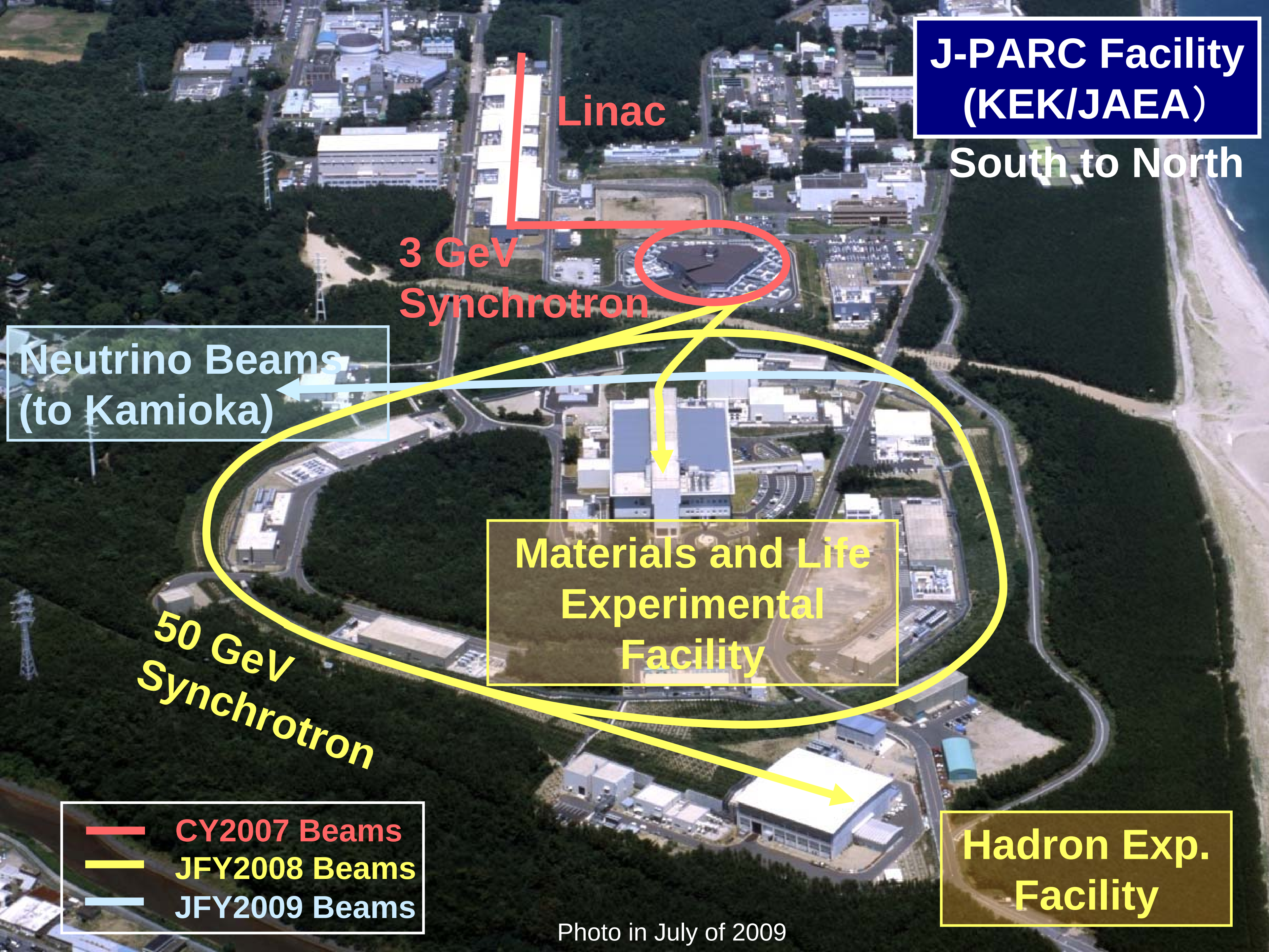
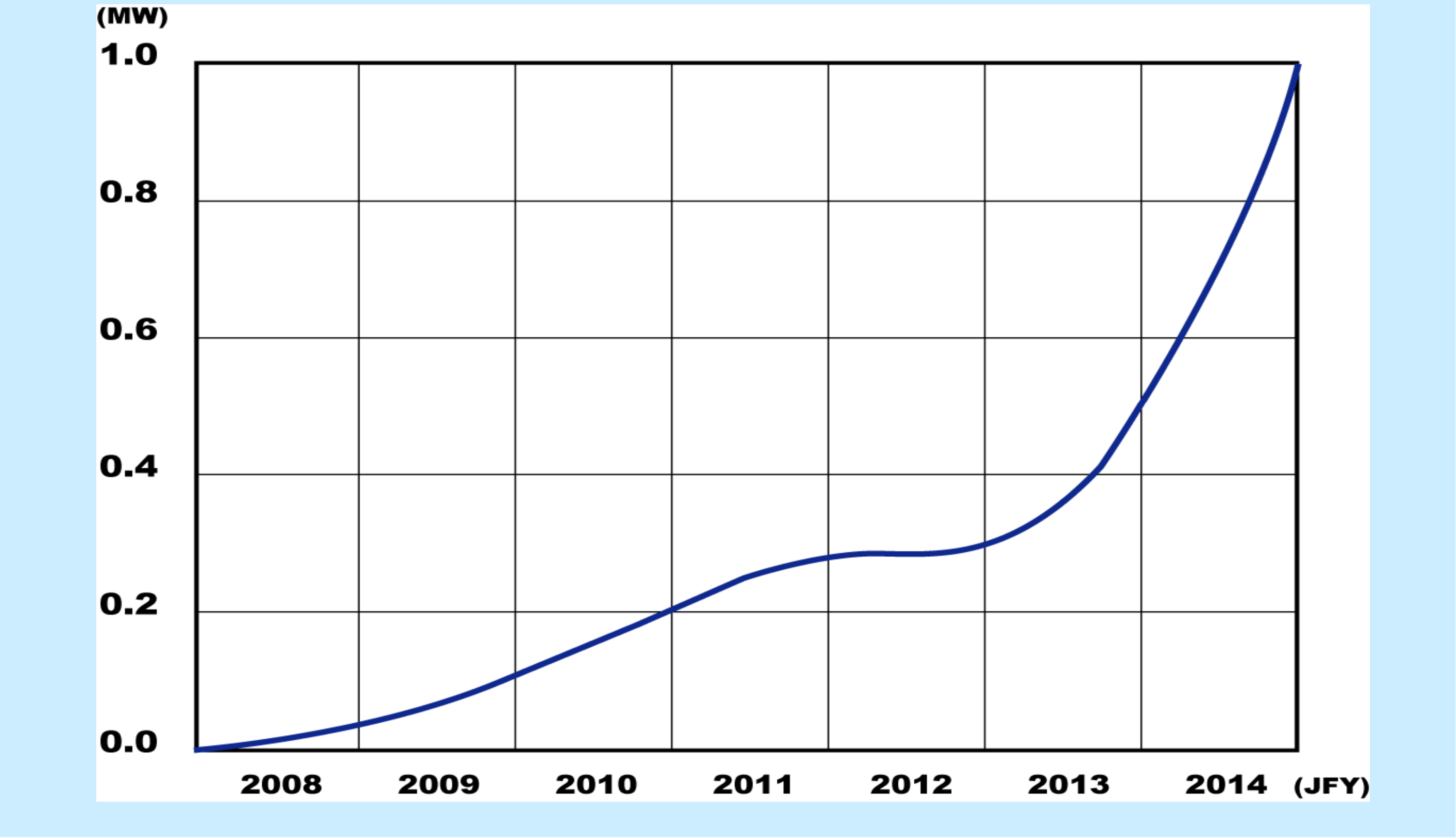
# R&D on Pressure wave issues at J-PARC

JAEA

Masatoshi FUTAKAWA


J-PARC Facility
(KEK/JAEA)
South to North
Linac
3 GeV
Synchrotron
Neutrino Beams
(to Kamioka)
Materials and Life
Experimental
Facility
50 GeV
Synchrotron
Hadron Exp.
Facility
CY2007 Beams
JFY2008 Beams
JFY2009 Beams
Photo in July of 2009

# Upgrade schedule




Recently, we reconsidered the upgrade schedule based on operational experiences regarding with accelerators.

Unexpected beam loss at RCS, etc. Improvement is needed.

In a few year, we will have 0.3 MW beam on the target.

# *Pressure wave & Pitting issues for High Power Mercury Target*

*1995 Pressure wave problem (K. Skala & G. Bauer)*
*1996 Prediction on cavitation due to pressure wave (J Carpenter)*
*1997 ASTE pressure wave measurement (JAERI)*
*2000 Pitting damage was found experimentally (JAERI)*
*2001 Pitting damage was confirmed in-beam tests (ORNL)*
*Design of mercury target was suspended in SNS(ORNL)*
*2002 Pitting damage formation over 10 million pulses was evaluated by MIMTM (JAERI)*
*Design of MT was resumed in SNS (ORNL)*
*R&Ds on mitigation system (ORNL & FZJ)*
*2004 Detail analysis regarding with the bubbling effect on pressure wave mitigation (The Univ. Tokyo)*
*Struggle to find suitable bubbler in mercury*
*2005 WNR test on bubbling effect (ORNL & JAERI, ESS)*
*2008Swirl bubbler to form fine bubbles in flowing mercury (Tsukuba Univ.)*
*2009 SNS target reached 1MW operation & PIE of real target.*

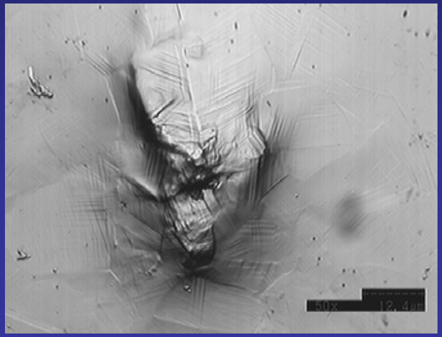
# Pressure wave & Pitting issues for High Power Mercury Target

1995 Pressure wave problem (K. Skala & G. Bauer)

1996 Prediction on cavitation due to pressure wave (J Carpenter)

1997 ASTE pressure wave measurement (JAERI)

2000 Pitting damage was found experimentally (JAERI)



2001 Pitting damage was confirmed in-beam tests (ORNL)

Design of mercury target was suspended in SNS(ORNL)

2002 Pitting damage formation over 10 million pulses was evaluated by MIMTM (JAERI)

Design of MT was resumed in SNS (ORNL)

R&Ds on mitigation system (ORNL & FZJ)

2004 Detail analysis regarding with the bubbling effect on pressure wave mitigation (The Univ. Tokyo)

Struggle to find suitable bubbler in mercury

2005 WNR test on bubbling effect (ORNL & JAERI, ESS)

2008Swirl bubbler to form fine bubbles in flowing mercury (Tsukuba Univ.)

2009 SNS target reached 1MW operation & PIE of real target.

# Pressure wave & Pitting issues for High Power Mercury Target

1995 Pressure wave problem (K. Skala & G. Bauer)

1996 Prediction on cavitation due to pressure wave (J Carpenter)

1997 ASTE pressure wave measurement (JAERI)

2000 Pitting damage was found experimentally (JAERI)

2001 Pitting damage was confirmed in-beam tests (ORNL)

Design of mercury target was suspended in SNS(ORNL)

2002 Pitting damage formation over 10 million pulses was evaluated by MIMTM (JAERI)

Design of MT was resumed in SNS (ORNL)

R&Ds on mitigation system (ORNL & FZJ)

2004 Detail analysis regarding with the bubbling effect on pressure wave mitigation (The Univ. Tokyo)

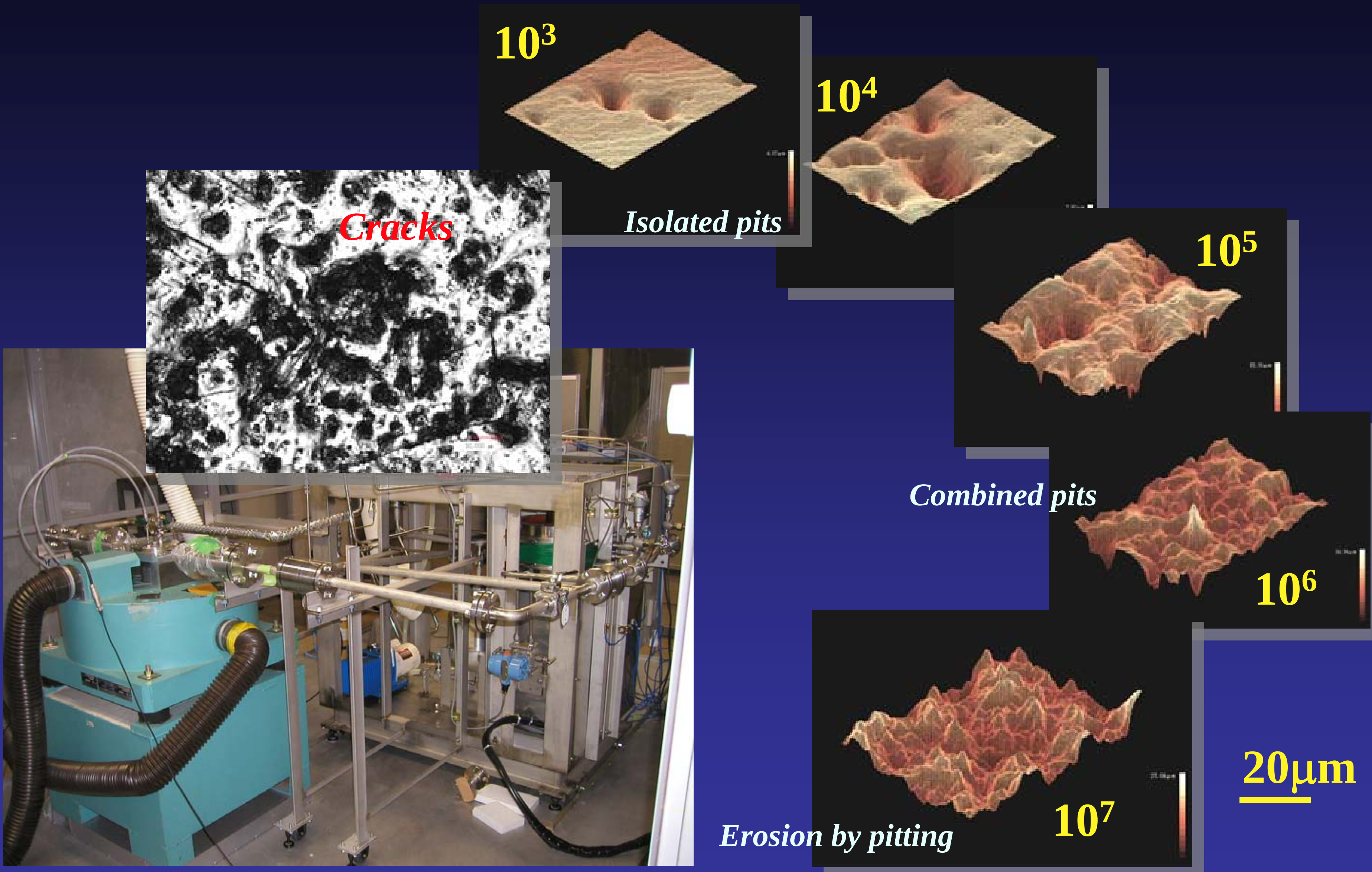
Struggle to find suitable bubbler in mercury

2005 WNR test on bubbling effect (ORNL & JAERI, ESS)

2008Swirl bubbler to form fine bubbles in flowing mercury (Tsukuba Univ.)

