Challenges for Flowing Targets

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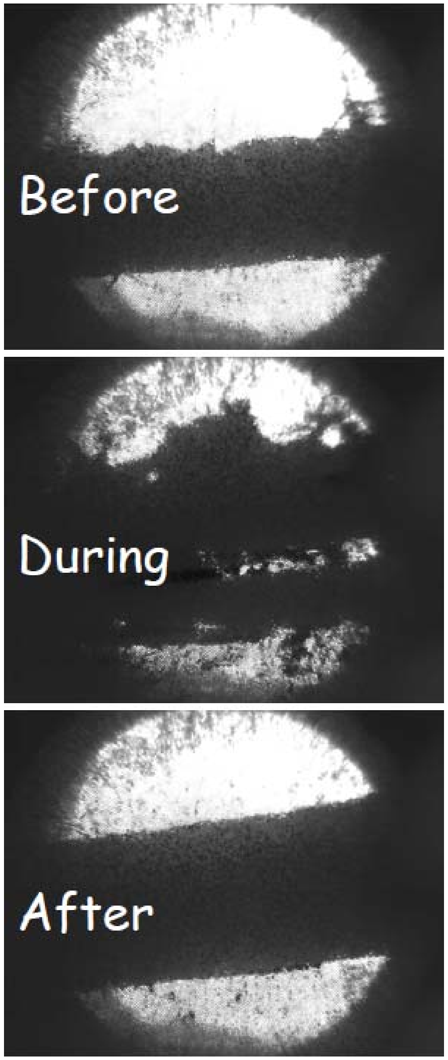
- Fundamentally, target challenges are driven by:
  - High power density
  - High energy density (pulsed systems)

    - Material limits on temperature, stress / shock

Complicating / exacerbating factors

- Physics requirements
  - Geometry
    - E.g., interaction with system components, stability
  - Materials (Z)
  - Environment (e.g., vacuum, magnetic field, temperature)
- Required target lifetime
  - Radiation damage tolerance, target maintainability
- Facility / safety / regulatory issues
  - Material hazards, toxicity
  - Credited safety components
  - Waste disposition

Herein lies difficulty for collaborations: These are facility and mission specific



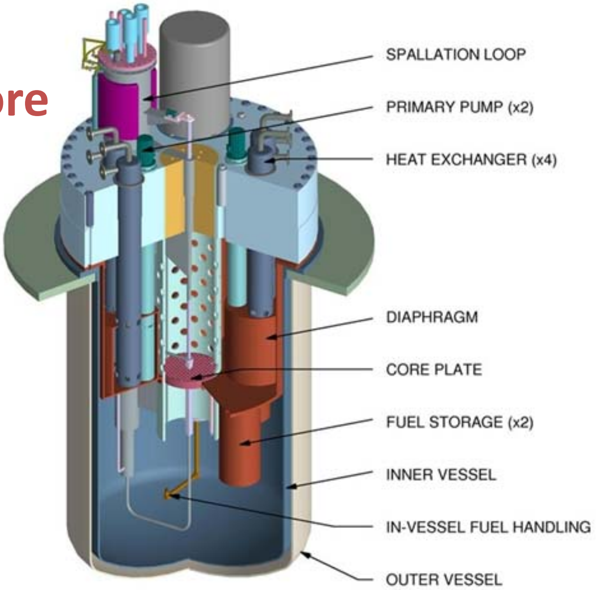
MERIT Experiment
1300 J/cc/pulse

Flowing targets are one way to deal with high power / energy density

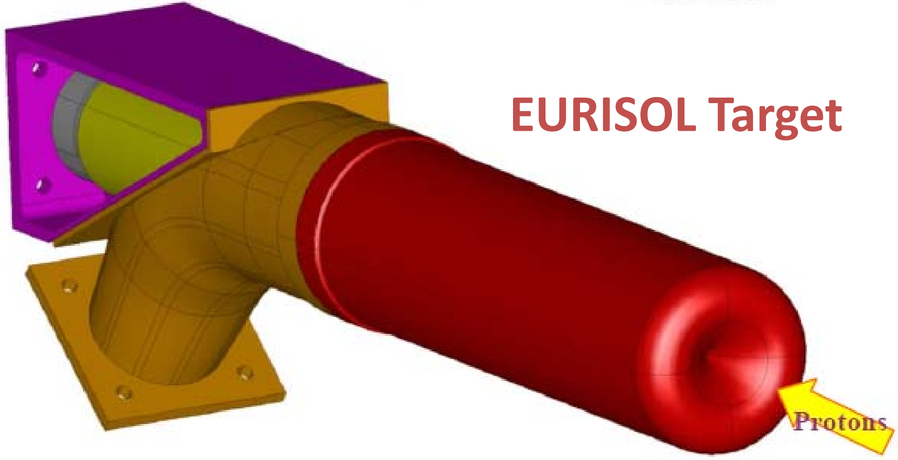
Liquid Metal Targets

- High power spallation targets:
  - SNS, JSNS (Hg, pulsed)
  - MEGAPIE (LBE, CW)
- ADS for waste transmutation:
  - MYRRHA (LBE, CW, “windowless” option)
- Neutrino factories:
  - MERIT (Free Hg jet , pulsed)
- RIB & ISOL targets:
  - EURISOL (Hg, CW)
  - ISOLDE (molten Pb, pulsed)
- Material test facilities
  - IFMIF (Lithium, CW)
  - MTS (hybrid W/LBE option, pulsed)

