Why In-Beam Testing and Development Is Important – The SNS Target Example

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The SNS mercury target is a first-of-a-kind design: MW-class, short-pulse, liquid-metal

- Target R&D during the design & construction phase – and into early SNS operations – obtained critical findings from **in-beam experiments with mercury test targets**

- In-beam experiments were generally aimed at understanding:
  - ‘thermal-shock’ response of the target vessel
    - needed for fatigue life evaluation
    - target lifetime pulses $10^8 \sim 10^9$
  - cavitation damage – an issue which became real at an awkward project time

SNS Mercury Target Module
1.4 MW, 1.0 GeV p, 60 Hz, 0.7 μs

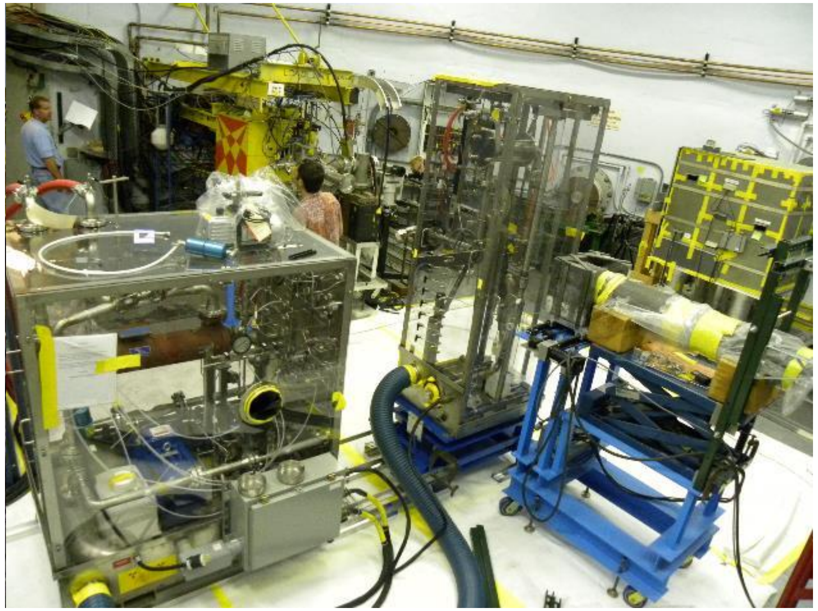
SNS in-beam target experiments started in the late 1990s and continued into 2011

- Most of these tests were performed at **LANSCE – WNR** in the 'Blue Room'

  (Los Alamos Neutron Science Center - Weapons Neutron Research)

- Typical beam parameters:
  - 800 MeV protons; 0.3 μs pulse length
  - 0.5 to 3.5 x10^{13} protons / pulse
  - Beam size:
    - Circular σ_r ~ 10 mm, or
    - Elliptical up to ~ 10 mm x 30 mm
  - Max. energy density similar to SNS @ 3+ MW
  - Max. pulse repetition rate: 2 per minute
  - Typical pulses on target: 100 (max. 1000)

LANSCE - WNR



WNR 'Blue Room'

WNR experiments in late 1990s attempted high-speed strain and pressure measurements of pulse response

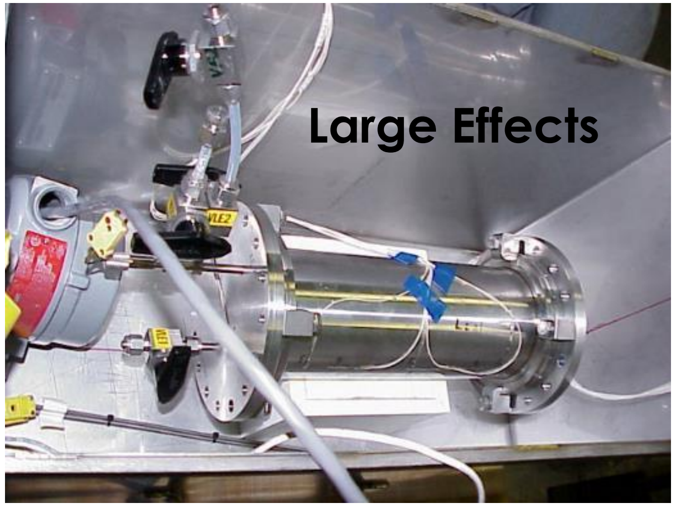
- Small, cylindrical mercury test targets
- Conventional strain gauges went numb after pulse for a few ms
  - All the important response finished by then
- Fiber optic sensors were the best option, but needed development
- Hg pressure measurement was unsuccessful
- Key outcome:
  - Commercial fiber sensors / signal processor from FISO Technologies were most promising for dynamic strain measurement needs

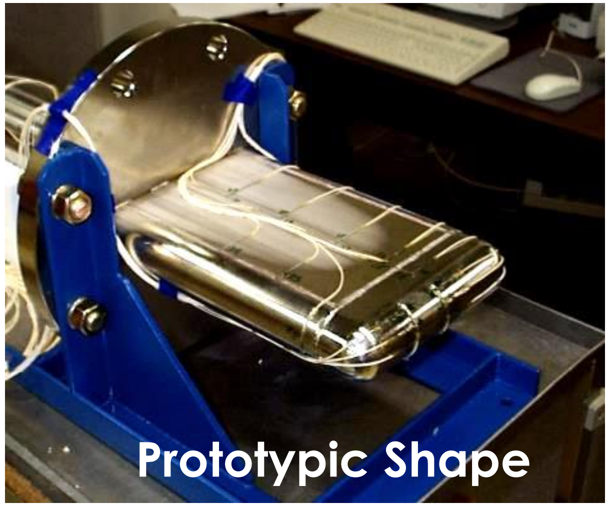
1st Test Target - 1997

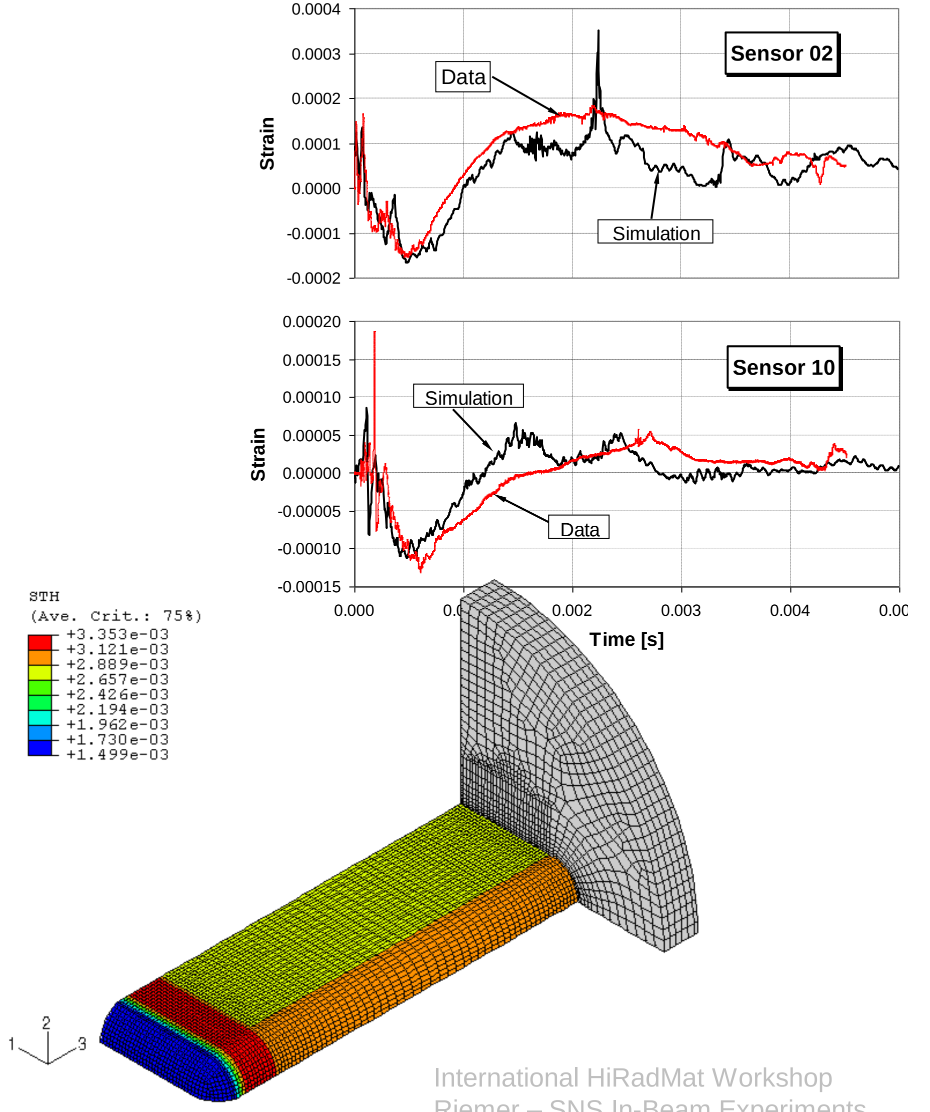
Target ‘A’- 1999

Experiment campaign in August 2000 produced credible sets of dynamic strain data on mercury and solid targets