2009 SNS target reached 1MW operation at 60 Hz & PIE of real target.

# Pitting formation by MIMTIM

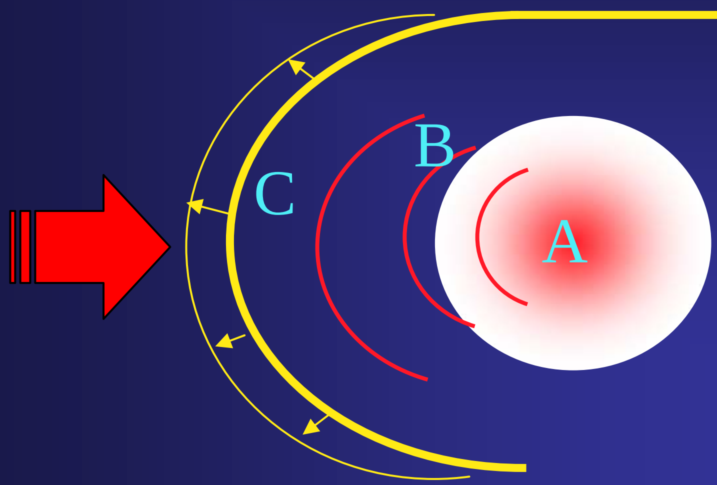



*Pitting damage data are accumulated up to over 10 million*

# *Pressure wave & Pitting issues for High Power Mercury Target*

*1995 Pressure wave problem (K. Skala & G. Bauer)*
*1996 Prediction on cavitation due to pressure wave (J Carpenter)*
*1997 ASTE pressure wave measurement (JAERI)*
*2000 Pitting damage was found experimentally (JAERI)*
*2001 Pitting damage was confirmed in-beam tests (ORNL)*
*Design of mercury target was suspended in SNS(ORNL)*
*2002 Pitting damage formation over 10 million pulses was evaluated by MIMTM (JAERI)*
*Design of MT was resumed in SNS (ORNL)*
*R&Ds on mitigation system (ORNL & FZJ)*
*2004 Detail analysis regarding with the bubbling effect on pressure wave mitigation (The Univ. Tokyo)*
*Struggle to find suitable bubbler in mercury*
*2005 WNR test on bubbling effect (ORNL & JAERI, ESS)*
*2008Swirl bubbler to form fine bubbles in flowing mercury (Tsukuba Univ.)*
*2009 SNS target reached 1MW operation at 60 Hz & PIE of real target.*

# Mechanisms of bubbling mitigation




**3 mechanisms for each region**

**Center of thermal shock : A**

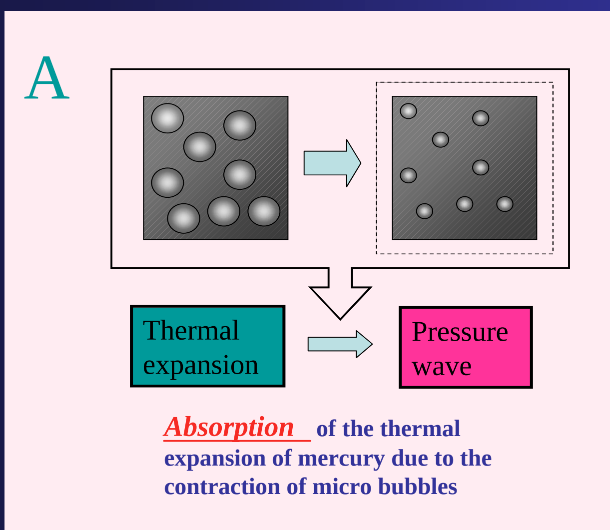
***Absorption***

**Propagation path : B**

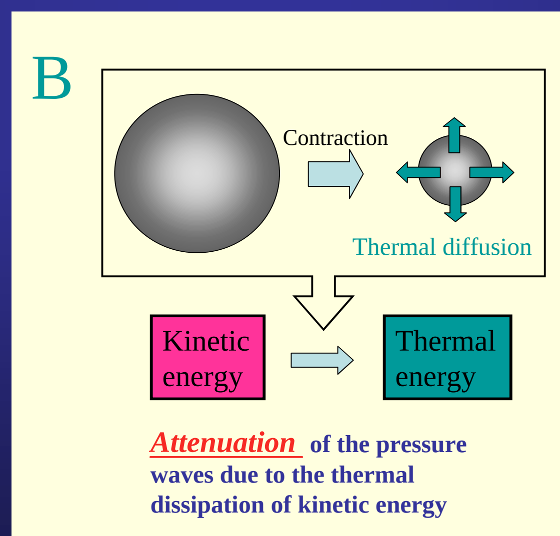
***Attenuation***

**Negative pressure field : C**

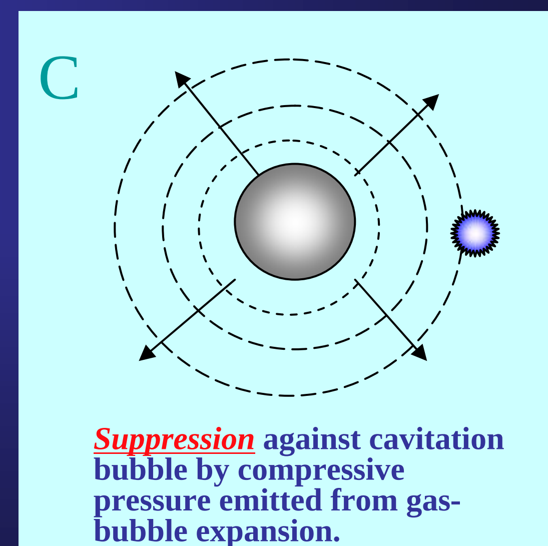
***Suppression***




**Absorption**




**Attenuation**




**Suppression**

# *Pressure wave & Pitting issues for High Power Mercury Target*

*1995 Pressure wave problem (K. Skala & G. Bauer)*

*1996 Prediction on cavittion due to pressure wave (J Carpenter)*

*1997 ASTE pressure wave measurement (JAERI)*

*2000 Pitting damage was found experimentally (JAERI)*

*2001 Pitting damage was confirmed in-beam tests (ORNL)*

*Design of mercury target was suspended in SNS(ORNL)*

*2002 Pitting damage formation over 10 million pulses was evaluated by MIMTM (JAERI)*

*Design of MT was resumed in SNS (ORNL)*

*R&Ds on mitigation system (ORNL & FZJ)*

*2004 Detail analysis regarding with the bubbling effect on pressure wave mitigation (The Univ. Tokyo)*

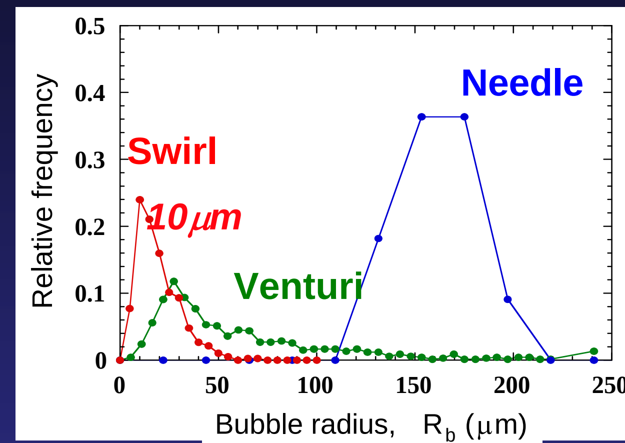
*Struggle to find suitable bubbler in mercury*

*2005 WNR test on bubbling effect (ORNL & JAERI, ESS)*

*2008 Swirl bubbler to form fine bubbles in flowing mercury (Tsukuba Univ.)*

*2009 SNS target reached 1MW operation at 60 Hz & PIE of real target.*

# Swirl bubbler to form fine bubbles in flowing mercury




Bubble formation at a swirl bubbler

*Taken by Prof. Kyoto*

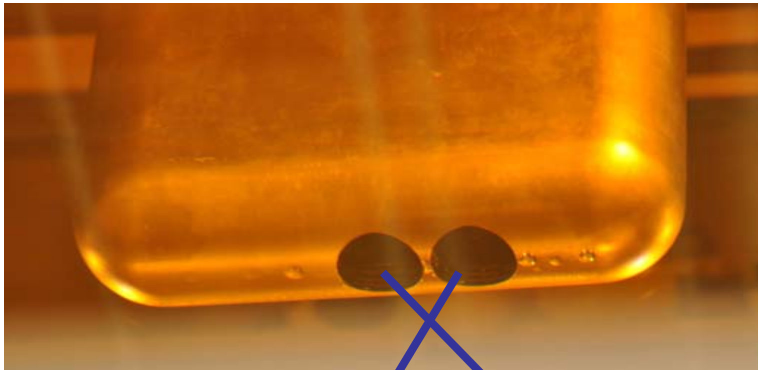
Bubbles fixed on transparent window in mercury flow

*Taken by SNS*

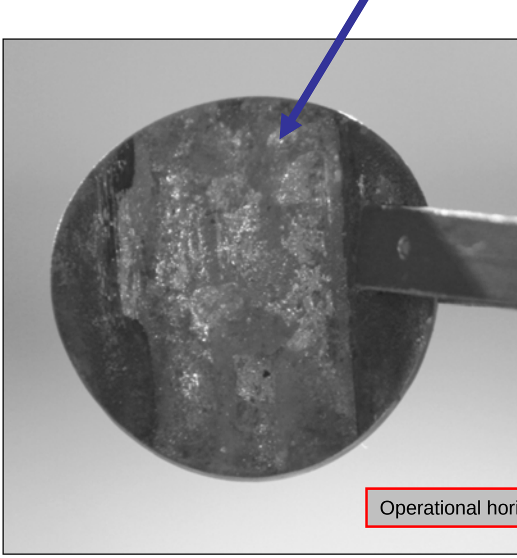
# *Pressure wave & Pitting issues for High Power Mercury Target*

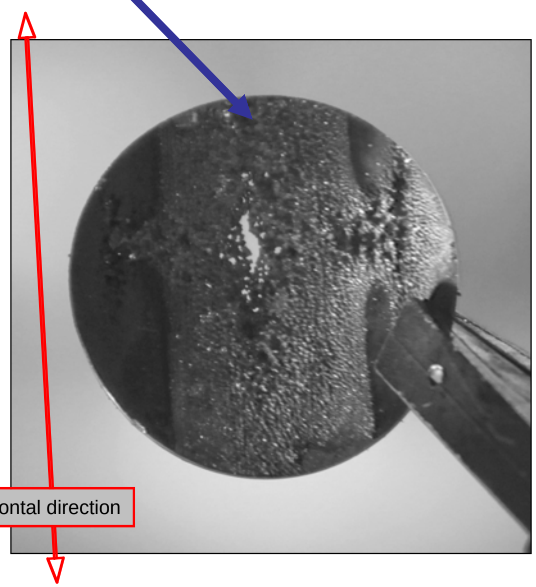
*1995 Pressure wave problem (K. Skala & G. Bauer)*
*1996 Prediction on cavitation due to pressure wave (J Carpenter)*
*1997 ASTE pressure wave measurement (JAERI)*
*2000 Pitting damage was found experimentally (JAERI)*
*2001 Pitting damage was confirmed in-beam tests (ORNL)*
*Design of mercury target was suspended in SNS(ORNL)*
*2002 Pitting damage formation over 10 million pulses was evaluated by MIMTM (JAERI)*
*Design of MT was resumed in SNS (ORNL)*
*R&Ds on mitigation system (ORNL & FZJ)*
*2004 Detail analysis regarding with the bubbling effect on pressure wave mitigation (The Univ. Tokyo)*
*Struggle to find suitable bubbler in mercury*
*2005 WNR test on bubbling effect (ORNL & JAERI, ESS)*
*2008 Swirl bubbler to form fine bubbles in flowing mercury (Tsukuba Univ.)*
*2009 SNS target reached 1MW operation at 60 Hz & PIE of real target.*

