High-Power (MW-Class) Targets for Hadron Beams

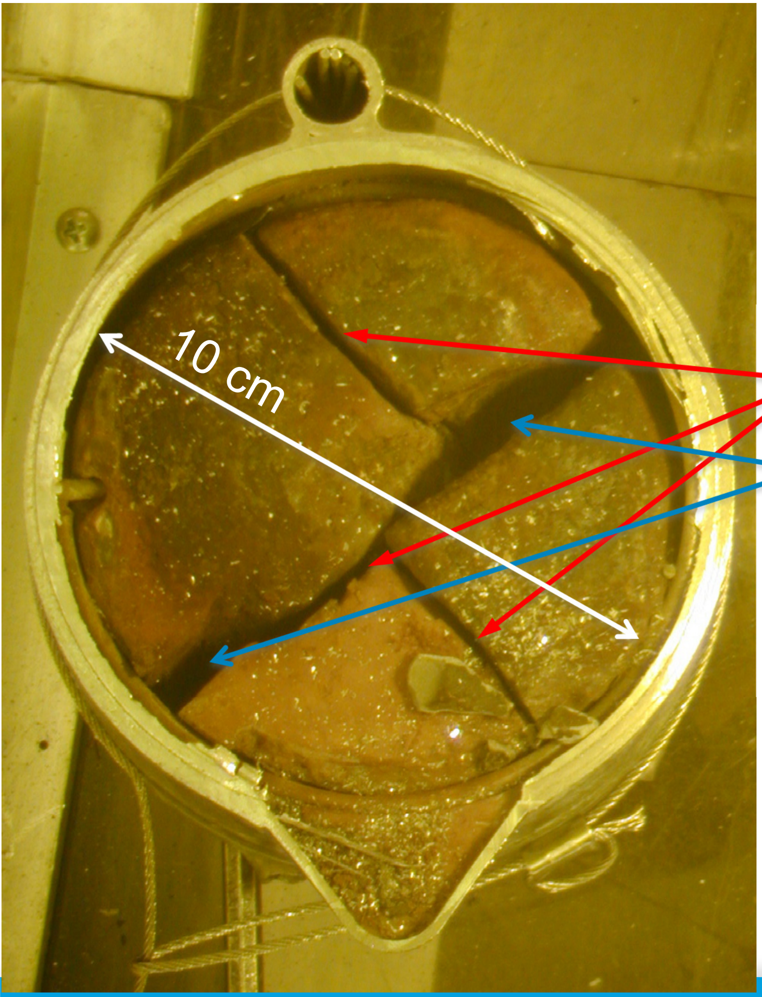
Eric Pitcher

European Spallation ESS AB, Lund, Sweden

What are the issues of concern for high-power targets?

- How to remove the heat deposited by the beam?
- Can reasonable target lifetimes be maintained?
- What are the safety concerns, and how are they best addressed?
- Do target operations become more complex at higher power?
- How to address the added complexity of short pulses?

Example: target degradation due to thermal stress and chemical corrosion

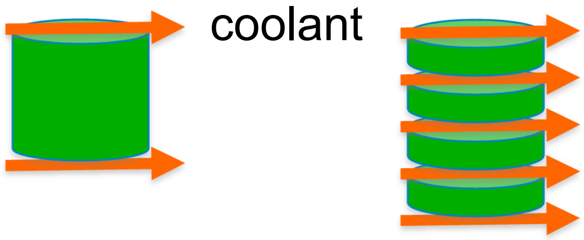


- Target is a solid cylinder of tungsten, edge-cooled
- 80-kW, 800-MeV proton beam
- Top cover plate has been cut off
- Radial cracks from thermal stress
- Portions corroded by highly oxidizing species produced when the proton beam passes through the cooling water

Target from the Manuel Lujan Neutron Scattering Center (LANL)
Source: M.J. Baumgartner, et al., AccApp'03 (2003) 399.