- Four mercury targets were tested for pulse response behavior
  - Two cylindrical ‘Large Effects’ targets
  - Two ‘Prototypic Shape’ targets
- **Parallel modeling work now had data to benchmark simulation results against**



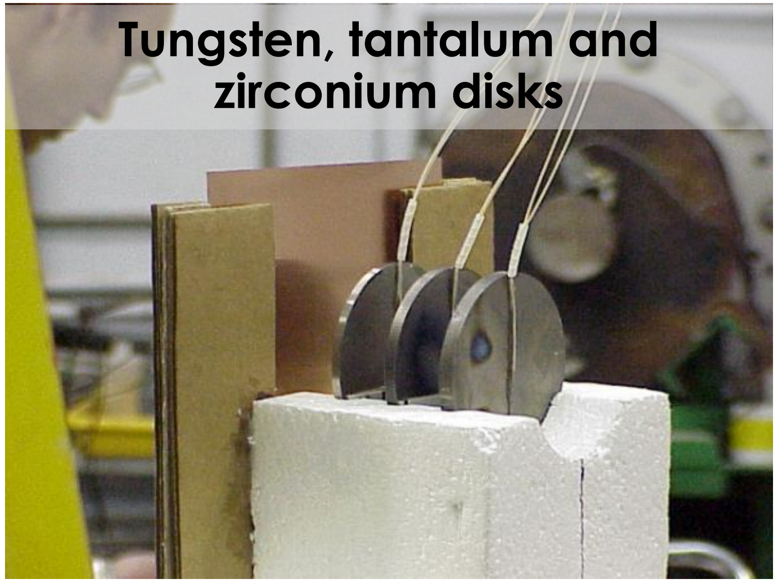




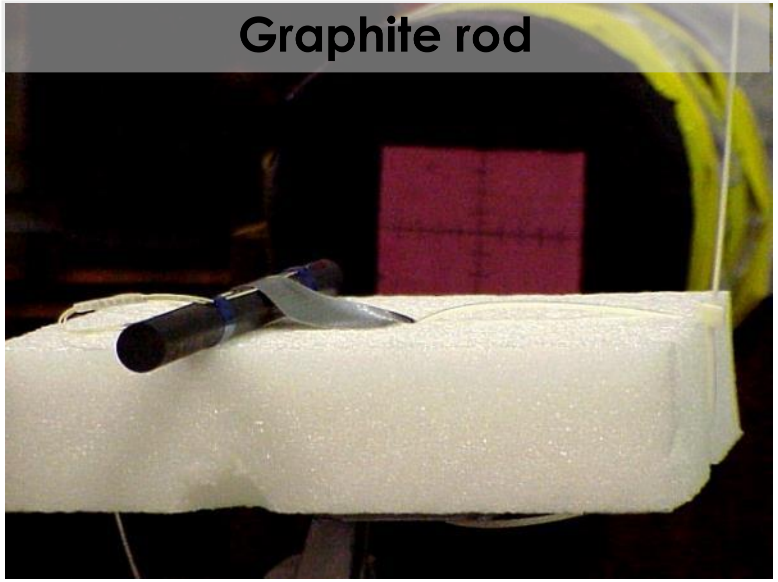
B.W. Riemer / Journal of Nuclear Materials 343 (2005) 81–91

WNR 2000 test campaign also examined pulse response of solid targets

- Simpler to model, but FISO system was pushed to limits to produce useful data
- Graphite rod simulated response match data well when offset beam condition was included

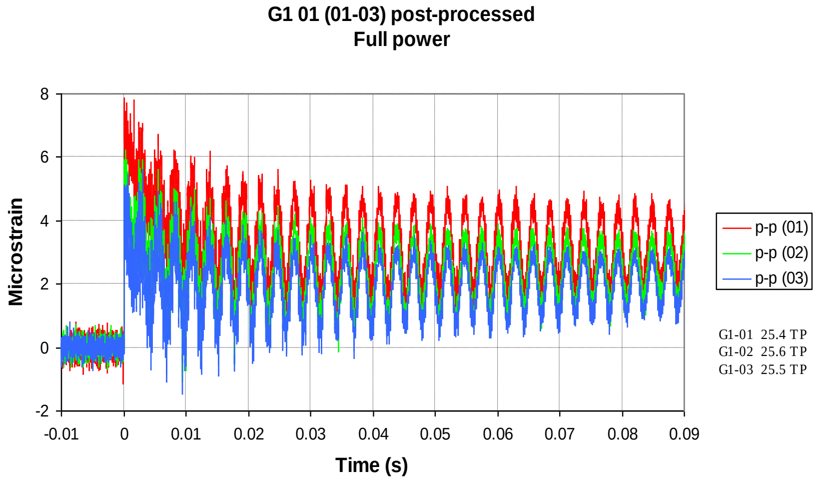


Tungsten, tantalum and zirconium disks



Graphite rod

Graphite rod measured strain



ASTE – AGS Spallation Target Experiments 1997 & 2001

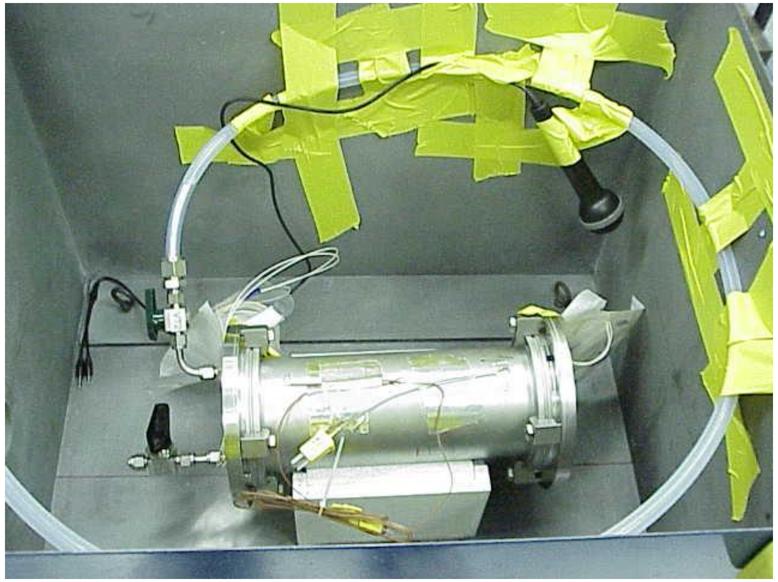
- A collaboration formed around mercury spallation target projects at the time
  - The SNS in Oak Ridge, Tennessee
  - The JSNS (J-Parc) in Tokai, Japan
  - The ESS in Jülich, Germany
- A single, large mercury target
  - ϕ = 20 cm, L = 130 cm
- Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory
  - 23 GeV protons
  - ~1 to 3 x10^{12} ppp
  - Beam size: circular σ_r ~ 15 mm


ASTE mercury target

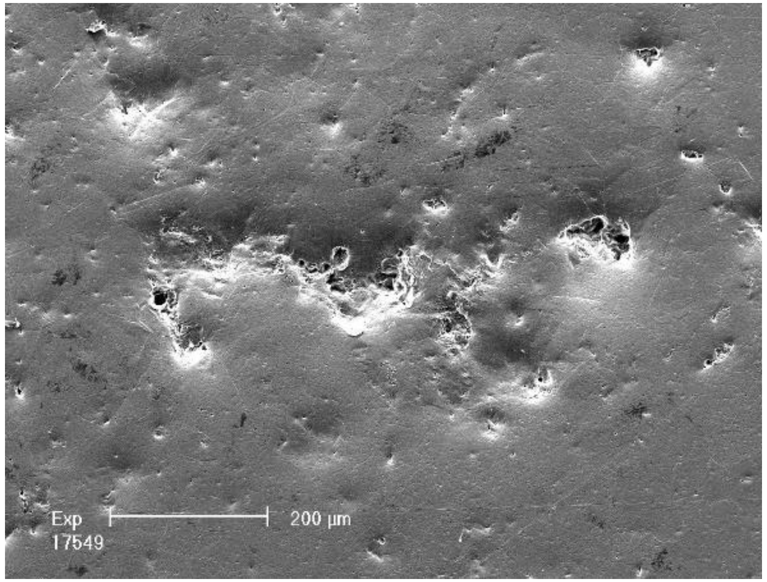
- Thermal shock tests
  - Strain sensors & LDV
- Shielding / neutronics tests

Beam induced cavitation damage and its mitigation became topic of mercury target R&D in late 2000