# Damage dependence on position

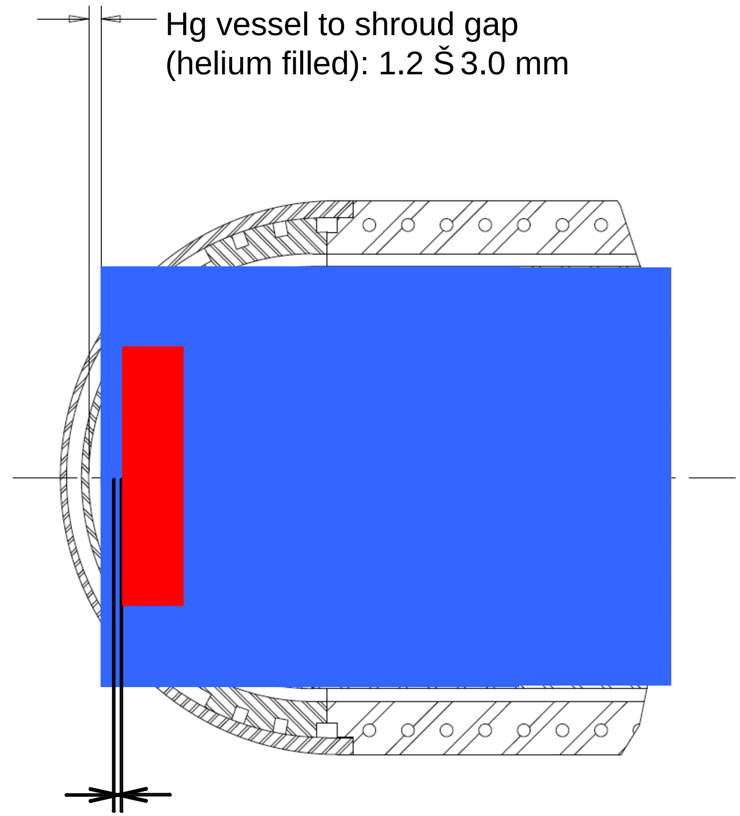


Specimen diameter: 60 mm
Largest hole: 9.2 x 2.1 mm ;
area ~ 11.5 mm$^2$



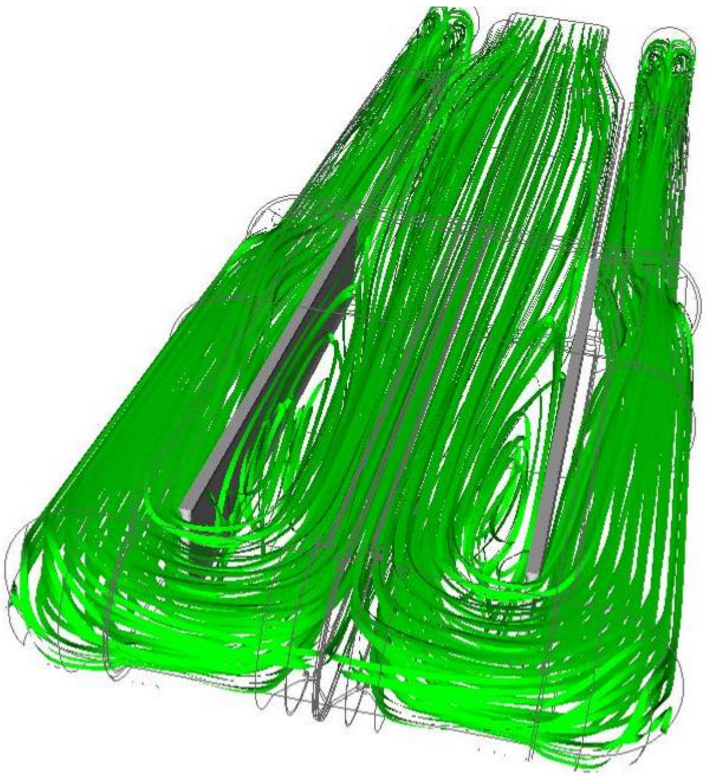
Hg vessel to shroud gap
(helium filled): 1.2 Š 3.0 mm



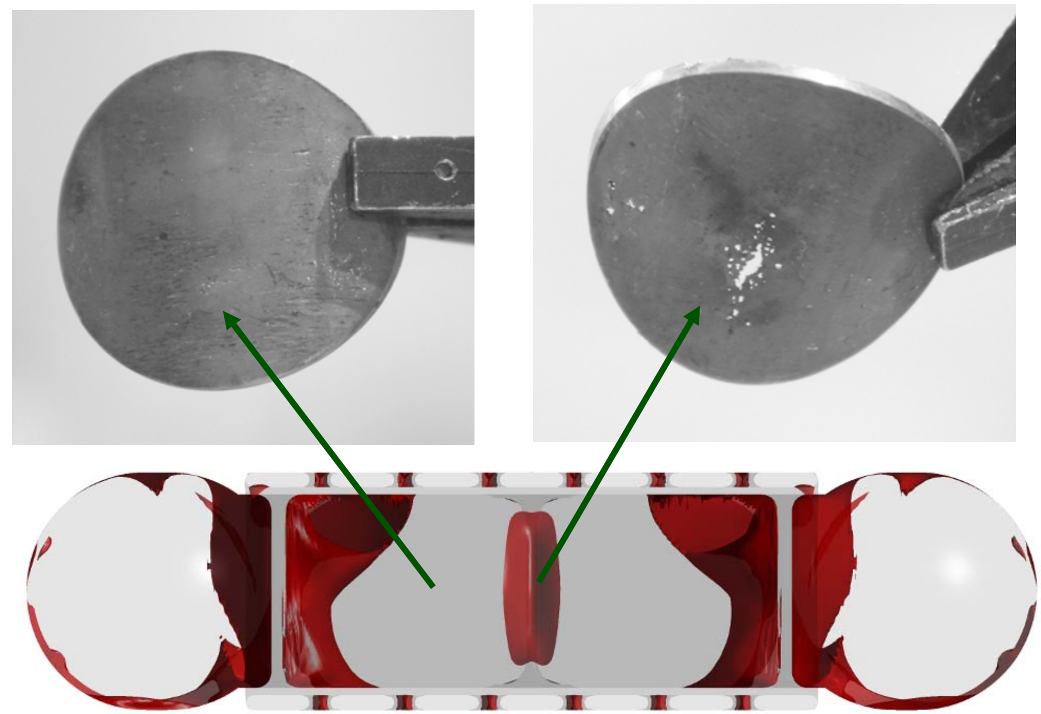
Hg vessel inner to outer window gap: 1.5 Š 2.5 mm
Hg vessel Inner & outer wall thickness: 3.0 mm

by B. Riemer ICANS XIX, 2010

# Damage difference by flowing ?



Mercury stream line
Stagnant area at center



0.35 m/s isosurfaces of instantaneous velocity
Mercury flow @ 270 rpm

by B. Riemer  ICANS XIX, 2010

# Mitigation techniques for damages due to pressure waves

- **Direct protection of beam window**
  - **Surface improvement: Kolsterizing, Plasma N&C**
  - **Flowing effect**
  - **Gas-curtain**
- **Reduction of pressure waves**
  - **Flattening beam profile**
  - **Micro-bubbles injection**

# Mitigation techniques for damages due to pressure waves

- **Direct protection of beam window**
  - **Surface improvement: Kolsterizing, Plasma N&C**
  - **Flowing effect**
  - **Gas-curtain**
- **Reduction of pressure waves**
  - **Flattening beam profile**
  - **Micro-bubbles injection**