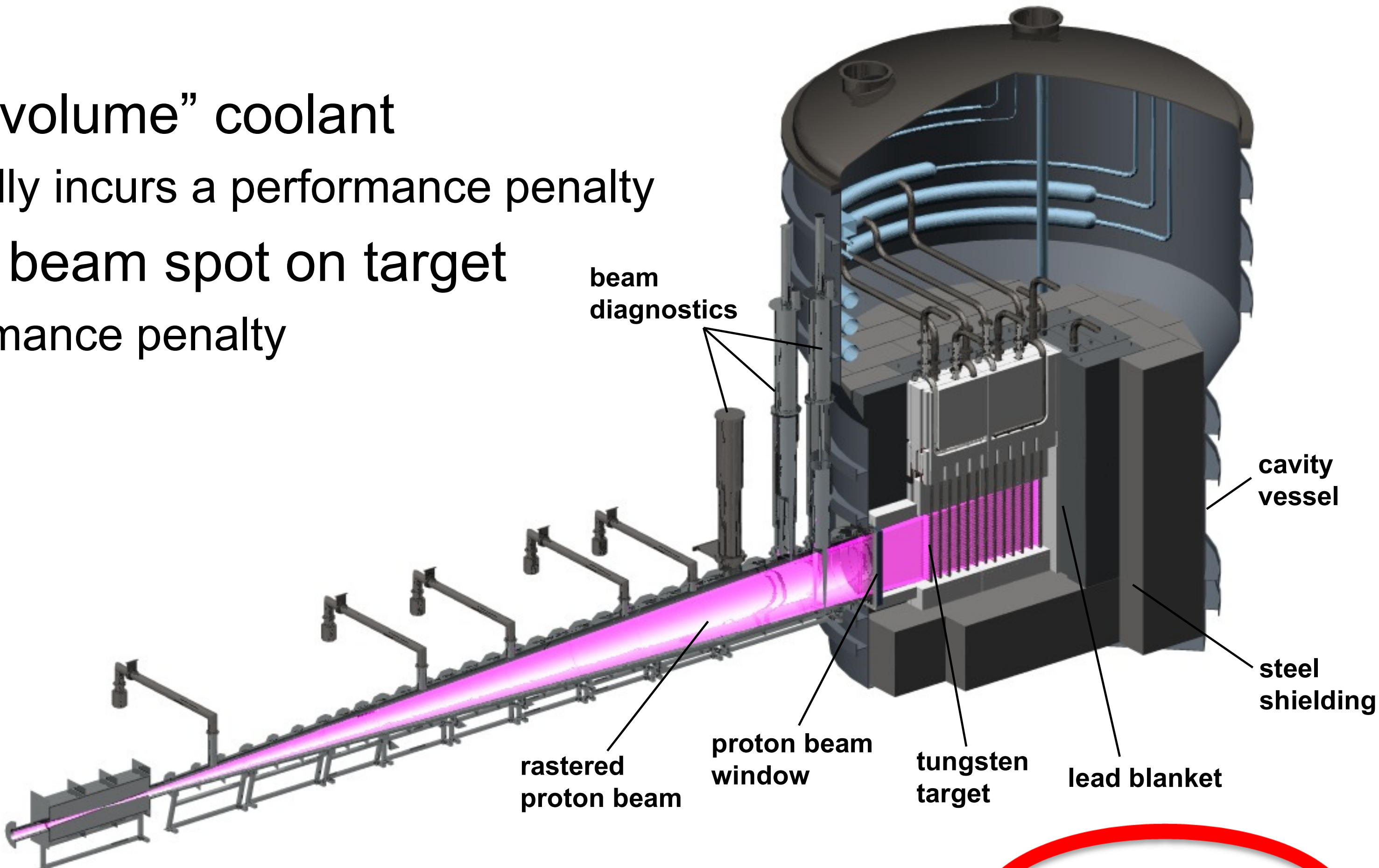
How to accommodate high beam power?

- Employ "volume" coolant
  - Normally incurs a performance penalty



How to accommodate high beam power?

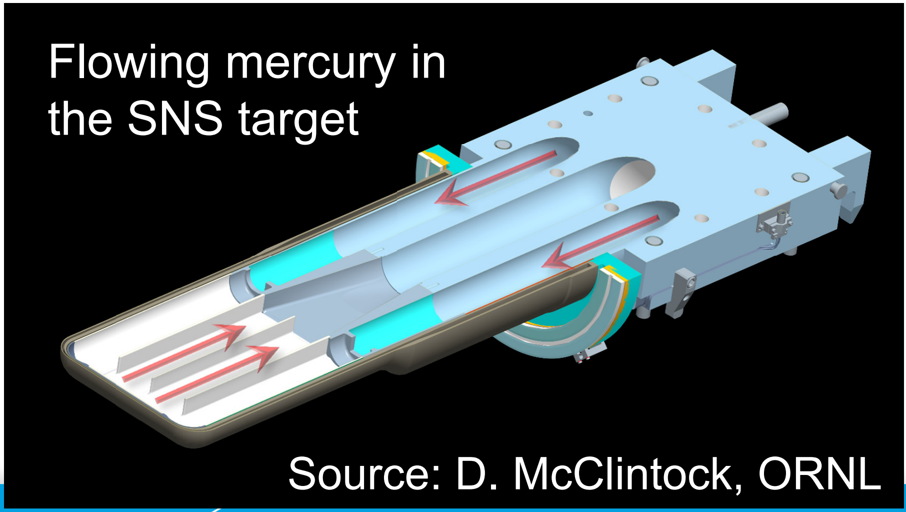
- Employ "volume" coolant
  - Normally incurs a performance penalty
- Increase beam spot on target
  - Performance penalty



Accelerator Production of Tritium design: 100 mA, 170 MW beam
Beam spot on target: 20 cm wide by 160 cm high ➔ 31 μA/cm^2