MYRRHA core & target



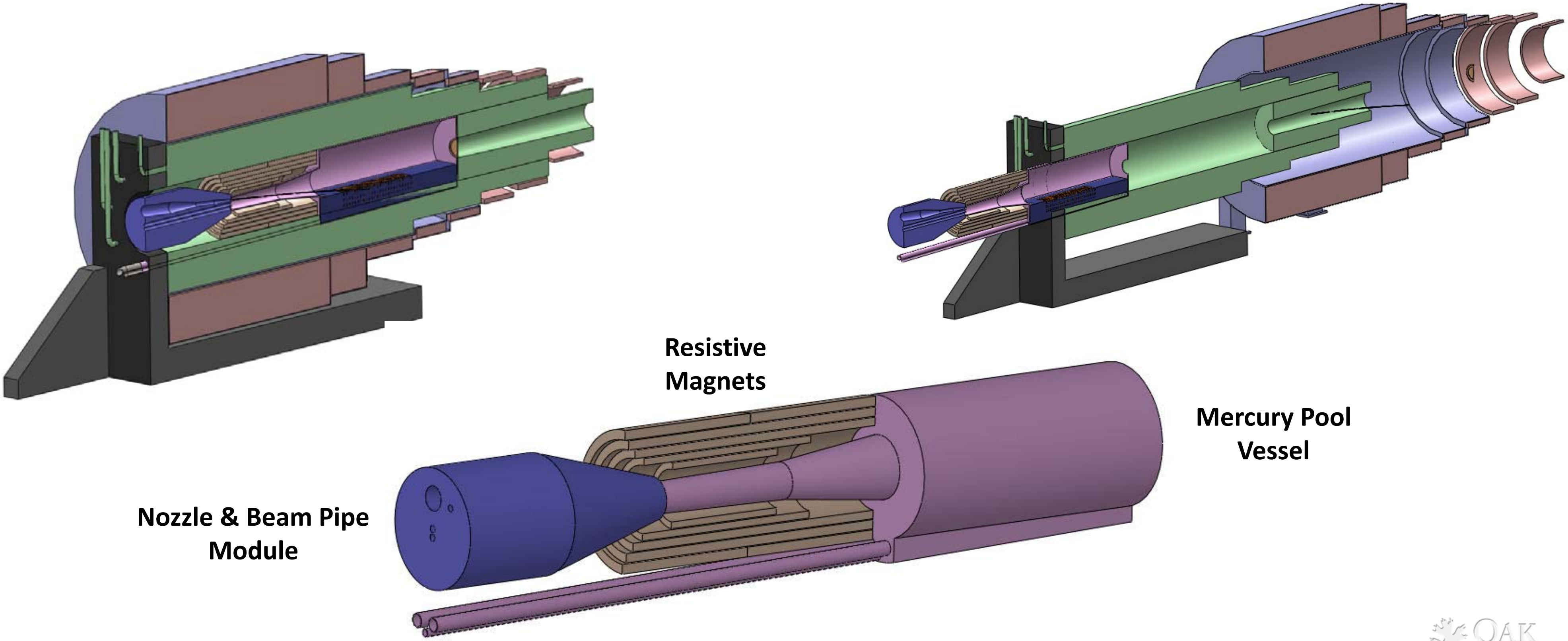
EURISOL Target



MEGAPIE Target

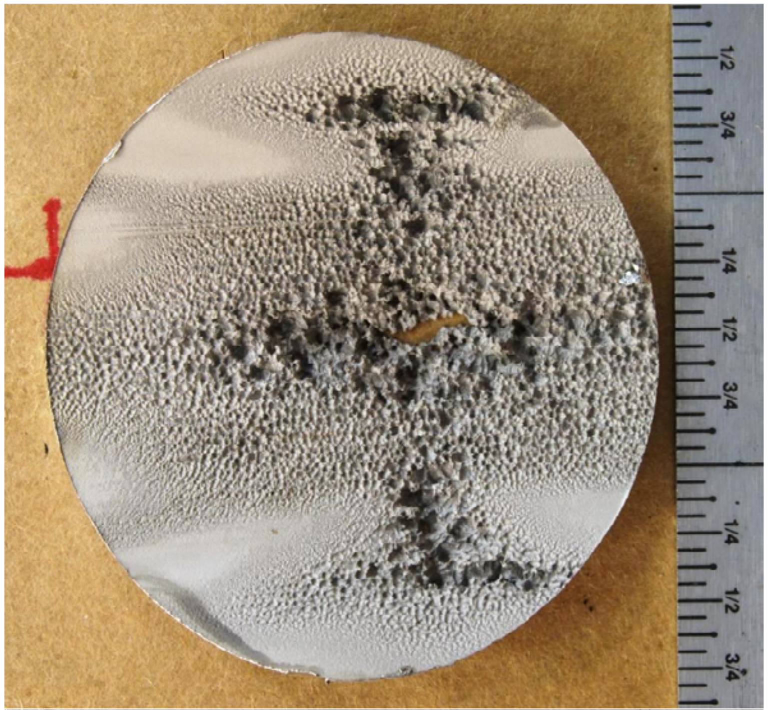
Spatial challenge example:
Neutrino Factory Target Concept

- Target System design challenges
  - Shallow beam / nozzle angles lead to mechanical interferences
  - Nozzle & drain piping require loss of SC magnet shielding
  - Components are large & heavy but require precise alignment
  - Inner resistive magnets severely complicates mercury system, forces an hourglass-shaped mercury volume