- J-PARC offline investigations of wave propagation through mercury produced disturbing result with pressure and rise time similar to spallation target (M. Futakawa et al. / International Journal of Impact Engineering 28 (2003) 123–135)
- **July 2001** WNR experiment confirmed damage cause by beam pulse using Large Effects targets



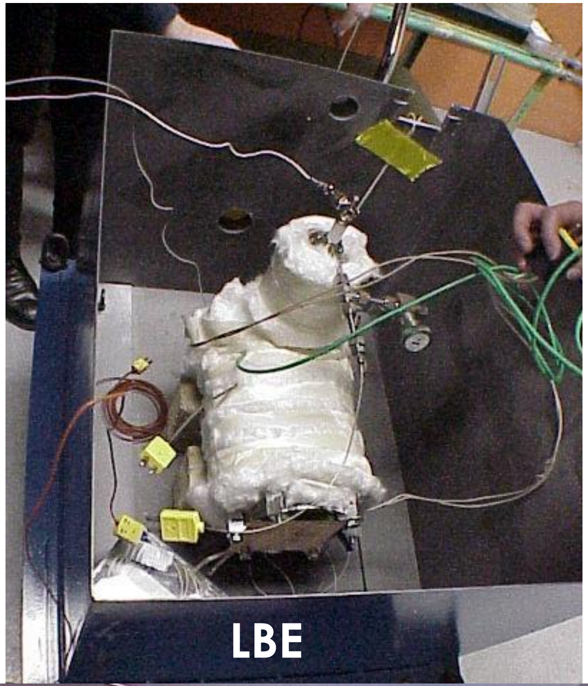
Damage after 200 pulses



B.W. Riemer et al. / Journal of Nuclear Materials 318 (2003) 92–101

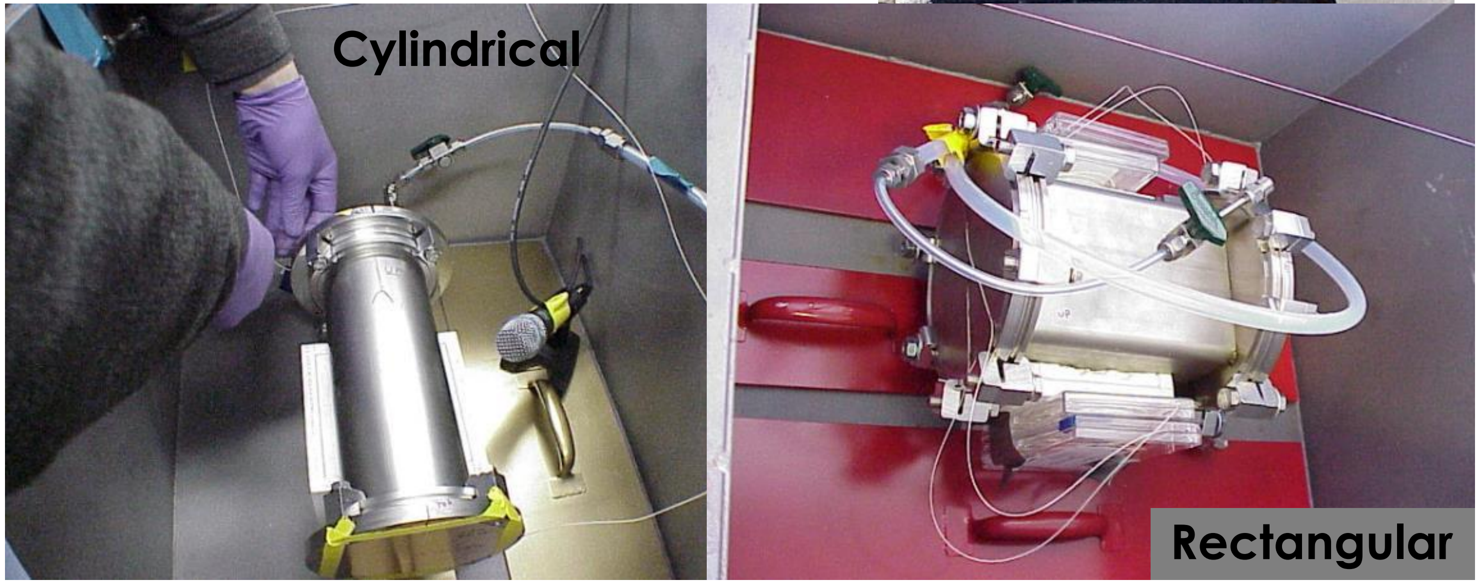
A 2nd WNR experiment in **December 2001** investigated damage dependence on:

- Target geometry
- Damage resistant materials & surface treatments
- 100 & 20 test pulses vs. 200
- A lead-bismuth eutectic target was also tested for LANL



Key outcomes:

- Materials & treatments alone helped but did not stop damage
- Geometry mattered
- 100 pulses enough
  - 20 too few



B. Riemer, Journal of Nuclear Materials 318 (2003) 92–101

In 2001 SNS was 5 years away from first beam on target

- Change from a mercury based design was barely possible
- Project leadership established October 2002 deadline for deciding whether to keep mercury or pursue alternative design
- Simulation / modeling alone was far from being able to capture all relevant physics of the pulsed mercury target to predict if it can survive desired lifetime
  - Fluid-structure interaction
  - Thermal-shock loading
  - Multiphase fluid (cavitation vapor, injected gas), flow

- Six months after the 2nd 2001 WNR test … another in-beam test campaign

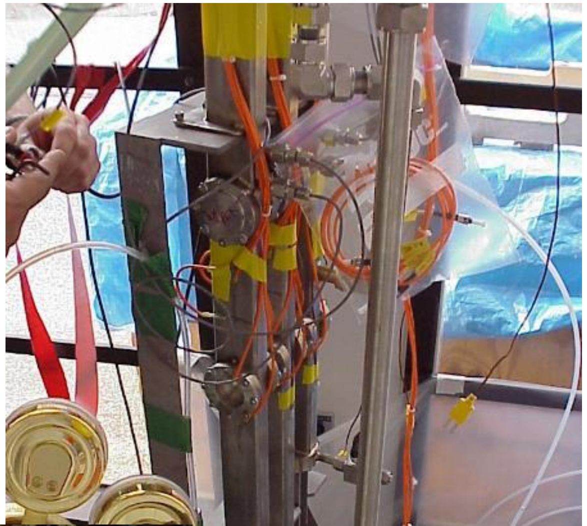
WNR **2002 experiment** investigated damage dependence on:

- Target geometry
- Intensity (ppp)
- Damage resistant materials and surface treatments
- Gas bubble injection
- Gas layer injection
- **Total of 19 target tests**
  - 100 pulses/test
  - 1 test @ 1000 pulses

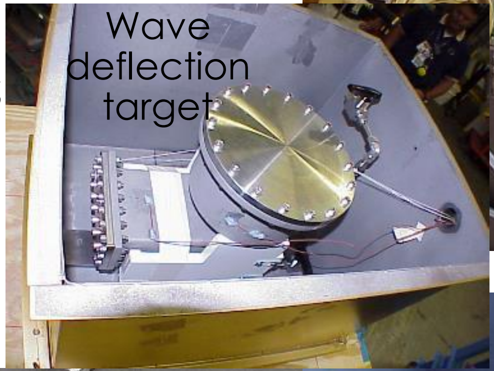
Key outcomes:

- Damage strongly non-linear with intensity
- Materials & treatments can help but not stop damage
- Gas injection promising, but

R&D must continue

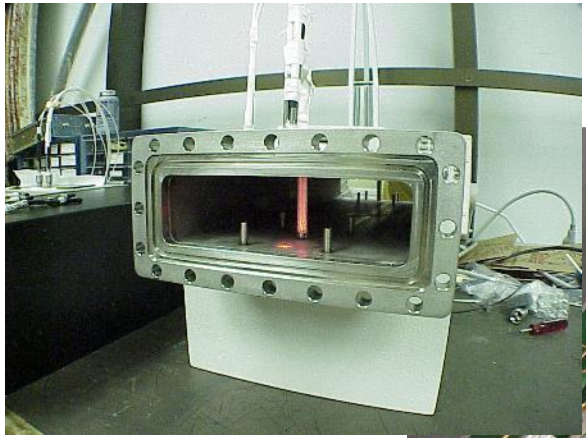


Small gas bubbles
(H. Soltner - FzJ)

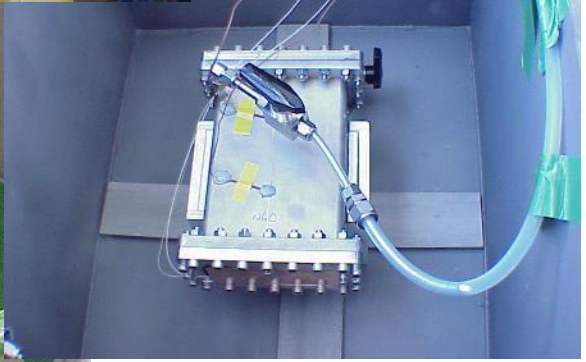


Wave deflection target

Bubble diagnostic target



ASTE2 target (FzJ)



