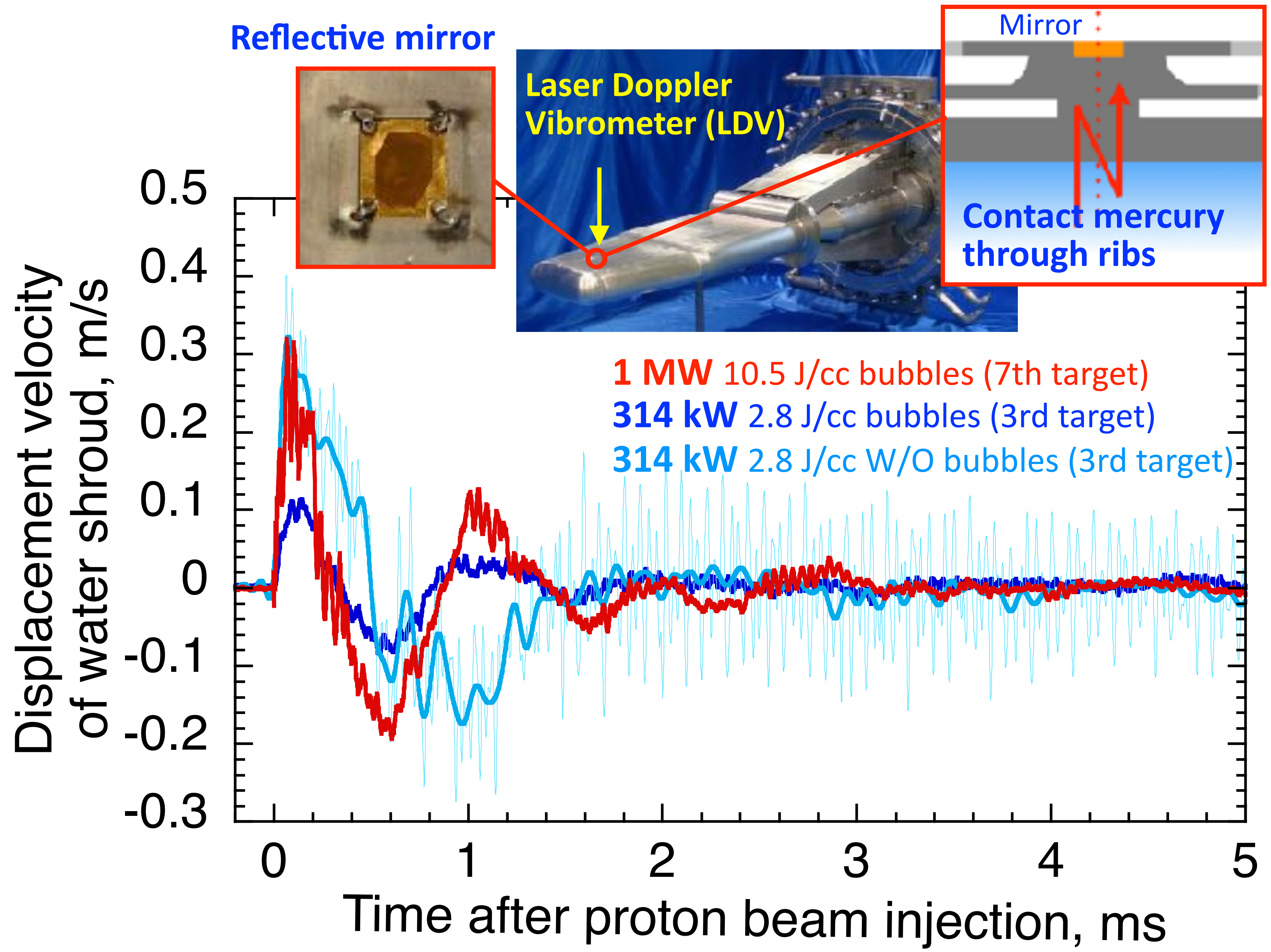
Absorb thermal expansion
by **contraction** of microbubbles

Attenuation



Attenuate by thermal dissipation of kinetic energy (**bubble oscillation**)

Bubbles works on shock absorber

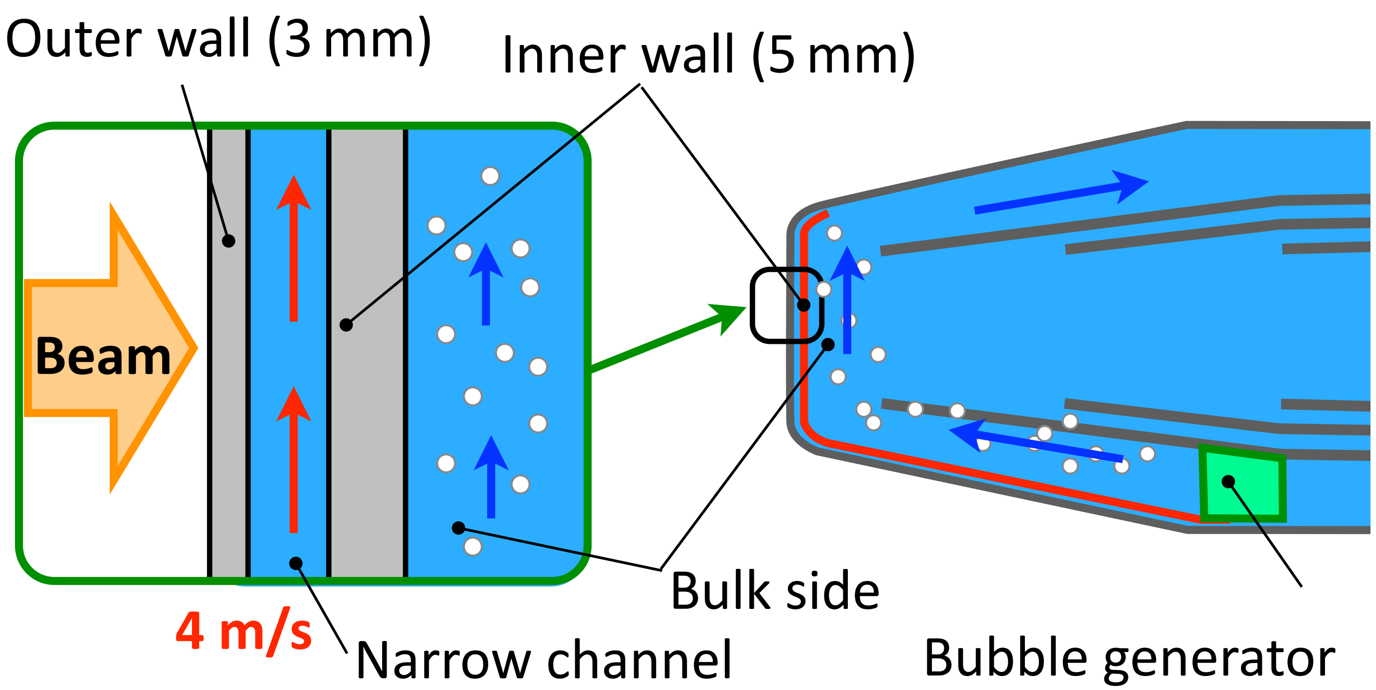


Vibration time responses for 3rd and 7th target

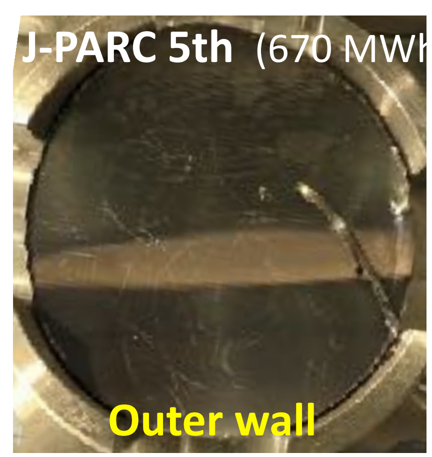
- Target system has the LDV diagnostic system (*LDV, Retro-reflecting corner cube mirror*)
- Peak amplitude of 1 $MW_{equiv.}$ study (OCT. 2015) showed similar amplitude of 300 kW W/O bubble ➡ **Bubbles extremely mitigates pressure waves**
- Peak amplitude of velocity for bubbles case seems to be 1/4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

Double-walled beam window

5th target ~

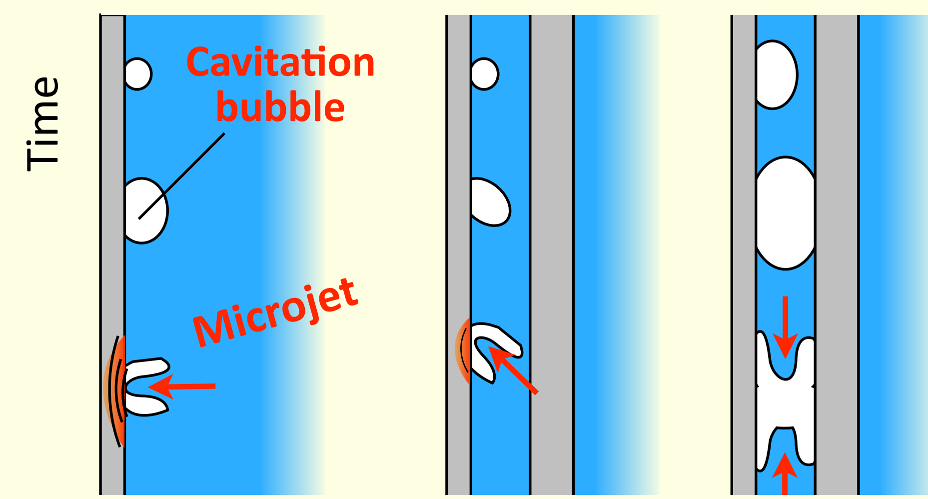


D. McClintock et al., J. Nucl. Mater. 431 (2012) 147–159



T. Naoe, et al., JNM in press

Expected damage mitigation effect



Single wall **Double wall**

Flow effect *Narrow gap effect*

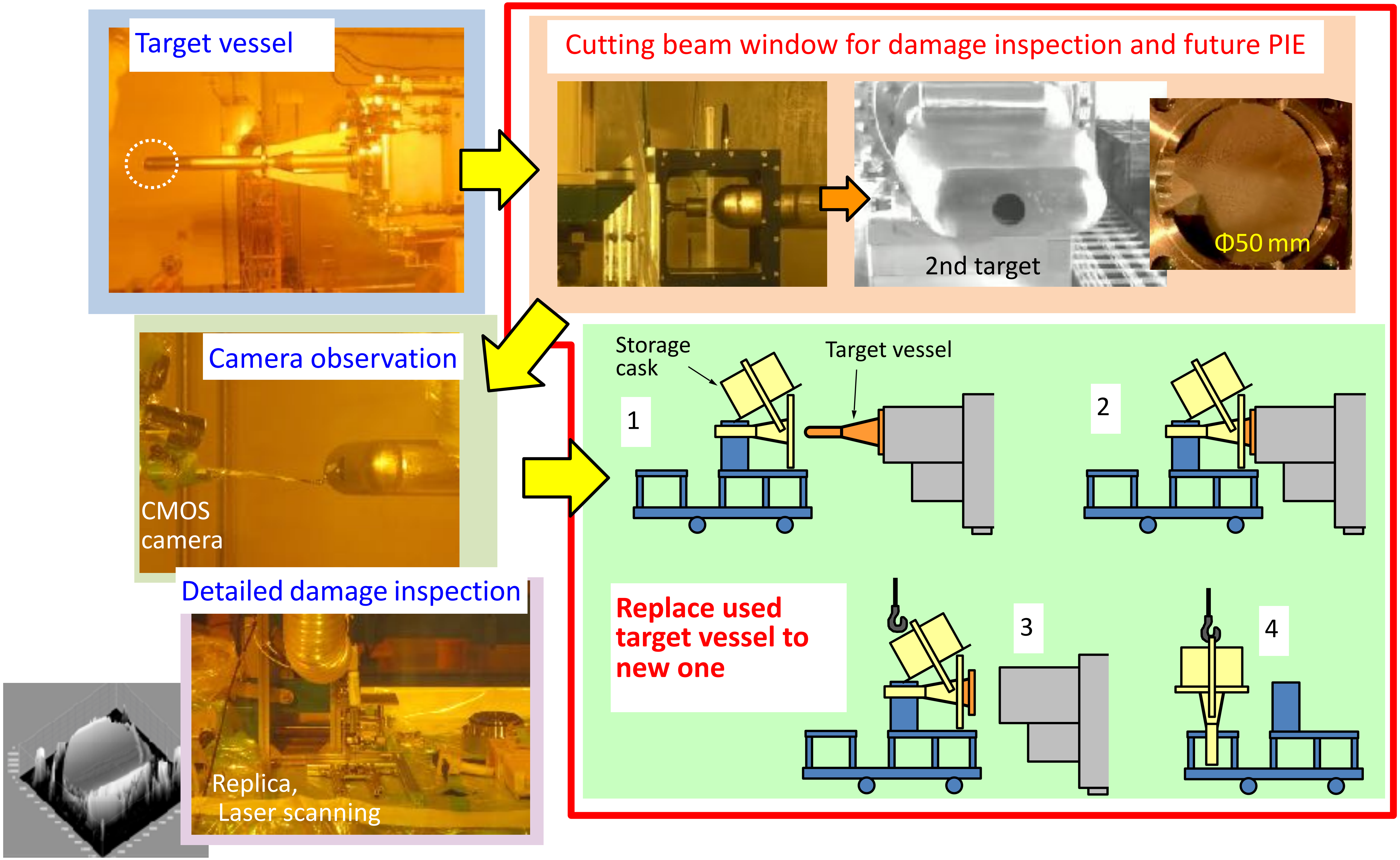
Deform bubble growing/collapsing by high-speed flow

Interrupt bubble growing/collapsing by narrow gap

Direction change of microjet ejection reduces cavitation damage at wall

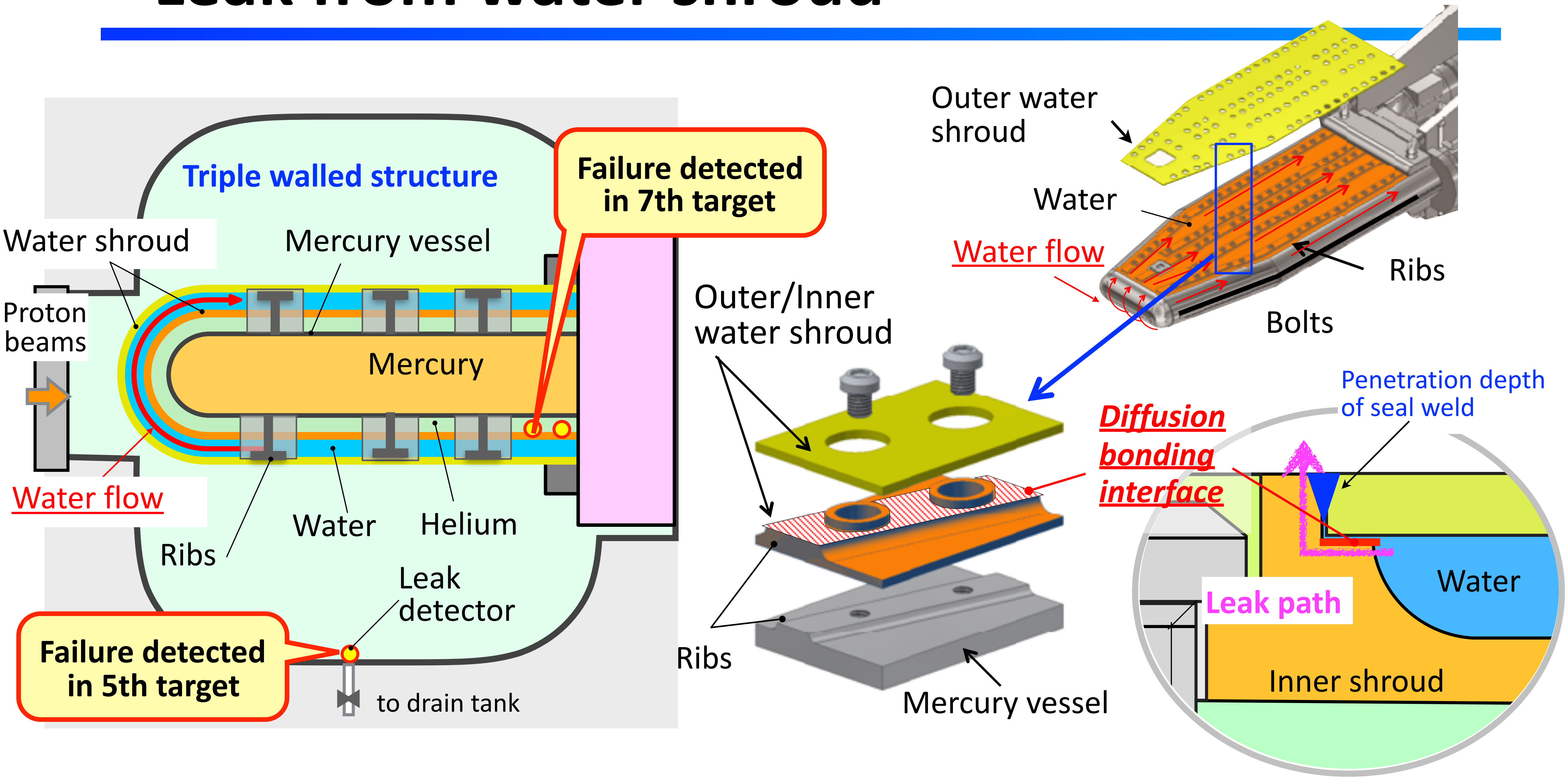
- Expects damage reduction effects inside narrow channel
  - Flowing effect (increase pressure gradient around surface)
  - Narrow channel effect (asymmetrically bubble collapsing)
- SNS/ORNL target has actual results of damage mitigation effect by double-walled structure