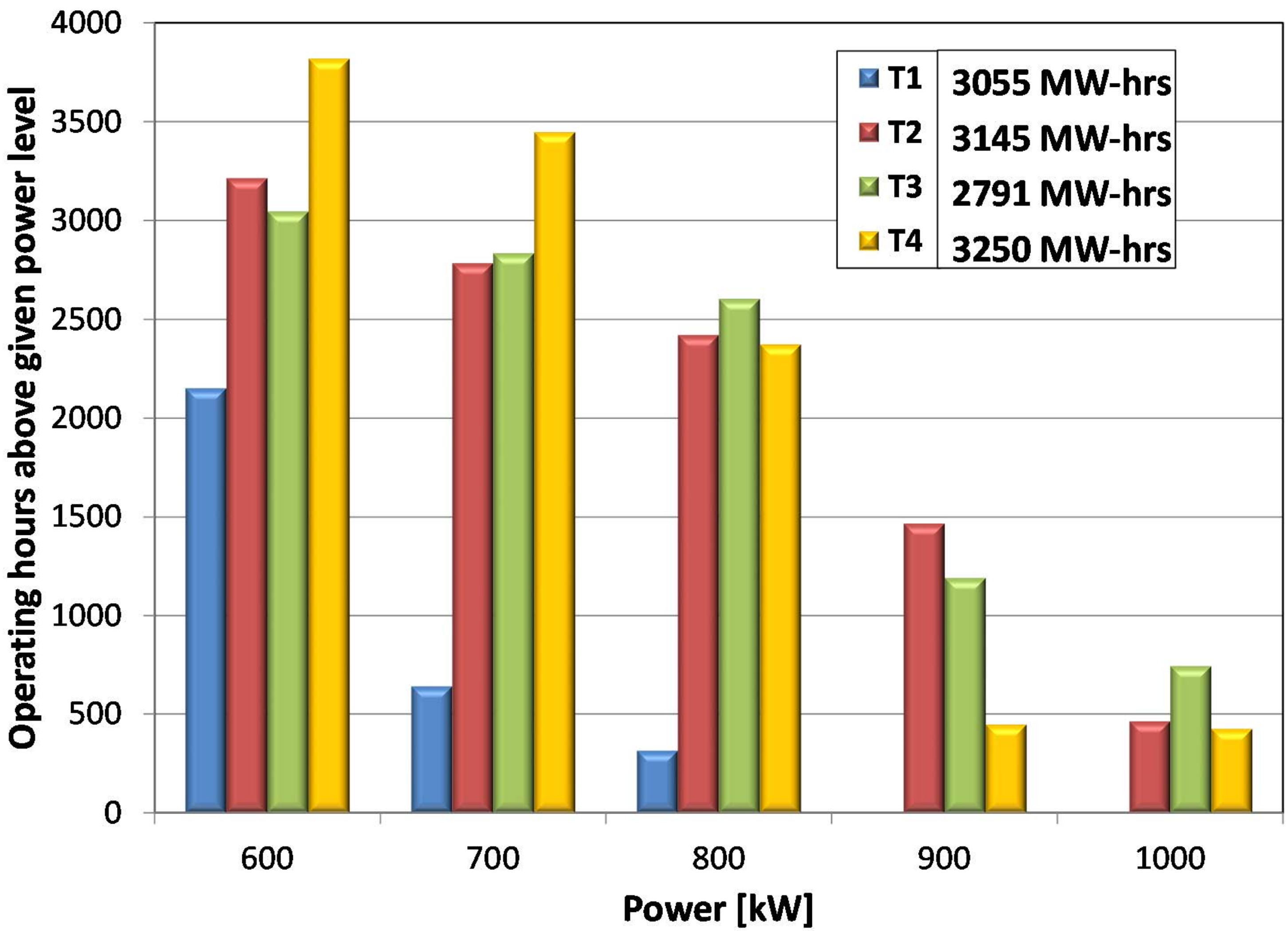


SNS mercury target challenges

- Target power capacity and lifetime are limited by
  - Beam-induced cavitation damage
  - Radiation damage
    - 10 dpa “soft” limit for SS316L
- Requirements for high facility production hours (5000/yr) and availability (>90%)
  - No more than 4 target replacements per year; *fewer better*
- Early target challenges were addressed with R&D
  - Target beam window cooling
  - Vessel fatigue from pressure pulse
  - Mercury compatibility with SS316
  - Remote handling
  - Large mercury process system



Early R&D has paid off:



Target #3 leaked (internally contained) – interrupted user program 2 weeks

Three of first four SNS targets operated without incident

- Although we strongly suspect cavitation damage, we have not located nor characterized T3's leak
  - PIE is a big challenge (difficult and expensive)
- Have not reached accelerator design power of 1.4 MW
- Energy upgrade to 1.3 GeV → 1.8 MW
- Other upgrades → 2+ MW possible

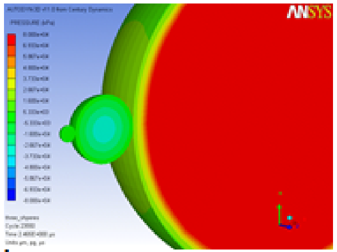
- SNS power / energy density is not so extreme
  - At 2 MW beam power, maximum power density is ca. 750 W/cc; maximum energy density ca. 13 J/cc/pulse

"Flowing" might also include rotating solid targets, or powder metal jets

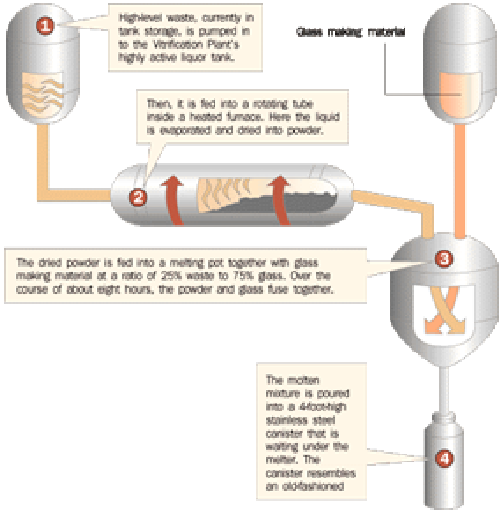
- In the same way that liquid metal targets increase the effective target-beam volume
- STS at SNS (Rotating W – water cooled, 30 – 60 rpm)
- ESS (Rotating tungsten target – gas cooled)
- FRIB (400 kW)
  - Fragmentation target (C, 20-60 MW/cm^3, 5k rpm)
  - Beam dump (10 MW/cm^3)
- Tungsten powder jet for neutrino factories
- Riken / RIBF / BigRIPS

STS rotating target test

Fluidised Powder targets
Advantages and issues



- **Solid**
  - Shock waves constrained within material – no splashing, or cavitation as for liquids
  - Material is already broken
  - Reduced chemistry problems compared with the liquid
- **Fragmented**
  - Small (roundish) grains can withstand higher stresses
  - Favourable disposal of the activated material through verification
- **Moving/flowing**
  - Replenishable
  - Favourable heat transfer (off-line cooling)
  - Metamorphic (can be shaped for convenience)
- **Engineering considerations:**
  - It is a mature technology with ready solutions for most issues
  - Few moving parts and away from the beam!
- **Issues & Questions:**
  - Its dusty
  - Erosion + powder break down. Can be tamed with careful design
  - Beam induced electrostatic charge? Unlikely to be a problem.
  - Eddy currents. Simulations suggest this is ok (T.Davenne)
  - Beam induced thermal expansion of the carrier gas (HiRadMat tests: N.Charitonides, I. Efthymiopoulos)
  - Grain to grain stress propagation: sand bags good for stopping bullets.

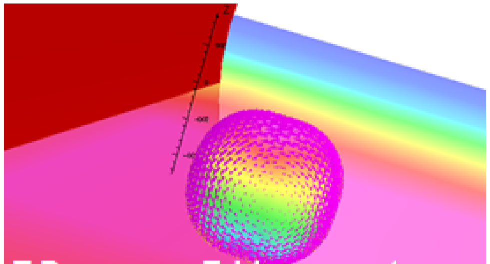


① High-level waste, currently in tank storage, is pumped in to the Vitrification Plant's highly active liquor tank.

② Then, it is fed into a rotating tube inside a heated furnace. Here the liquid is evaporated and dried into powder.

③ The dried powder is fed into a melting pot together with glass making material at a ratio of 25% waste to 75% glass. Over the course of about eight hours, the powder and glass fuse together.

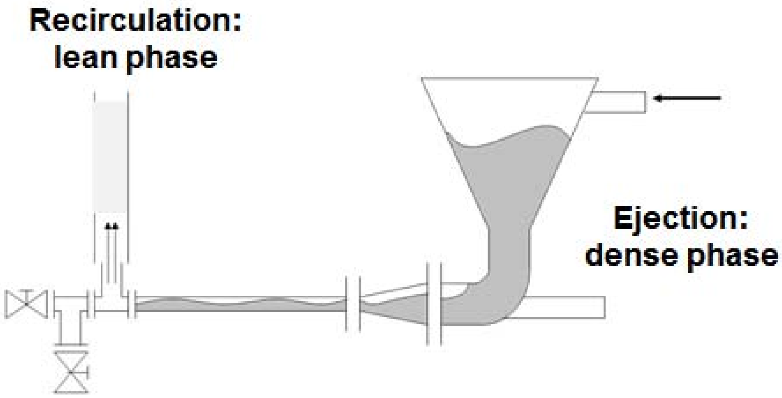
④ The molten mixture is poured into a 4-foot-high stainless steel canister that is waiting under the melter. The canister resembles an old-fashioned



