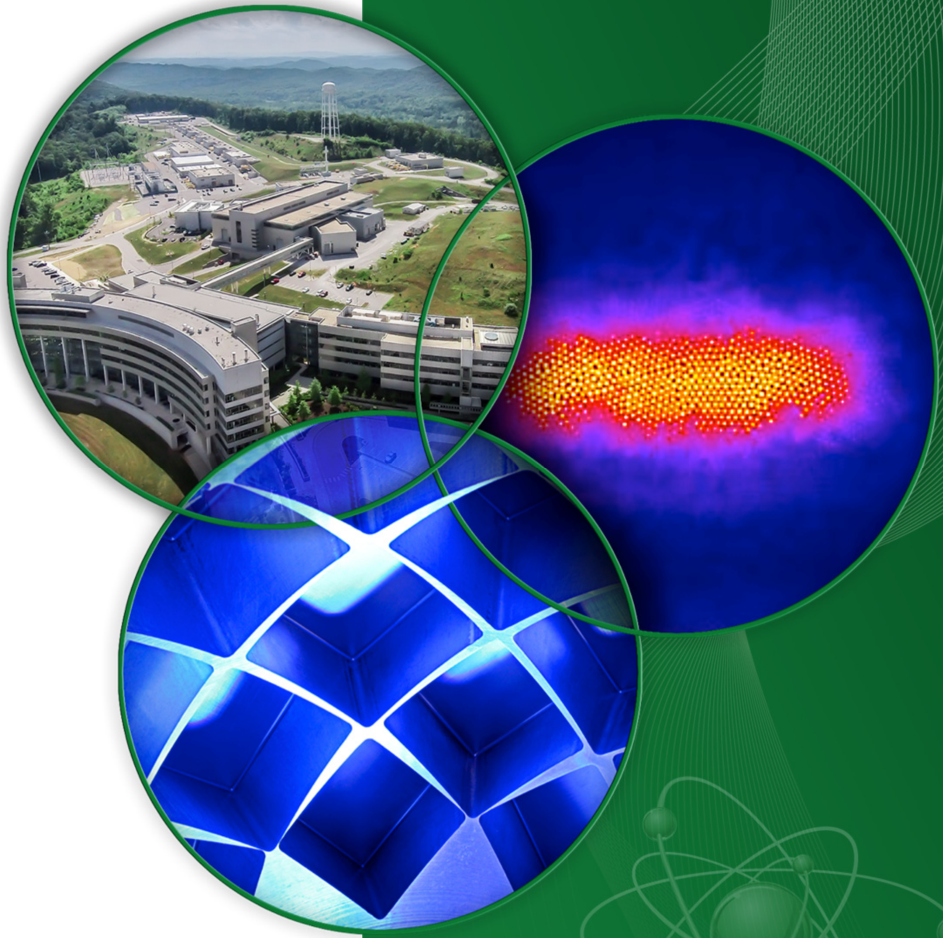
# High Power Proton Beam Targets: Technological Evolution, Current Challenges, and the Future



