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Cavitation damage in double-walled mercury target vessel

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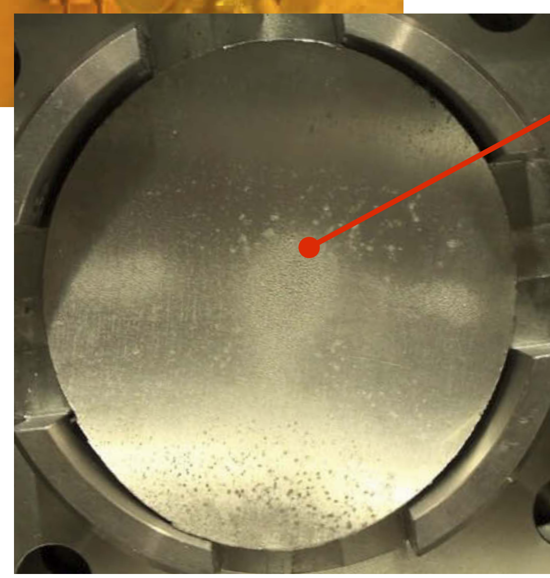
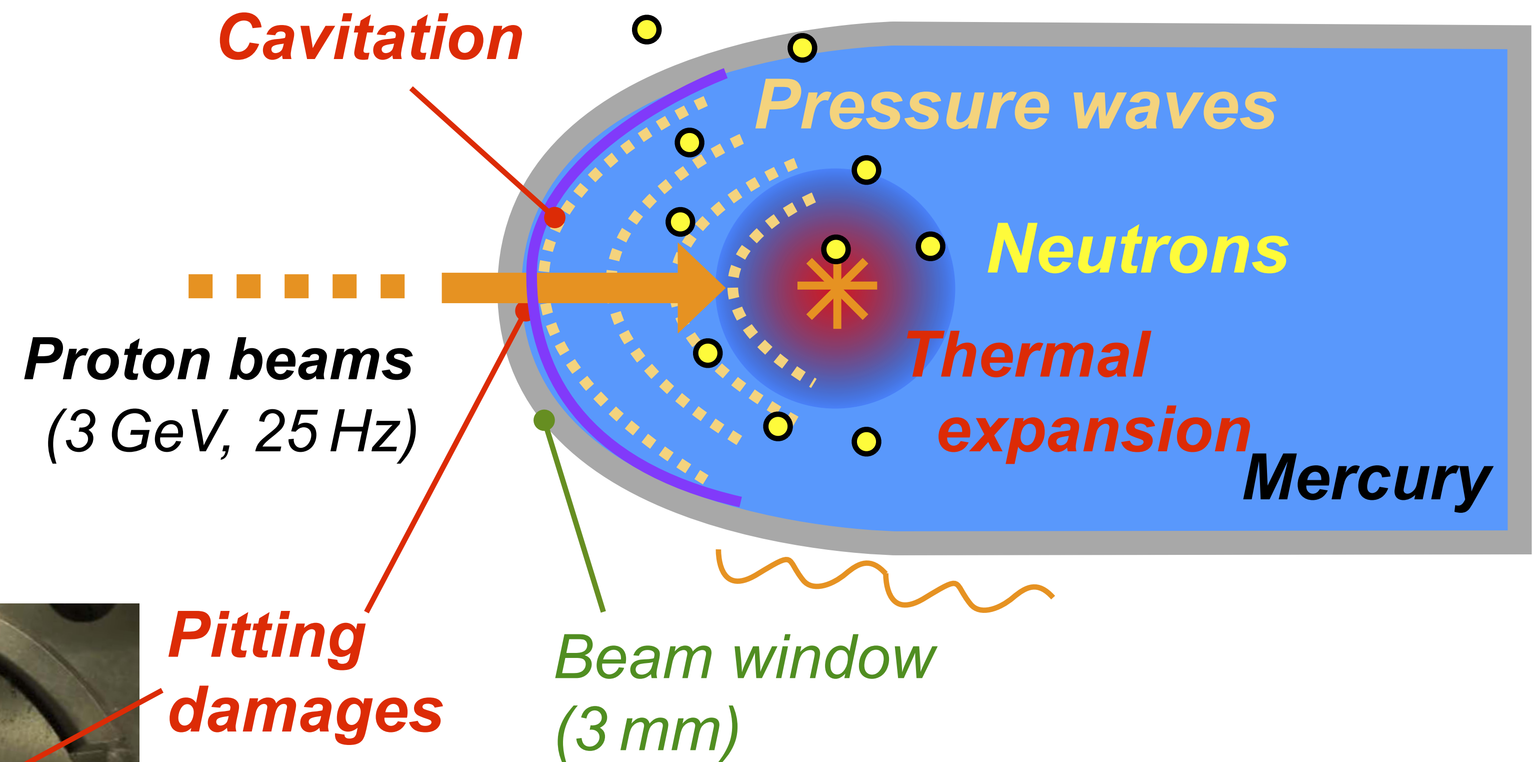
Outline

- Background and purpose
- Cavitation damage inspection
- Correlation between damage distribution and negative pressure period
- Future plan for damage mitigation
- Summary

Cavitation damage in mercury target





Inside beam window of 1st JSNS target
475 MWh (200 kW at maximum)

- Cavitation-induced erosion degrades structural integrity of the target vessel, e.g. mercury leakage and fatigue failure
- Damage increases with the beam power
- Cavitation damage mitigation is necessary under high power operation
  Designed lifetime of JSNS target is 2500 MWh (tentative dose limit 5 dpa)

Cavitation damage mitigation

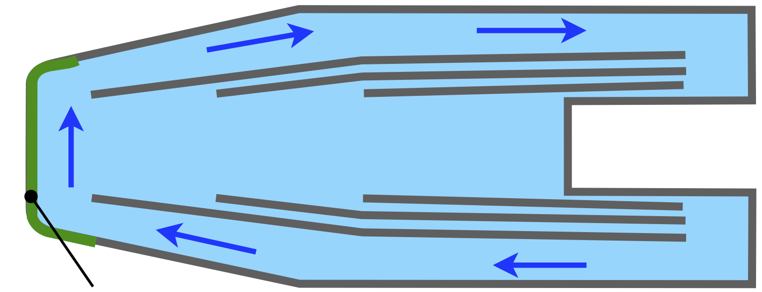
Target

1st

Surface hardening

Reduce cavitation damage

Nitriding & Carburizing, Kolsterising



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

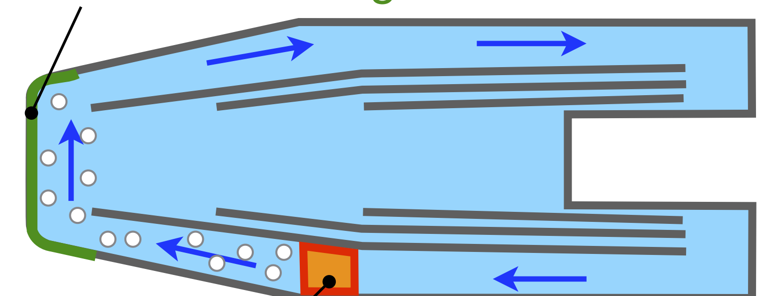
3rd

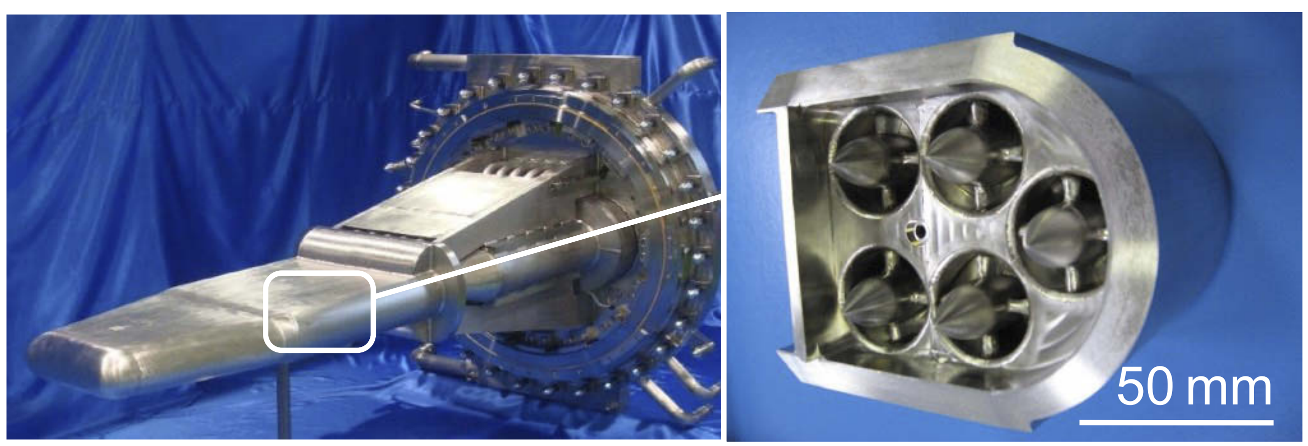
4th

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

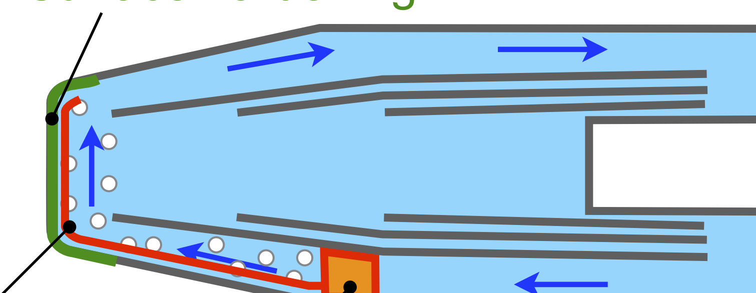
5th

|

8th

Double walled structure

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

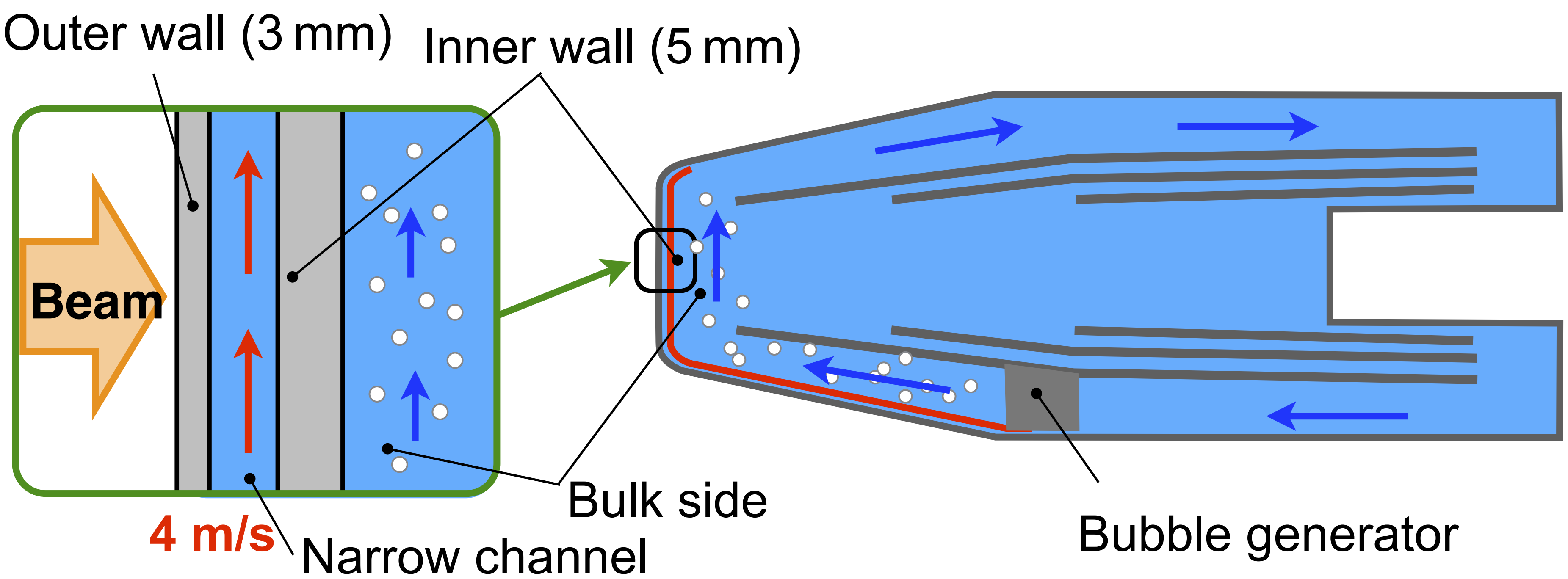


Order of target vessel operation

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

Double-walled beam window

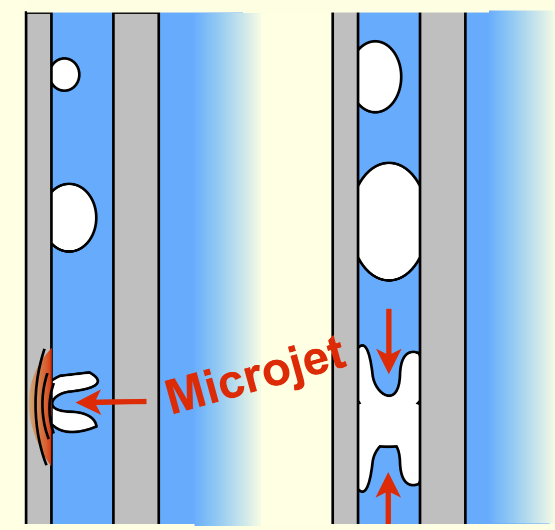
5th target ~



Schematic illustration of mercury vessel

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

Expected narrow channel effect



Small bubble

Microjet ejects vertical to wall

Large bubble

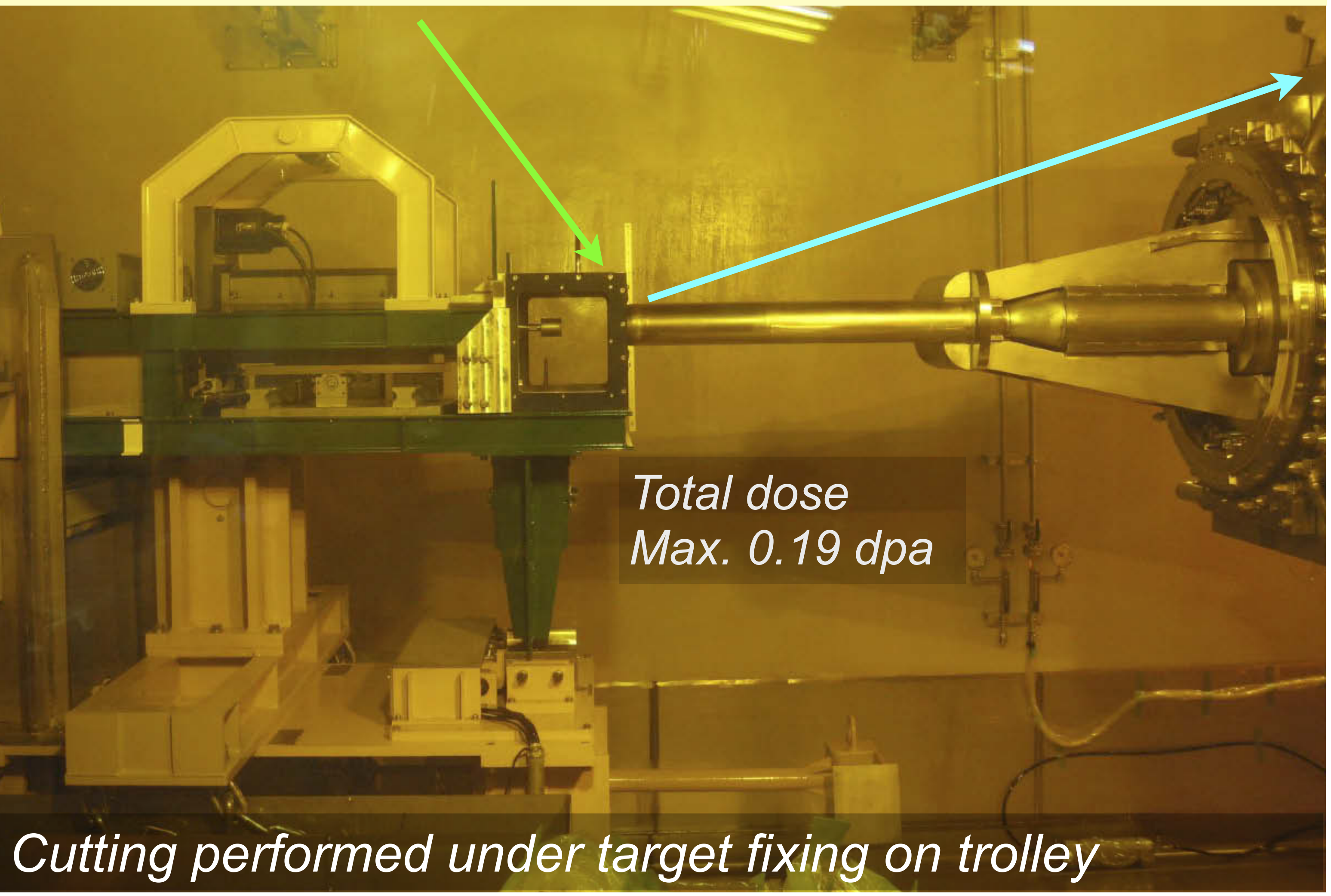
Microjet ejects parallel to wall

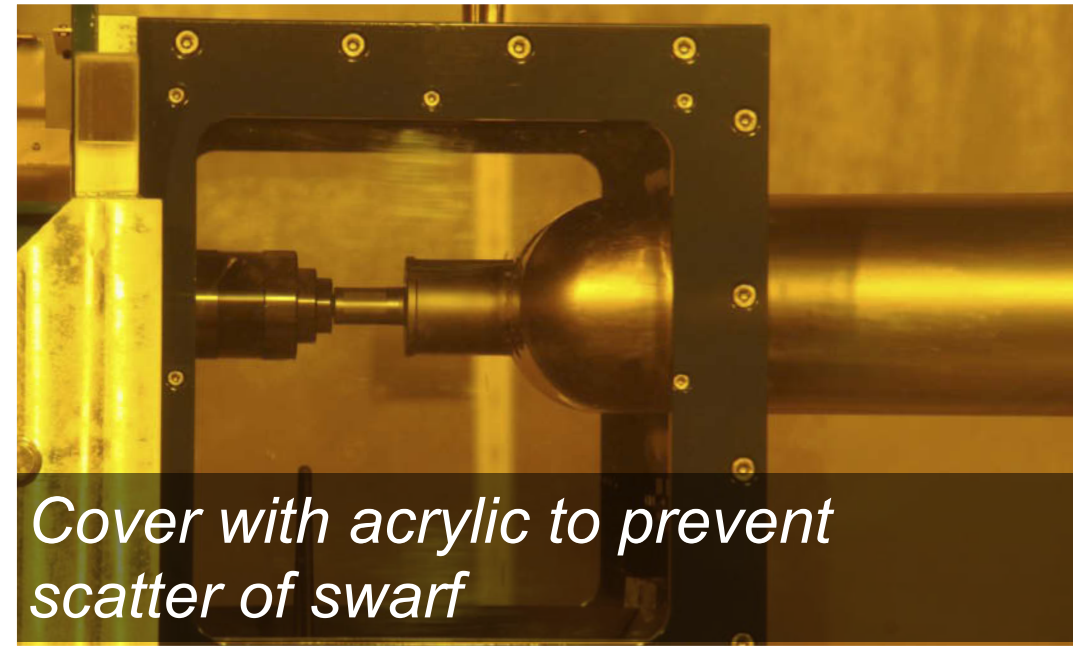
Purpose **Investigate the effect of double-walled structure on cavitation damage mitigation**