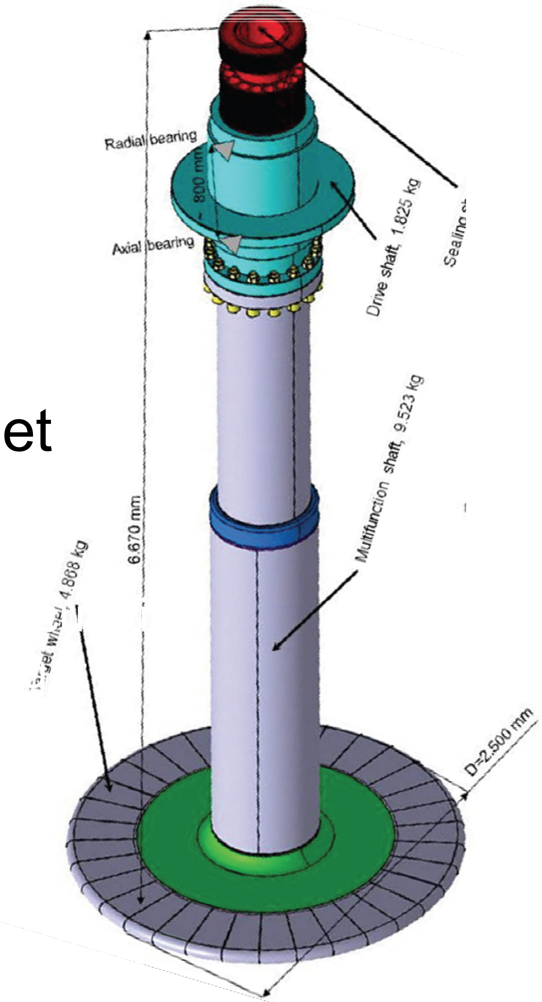
How to accommodate high beam power?

- Employ "volume" coolant
  - Normally incurs a performance penalty
- Increase beam spot on target
  - Performance penalty
- Use a liquid metal (or powder) as the target
  - Potentially a performance penalty



How to accommodate high beam power?

- Employ “volume” coolant
  - Normally incurs a performance penalty
- Increase beam spot on target
  - Performance penalty
- Use a liquid metal (or powder) as the target
  - Potentially a performance penalty
- Employ a rotating target
  - Operationally more complex



European Spallation Source
rotating tungsten target

How to accommodate high beam power?

- Employ "volume" coolant
  - Normally incurs a performance penalty
- Increase beam spot on target
  - Performance penalty
- Use a liquid metal (or powder) as the target
  - Potentially a performance penalty
- Employ a rotating target
  - Operationally more complex
- Rule of thumb:
  Performance ~ $(\text{beam power})^{0.8}$

How to maintain reasonable target lifetime?

- Maintain a reasonable beam current density on target by:
  - Increasing the beam spot size
  - Using a rotating target
  - Reasonable estimate: target will survive at least one year at 30 μA/cm^2
- Keep cyclic thermal stresses low by design
- Option: remove all structural components from the beam's path
  - No proton beam window
  - No target container or coolant boundary
- Develop structural materials that can withstand higher hadron dose
  - Support campaigns like:
    - the SINQ Target Irradiation Program (STIP) at the Paul Scherrer Institute
    - the RaDIATE Collaboration (Fermilab, Rutherford Appleton Lab, CERN, others)

Target safety becomes ever more important with increasing beam power

- Radionuclide inventory in a 1-MW target is roughly on par with that of a 100-kW fission reactor
- Following beam shutdown, means to remove the target decay heat must be robust and highly reliable
- Good practice: adopt the safety approach developed for nuclear facilities
  - Identify and assess the hazards
  - Those hazards with severe consequences and high frequency undergo detailed design basis accident (DBA) analysis
  - Controls identified to mitigate the likelihood or consequence of a DBA are deemed “credited controls,” which must meet a higher standard in quality and pedigree

A “safety by design” philosophy should be adopted at the earliest stages of target design

- Safety of the public and of workers should be an important factor when making design choices
- Hierarchy:
  1. **Passive safety features**
     Easiest to defend to regulators
     Normally the least-cost option
  2. **Engineered controls**
     Active safety systems with an established pedigree
     Should be simple in concept, implementation and operation
  3. **Administrative controls**
     Relies on established processes and procedures
     Typically involves high operational overhead
     Subject to human error

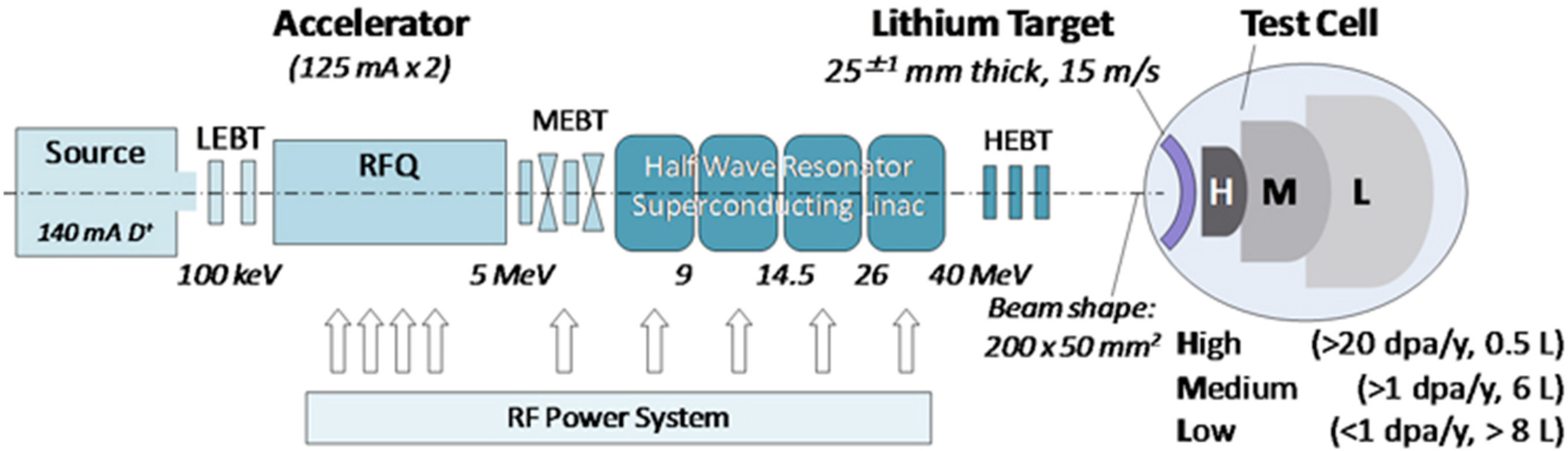
Operational impacts of high-power targets