RECT target

J.R. Haines et al. / Journal of Nuclear Materials 343 (2005) 58–69

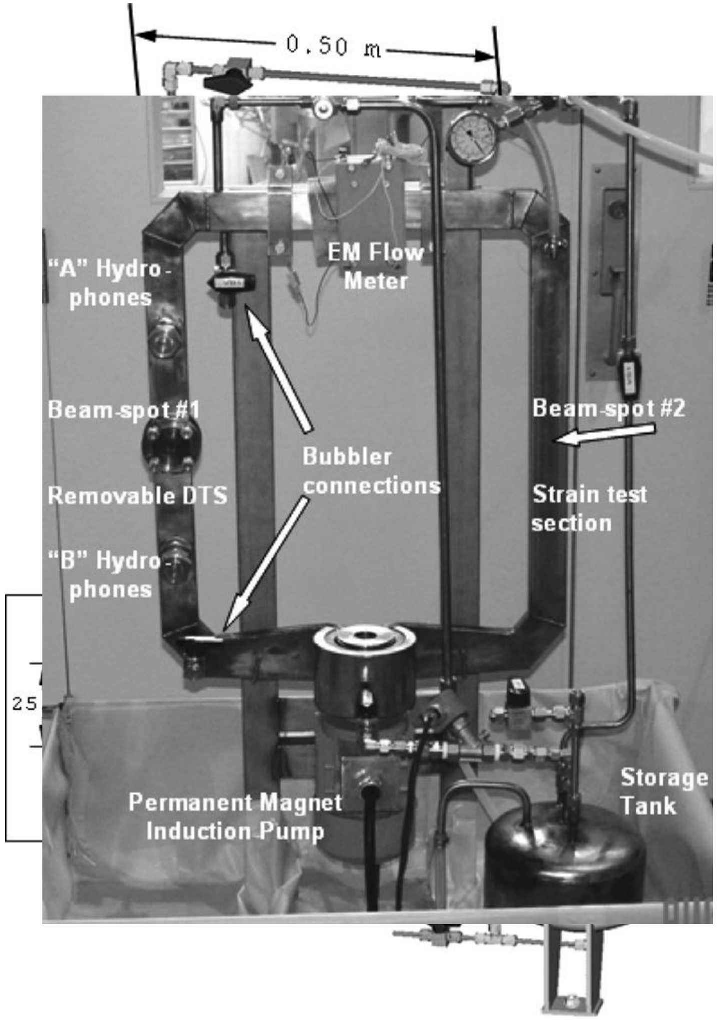
In-beam tests contributed to decision to keep mercury for the SNS target design, with caveat that R&D continue

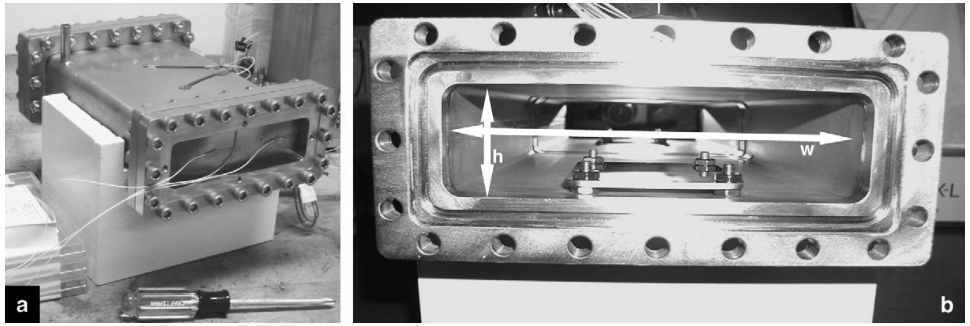
- Collaboration with J-Parc strengthened (ESS – FzJ halted)
- Emphasis on injection of small gas bubbles
- J-Parc contributed greatly with MIMTM experiments

  (Magnetic Impact Test Machine)
  - Offline device for generating pulsed cavitation in mercury
  - High cycles, many materials, gas injection, diagnostic correlation to damage (aka, cavitation damage potential)
- SNS repurposed the Target Test Facility (TTF) for offline gas injection development
  - Full scale, SNS prototypic mercury test loop

Next round of in-beam testing pursued effects of mercury flow, gas injection and energy density

- **2005 WNR campaign** we introduced a small flowing mercury loop with a bubbler: the In-Beam Bubble Test Loop IBBTL
  - Rectangular flow channel, exchangeable damage specimens at beam spot, flow speed of 0.4 m/s
  - Compared stagnant vs. flow vs. flow + bubbles
- Rectangular targets used for energy density investigations
  - Protons/pulse fixed, spot size changed





B. Riemer et al. / Journal of Nuclear Materials 377 (2008) 162–173

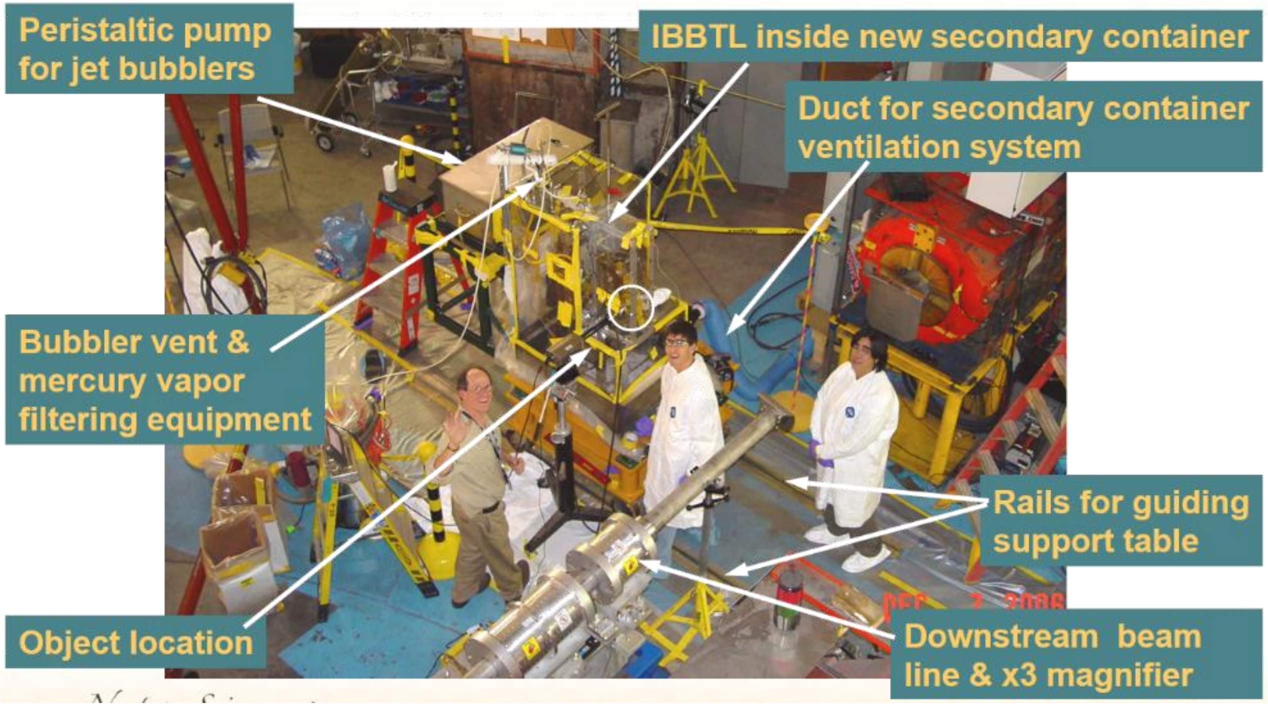
Key 2005 in-beam test results

1. Flow reduced damage vs. stagnant mercury
2. Injection of small bubbles w/flow reduced damage vs. flow
3. Bubble injection reduced vessel strain, especially at measuring points at distance from the beam spot
   - Less reduction near / at the beam spot
   - We did not understand the bubble population we created
4. LDV vibration response was attenuated with gas
5. LDV derived data correlated with observed damage
6. Acoustic measures of wave propagation in bubbly mercury indicated scattering vs. attenuation of sound
   - Suggesting bubbles were somewhat large