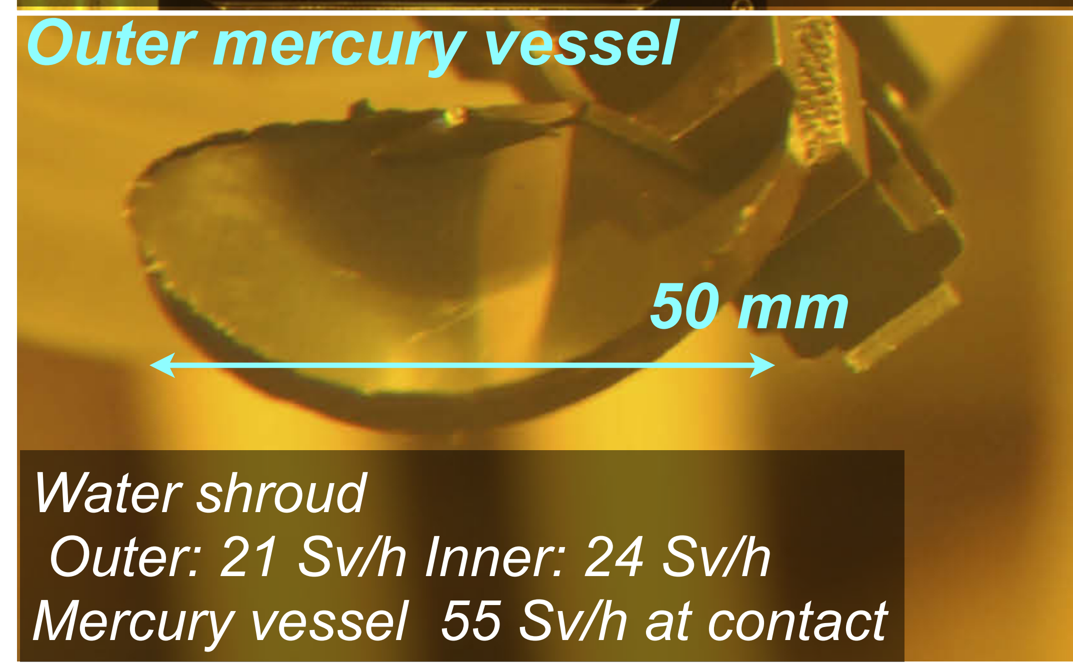
- 5th target damage inspection
- Compared damage distribution with negative pressure period

Cutting and inspection of 5th target

Measured dose rate at the center of beam window is 245 Sv/h at 680 MWh after 4 moths cooling

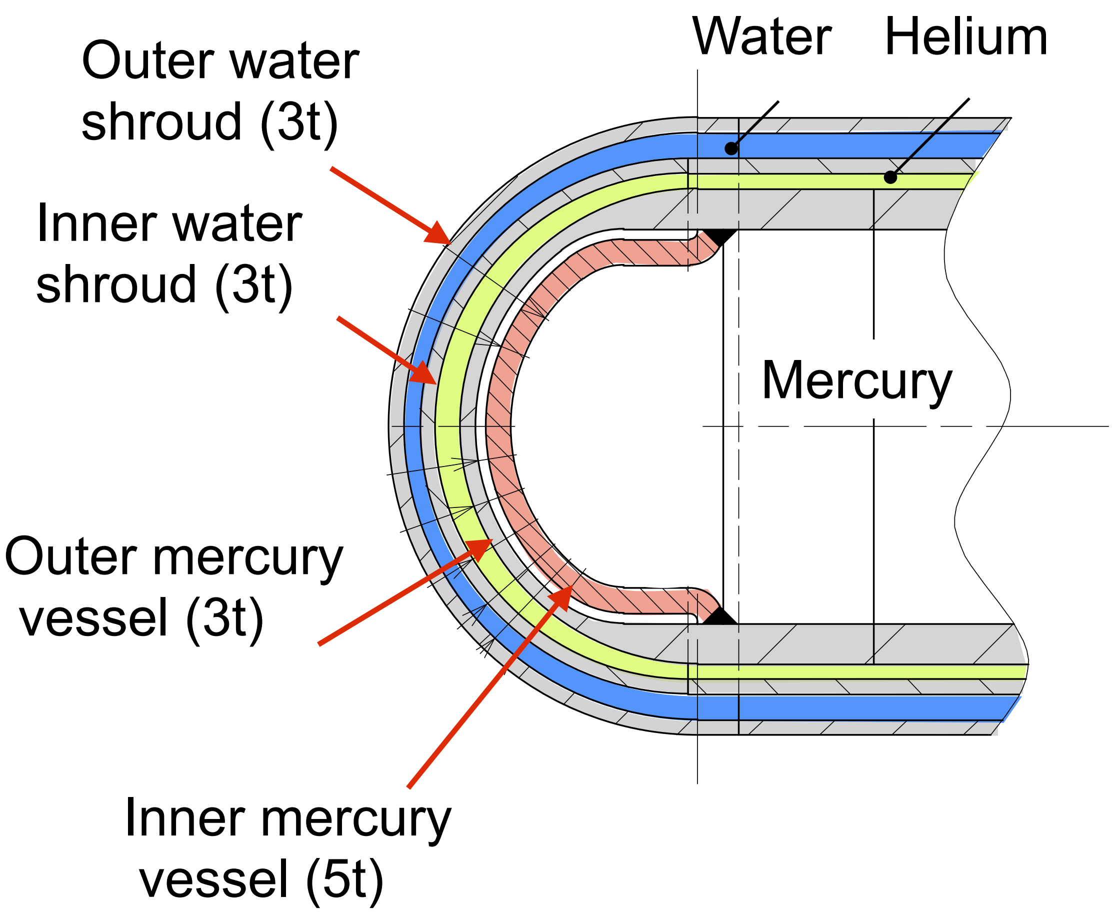




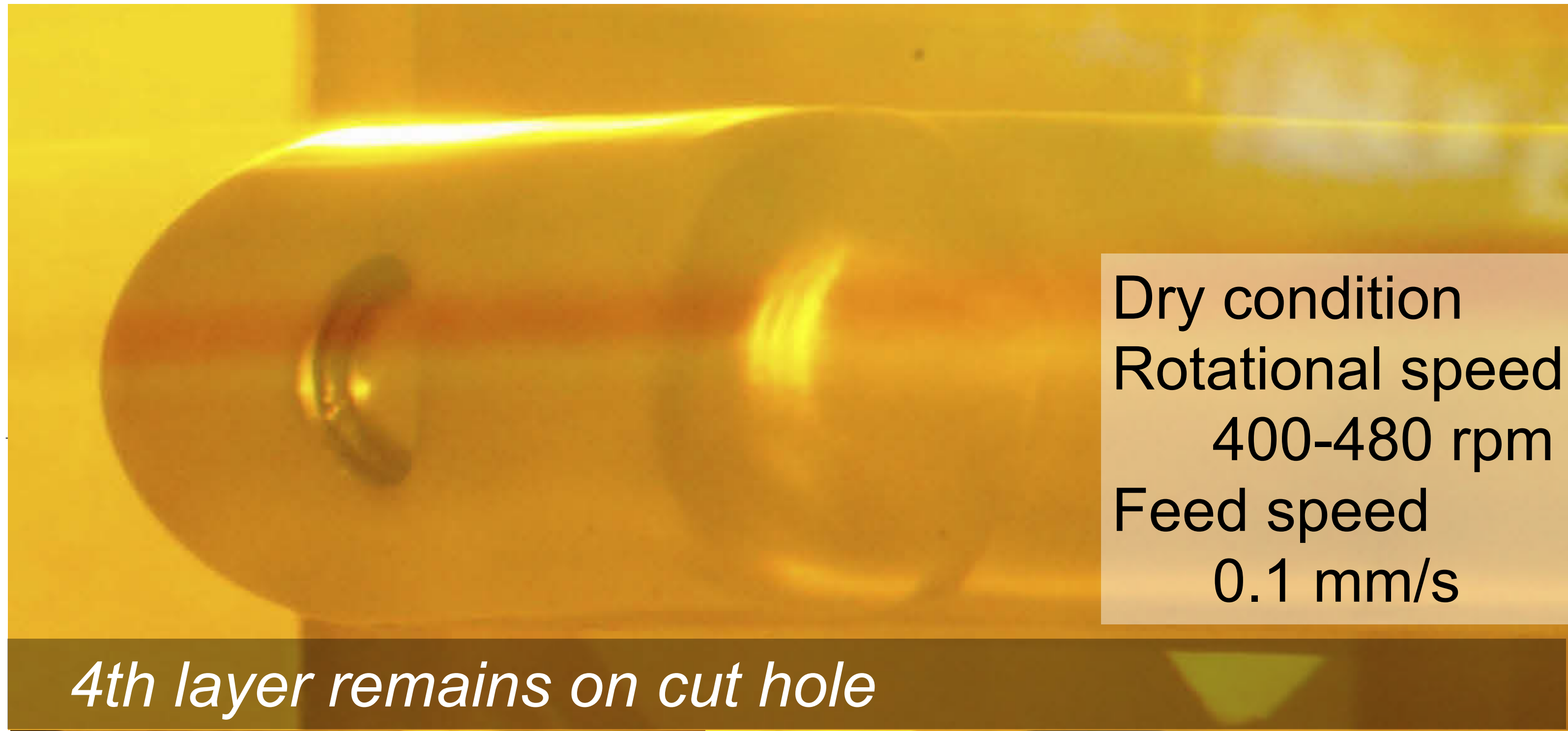


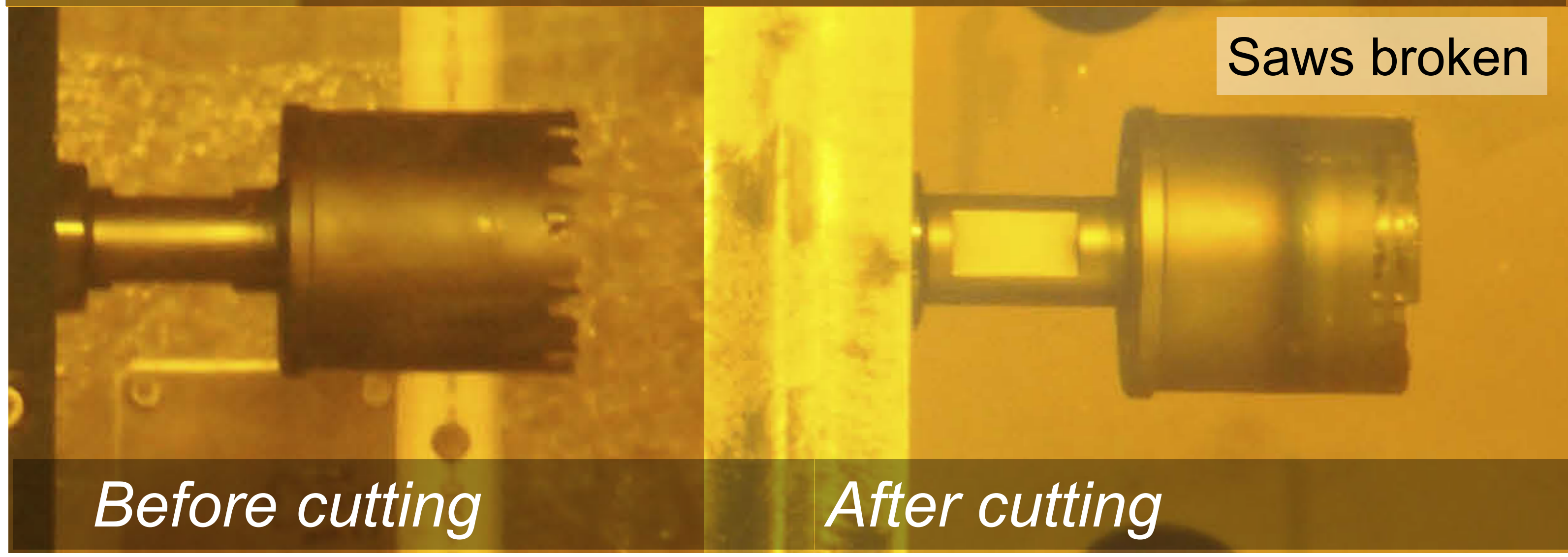
- 5th target vessel was failed by water leak from water shroud
- Before replacing target to 7th target, beam window part was cut using annular cutter 50 mm in inner diameter to inspect inside damage
- Cut performed without any lubricant by full-remote handling

Difficulties of cutting multi-layered wall



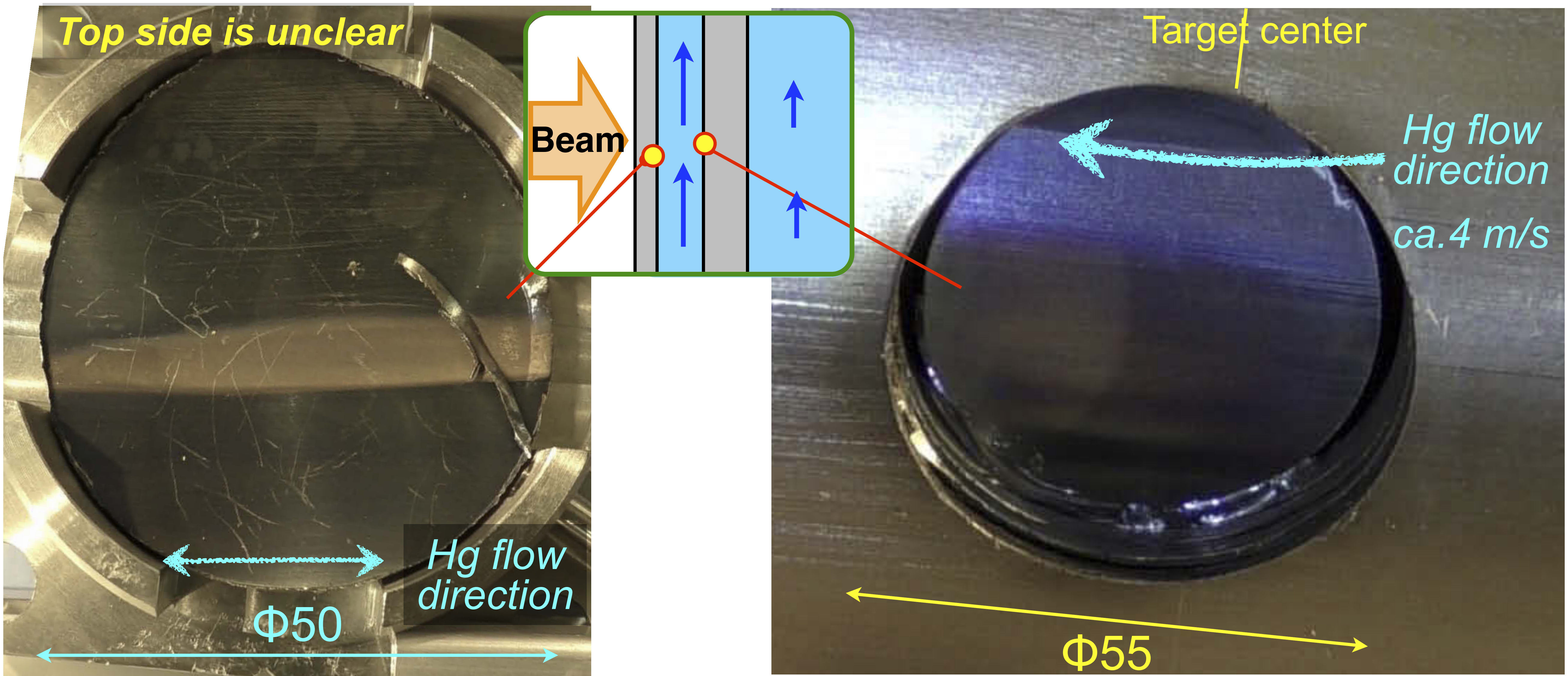
Vertical cross section of double walled target (5th target)





- 5th target (4 layers structure) was cut using annular cutter
- All prepared cutters (tip of saw) were broken by heat of dry cutting (>500ºC)
  Need to reconsider cutting condition and material of saw (coating, etc.)
- Innermost layer of beam window is still remains on cut hole
  The effect of gas microbubbles injection on cavitation damage was not confirmed

Damage inside narrow channel



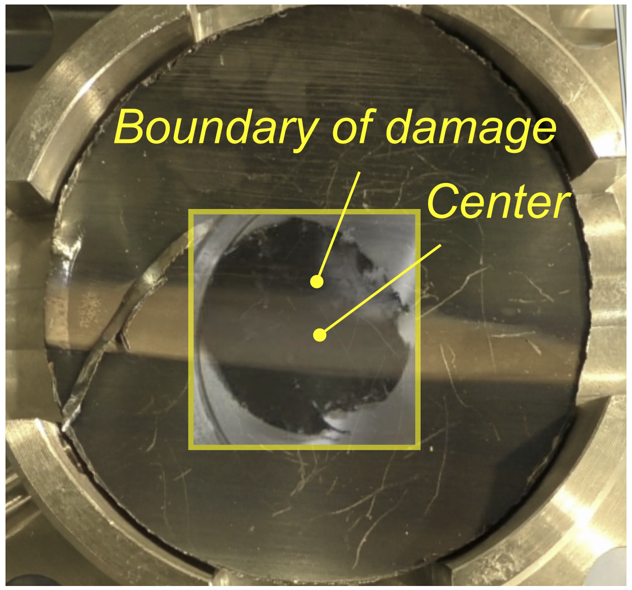
Outer mercury vessel

Inner mercury vessel
(narrow channel side)

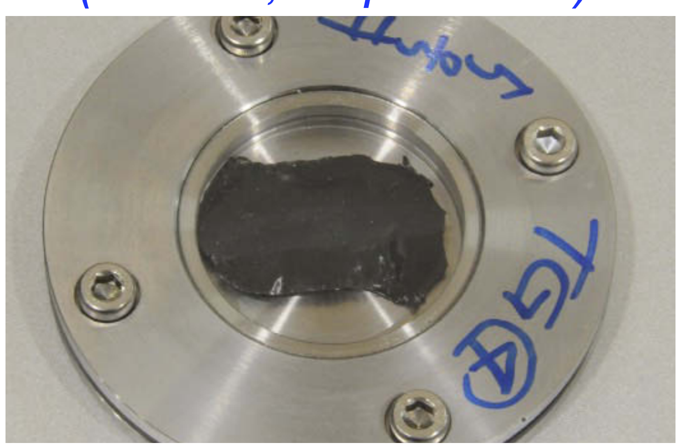
- Annular cutter was ca. 7.5 mm offset from center
- Horizontal damage band due to change of roughness was observed
- Machined scratch is recognized at top and bottom side, eroded depth seems small
- Color of surface is changed by heat of cutting
- Severe damage due to the cavitation and erosion was not observed on inner side