J. Galambos ORNL

2016 IPAC, Busan Korea

ORNL is managed by UT-Battelle
for the US Department of Energy

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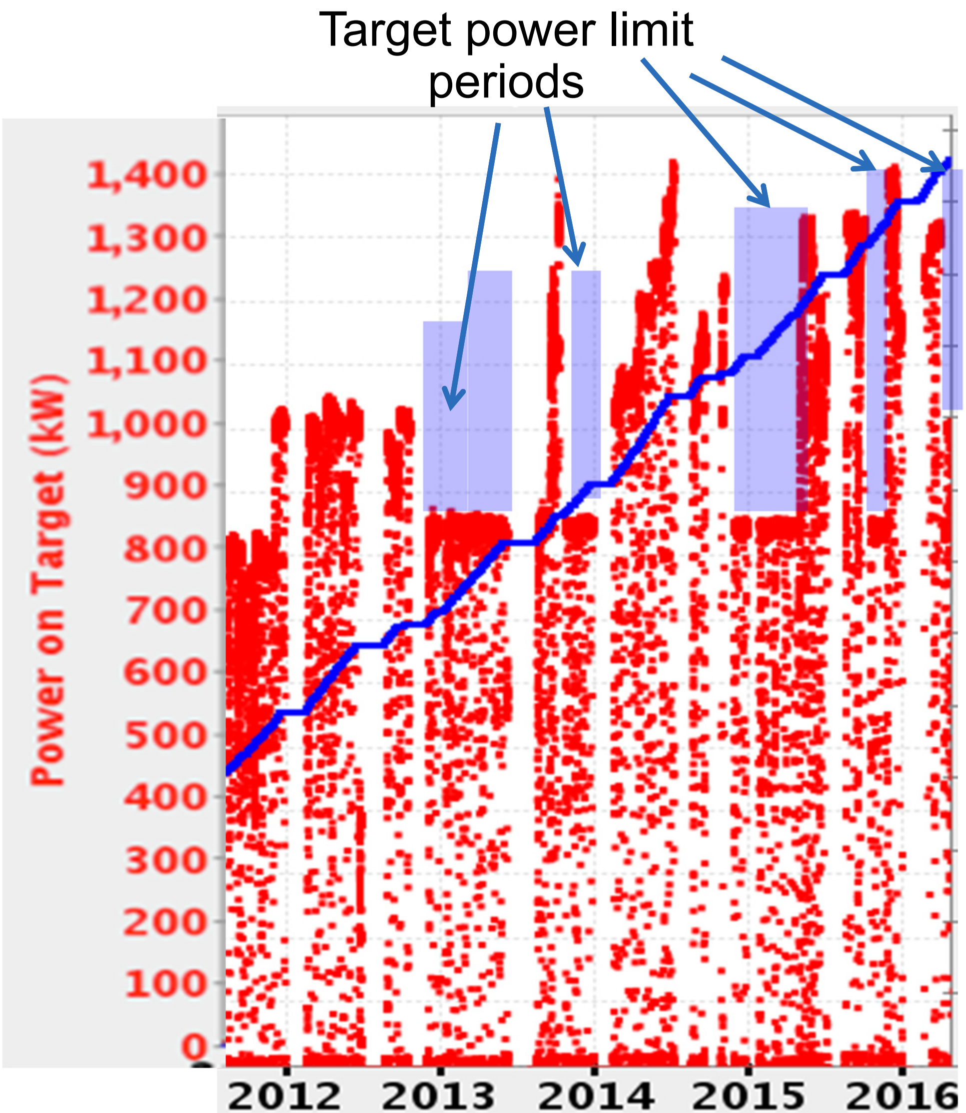
# High Power Proton Beam Targets: *The Ultimate (De)accelerator*

- Design Considerations
  - Maximize intense secondary yield production
  - Remove heat
  - Handle pressure pulse
    - High cycle fatigue
    - Cavitation
  - Radiation damage
  - Robotic access / disposal
- Unfortunate reality
  - Impossible to have realistic test stand
    - New high power targets pushing frontier are experiments
    - Complicated fabrication – long lead time

# Targets Can Limit Facility Performance




- At SNS, targets have had a stronger limit on operational beam power than the accelerator the last 3.5 years
- J-PARC neutron source beam power is presently limited by target



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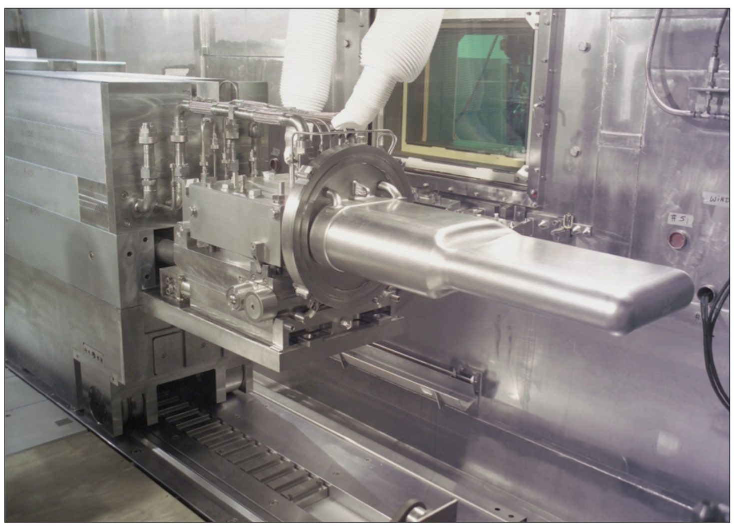
# SNS Target History: Unplanned Leakage is the Norm

