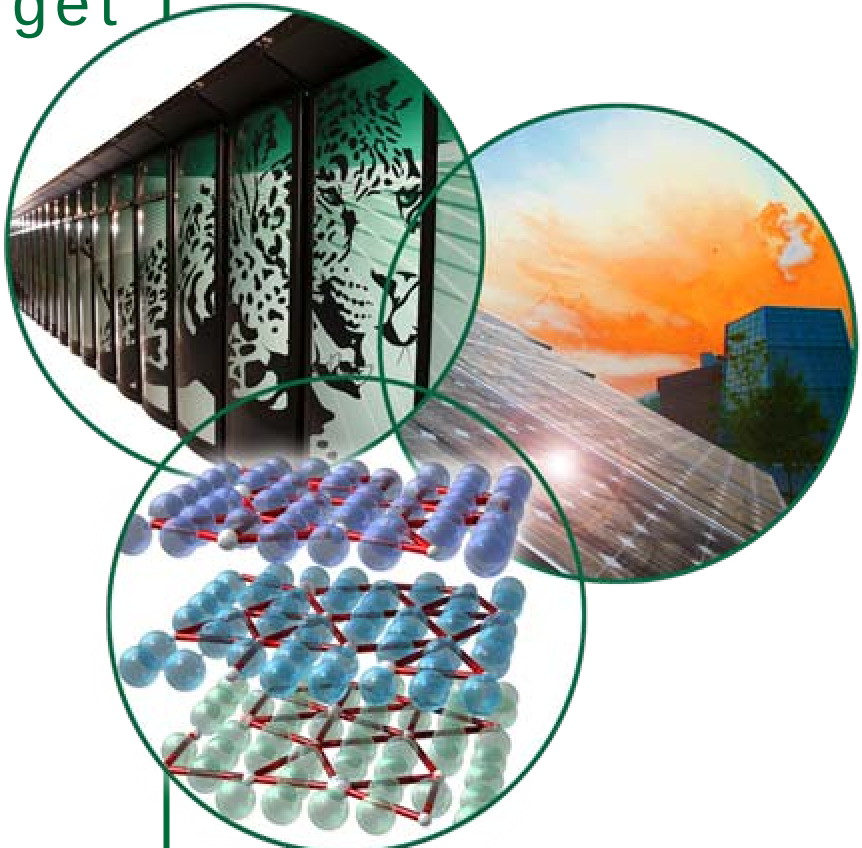
10th International Workshop on Spallation Materials Technology
October 18-22, 2010, Beijing, China

R&D on Mitigating Cavitation Damage in the Spallation Neutron Source Mercury Target



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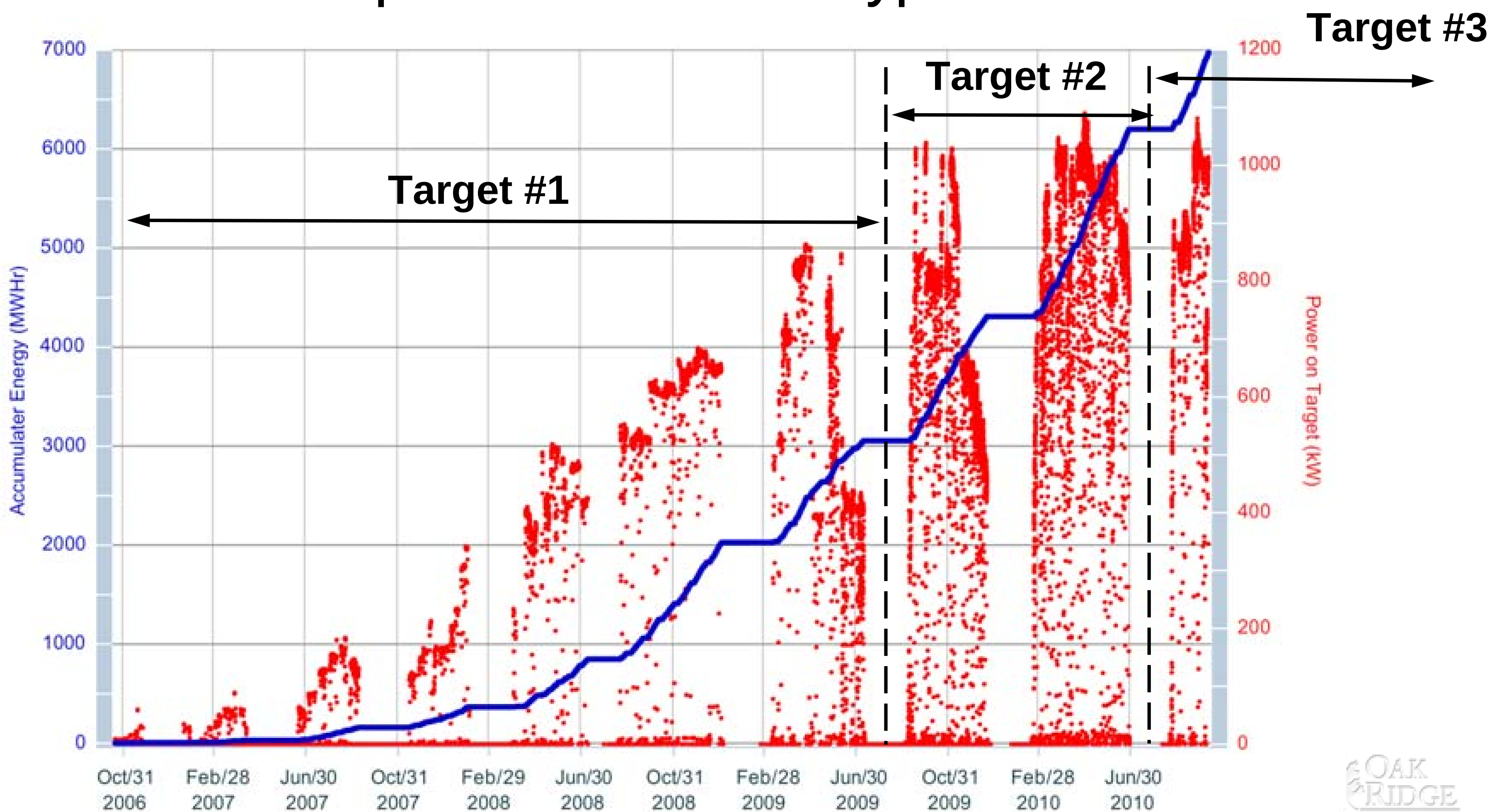
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Worst case scenario for severely shortened target life has not occurred

- First two target modules were run to more than 3000 MW-hrs
- Operation at MW power level is now typical



Focused goal of the R&D effort

- Develop sufficiently effective damage mitigation technologies such that cavitation is not the life limiting mechanism for the SNS mercury target – for any future beam power (2+ MW)

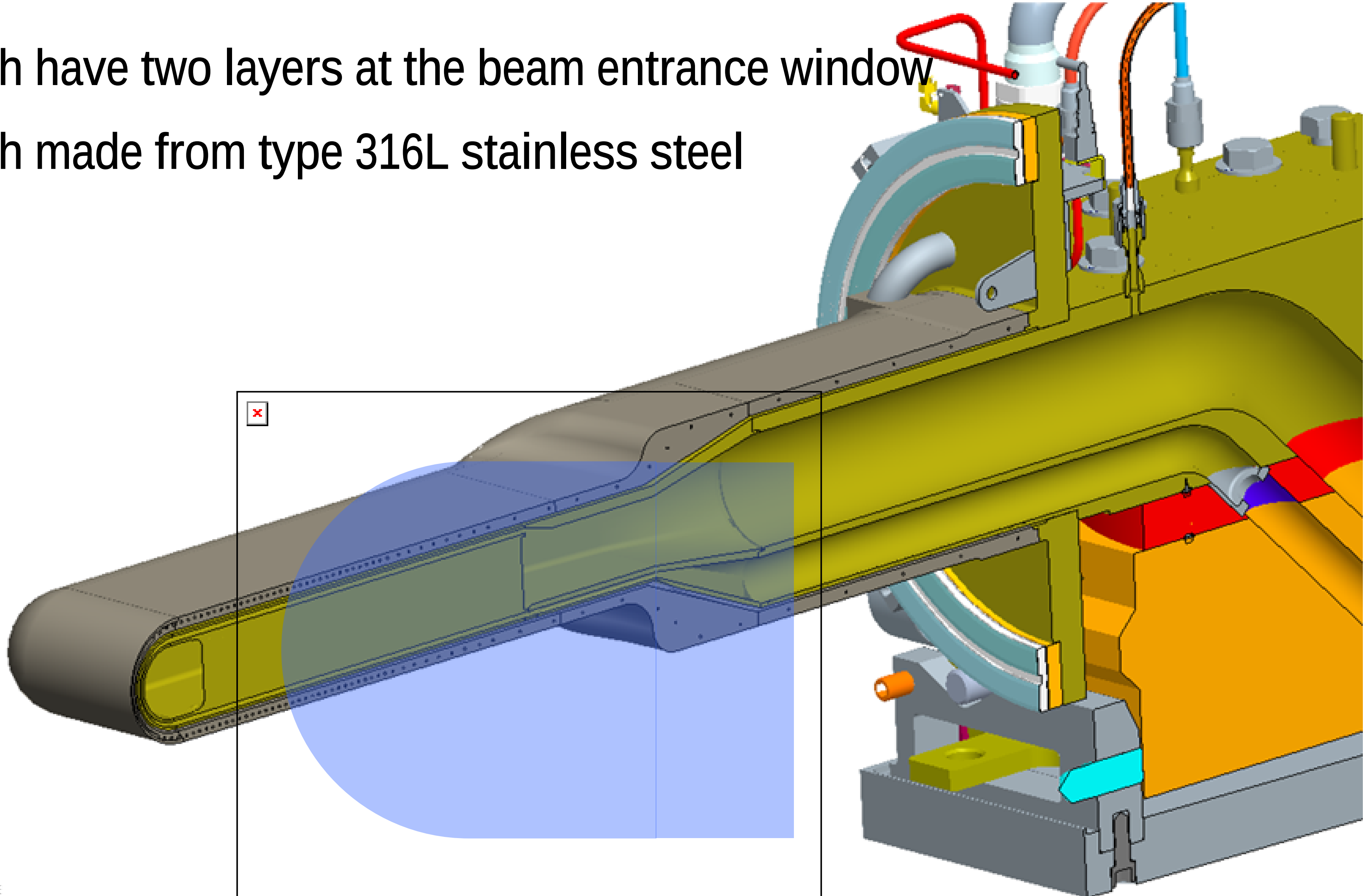
Elements of the effort

- Experimental, simulation and theoretical activities
  - Five full time and ~12 part time staff at ORNL
  - Subcontracts with universities and industries
  - Collaborations with JPARC and RAL
  - and …