# Effect of surface improvement and coatings

316SS

Gas nitriding

Plasma nitriding

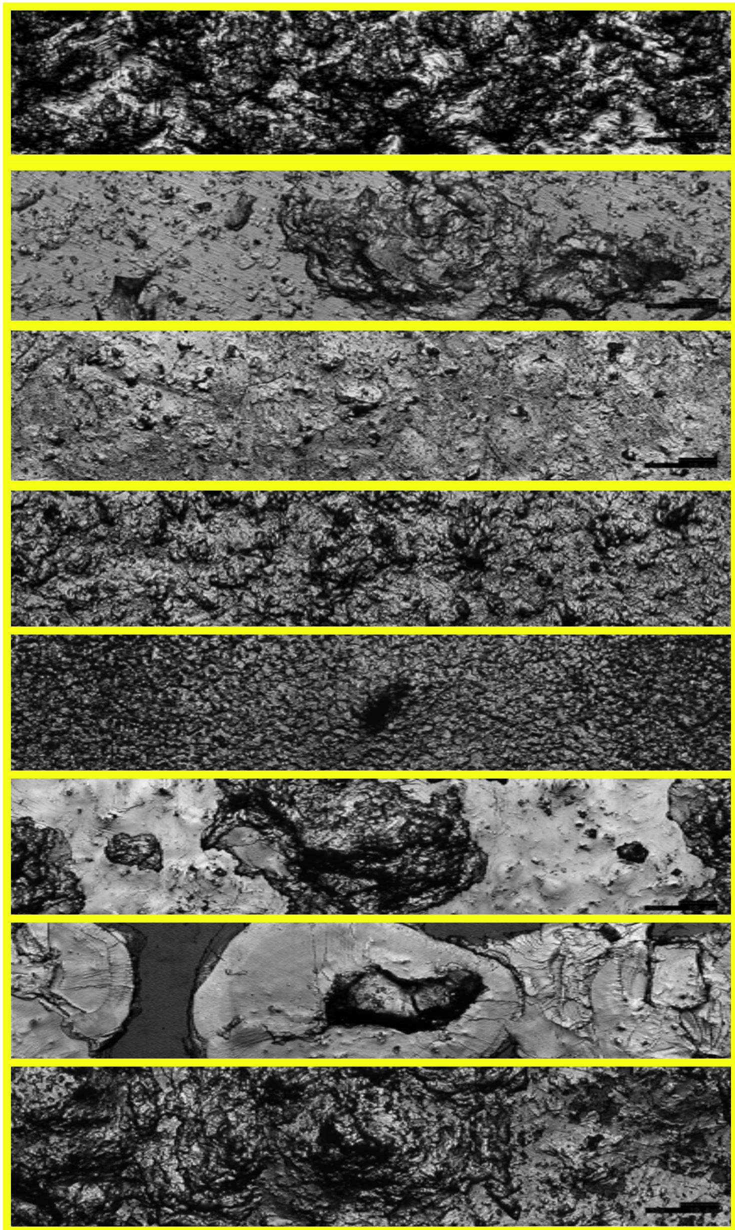
Kolsterising®

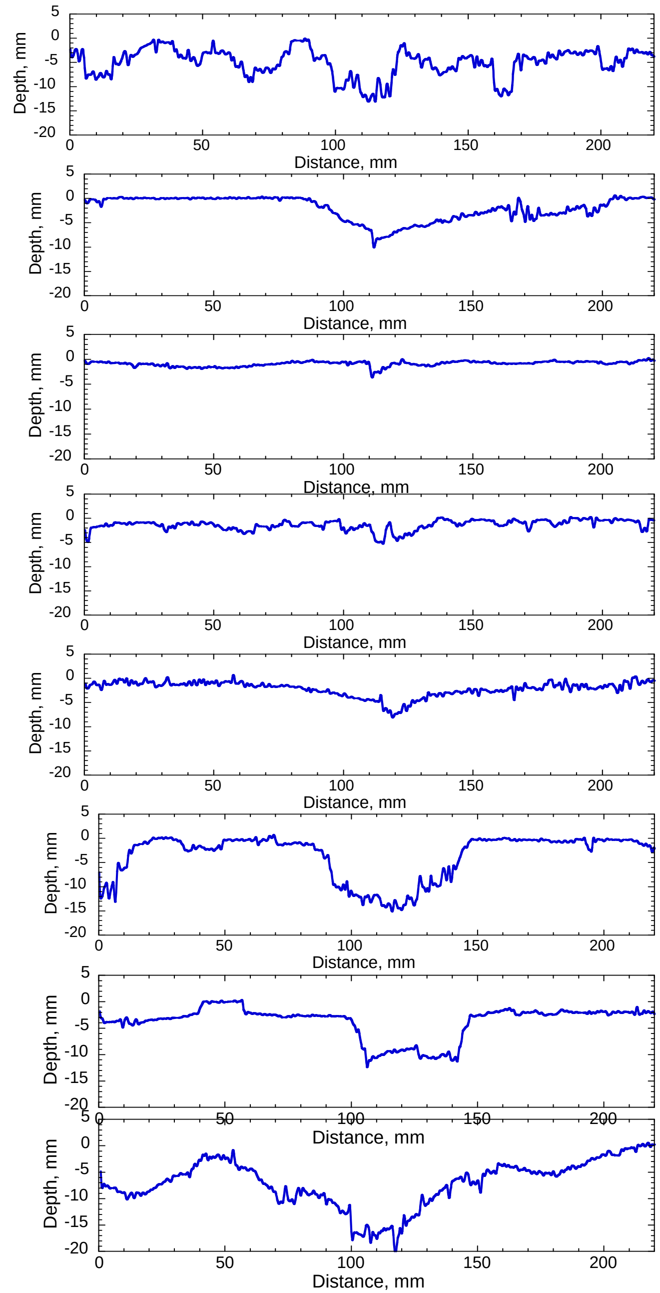
Boron

TiN

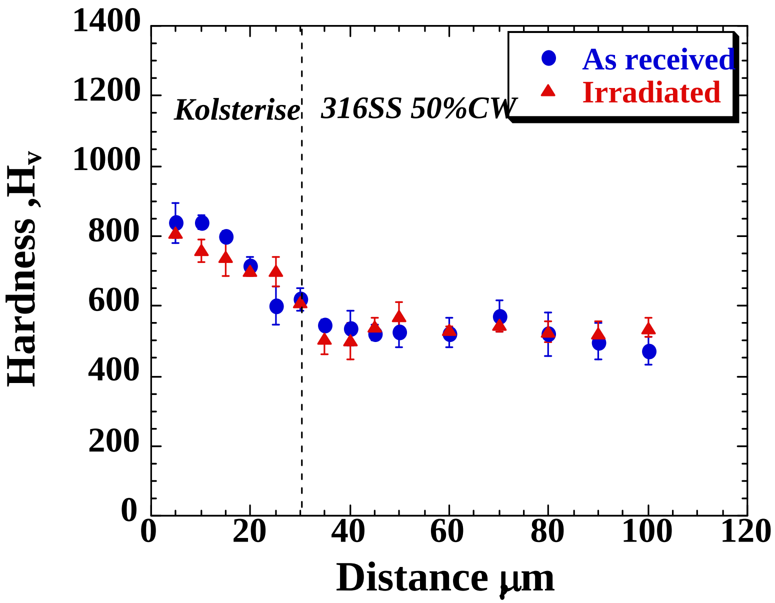
TiAlN

DLC

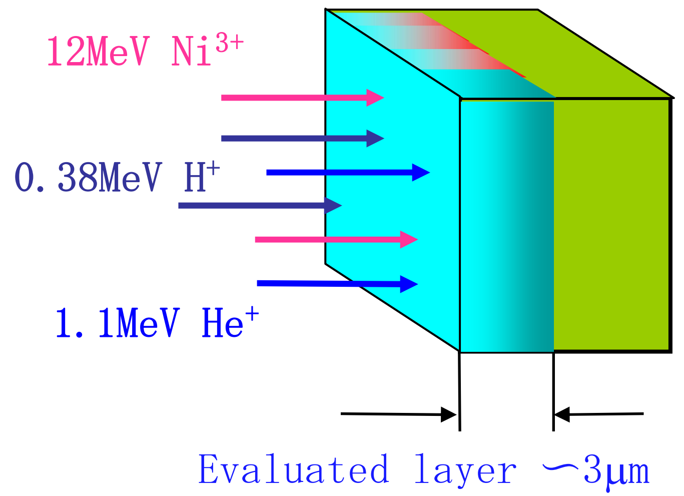




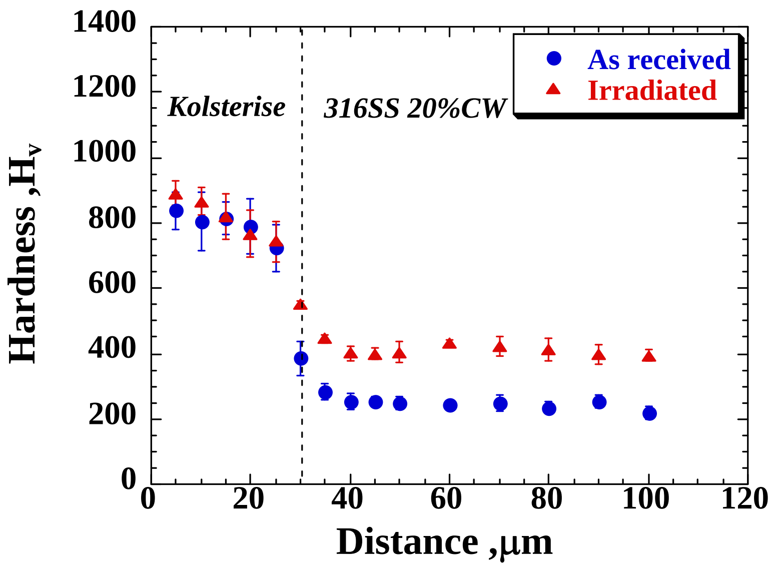
# Hardness change by irradiation

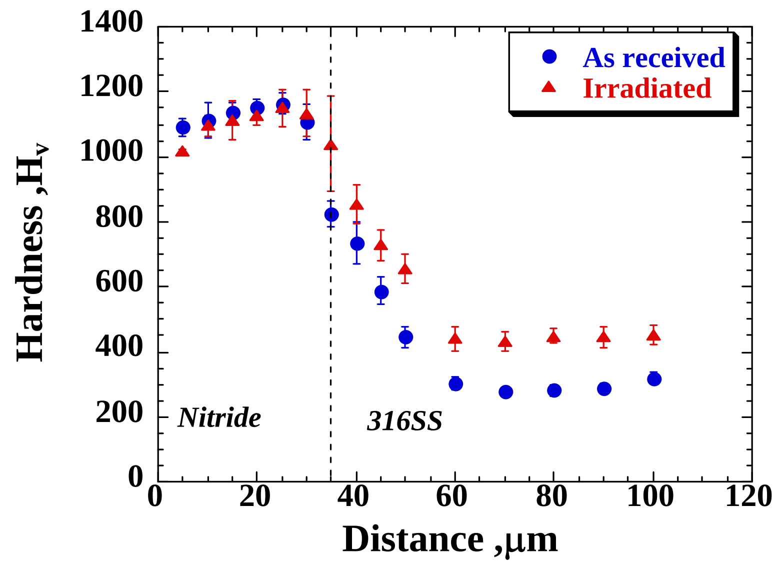



## *Triple ion beam irradiation*



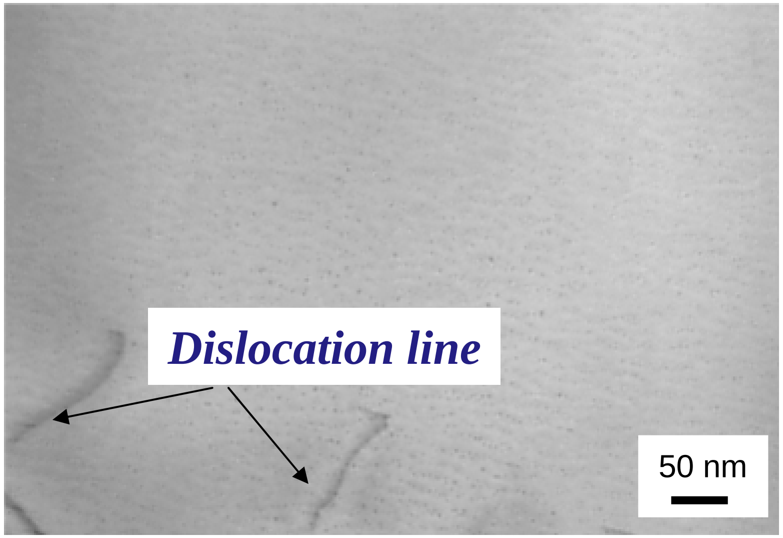

*200°C*
*Ni:10dpa*
*H : 20000appm*
*He:2000appm*



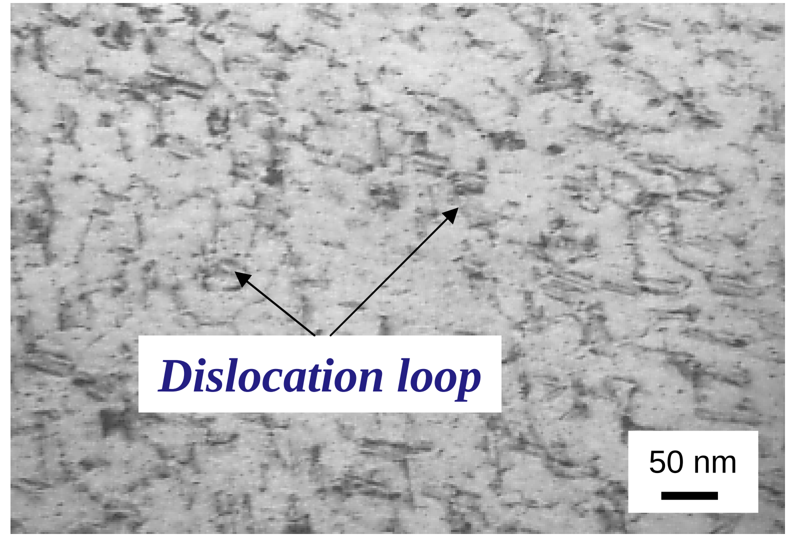



# Microstructure change due to irradiation

***316SS 20%CW Unirradiated***




***316SS 20%CW Irradiated***




Dislocation Loop Formation

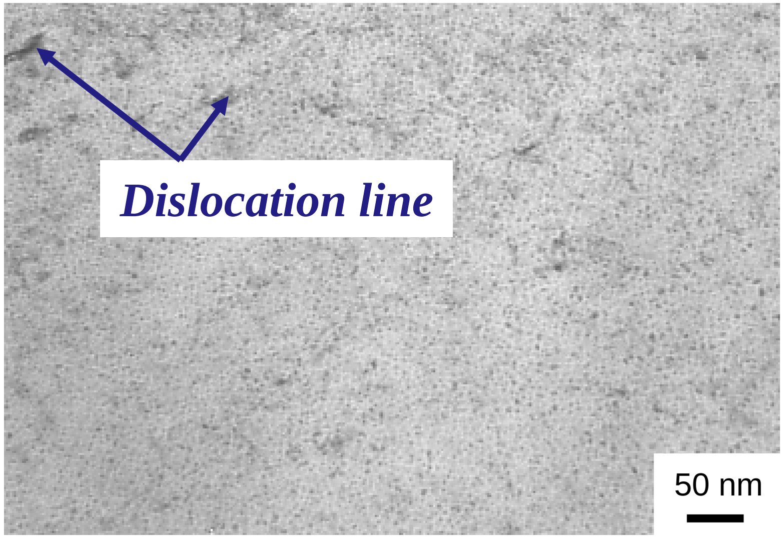
***316SS 50%CW Unirradiated***


***316SS 50%CW Irradiated***

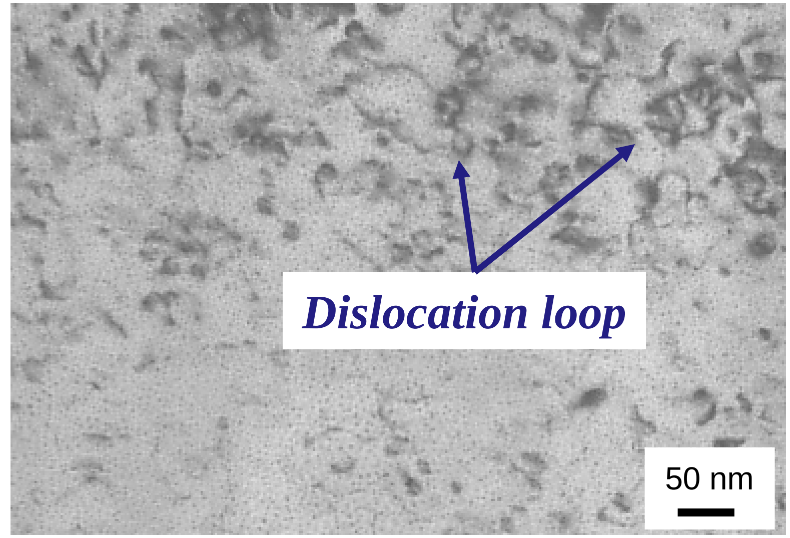

No Change

# Microstructure change due to irradiation

***Kolsterise  Unirradiated***

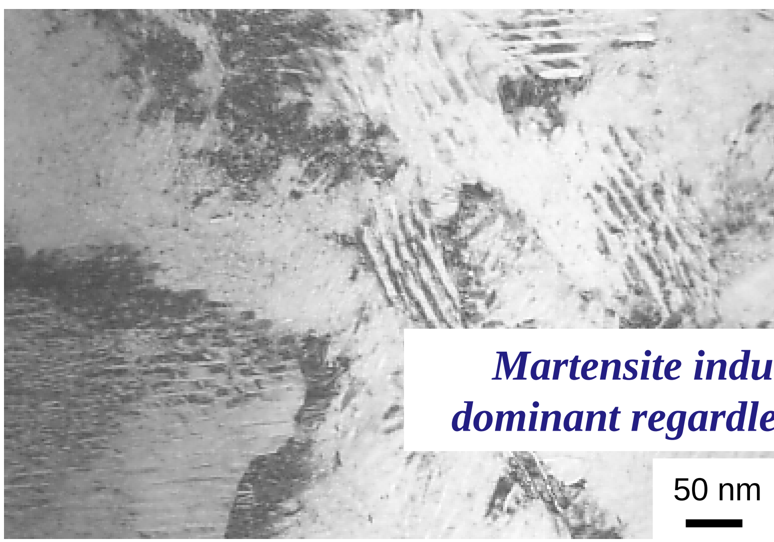



***Kolsterise  Irradiated***




Dislocation Loop Formation

***Nitride  Unirradiated***




***Nitride  Irradiated***

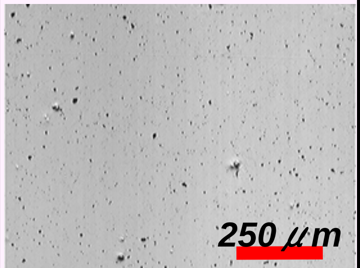
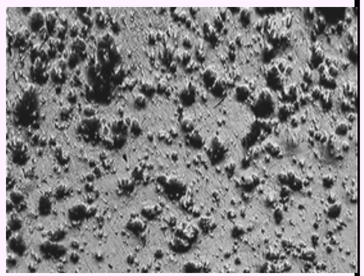
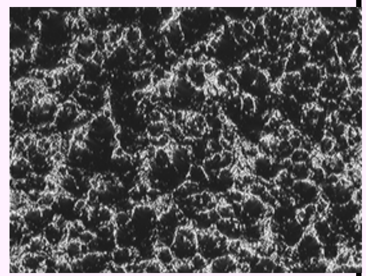
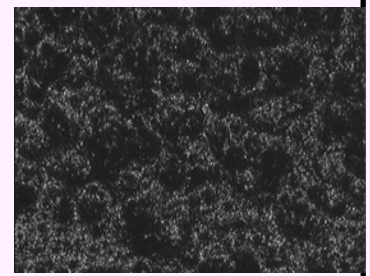
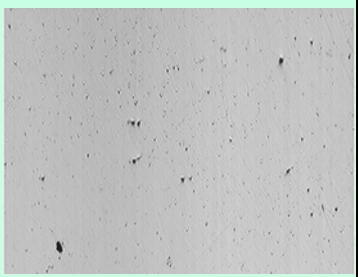
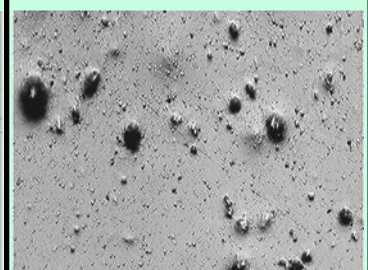
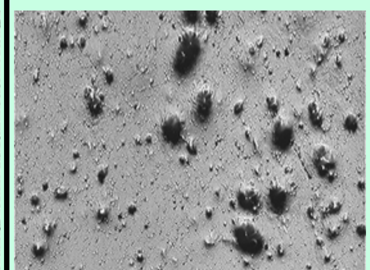
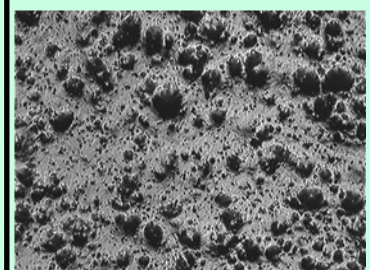
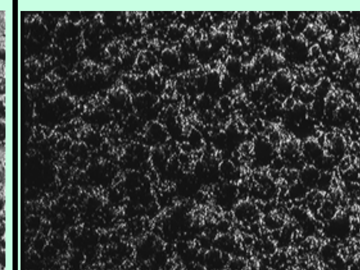
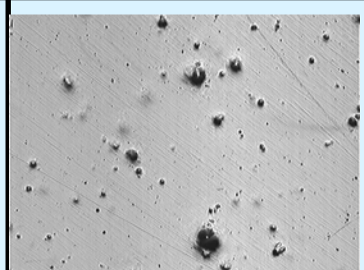
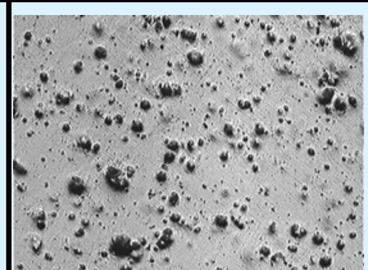

