Present status of cavitation damage mitigation techniques for the mercury target vessel at J-PARC pulsed spallation neutron source

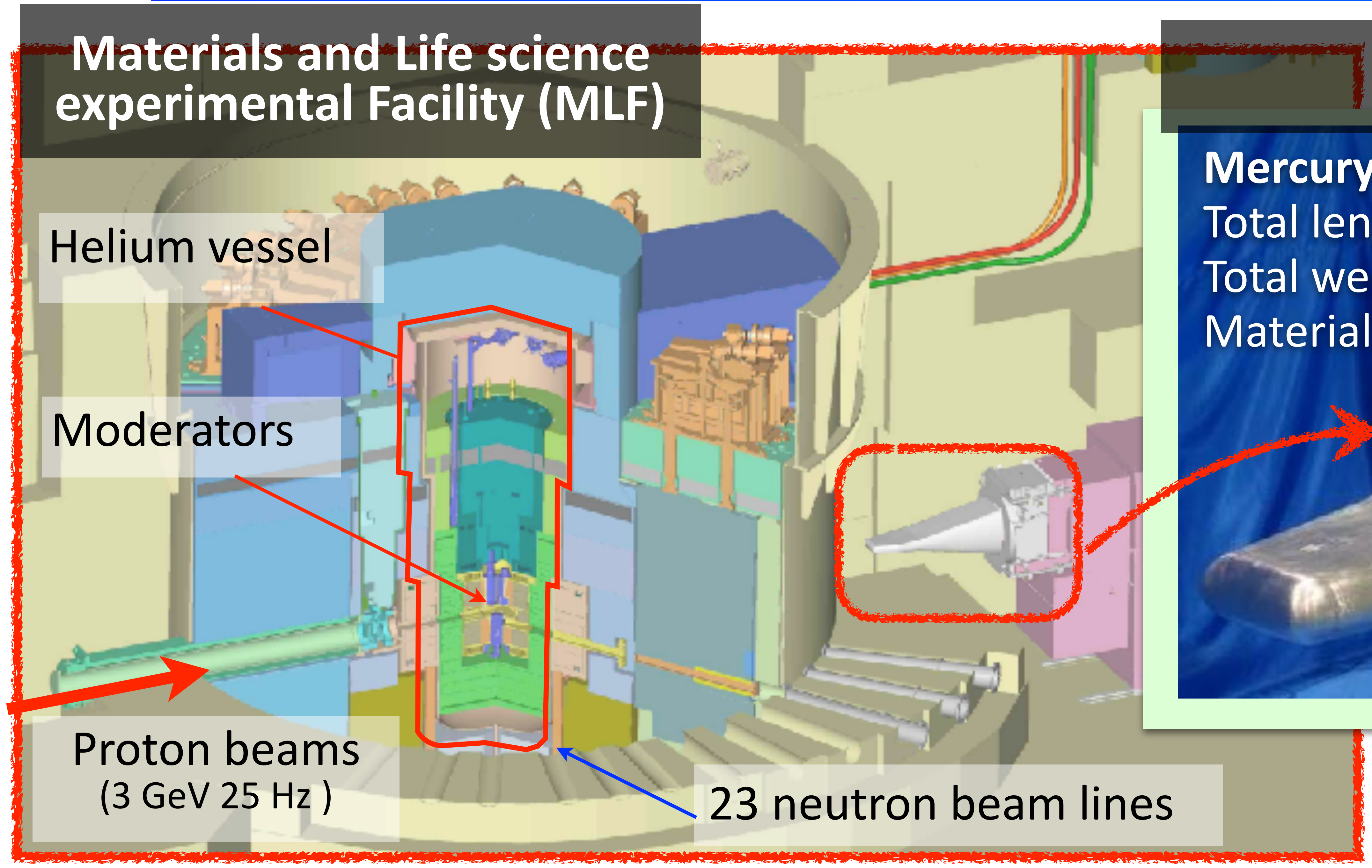
Takashi Naoe, Hiroyuki Kogawa, Takashi Wakui,
Koichi Saruta, Makoto Teshigawara,
Hidetaka Kinoshita, Katsuhiro Haga

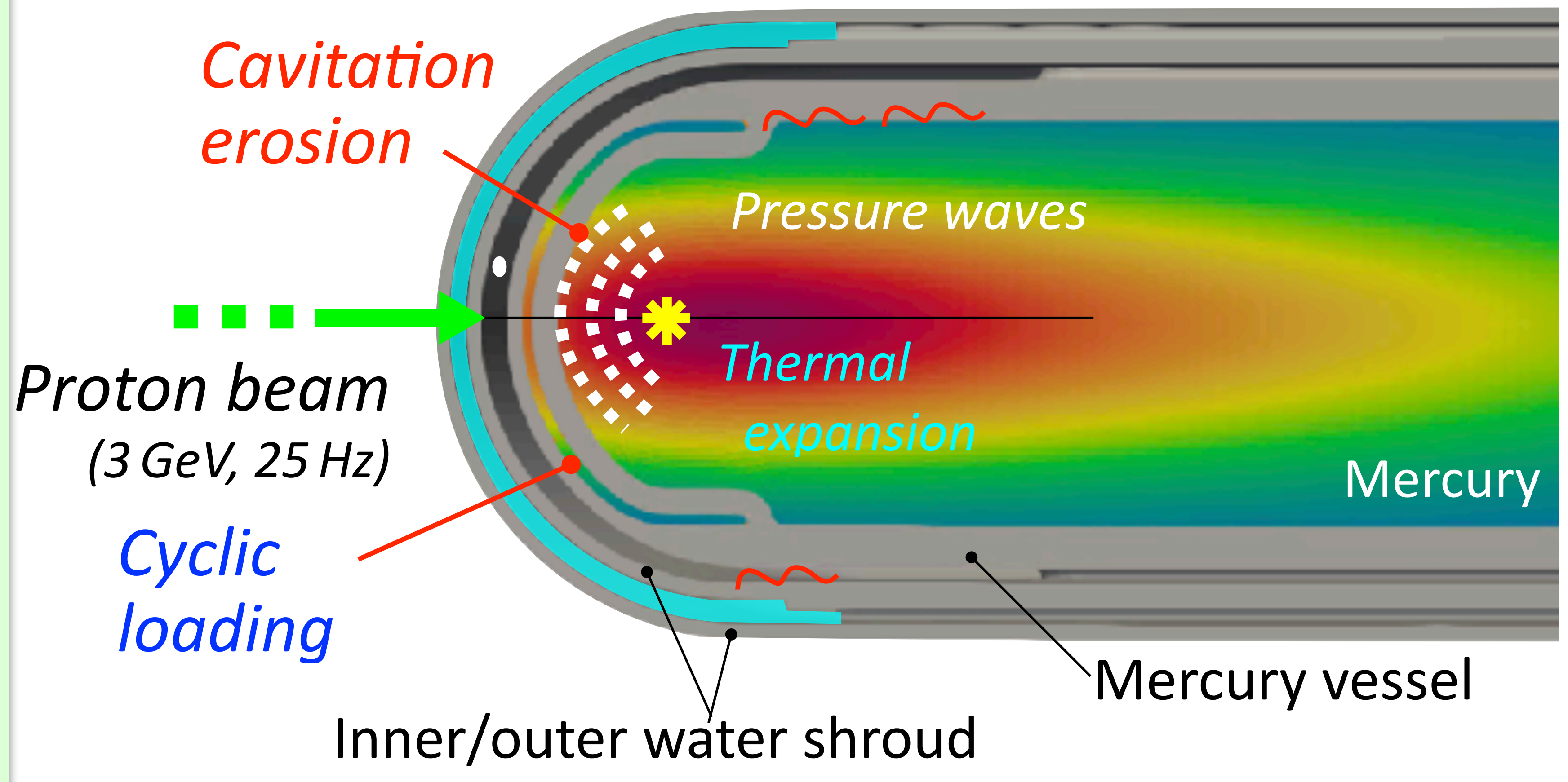
J-PARC Center, Japan Atomic Energy Agency

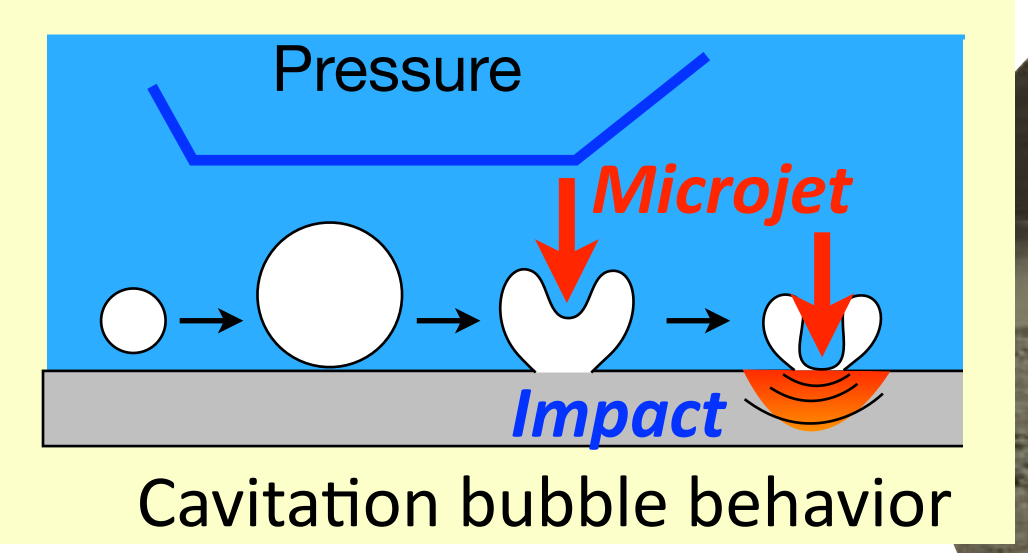
Contents

- Background and motivation
- Cavitation damage mitigation techniques
- Target diagnostic system
- Improvement of beam window cutting for damage inspection
- Correlation between damage and acoustic vibration
- Comparison between measured and predicted damage depth
- Summary