P I E

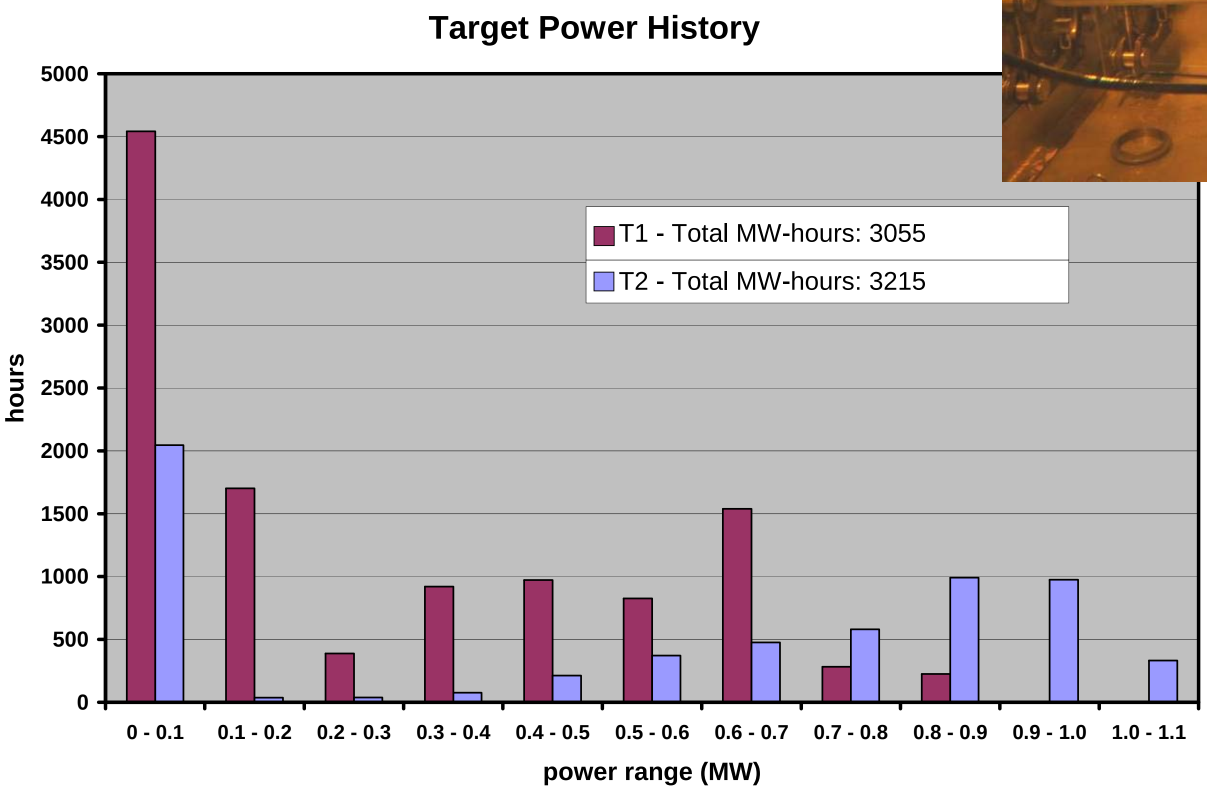
SNS Mercury Target Module —
Mercury vessel surrounded by a water-cooled shroud

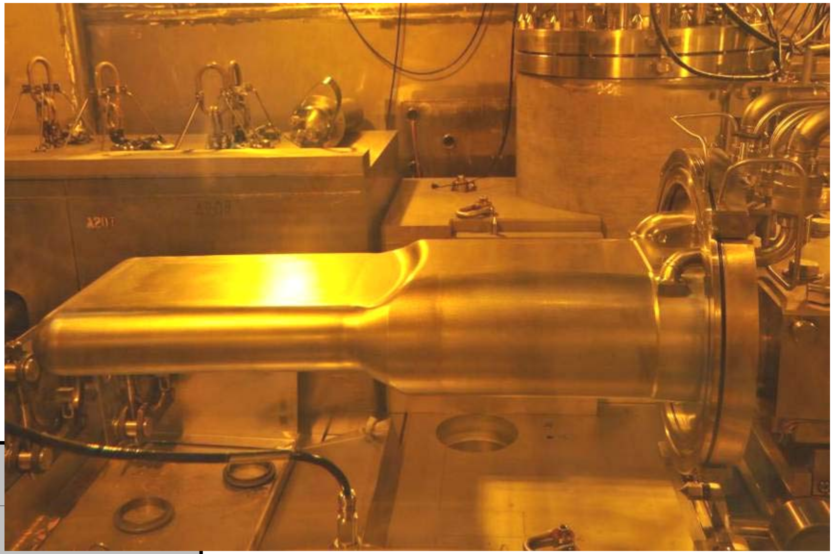
- Both have two layers at the beam entrance window
- Both made from type 316L stainless steel



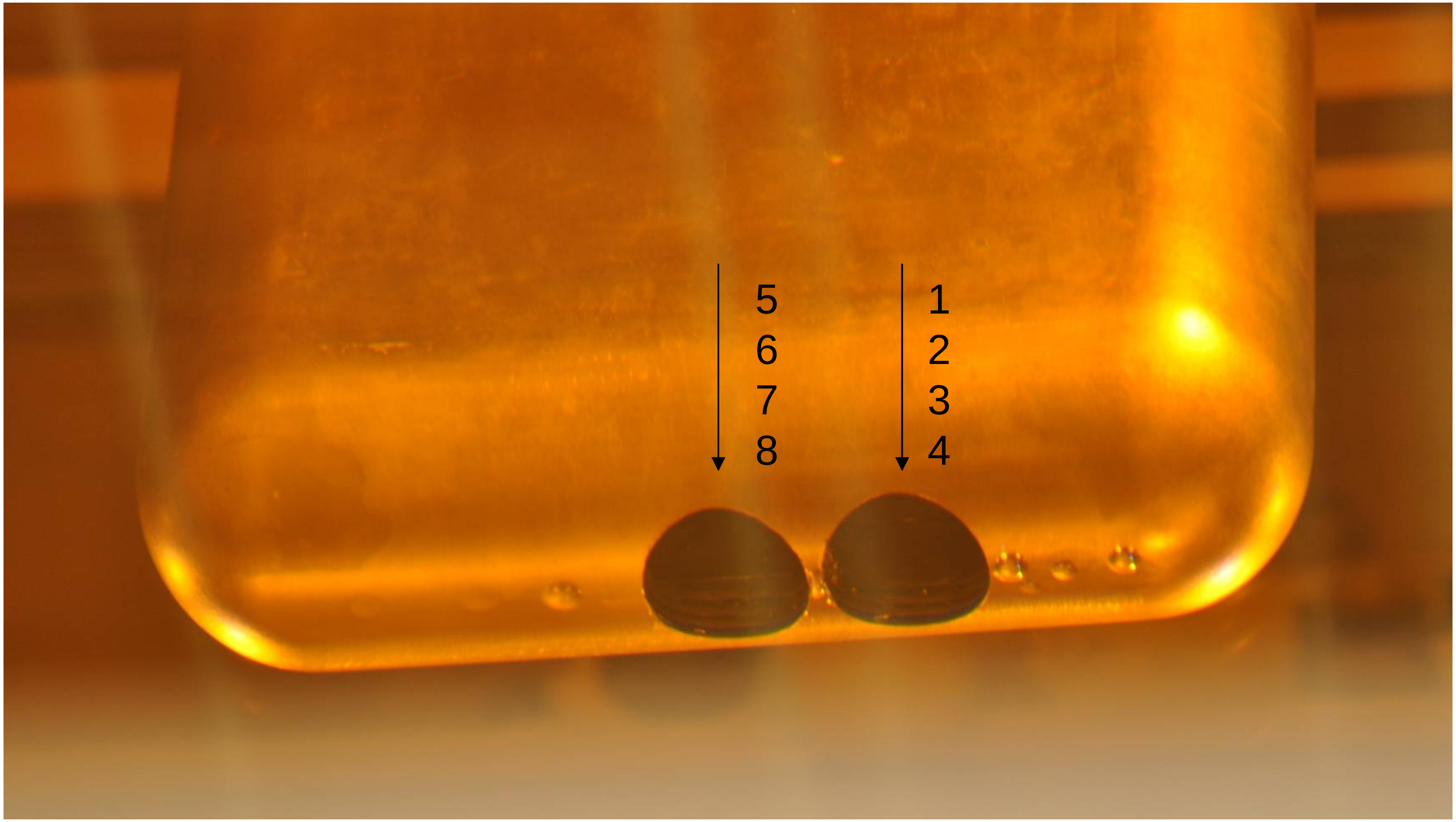
Target #1 was replaced in July 2009 during a planned maintenance period

- No indications of a leak or any problem
- Radiation damage was estimated to be 7.5 dpa





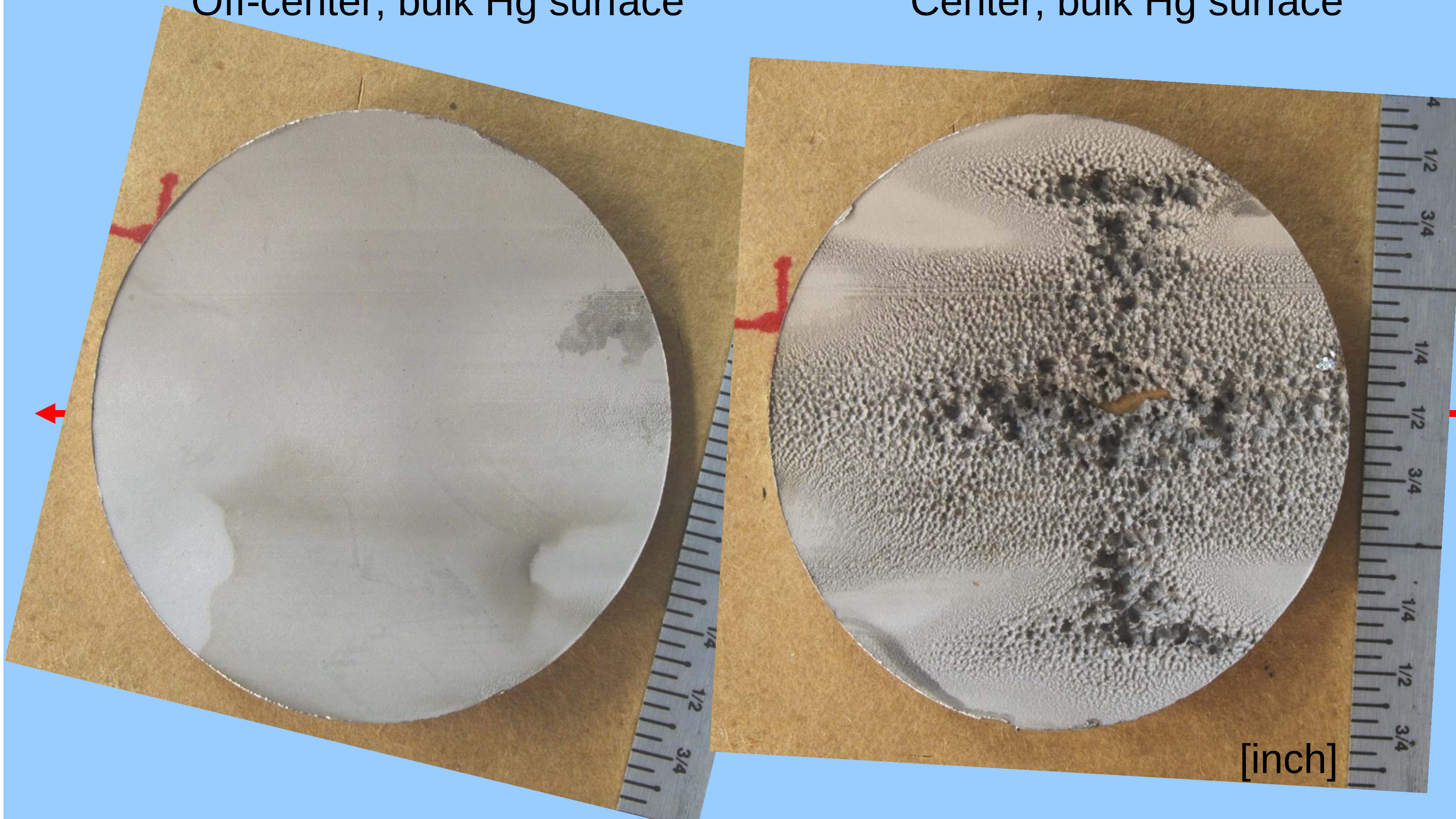
Target #1: Two hole cuts were made
4 layers each cut location
Specimens # 1, 5, 6 and 7 sent to Babcock & Wilcox for detailed examination and analysis