Cutting and replacement of target vessel



- Target vessel replaces every year (Designed lifetime: 5000 MWh)
- Cut beam window for damage inspection and future PIE
- Replace new target by full-remote handling

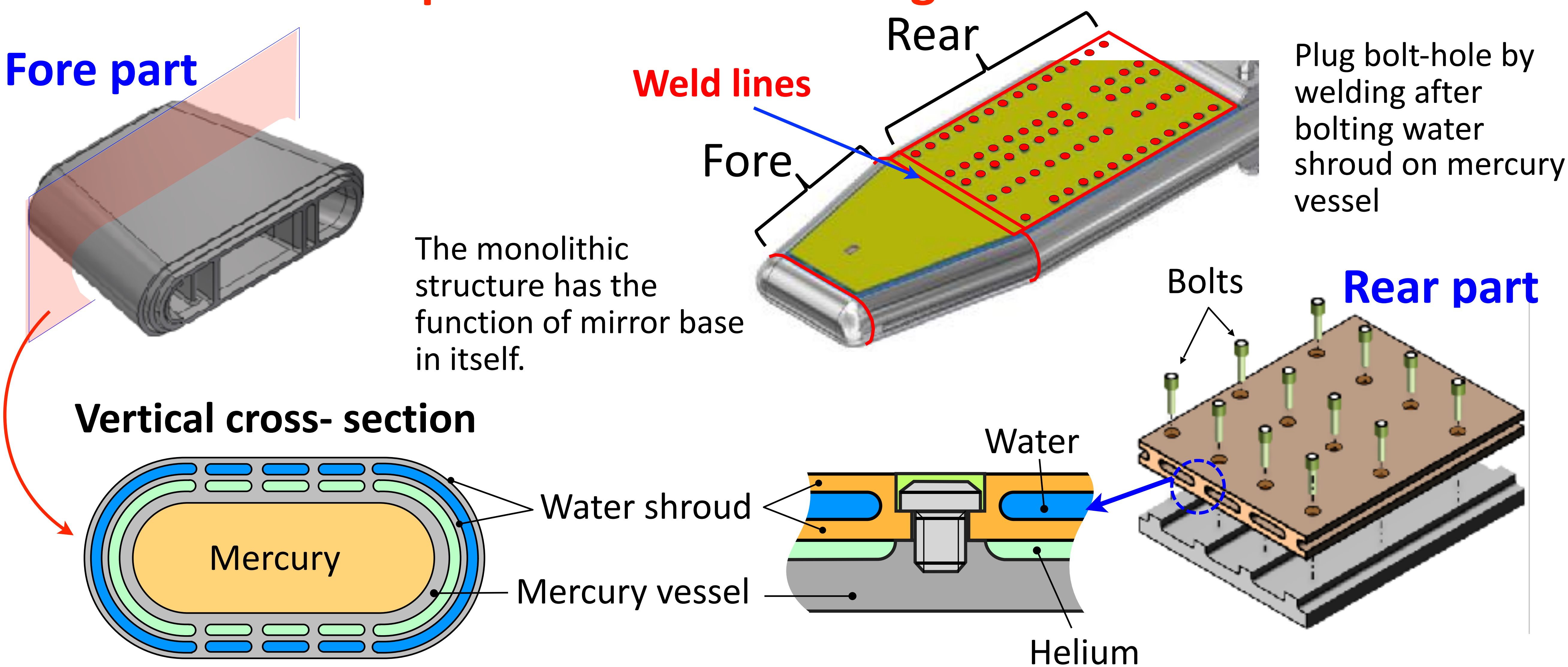
Leak from water shroud



- 5th and 7th targets were failed due to water leak at water shroud
- Water leaked to outside of target vessel (#5), inside of target vessel (#7)
- Bolt head and outer/inner shroud interface was welded by TIG weld
- Lack of penetration depth for seal welding led leakage of water (#5)
  Fatigue crack was propagated thermal cycles by beam trip from weld defect

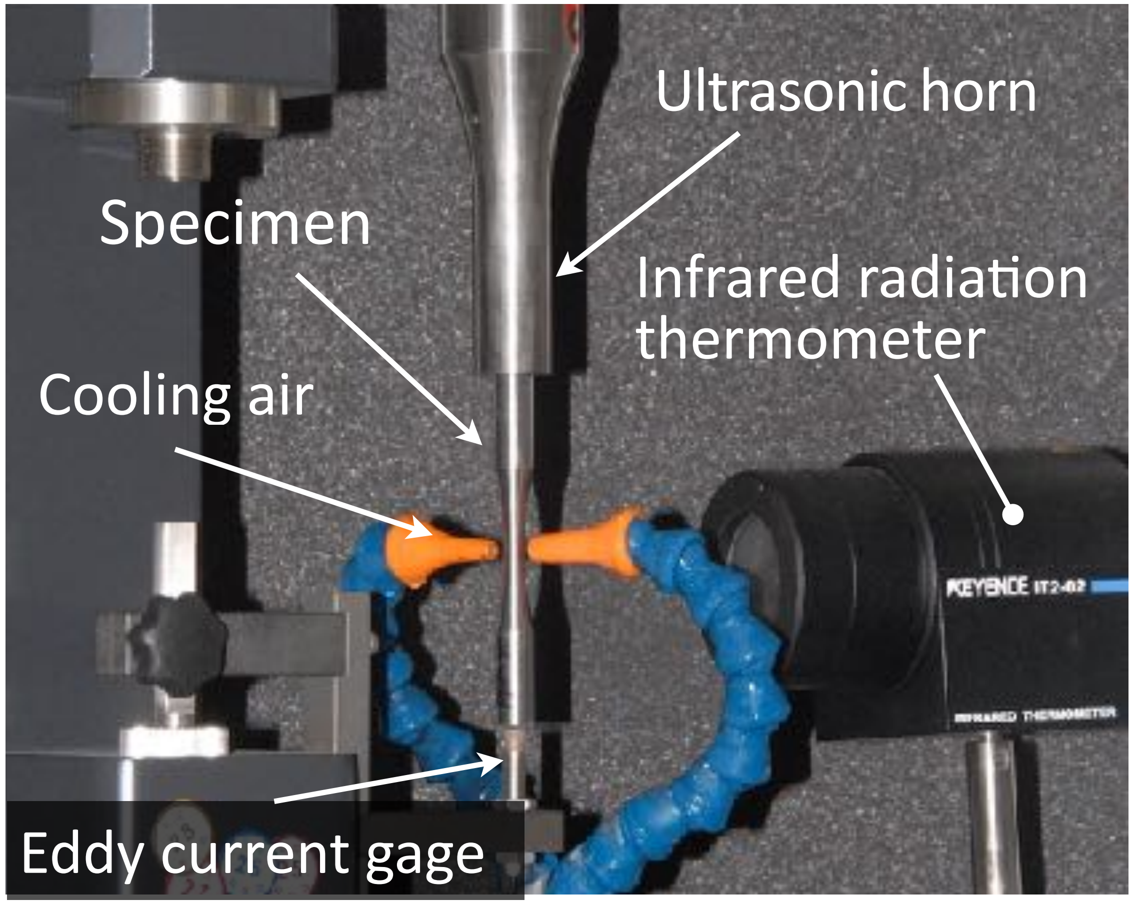
Lesson and improvement from failures

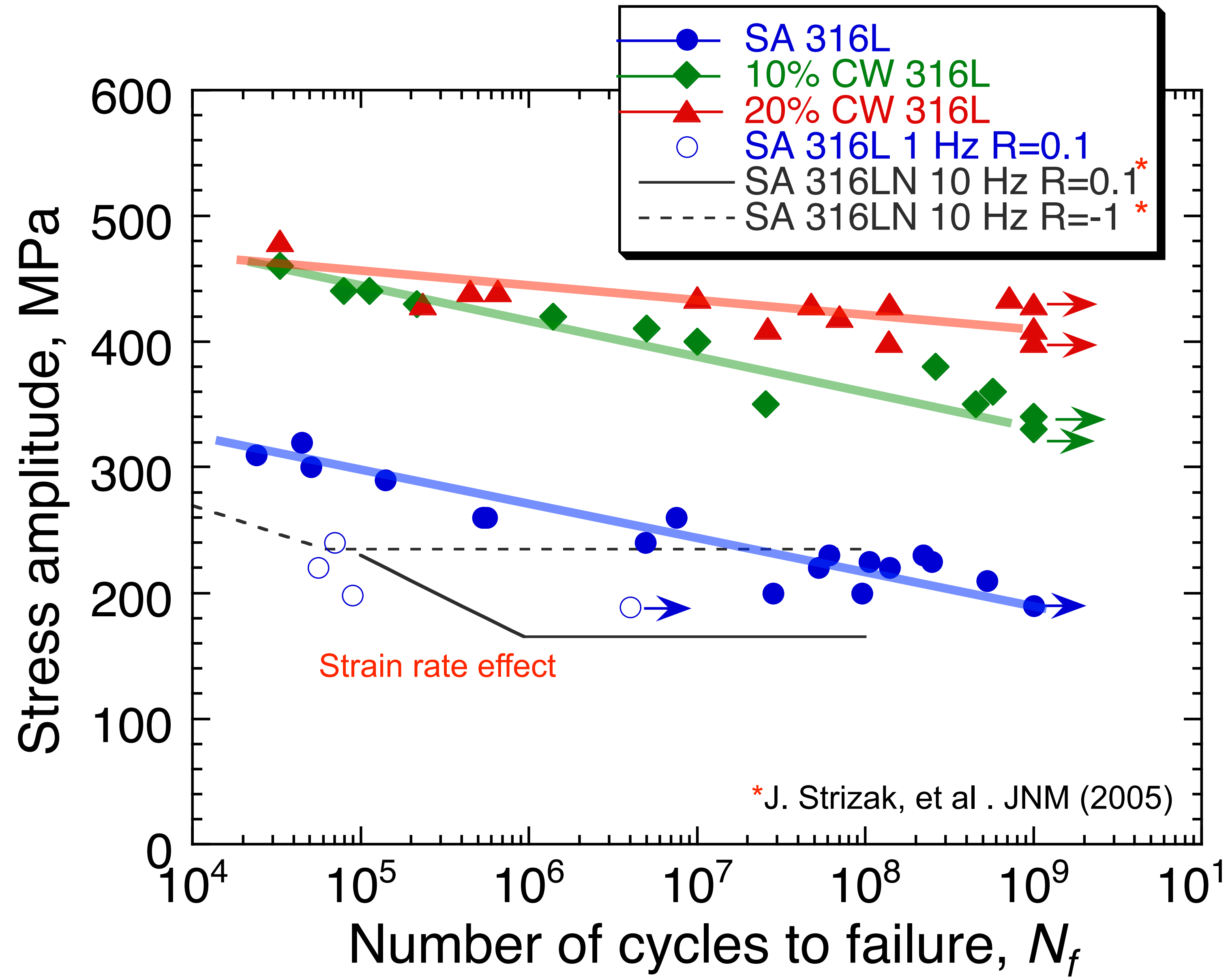
Improvement for 8th target



- Wire EDM was applied to reduce welding line and to eliminate diffusion bonding
- Monolithic structure of LDV mirror base seemed to be induce un-welded region which acts as notch, and fatigue crack propagated by pressure waves
- Strengthen the inspections for weld lines by RT and UT

Gigacycle fatigue

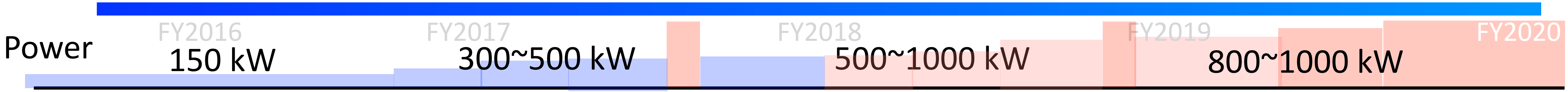




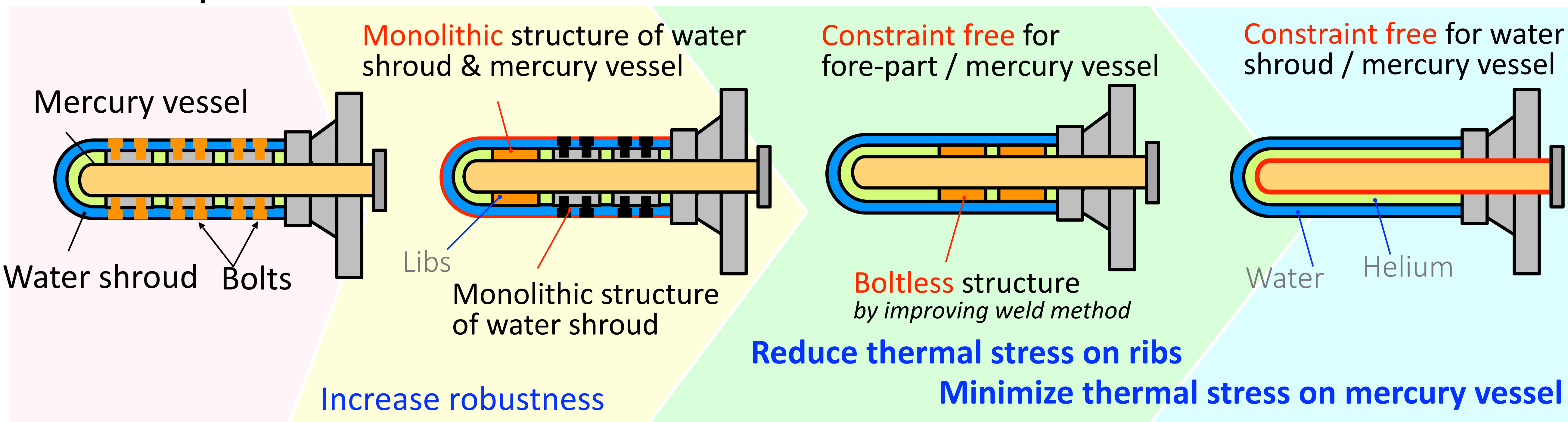
- Cyclic loading (50 1/s, 4.5×10^8 cycles at 25 Hz) by proton beam-induced pressure waves
- Gigacycle fatigue, non-metallic inclusion, insufficient data for welding
- Stress applied through the ultrasonic resonance of 20kHz (430 Hz for intermittent loading)
- Target vessel (triple walled structure) assembled with TIG weld

  →Now we are investigating effect of **welding and weld bead** on gigacycle fatigue

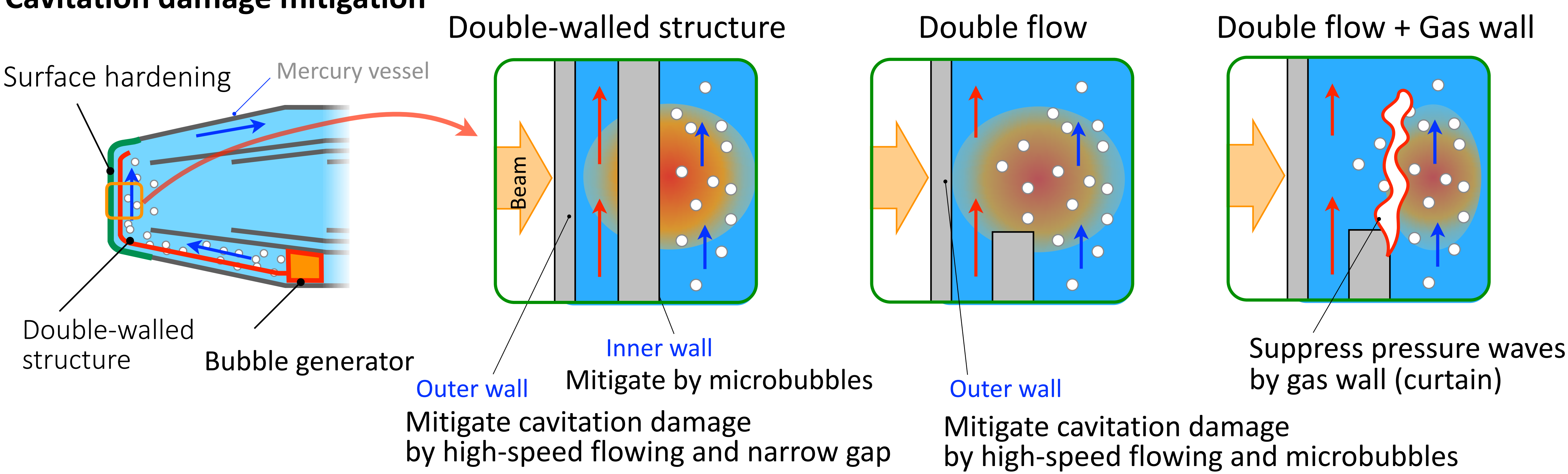
Upgrade scheme to achieve MW stable operation