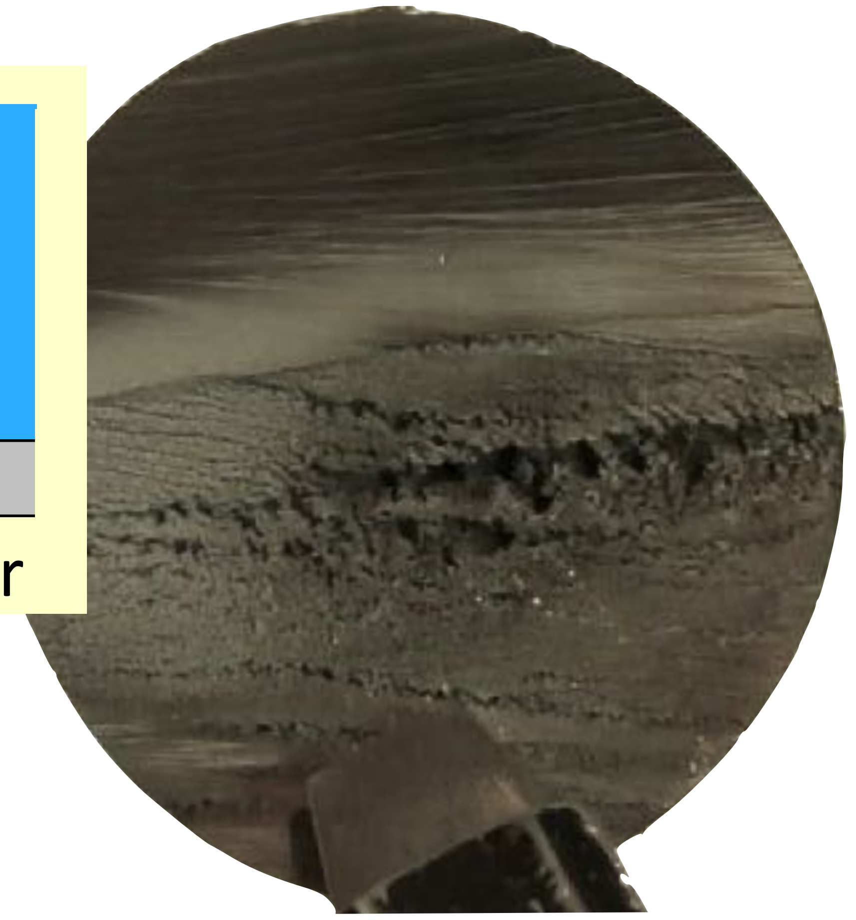
Background and motivation







Cavitation bubble behavior


Cavitation erosion of used target vessel

Factors in decision for lifetime

- **Irradiation damage :** Reduction of ductility occurs along with operation time
- **Fatigue damage :** Cyclic stress by pressure waves is repeated up to gigacycle
- **Cavitation erosion:** Erosion penetrates the beam window within a few days at 1 MW operation

Issue for achieving the high-power stable operation at 1 MW in long term

Beam energy is 40 kJ/pulse at 1 MW, 2.4x higher than SNS at the same power

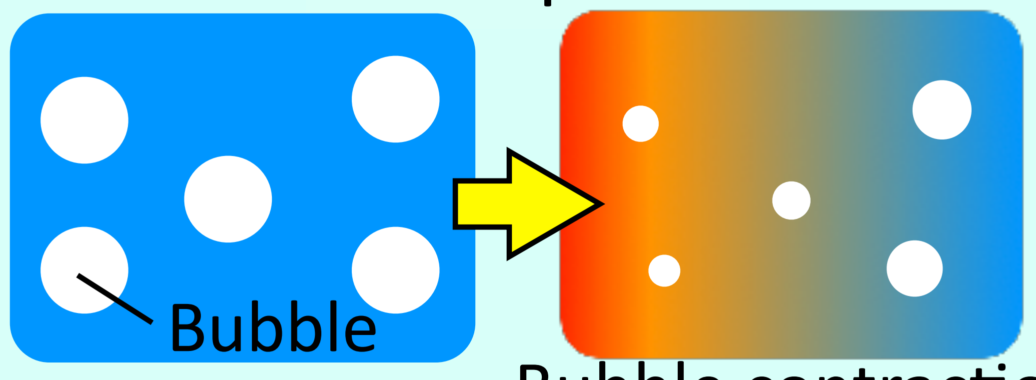
→ **Developing and upgrading cavitation damage mitigation techniques**

Developing and upgrading cavitation damage mitigation techniques

Gas microbubbles injection

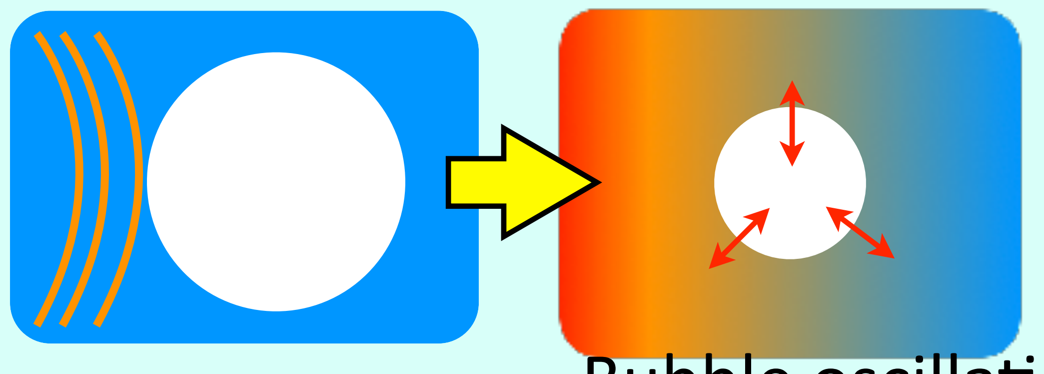
- Suppress pressure wave by gas microbubbles (R_b<150 μm, α > 0.01%) **(2012~)**
- Effects depends on radius and void fraction

Absorption



Absorb thermal expansion by contraction of microbubbles

Attenuation

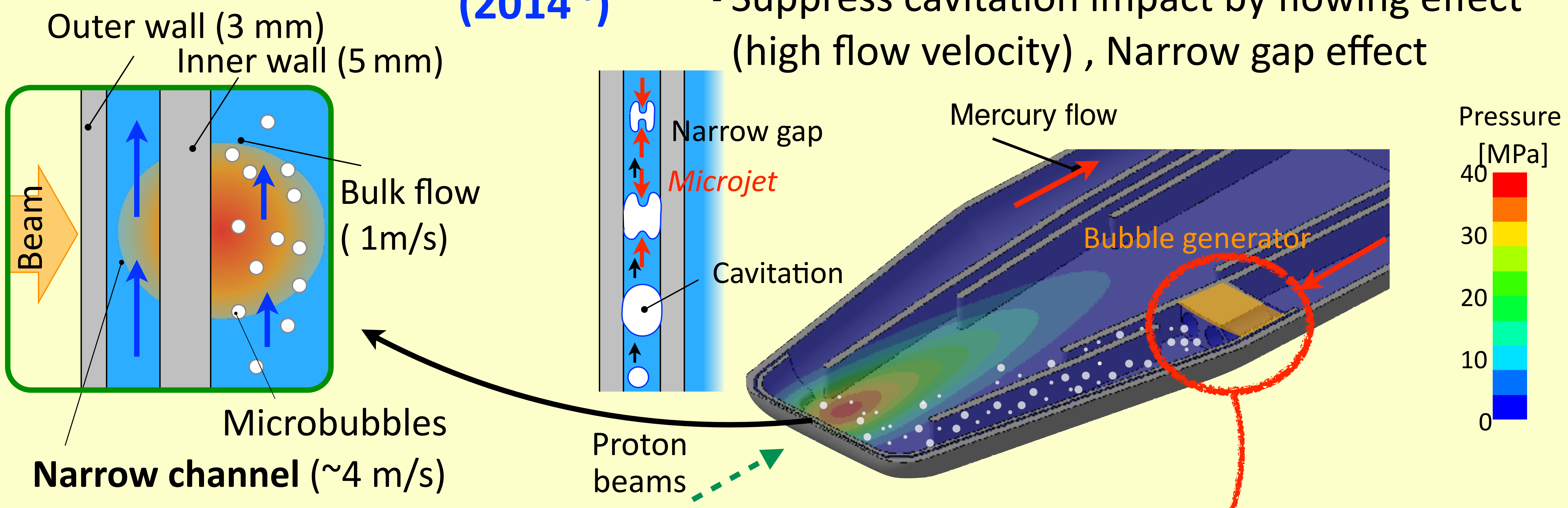


Attenuate by thermal dissipation of kinetic energy

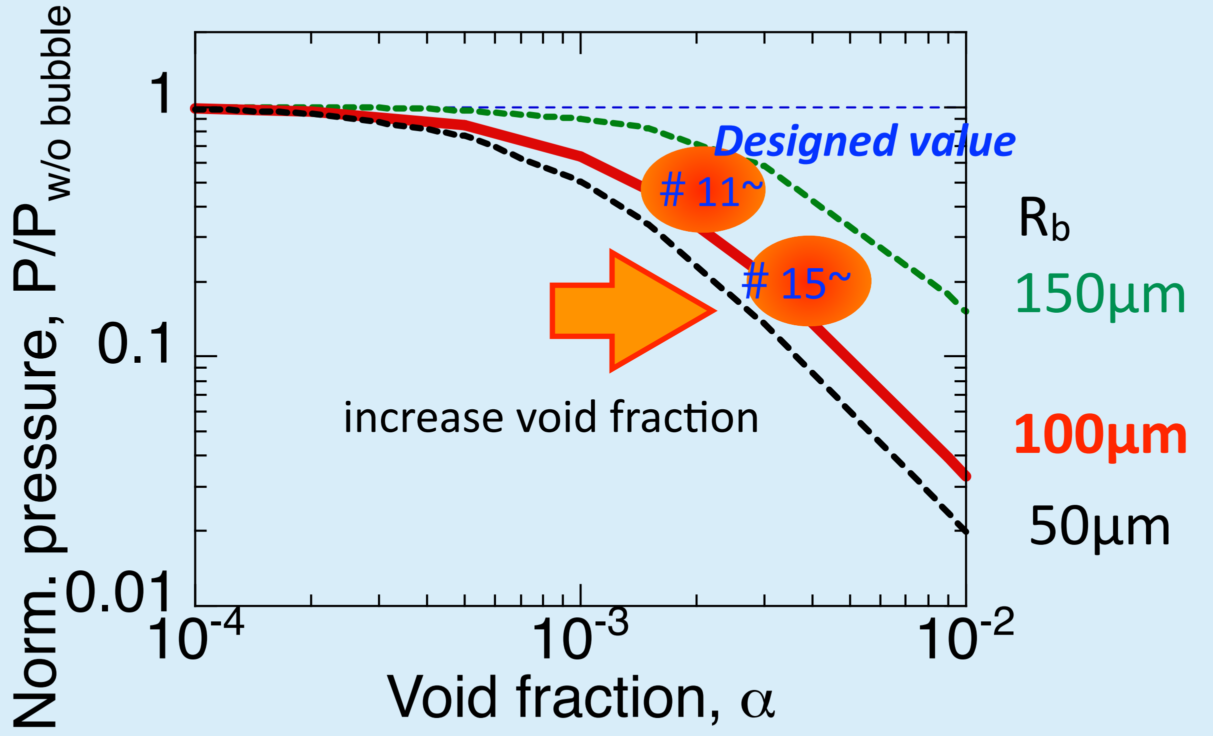
Double walled structure at beam window

(2014~)