No Change

*Martensite induced by nitiriding is dominant regardless of w/o irradiation.*

# Mitigation techniques for damages due to pressure waves

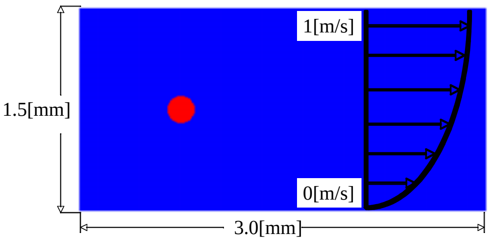
- **Direct protection of beam window**
  - Surface improvement: Kolsterizing, Plasma N&C
  - Flowing effect
  - Gas-curtain
- **Reduction of pressure waves**
  - Flattening beam profile
  - Micro-bubbles injection

# Flowing effect on damage

| | $10^2$ impacts | $5\times10^3$ | $10^4$ | $5\times10^4$ | $10^5$ |
|---|---|---|---|---|---|
| ***Stagnant*** |   ***$A_e/A_0$=0.028*** |  ***$A_e/A_0$=0.30*** |  ***$A_e/A_0$=0.61*** |  ***$A_e/A_0$=0.88*** | ***Fraction of eroded area*** $A_e/A_0 = \frac{\text{Eroded}}{\text{Measured}}$ |
| ***0.3m/s*** |  ***$A_e/A_0$=0.016*** |  ***$A_e/A_0$=0.11*** |  ***$A_e/A_0$=0.18*** |  ***$A_e/A_0$=0.32*** |  ***$A_e/A_0$=0.86*** |
| ***1.0m/s*** | Damaged area is clearly decreased by mercury flow<br>***Damage is slightly decreased with increasing in flow velocity*** | |  ***$A_e/A_0$=0.04*** |  ***$A_e/A_0$=0.18*** | |

**In low cycle test (100 impacts), damage is hardly changed by mercury condition**

# Effect of flowing on bubble collapse behavior




QuickTime?遣
Microsoft Video 1 闉恚莭社蒓敉赡
菣潸敲蒎莭蒨缮蔷濠侨菫墙葯钦颣髒黔菑臂

**Micro-jet impact angle is inclined, because the growth behavior is affected by the flowing.**

*Tanaka, et al, CAV2006* (2006)

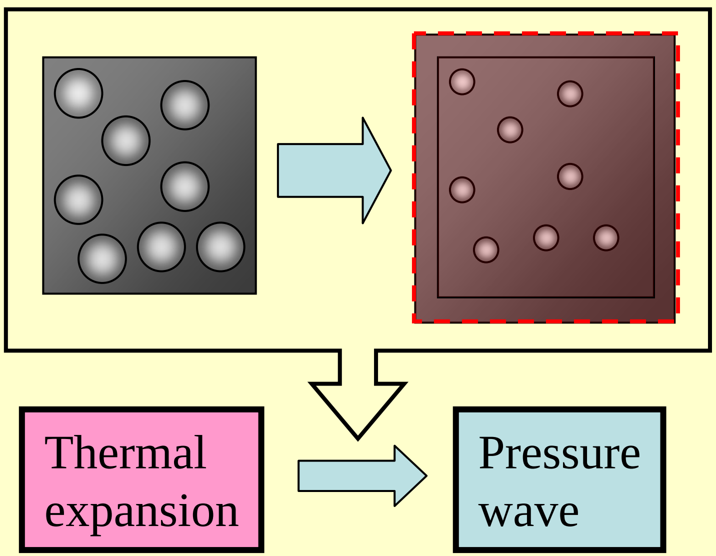
# Mitigation techniques for damages due to pressure waves

- Direct protection of beam window
  - Surface improvement: Kolsterizing, Plasma N&C
  - Flowing effect
  - Gas-curtain
- Reduction of pressure waves
  - Micro-bubbles injection
  - Flattening beam profile

# What is expected by introducing micro bubbles?

## Decrease of pressure rise

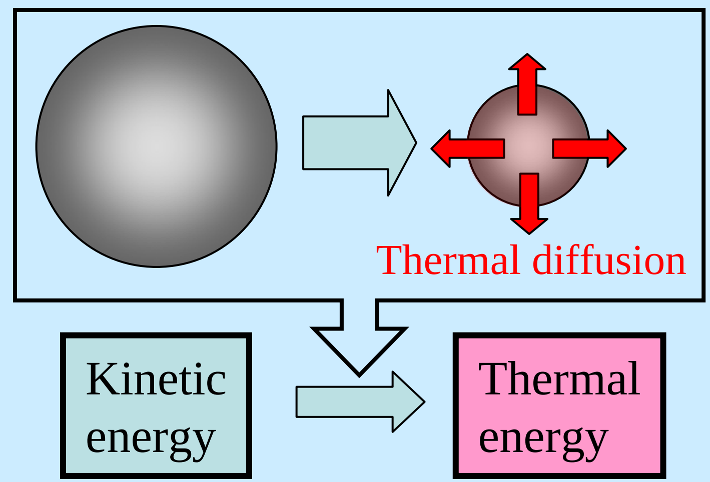
➢Absorption of thermal expansion



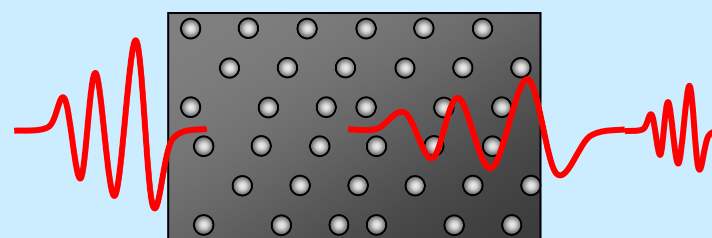

$$\frac{dp}{dt} = c_m^2 \left[\frac{\beta}{C_{pL}}\right] Q_{\mathrm{input}}$$

## Attenuation of pressure waves

➢Thermal, Viscous and Acoustic damping




➢Dispersion of pressure waves

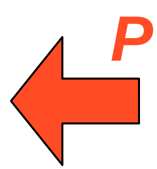


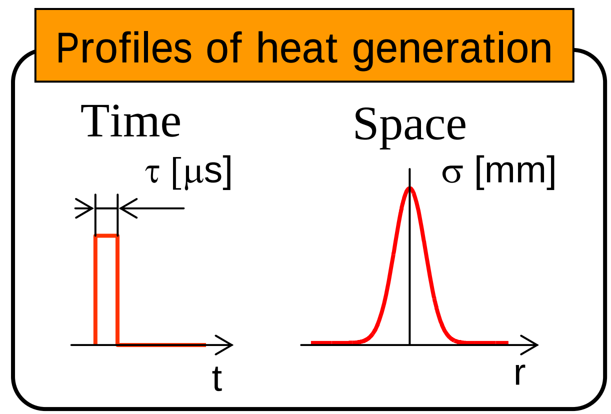
# Influence of the elasticity of the solid wall on the pressure wave in liquid mercury

***Inertia effect***

| Mercury | | Solid wall (316SS) |
|---|---|---|
| $13579.04[kg/m^3]$ | $>$ | $7946[kg/m^3]$ |

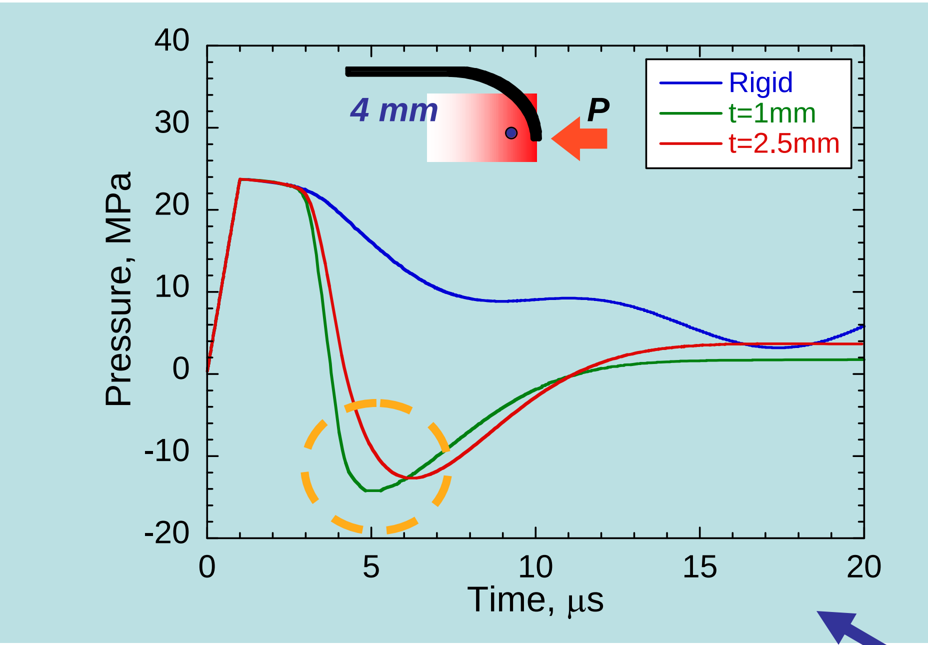
QuickTime?遣
闘恚葩社蕪赦贍
菽潸敲蒬蒒蒨缮蔷濠侨堇墙药钦粫髒黔菑礐

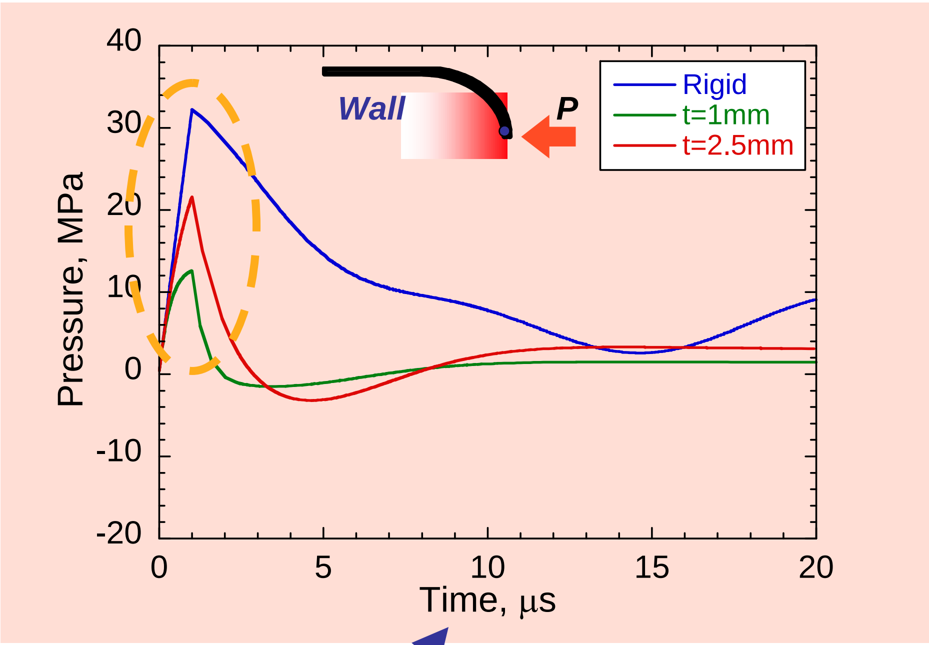



The density of liquid mercury is greater than the density of the solid wall (316 Stainless Steal). The influence of the elasticity of the solid wall in the thermal expansion of liquid mercury is examined.

# Influence of the elastic solid wall on pressure wave




**No-bubble**

**1.0, 2.5 mm wall**

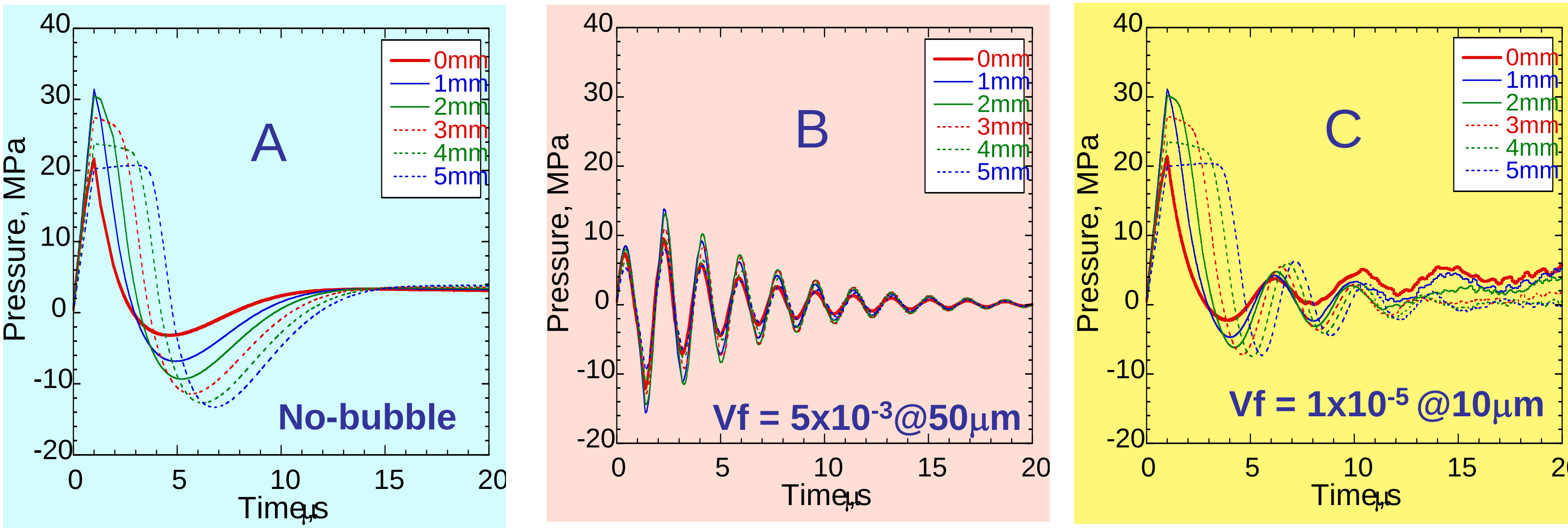
**12 J/cc**

QuickTime?道
闘恚茆社蕤敉赡
菮潛敲流蒒蒨缮蔷濠侨堇墙药钦颡髒黔菑肴

**Proton injection**

Strong tensile pressure is induced due to inertia effect which was enhanced by the low stiffness of solid wall. On the other hand, compressive pressure along the wall was reduced by the low stiffness.