Worst damage was in inner mercury vessel window, center location, surface facing bulk mercury (#5)

Off-center, bulk Hg surface

Center, bulk Hg surface



Specimen diameter: 60 mm
Original thickness: 3 mm

PIE presentation by David McClintock

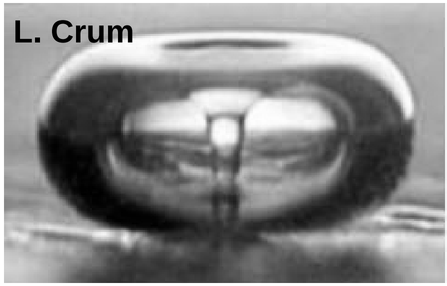
Two *primary* mitigation approaches:

- Protective gas walls can isolate the vessel from the damaging effects of cavitation bubble collapse

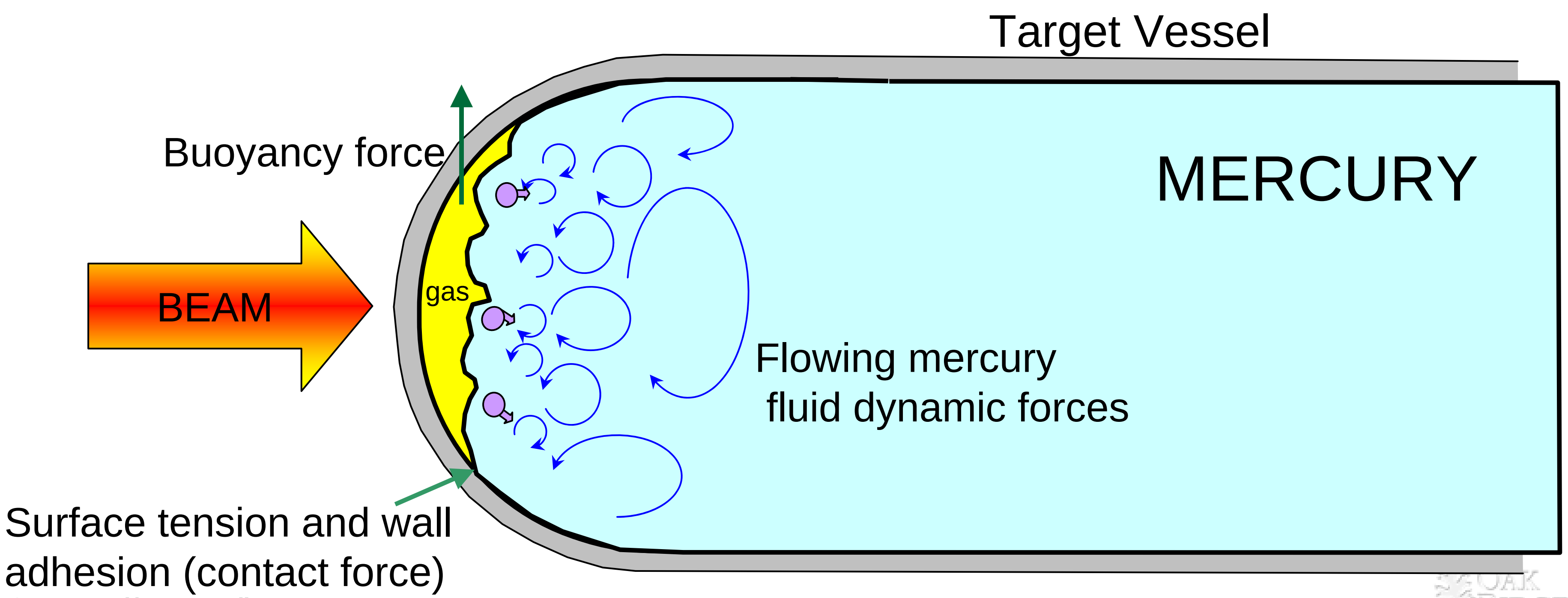
- Small gas bubble injection can absorb the initial pressure pulse, reduce cavity growth, and attenuate pressure wave propagation
  – Volume fraction: requirement remains uncertain
  – Bubble diameters ca. 100 μm (also uncertain)

• Alternate vessel materials and protective surface treatments have been studied
• Kolsterising® process adopted to enhance cavitation damage resistance

Gas wall mitigation



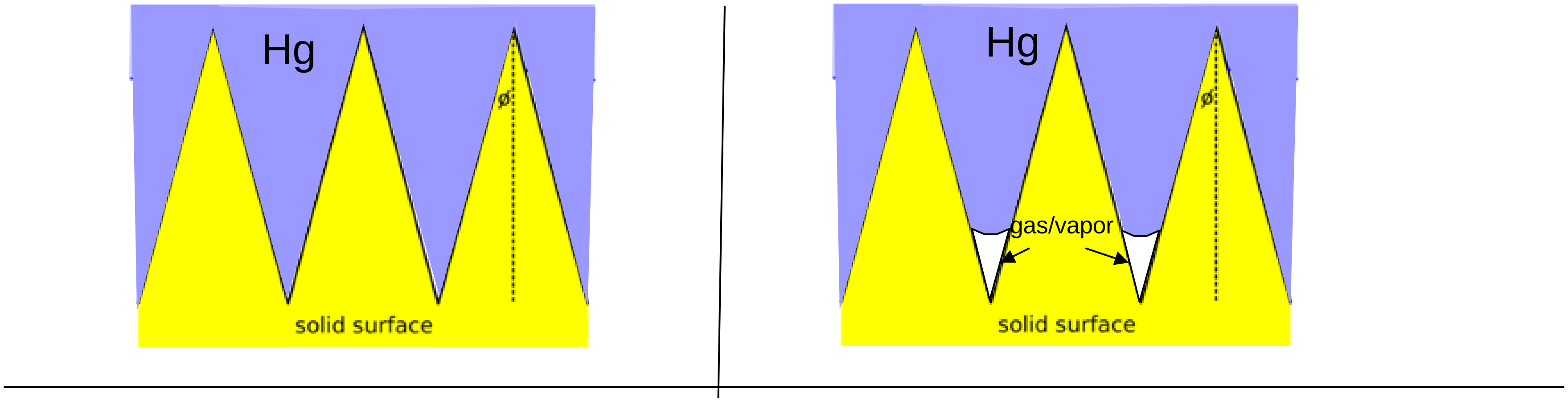
- Damage mechanisms from cavitation:
  - High speed fluid jets running into wall surface
  - Shock waves from bubble collapse
- A gas layer between the wall and the mercury can reverse the jets and protect the wall from shock waves



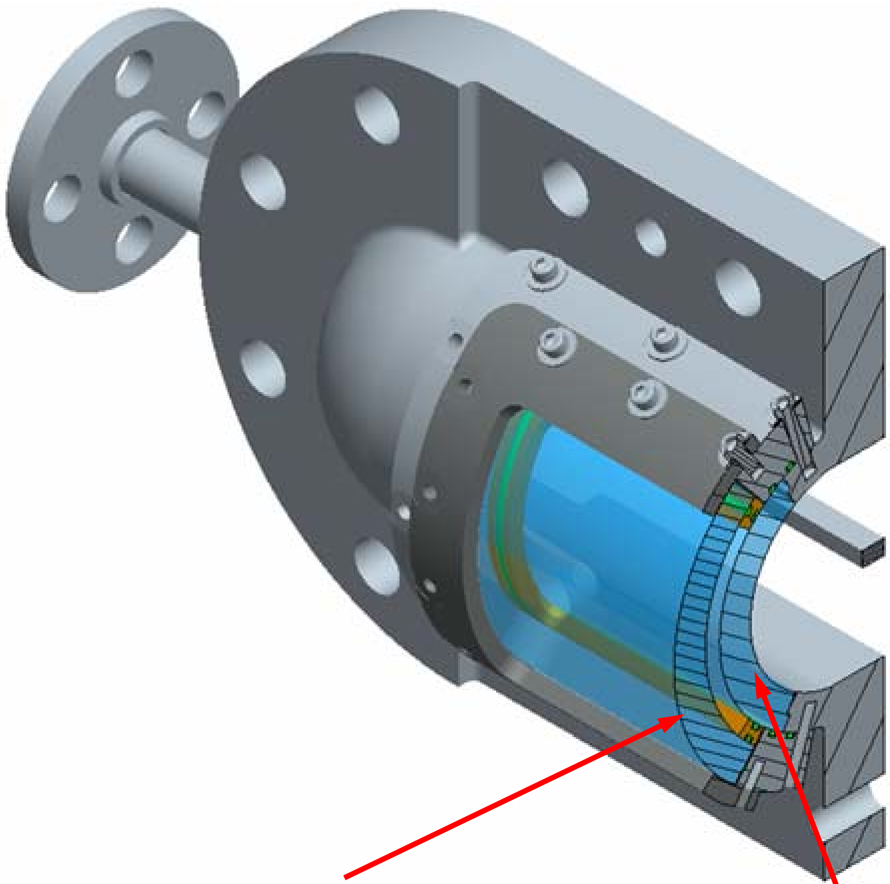
Three gas layer approaches

- Free Gas Layer – gas is injected locally on the inside of the target wall
  - Very hard to get good coverage with SNS flow configuration
  - Possibly suited to sweeping mercury flow
- Porous Wall Gas layer – a porous layer of material is used to distribute gas across the vulnerable boundary
  - Mercury intrusion in a practical target operation very difficult to control and will lead to problems
- Surface texturing – features on vessel wall to enhance gas adhesion / holdup
  - Most promising with SNS flow configuration