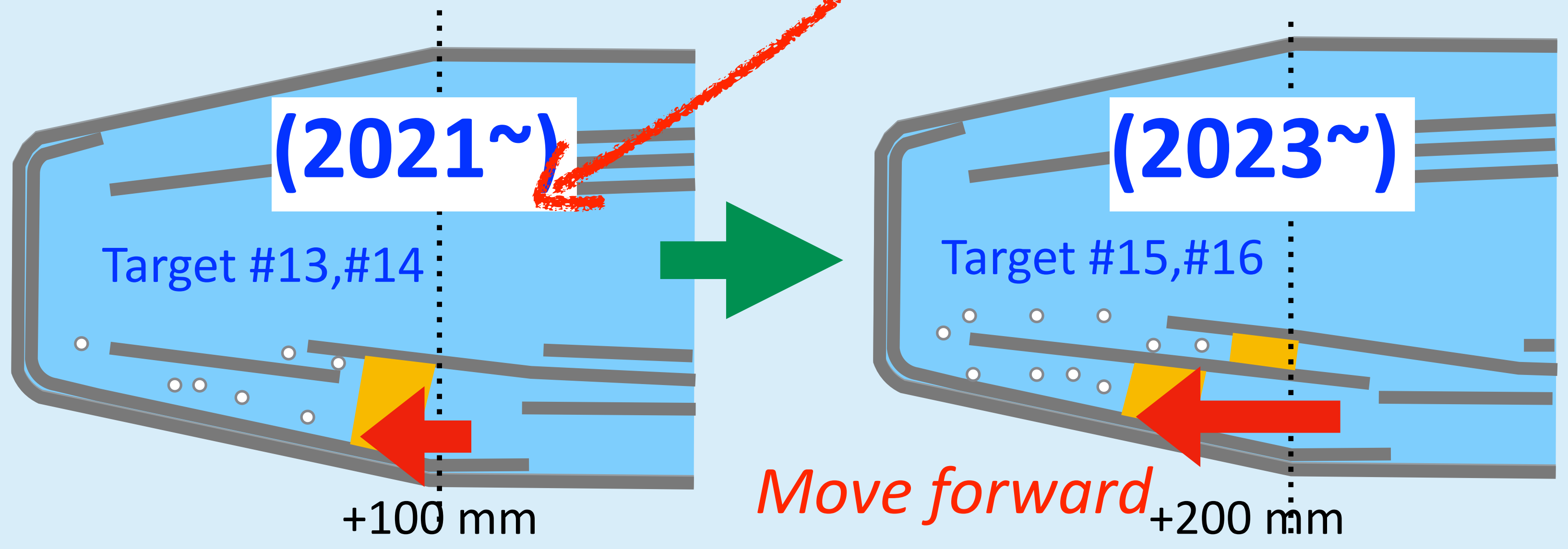
- Suppress cavitation impact by flowing effect (high flow velocity) , Narrow gap effect



Upgrading to increase bubble void fraction at beam window

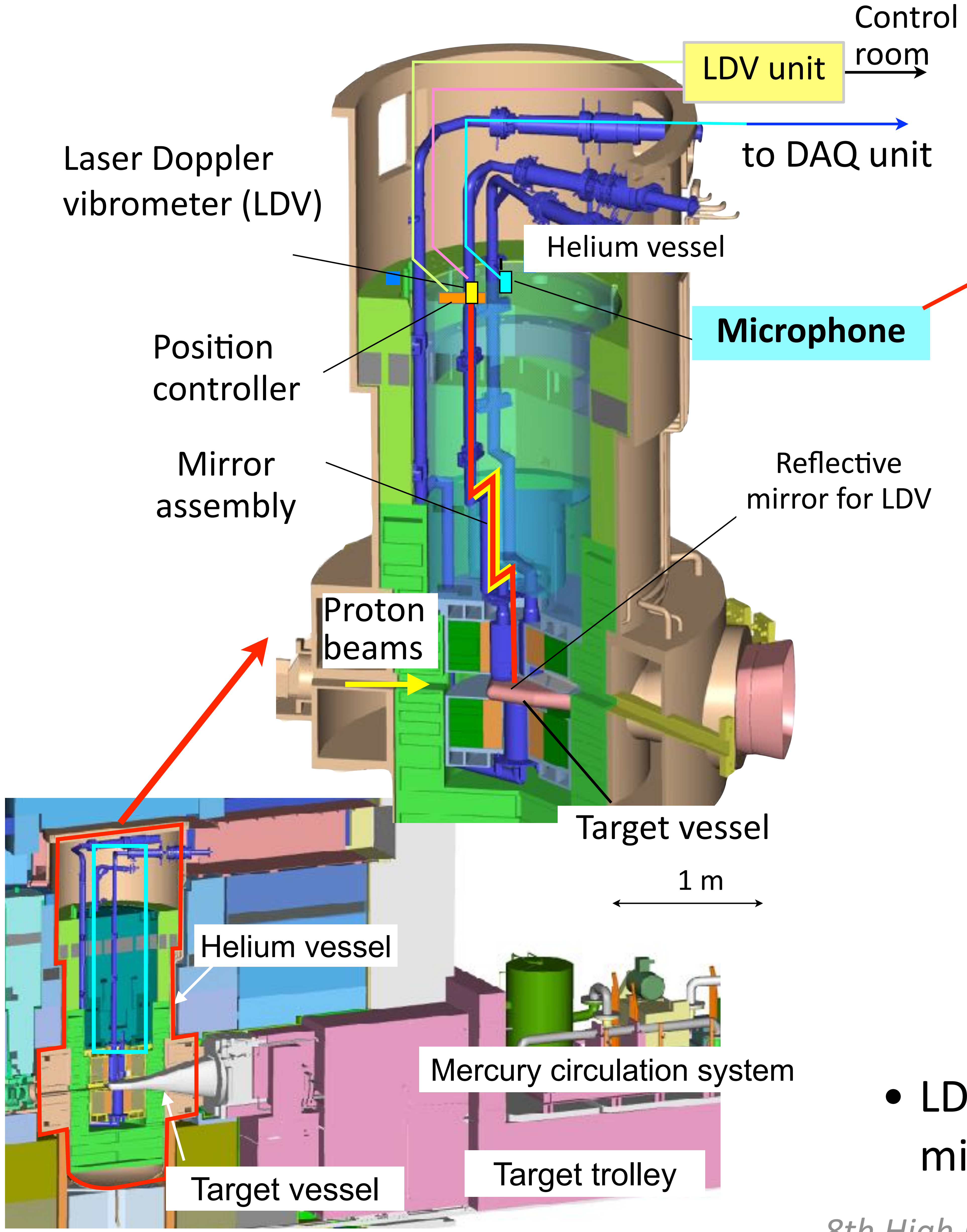


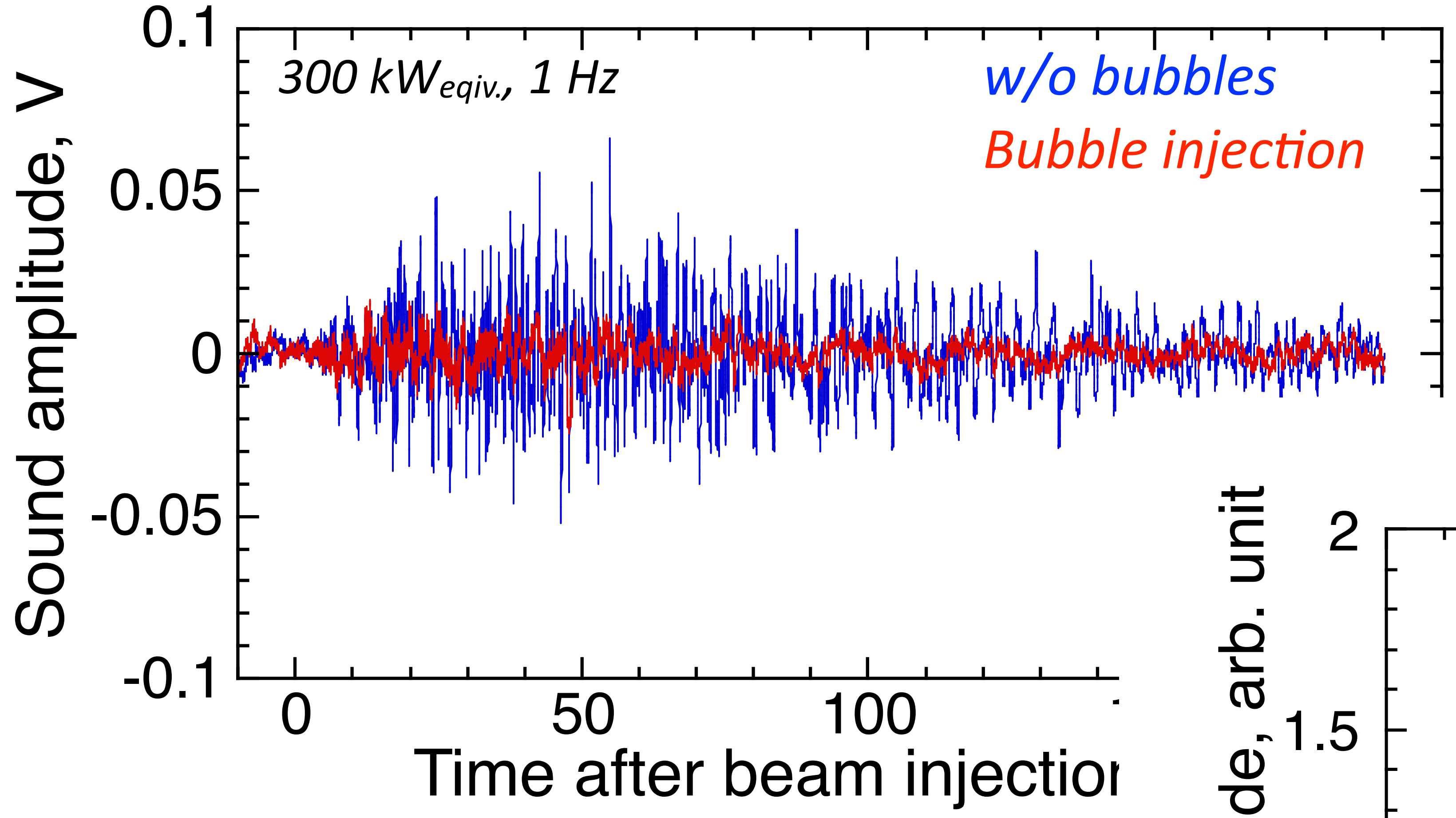
Pressure wave mitigation by bubble (calculation)