| Target | Date Installed | Target Failed | Calendar days between beam |
|---|---|---|---|
| T1 | 4/26/06 | | |
| T2 | 8/17/09 | | |
| T3 | 7/29/10 | 4/3/11 | 17 |
| T4 | 4/19/11 | | |
| T5 | 1/25/12 | | |
| T6 | 8/2/12 | 9/22/12 | 14 |
| T7 | 10/3/12 | 10/11/12 | 45 |
| T8 | 11/16/12 | | |
| T9 | 10/14/13 | | |
| T10 | 7/23/14 | 9/12/14 | 37 |
| T11 | 9/22/14 | 10/27/14 | 23 |
| T12 | 11/18/14 | 9/25/2015 | 14 |
| T13 | 10/8/15 | 3/22/2016 | 7 |
| T14 | 3/28/2016 | | |

- Unplanned outages have a large impact on the SNS user program
- 7 of 14 installed targets were replaced because they leaked
- “Fast” replacement mitigates science impact

# Irradiated Targets are Nuclear Technology

- SNS exposed target dose rate ~ 35,000 Rads/hr (350 Sv/hr)
- Robotic manipulation is a must
- Disposal is complicated
  - Approved disposal container



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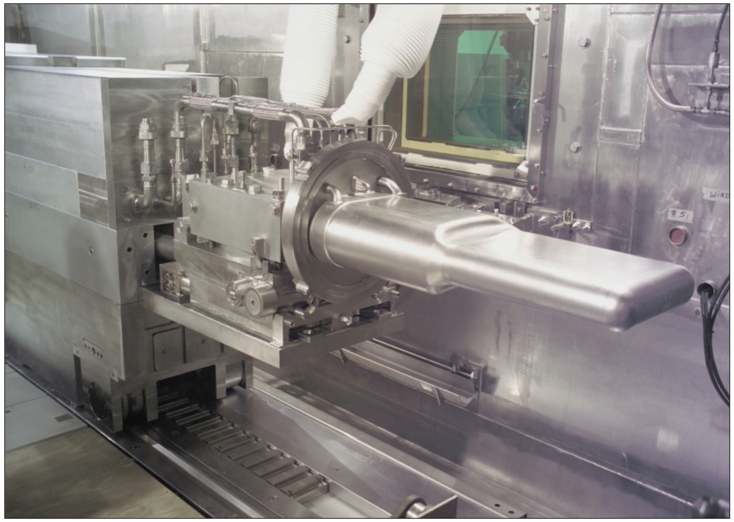