Regimes of gas layer thickness

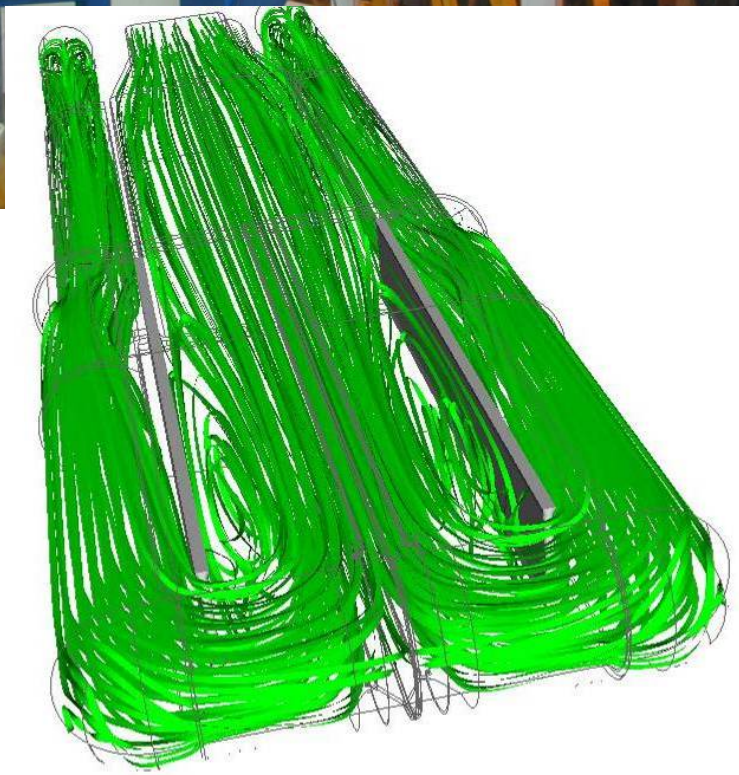


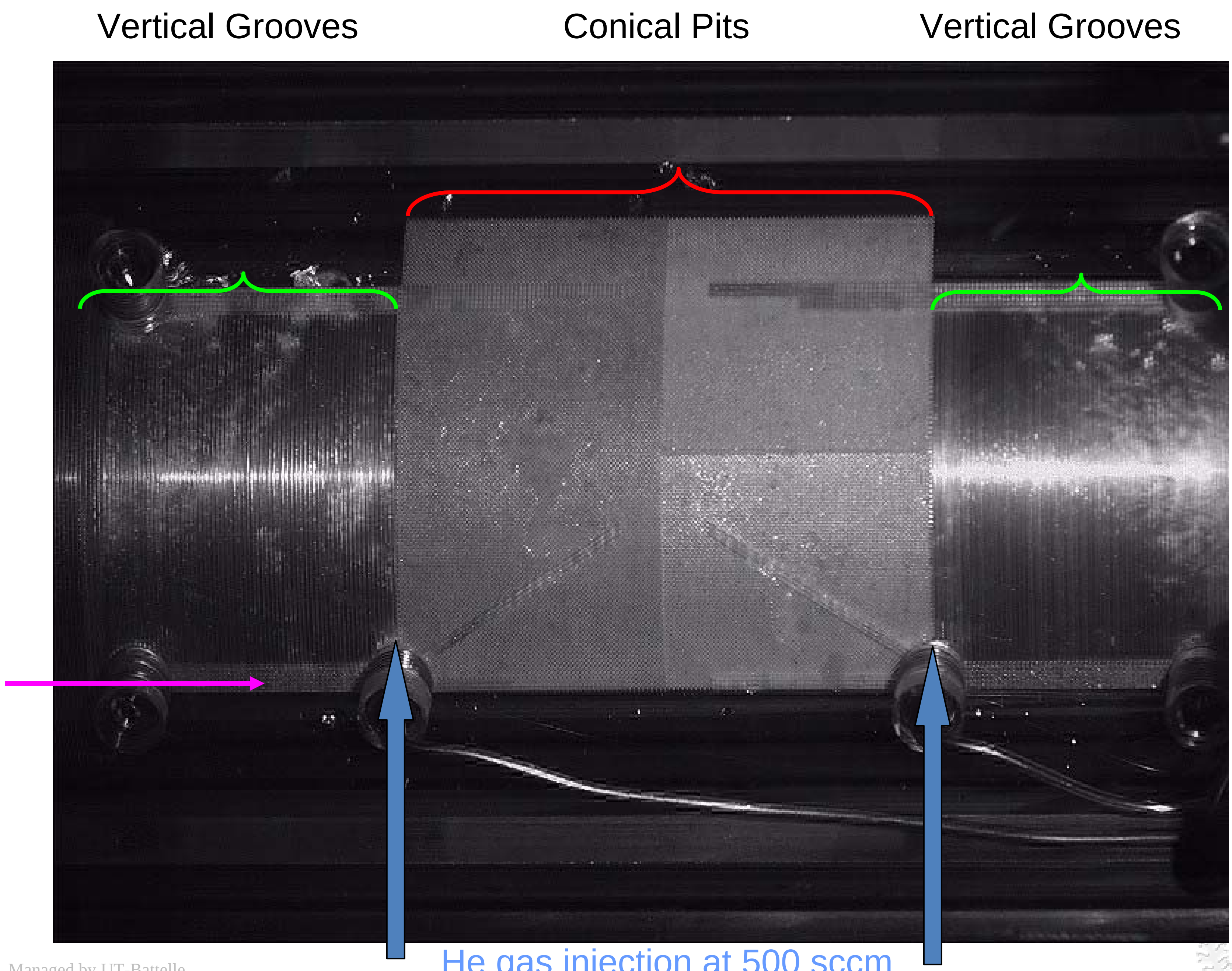
Target Test Facility with gas wall test section



Outer acrylic window

Replaceable test insert




Vertical Grooves
Conical Pits
Vertical Grooves
He gas injection at 500 sccm

Can this work?

- Will this provide effective damage mitigation?
  - Damage test experiment using JAEA MIMTM device was a failure
    - *Driving* pressure wave mechanism was defeated by introduction of gas in test chamber; control surfaces were not damaged
  - In-beam experiment at LANSCE – WNR* in 2008 indicated partial gas coverage with cone type texturing was very effective
    - Only 100 beam pulses
- What is the required area for gas coverage?
  - This depends on lessons from PIE

*LANSCE – WNR
Los Alamos Neutron Science Center
Weapons Neutron Research

The 2008 WNR experiment had two main areas of investigation

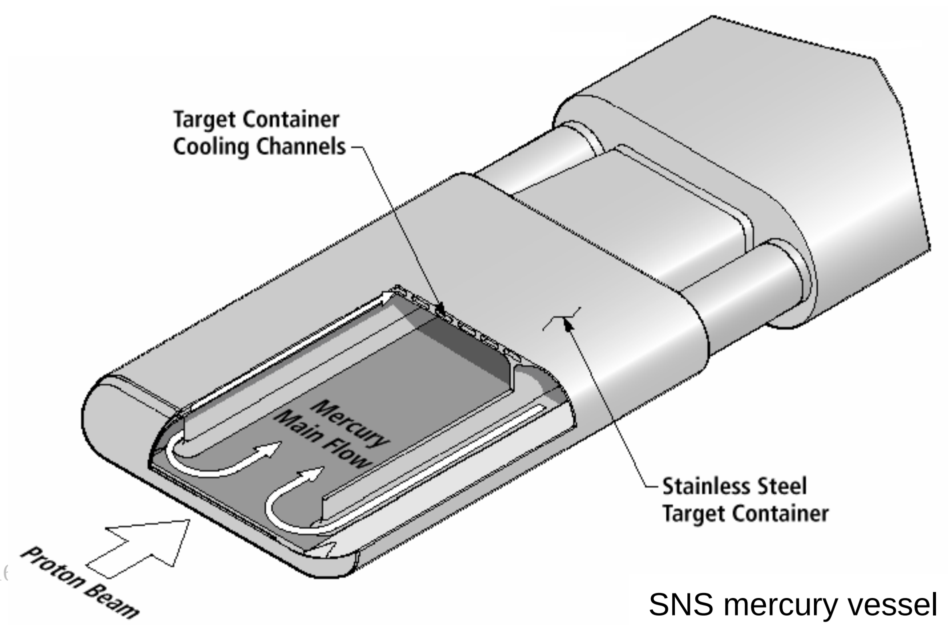
- Damage vulnerability of the SNS target cooling channel
- Damage dependence on beam intensity

- The experiment (sans the damage results) was described in detail at IWSMT-9 (J. Nucl. Mater. 398 (2010), p. 207-219)
- Results were presented at ICANS-XIX (paper in proceedings)

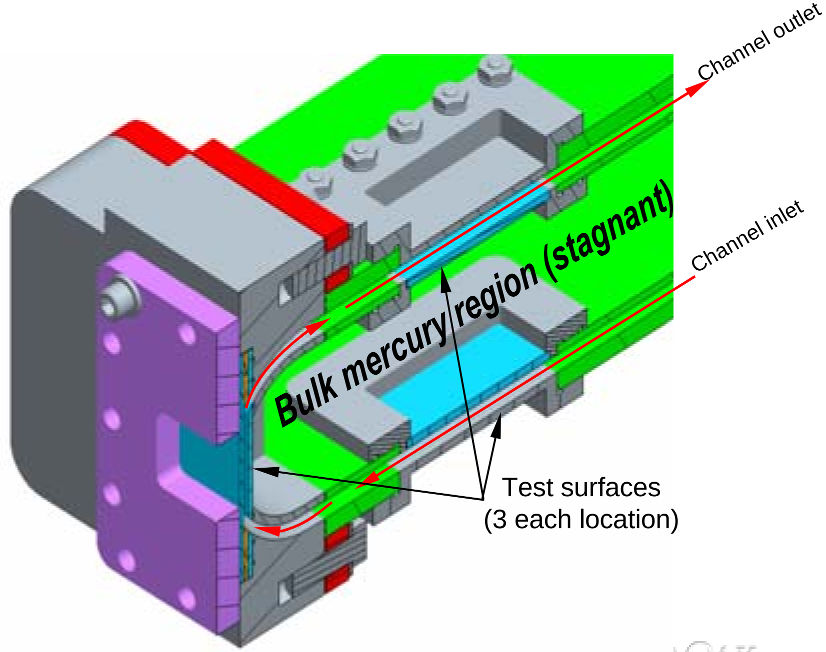
- Secondary objectives:
  - Gas wall mitigation with surface texturing enhancement
  - Long pulse test

Window Flow Vulnerability Test Loop (WFVTL) experiment

- Question: is a design change to SNS target to eliminate mercury channel necessary?
  - Previous in-beam test results for channel damage had indicated this region is especially vulnerable (high damaged area fraction)
- Investigated damage reduction vs. flow velocity
  - Previous in-beam test indicated damage *reduced by flow*