Cavitation damage around center

Outer mercury vessel

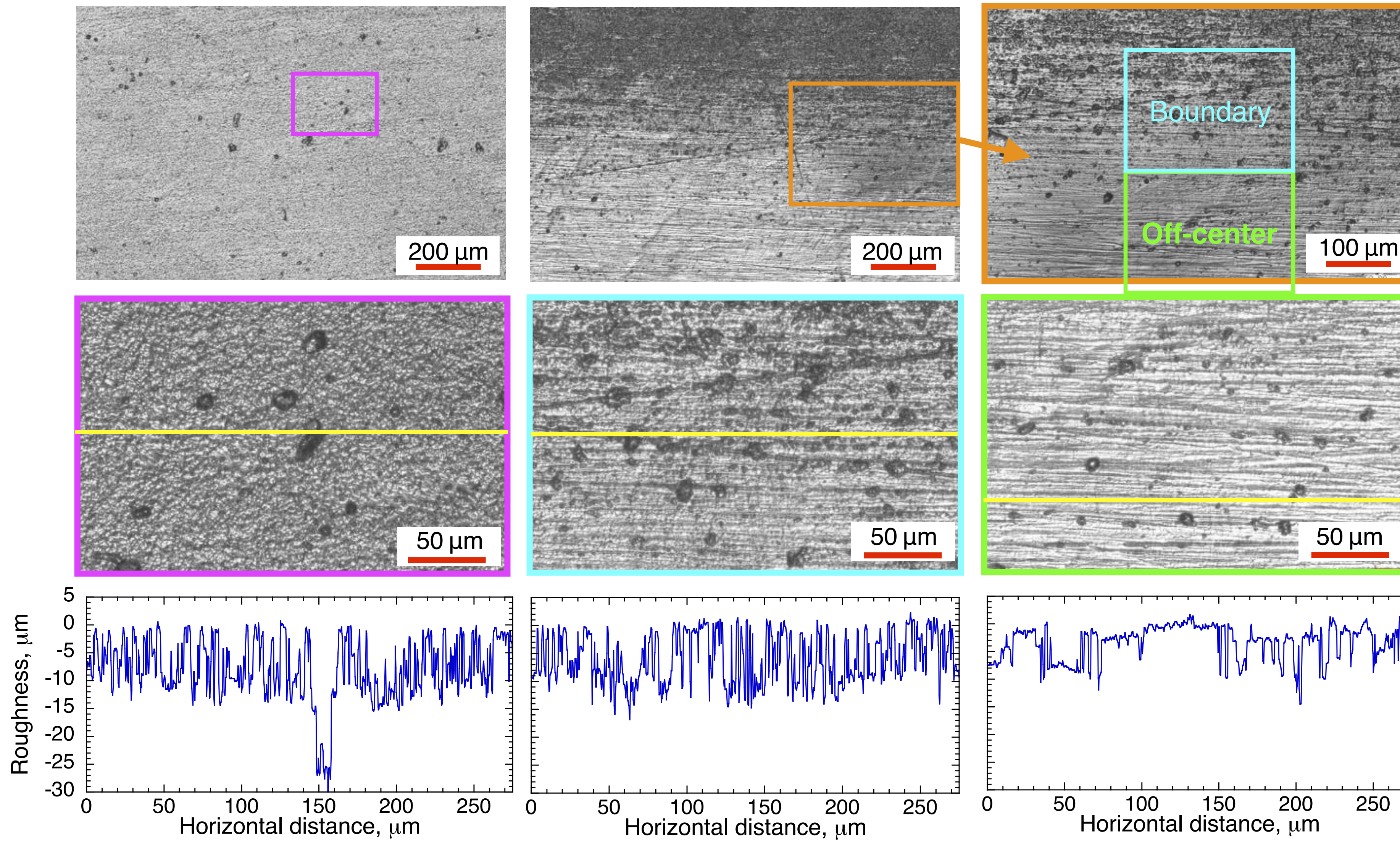


Silicone rubber replica (Struers, RepliSet F1)



Replica enclosed in glass cell and measured depth profile by LSM

Center of band-like damage | Boundary of band-like damage

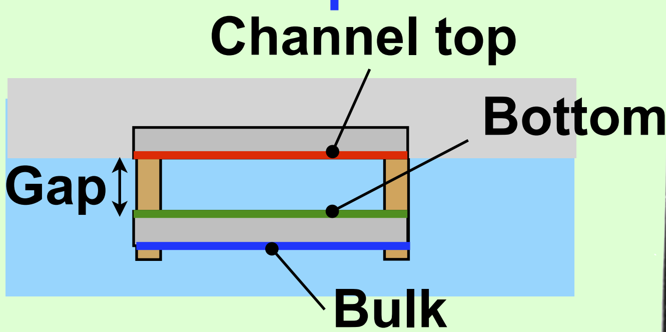


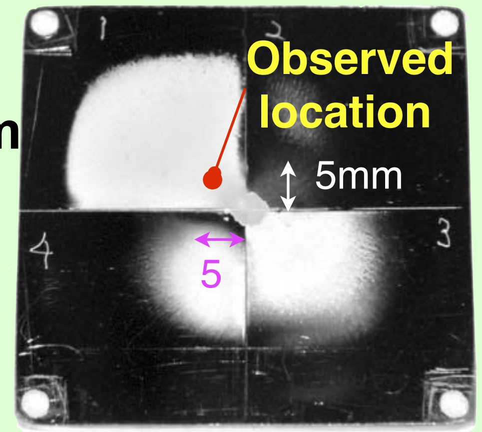
- Damage band seems to be formed by accumulated pits
- Maximum depth at around center is not changed much compared with off-center
- Relatively deep pits are scattered with rough surface
- Maximum damage depth at center is 25±5 µm (deeper than predicted value 10-15 µm)

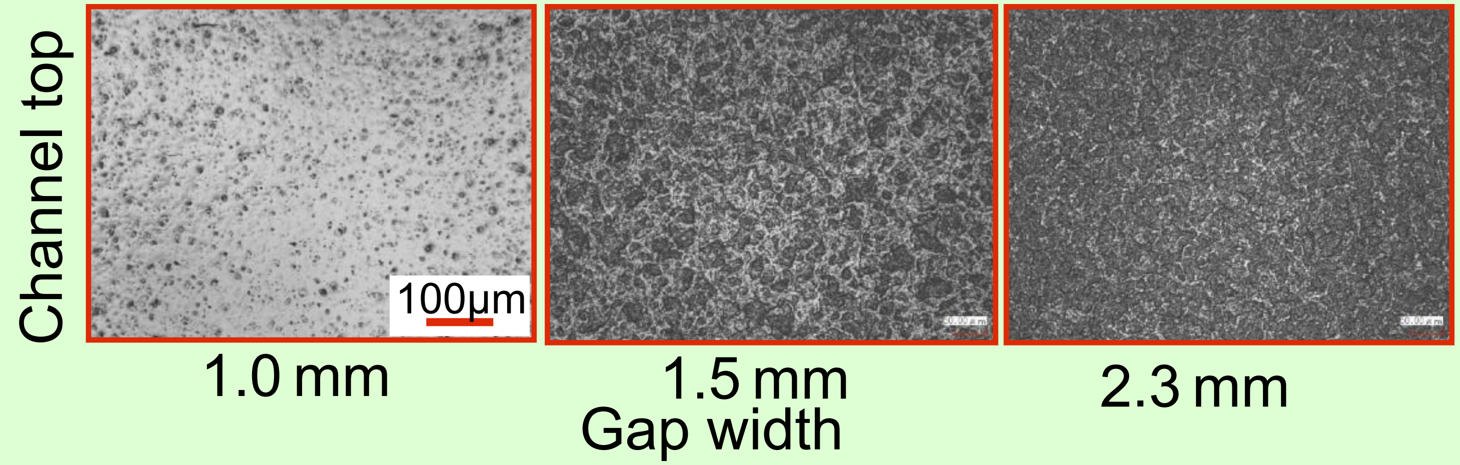
Why the band-like damage was formed

Possible reasons : Un-uniform gap, Flow distribution, Pressure distribution, etc.

Off beam experiment

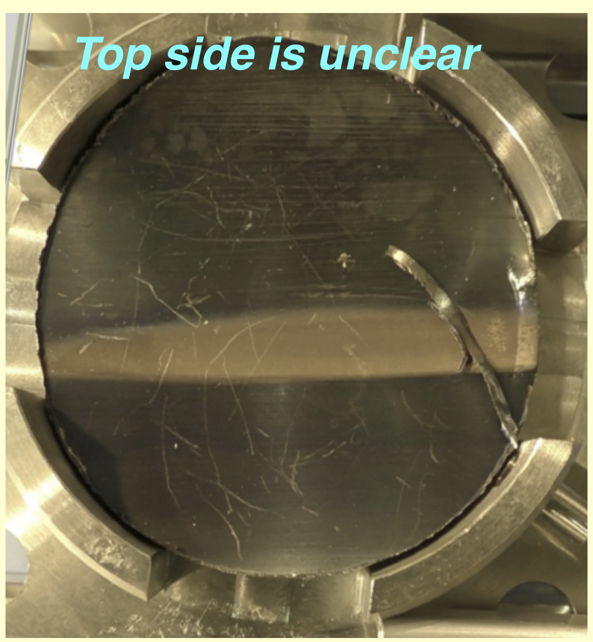


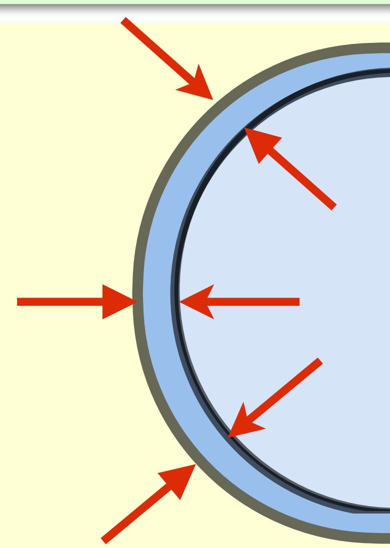


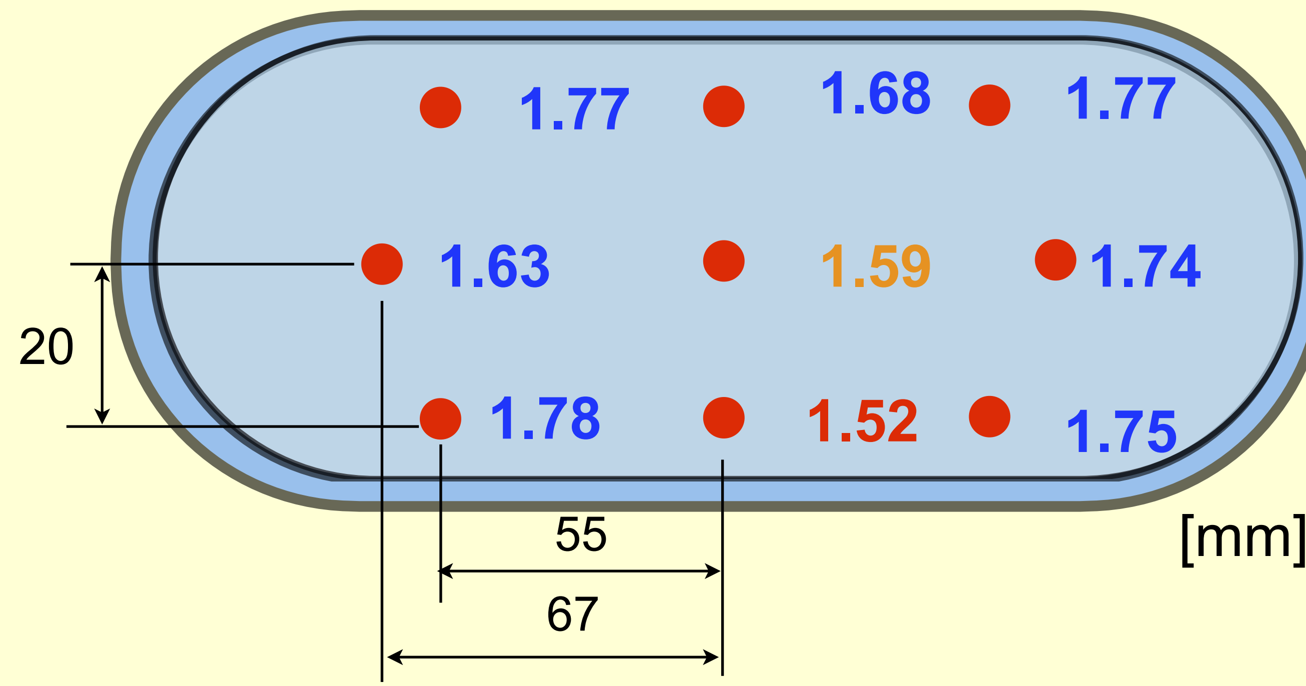


Specimen surface after 10^6 impact test

- *Damage seemed to be increased with increasing in gap width in off-beam experiment*



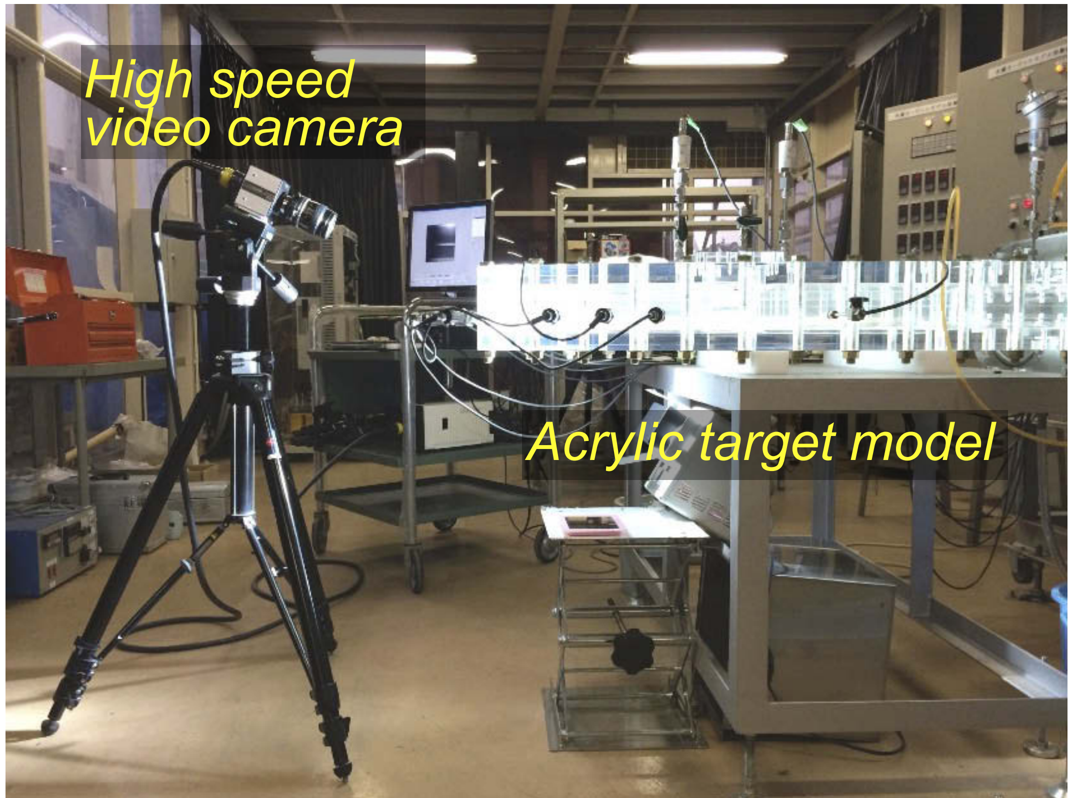


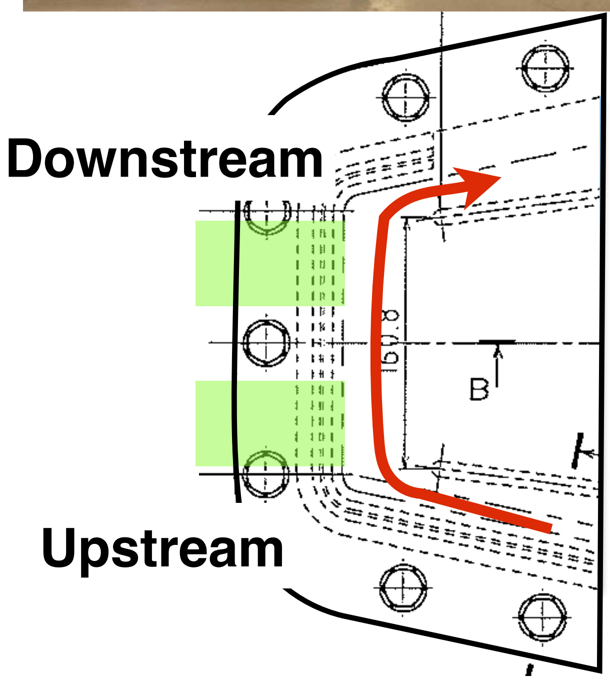


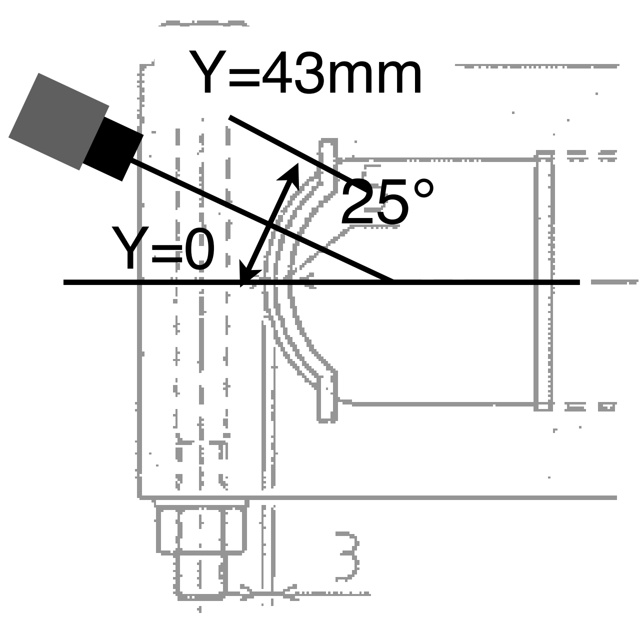
Measured gap between outer and inner wall *(in fabrication inspection)*

- *Gap at center part is slightly narrower than other part ….. not so much*
  Opposite trend with off beam experiment

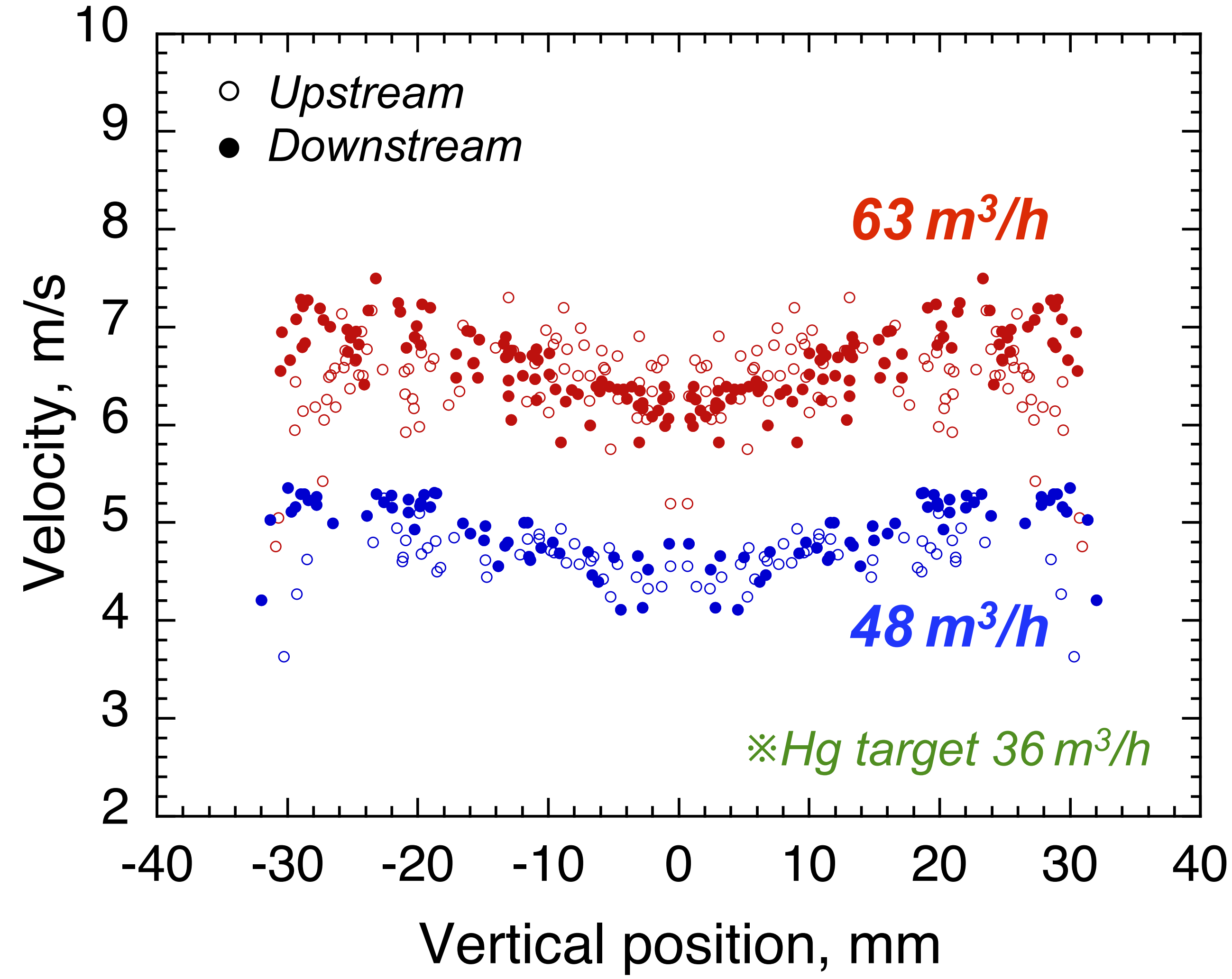
Flow velocity distribution in narrow channel