Structure improvement



Cavitation damage mitigation

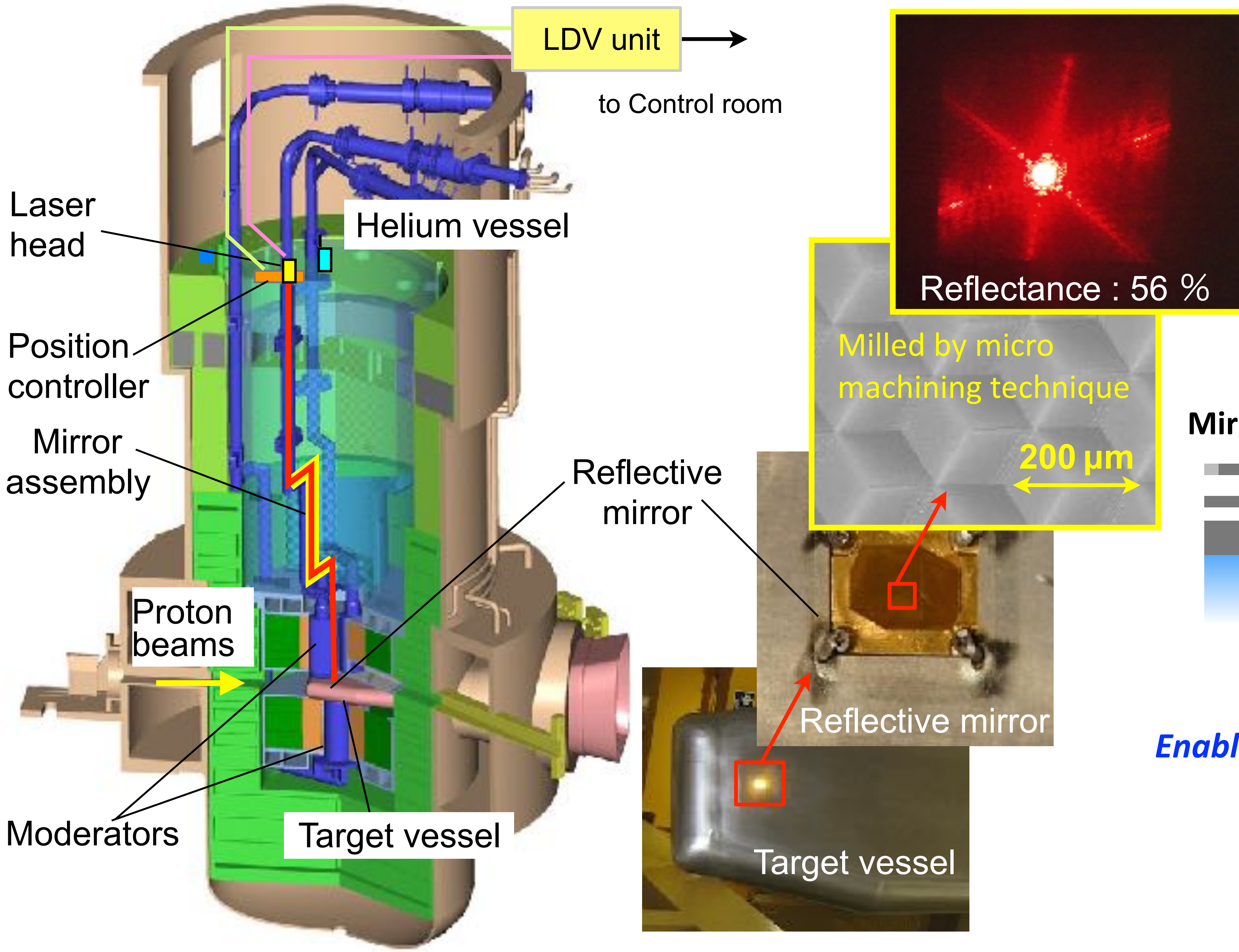


Summary

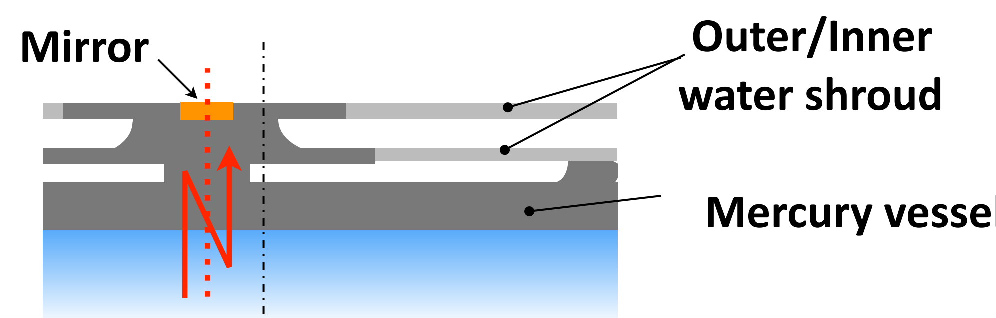
- Cavitation damage in mercury is the critical issue to decide lifetime of target vessel
- 1 $MW_{equiv.}$ beam experiment was achieved in 2015, and confirmed excellent effect of injecting gas microbubbles on pressure wave mitigation by LDV measurement
- Mitigation technologies are developed and demonstrated their effectiveness to reduce cavitation damage
- Effect of microbubbles injection and double-walled structure will be checked by 8th target inspection (2018 summer)
- Target structure is gradually updated for achieving 1 MW stable operation

Backup slides

Target diagnostic system



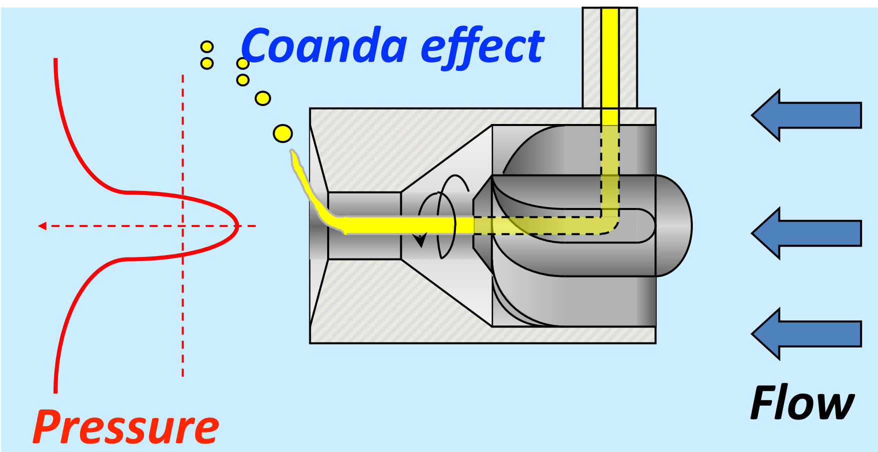
Laser Doppler vibrometer (LDV)
Velocity range: 0.01—10 m/s
Frequency range: 0.3—3 Hz
Data sampling: 1MHz



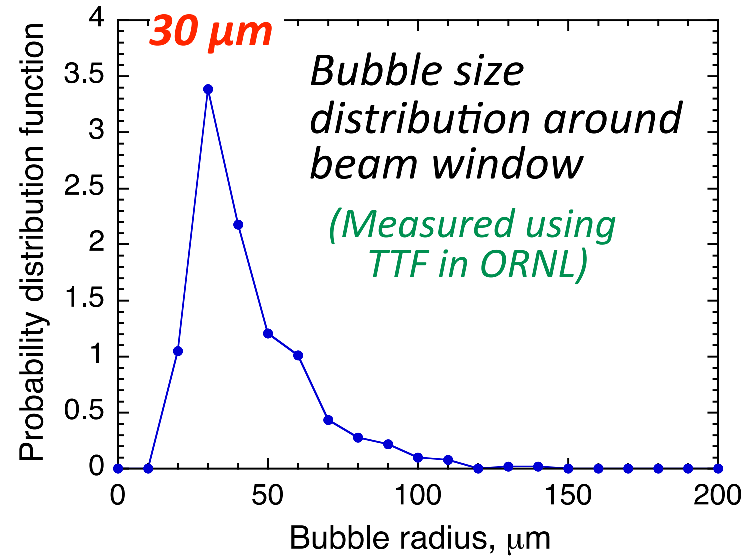
Enable to detect pressure waves in mercury

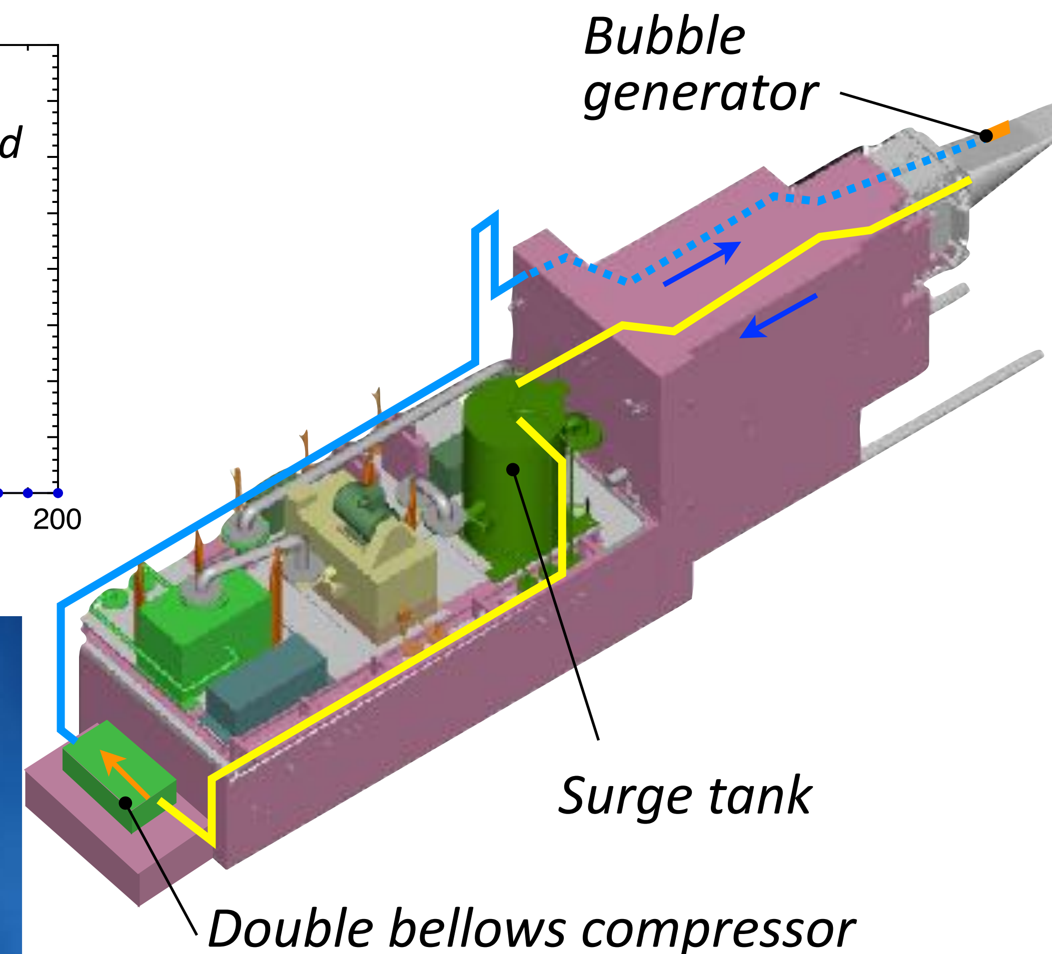
- LDV have been installed for monitoring the vibration of target vessel by proton beam injection
- Corner cube reflector was directly machined on pure gold plate by newly developed micro machining technique (Ni mirror of #1 target corroded)
- Mirror part is directly contacting with the mercury (mono-structure)

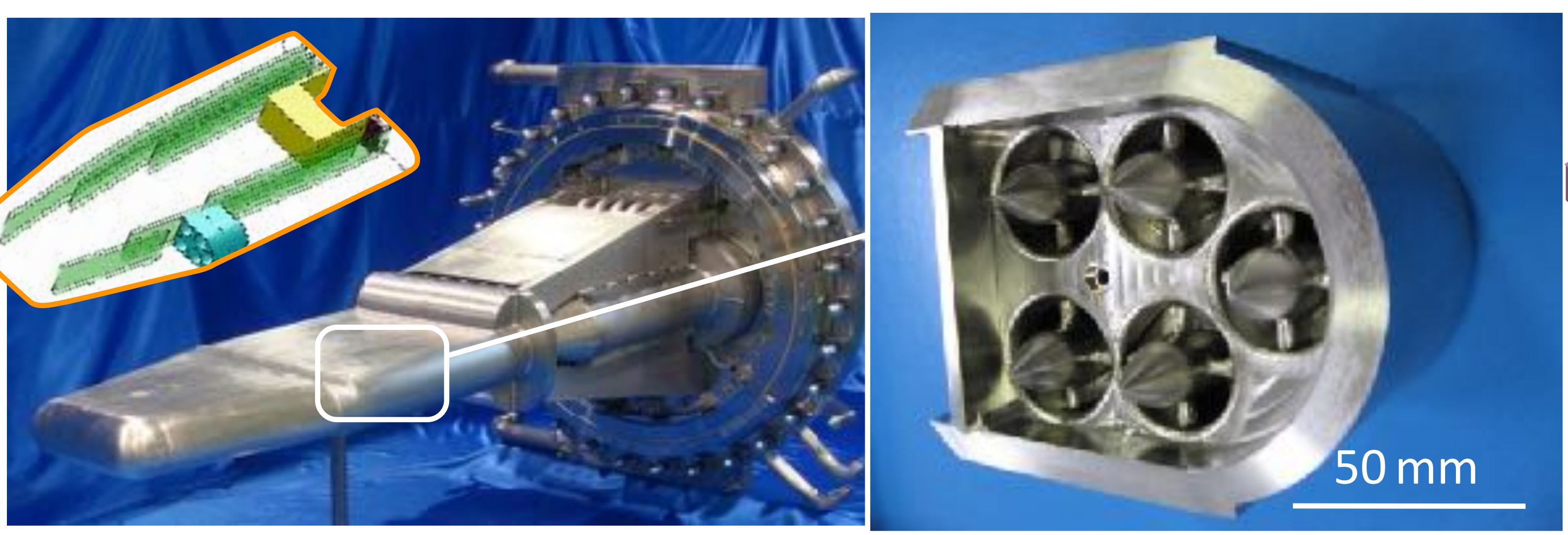
Gas microbubbles injection system



Swirl type bubble generator





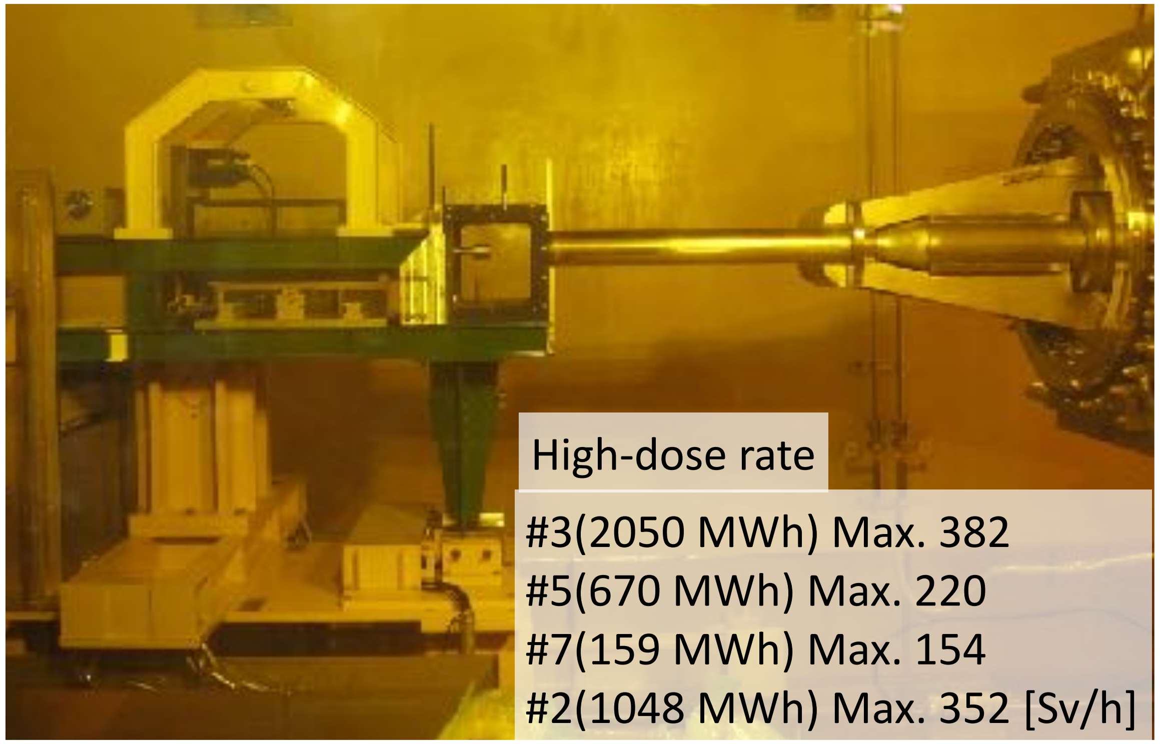


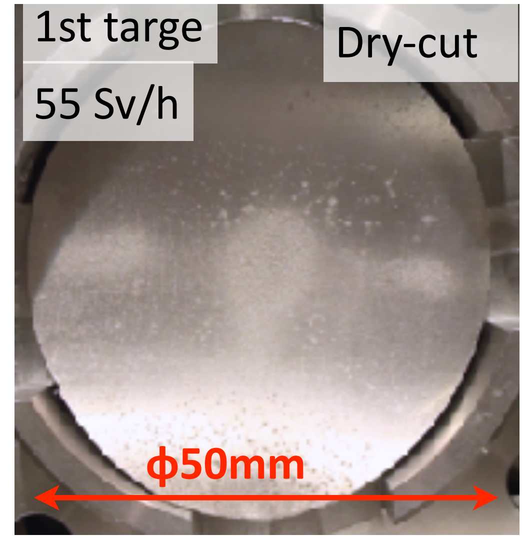
#3 target vessel with bubble generator

Mercury circulation system
(Closed helium gas loop)