- High-power target facilities normally require hot cells and remote handling capability to service the target
- Substantial operations infrastructure needed
  - Radiation protection staff (needed for accelerator as well)
  - Radioactive emissions and environmental monitoring (accelerator too)
  - Expertise in regulatory processes and procedures pertaining to the protection of the public and workers for off-normal events
  - Waste processing and disposal

Shipping cask and custom trailer for the 1-MW MEGAPIE target
Source: M. Wohlmuther, PSI

IFMIF
International Fusion Materials Irradiation Facility

- D,Li stripping source with beam power of 40 MeV × 250 mA = 10 MW
- Achieved using two separate 125-mA D^+ accelerators
- Both beams are directed onto a windowless flowing lithium target
- Currently in the Engineering Validation and Demonstration stage

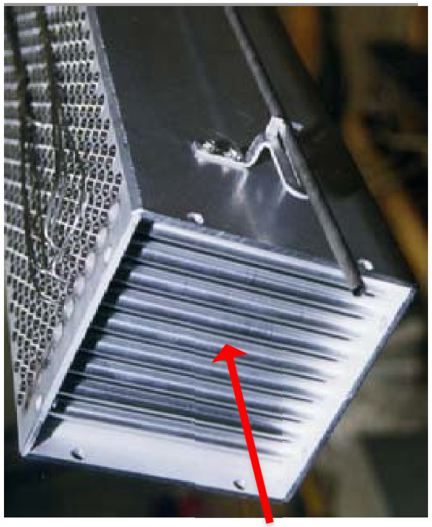


Operating since 1997, SINQ at the Paul Scherrer Institute for neutron scattering research

- Cyclotron delivers 1.8 mA of 575 MeV protons (1 MW) to SINQ
- Continuous improvements in the target neutronic performance through design innovations and materials evolution
- Water-cooled Pb target with Zircalloy and Aluminum structures

Target 6

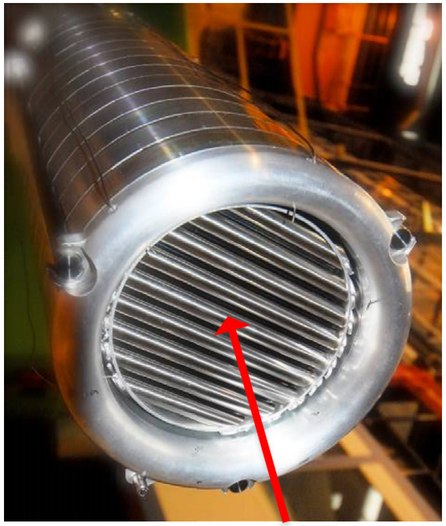
Pb-filled Zircalloy tubes



proton beam

Target 7

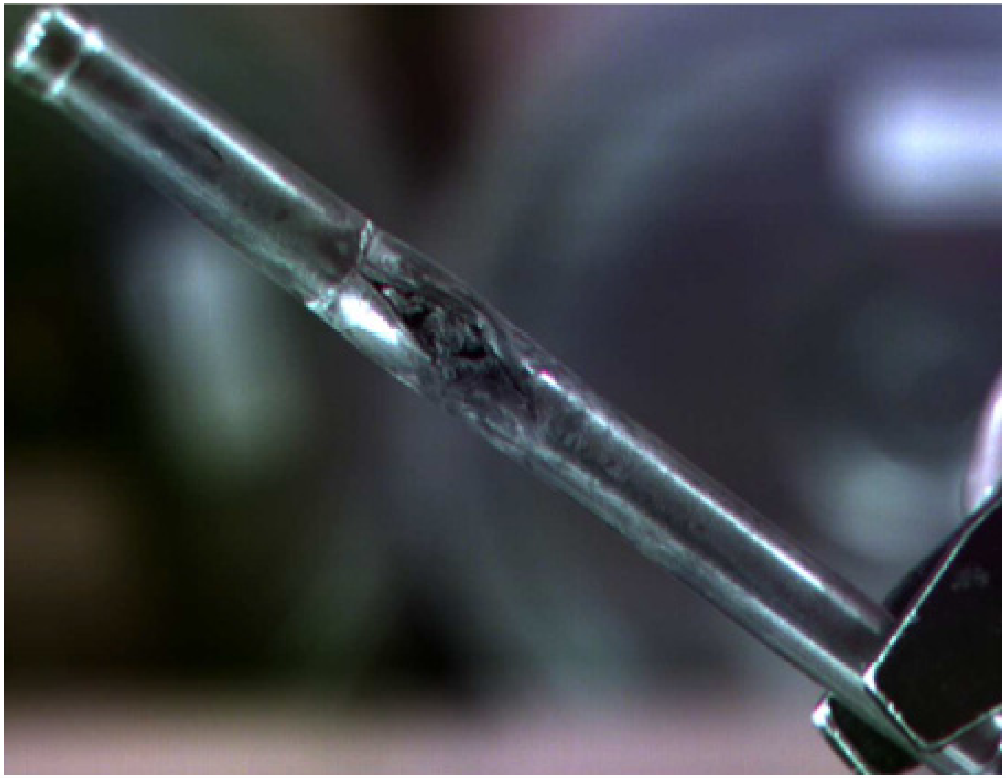
Pb-filled Zircalloy tubes, with Pb annulus