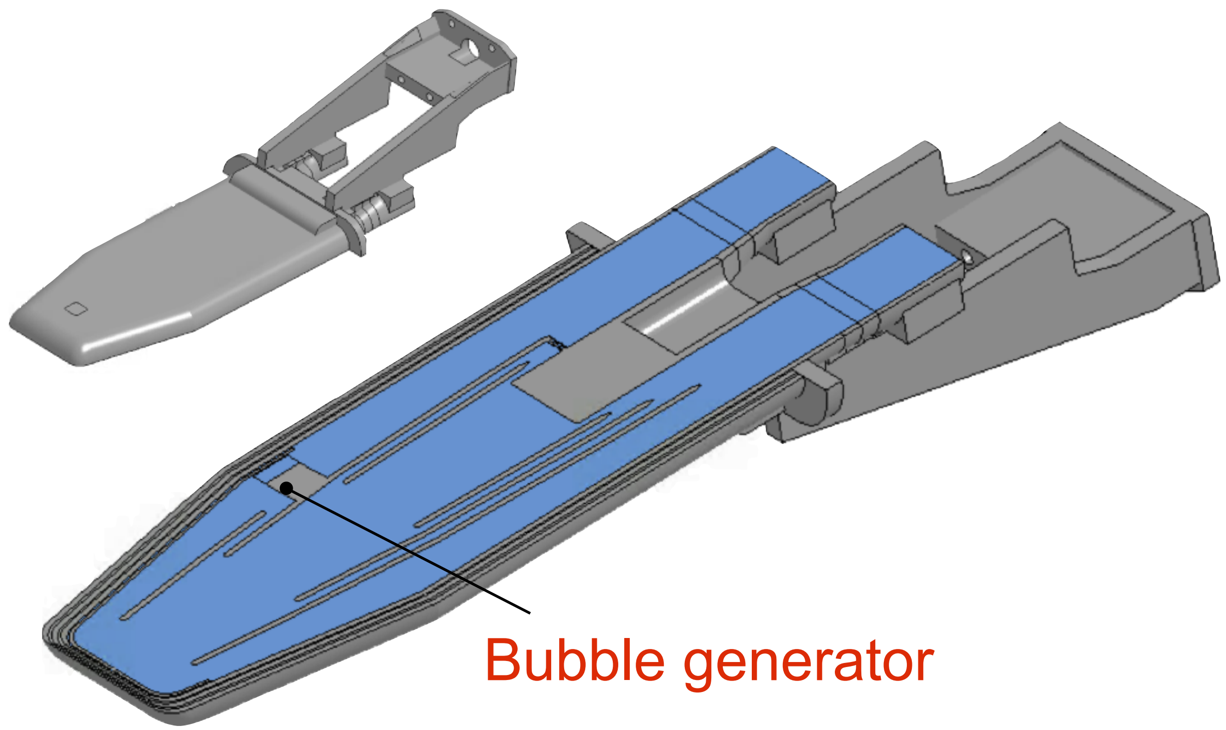


Water experiment with acrylic full-size model



- Flow velocity distribution in narrow channel was experimentally investigated using full-size acrylic model with water loop
- Flow velocity at center part is slightly slower than top&bottom side

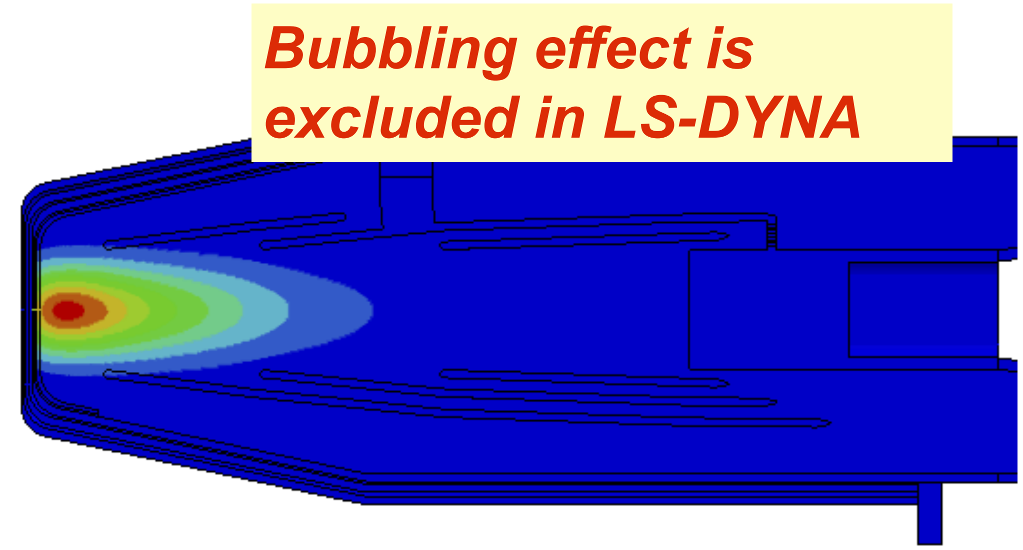
Pressure wave simulation by LS-DYNA

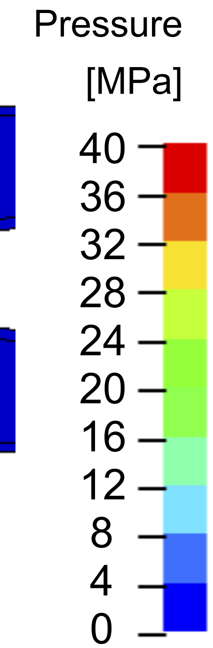


Half-model of target vessel

Total nodes: 5,072,820
Total elements: 4,495,996
Full solid model
(hexahedral elements)

Mercury : Elastic fluid with cut off pressure of -0.15 MPa
SS Vessel : Elastic





Example of initial pressure distribution
Beam power: 1MW
Peak energy deposition: 15.3 J/cc
JSNS Gaussian beam profile

Temperature rise

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

Pressure rise

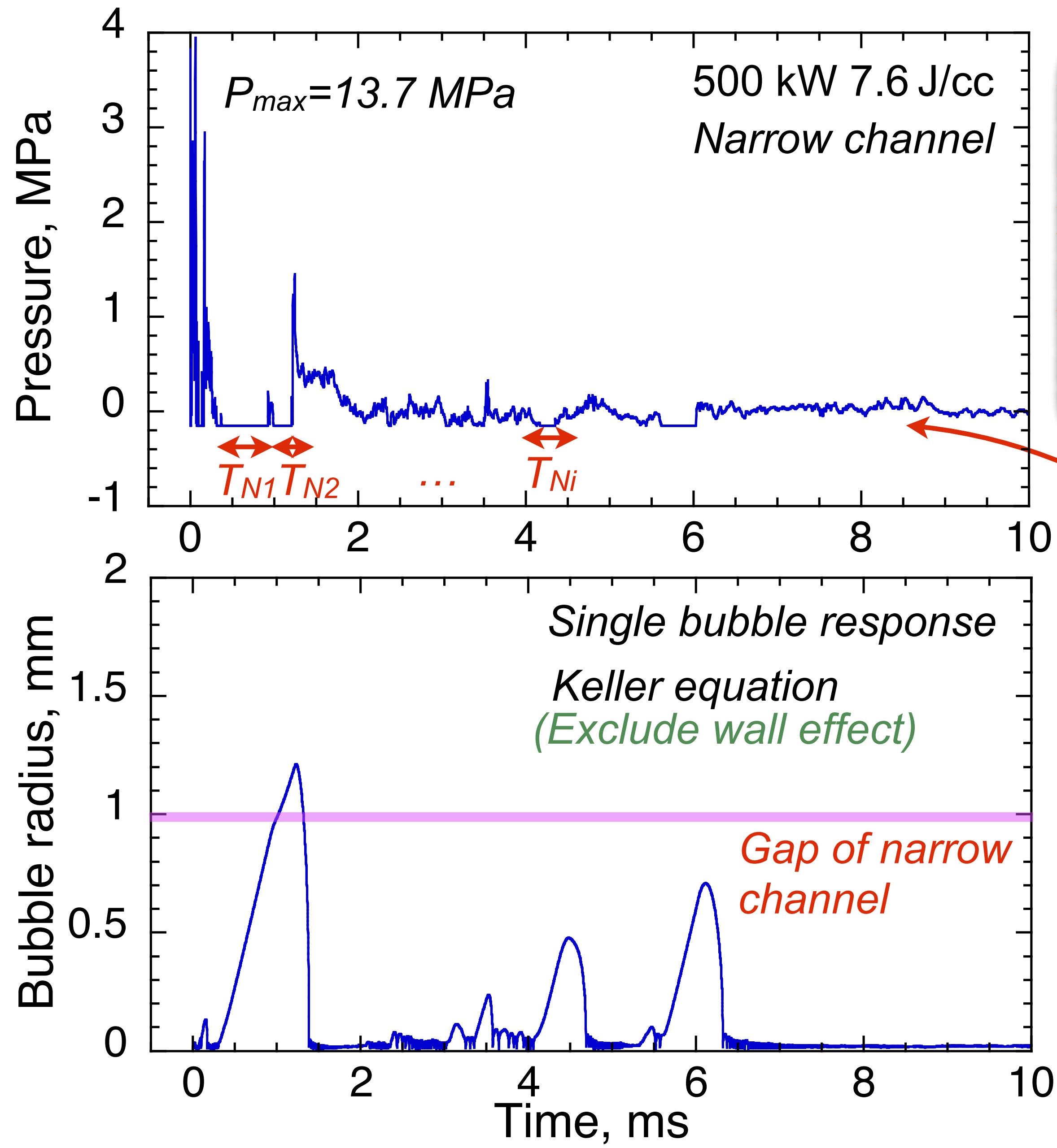
$$\Delta P = \beta K_T \Delta T$$

C_V: Specific heat
ρ: Densiry
β: Thermal expansion ratio
K_T: Bulk modulus

ΔT=8.15ºC@15.3J/cc
ΔP=38MPa@15.3J/cc

- Distribution of pressure waves in target vessel was calculated by LS-DYNA
- Initial pressure distribution based on nuclear heating calculated by PHITS and JENDL

Negative pressure period



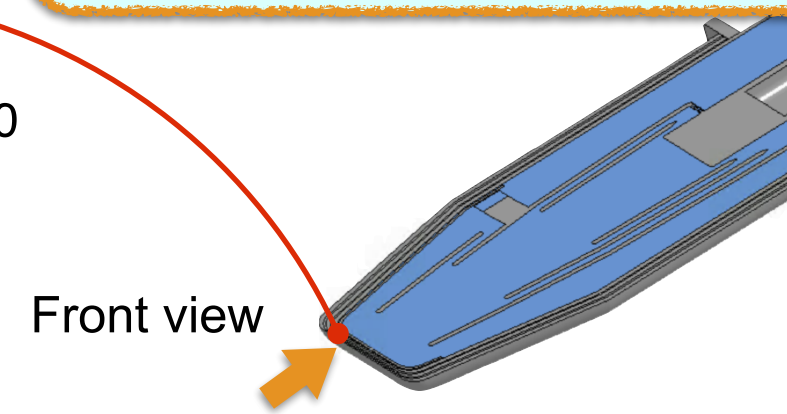
Pressure and bubble response at bulk side

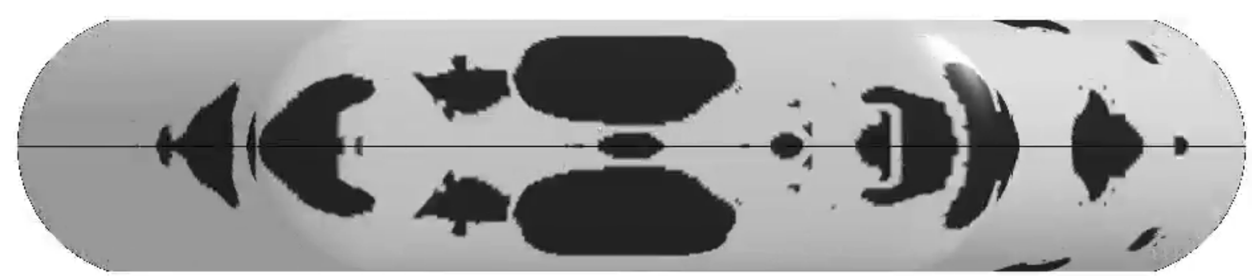
Negative pressure period

Accumulated value at each element

$$T_{N_{accum}} = \sum_{i=1}^{n} T_{N_i}$$

T_N=Saturation time of cut off pressure (-0.15 MPa)



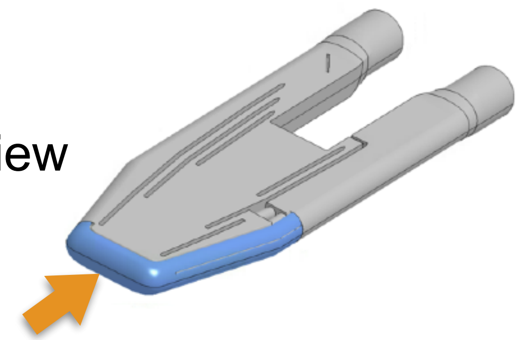


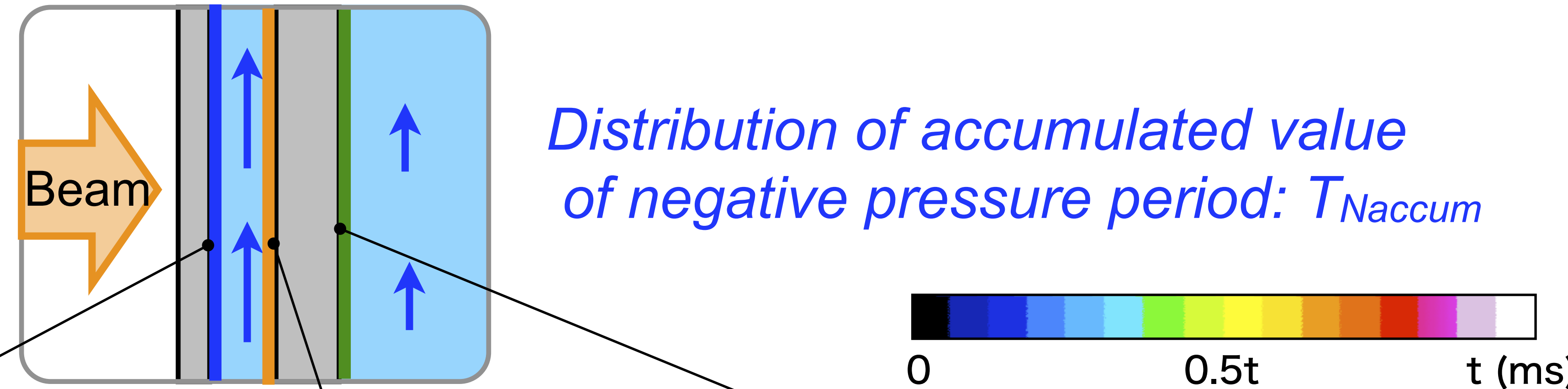
Black denotes the region of pressure saturating at -0.15 MPa

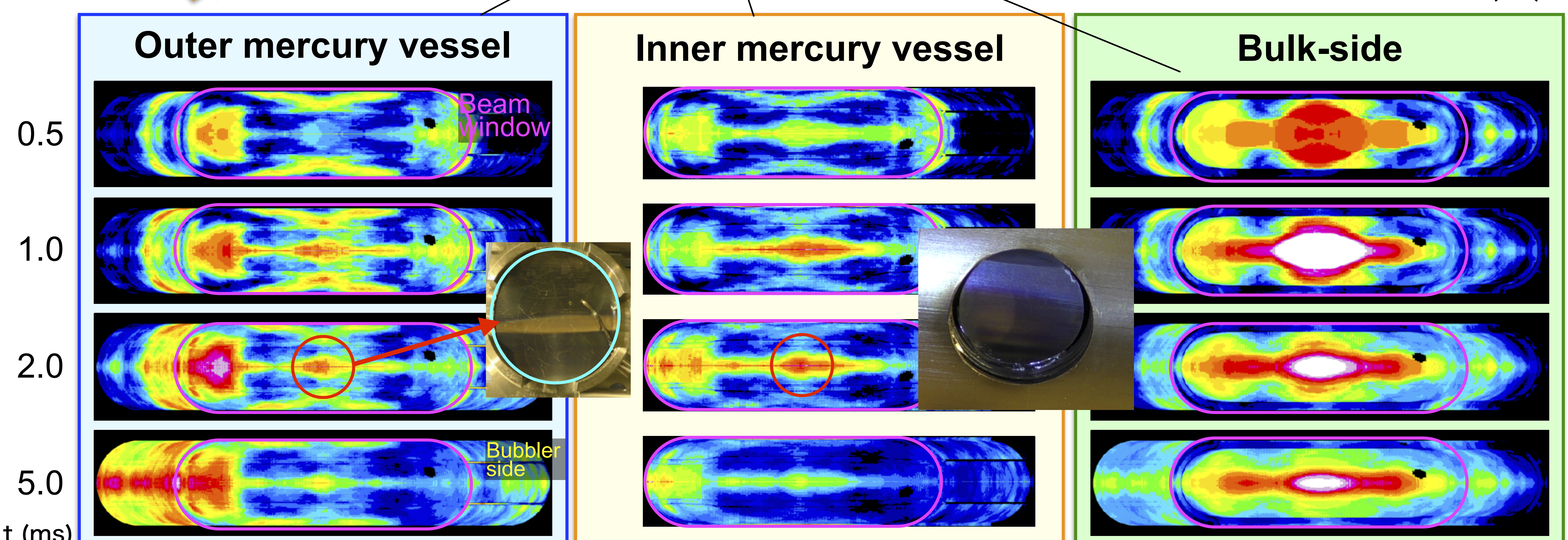
- Negative pressure period, which is correlated with degree of cavitation damage, was calculated using pressure time response
- Here, we focus attention on the distribution of accumulated saturation time

Negative pressure distribution

Gaussian beam profile
500 kW, 7.6 J/cc



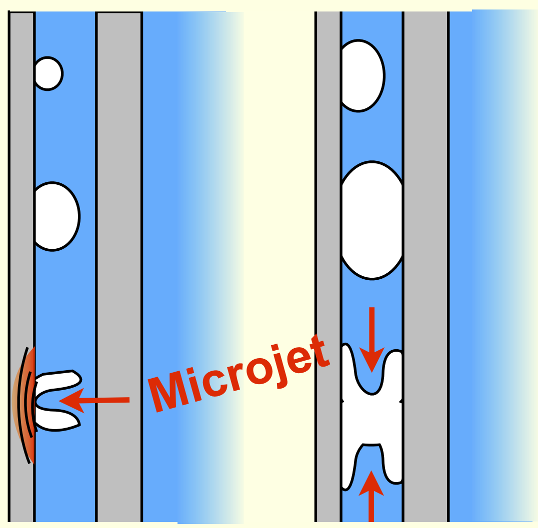




- Accumulated negative pressure period up to 2 ms seems to be correlated with the damage distribution on cut out disk
- Short time of negative pressure period is effective to form damage in narrow channel