Optimization of bubble generator by machine learning

Target diagnostic system by acoustic vibration measurement



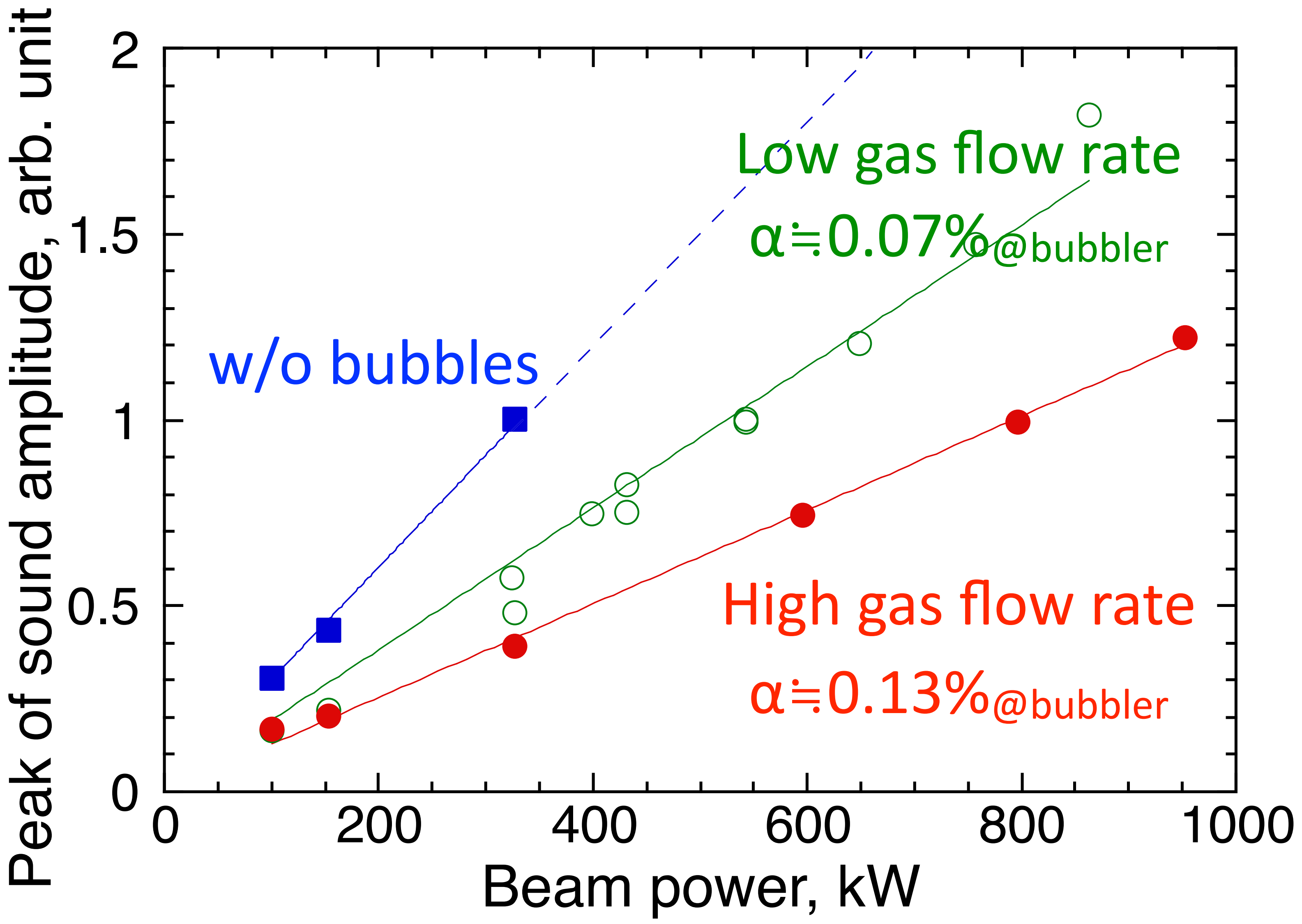


Time response of sound obtained by microphone

Sound signal contains information of vibration on the target vessel surface induced by pressure waves in mercury

Sound

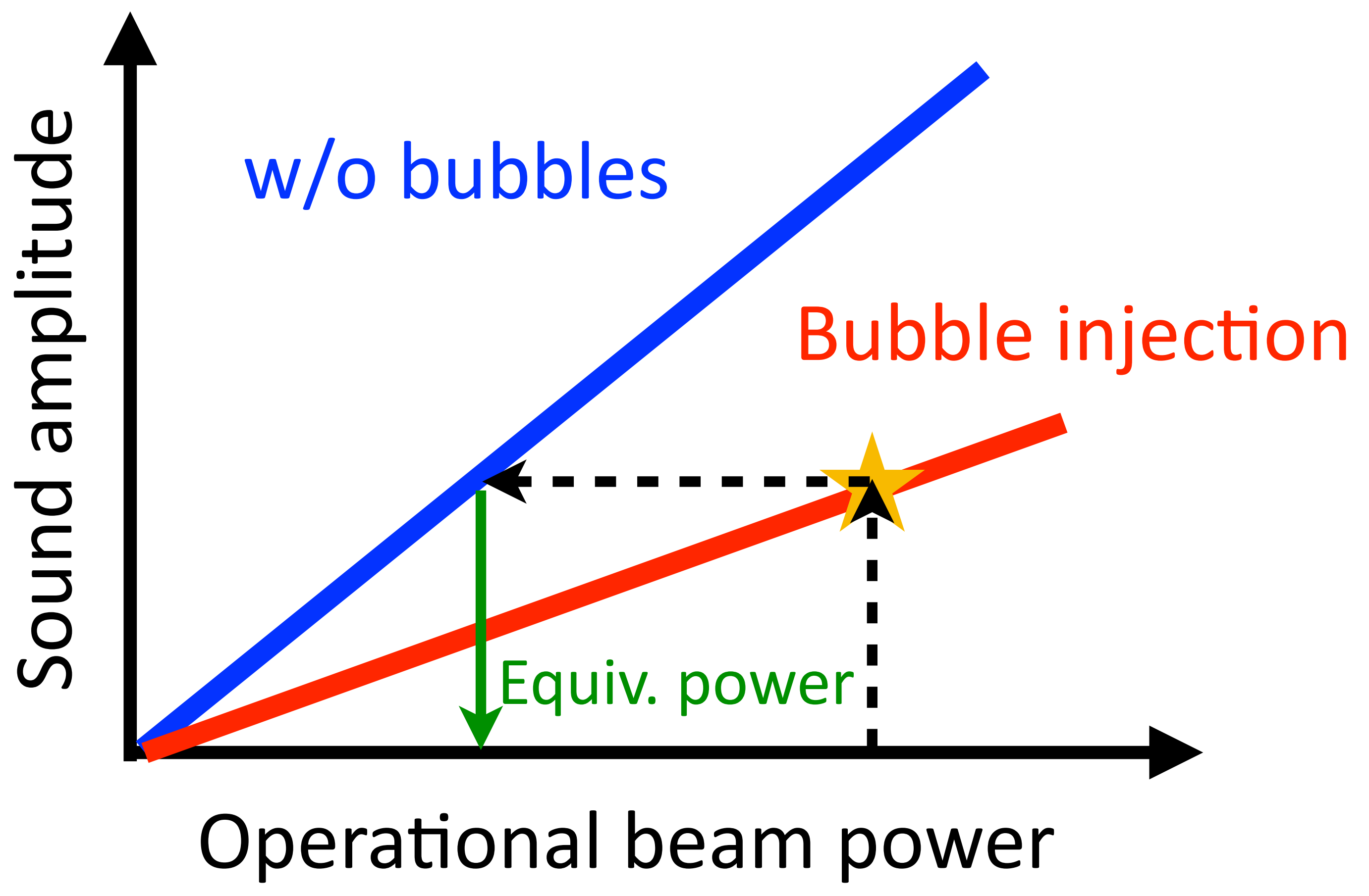
No-bubble - Bubble



Change in sound amplitude by beam power and gas flow rate for microbubble injection

- LDV and microphones are installed to monitor the status of gas microbubble through the beam-induced acoustic vibration

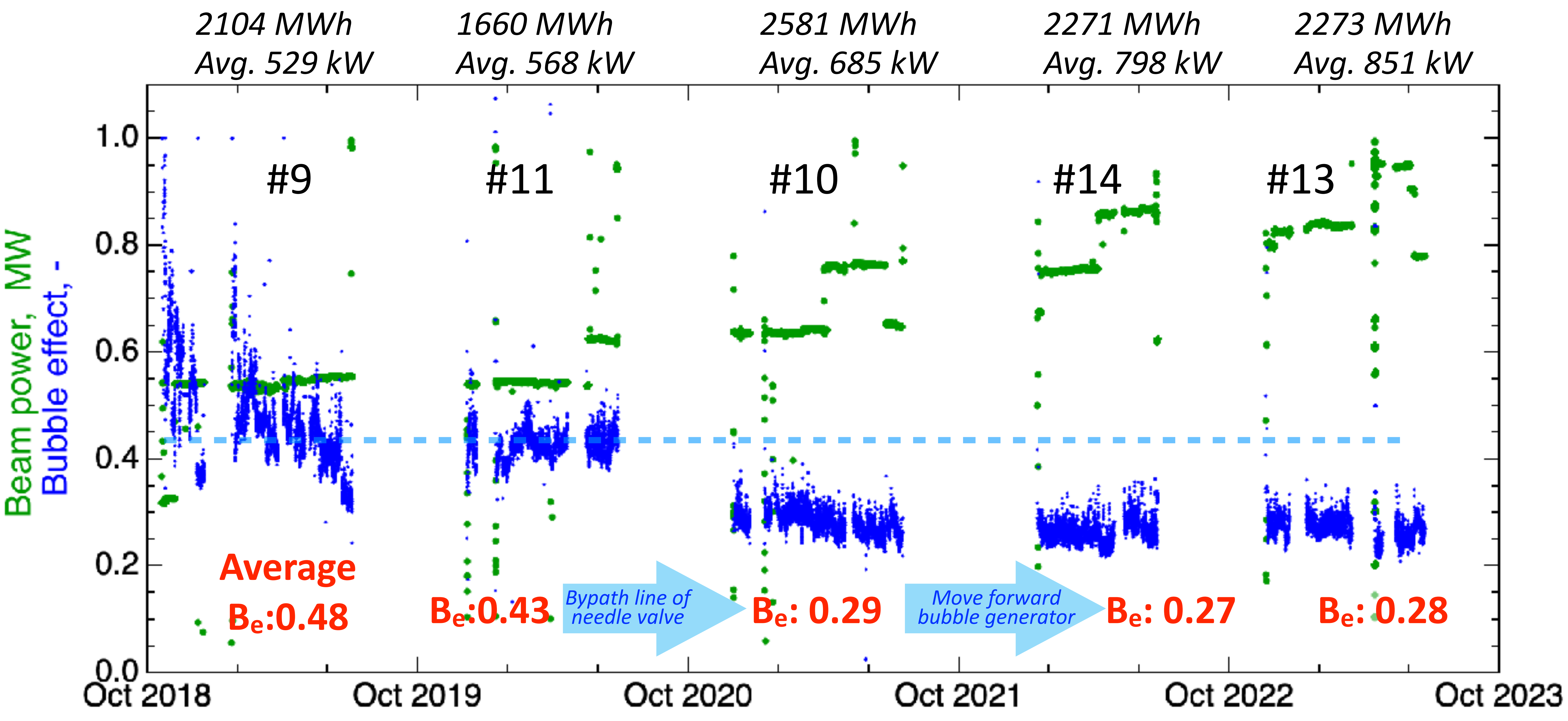
Change in acoustic vibration by bubble injection



Scale of pressure wave mitigation by bubble injection

$$\text{Bubble effect } B_e = \frac{\text{Equivalent power under bubbling}}{\text{Operational beam power}}$$