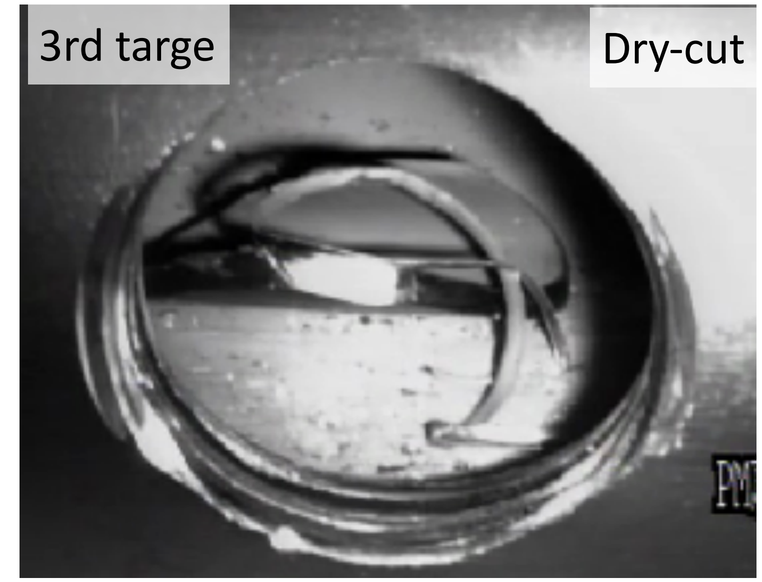
- Swirl type microbubble generator was installed from 3rd target vessel with gas circulation system to mitigate proton beam-induced pressure waves
- Peak bubble radius is 30 μm, void fraction (He/Hg flow ratio) is 10^{-2} at bubble generator

Difficulties in cutting by full remote handling

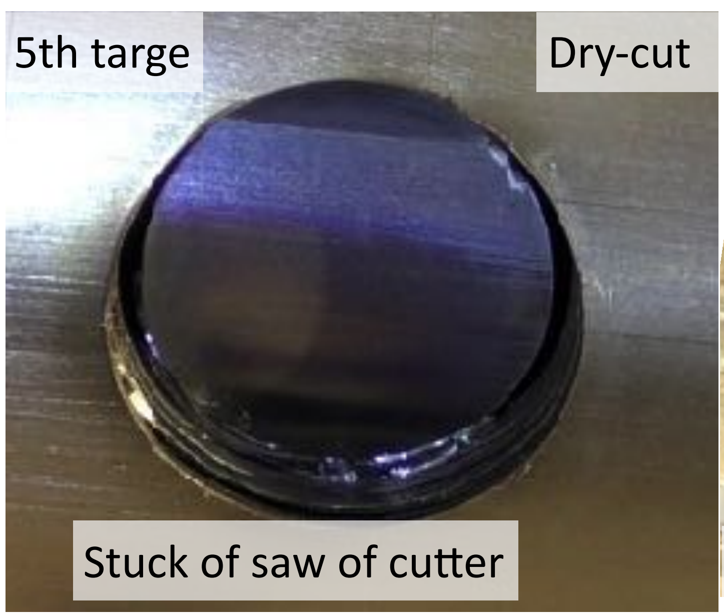


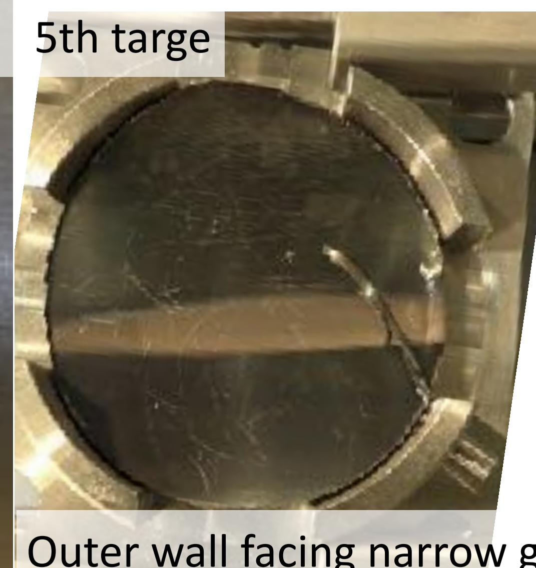


Succeed 1st cut

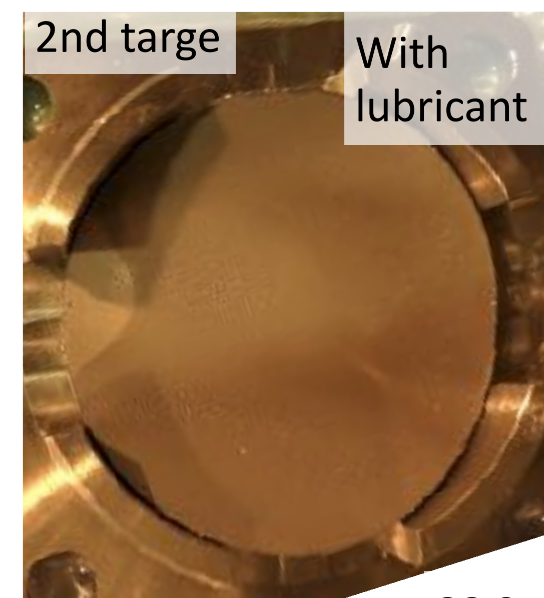


Inner most wall of 3rd target fallen inside vessel





Narrow gap mitigate damage but not enough for MW stable operation

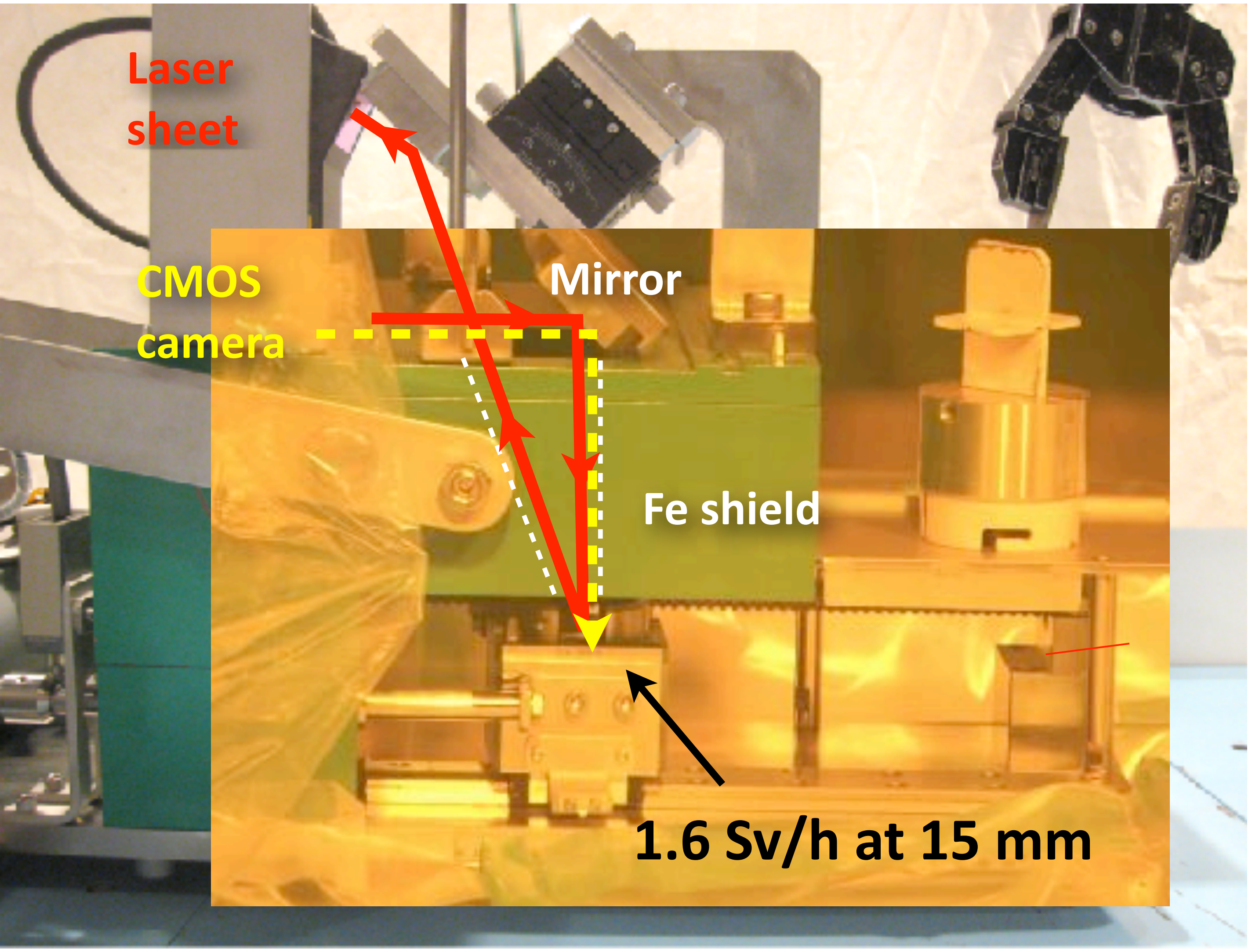


88 Sv/h

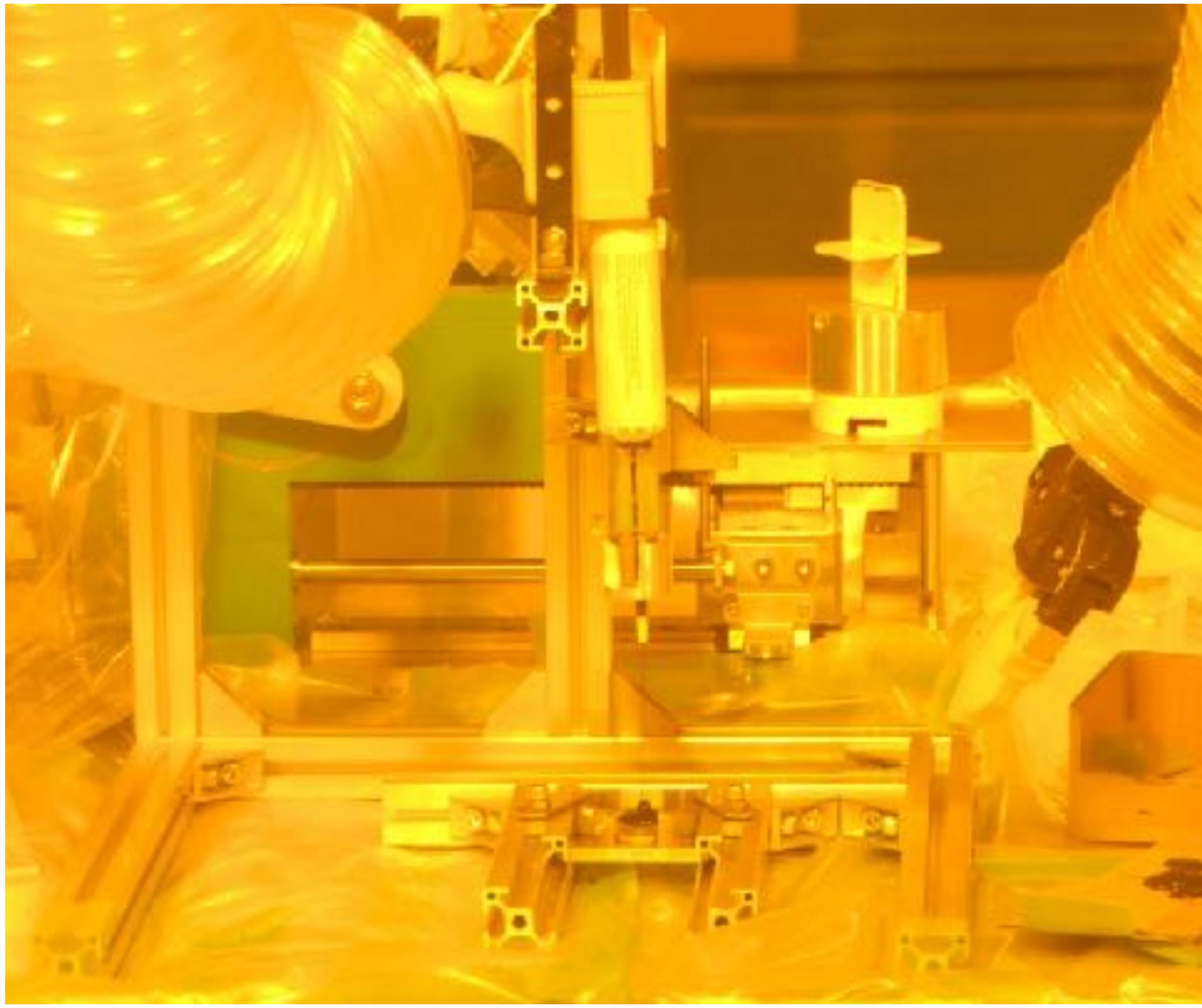
Inner most wall of 5th target remained window

Cutting performed under target fixing on trolley by full-remote handling
Nos. 1,3,5 targets cut without any lubricant —>Failed #3 and #5 cutting
No quantitative information was obtained for bubbling effect —> #8 will cut 2018
Succeeded #2 cut by optimizing cut condition (w/ lubricant)

Damage depth measurement



Laser profilometer

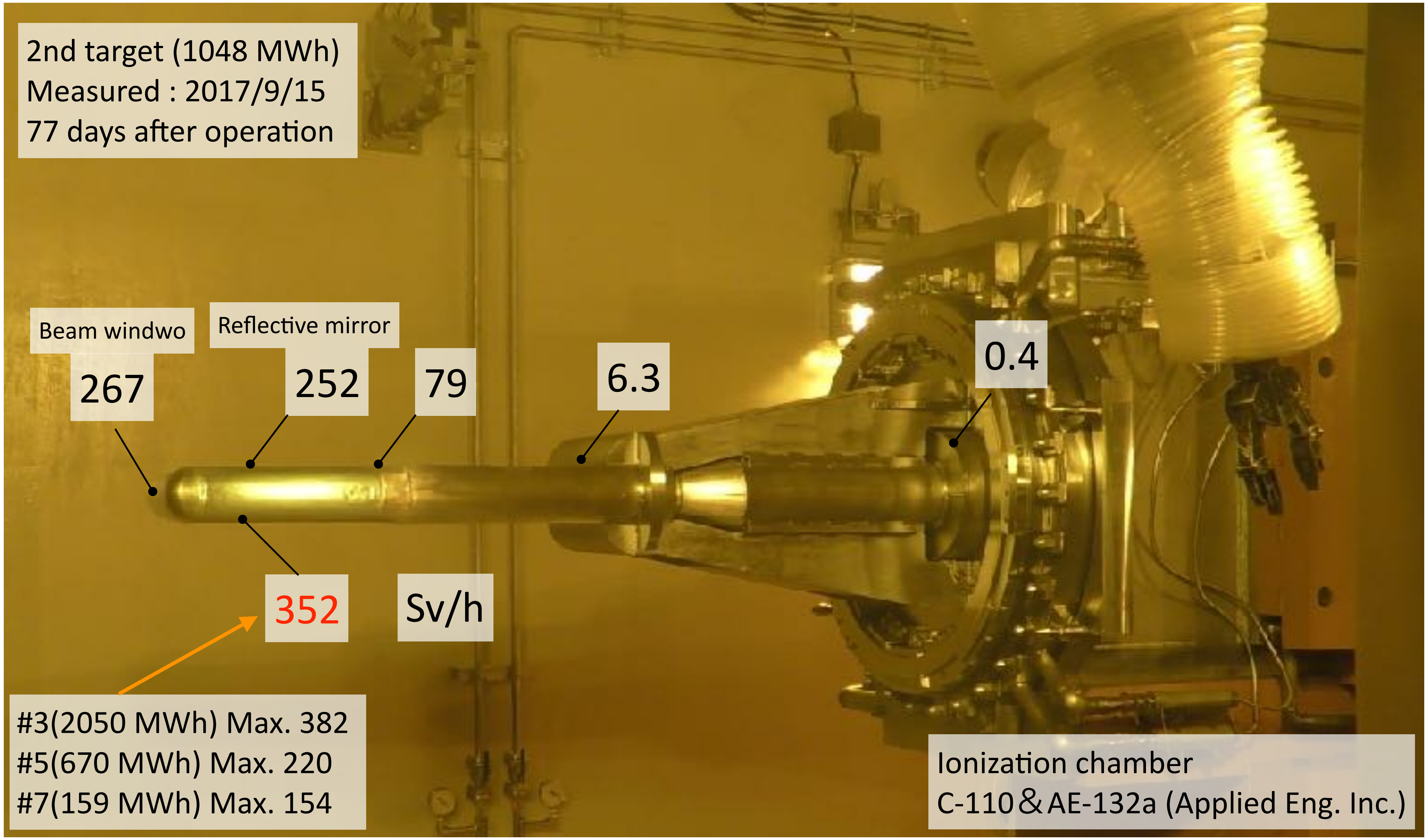


Replicate surface (silicon-rubber) for LSM observation

- **Prepared two types of measurement systems:**

  Laser profilometer for deep damage (0.1 mm~penetrated damage)
  Replica for detail observation (0.1 µm~0.5 mm)