T.Davenne - Eddy currents

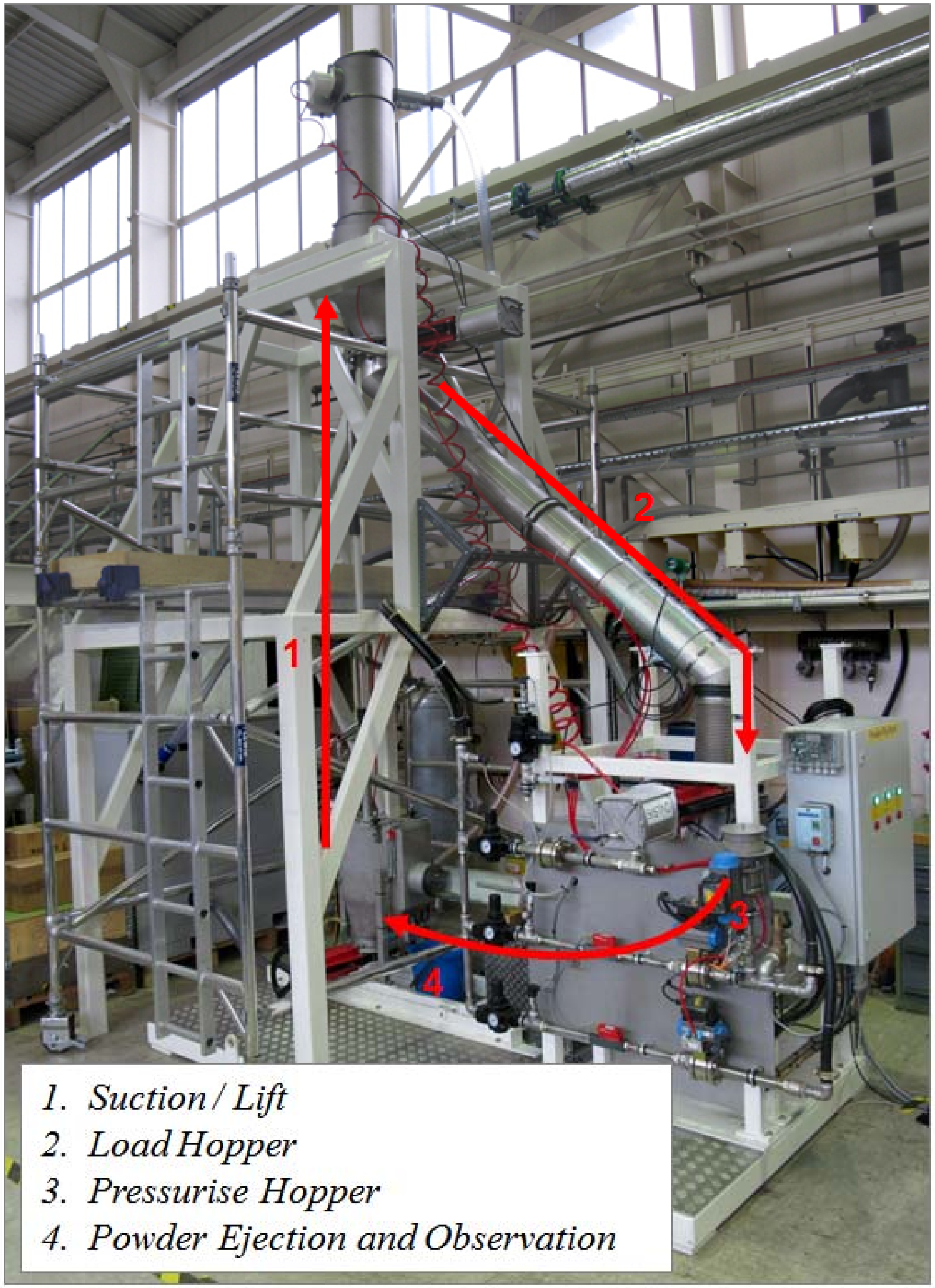
The rig: tests on pneumatic conveying of tungsten

- Powder
  - Rig contains 100 kg Tungsten
  - Particle size < 250 microns
- Parameters
  - Stainless-steel or glass nozzle
  - Nozzle length: 0.5 – 1.2 m
  - Driver pressure: 1 – 4 bar
- Batch process:
  1. Suction / Lift
  2. Load Hopper
  3. Pressurise Hopper
  4. Ejection / observation



Recirculation: lean phase

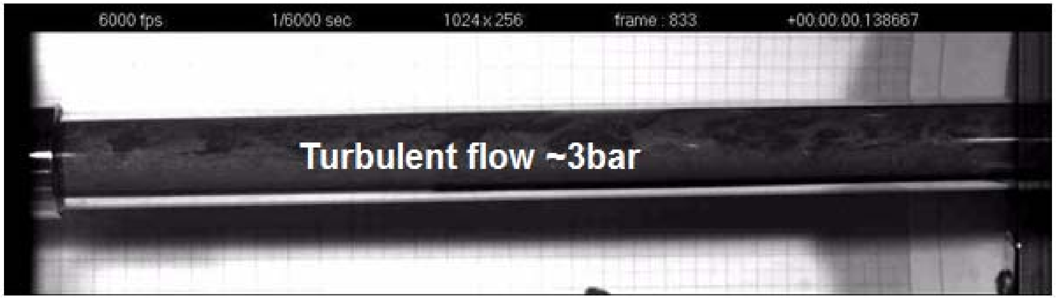
Ejection: dense phase

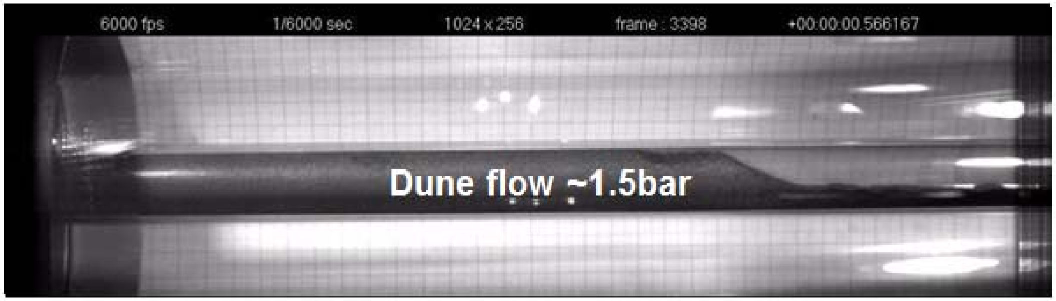


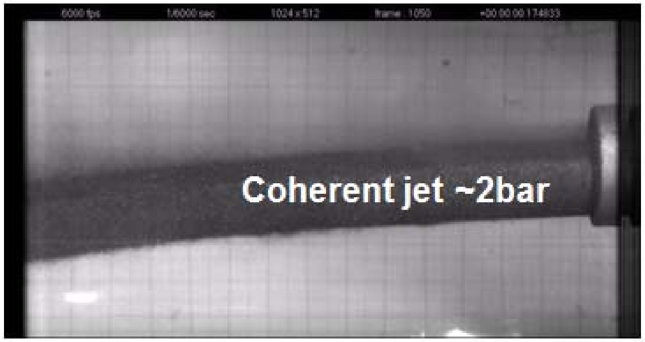
1. Suction / Lift
2. Load Hopper
3. Pressurise Hopper
4. Powder Ejection and Observation

Dense phase conveying: good news!