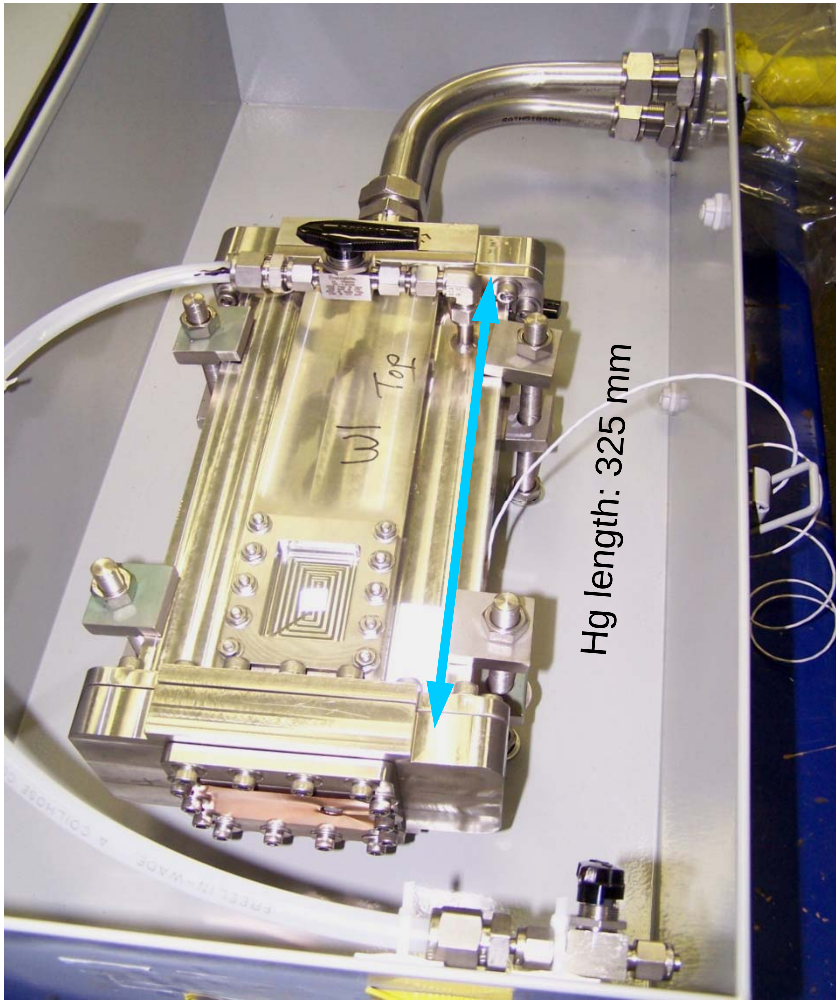


SNS mercury vessel



WFVTL target module section

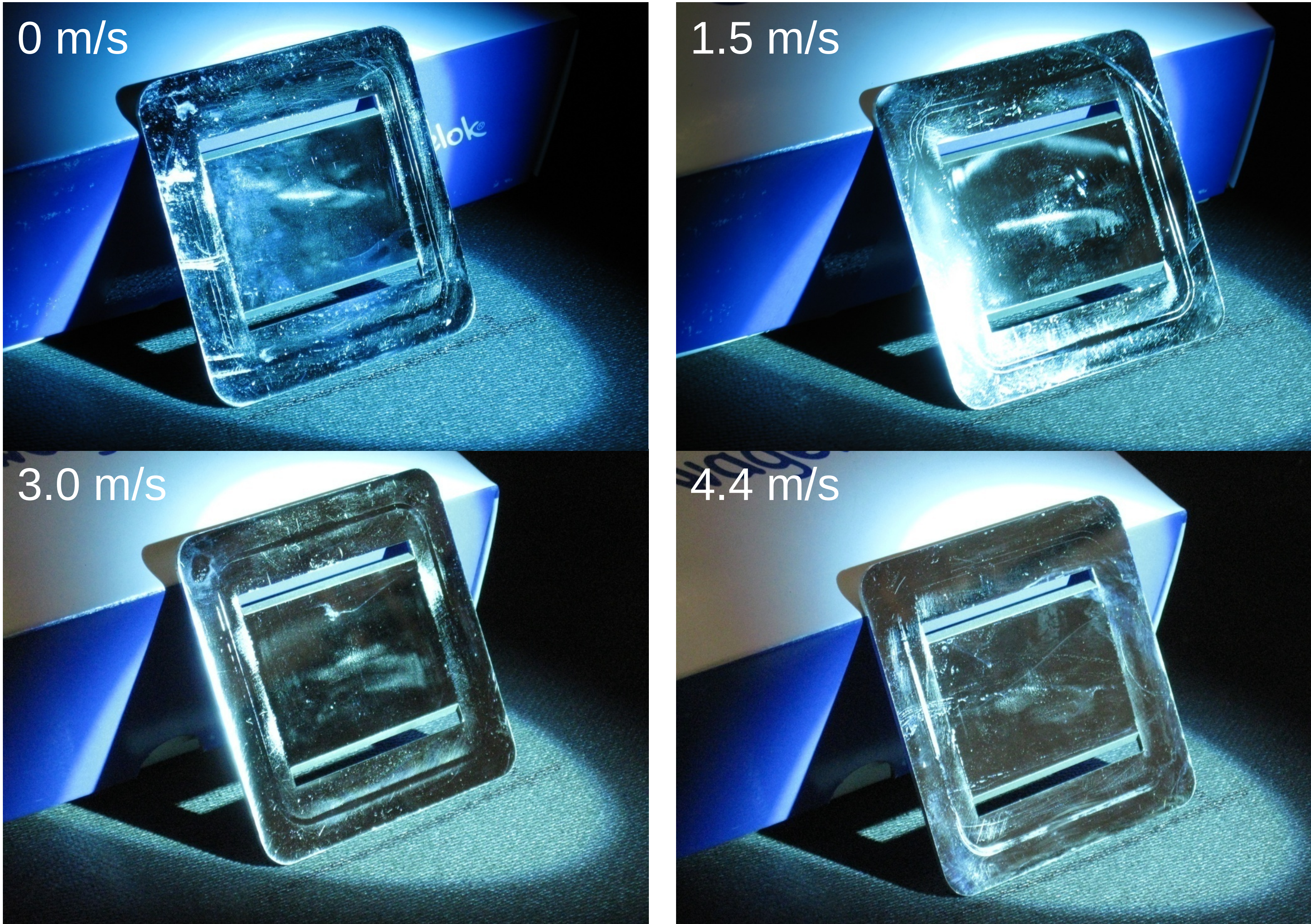
WFVTL target module and mercury loop



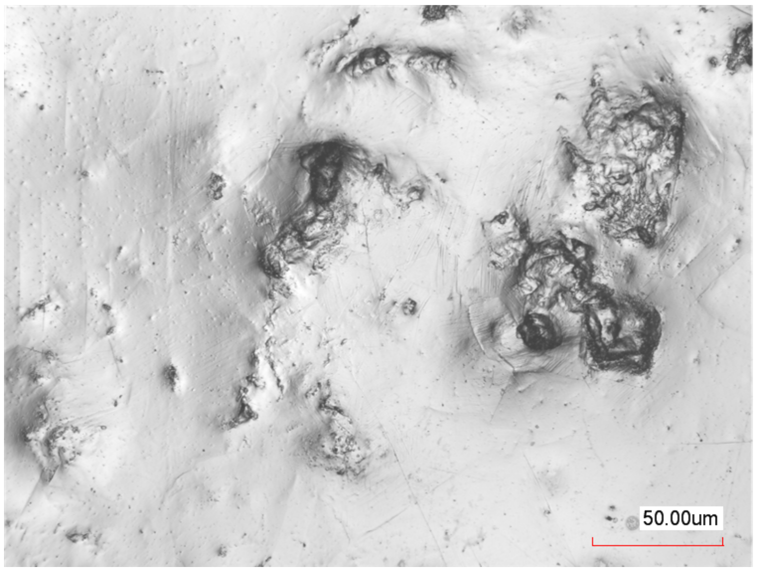
Test target module
Nine damage test surfaces

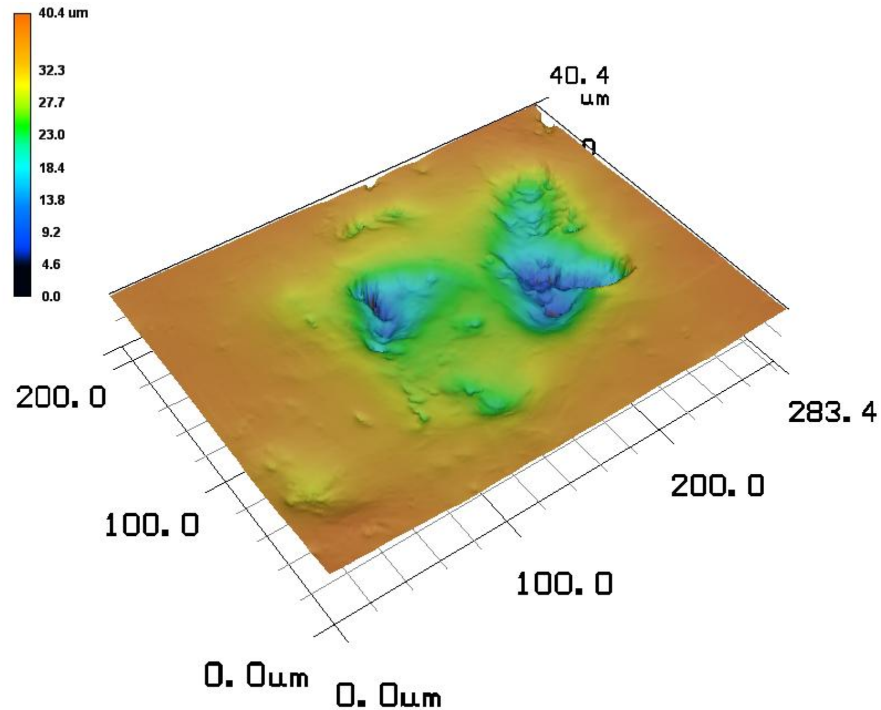
- Variable speed centrifugal pump was employed for channel flow speeds for up to 4.4 m/s
- Channel flow connection to pump loop via flexible hoses
- Target test modules were exchanged between conditions
- Bulk mercury volume was stagnant

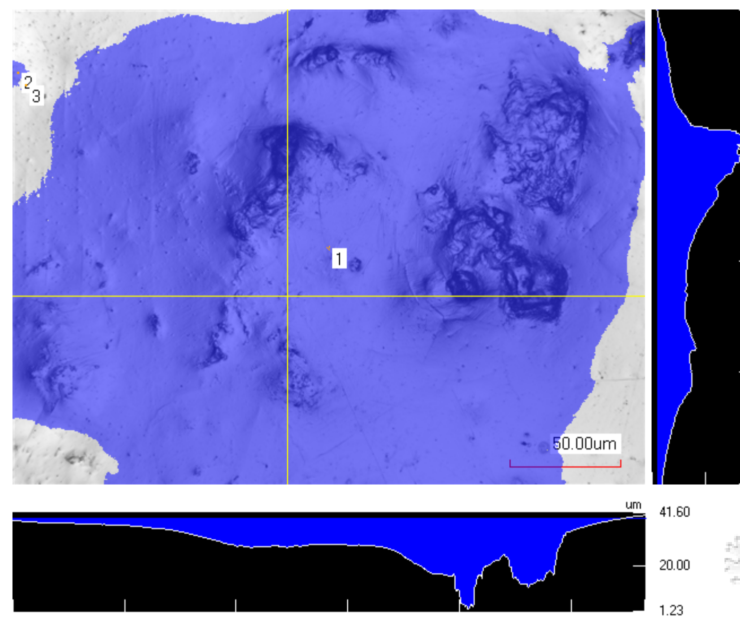
Front inside plate – channel side



W1 front bulk side example
(worst overall damage)