Radiation dose rate of used target vessel



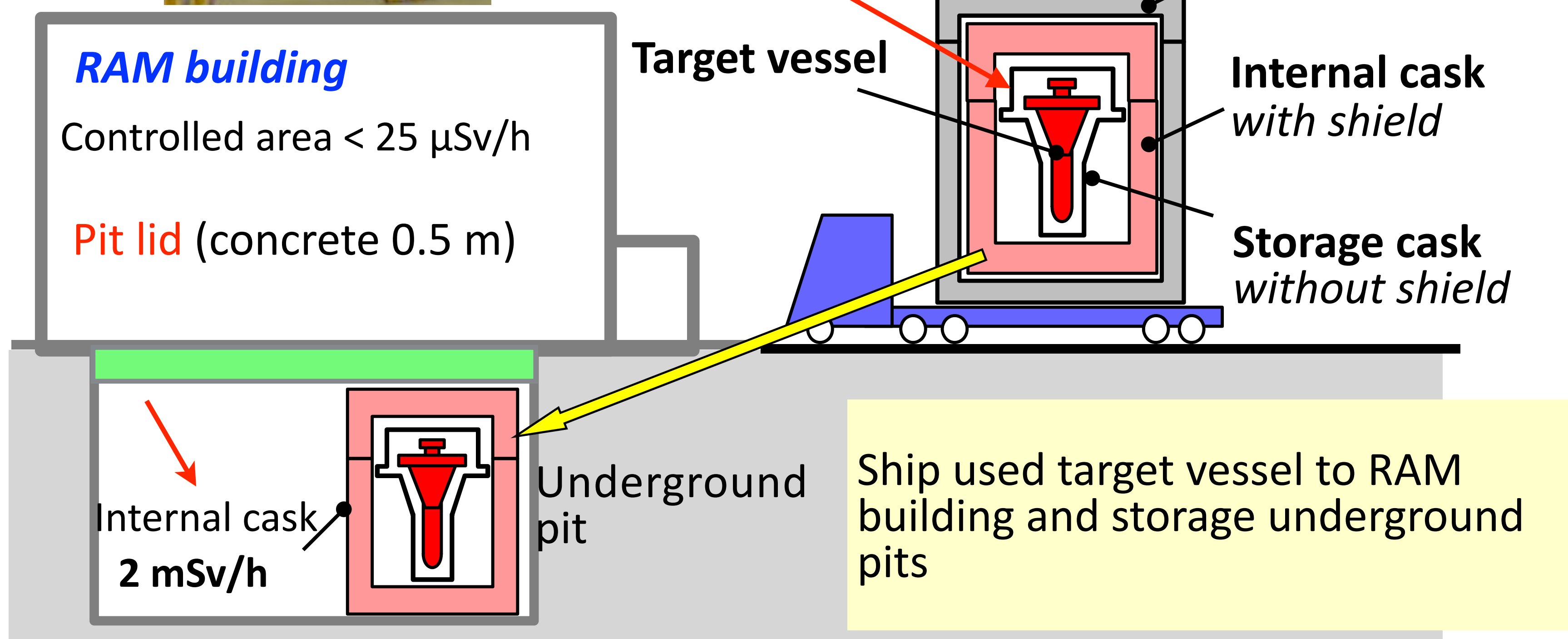
- Beam window is irradiated proton and neutron irradiation
- Difference between top and bottom sides around mirror is affected by moderator and reflector
  (Volume of neutron absorber around top side is larger than bottom side)
- Remaining mercury and radioactive materials are also affected dose rate

Storage building for used components

RAM (Radio Active Material) building

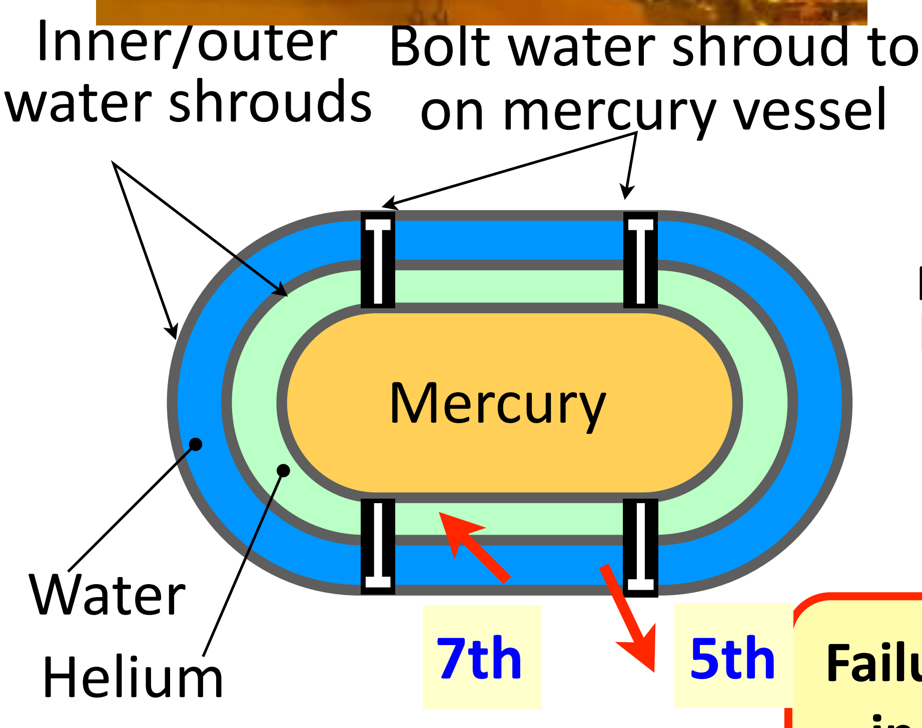
Pits for storage used target

Transport scenario for used target

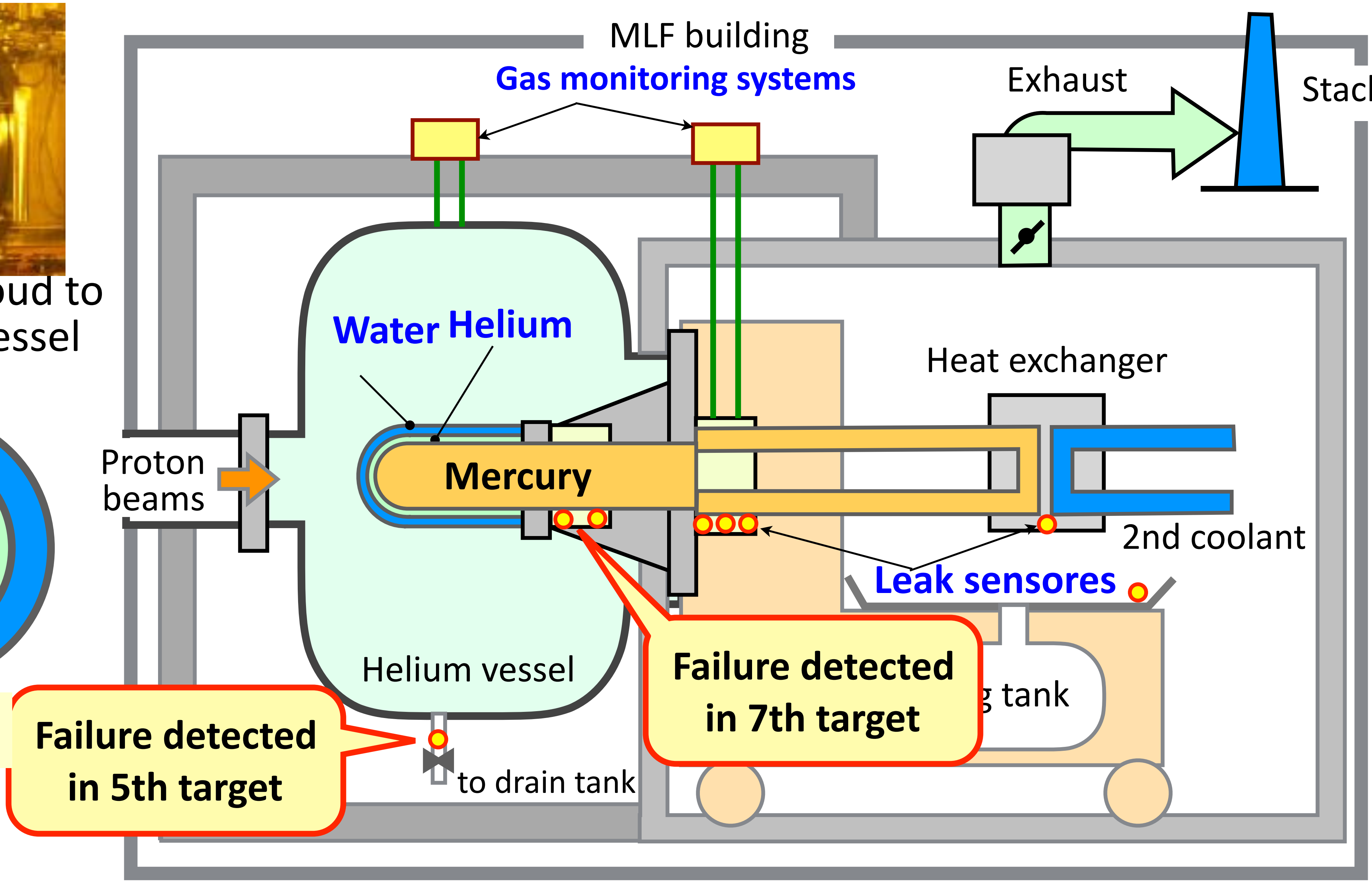


- MLF building has storage room for used targets (capacity:8)
- Not enough for 30 years operation (1 target/year)
- Storage building (capacity:15-20) was completed and will transport in next summer

Troubles in 2015 — 5th and 7th targets —



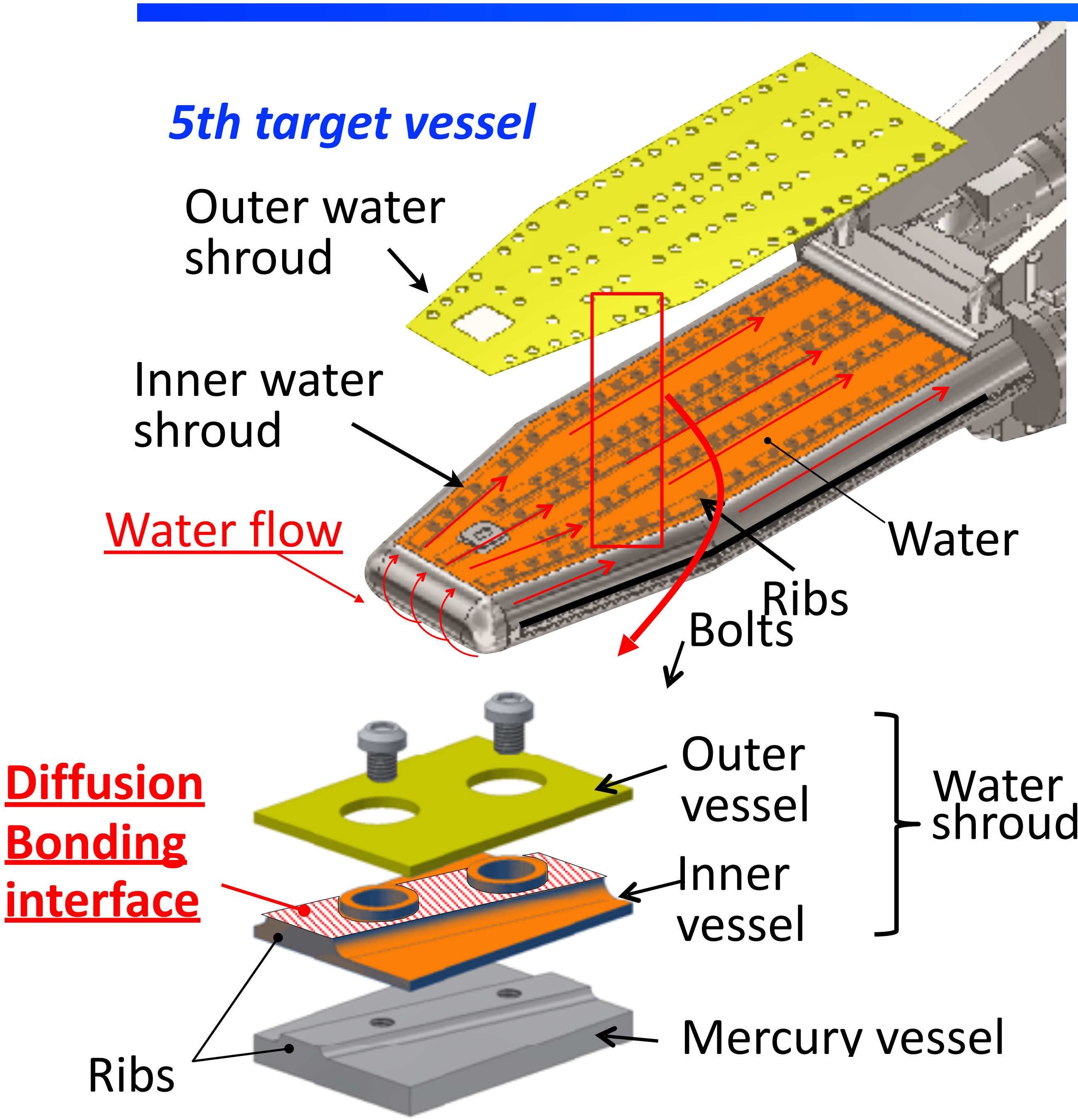
Vertical cross-section of target vessel

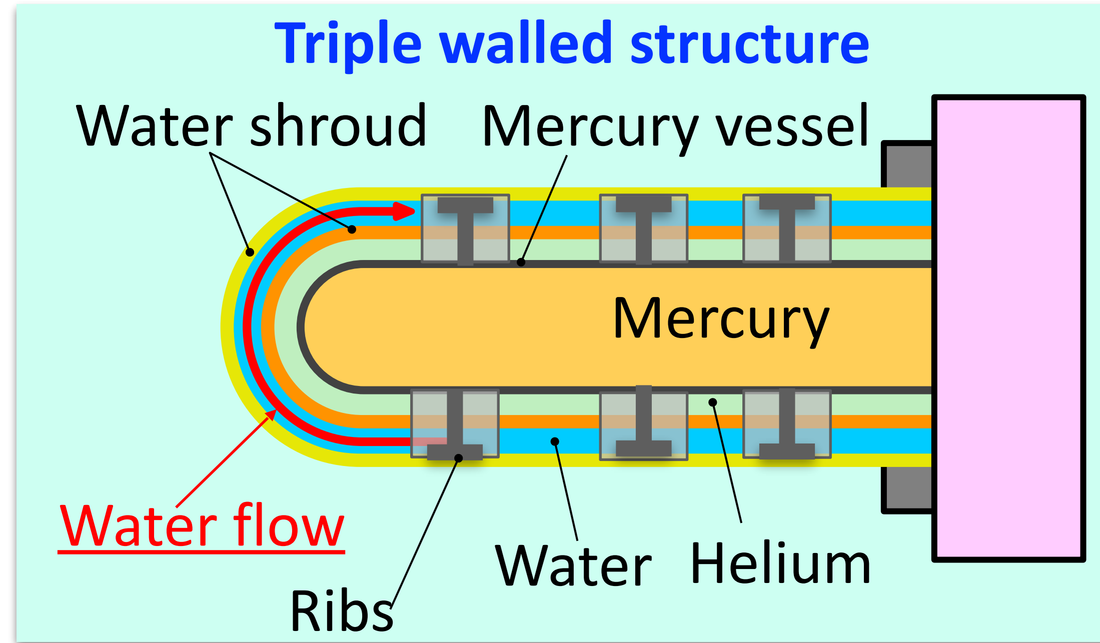


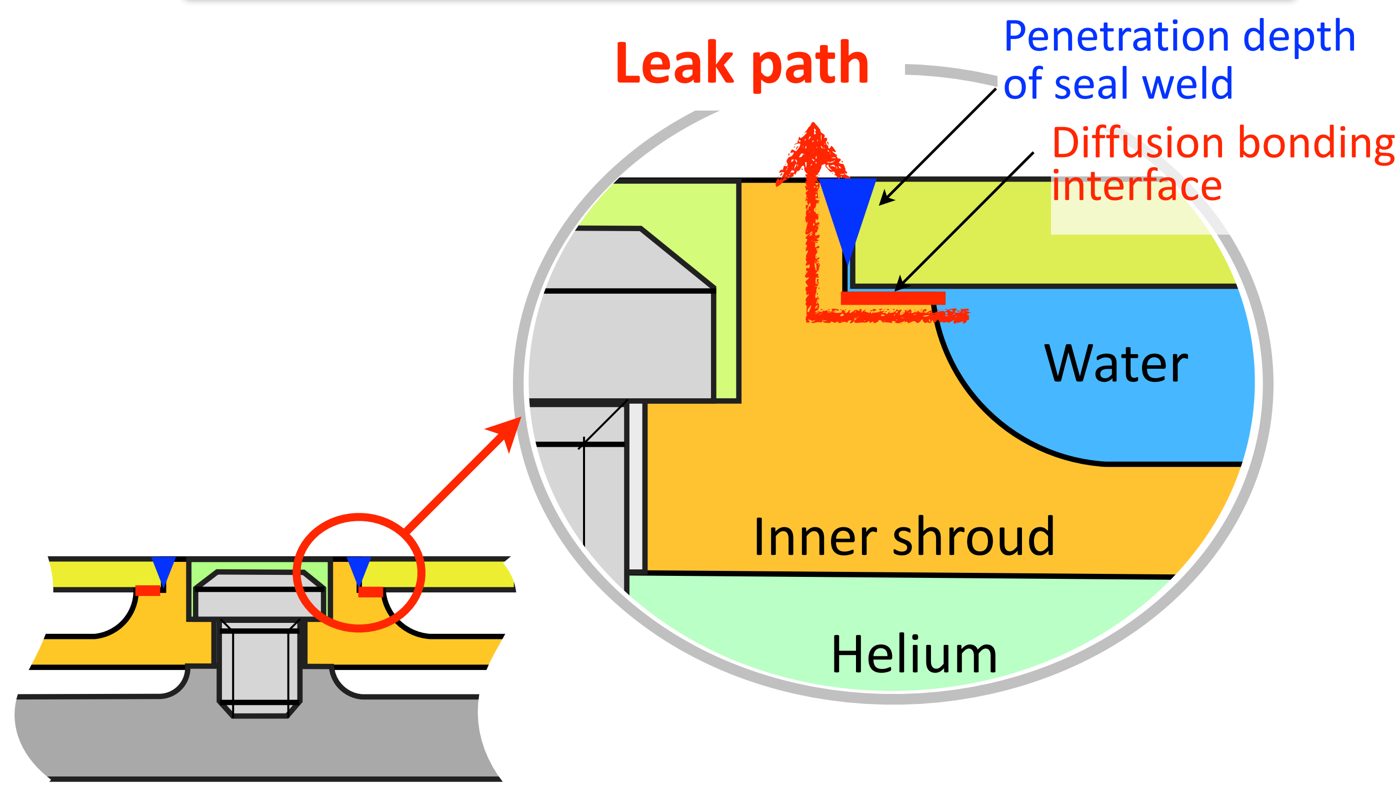
- 5th and 7th targets were failed due to water leak at water shroud
- Leak sensor at the drain tank of helium vessel was detected leak for 5th target
  Water leaked to outside of target vessel
- Leak sensor inside target vessel was detected leak for 7th target
  Water leaked to inside of target vessel