proton beam

Strive to minimize the consequences of inadvertent operator error

- Beam over-focus condition on the SINQ target due to an operator setting magnets for the wrong beam tune
- Cladding breached and cooling water contaminated
- Many STIP samples lost (a 1.5-year irradiation campaign)
- Impacts to operations, safety, and technical accomplishment



A rotating solid target was first proposed for the German SNQ project

- Beam power was to be 1.1 GeV × 5.5 mA = 5.5 MW
- 250-μs pulses at 100 Hz

beam impingement

Prototype of a rotating tungsten target from the German SNQ project, ca. 1985.

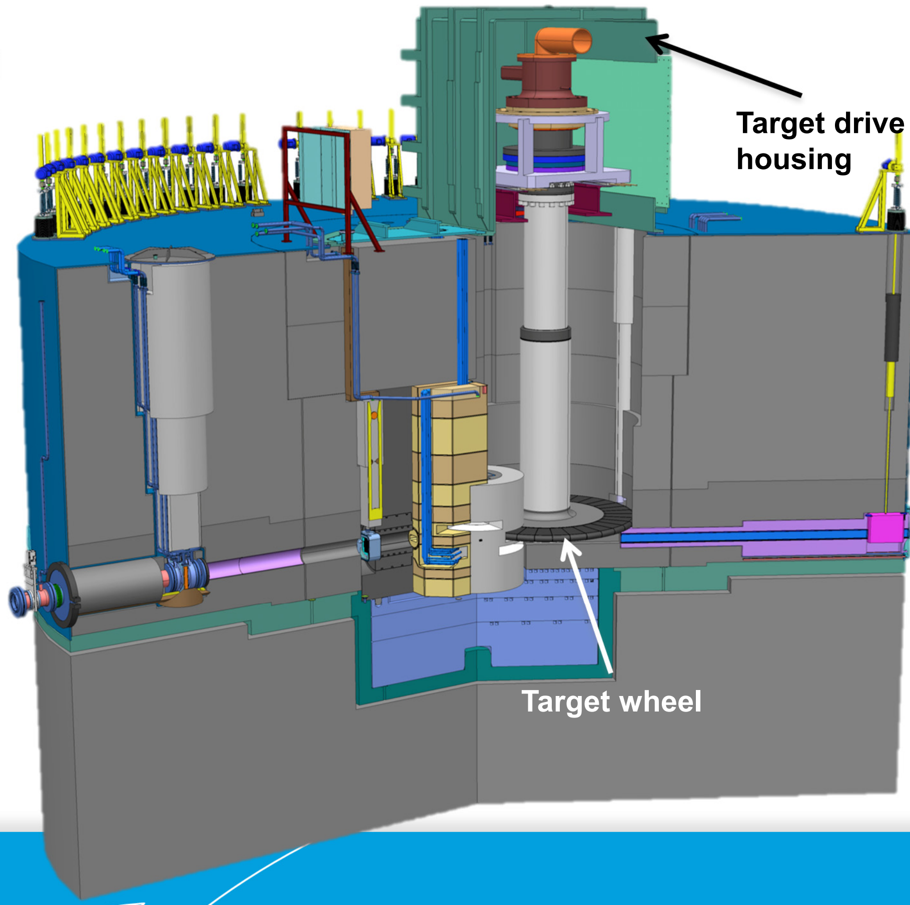
Rotating Target Prototype for the SNS Second Target Station

- Target wheel:
  - 1.2 m diameter by 8 cm high
  - 2000 kg
  - Rotational speed of 30 to 60 rpm
- Suspended on a 3.5 m long shaft
- Designed for 3 MW beam power
- Estimated lifetime of 10 years
- Successfully tested to 2600 hours
- Collaboration of SNS, ESS-Bilbao, and IDOM