- Beam flux intensity tests results were confusing

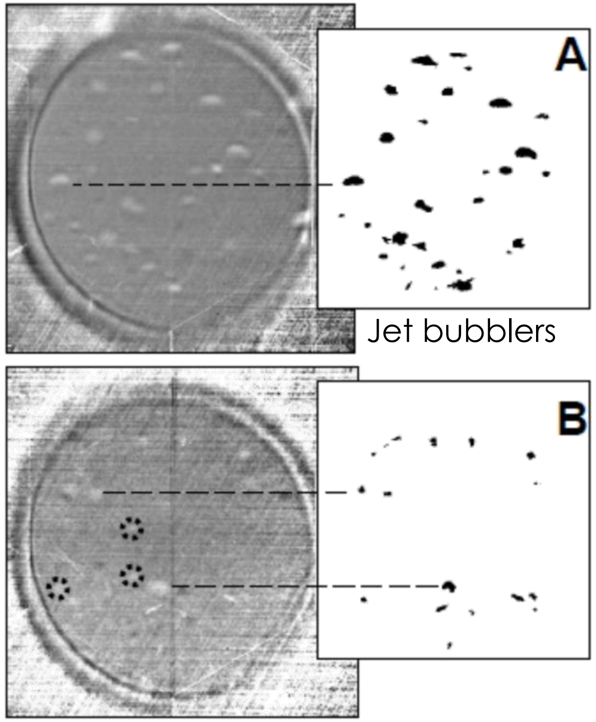
Proton radiography 2006 at LANSCE attempted to measure bubbles population in flowing mercury

- Repurposed the IBBTL for this experiment

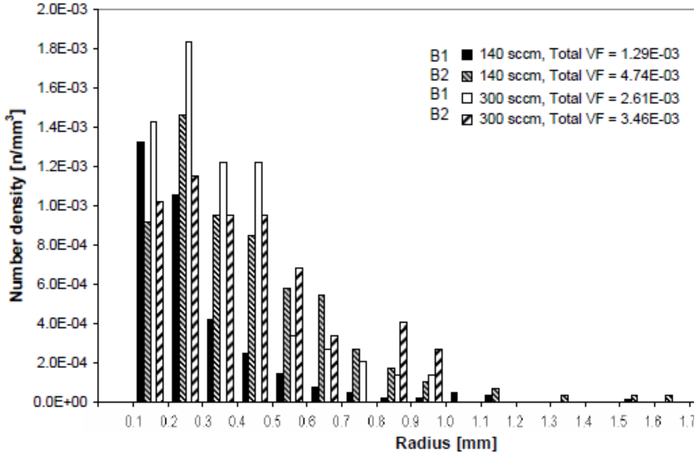


Proton radiography 2006 at LANSCE imaged bubbles injected into mercury

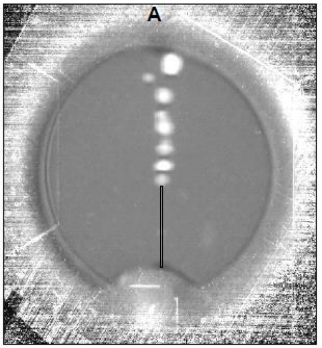
- Visualized through either 22 mm or 6 mm of Hg
- Mercury stagnant or flowing at 0.4 m/s
- Three bubblers tested; three gases: He, Ar, Xe
- Acoustic measures
- Key findings:
  - Credible bubble size distribution data
  - Smallest visible bubble size: R~ 0.24 mm
  - Total volume of small bubbles determined ~0.1%
  - Good agreement between acoustic measures & theory
  - No value added in using Argon or Xenon



Jet bubblers



Needle bubbler



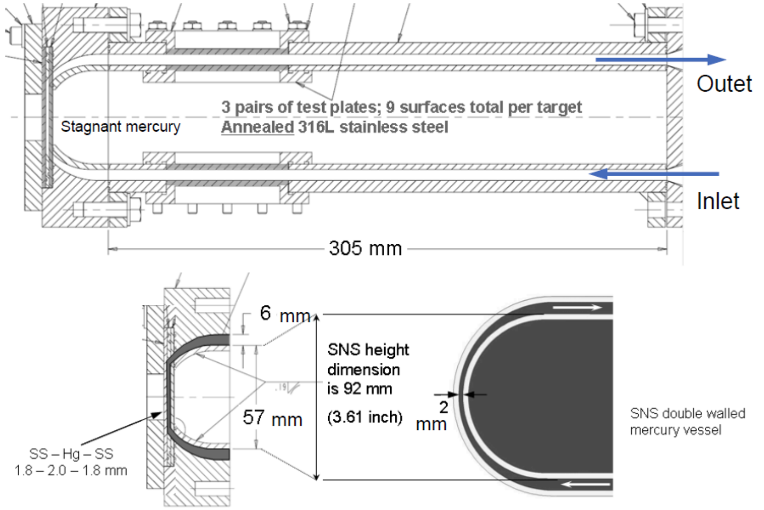
B. Riemer, et al., *Proc. ICANS-XVIII, Dongguan, China, 2007*
B. Riemer, et al., *Proc. AccApp'07, Pocatello, Idaho, 2007*

We returned to the **WNR in 2008** to further investigate cavitation

- Damage in mercury cooling channel feature of SNS target
  - Water (stagnant) also tried in channel
- Damage dependence on proton flux intensity in rectangular targets
- Damage on a target with a gas layer enhanced by surface texture
- LDV vibration data to estimate 'Cavitation Damage Potential' (CDP) and correlation to observed damage
- Acoustic sensing of cavitation
- Beam fluorescence of chromium-doped alumina sprayed onto steel
- A long-pulse test for cavitation damage
- 12 test targets in all, 72 hours of beam time

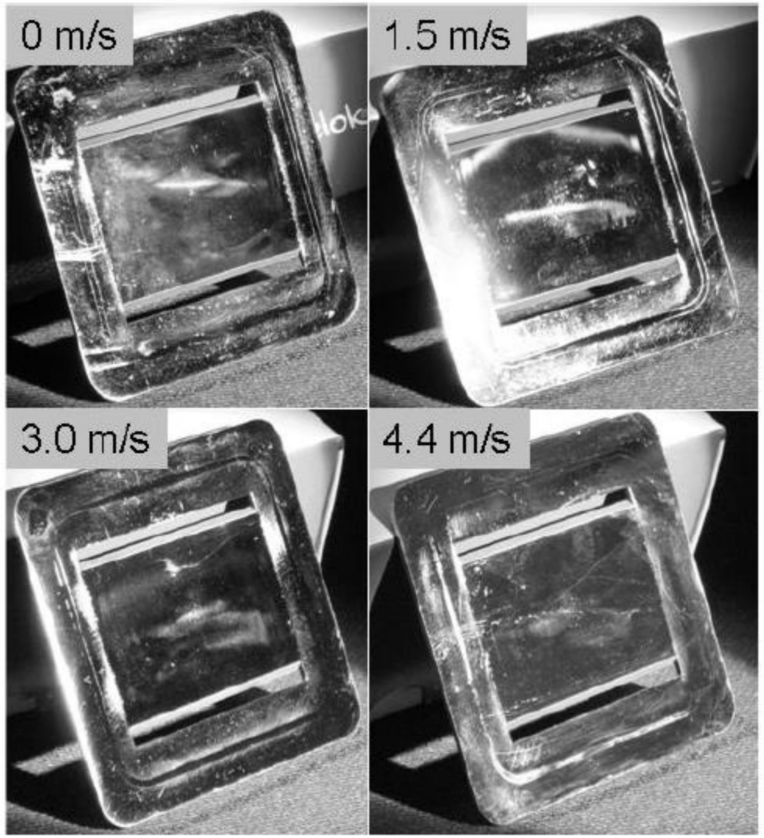
Tests on SNS flow channel used several targets

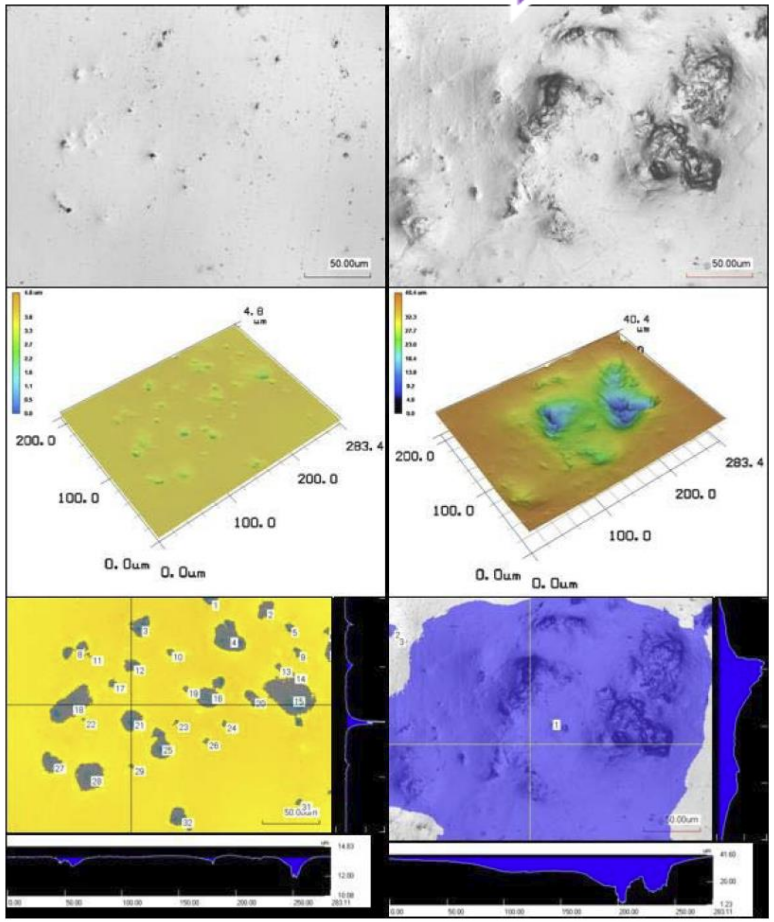
Test target design and setup → **Stage 1 PIE** → **Stage 2 PIE**