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

Structure of mercury target vessel (~5th target)



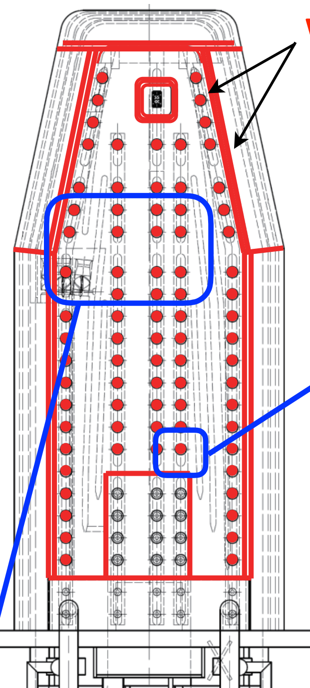


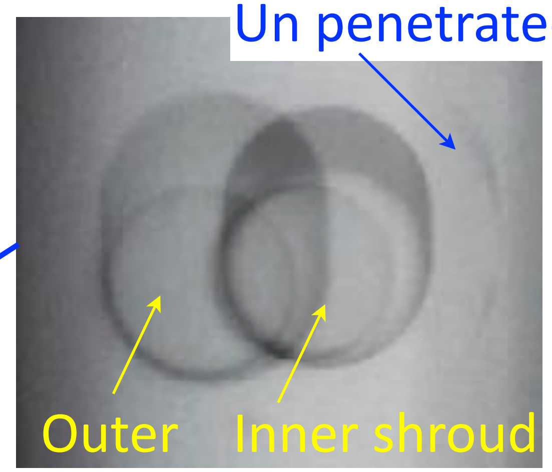


Vertical cross section of the target viewed from the target side

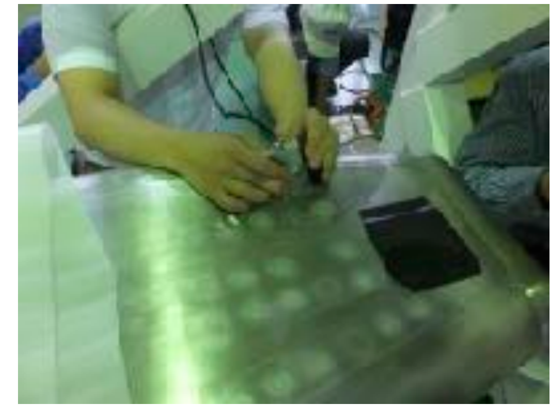
- Target vessel has triple walled structure (Inner/Outer water shroud, Mercury vessel)
- Outer and inner water shroud (diffusion bonded) was bolted to mercury vessel
- Bolt head and outer/inner shroud interface was welded by GTAW

Improvement of inspection

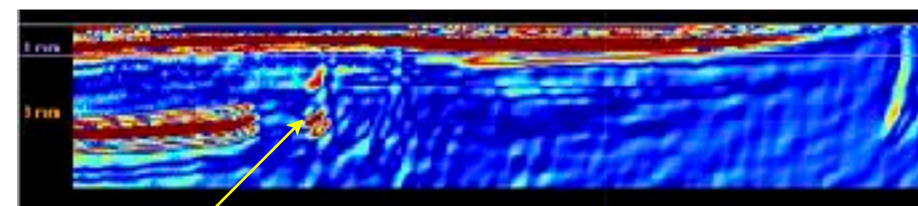


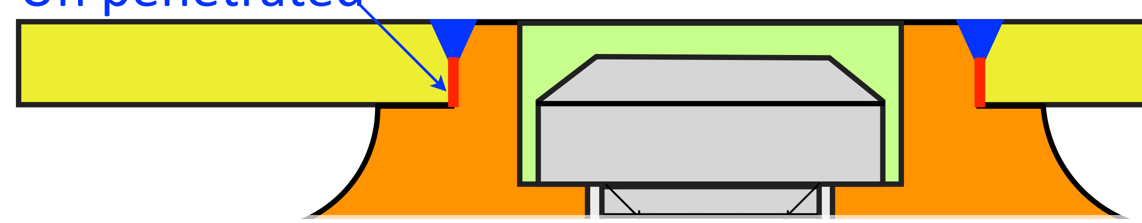


6th target vessel was inspected to investigate inspection processes of RT and UT



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





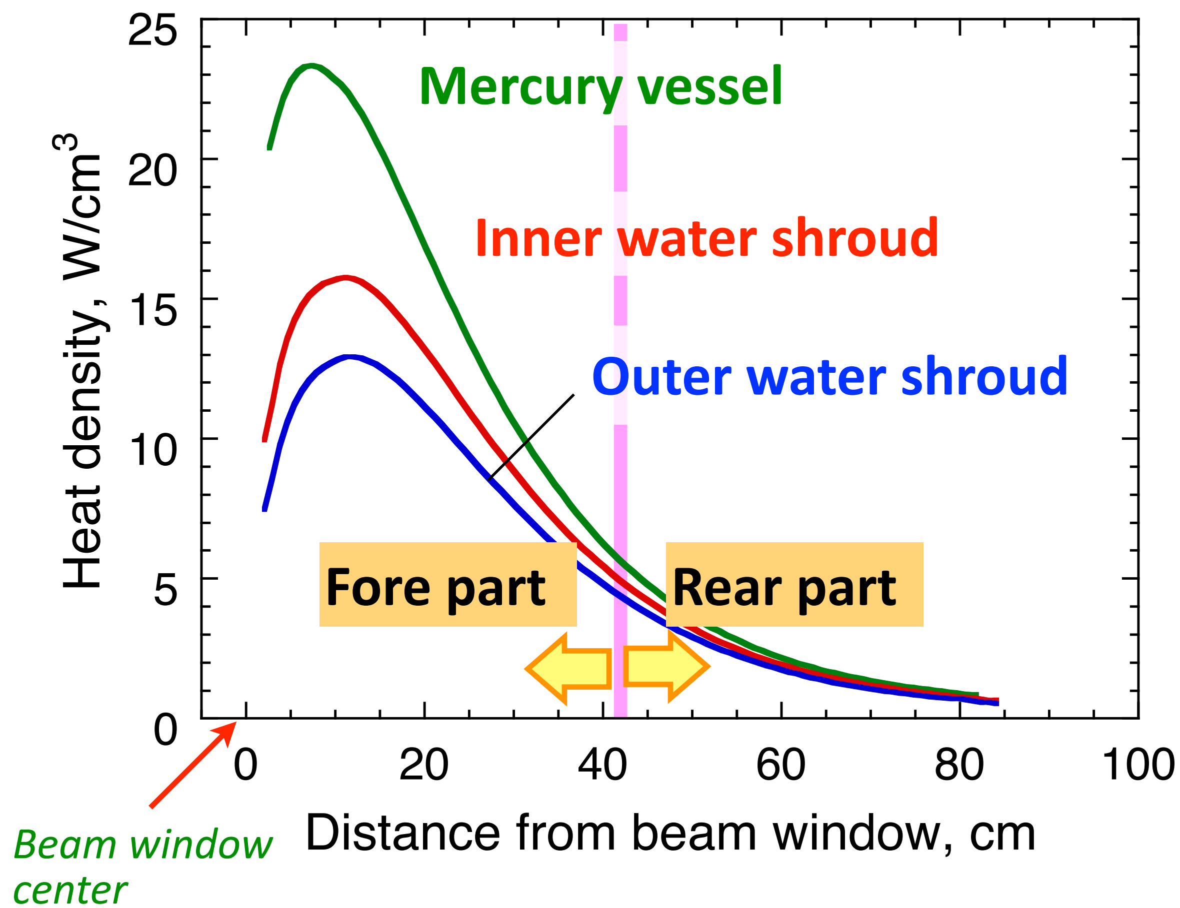
Radiographic Testing (RT)

Ultrasonic Testing (UT)

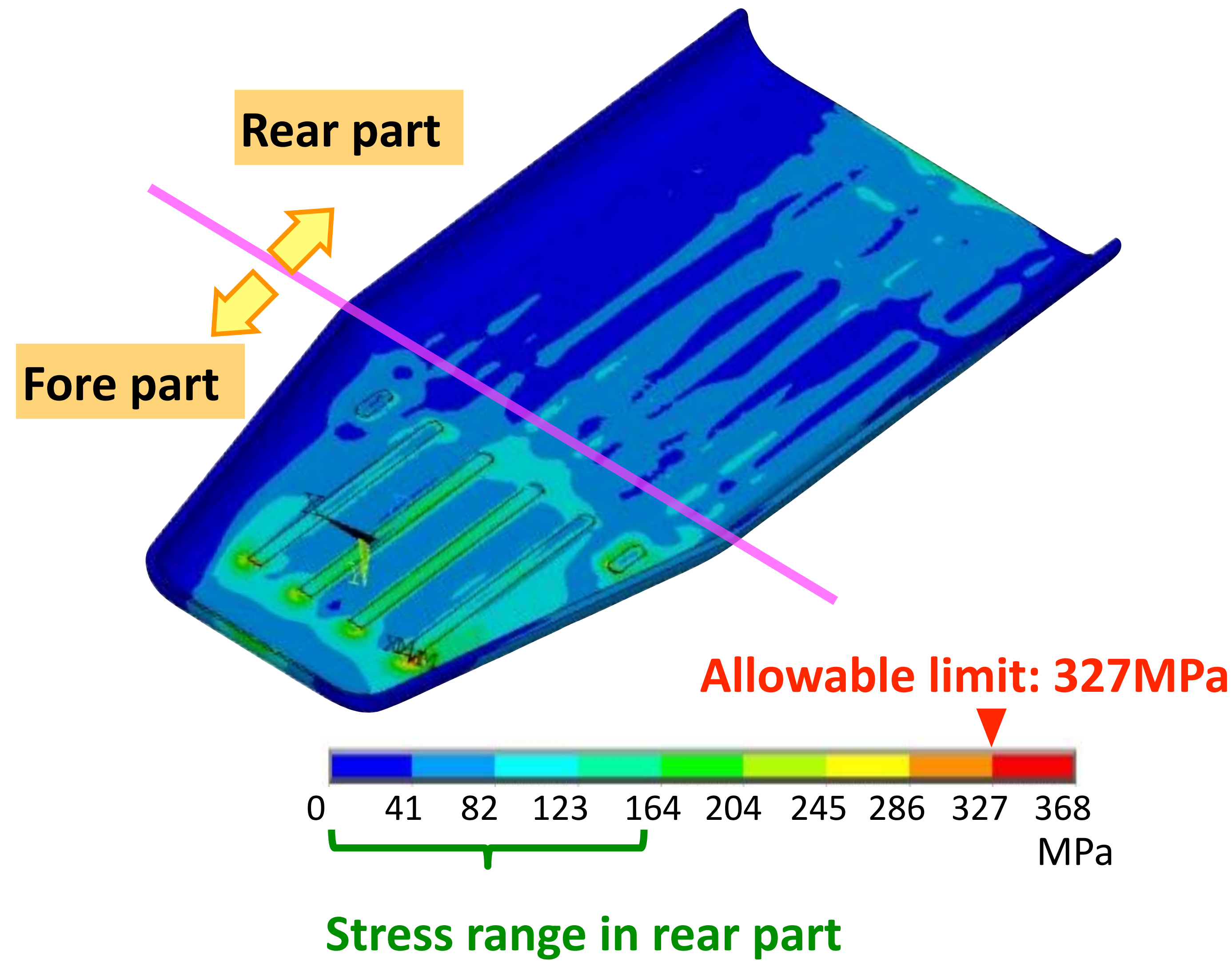
Details of nondestructive inspection for target vessel will be shown in Wakui's poster

- 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)

Heat density and thermal stress



Heat density distribution at 1MW



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

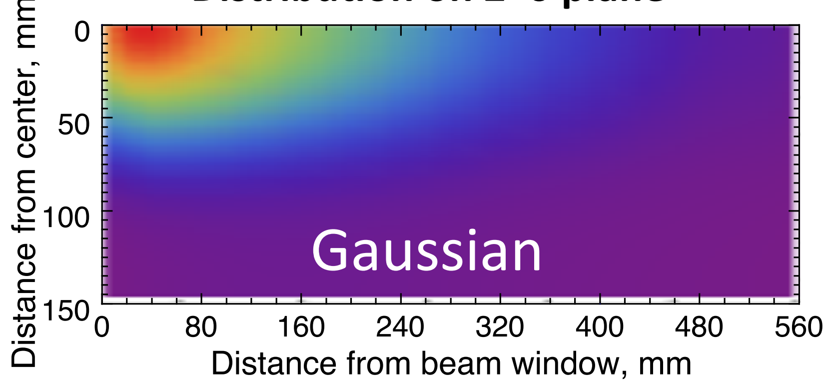
Heat distribution in mercury target

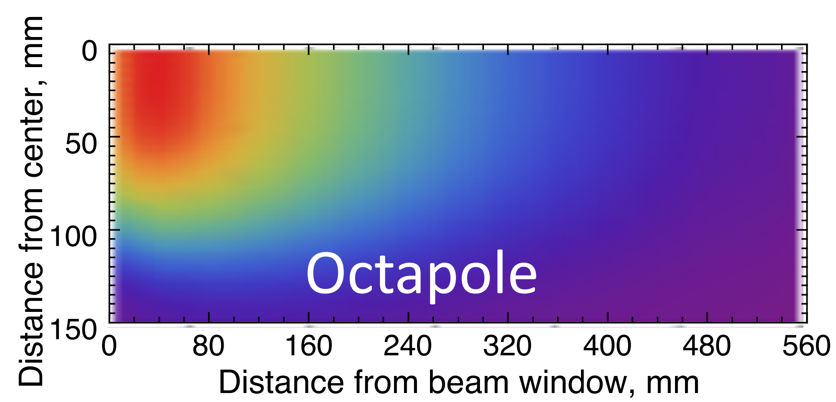
1 MW proton beam condition

Half of input beam energy change to heat in mercury

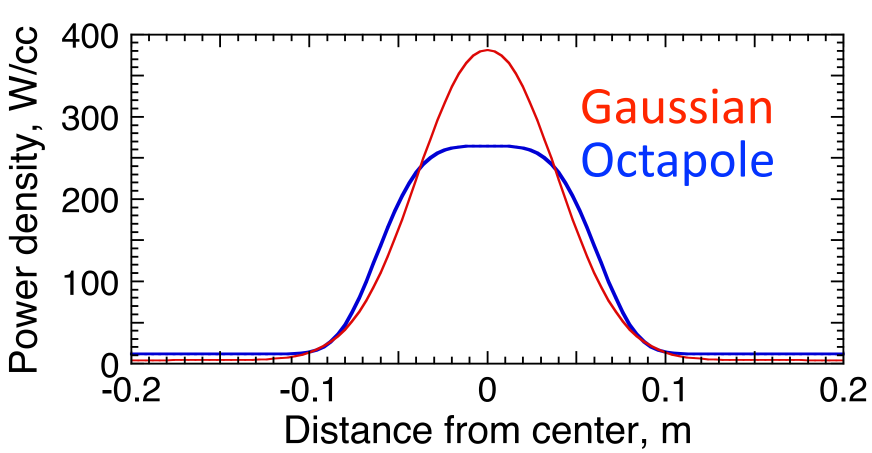
	Gaussian beam profile	Adding Octapole magnet
Total energy in mercury	480 kW	491 kW
Peak energy deposition	Max=381.397 W/cc (15.25 J/cc)	Max=264.73 W/cc (10.58 J/cc)