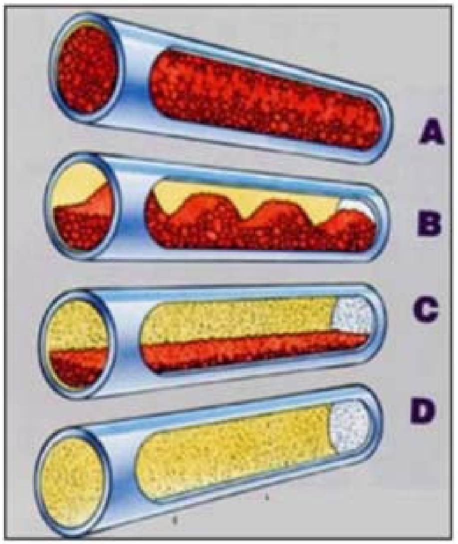
Tungsten **can** be conveyed in the dense phase, in the lean phase and makes interesting dense/coherent jets







Theoretical powder conveying regimes



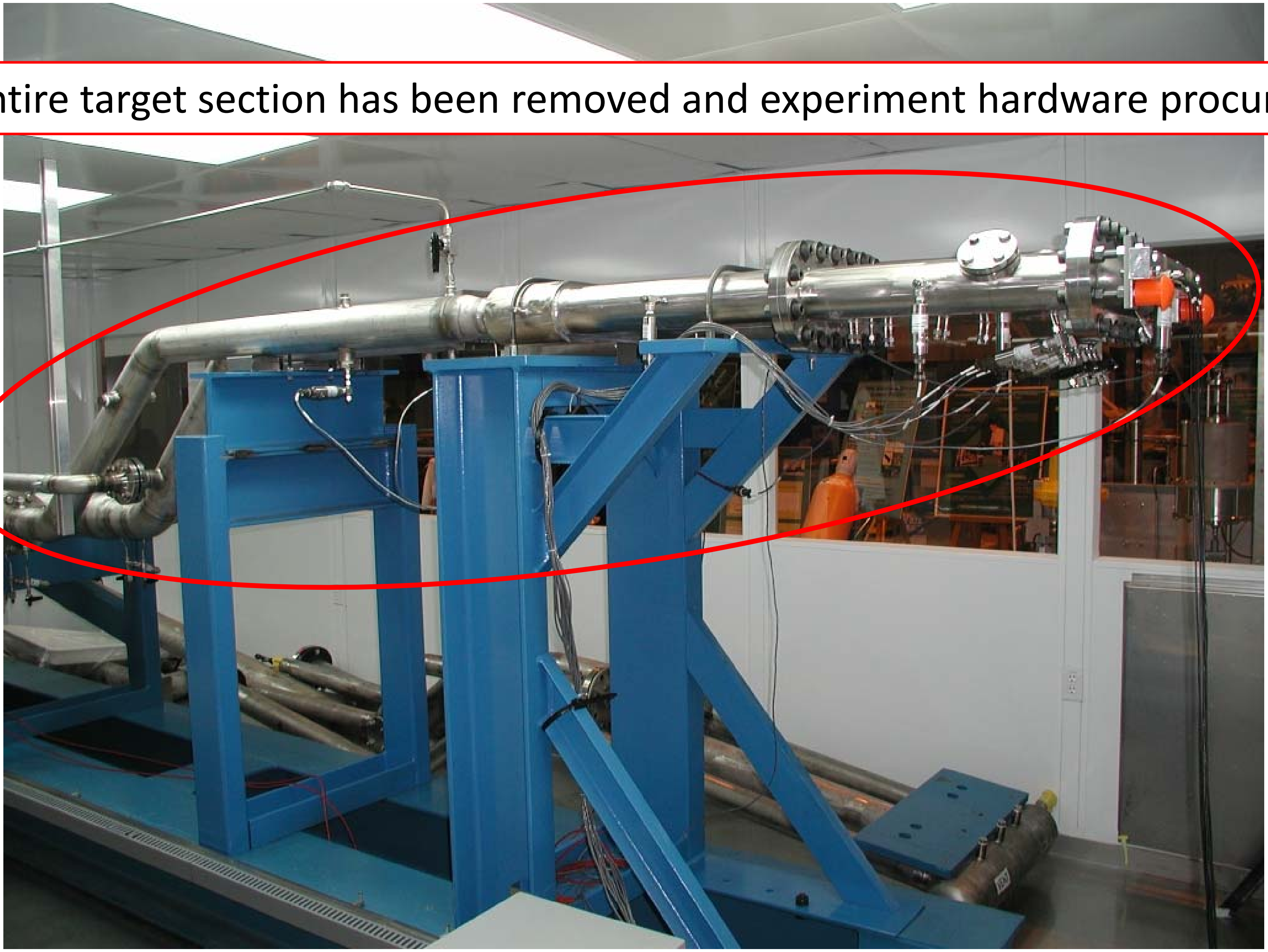
Challenges for future flowing targets using high power and / or energy density

- Steady state heat removal to limit temperature and stress
  - Target material limits
  - Target containers
  - Beam windows
- Pulsed:
  - Shock induced cavitation, target stability
- Both:
  - Irradiated target and container properties
  - Process systems for liquid metals (or powders)
  - Remote handling requirements
  - Waste disposition