Hg length: 325 mm

- Variable speed centrifugal pump employed for channel flow speeds for up to 7 m/s
  - Only ca. 4.4 m/s achieved
- Test targets connected to loop via flexible hoses



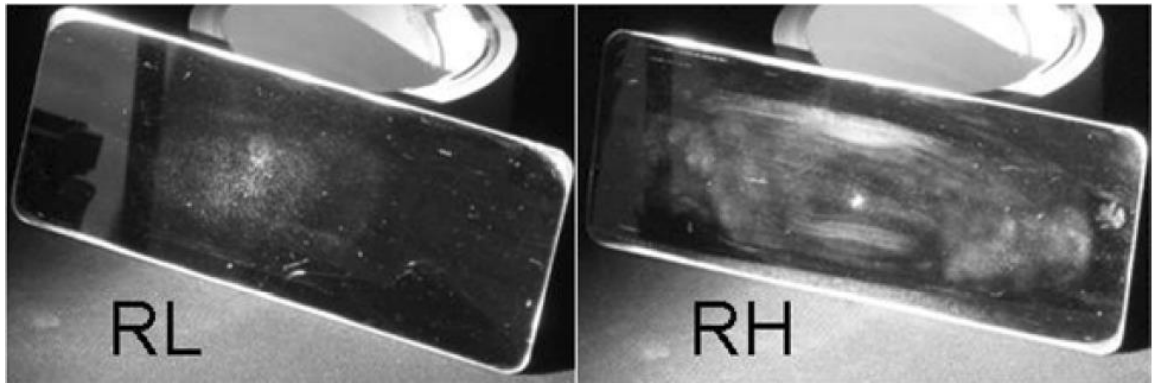


- **Channel damage less than bulk side**
- **Flow speed helps … to a point**

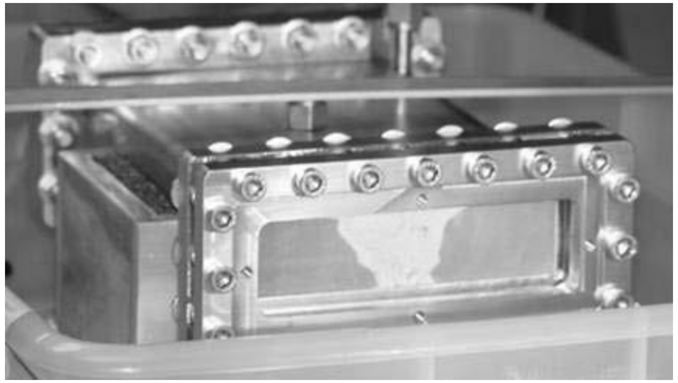
B. Riemer, et al., Proc. ICANS-XIX, Grindelwald, Switzerland, 2010
B. Riemer, et al., Jnl. of Nucl. Mat. 398 (2010) 207

Beam flux test fixed total energy deposited in each rectangular target

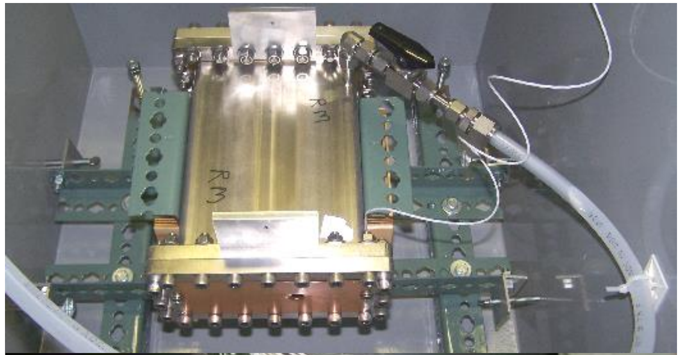
- Flux varied by changing beam spot size
- Maximum pit depth scaled by about the *square of peak proton flux*

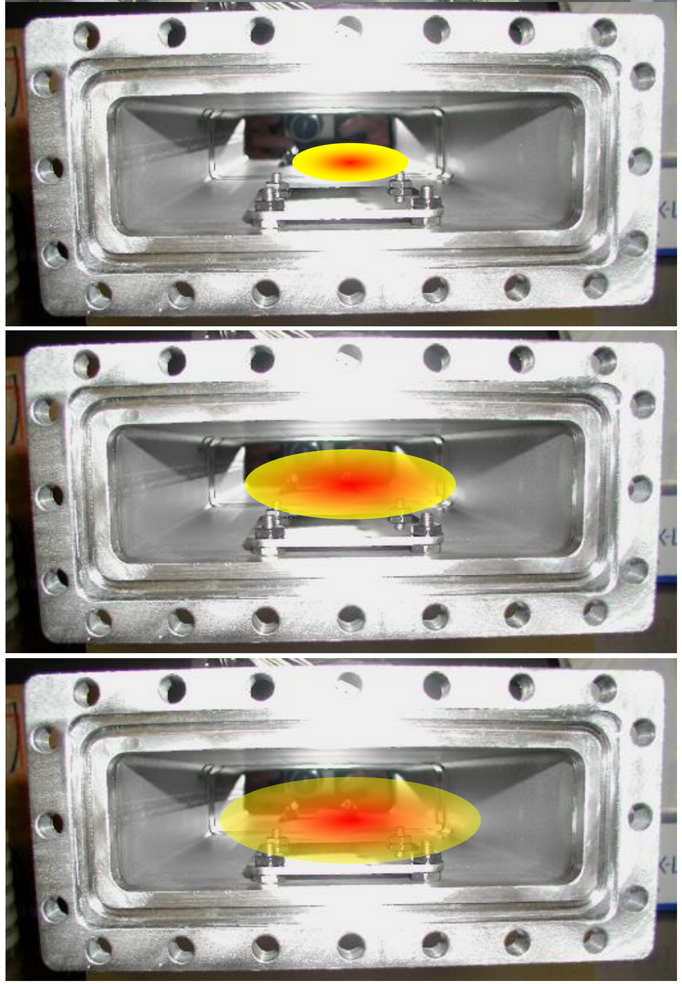


- Gas layer target:
  - No damage observed
- Long-pulse
  - No clear damage evidence