Distribution on Z=0 plane

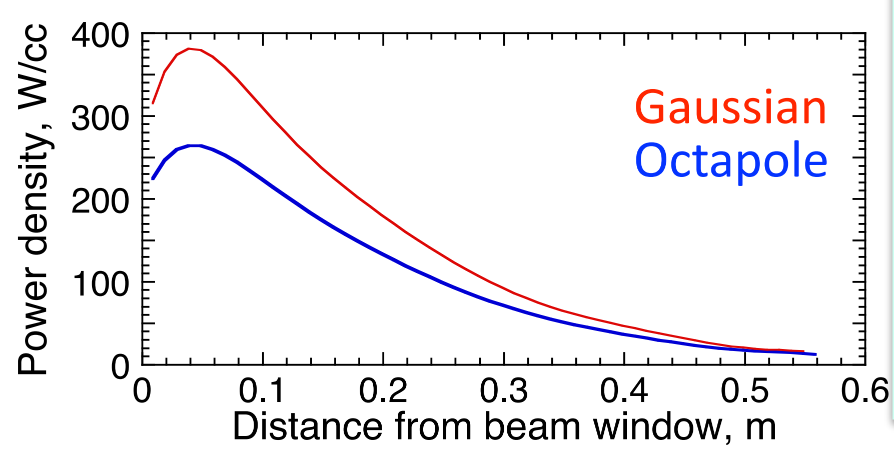




Horizontal direction X=30 mm Z=0 plane



Beam direction Y=X=0



Rise of mercury temperature

$$\Delta T = \frac{\Delta Q}{\rho C_V}$$

Rise of pressure in mercury

$$\Delta P = \beta K_T \Delta T$$

C_V: Specific heat 139 [J/(kgK)]

ρ: Density 13500 [kg/m³]

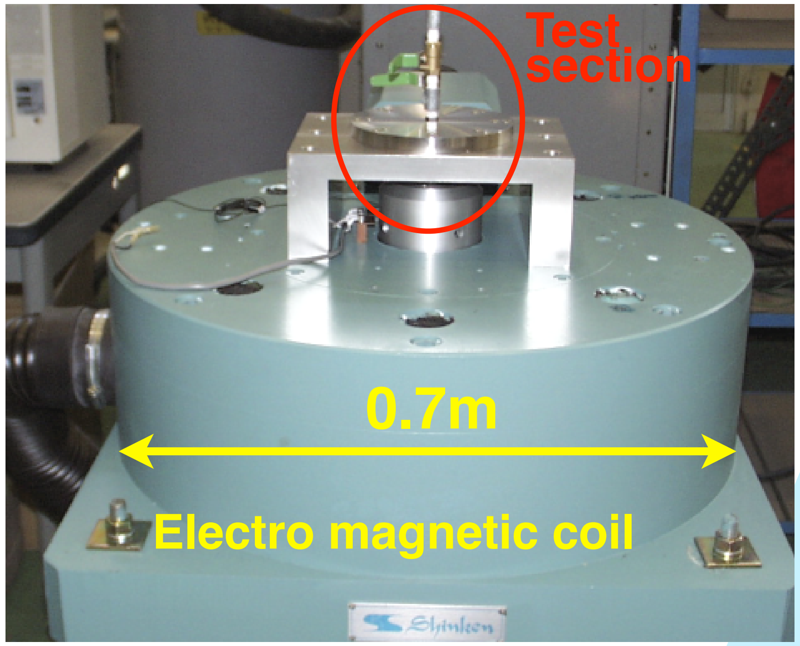
ΔT=8.52°C@400 W/cc(16J)

β: Thermal expansion rate 180.99e-6 [1/K]

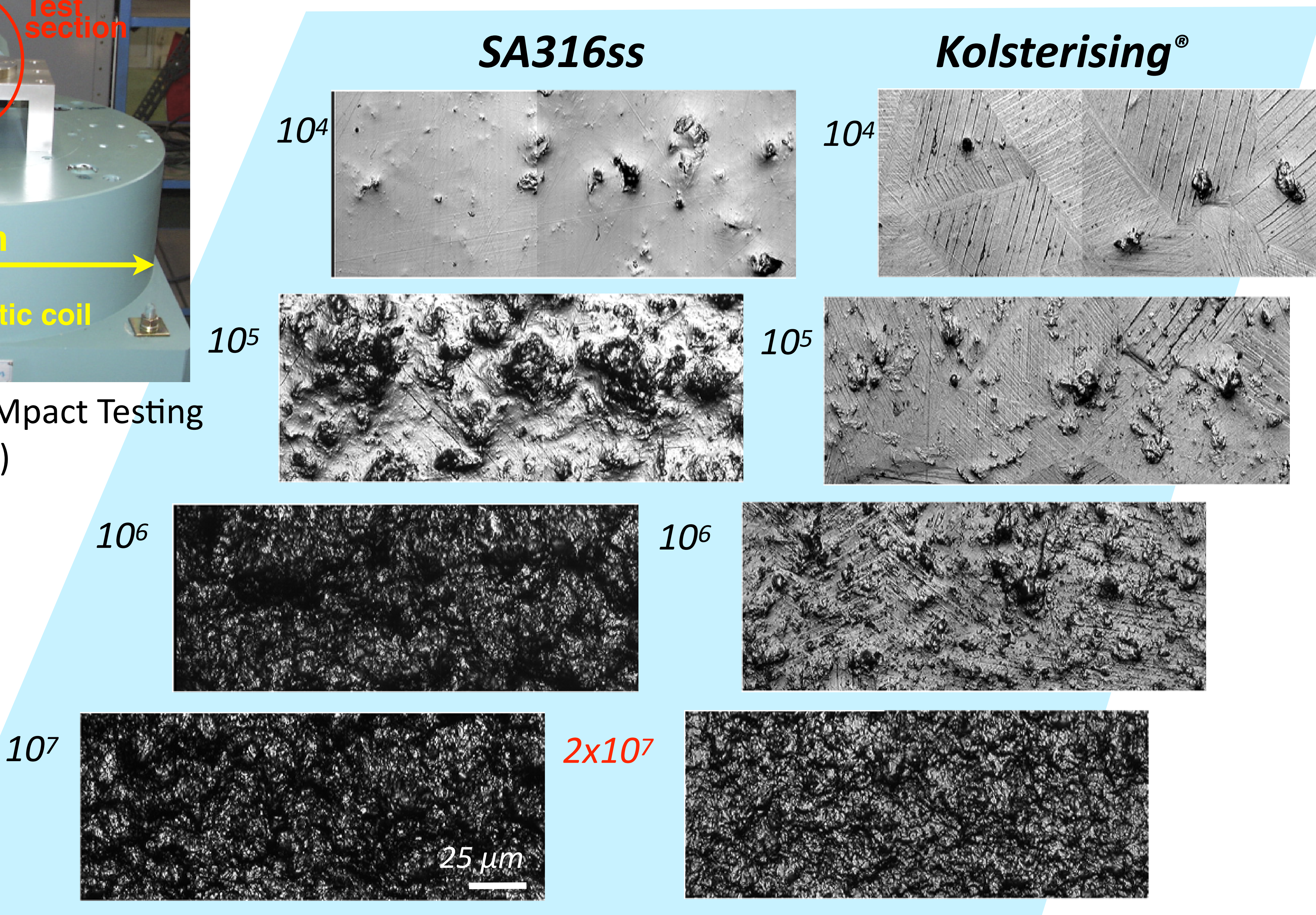
K_T: Bulk modulus 25.6 [GPa]

ΔP=40MPa@400W/cc(16J)

Surface hardening treatment

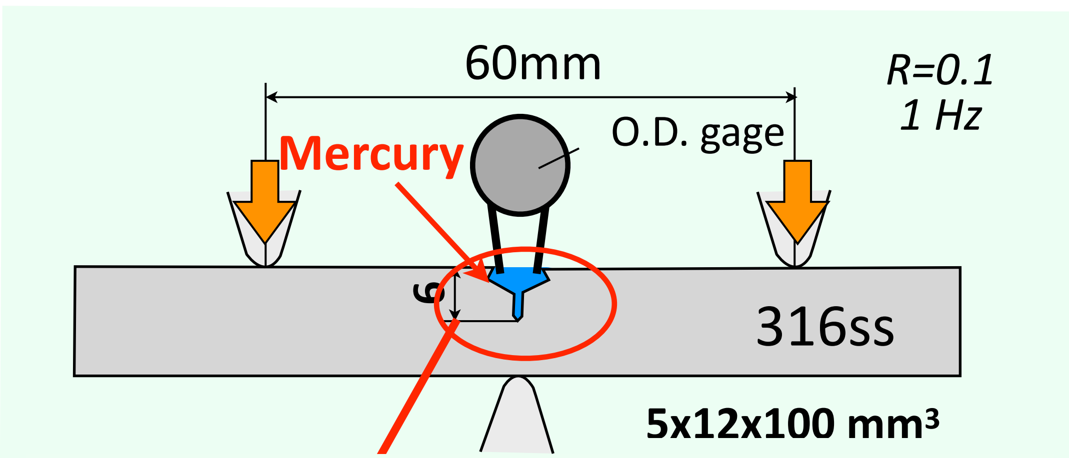


electroMagnetic IMpact Testing Machine (MIMTM)

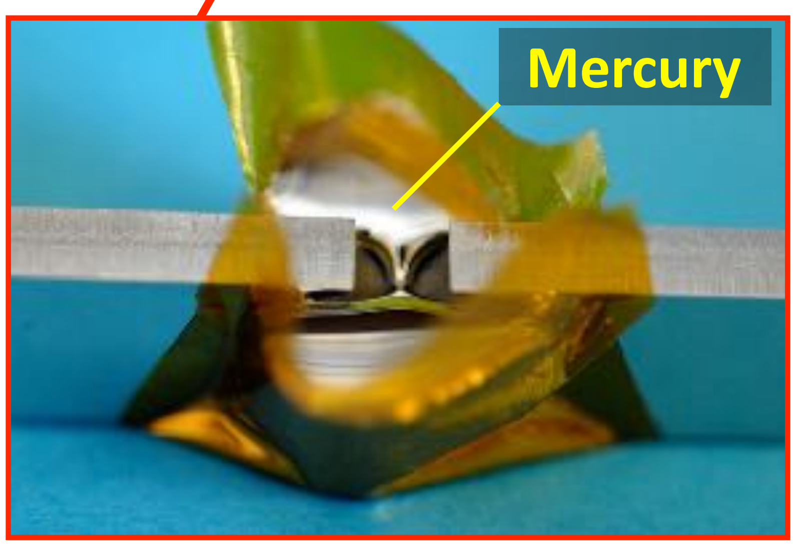


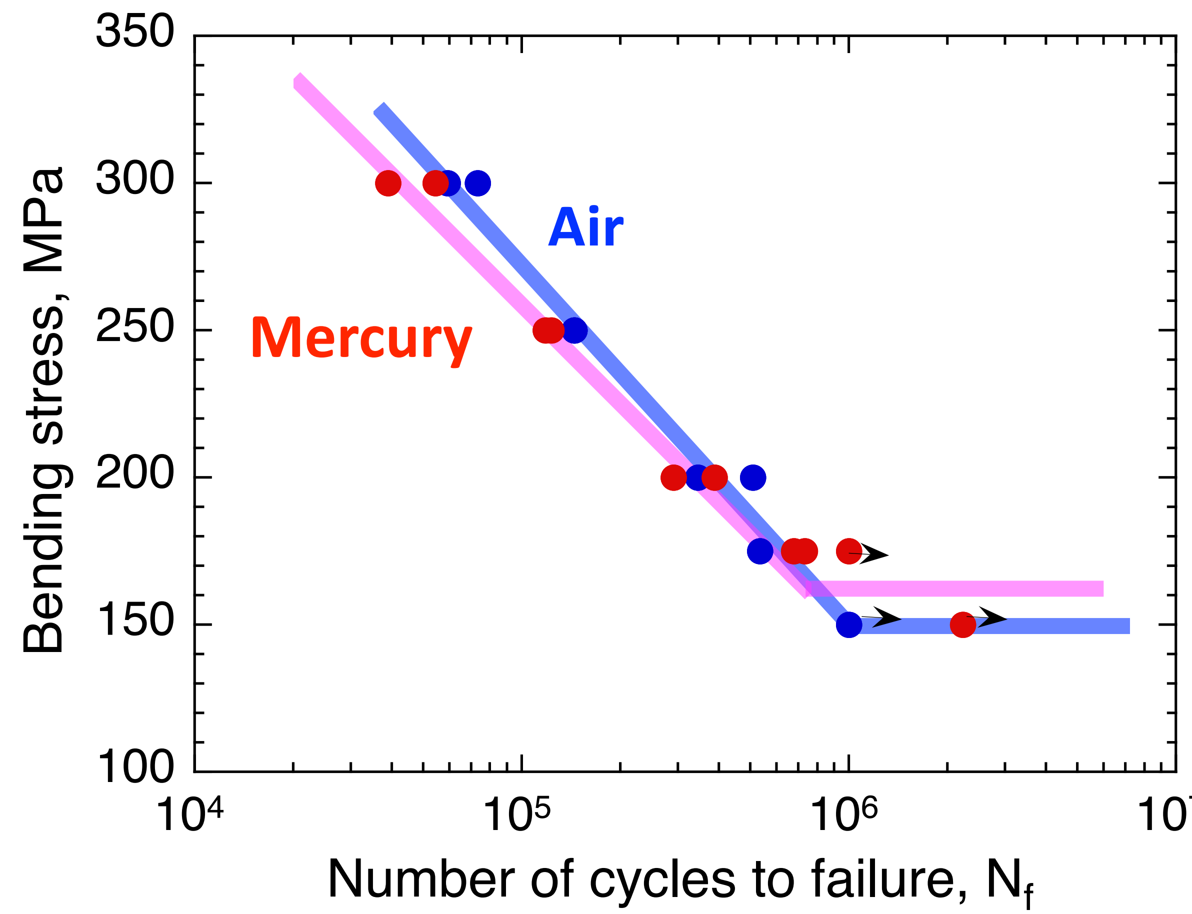
- Cavitation damage tests in stagnant mercury
- Incubation period for erosion damage extends 10 times by Kolsterising®