# Effect of bubble void fraction on pressure waves




**Wall thickness: 2.5 mm, Measuring point: 0〜5mm**

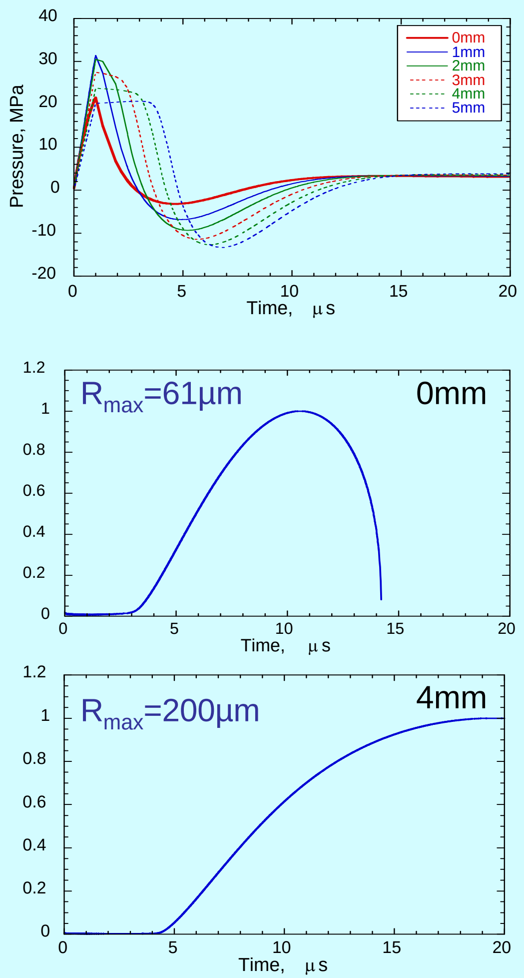
***Compressive pressure : A>C>B due to absorption***

***Tensile pressure : A>B>C due to attenuation***

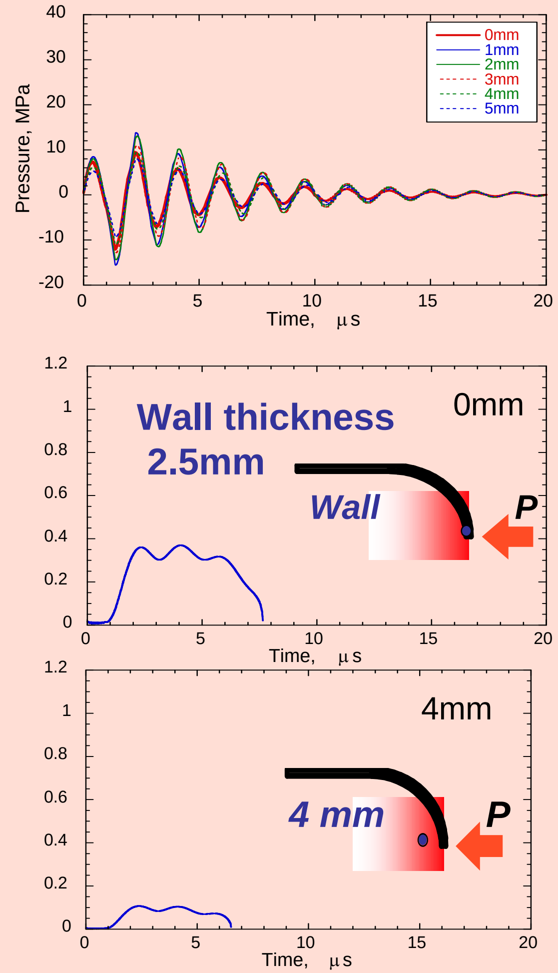
Compressive pressure is reduced well by absorption of thermal expansion.Tensile pressure is influenced by the bubble dynamics with viscous and thermal damping and dispersion.

# Tensile pressure related to cavitation bubble growth

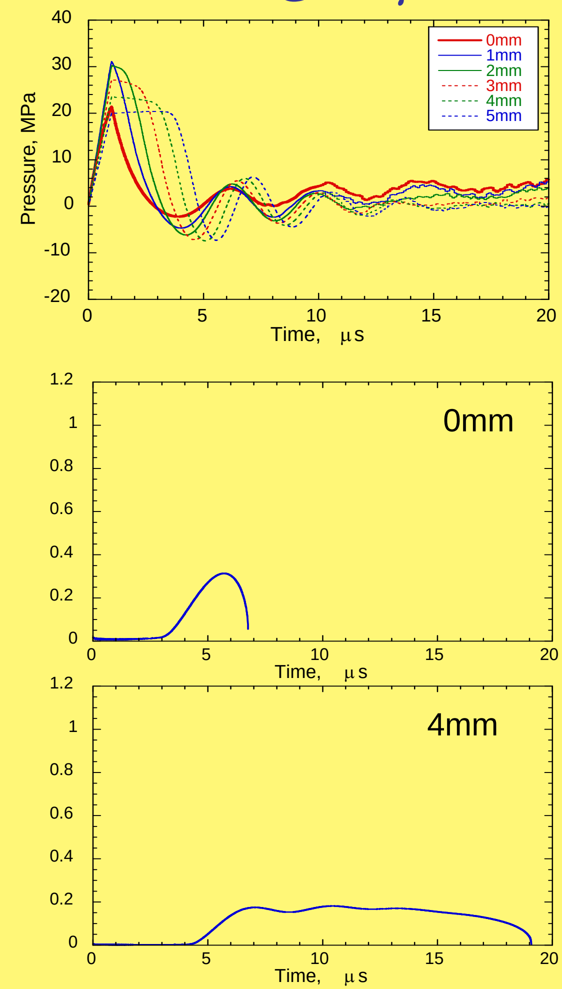
## *No-bubble*




## *Vf = 5x10$^{-3}$ @ 50 μm*




## *Vf = 10$^{-5}$ @ 10 μm*

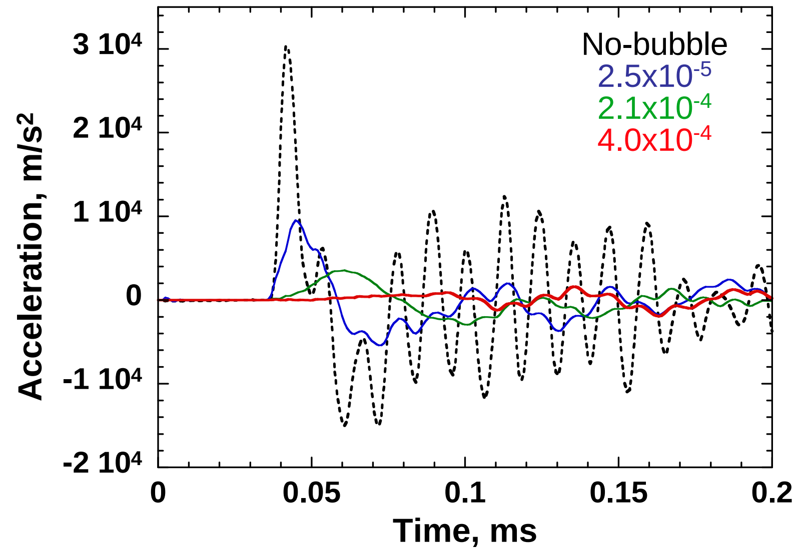



Cavitation bubble growth is influenced by tensile pressure: amplitude and imposing period.

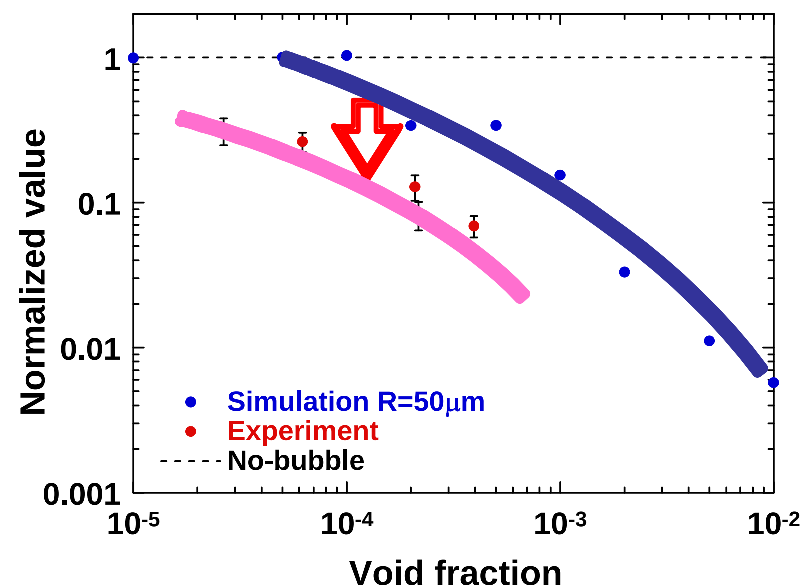
# Effect of bubble size distribution

QuickTime?

Electric spark    Very rapid pressure rise



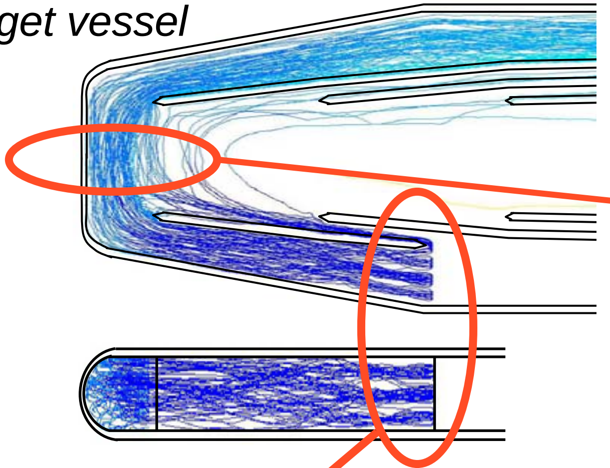

Attenuation may be enhanced
by randomly distributed bubbles
with different sizes.

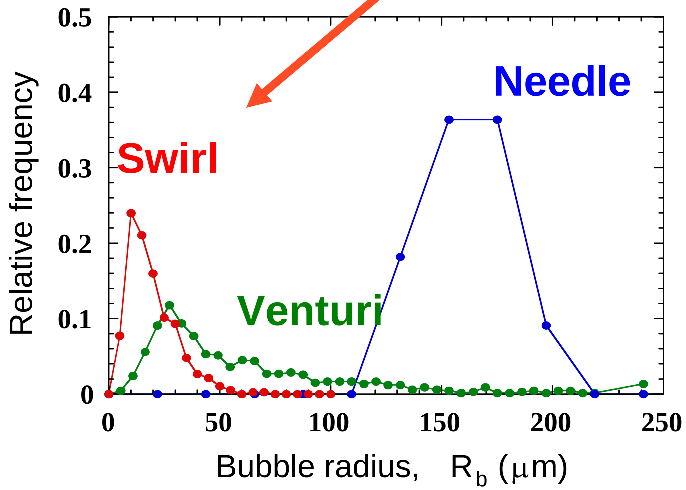


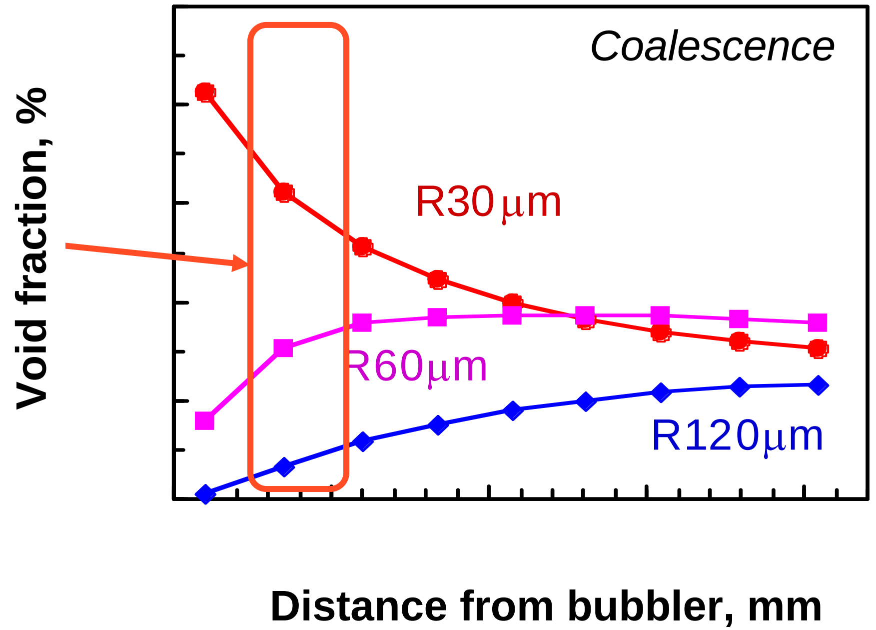

Ref. P. Smereka, J. Fluid Mech. (2002), 454, 287.