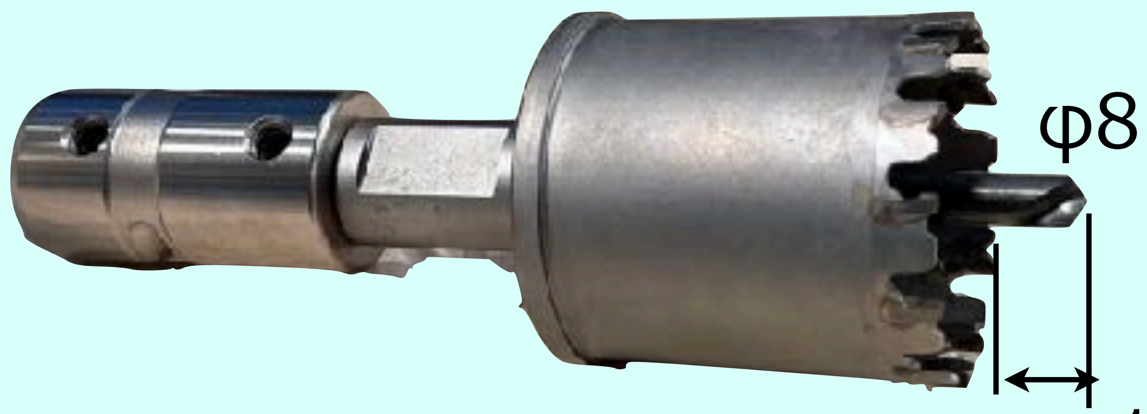
Bubble effect =1 denotes bubble is not working
Less value means higher mitigation effect



Trend of beam power and bubble effect during user operation

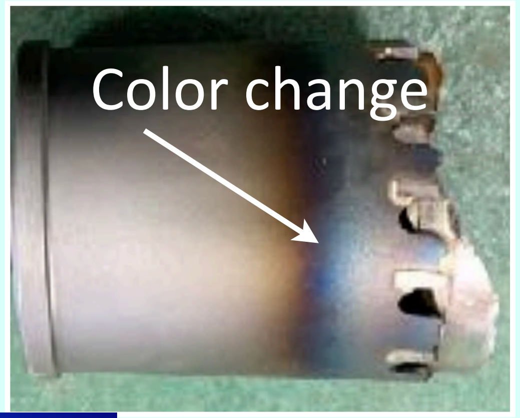
- Reduction of sound amplitude related to the gas flow rate is used for as an index of bubble effect (**B_e**)
- **B_e** is high and fluctuated in target #9 because gas flow rate is low and unstable
- **B_e** for targets #10, #14, #13 are good, and almost stable by improving gas flow rate independent of beam power

Improvement of beam window cutting

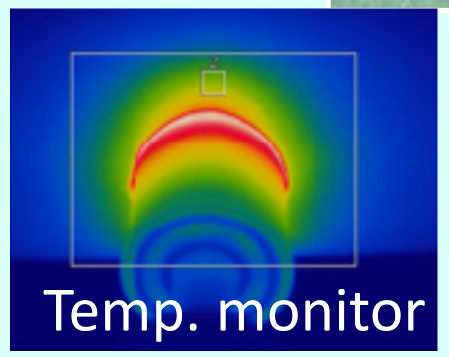


Annular cutter with center drill

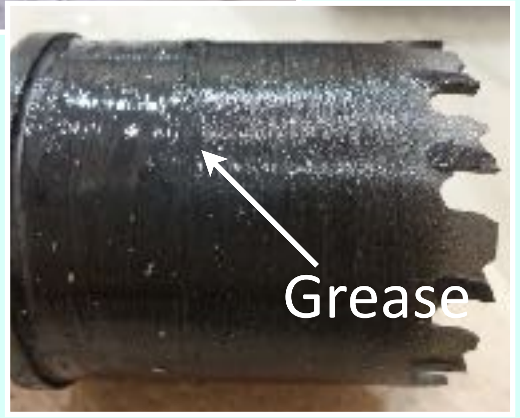
Initial constraints
- Horizontal cut to prevent mercury spilling
- Dry cut for remote handling



Dry cut T_{max}: 180°C
- **Friction heating** by dry cut leads difficulties of cutting (2011~2015)



Cut with lubricant T_{max}: 81°C
- Water base **lubricant** reduce friction heating but increase of tritium release (2017~2019)

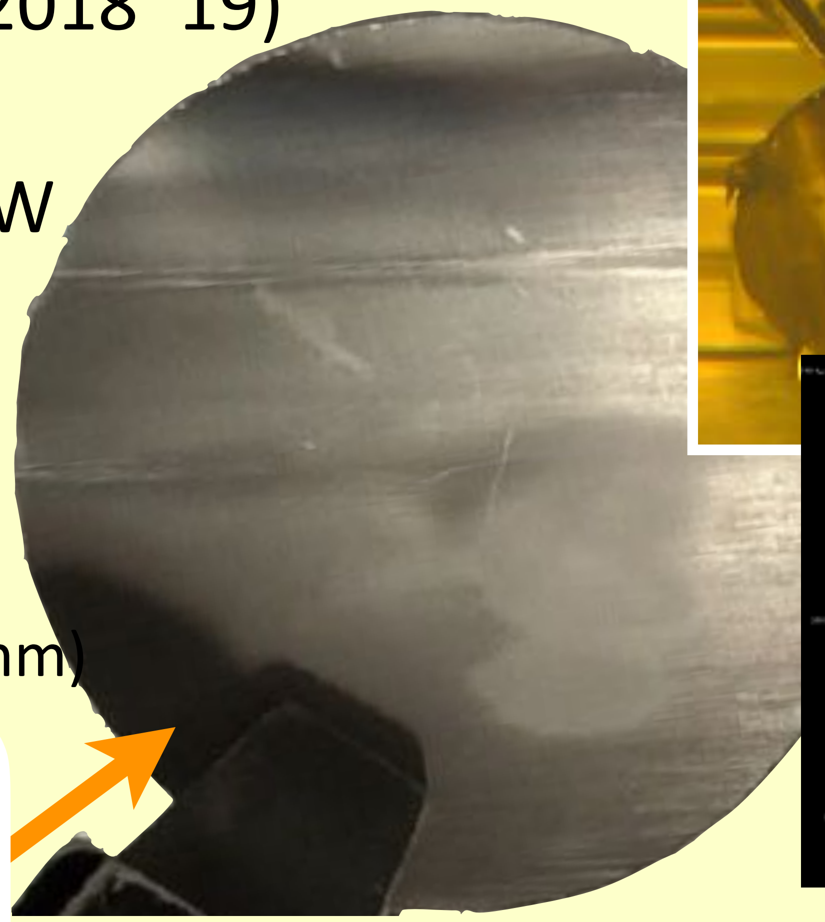


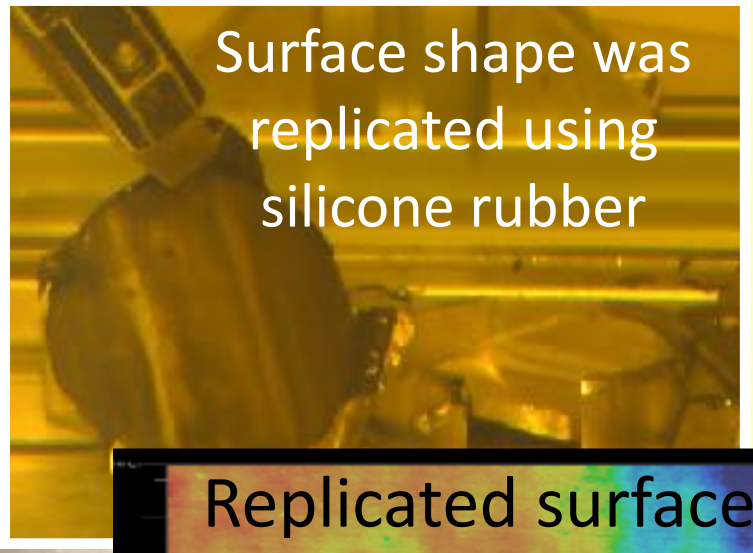
Semi-dry cut T_{max}: 150°C
- **Semi-dry cut** with grease on surface **coating** to reduce tritium release and mitigate friction hearing (2020~)
- Adopted **center drill** to ensure extract cutout specimens (2023)

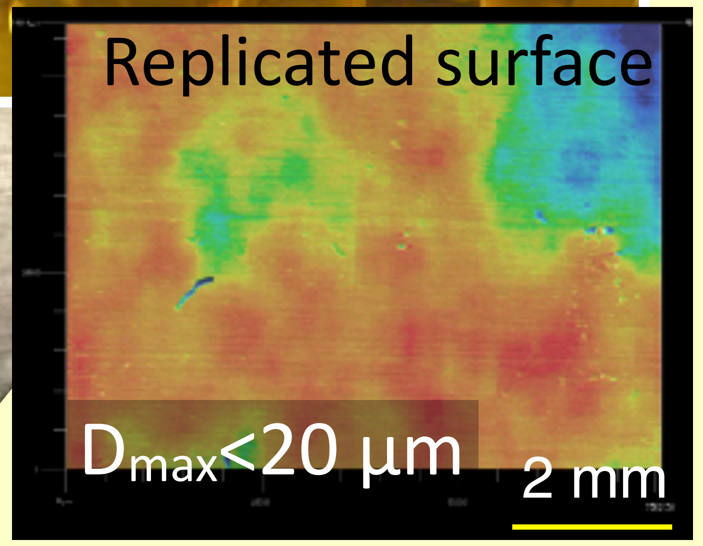
Difference of erosion damage by bubble effect