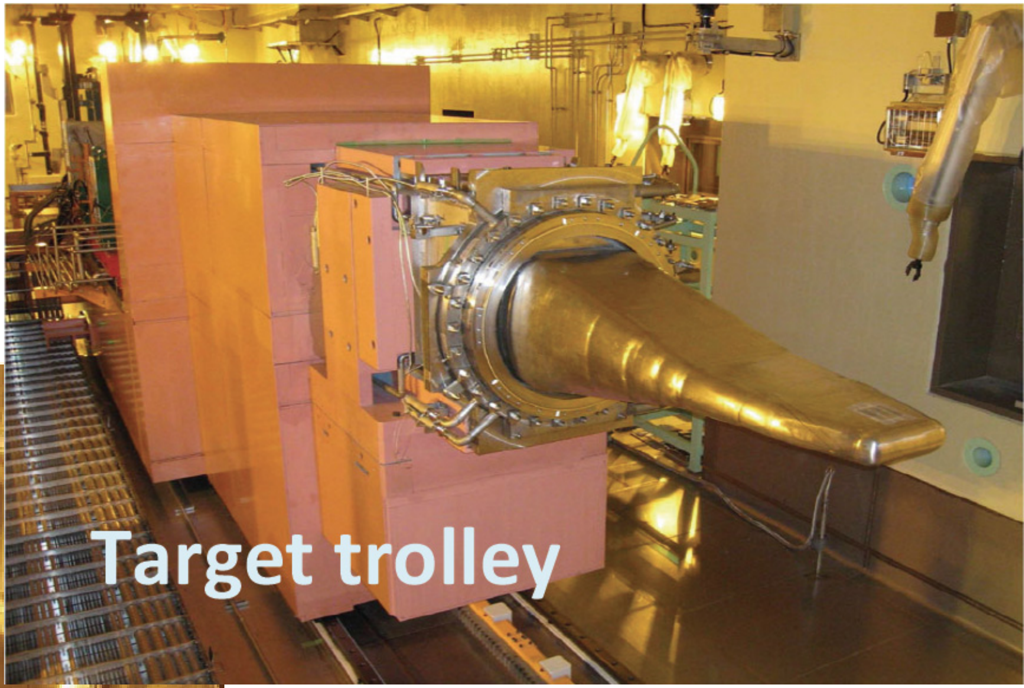
Source: M.J. Rennich, et al., ICANS-XIX (2010) TO059.

The European Spallation Source proposes to use a helium-cooled rotating tungsten target

- 2 GeV × 2.5 mA = 5 MW
- 2.86 ms pulses at 14 Hz
- Target susupended on a 6-m shaft
- Target rotation synchronized with the beam pulse
- Estimated lifetime = 5 years
- 2.5 m diameter target wheel
- Helium mass flow rate is 3 kg/s
- Helium temperature rise is 200° C

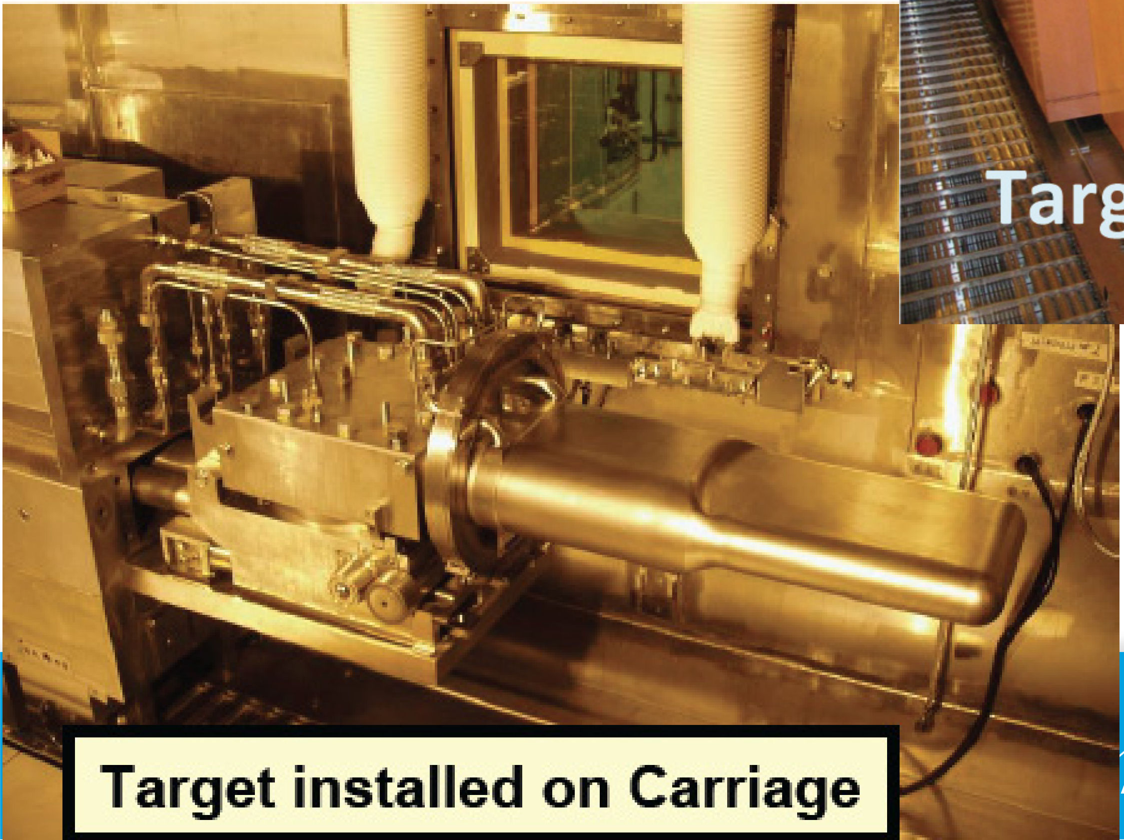


SNS (ORNL) and JSNS (J-PARC) are MW-class spallation targets that use flowing mercury