100 pulses

Based the in-beam experiment results:

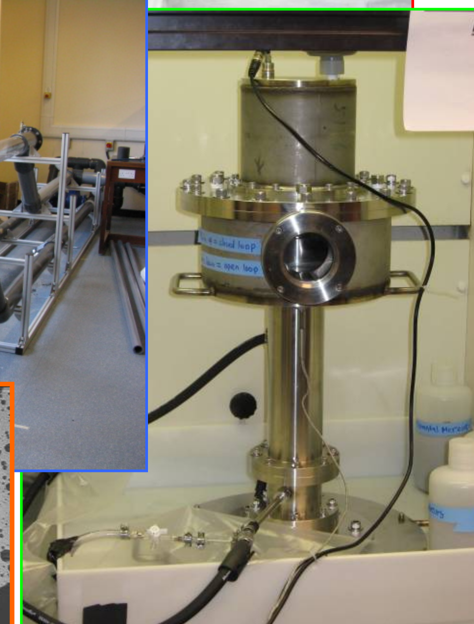
- Design changes to the SNS target to eliminate the mercury cooling channel – either by replacement with water or by bulk side cooling flow – were not recommended

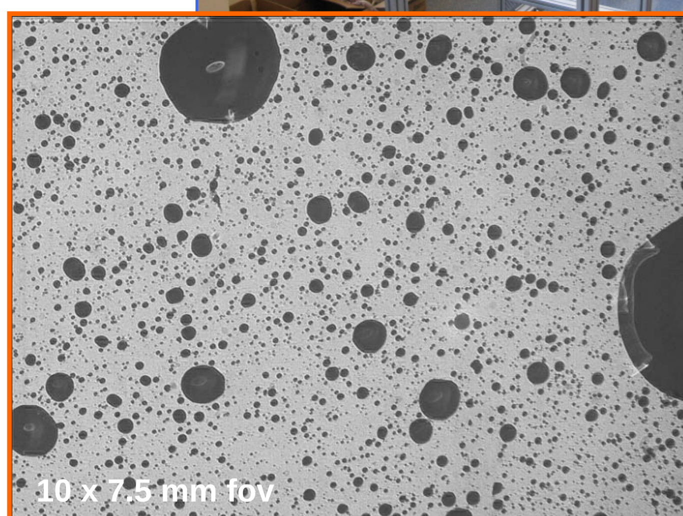
Observed damage in SNS target #1 was consistent with this experiment

- Bulk side surface damage is much worse than channel
  - *At the beam entrance window*
    - Other areas remain uncertain

Bubble diagnostics

- Dynaflow Inc's Acoustic Bubbler Spectrometer (ABS)
- Boston University's acoustic void fraction resonator
- Univ. of Southampton's acoustic void fraction diagnostic
- Proton radiography
- Medical ultrasound
- Optical (at view ports)



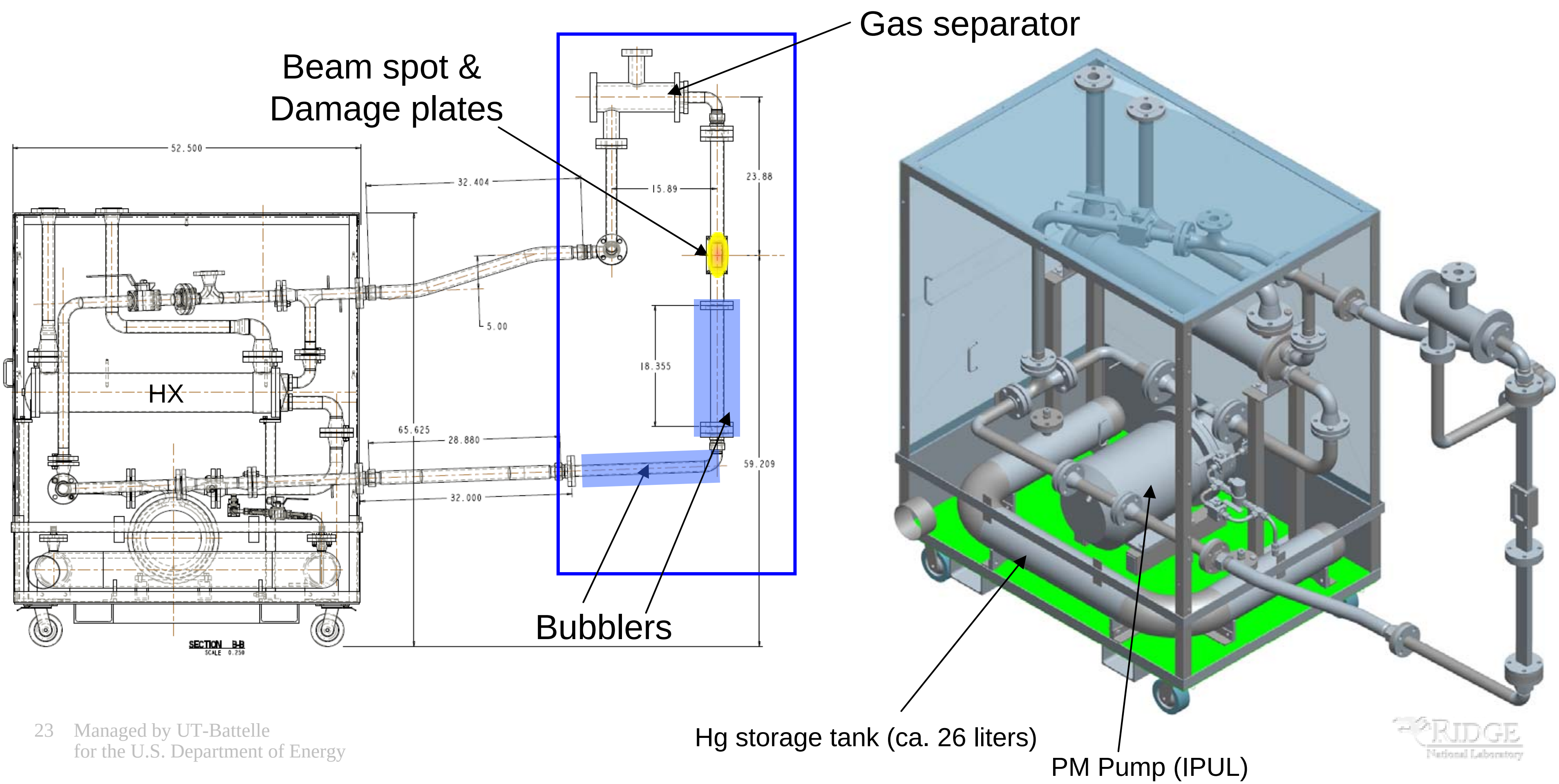


Next WNR experiment will focus on small gas bubble mitigation

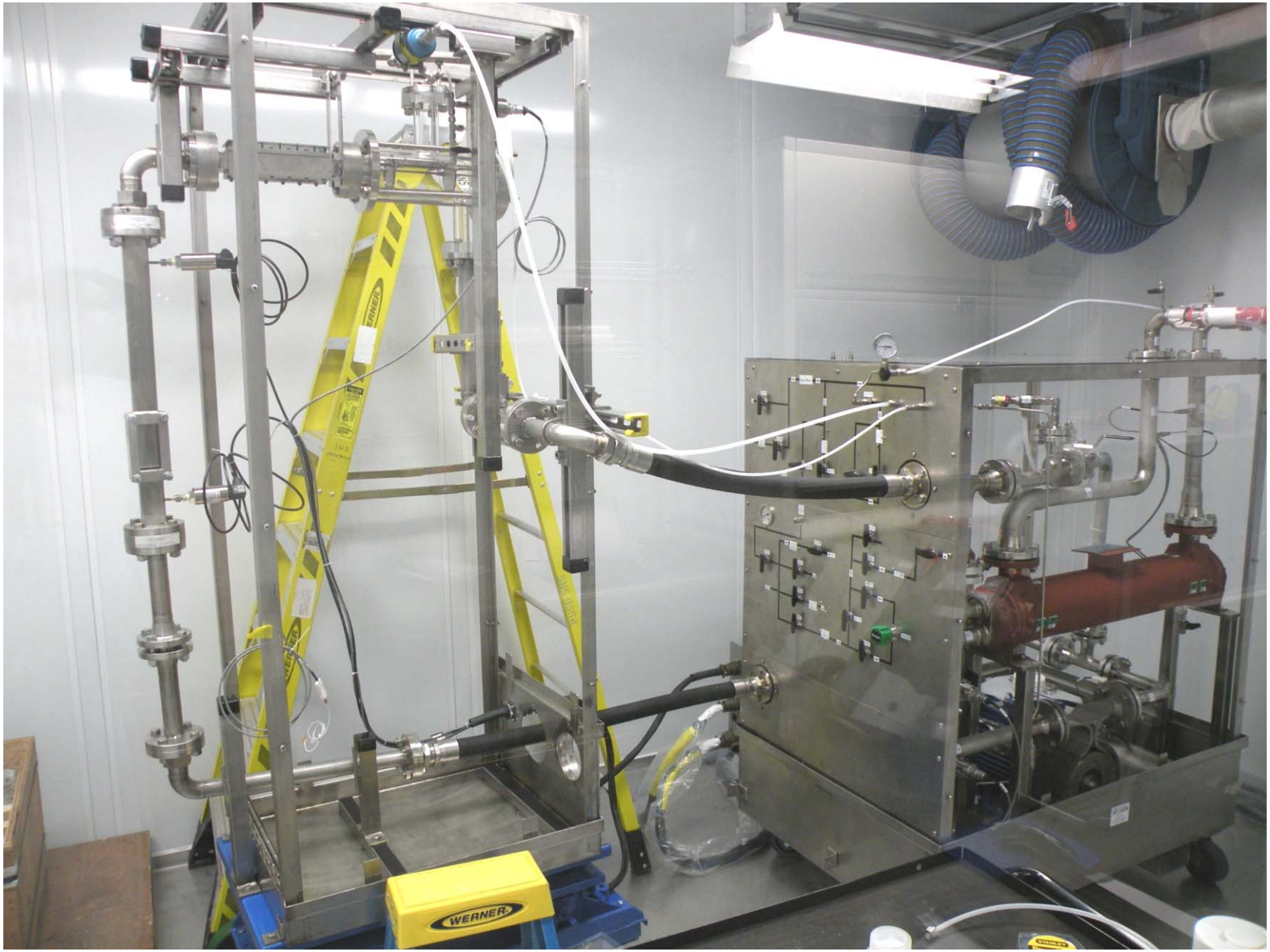
- Prior in-beam tests showed no better than 4x reduction in damage
  - Maybe ½ of that was from associated mercury flow
  - Bubble populations were not well characterized; bubbles too large
- Tests in MIMTM have shown ca. 15x reduction, but
  - Question regarding surface imposed pressure pulse, 0.5 ms rise time pressure vs. beam induced < μs rise time pressure