Challenges specific to short-pulse, liquid metal spallation targets

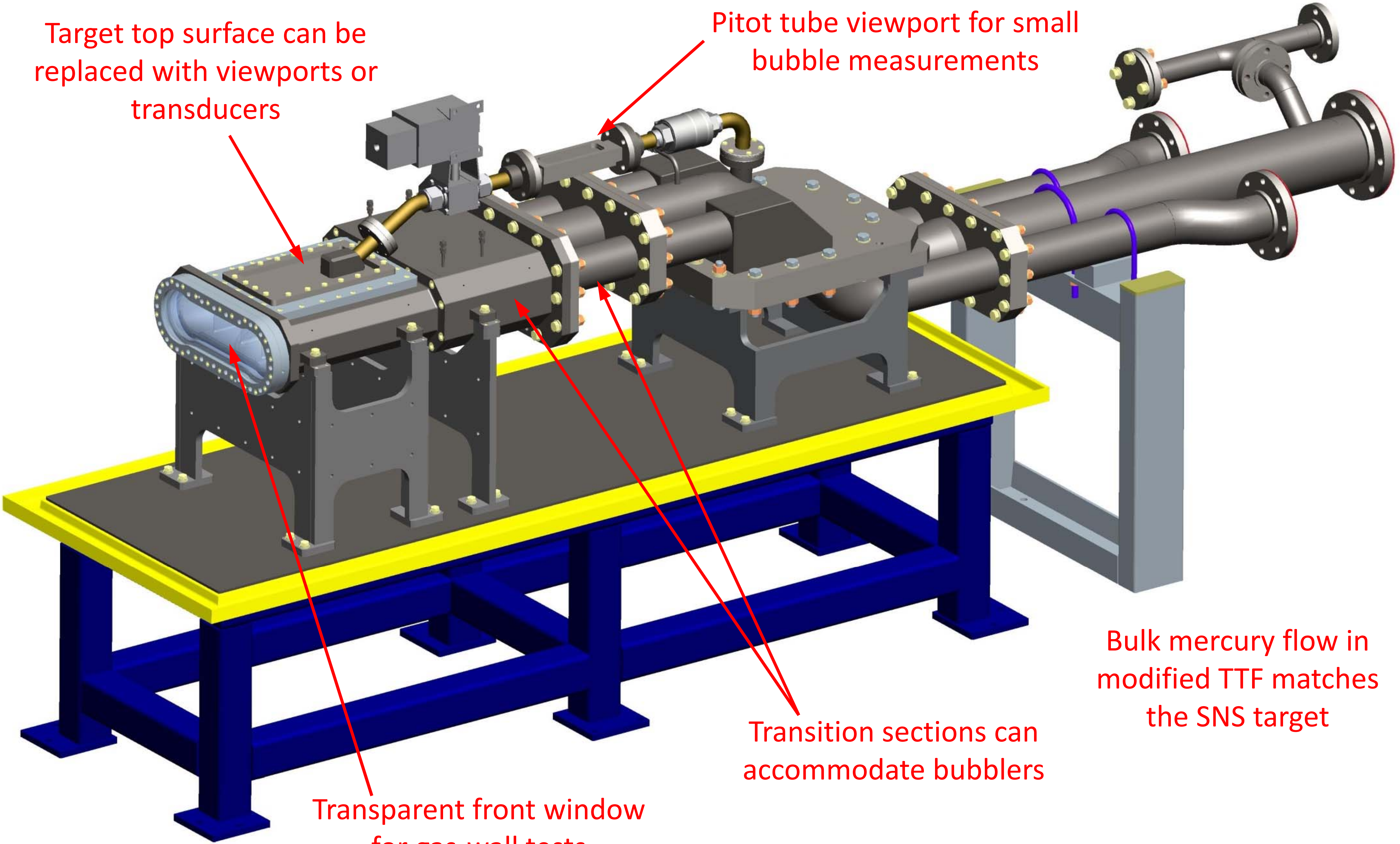
- Cavitation damage mitigation
  - Protective gas walls
    - Two-phase modeling, validation experiments
  - Small gas bubbles
    - Bubble generation and measurement
    - In-beam evaluation of mitigation efficacy
  - Post irradiation examination

Modifications to the SNS Target Test Facility supporting gas mitigation



Entire target section has been removed and experiment hardware procured

Experiments for gas mitigation in the SNS Target Test Facility



Target top surface can be replaced with viewports or transducers

Pitot tube viewport for small bubble measurements

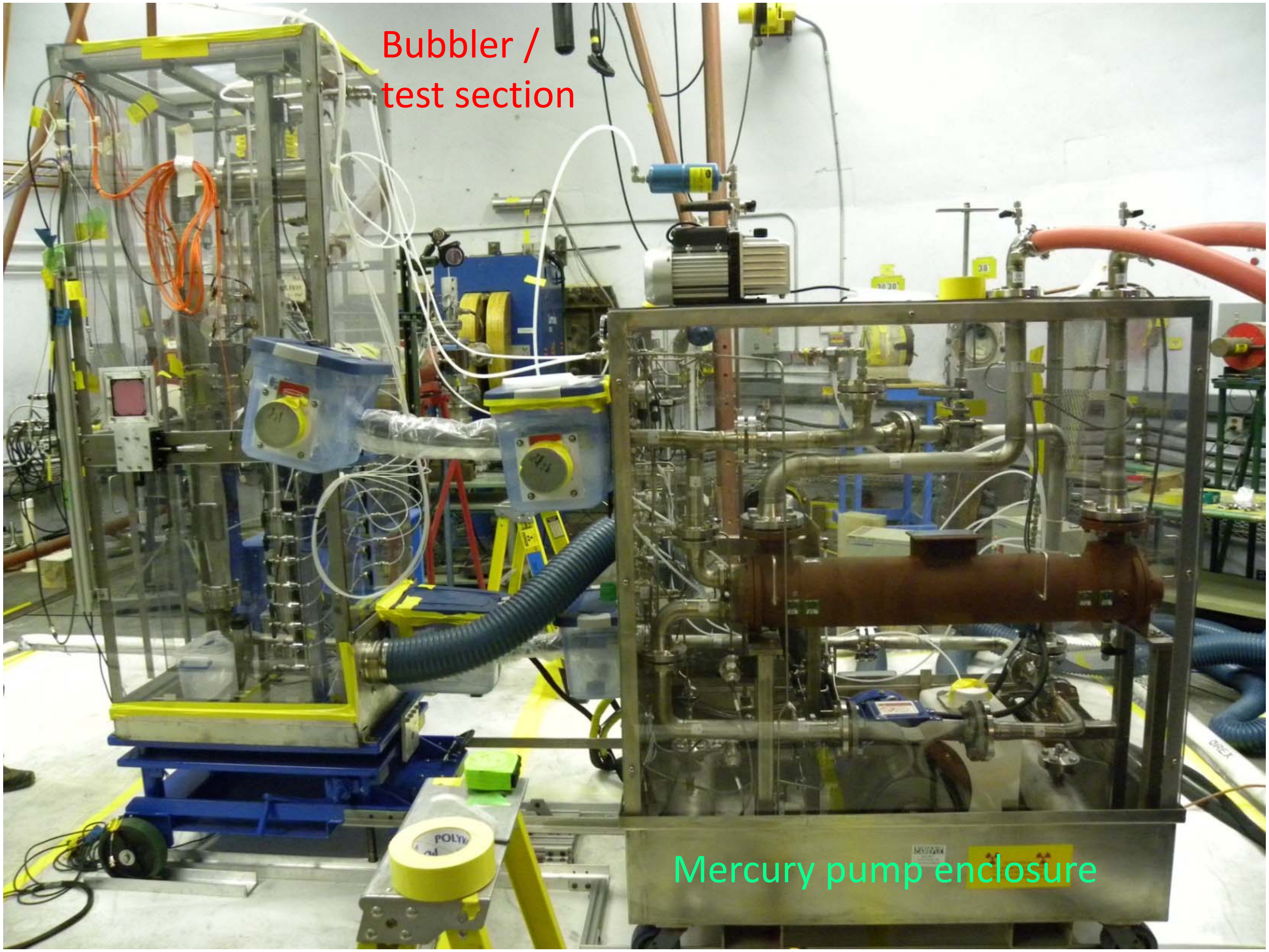
Bulk mercury flow in modified TTF matches the SNS target