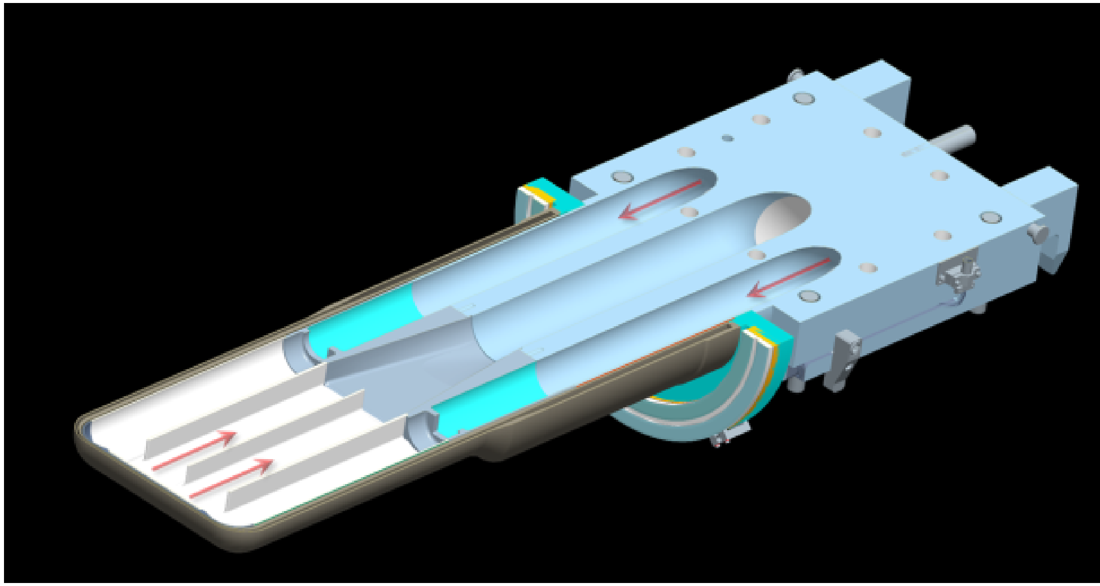
JSNS target

SNS target



Cavitation erosion to the container wall in a mercury target subjected to short (~1 μs) pulses

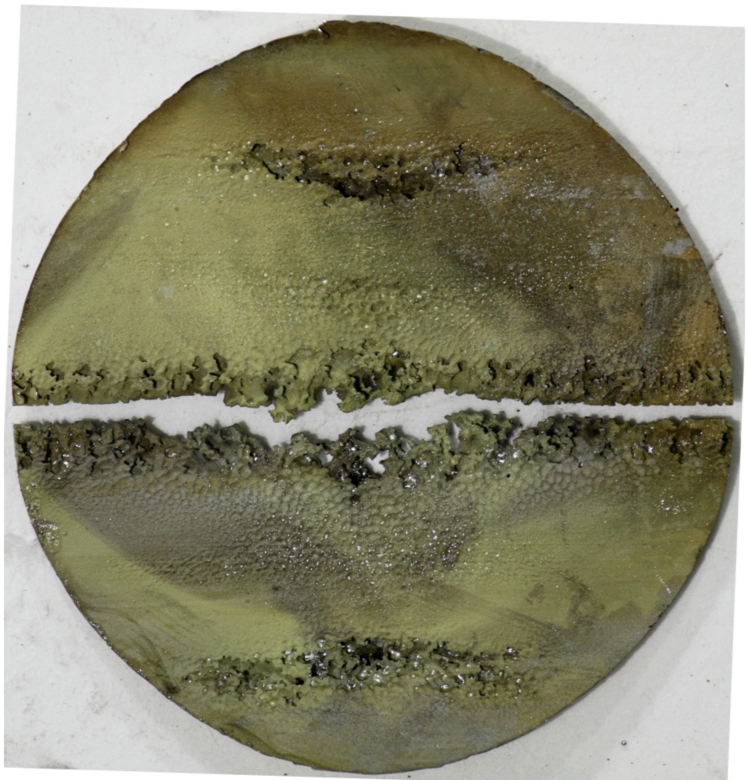
- SNS mercury target container, made of 316L stainless steel
- 900-MeV proton beam deposits up to 12 kJ per pulse in mercury