A new mercury test loop: Multi Bubbler Test Loop (MBTL)

- Candidate bubblers are being evaluated for producing populations of potentially greater mitigation efficacy

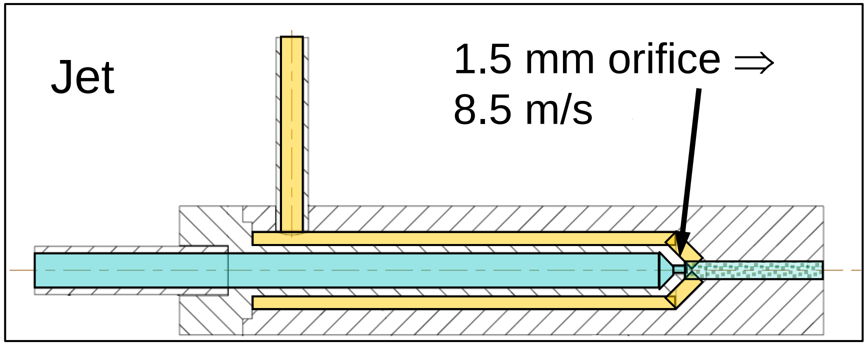


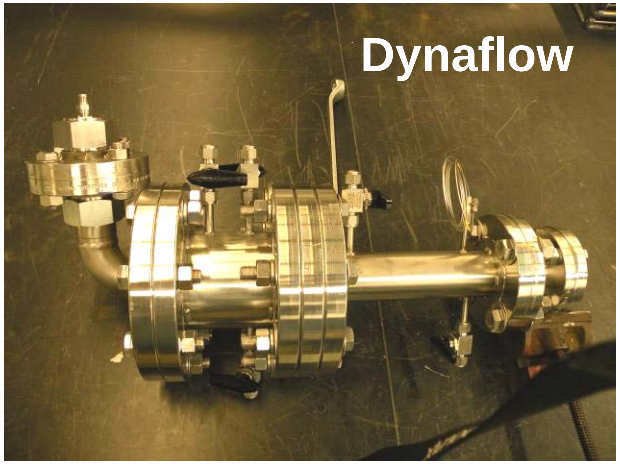
MBTL in vapor controlled lab space

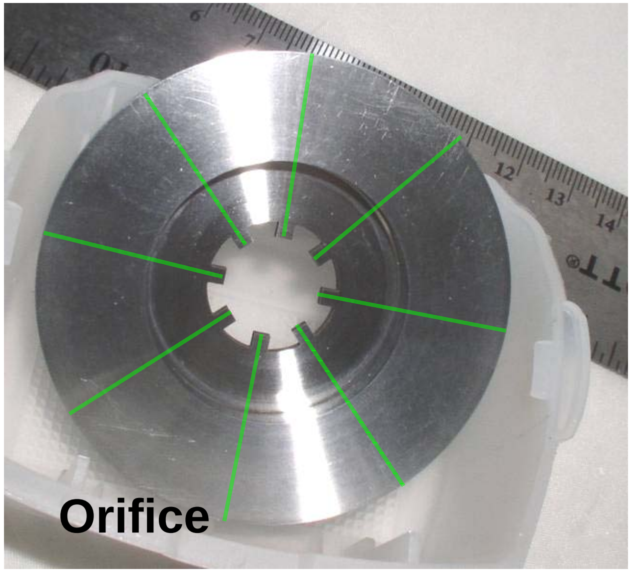


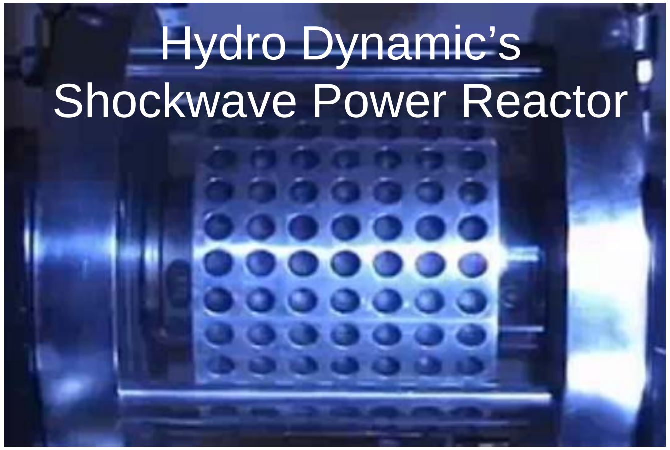
Bubble generators

- Flow channel miter bends
- Univ. of Tennessee swirl bubblers

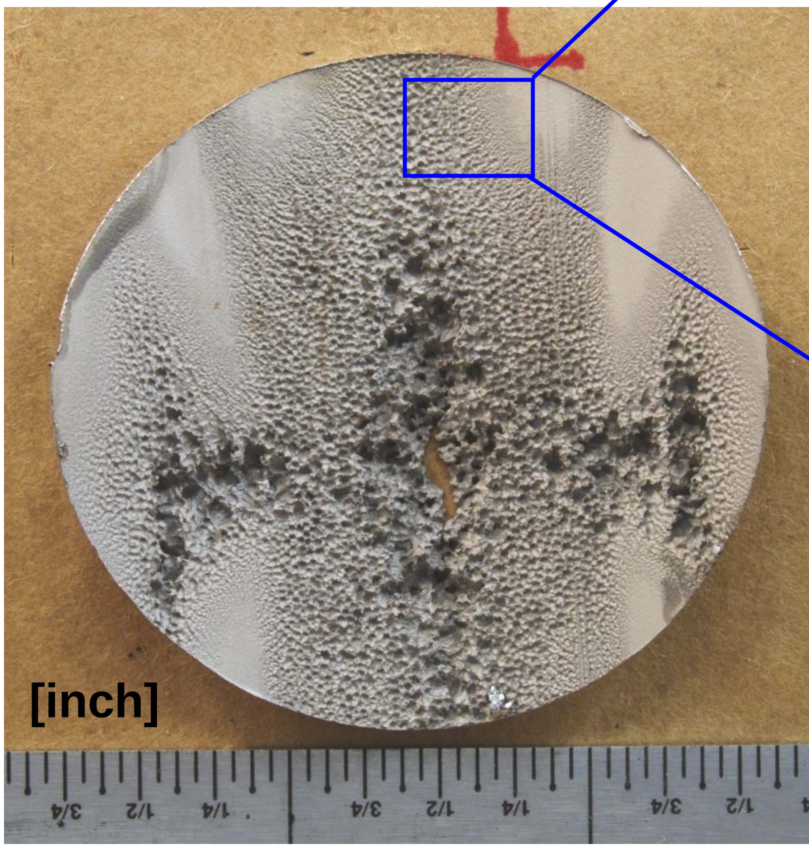


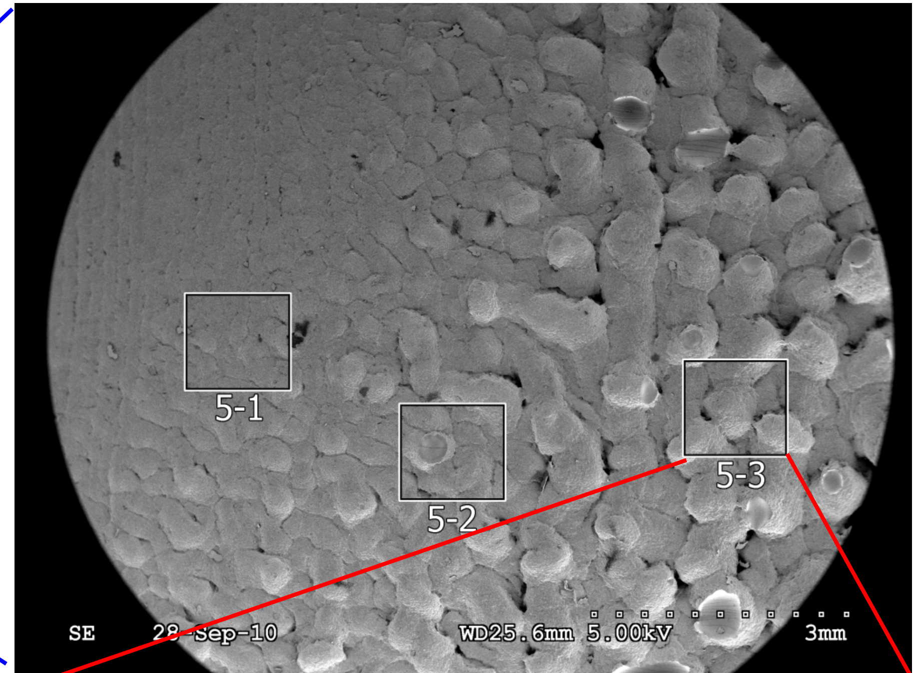


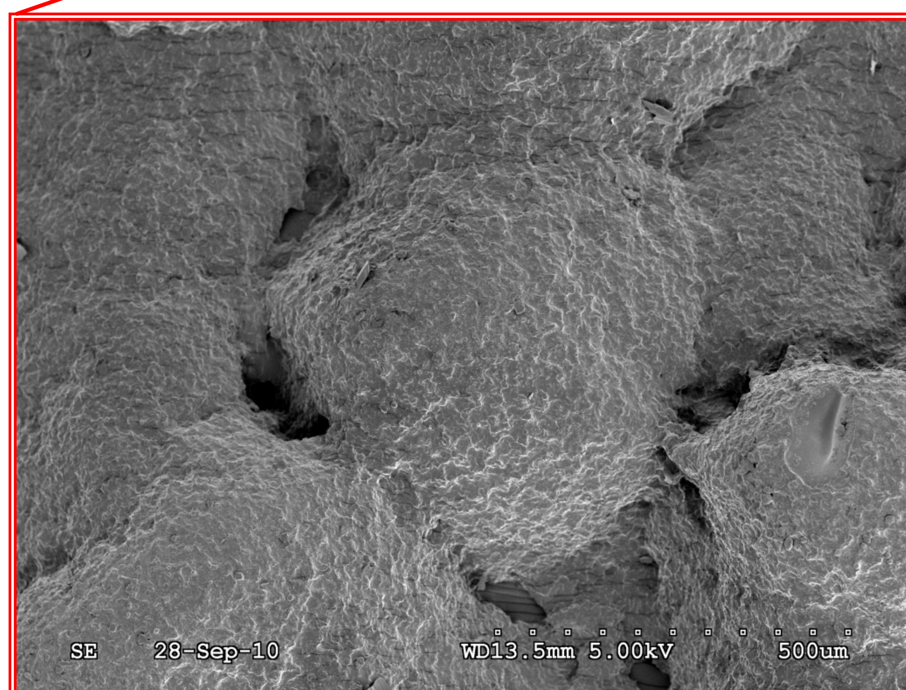




SEM of surface replicates

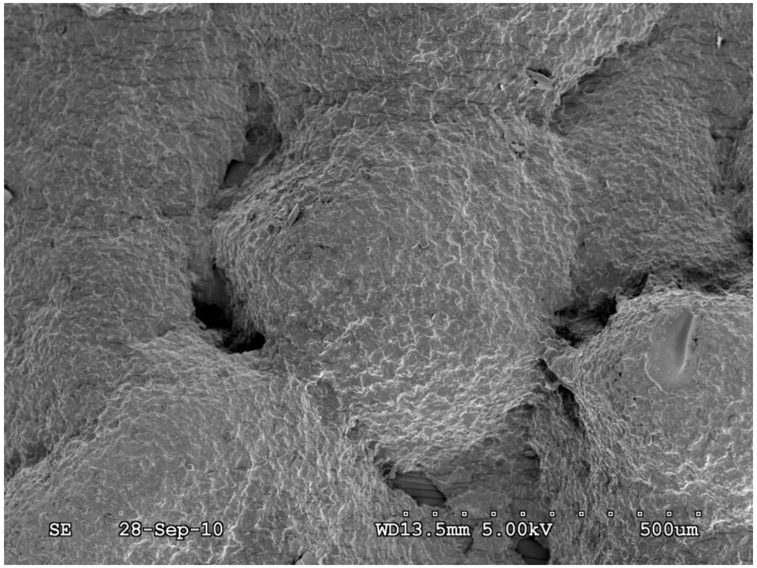


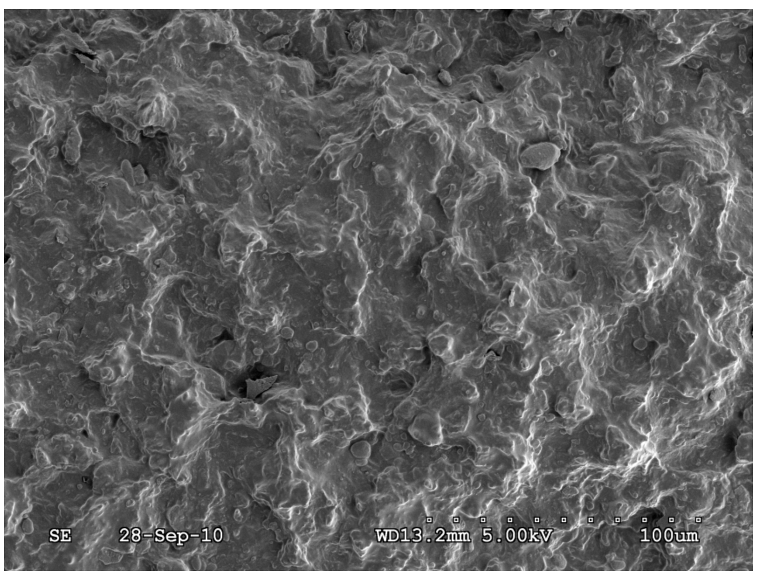




Replicate is inverse of specimen

Pit / surface morphology has similarities to ultrasonic horn damage in mercury





S. J. Pawel, Jnl. Nucl. Mat. 343 (2005)

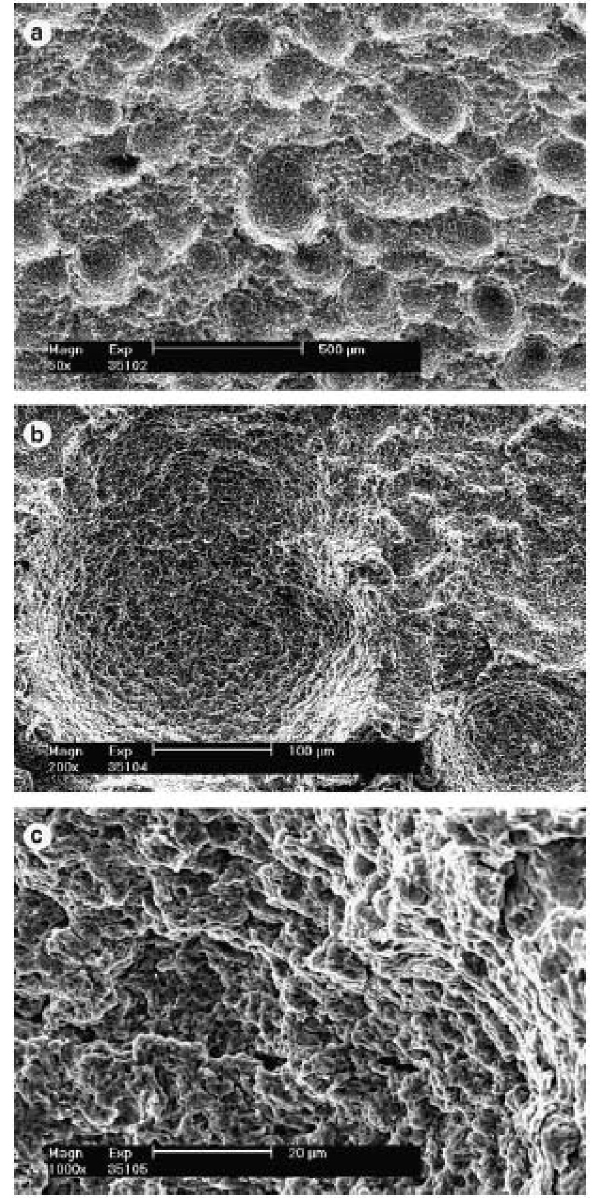
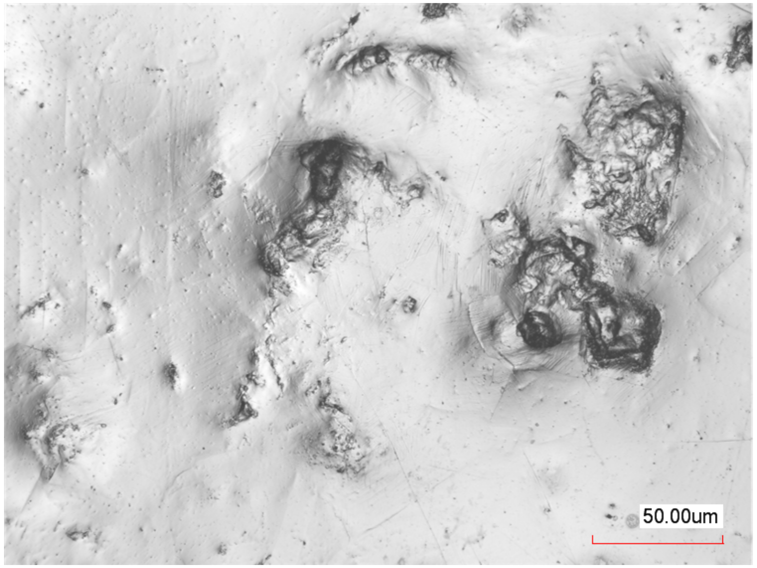


Fig. 3. SEM images of baseline 316LN specimen following 5.5 h sonication in Hg. (a) at top, pit-like surface relief on generally roughened surface; (b) middle, shows magnified view of the pit in the center of (a); (c) highest magnification, showing detail – similar to mechanical tearing – at the edge of the pit.