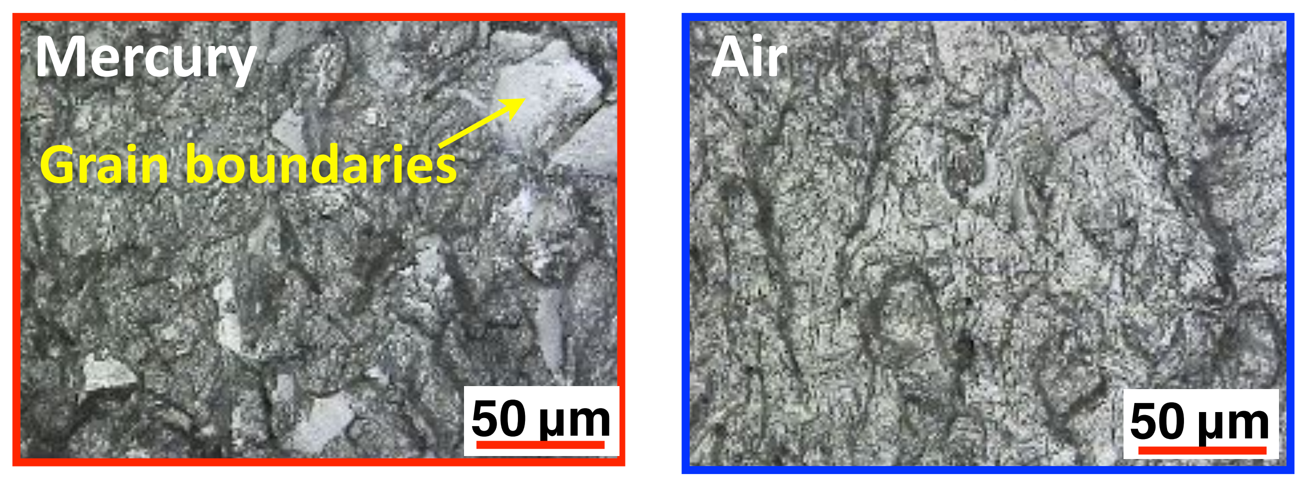
Fatigue behavior in mercury



3-point bending fatigue test with V-notch



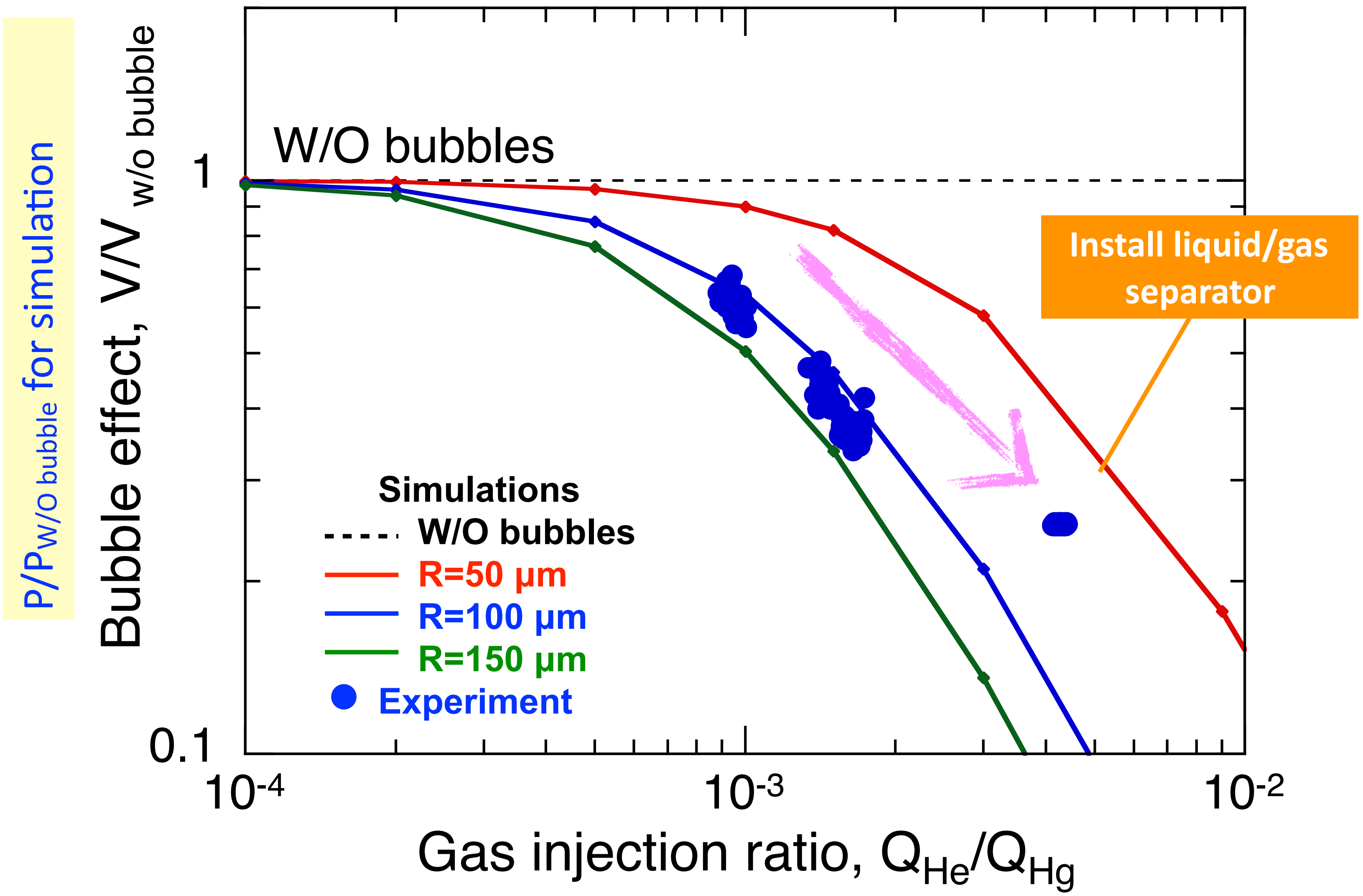


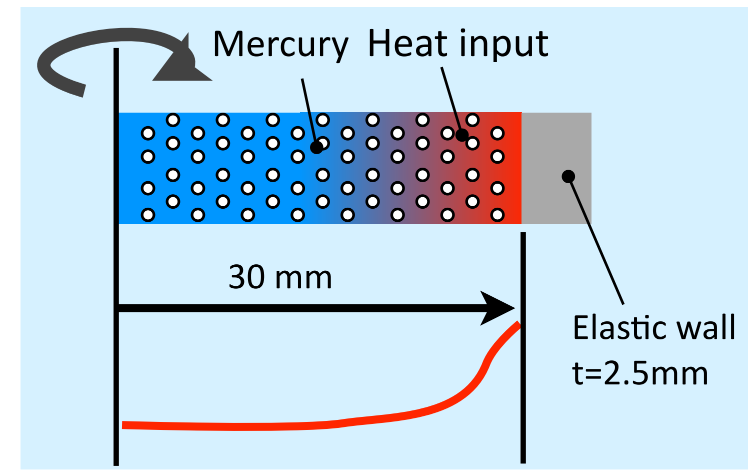


Fracture surface at 300 MPa

- Fatigue strength was degraded by mercury immersion at high stress imposed area
- Fatigue crack propagation accelerates by mercury immersion in the high-stress intensity factor range

Effect of void fraction on pressure wave mitigation





Pressure wave propagation in bubbly mercury (uniform size) obtained from simulation

- Peak amplitude of LDV is correlated with the void fraction
  Peak velocity was normalised at w/o bubble case predicted based on beam experiments
- LDV denotes the same tendency of the numerical simulation

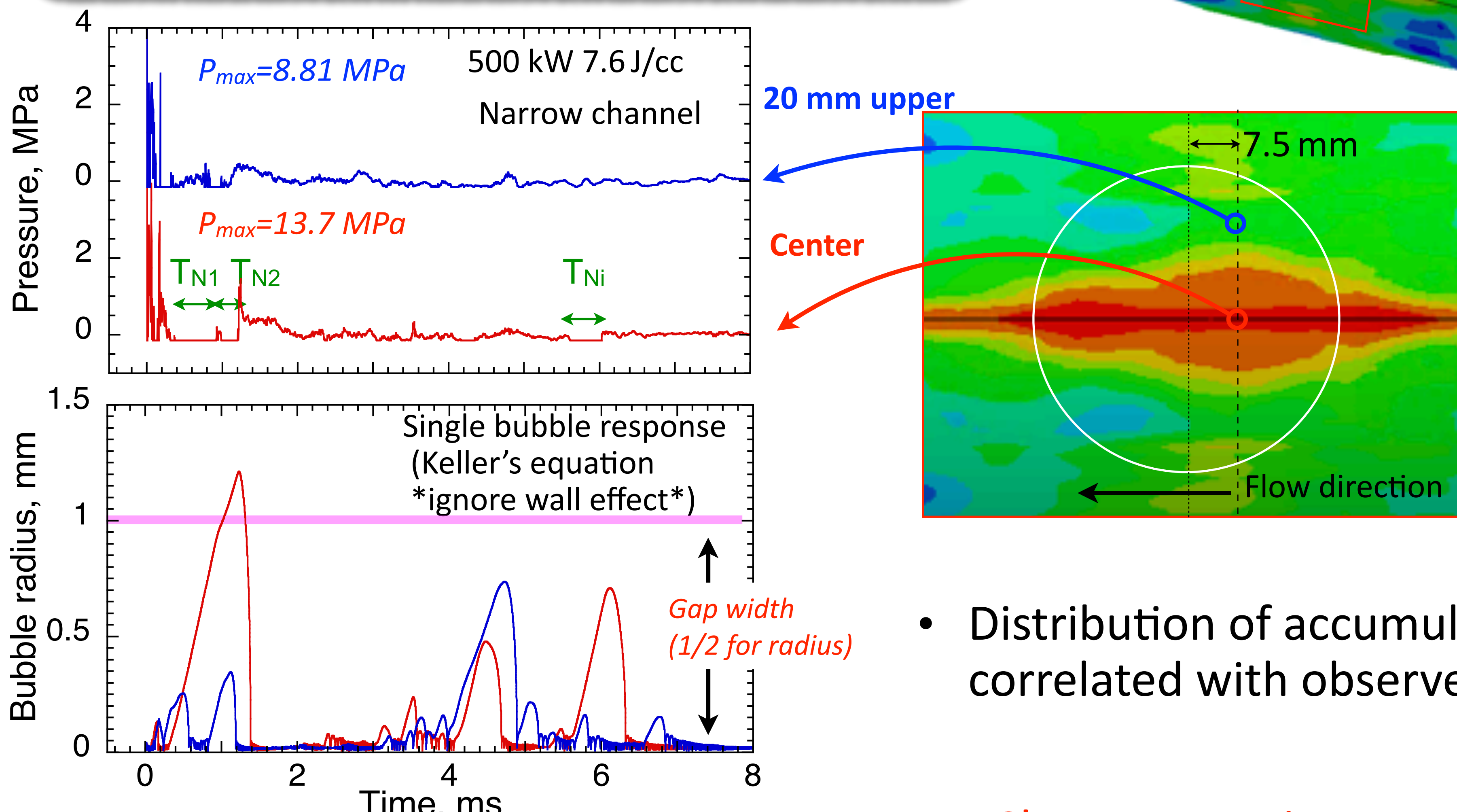
Damage and pressure response in narrow channel

Negative pressure period

Accumulated time of negative pressure period $T_{N_{accum}} = \sum_{i=1}^{n} T_{N_i}$

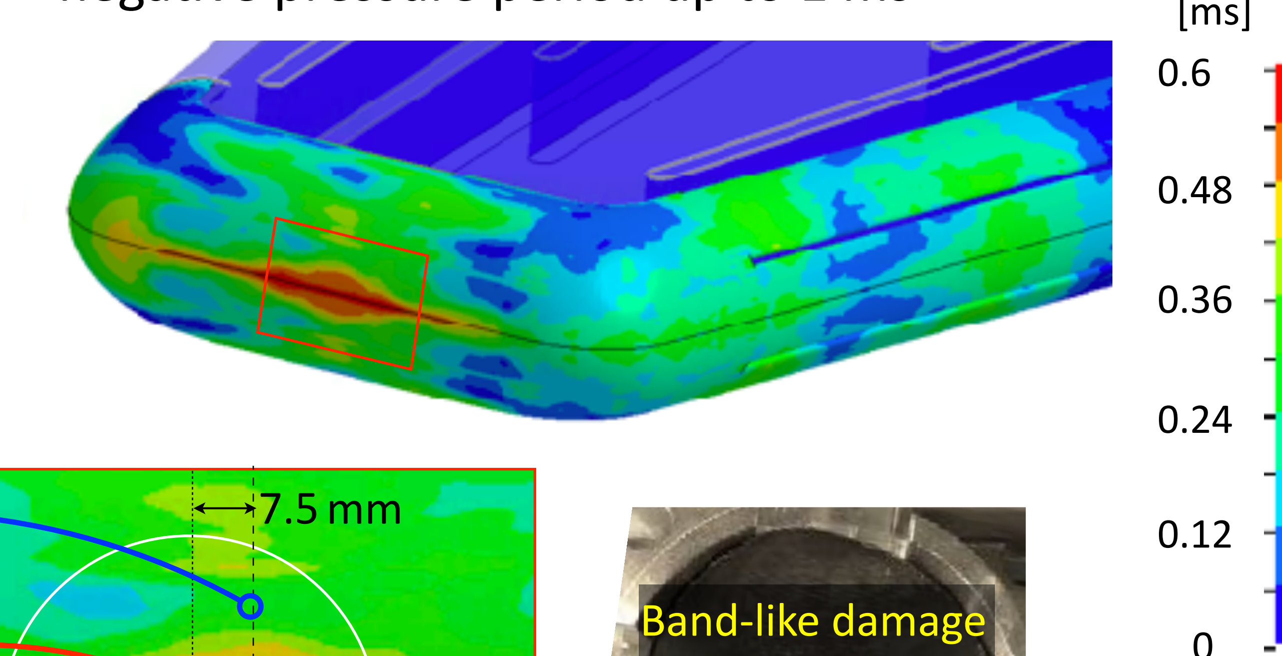
T_N=duration of negative pressure (-0.15 MPa)

-0.15 MPa -> threshold for cavitation



Time responses of pressure and cavitation bubble in narrow channel at 500 kW conditions

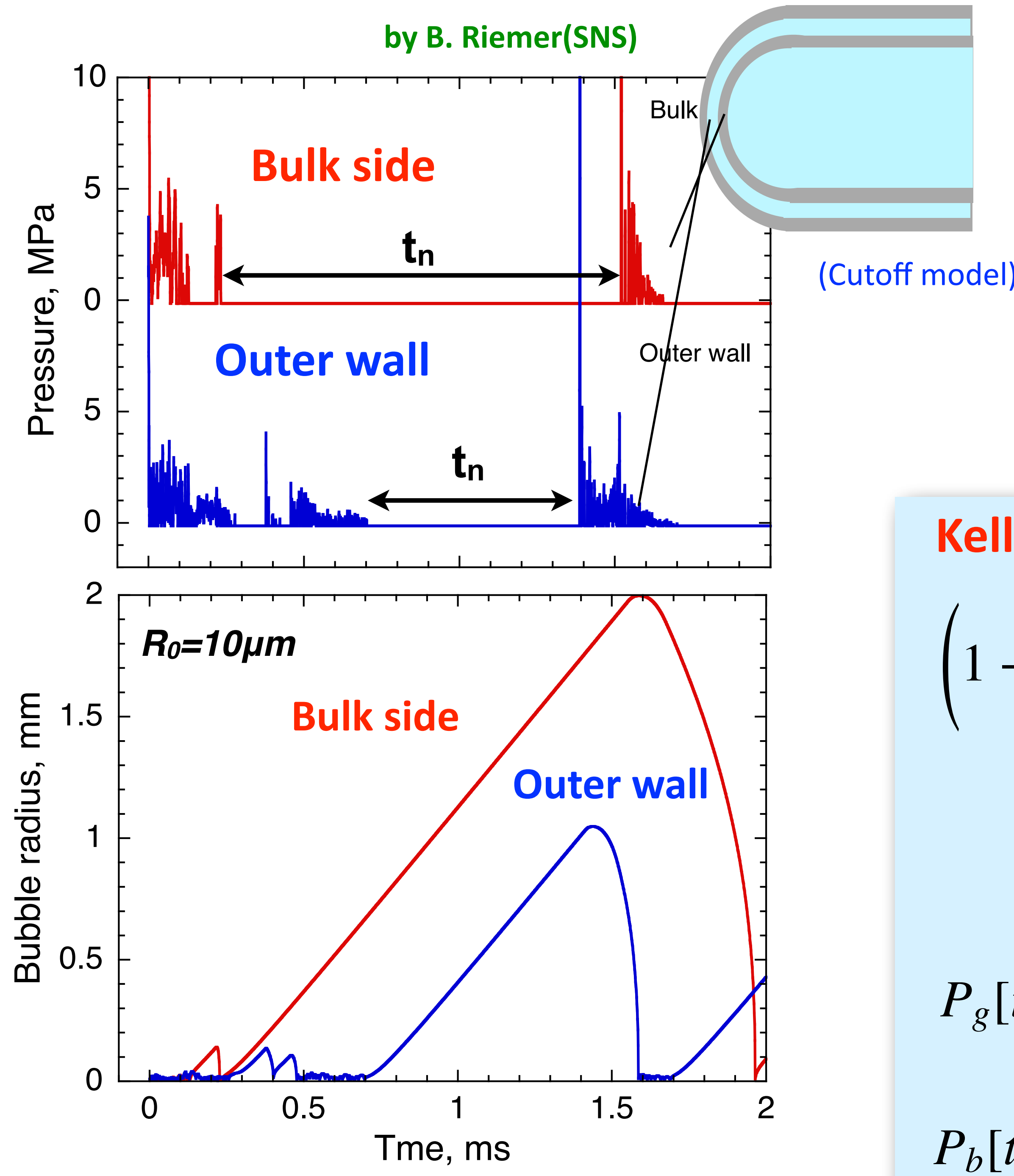
Distribution of accumulated negative pressure period up to 1 ms

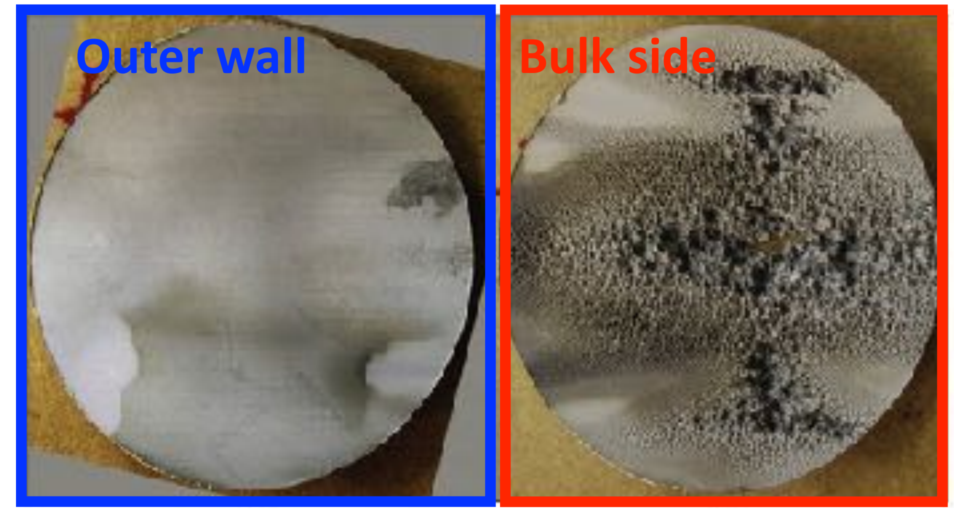


- Distribution of accumulated negative pressure period correlated with observed damage distribution

Shorter negative pressure period reduces cavitation damage in narrow channel

Bubble behavior in the narrow channel





D. McClintock et al., J. Nucl. Mater. 431 (2012) 147–159

Keller equation Single bubble

$$\left(1-\frac{\dot{R}}{C_L}\right)R\ddot{R}+\left(\frac{3}{2}-\frac{\dot{R}}{2C_L}\right)\dot{R}^2=$$

$$\frac{1}{\rho}\left(1+\frac{\dot{R}}{C_L}\right)(P_b[t]-P[t+R/C_L]-P_0)+\frac{R}{\rho C_L}\dot{P}_g[t]$$

$$P_g[t]=\left(P_0-P_V+\frac{2\sigma}{R[t]}\right)\left(\frac{R_0}{R[t]}\right)^3+P_v$$

$$P_b[t]=P_g[t]-\frac{2\sigma+4\eta\dot{R}[t]}{R[t]}$$

R: Bubble radius
ρ: Density
σ: Surface tension
P: Pressure
η: Viscosity

- Short interval of negative pressure is not effective to bubble growth
- Maximum bubble size at narrow channel is a half of bulk side
- Insufficient data to explain a significant damage difference