Pressure and bubble responses at center

Expected narrow channel effect

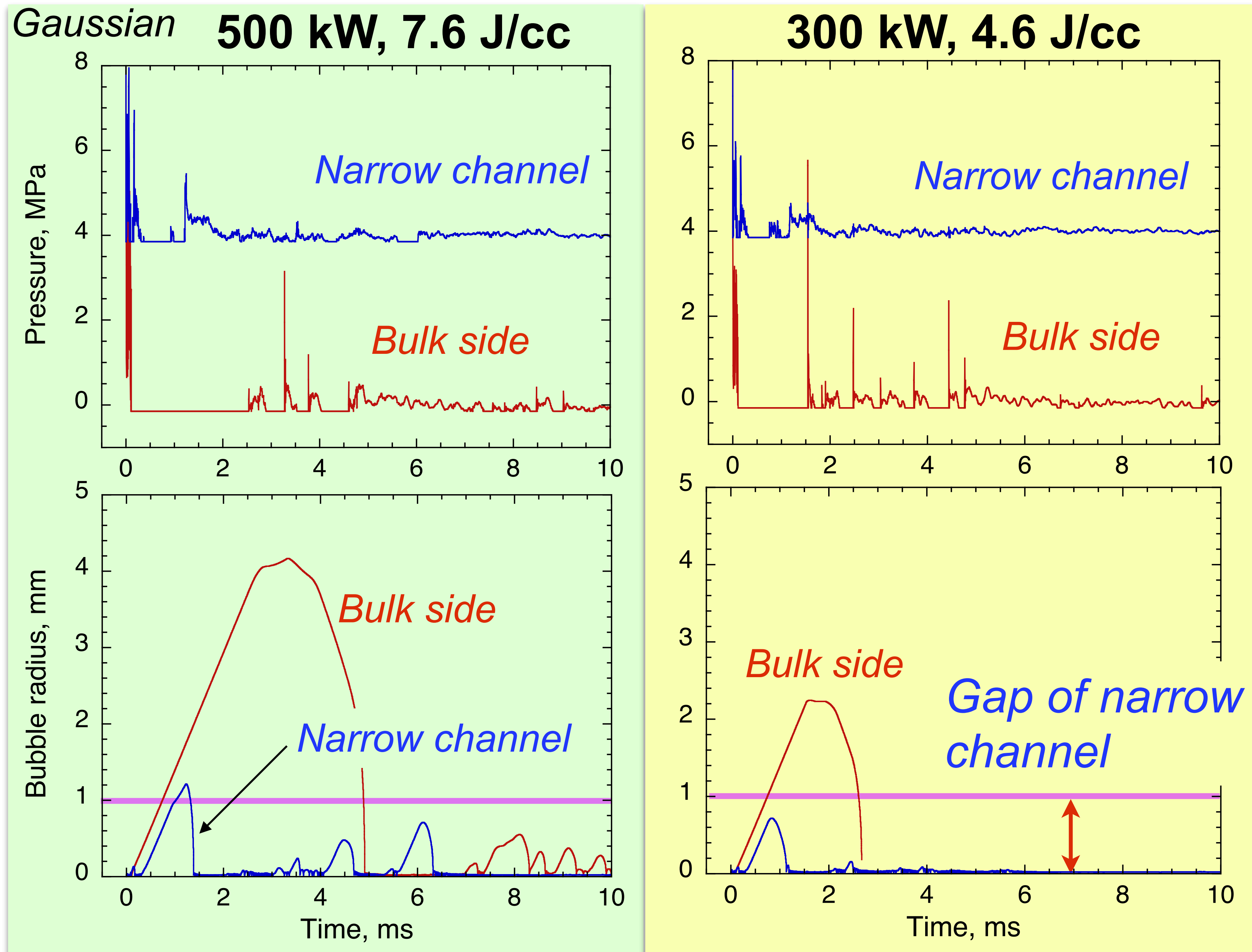


Small bubble

Microjet ejects vertical to wall

Large bubble

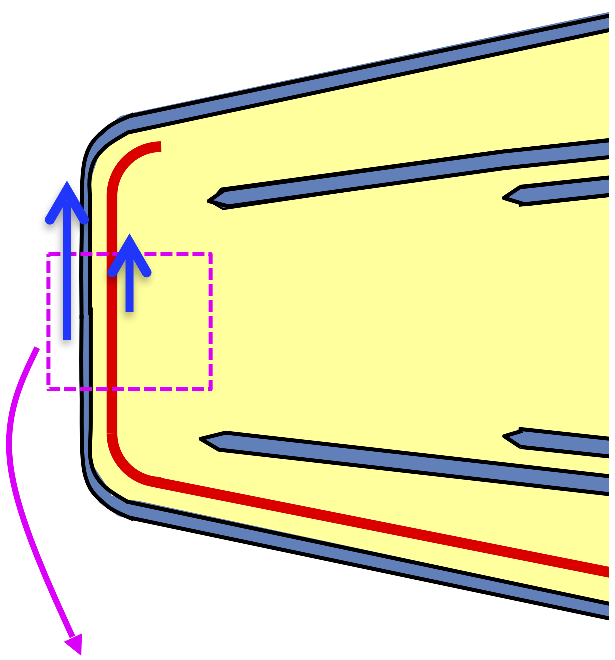
Microjet ejects parallel to wall



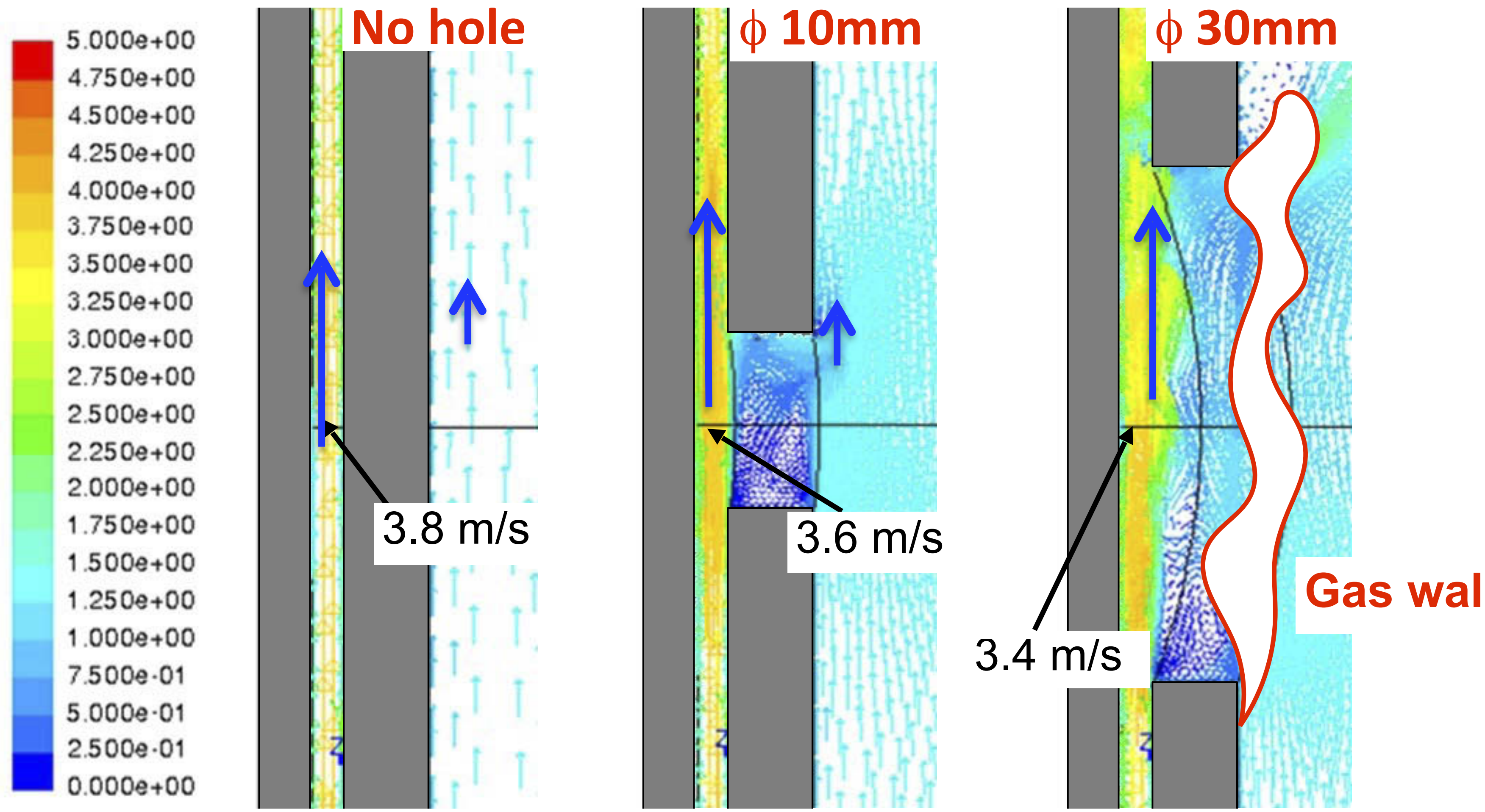
- Bubble growing and collapsing occurs before 2 ms in 300 kW
- In the case of 300kW (take bubble effect into account), it has the possibility to occur violent cavitation bubble collapse

Future plan to improve target and mitigate cavitation damage

Double flow target concept



Inner wall failure was assumed as a circular hole at the center



Q : Flow rate through the hole

Q : 0.2 cc/s (0.03%)

Q : 27.3 cc/s (3.2%)

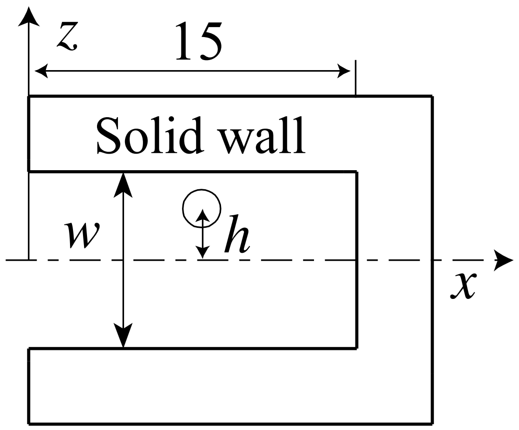
- Cavitation damage mitigation effect is still expected because the fast flow velocity in the narrow channel is maintained even after the inner wall is failed
- Double flow target (single window at center, pre-hole inner wall) has the benefits of narrow channel and bubble injection
- Gas wall for absorbing pressure waves is an option for double flow target

Summary

- Beam window of used JSNS 5th target vessel after 670 MWh (av. 406 kW) was cut and observed
- Measured damage depth of narrow channel by the replica was approximately 25 μm (deeper than predicted depth)
- Band-like damage damage was observed on narrow channel-facing outer mercury vessel, but no-obvious damage was observed on inner mercury vessel
- Short time negative pressure might be affected damage formation, but inner side damage is unexplained by simulation
- Effect of microbubbles on cavitation damage mitigation is still unclear due to failure of cut out of innermost beam window, we should be revise the cutting process and tools

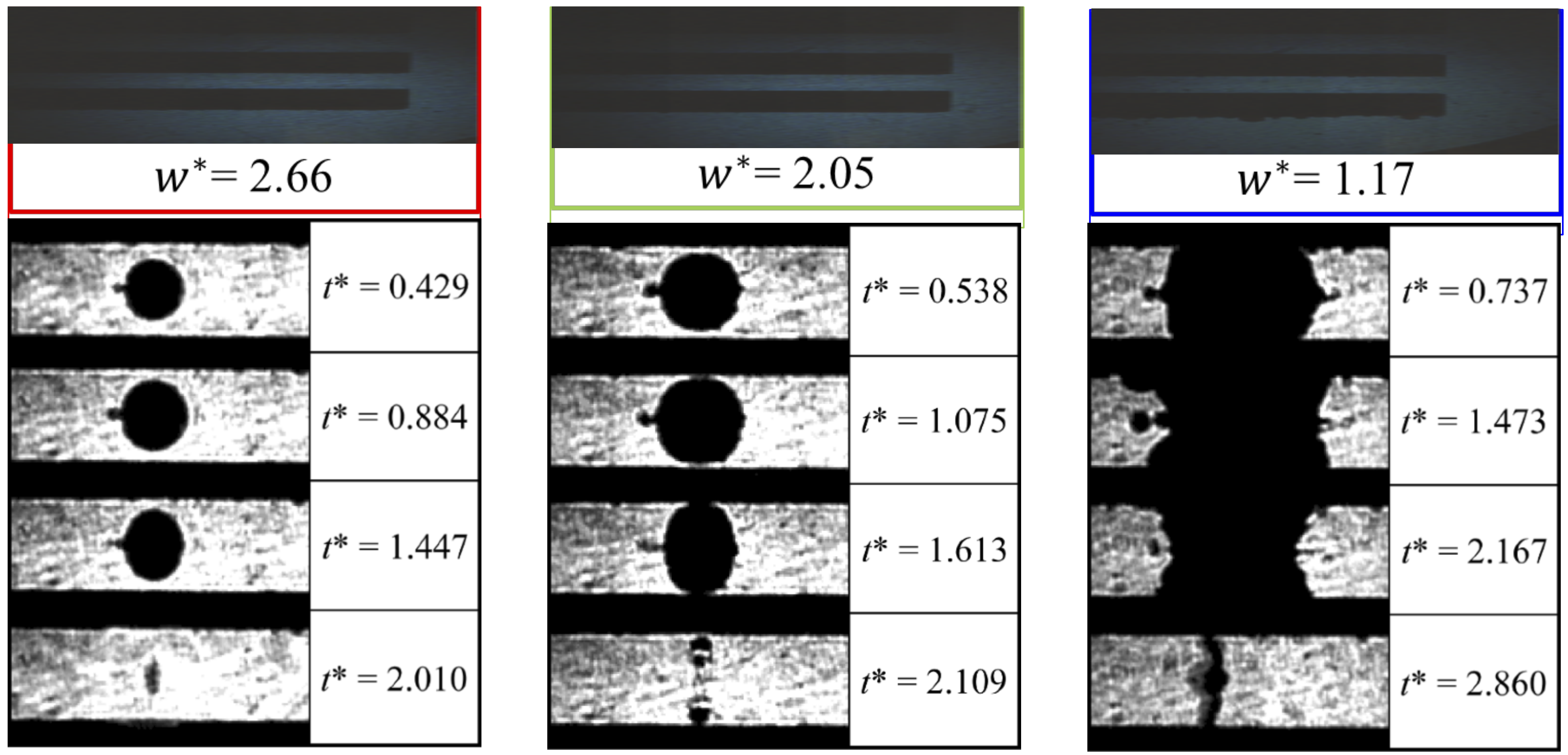
Backup slides

Bubble behaviors in narrow gap



$$w^* = \frac{w}{R_{max}}$$

$$h^* = \frac{h}{R_{max}}$$



Record: 400,000 fps, Play: 20 fps | Record: 200,000 fps, Play: 15 fps | Record: 50,000 fps, Play: 15 fps

Splitting collapse | *Neutral collapse*

large w^* ⟵⟶ small w^*

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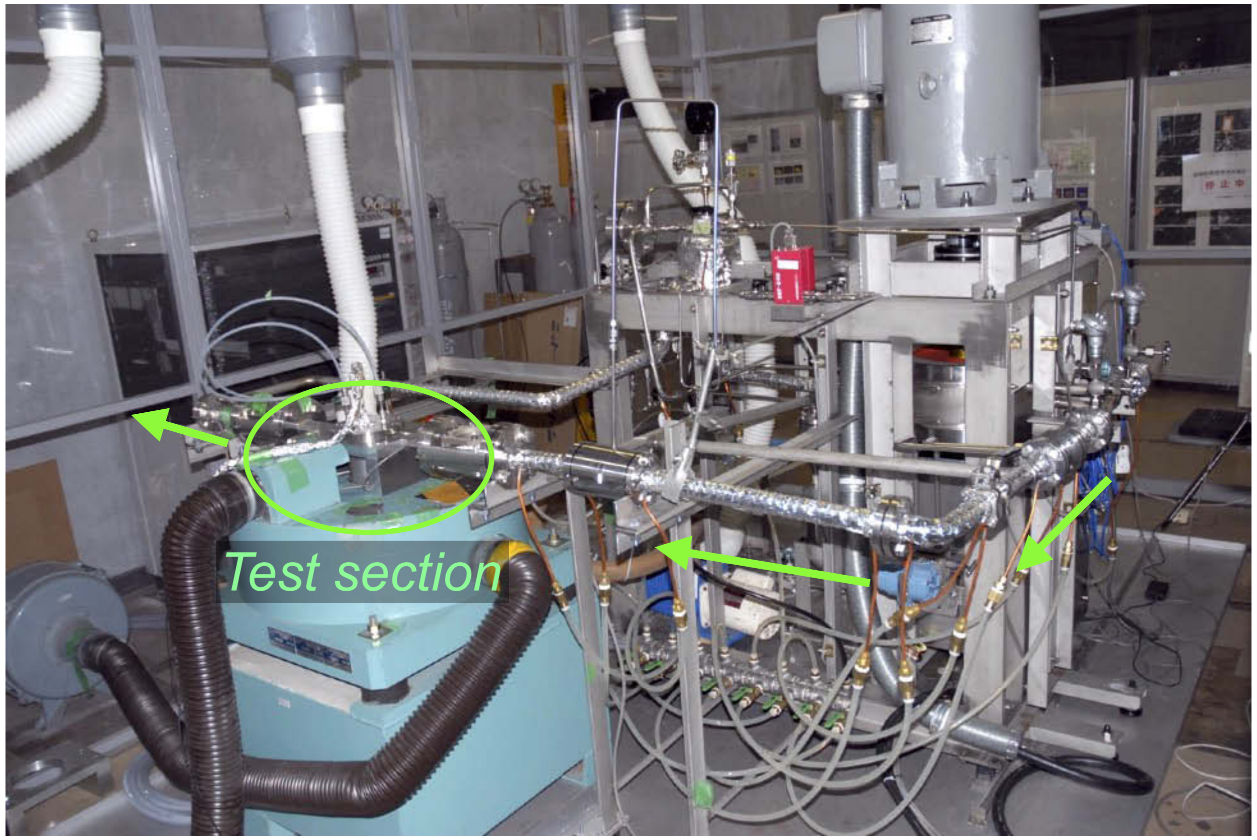
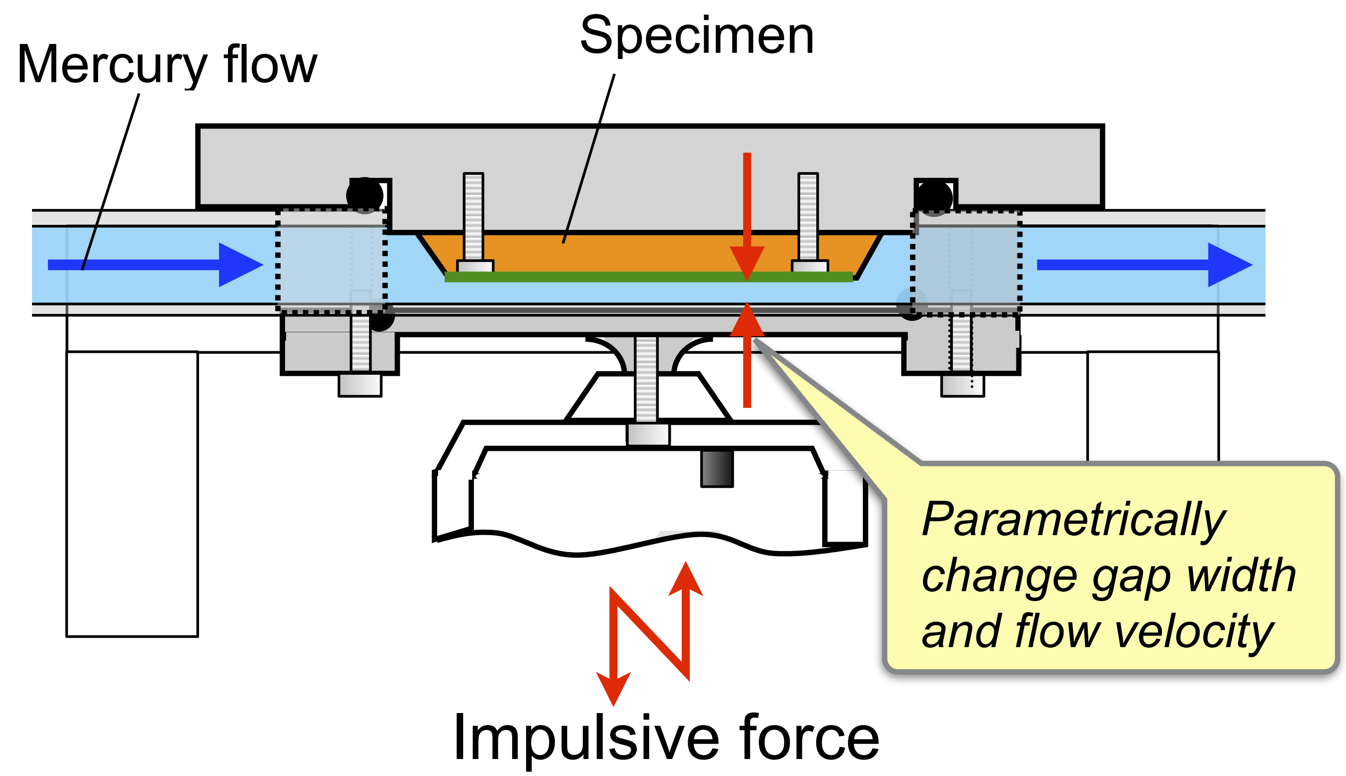
IWSMT-12