Target #9 (2018~19)
2104 MWh
Avg. 529 kW

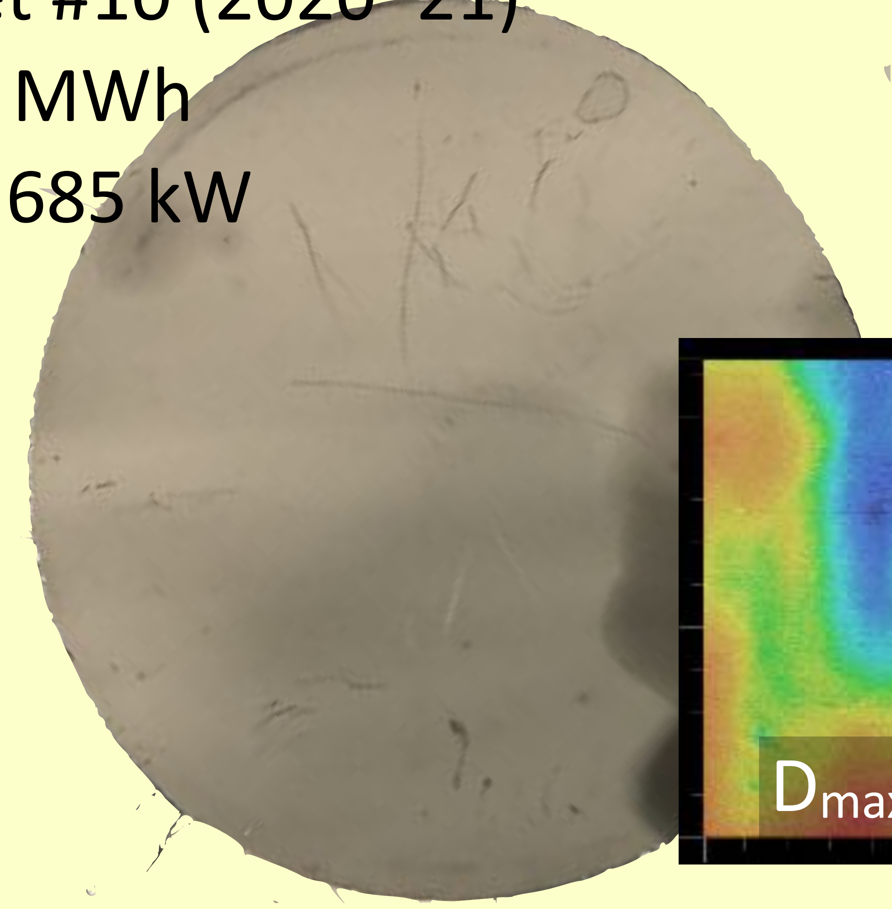
Narrow channel

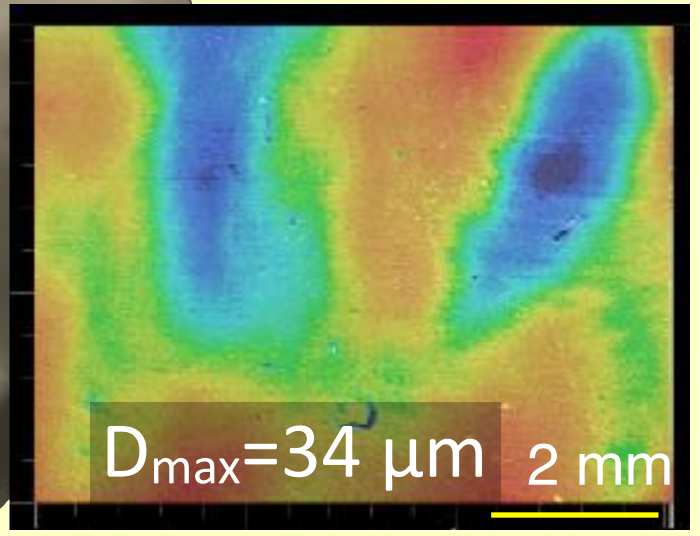






Target #10 (2020~21)
2581 MWh
Avg. 685 kW

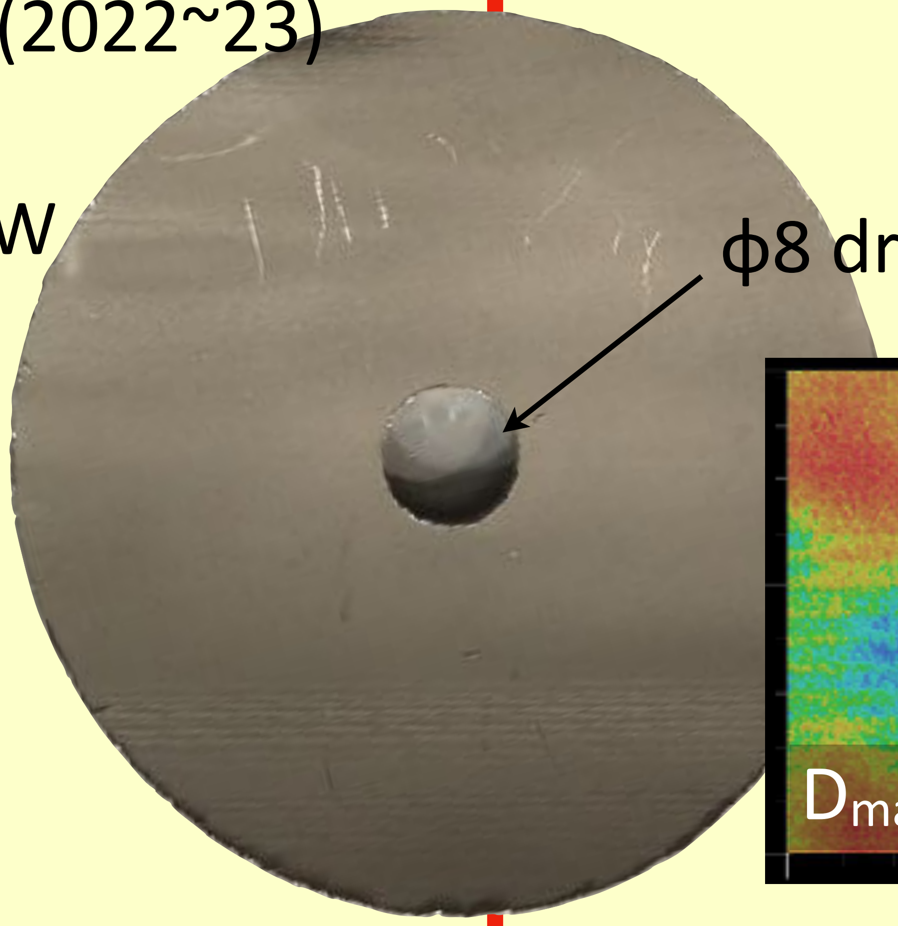


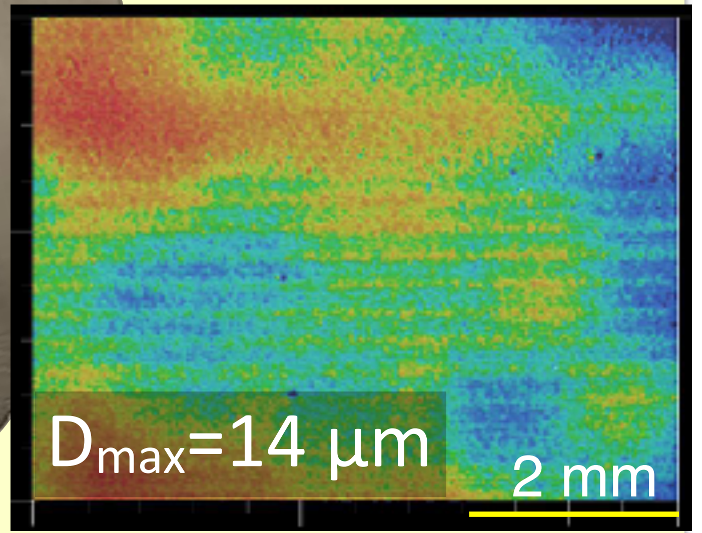


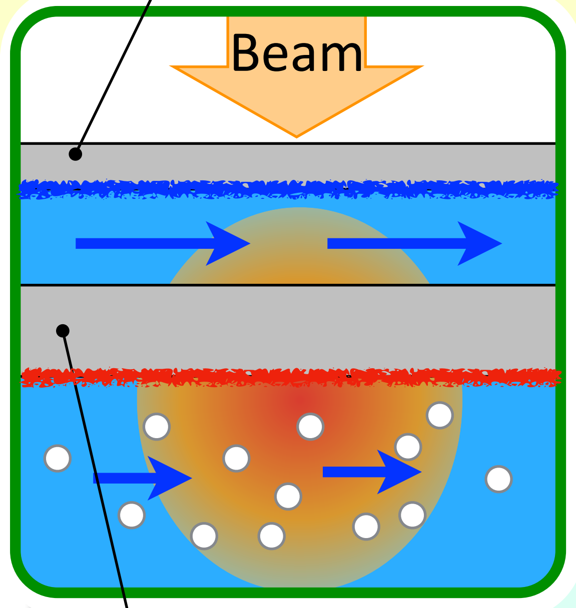
Target #13 (2022~23)
2273 MWh
Avg. 851 kW

Center

ϕ8 drill hole







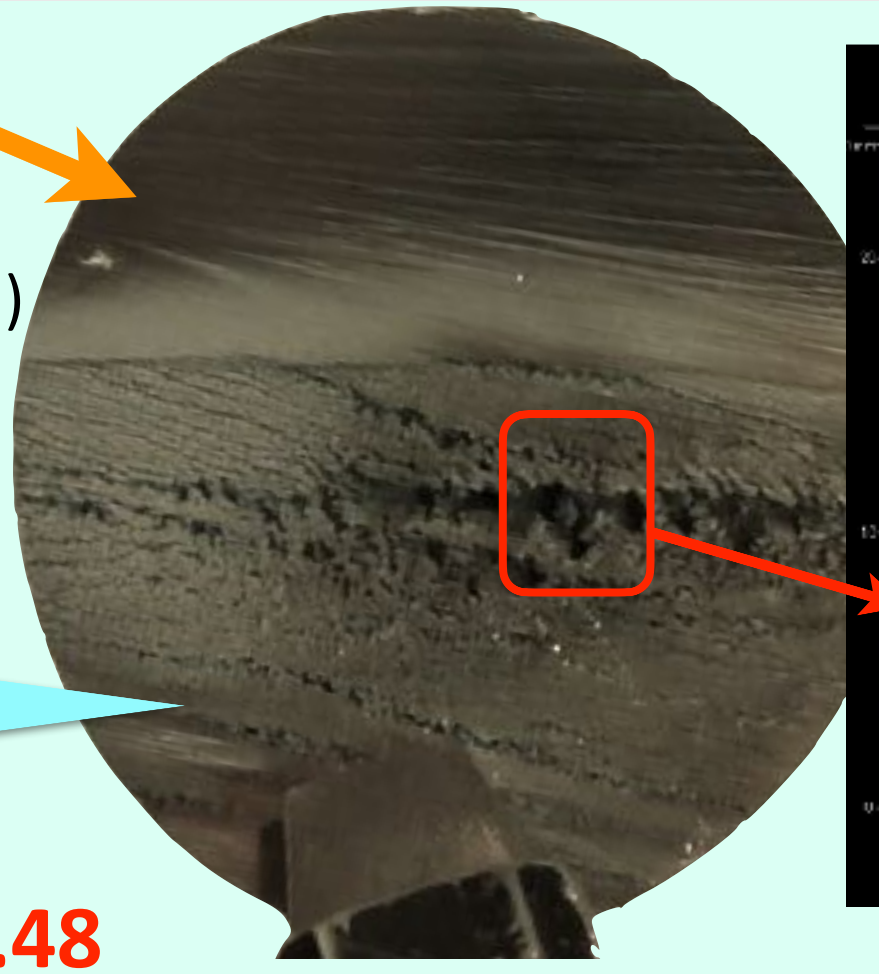
Outer wall (3 mm)