Transition sections can accommodate bubblers

Transparent front window for gas-wall tests

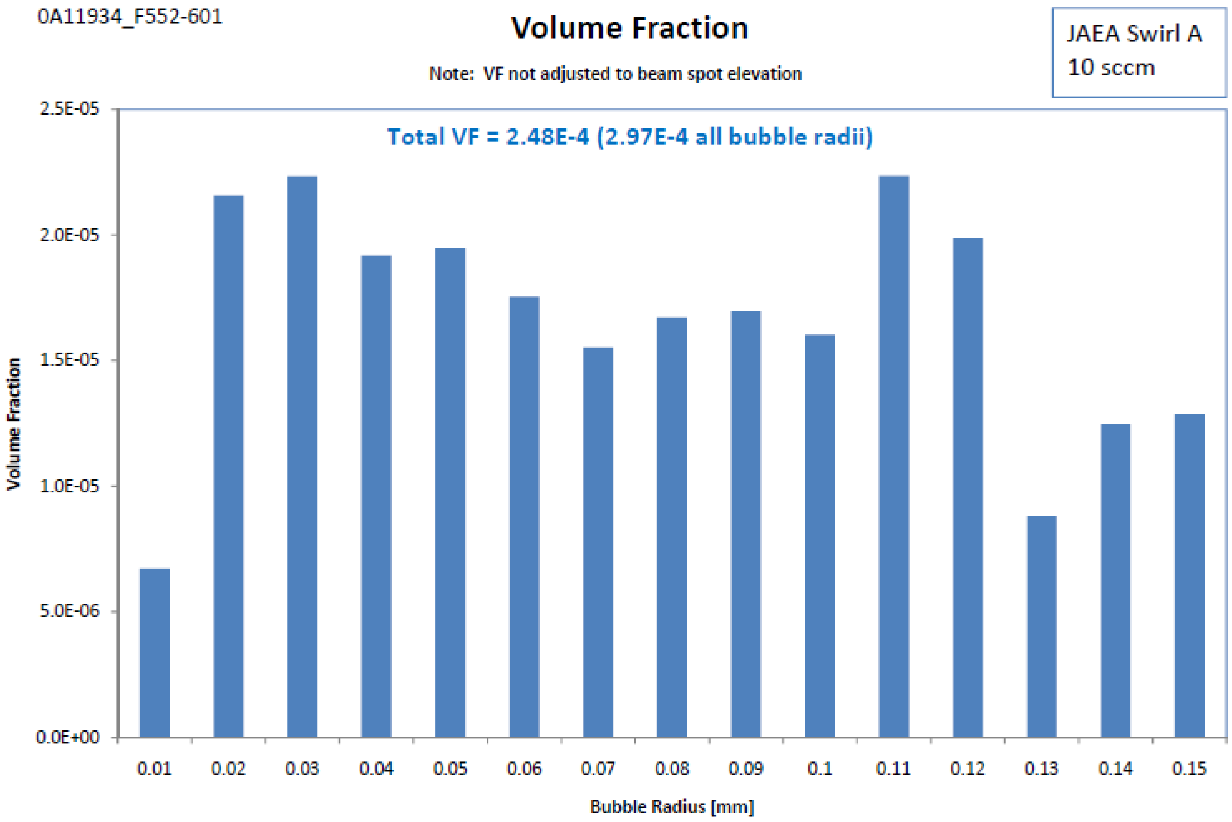
Small gas bubble mitigation experiment at LANSCE - WNR

Collaboration with J-PARC
Irradiations done in 2011

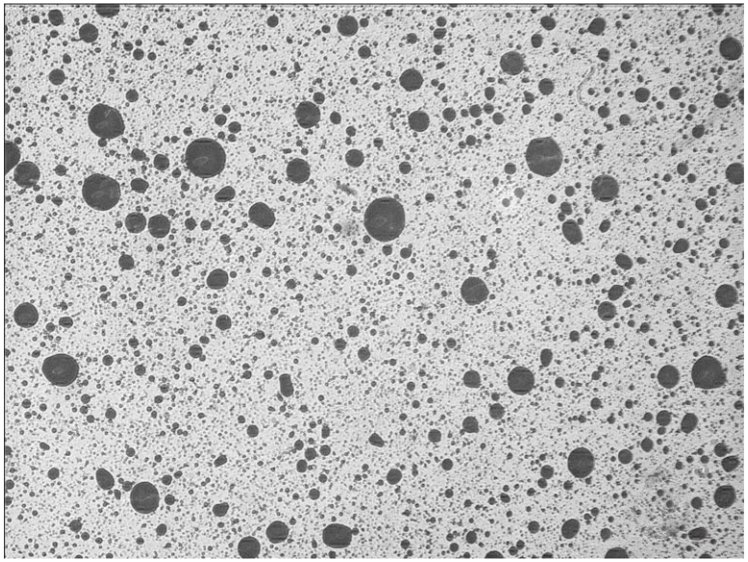


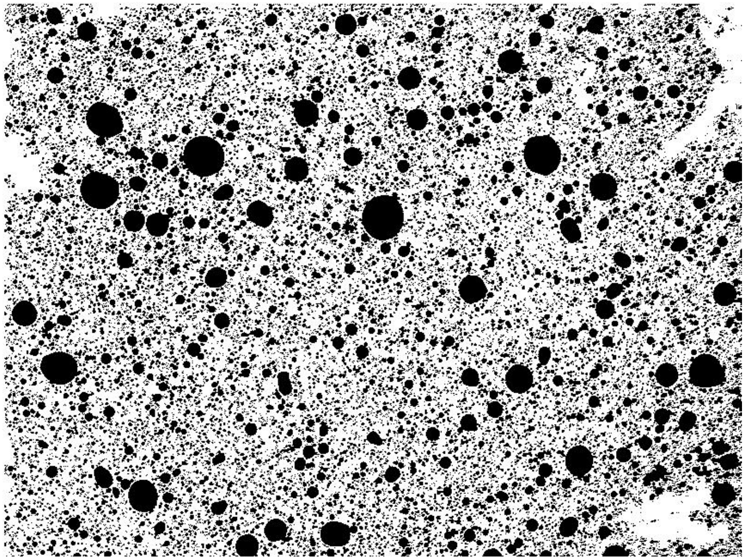
Ten candidate bubblers were evaluated

- Three selected for in-beam testing
- Damage evaluation now underway



Bright field image of bubbles that rise up to horizontal view port (FOV: 10 x 7.5 mm)