Future plan for investigating narrow channel damage



MIMTM (electro Magnetic IMpact Testing Machine) with mercury circulation loop

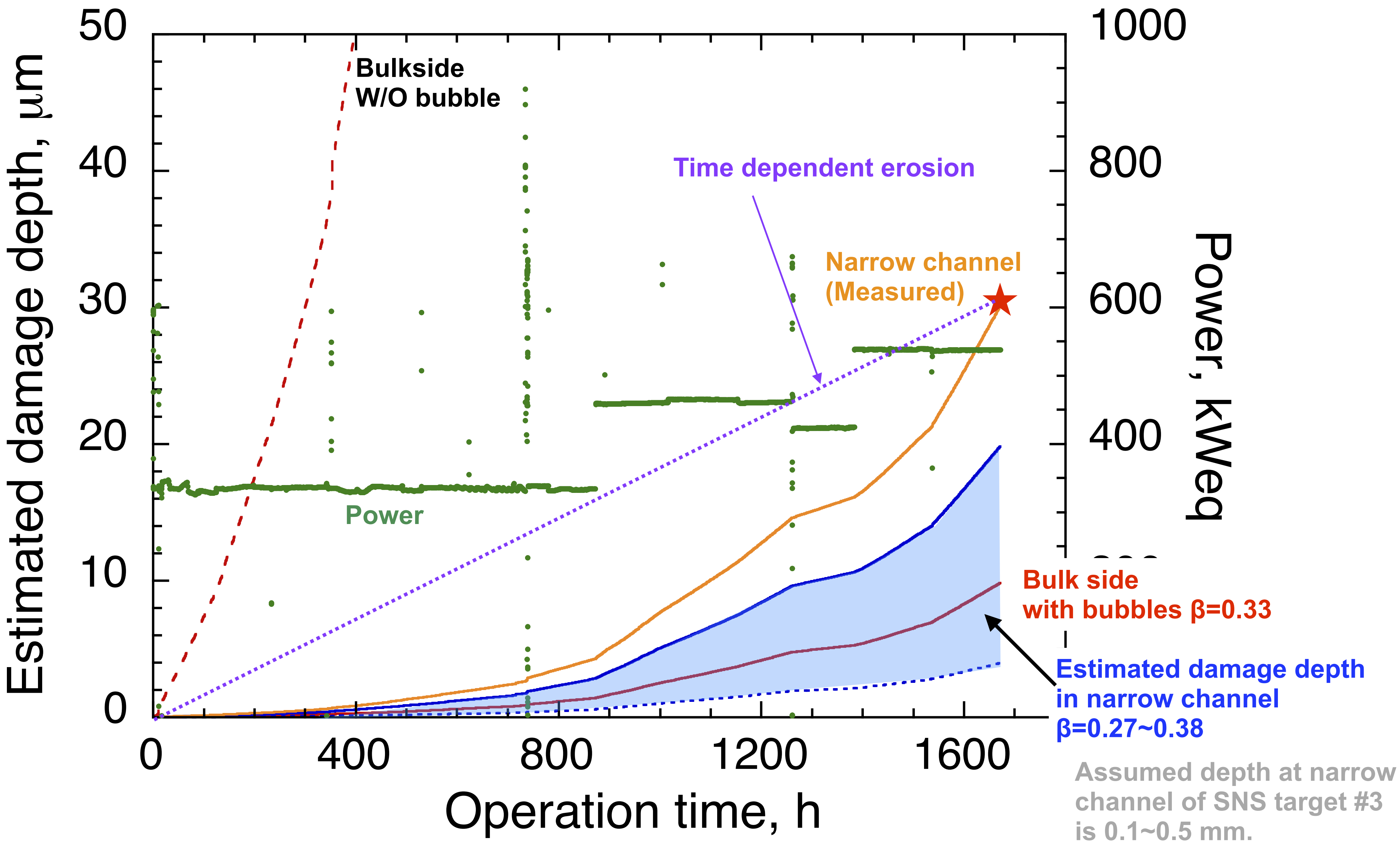


MIMTM test section

- Previously conducted off-beam damage experiment under stagnant mercury will extend under flow condition
- Under stagnant condition, damage was reduced with the decreasing in gap width
- Relationship among flow velocity, gap width, and cavitation damage in mercury will be investigated using MIMTM with mercury circulation loop

Estimated depth change

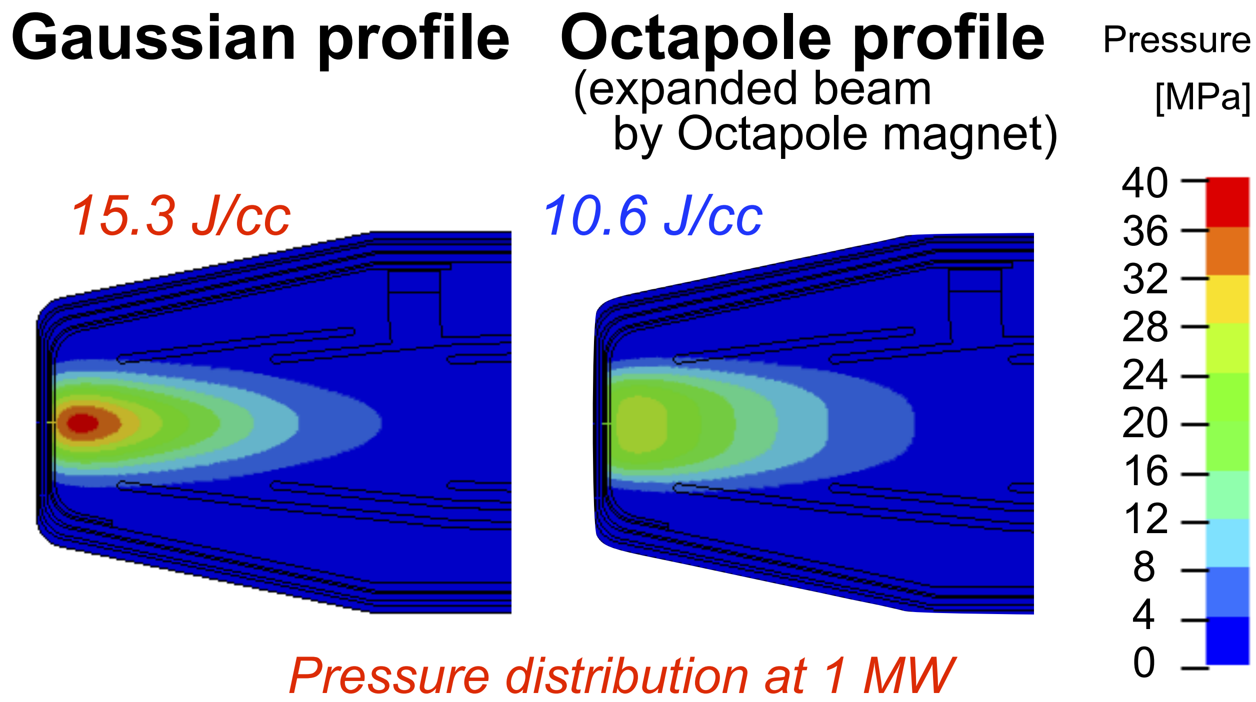
Power depend or time depend?

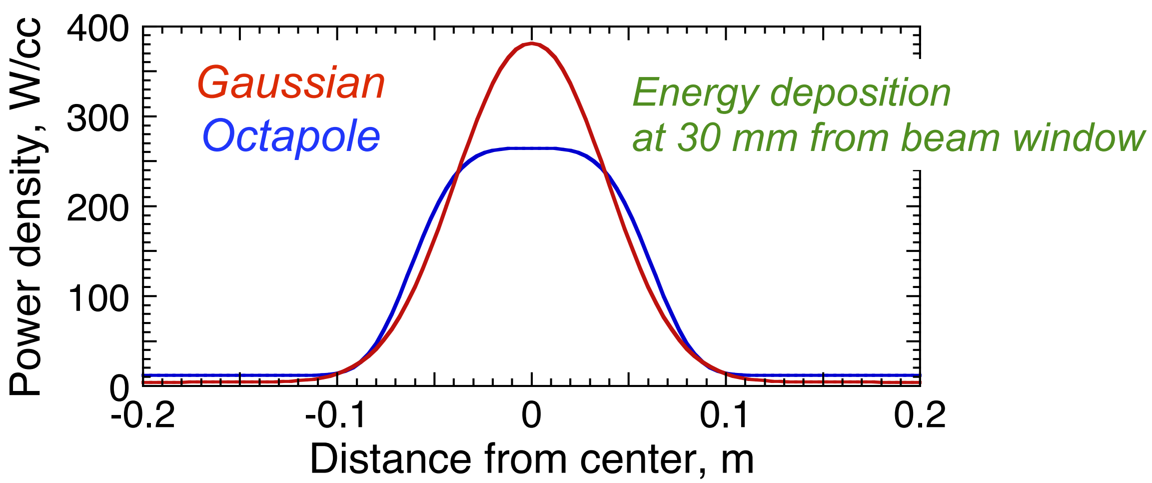


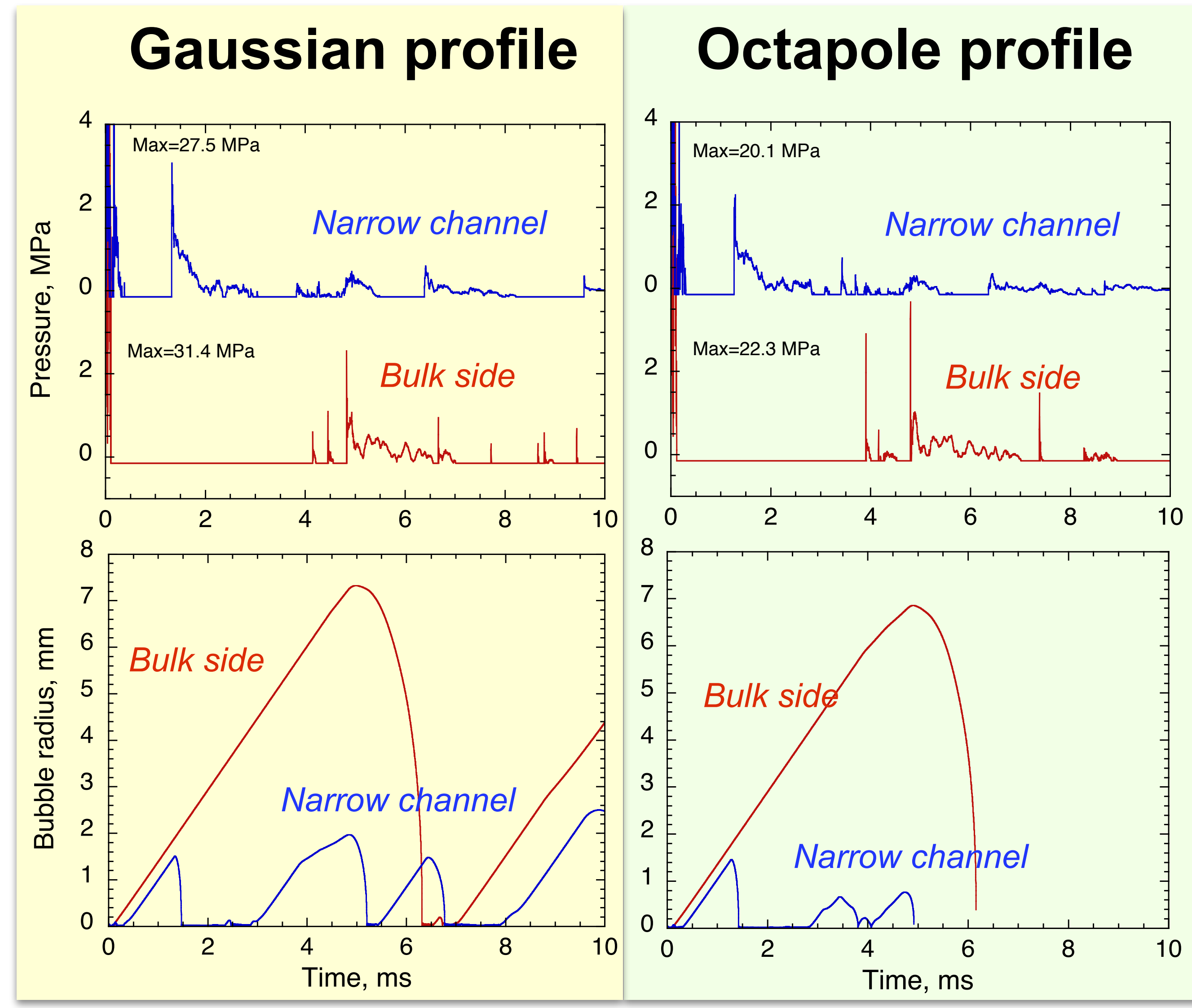
Assumed depth at narrow channel of SNS target #3 is 0.1~0.5 mm.

- Measured depth of pit at narrow channel is about 25 μm
- If this damage was time dependent erosion, < 0.1 mm at 5000 hours
- If power dependent damage , depth of 5000 hr at 550 kWeq —> about 0.7 mm
- Is the double wall effect smaller than bubbling?

Beam profile dependency on pressure

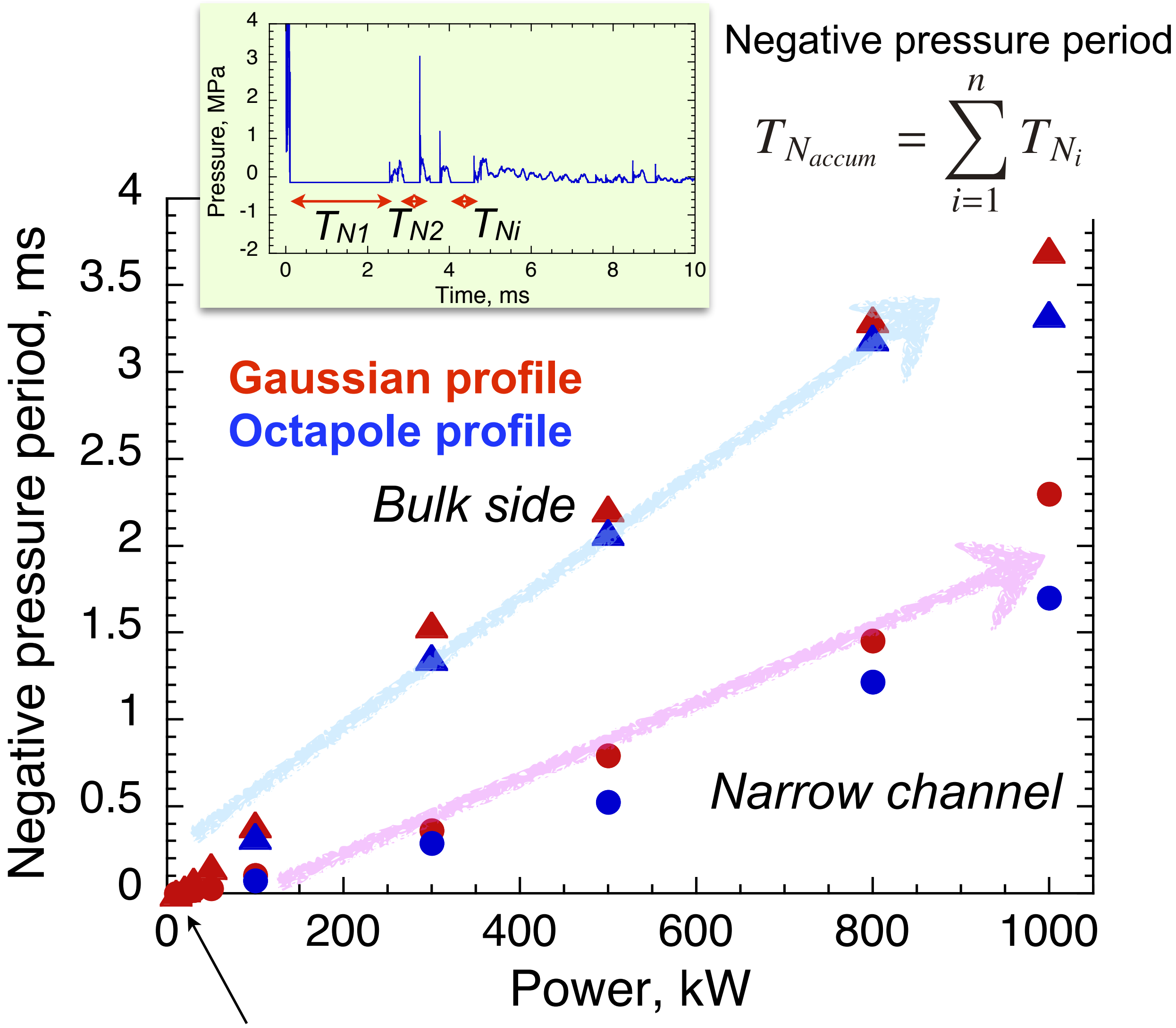




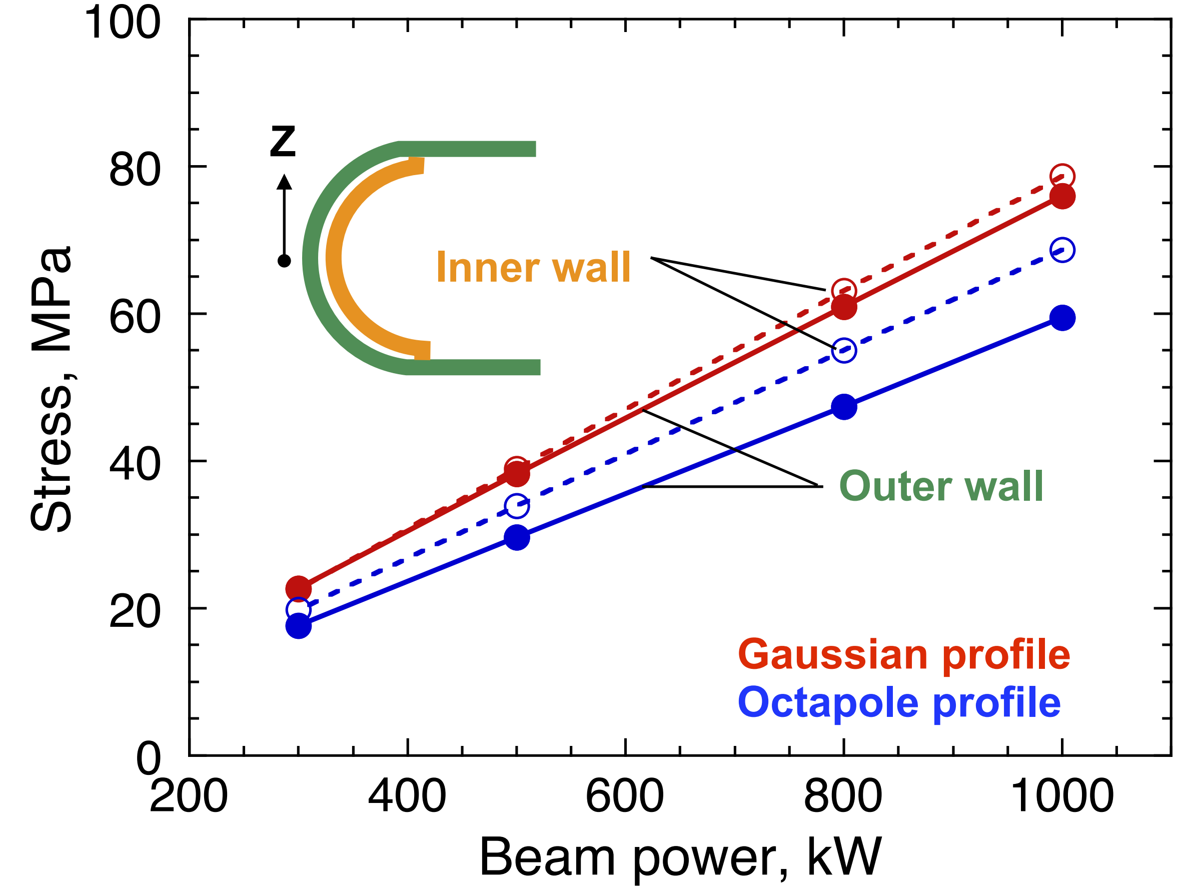


- Effect of proton beam profile on cavitation damage was examined by pressure wave simulation
- Time response of pressure and negative pressure period at the narrow channel is hardly changed