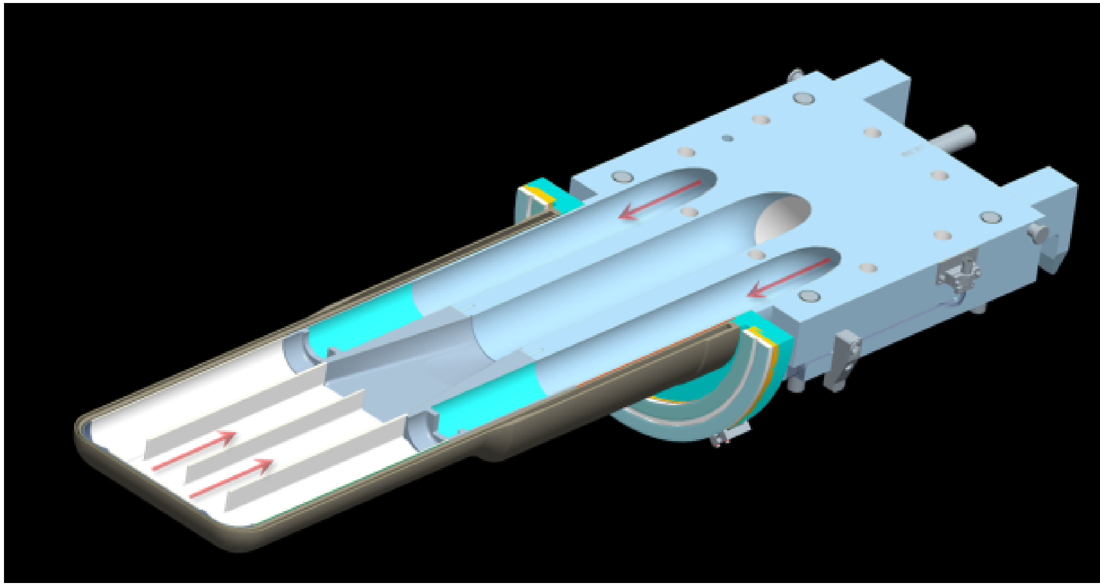
D.A. McClintock, et al., JNM 431 (2012) 147.

Cavitation erosion to the container wall in a mercury target subjected to short (~1 μs) pulses

- SNS mercury target container, made of 316L



D.A. McClintock, et al., JNM 431 (2012) 147.

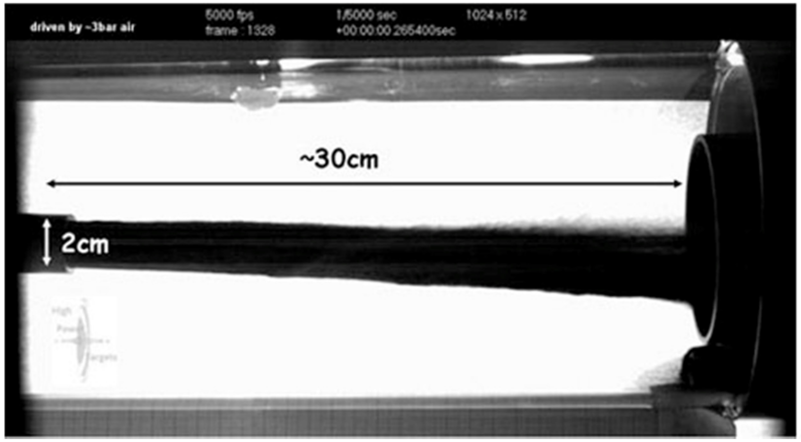


- Thermal expansion causes pressure waves that are reflected at the container walls, causing cavitation erosion at certain locations

Methods for addressing the pressure waves from short pulses

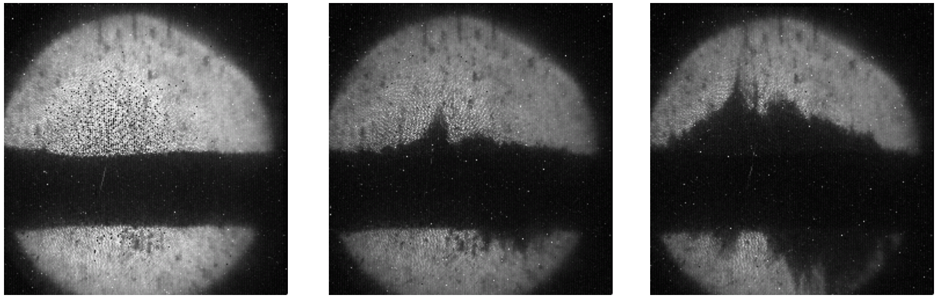
- Add helium gas to the liquid metal
  - Bubbles must be small and well distributed
  - Successfully demonstrated at JSNS (Futakawa et al., ICANS-XIX)
- Remove the container altogether
  - Free jets of heavy metal

Tungsten Powder Jet Target



T.W. Davies, et al., Powder Technology 201 (2010) 296.

Mercury Jet Target (MERIT Expt)



t = 0 *t = 0.175 ms* *t = 0.375 ms*

I. Efthymiopoulos, IEEE Nucl. Sci. Symp. (2008) N58-5.

Summary

- Multiple means have been devised to deal with the high power deposited in hadron targets, ranging from windowless designs to 3000-cm^2 beam spots on target
- Due to the significant radionuclide inventory in MW-class targets, safety is an important consideration in target design
- The infrastructure needed to handle and dispose the highly radioactive components of MW-class targets is significant, with attendant operating costs
- Maintaining reasonable target lifetimes will continue to be a struggle as beam powers increase
- Recent efforts to design targets to handle hadron beams with significant energy (>10 kJ) in a short pulse (<1 μs) are yielding promising results, but more work likely remains