WNR & MIMTM damage morphology seems different … dominant mechanism by jet impingement

WNR 100 beam pulse test
WFVTL static Hg surface



MIMTM off-line damage test
Static mercury

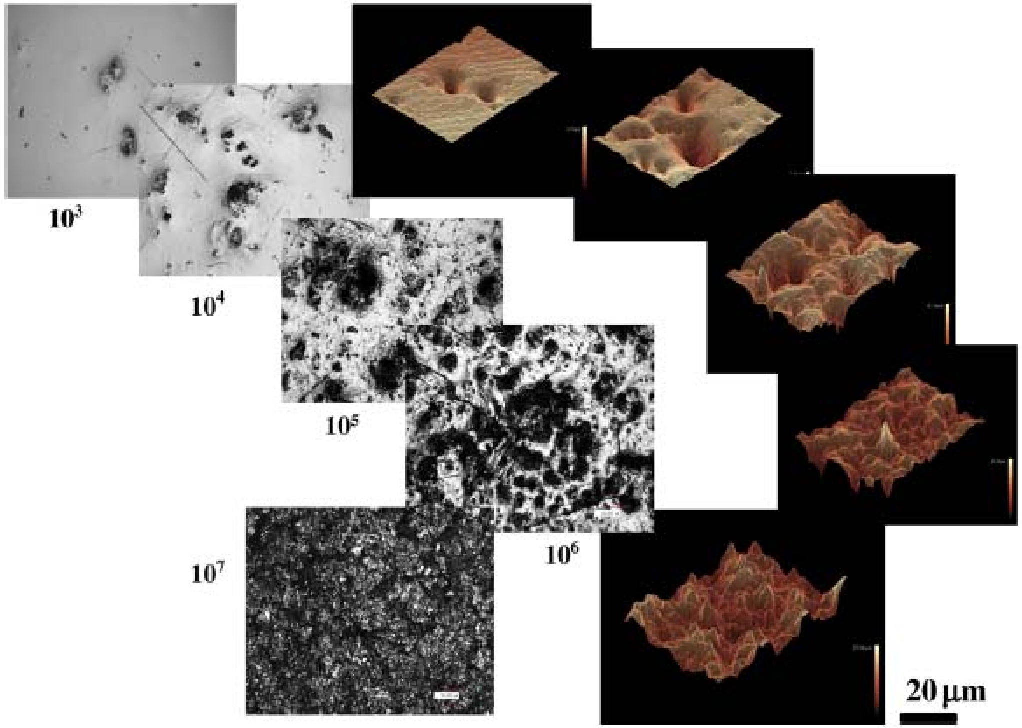


Fig. 2. Micrographs and 3D-images of pitting damage on SA316SS specimens.

M. Futakawa et al. / Jnl. Nucl. Mat. 356 (2006) 168–177

Current overall status

- Current push is on small gas bubbles
  - WNR experiment preparations underway
- Gas wall development has been taken far
  - Mitigation efficacy looks good from in-beam tests
  - Channel cooling concern is resolved
  - Partial gas coverage at beam window with SNS flow configuration is possible with surface texturing
    - Sweeping flow more amenable to GW
  - Wetting condition change over long term operation
  - PIE of targets is key to knowing <u>required extent of coverage</u>

Next

- Increasing emphasis and importance on PIE
  - Irradiated material properties also key to long target life
- MBTL / WNR irradiation now CY2011
- SNS power increasing
  - Proton energy upgrade to 1.3 GeV brings beam power to1.8 MW
  - AIPs -> up to 3 MW (to be shared with Second Target Station)
- Growing effort on next generation target conceptual designs
  - Incorporating gas wall, small gas bubbles and / or alternate flow configurations