Gas layer with acrylic textured wall in pretest

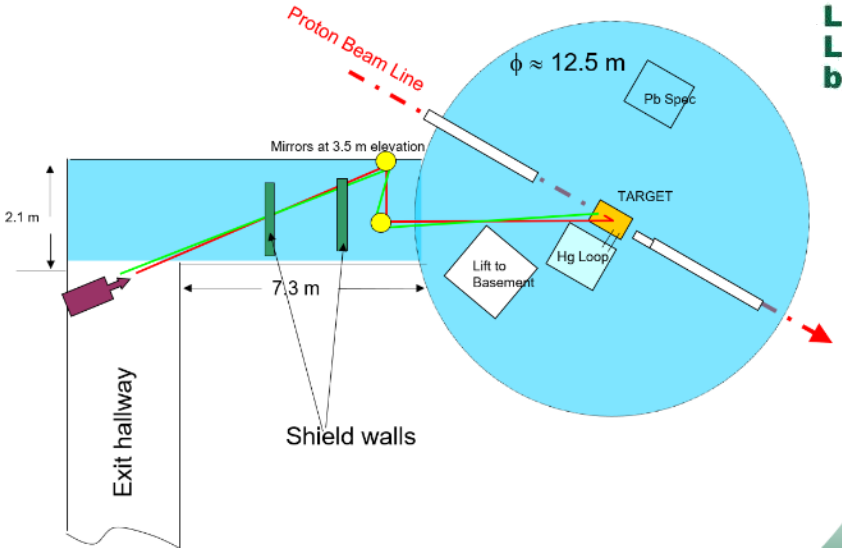




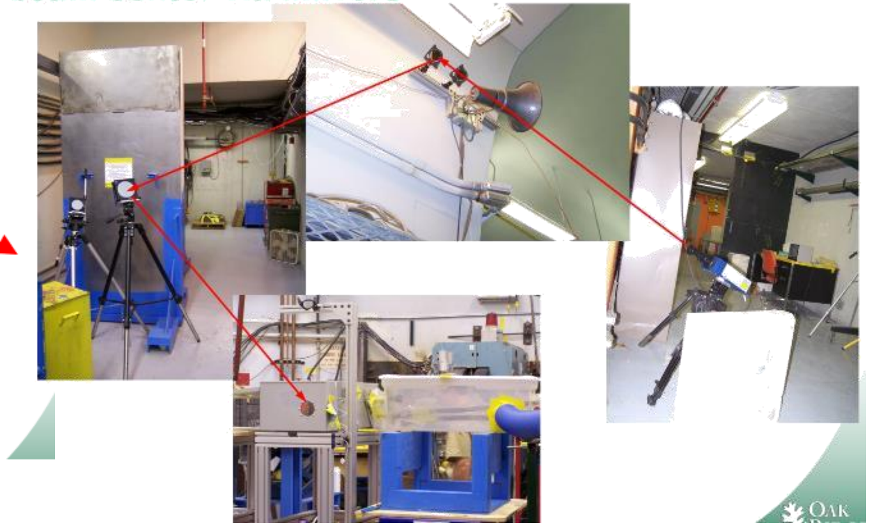
Laser Doppler Vibrometer detection of cavitation

- Remote optical sensing of vibrations associated with cavity collapse gave indications of cavitation intensity
  - Technique pioneered by J-Parc

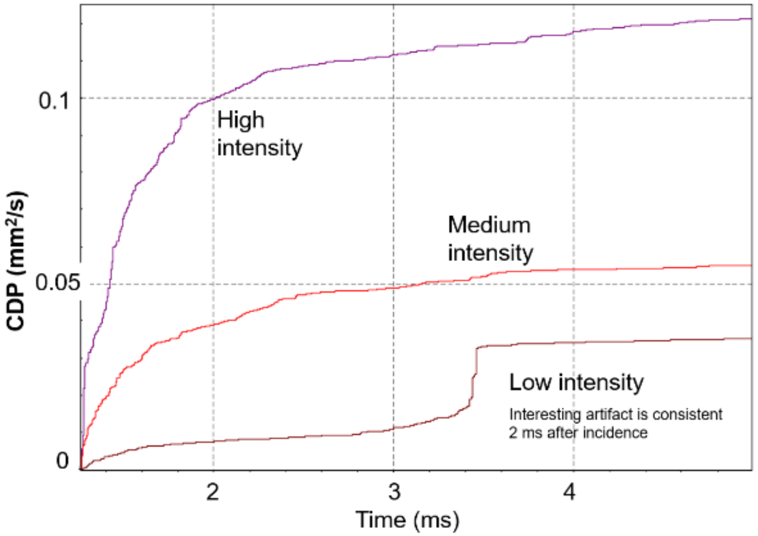
WNR "Blue Room" layout & LDV path



LDV unit was protected in a low radiation location
Laser was pointed to a spot on each target near the beam center via mirrors

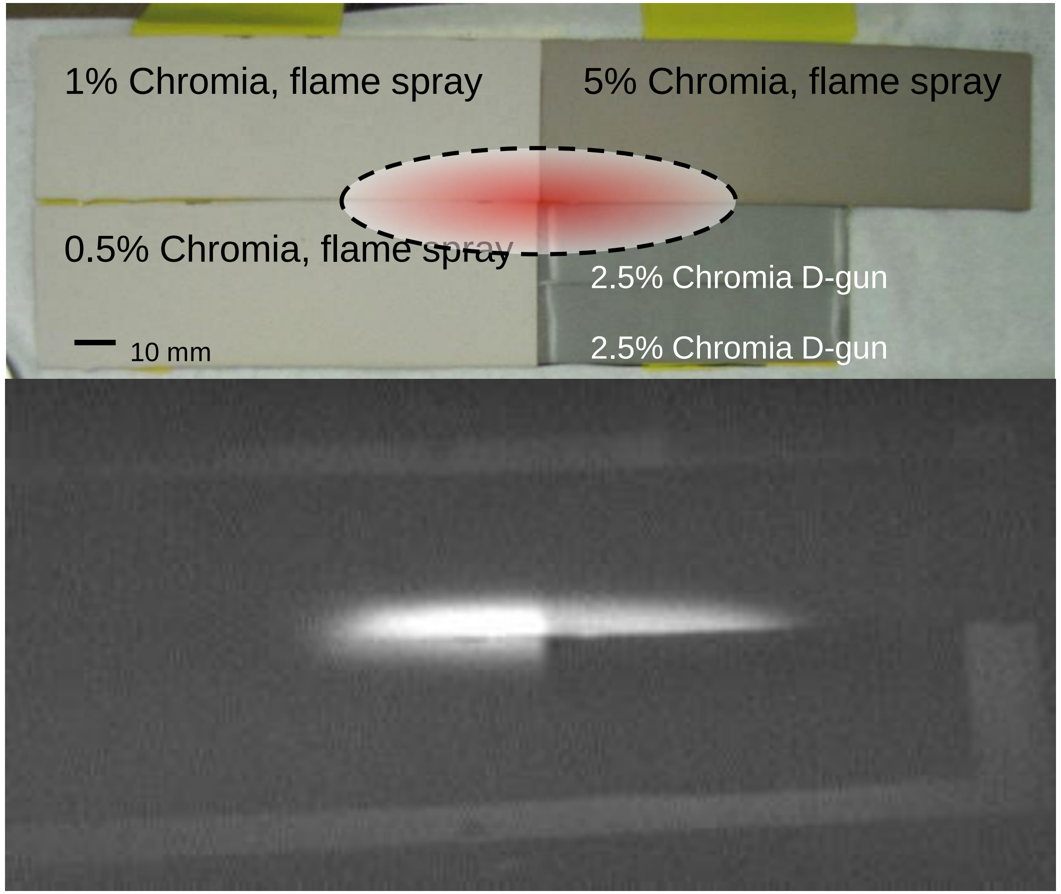


1. Band pass 15 kHz – 300 kHz
2. Time integrate filtered velocity



Successful demonstration test of flame-sprayed Cr-doped alumina on steel

- Process used on SNS targets, aka ‘Target Imaging System’



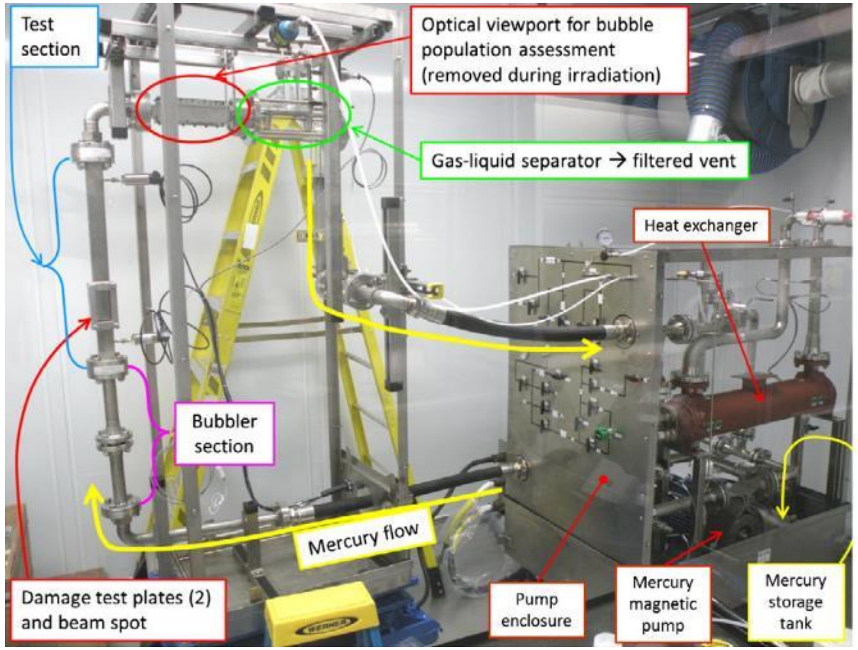
Final SNS in-beam experiment in 2011 investigated gas bubble injection for reducing pulse damage and fatigue

- New flowing mercury test loop used exchangeable damage test specimens (beam windows) and 3 types of bubblers
- Variable mercury flow speed and gas injection rates
- Small bubble populations were assessed by novel offline method prior to beam testing
- Online measurements for strain, vibration (LDV), cavitation acoustic emission, pressure, sound
- PIE of damage test specimens: 19 cases x 2 specimens
  - Automated scanning optical microscopy (1800 images / case)
  - 3D laser profiling microscopy