Power dependency of negative pressure



Pressure is not saturated at lower than 10 kW



Z stress at center

- Negative pressure period that might be correlated with the cavitation damage is change with the beam power, not big difference by beam profile
- However, expanding beam (reducing peak energy deposition) is effective to reduce applied stress at the beam window

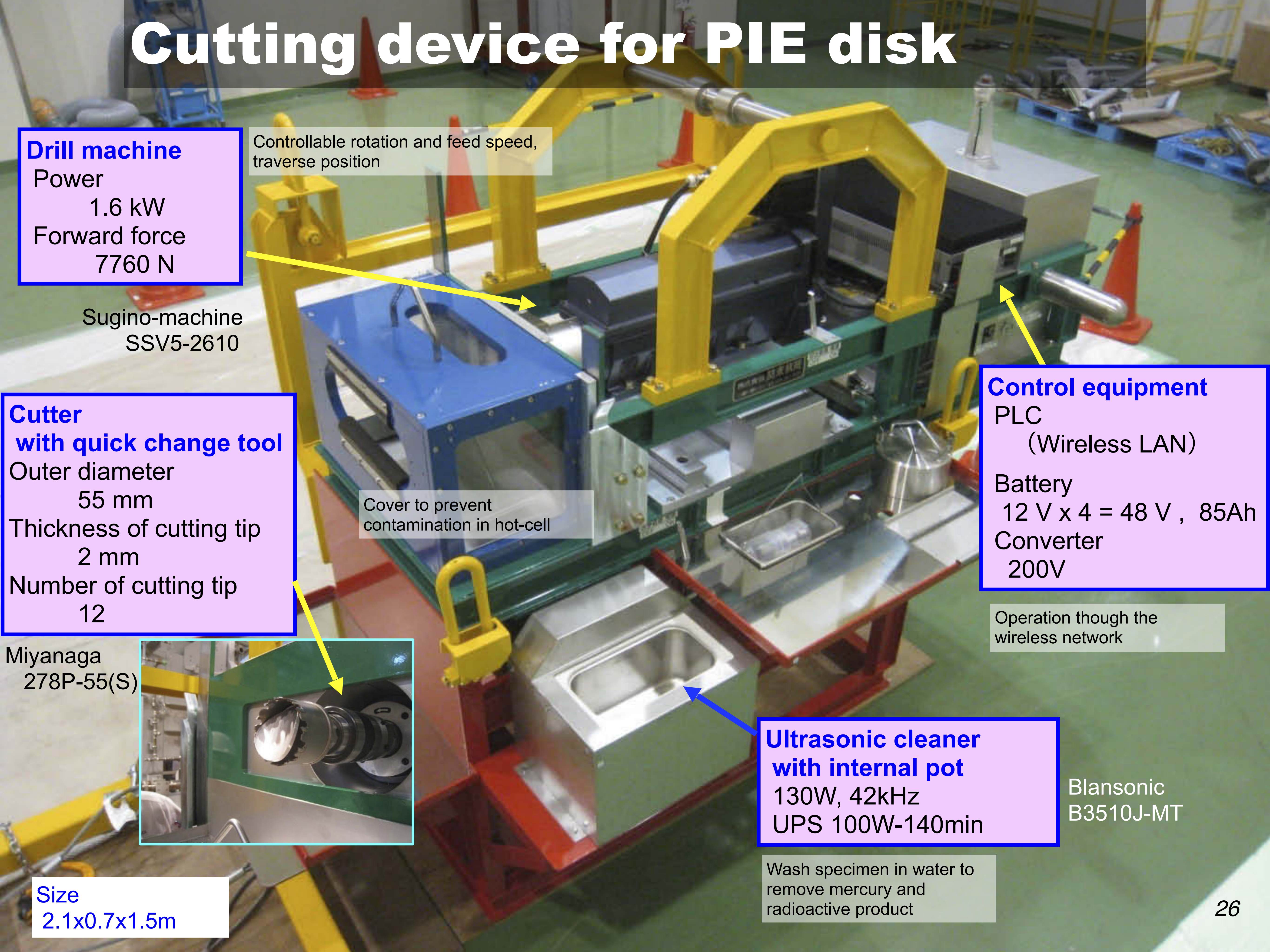
Operation histories of JSNS target

Target		Damage mitigation technology	Total power, MWh	Operating time, h	Average power, kW
1st	2008. 5~	**SH** SH: Surface hardening	471	3713	126
3rd	2011. 12~	**SH+MBI** MBI: Microbubble injection	2050	7537	272
5th	2014. 10~	**SH+MBI+DW** DW: Double-walled structure	670	1672	406
7th	2015. 10~	**SH+MBI+DW**	170	330	517
2nd	2016. 2~ in operation	**none**	414	1906	217

Observed in 2015

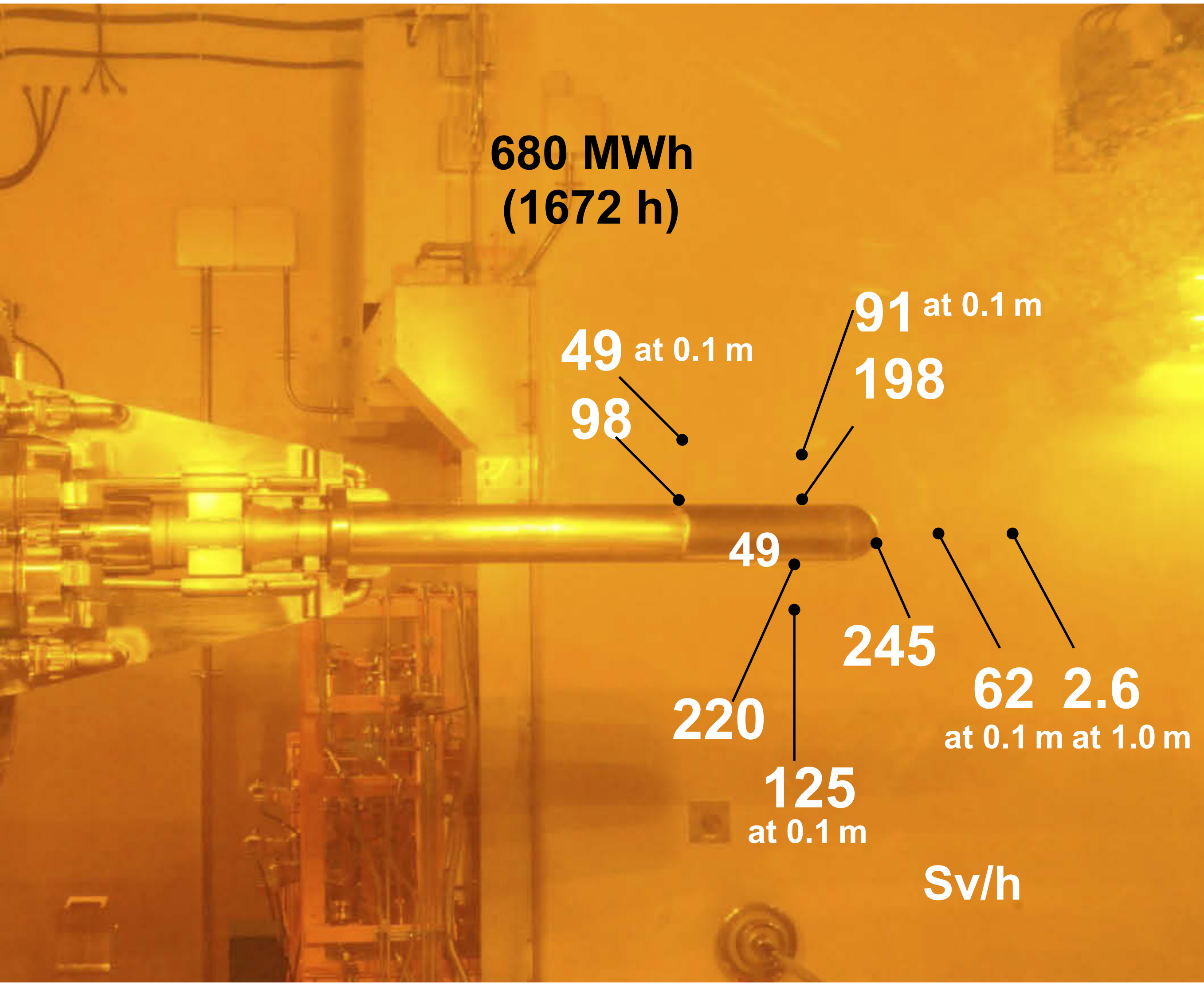
- 1st target operation was stopped due to the earthquake
- 5th and 7th targets operation were stopped by trouble of water shroud
  - Failed at 1month (5th) and 2 weeks (7th) after ramped up 500 kW operation
- Current average beam power is 200 kW (2nd target)