# What is realistic bubble conditions to mitigate damage ?

*Bubble distribution in target vessel*





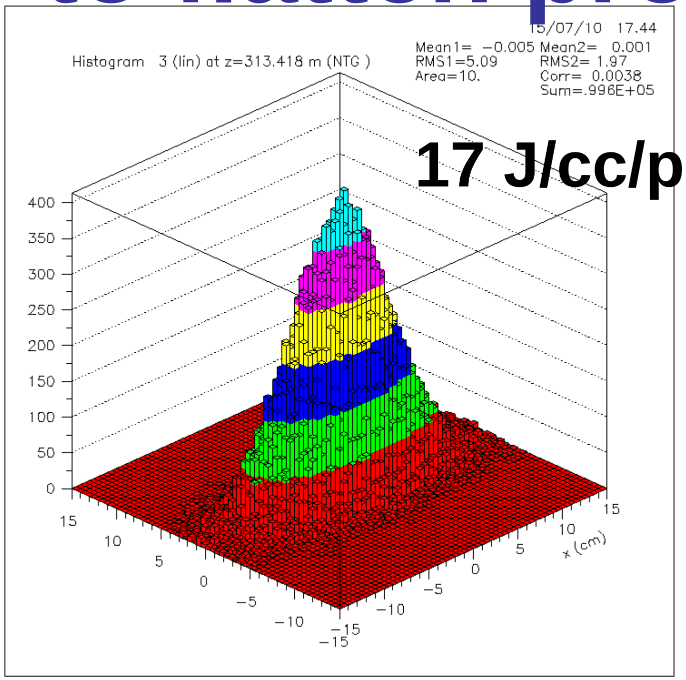

**Expected bubble condition**
**$10^{-4}$ & < 30 $\mu$m**

**Attenuation effect on tensile pressure**
**Mitigation of cavitation intensity**

# Mitigation techniques for damages due to pressure waves

- Direct protection of beam window
  - Surface improvement: Kolsterizing, Plasma N&C
  - Flowing effect
  - Gas-curtain
- Reduction of pressure waves
  - Micro-bubbles injection
  - Flattening beam profile

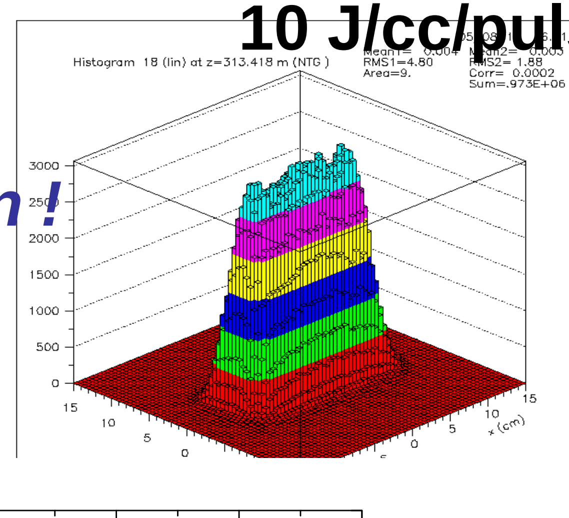
# Study on octupole electromagnet to flatten proton beam profile

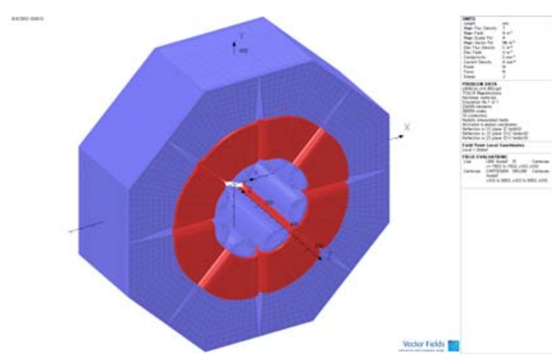


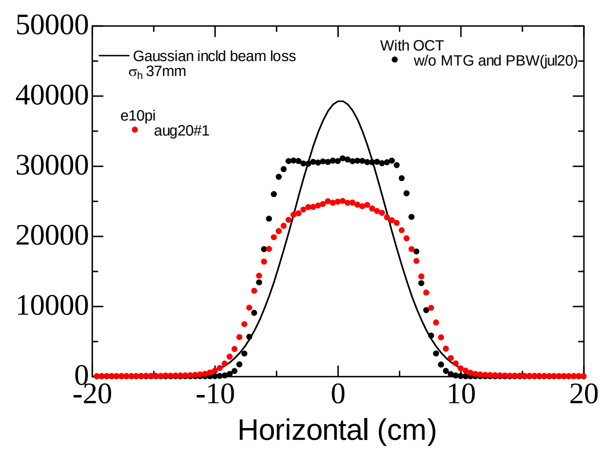

**17 J/cc/pulse**

***Reduction !***

**10 J/cc/pulse**





# Summary

## How can we mitigate the pitting damage ?

Flowing effect  1m/s at JSNS cross flow type

Attenuation due to microbubble injection

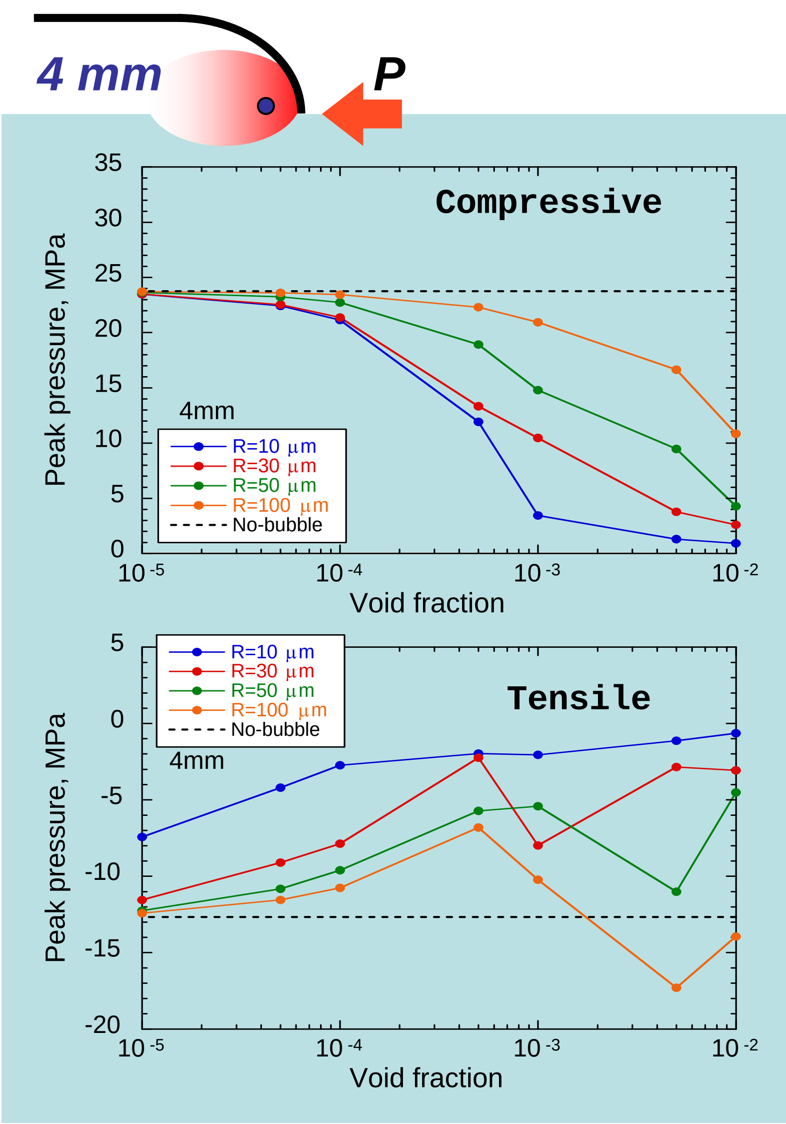
Flattening beam profile

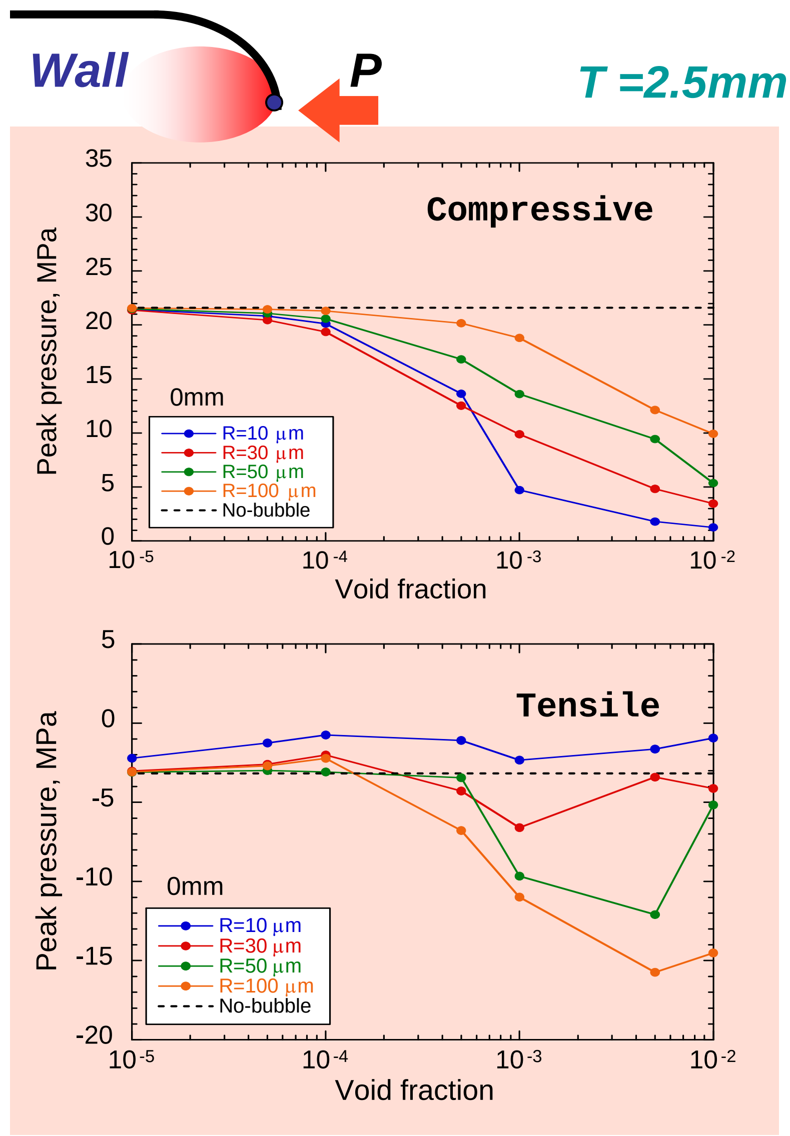
**In-situ Target Study by LDV & Sound**
**"PIE" is important**

Sound !

音響

# Compressive and tensile peak pressure




Compressive pressure peak related to thermal expansion is absorbed well at higher than $10^{-3}$ Vf.
Tensile pressure peak is attenuated by small bubbles at even lower than $10^{-4}$ Vf.

# Mitigation techniques for damages due to pressure waves

**Protection for beam window**

Surface improvement: Kolsterizing, Plasma N&C

Flowing effect

Gas-curtain

**Reduction of pressure waves**

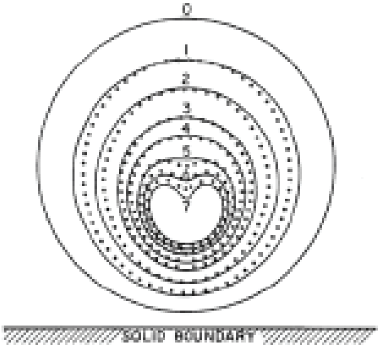
Micro-bubbles injection

Flattening beam profile

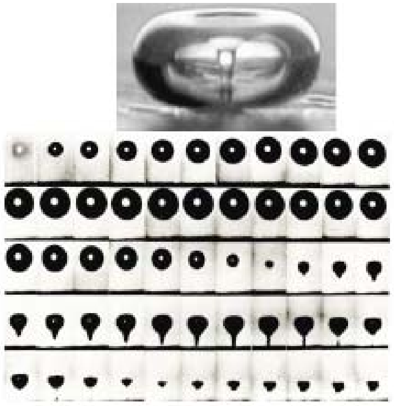
# Micro-ject direction depends on boundary condition

**Solid boundary**

**Jet to solid**




Lauterborn, W. and Bolle, H. (1975). Experimental investigations of cavitation bubble collapse in the neighborhood of a solid boundary. *J. Fluid Mech.*, 72, 391--399.

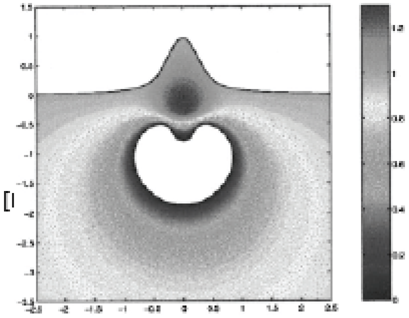


Implosion Phenomena
photos by Larry Crum

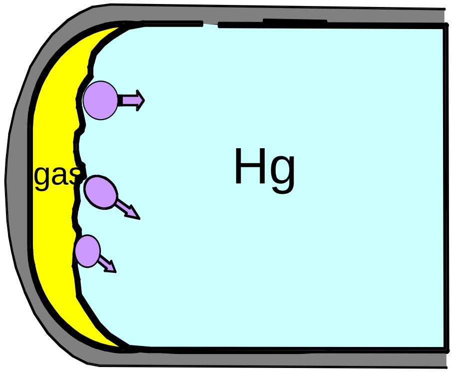
**Free boundary**

**Jet to liquid**

Numerical Simulation

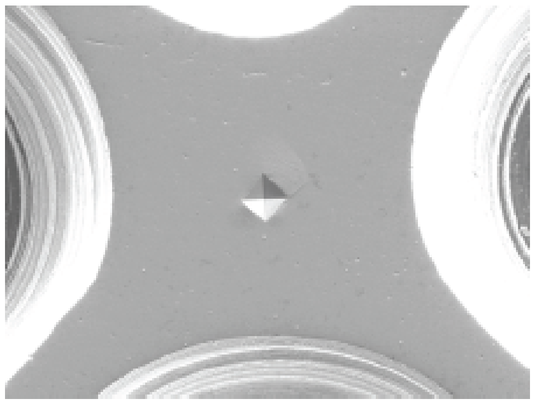


R. B. Robinson, J. R. Blake, T. Kodama, A. Shima, and Y. Tomita, 2001. Interaction of cavitation bubbles with a free surface, *J. Appl. Phys.* 89, 8225.



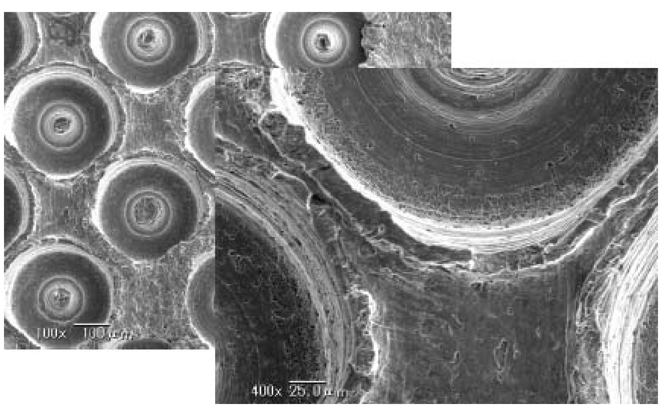
# Gas Wall Results at WNR2008

No discernable damage was detected.