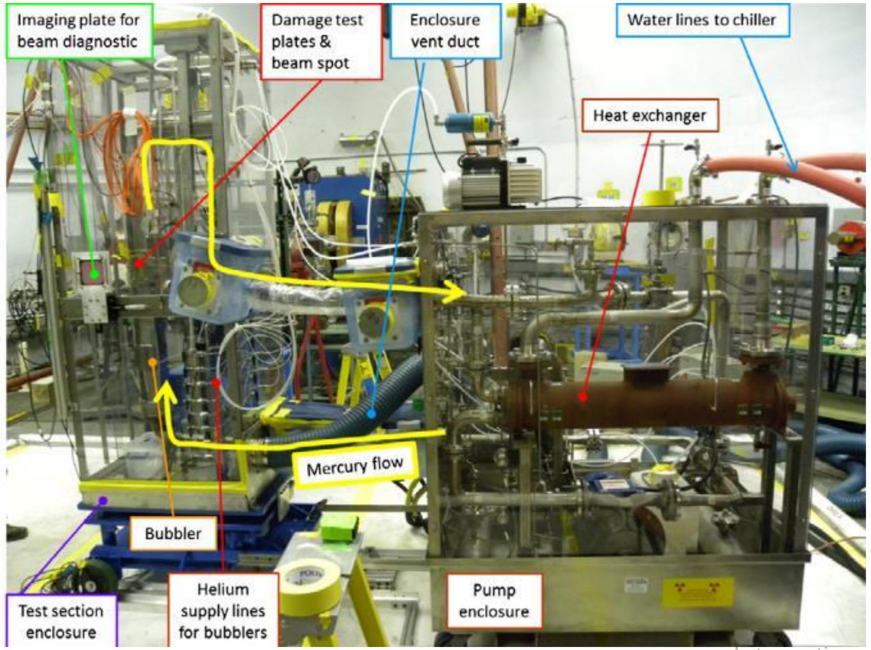
B.W. Riemer et al. / Journal of Nuclear Materials 450 (2014) 192–203
M. Wendel eat al. / Measurements of Gas Bubble Size Distributions in Flowing Liquid Mercury, FEDSM2012-72015

Multi Bubbler Test Loop was assembled and tested at ORNL

- Flow cross-section of 47.8 x 22.4 mm
- Mercury flow speeds from 0 to 1.7 m/s
- Helium gas injection rates from 0 to 0.8 SLPM
- Pule intensities from 1.45 to 3.40 x10^{13} /pulse; 100 pulses per case
  - Beam profile: σ_X = 7 mm, σ_Y = 17 mm
  - Flux intensities comparable to SNS, JSNS



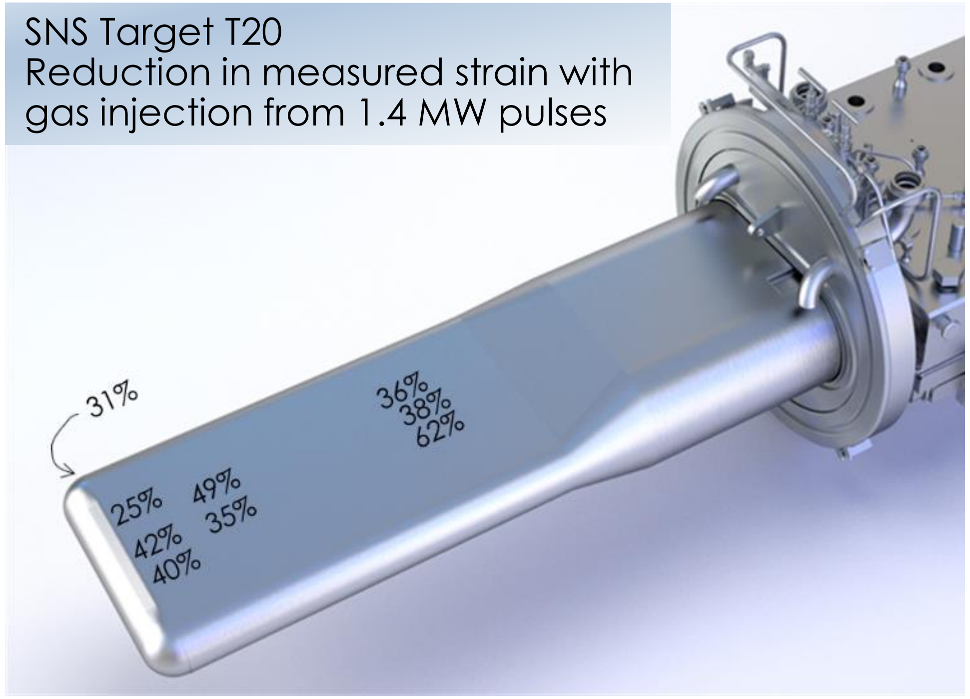
MBTL pre-beam testing



MBTL in WNR Blue Room

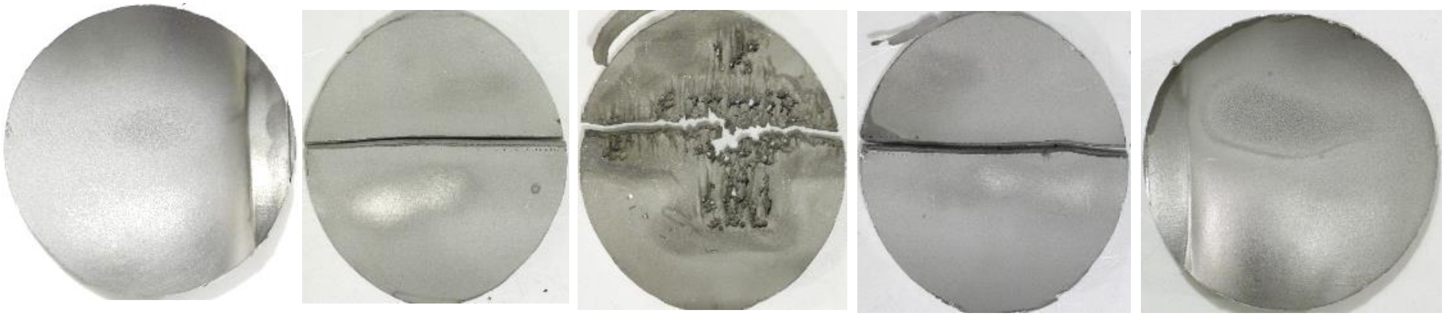
Key findings from in-beam experiments illuminated path forward for high power SNS operation, with gas injection

Fatigue life enhancement & cavitation damage reduction

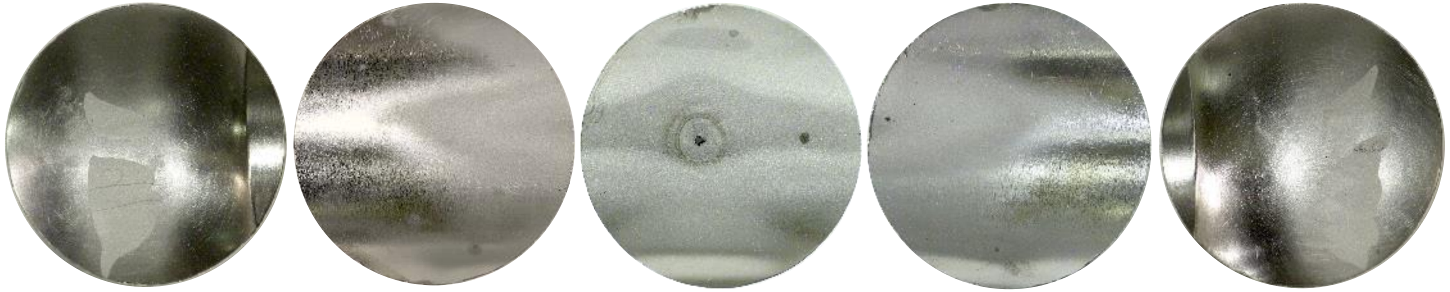

SNS Target T20
Reduction in measured strain with gas injection from 1.4 MW pulses

PIE specimens cut from SNS inner beam window

Target 16 – no gas injection



Target 20 – with gas injection



SNS targets have been reliable at 1.4 MW with gas injection

2MW operation of the SNS mercury target coming in 2024

In-beam experiments were a major part of SNS target development & solving challenges in meeting power goals

- New target / beam intercepting device technologies – tasked with unprecedented operating requirements – <u>need relevant in-beam test data</u>
  - Determine behavior of materials and designs when simulations cannot
  - Develop and verify simulation techniques

- **Facilities like HiRadMat are vital to the Target / BID community**
  - **New performance challenges are persistent**
  - **Failure to meet reliability requirements has bigger consequences with growing costs of new & upgraded science facilities**