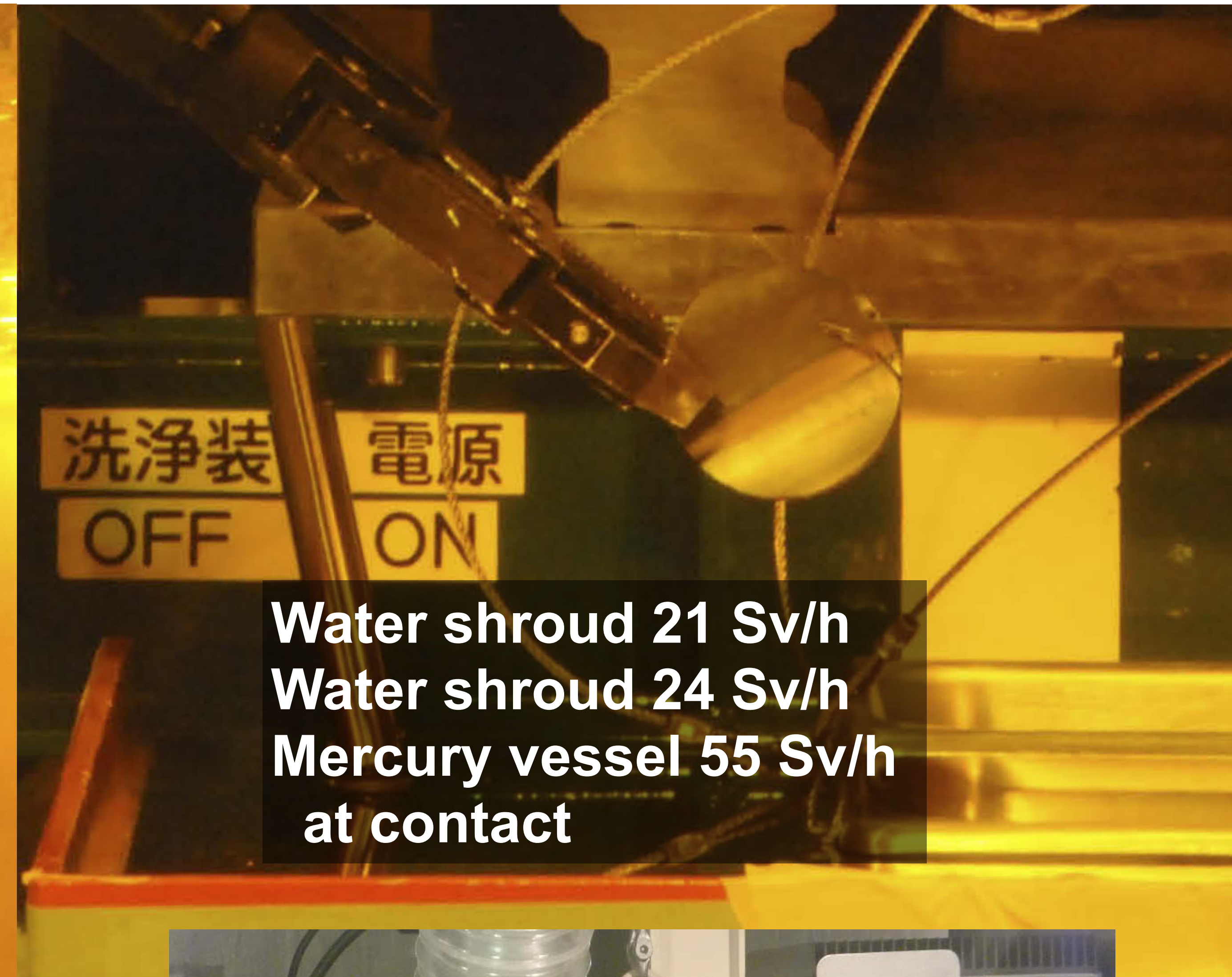
Cutting device for PIE disk

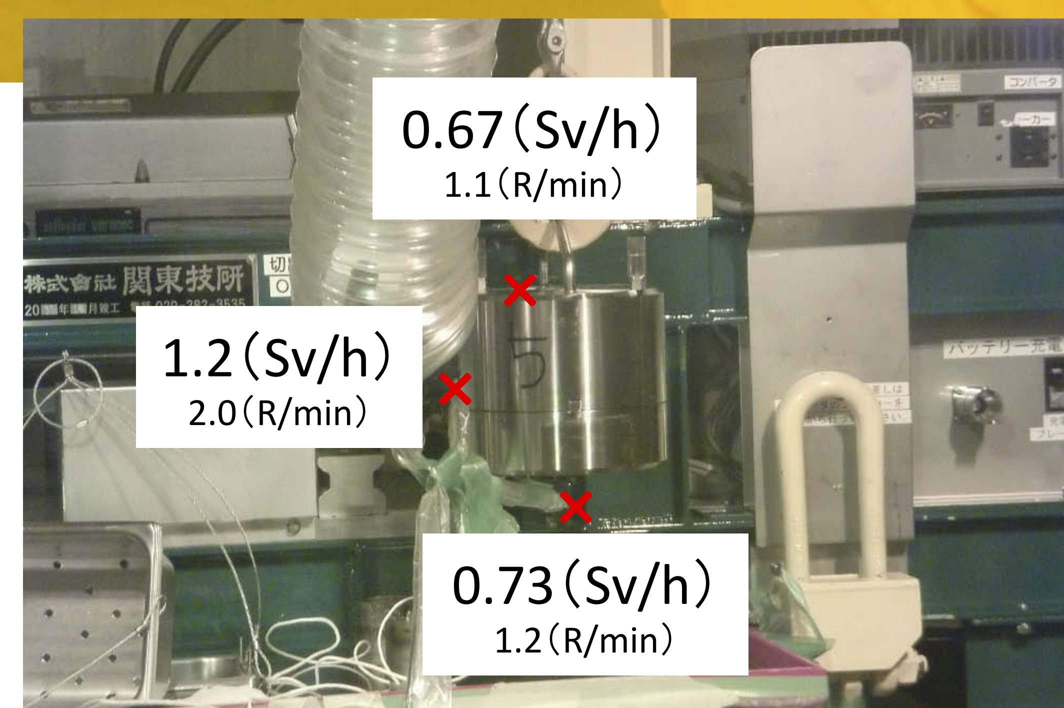


J-PARC

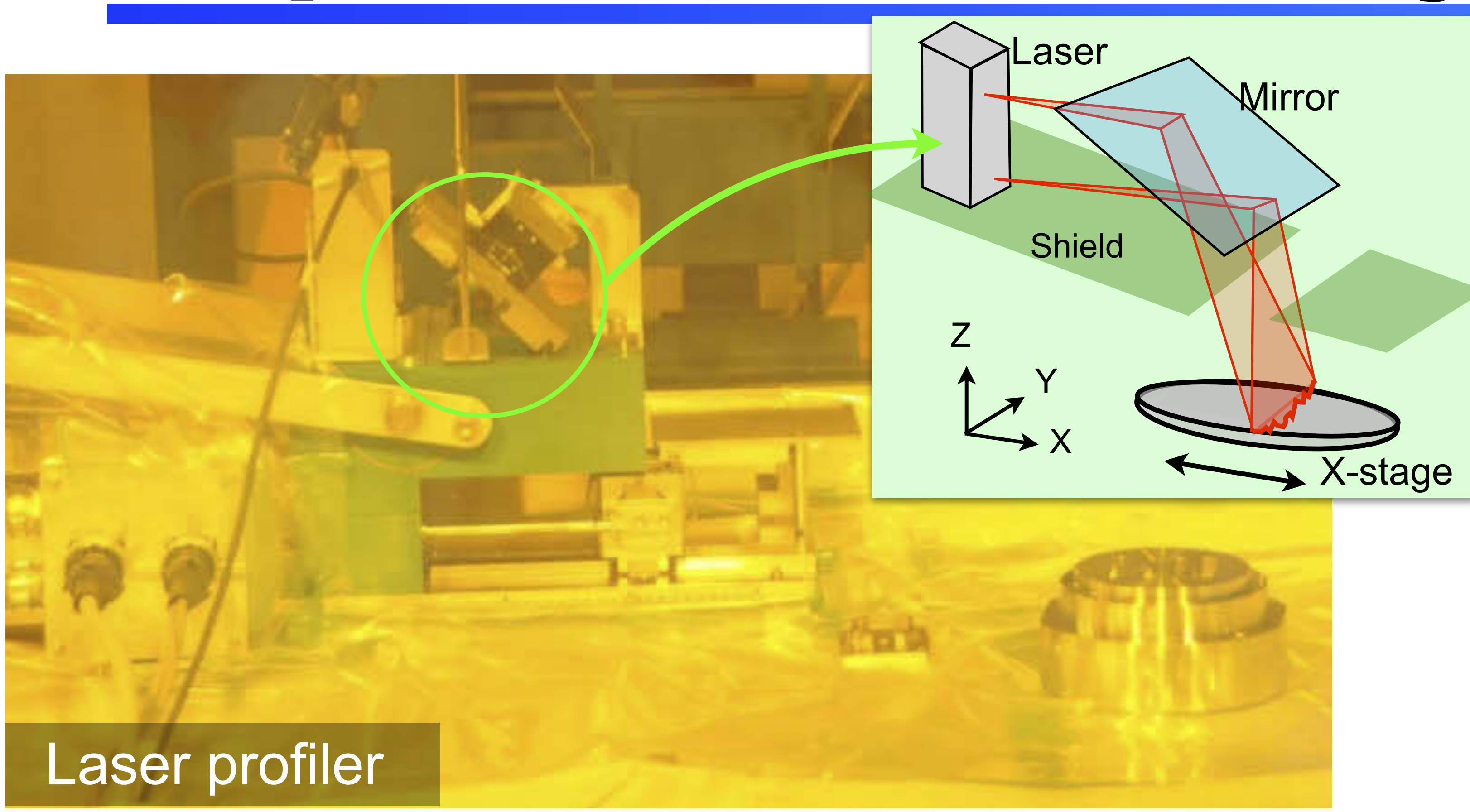
Dose rate of target vessel target #5

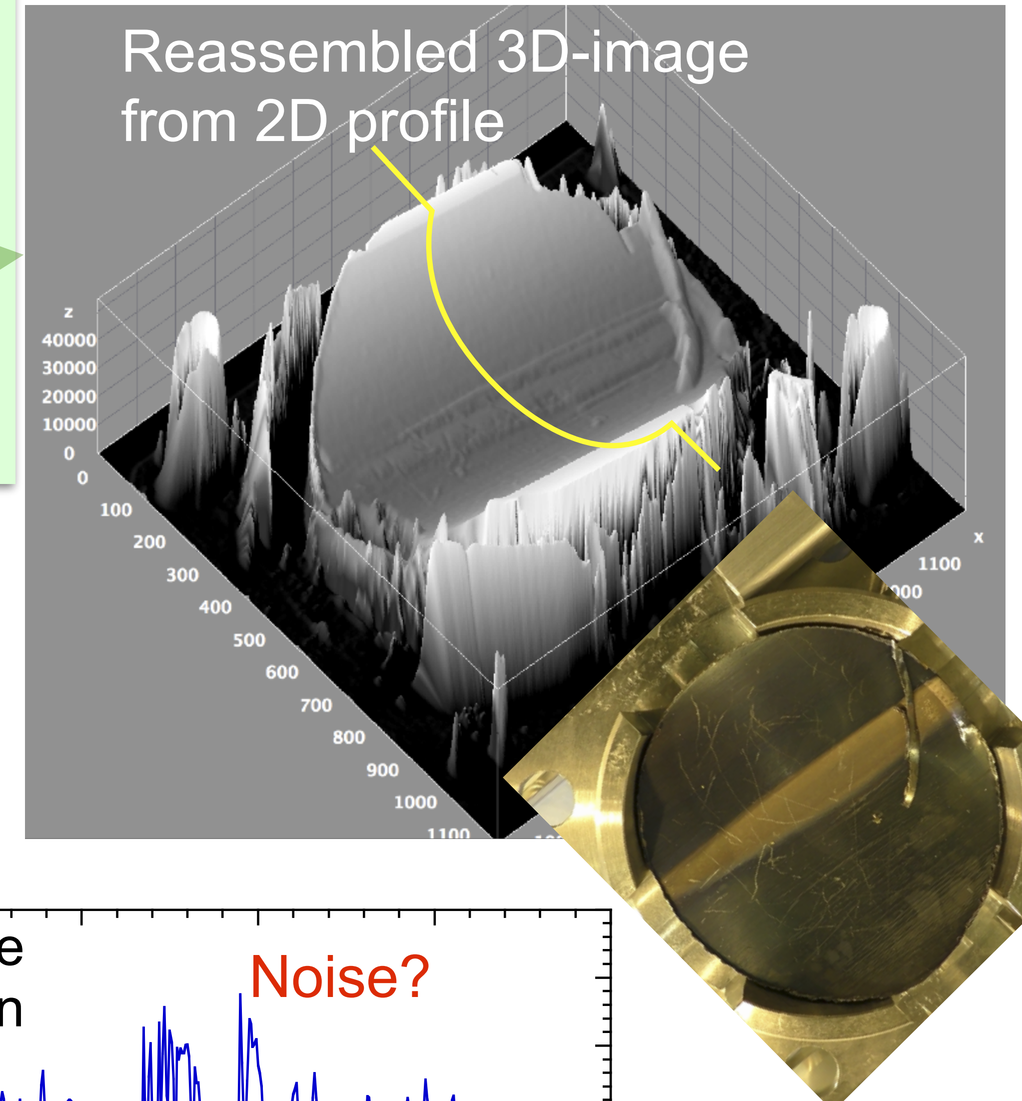


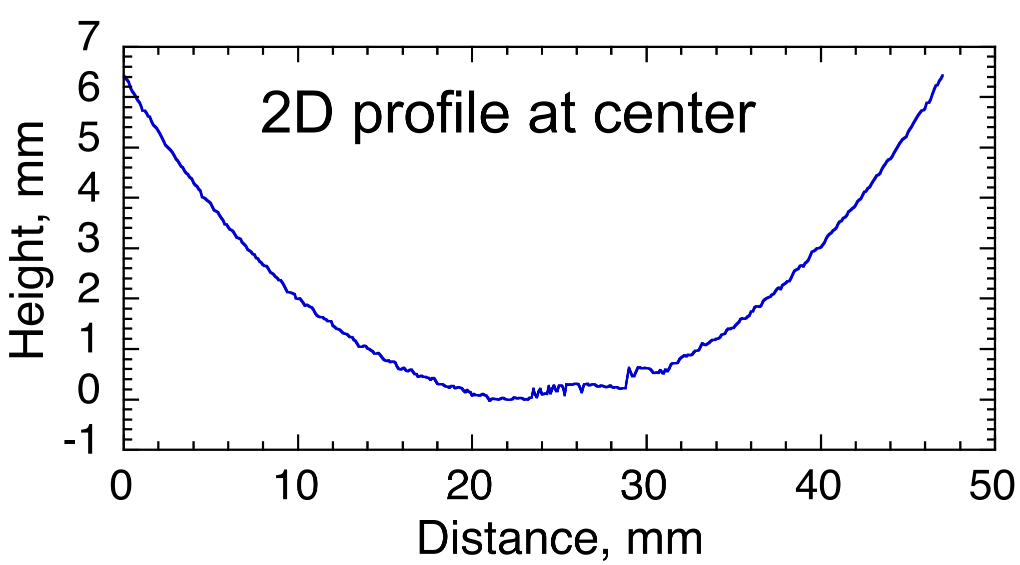


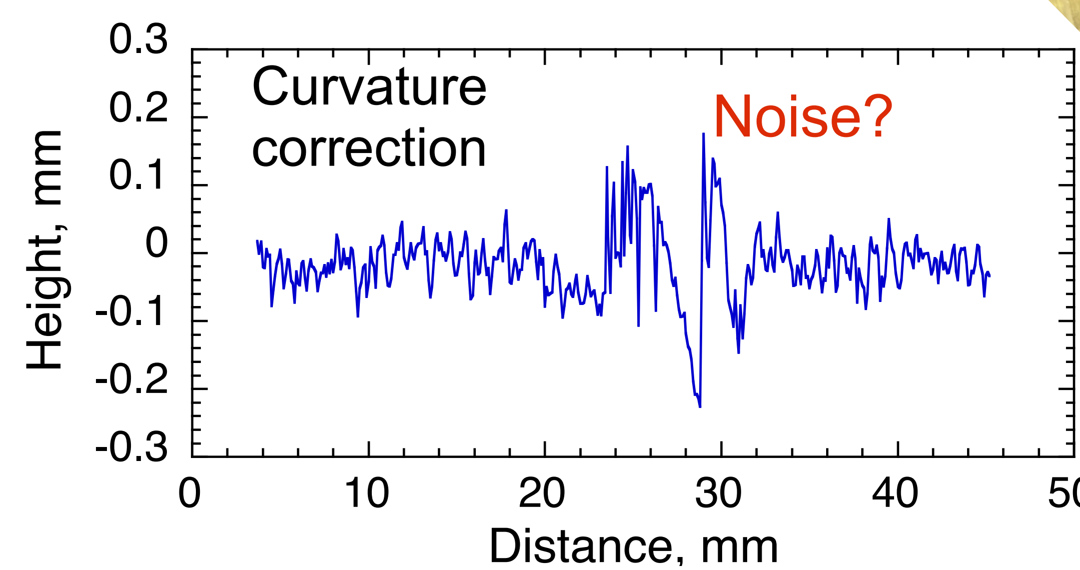


Depth measurement by laser profiler





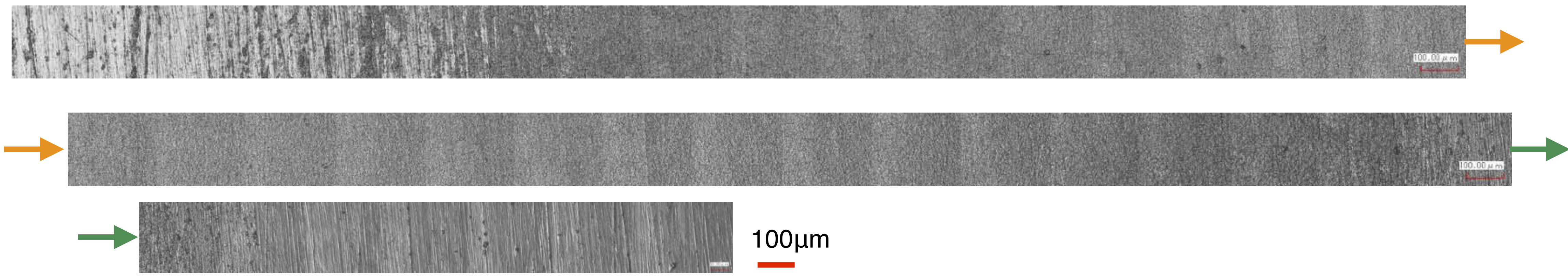


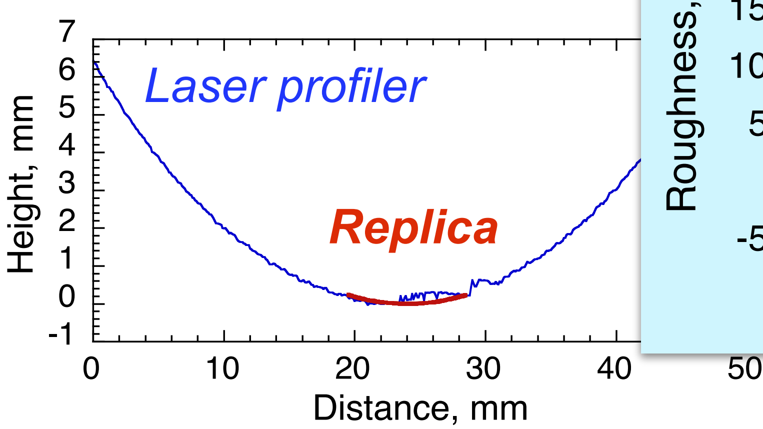


- Damage depth profile was measured using laser profile of 0.1 mm in resolution
- Resolution of this machine is insufficient for damage on specimen

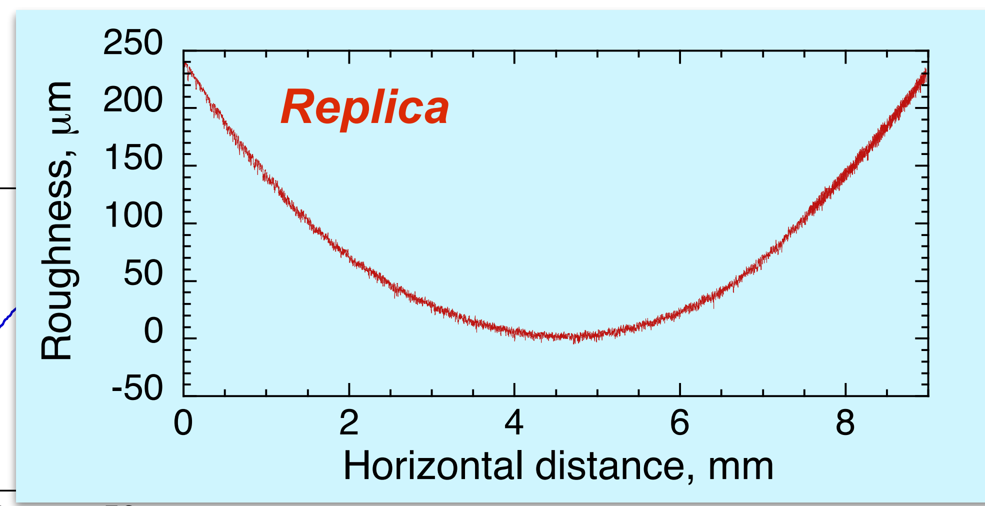
Depth measurement by replica

Jointed image

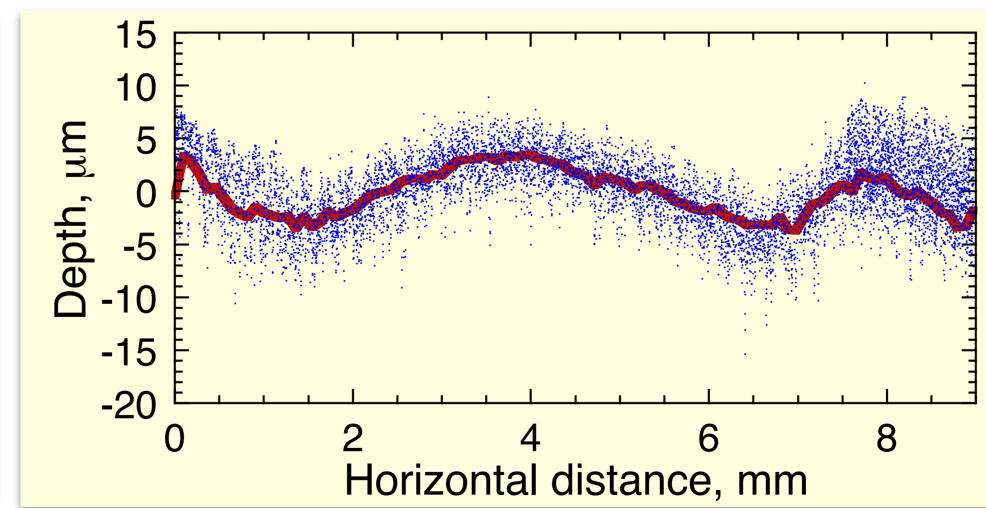




Jointed depth profile

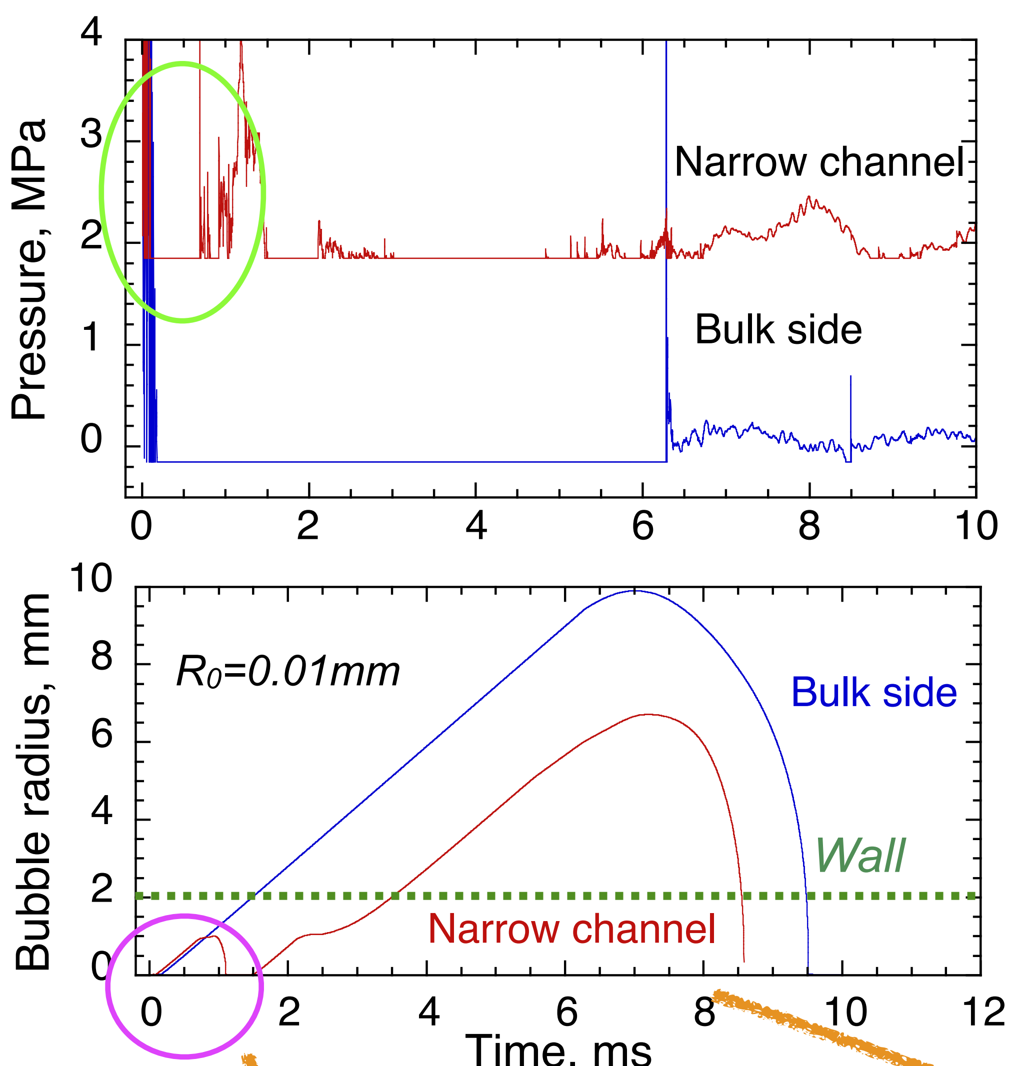


Curvature correction



- Silicone rubber replica (Struers Repliset-F1, 0.1 µm in resolution) was used to quantitatively measure the damage depth using laser microscope
- Clear surface erosion was not detected
- Surface roughness (swell) is about ±10 µm

Cavitation bubble in narrow channel



Keller equation *Single bubble*

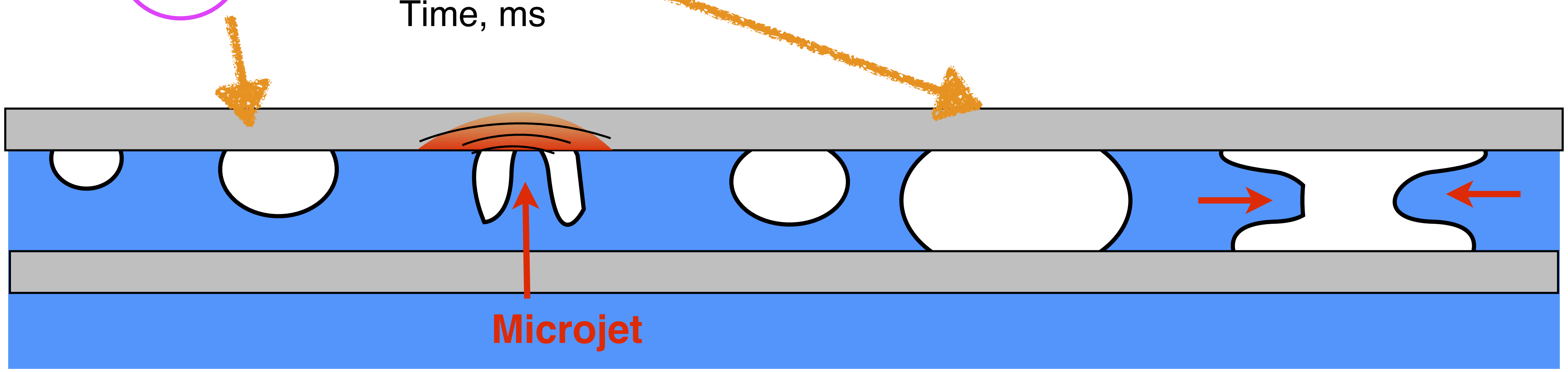
$$\left(1-\frac{\dot{R}}{C_L}\right)R\ddot{R}+\left(\frac{3}{2}-\frac{\dot{R}}{2C_L}\right)\dot{R}^2=$$

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

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

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

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



* Size of cavitation bubble caused by shot time negative pressure is less than gap size
* Bubble caused by short time negative pressure seems affected to band shape damage