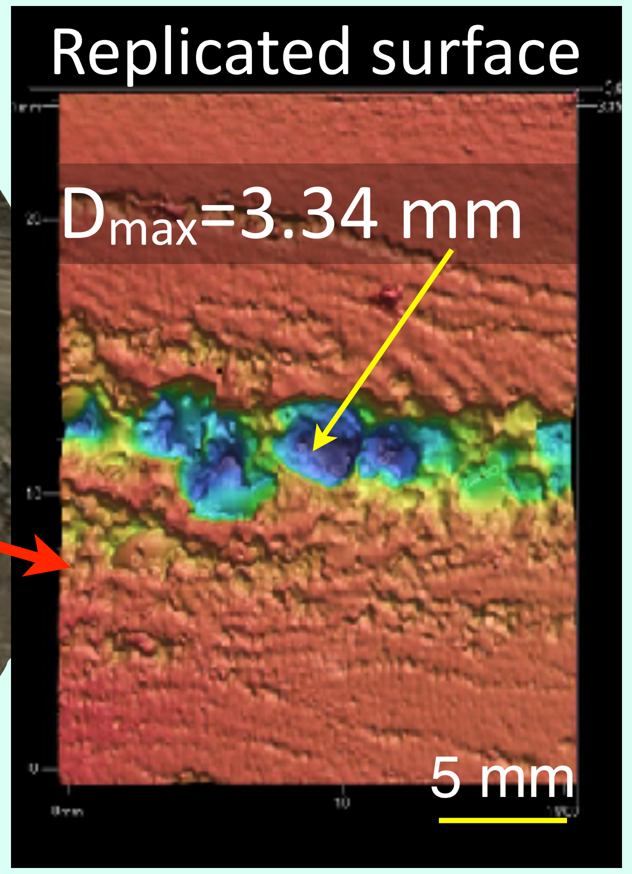
Inner wall (5 mm)

- Severe erosion damage is not observed on narrow channel surface, and confirmed no power dependency

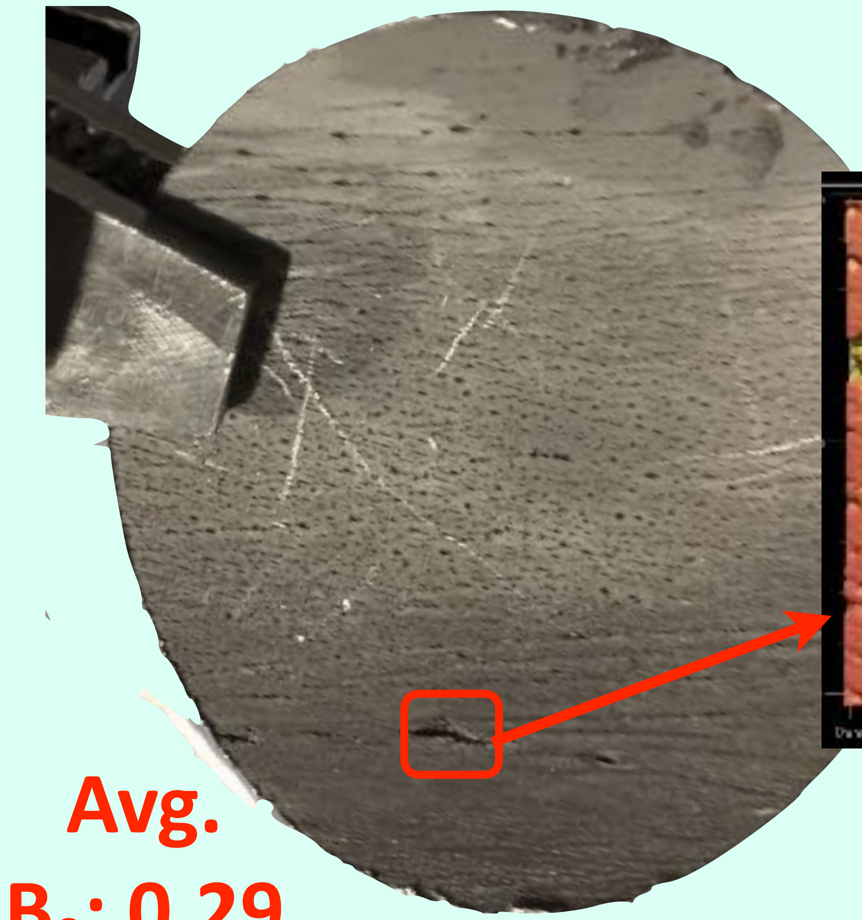
Bulk side

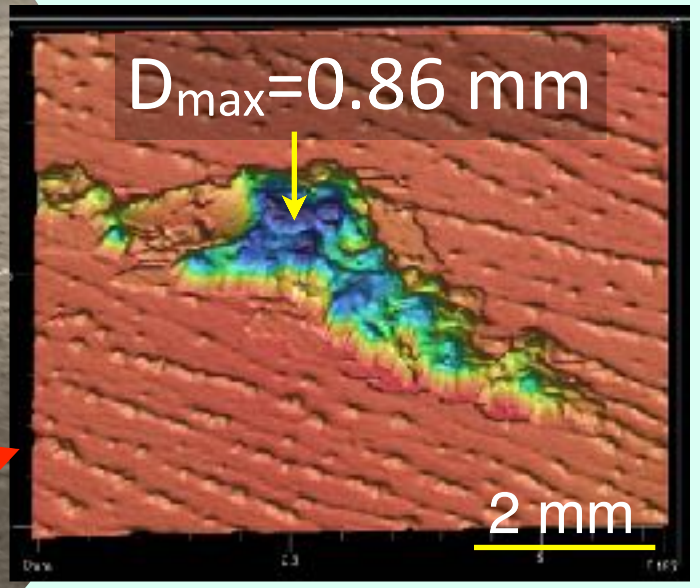
Bubble effect is not enough





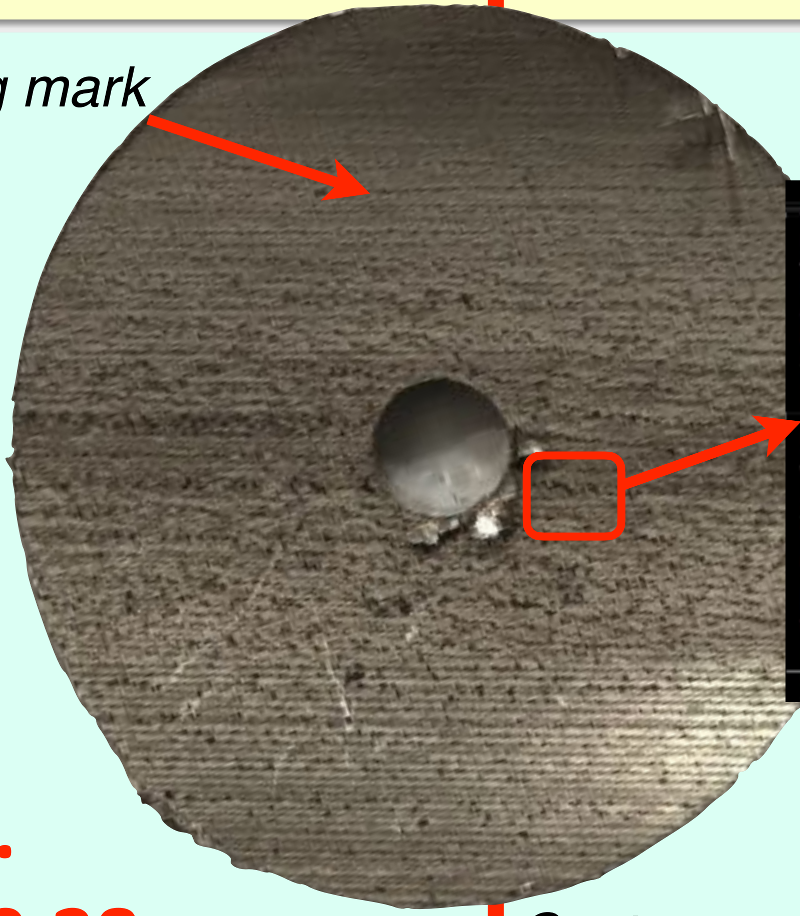
Avg. B_e:0.48

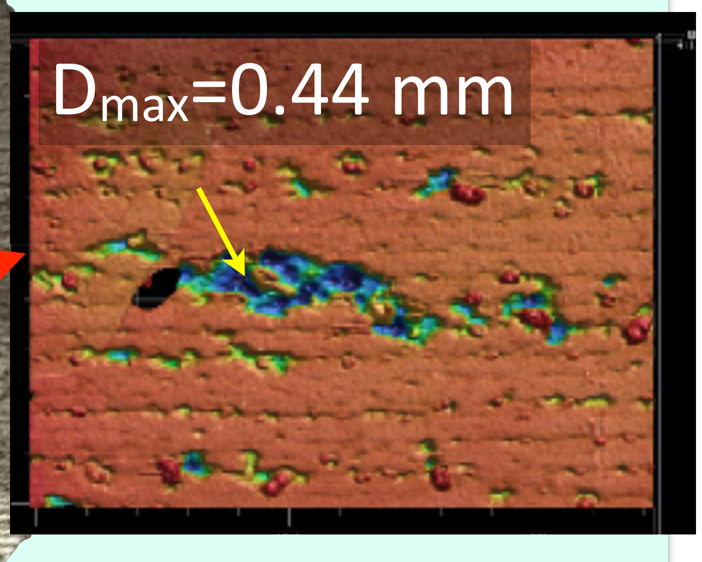




Avg. B_e: 0.29

Polishing mark





Avg. B_e: 0.28

Center

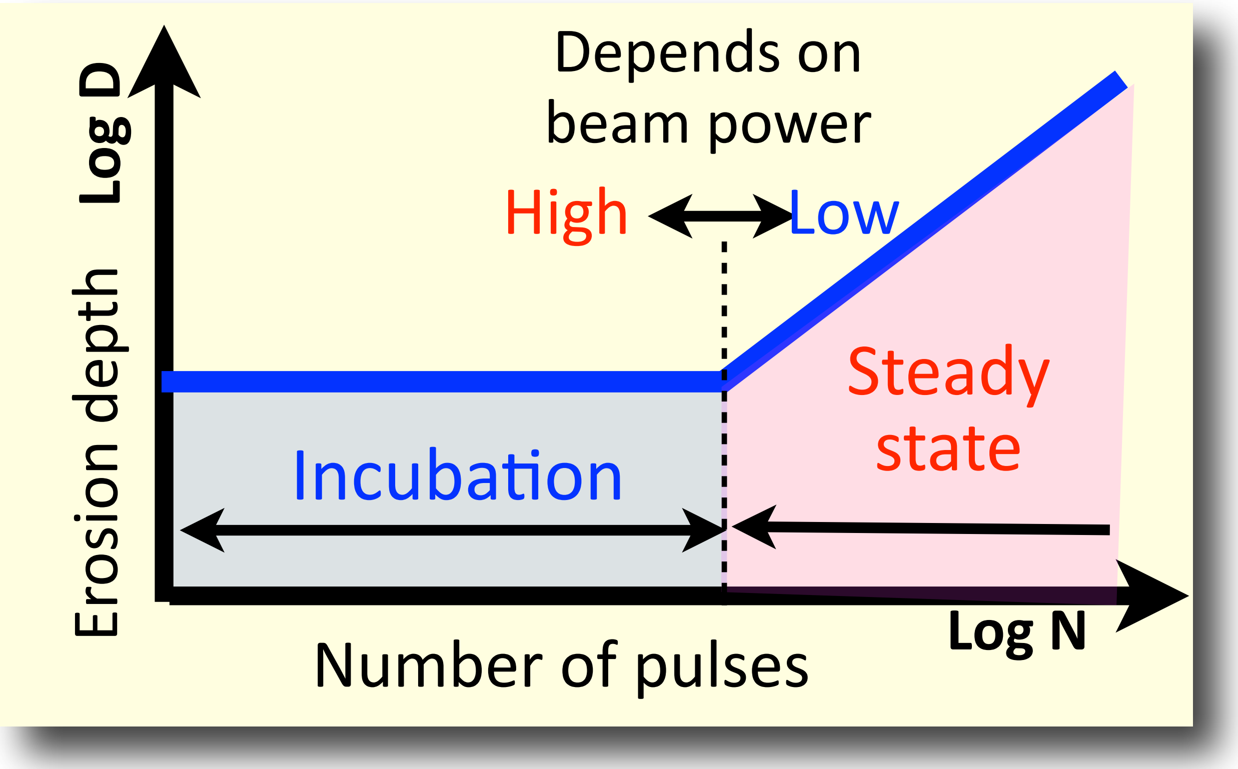
Approx. 5 mm offset from center to protect damage at center from drill for target #13