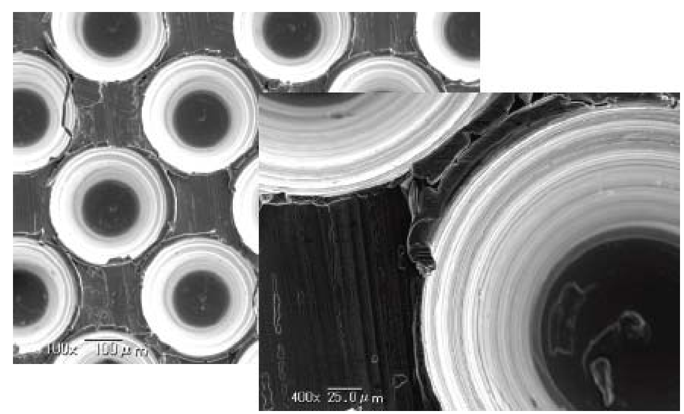


## MIMTM $10^6$ pulses

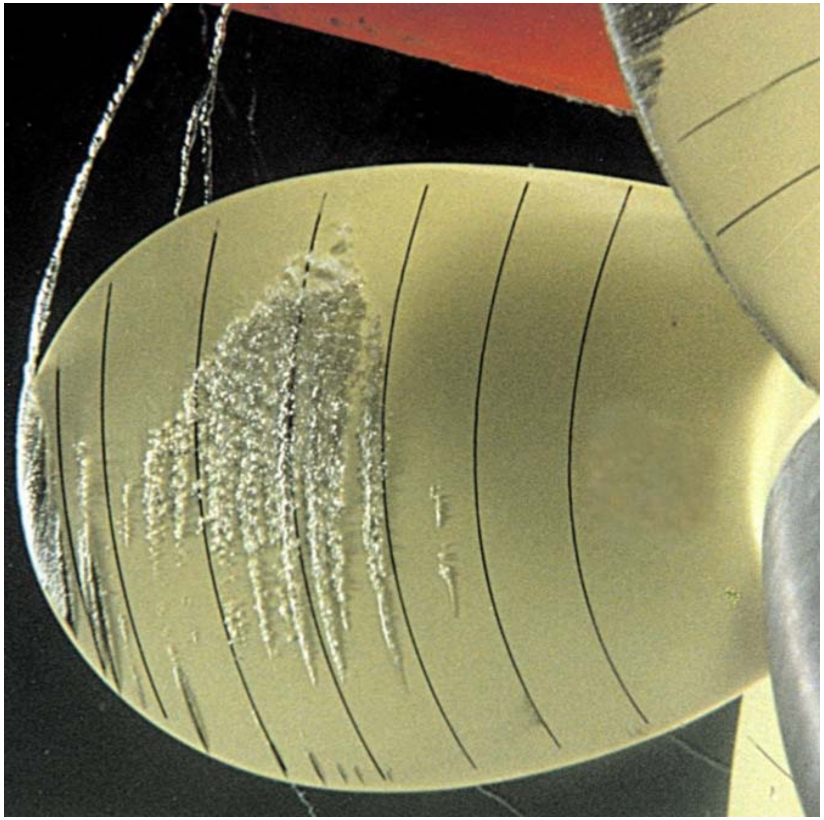
No-curtain

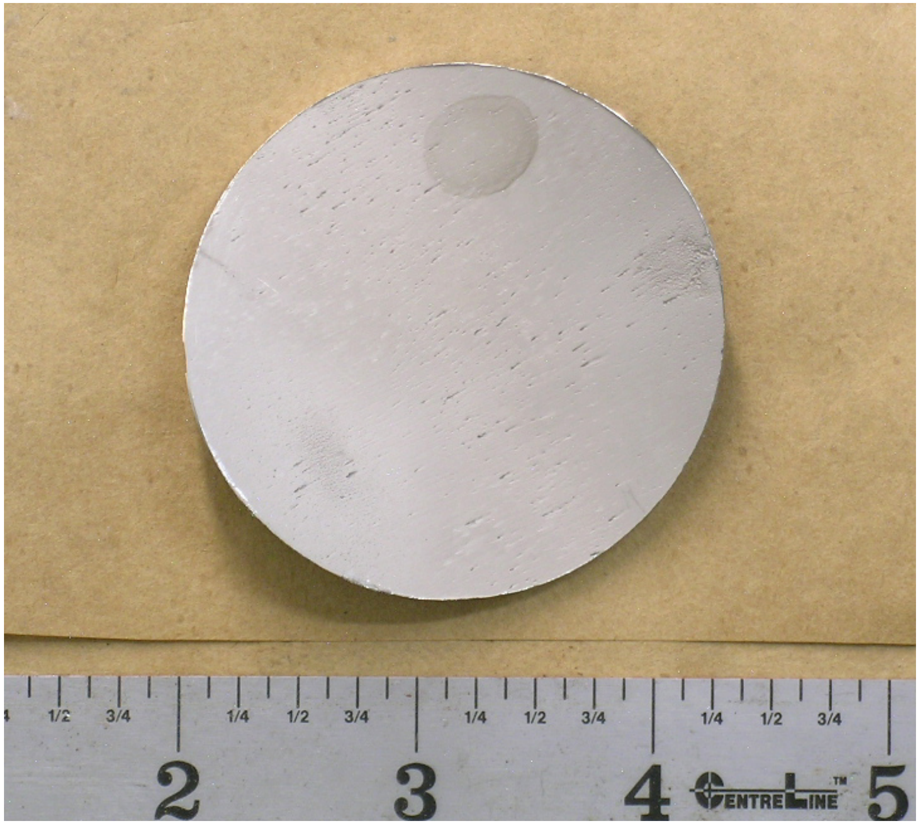


Gas-curtain



# Effect of strong flow on damage morphology ?






**Narrow channel at 2 m/s ?**

# Flowing effect on bubble collapsing behavior

QuickTime?遣
闘恚蓈社蒓敇贍
鼓潜敲蓅蒒蒨缮蔷濠侨董墙菂钦颣髒黔菑礐

QuickTime?遣
闘恚蓈社蒓敇贍
鼓潜敲蓅蒒蒨缮蔷濠侨董墙菂钦颣髒黔菑礐

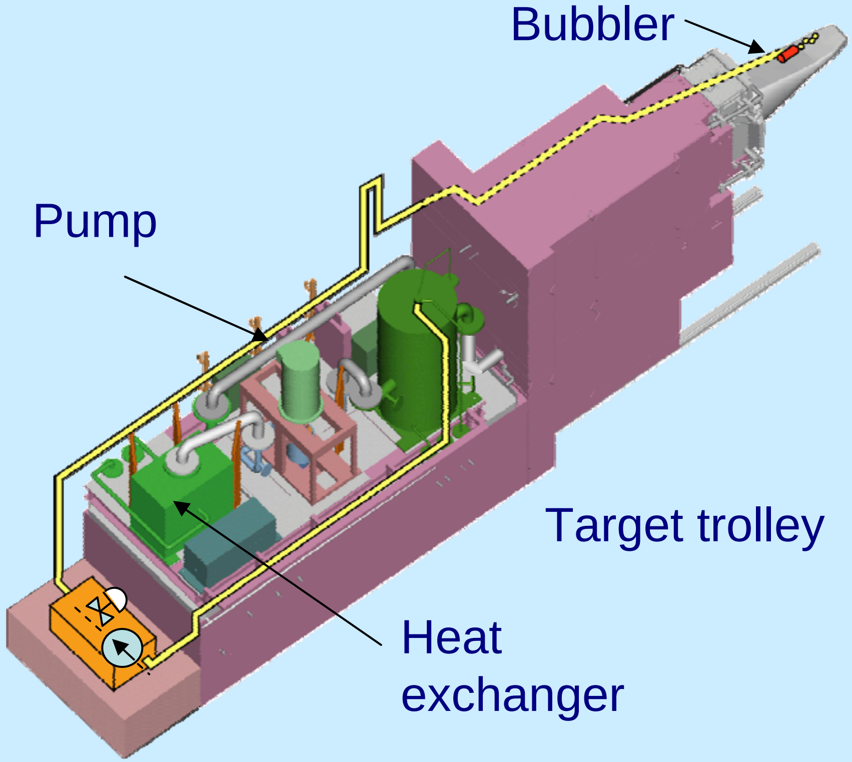
**Flowing velocity**

**Stagnant**

# Improvement in target system

## Gas supplying system

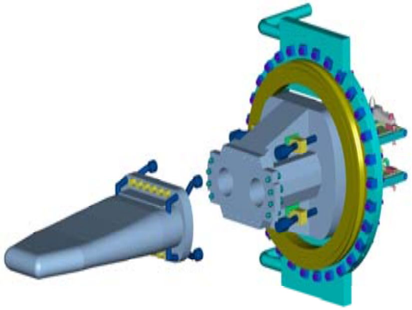
to control gas pressure and flow rate

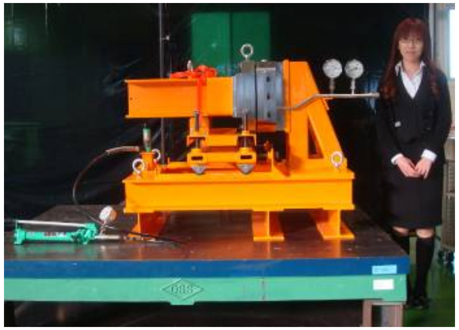


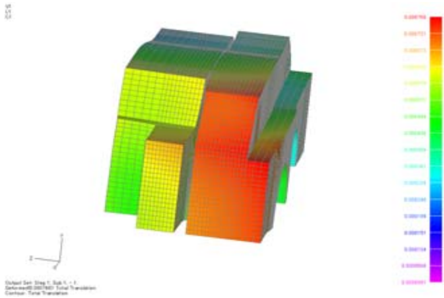

Element component tests will be carried out in water loop. Concept design is being made by a company.

## Separate-type compact target

to reduce waste volume and install bubblers



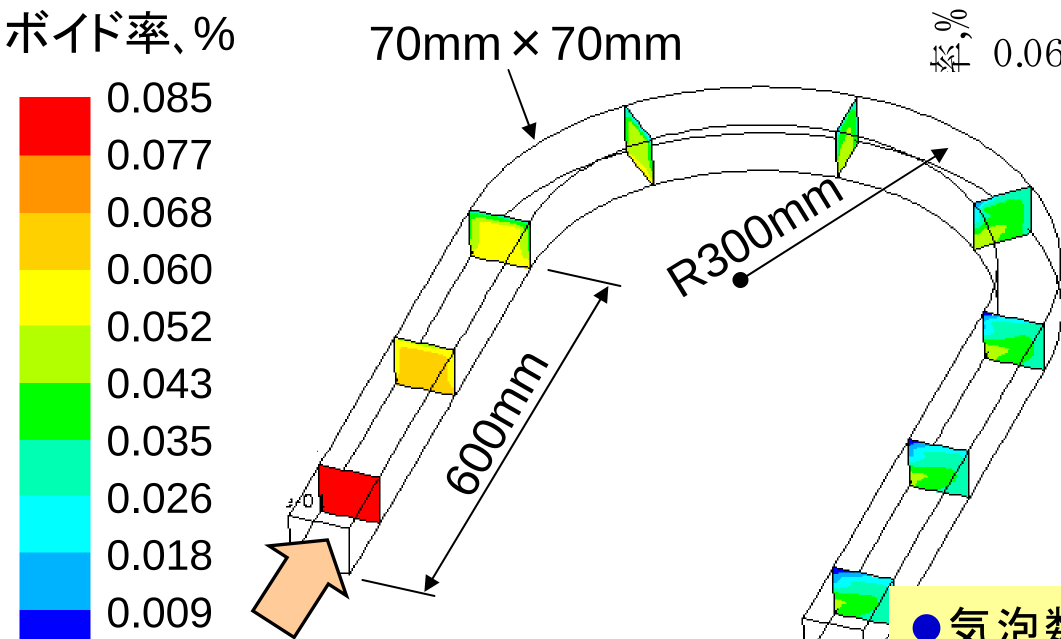




Seal test was carried out using flange with multi-hole: inlet and outlet pipes for Hg, He and cooling water.

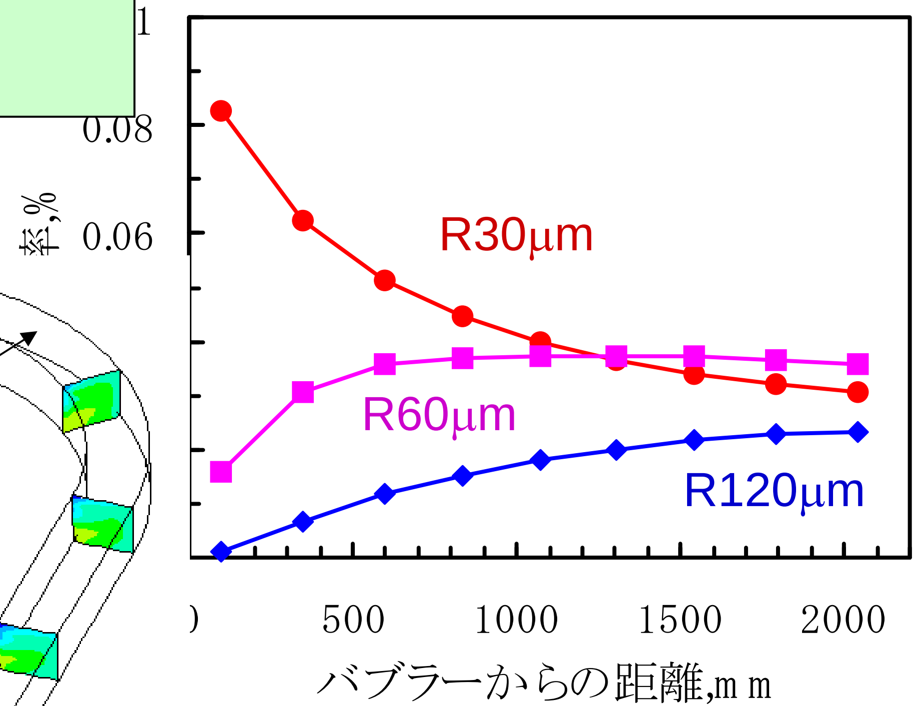
# 単純モデルによる合泡評価

| 解析条件 | ●気泡流動：Population Balanceモデル<br>●初期気泡半径：30μm<br>●注入量：水銀流量の0.1%<br>●合泡・分裂を考慮 |
| --- | --- |




水銀流速　　：1m/s
気泡ボイド率：0.1%

気泡の合泡とボイド率の変化




- 気泡数の多い初期は、合泡が活発である
- 合泡により600mm下流ではR30μmの気泡は半分になるが、R60μmと合わせると尚0.08%のボイド率となる。