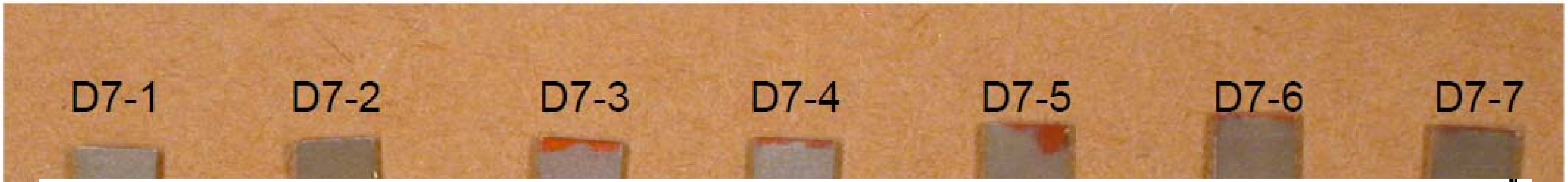


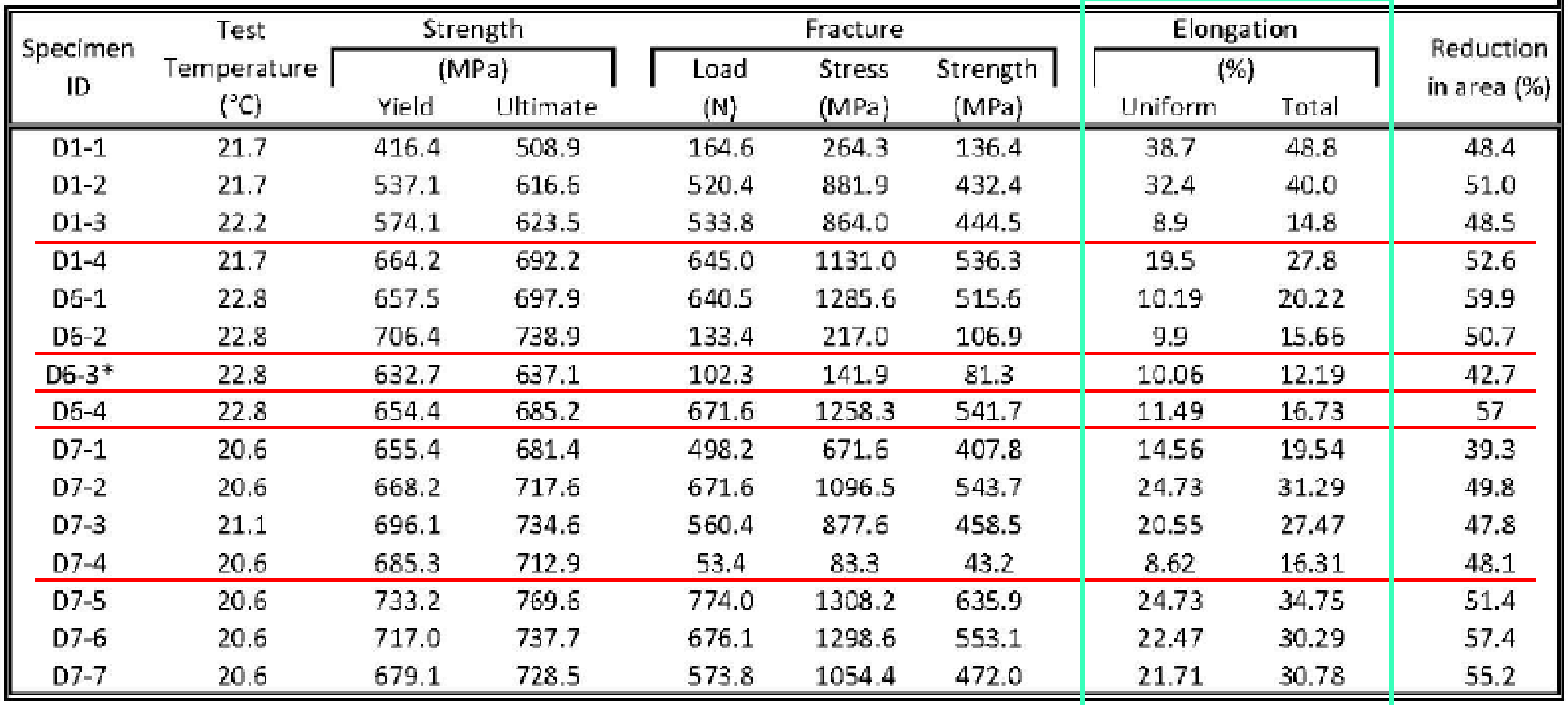
Analyzed image provides bubble size distribution data (ImageJ)

More generic target challenges

- Target / container irradiated mechanical property data
  - Raise dpa limit for SS316L, other “standard” alloys
  - Establish relevant data for other alloys, e.g., titanium, duplex steels
- Compatibility of liquid metals with vessel and window materials
  - Corrosion, liquid metal embrittlement

Tensile specimens were machined from samples cut from SNS target #1 disks and pulled to failure





Specimen ID	Test Temperature (°C)	Strength (MPa) Yield	Strength (MPa) Ultimate	Fracture Load (N)	Fracture Stress (MPa)	Fracture Strength (MPa)	Elongation (%) Uniform	Elongation (%) Total	Reduction in area (%)
D1-1	21.7	416.4	508.9	164.6	264.3	136.4	38.7	48.8	48.4
D1-2	21.7	537.1	616.6	520.4	881.9	432.4	32.4	40.0	51.0
D1-3	22.2	574.1	623.5	533.8	864.0	444.5	8.9	14.8	48.5
D1-4	21.7	664.2	692.2	645.0	1131.0	536.3	19.5	27.8	52.6
D6-1	22.8	657.5	697.9	640.5	1285.6	515.6	10.19	20.22	59.9
D6-2	22.8	706.4	738.9	133.4	217.0	106.9	9.9	15.66	50.7
D6-3*	22.8	632.7	637.1	102.3	141.9	81.3	10.06	12.19	42.7
D6-4	22.8	654.4	685.2	671.6	1258.3	541.7	11.49	16.73	57
D7-1	20.6	655.4	681.4	498.2	671.6	407.8	14.56	19.54	39.3
D7-2	20.6	668.2	717.6	671.6	1096.5	543.7	24.73	31.29	49.8
D7-3	21.1	696.1	734.6	560.4	877.6	458.5	20.55	27.47	47.8
D7-4	20.6	685.3	712.9	53.4	83.3	43.2	8.62	16.31	48.1
D7-5	20.6	733.2	769.6	774.0	1308.2	635.9	24.73	34.75	51.4
D7-6	20.6	717.0	737.7	676.1	1298.6	553.1	22.47	30.29	57.4
D7-7	20.6	679.1	728.5	573.8	1054.4	472.0	21.71	30.78	55.2

Table 8.5.1: ORNL SNS Irradiated Tensile Testing Results Summary.