- Damage on bulk side correlated with the bubble effects obtained by sound measurement
- Damage is concentrated around center, is seemed to be growing along polishing mark (surface finish will be improved)

Prediction model construction for damage depth

Empirical equation for depth prediction

based on off-beam damage experiment

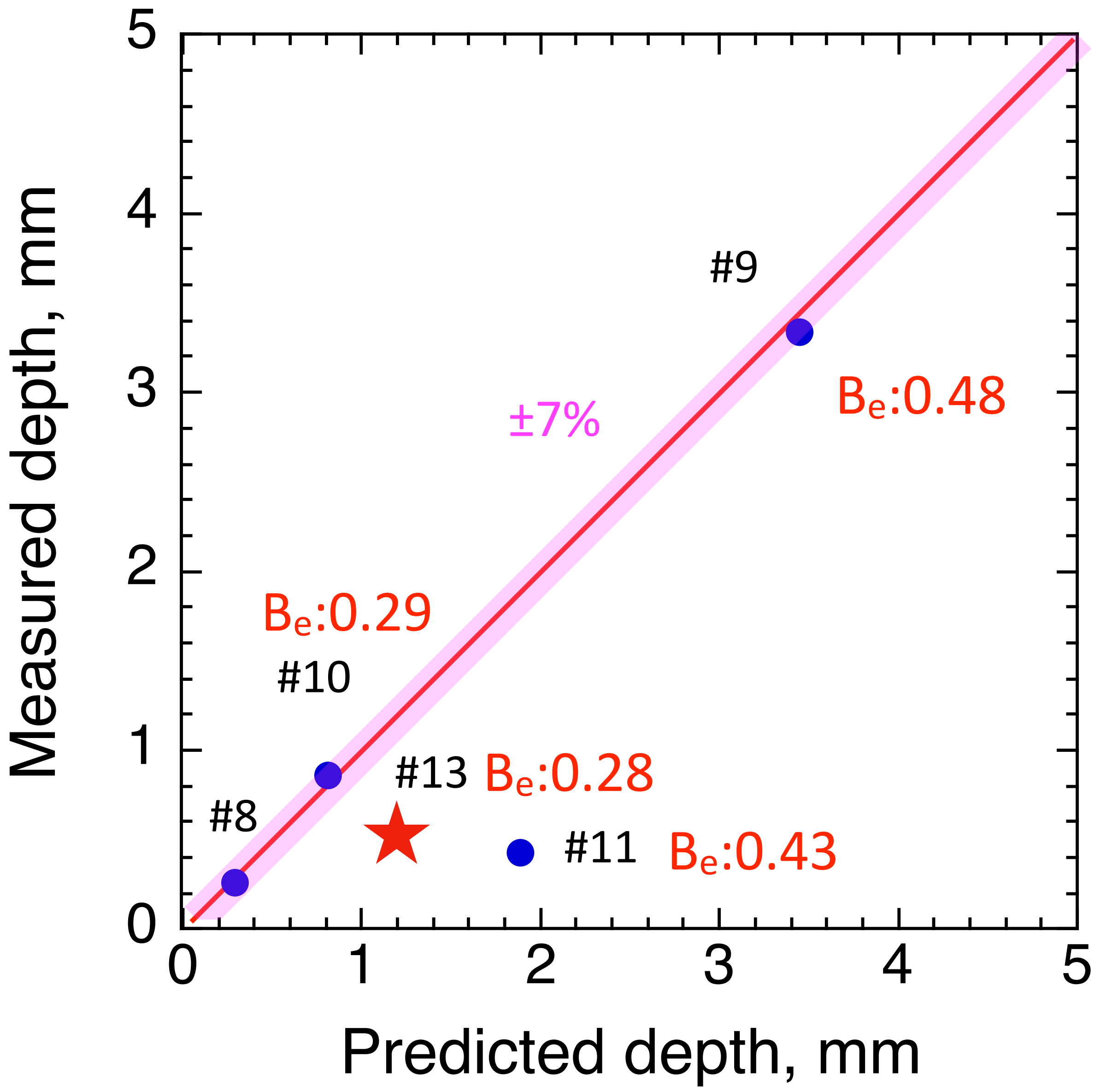


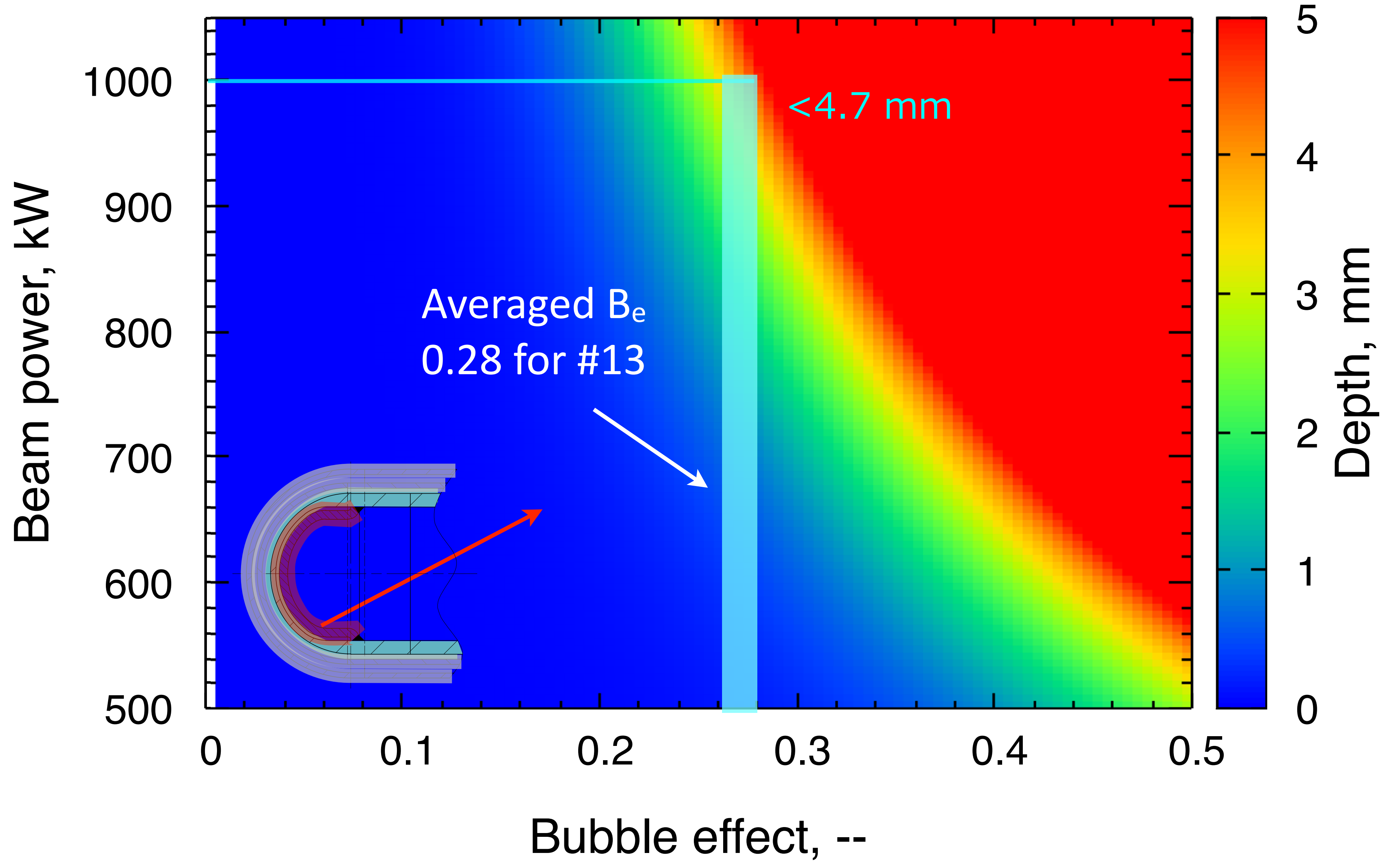
T. Naoe, et al., J. Nucl. Mater. 468 (2016)

$$D_{max} = f(P_{equiv.}, N)$$
$$= a(B_e P)^b N^c$$

Damage depth can be predicted from beam power, ***P***, number of pulses, ***N***, and bubble effect ***B_e***

a,b,c: constants to correlate off-beam experiment with actual damage are gradually updating based on damage data with bubble





Damage depth on inner wall facing bulk mercury after 4000 hours (1 year)

Planning 3600 hours operation in target #15

- Measured damage depth for target #13 is smaller than that of predicted depth, that may be caused by improvement of local void fraction around the beam window
- As a conservative estimation, the damage without penetrating inner wall,
  1 MW 4000 hours (1 year) operation is acceptable (D_{max}<4.7 for B_e=0.28, D_{max}<1.4 based on #13)
  1 MW 8000 hours (2 years) operation may acceptable predicted damage based on #13 observation (D_{max}<4.7 for B_e=0.28)

Summary

- Mercury target vessel for J-PARC pulsed neutron source is gradually updated to mitigate the pressure wave induced cavitation damage on interior surface.
- No cavitation erosion were observed on narrow channel surfaces, independent of the beam power and operation period.
- Damage depth of cavitation on the bulk side surface faced bubbly mercury was mitigated correlated with the bubble injection defined as the bubble effect ($\mathbf{B_e}$) estimated by the beam-indued acoustic vibration measurement.
- 1 year operation at 1 MW/pulse (designed life) will be acceptable when the damage mitigation by bubble injection acts as same with the target #13.
- Further improvement of the bubble generator to increase bubble void fraction is applied for target #15, and its optimization will be continued.


Thank you for your attention !