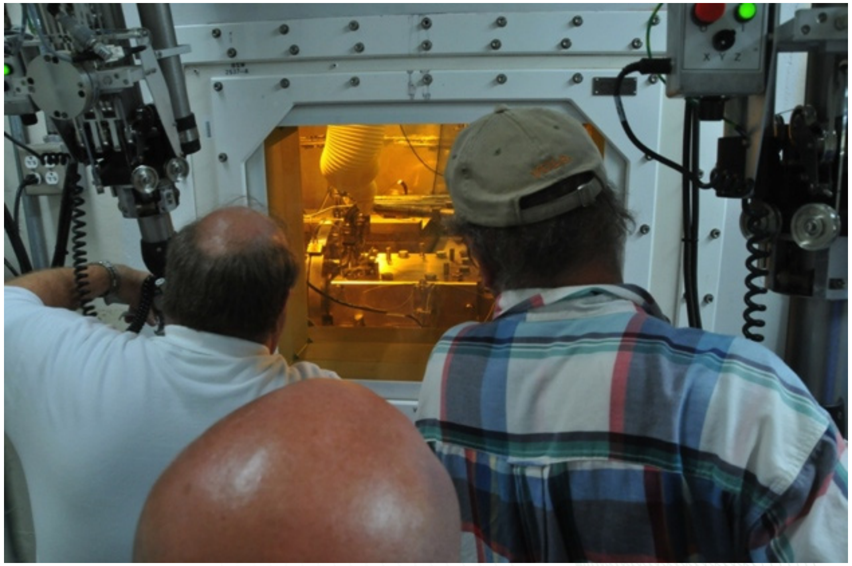



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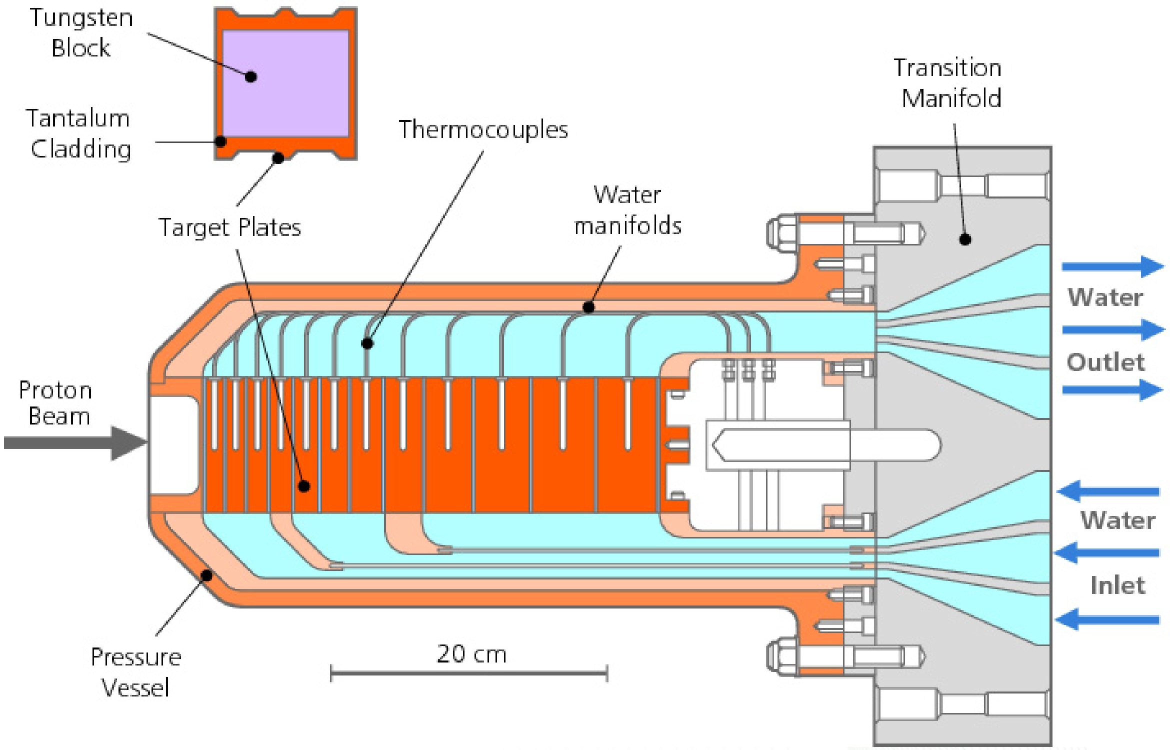
# First Generation: Stationary Solid Targets

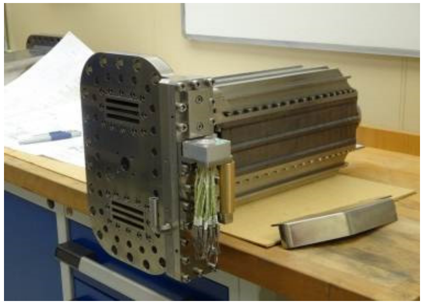
- Neutron production:
  - Ta clad tungsten targets
  - Water cooled
- Works well up to few hundred KW

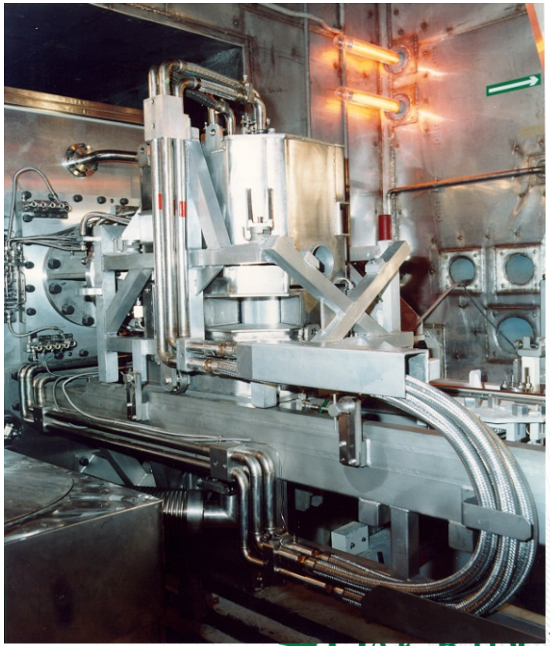
ISIS Target Station 1 target:



# ISIS Target Station 1
## *(Courtesy D. Jenkins)*

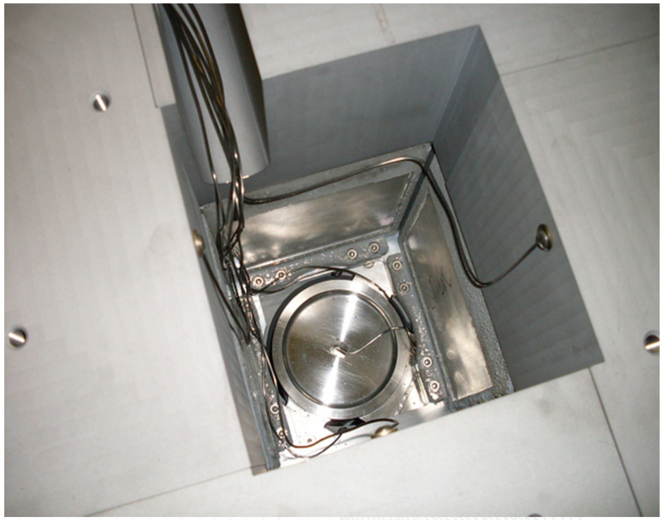
- Purpose: neutron production, operated over 30 years
  - ~ 150 kW, 800 MeV, 50 Hz
  - Short pulse (< 1 $\mu$s)
  - Monolithic target/moderator assembly – horizontal insertion
- 5 year life, monolithic moderator/target



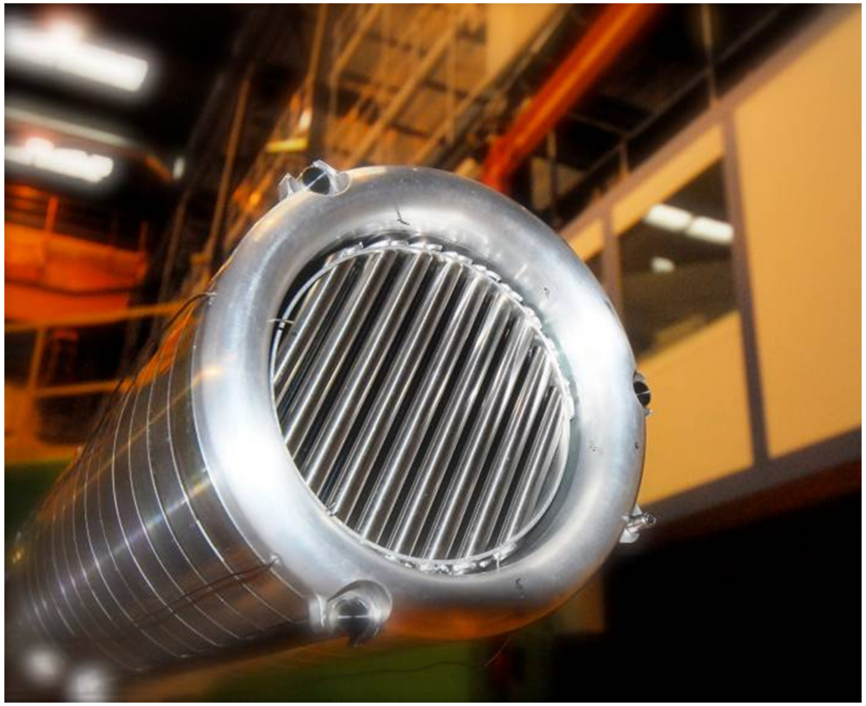


# LANL Lujan Center
## *(Courtesy C. Kelsey)*

- Purpose: neutron production, operated over 30 years
  - 100 kW, 800 MeV, 20 Hz
  - Short pulse (250 ns)
  - Split target for multiple moderator optimization
  - Monolithic target/moderator assembly
    - Vertical insertion into target crypt



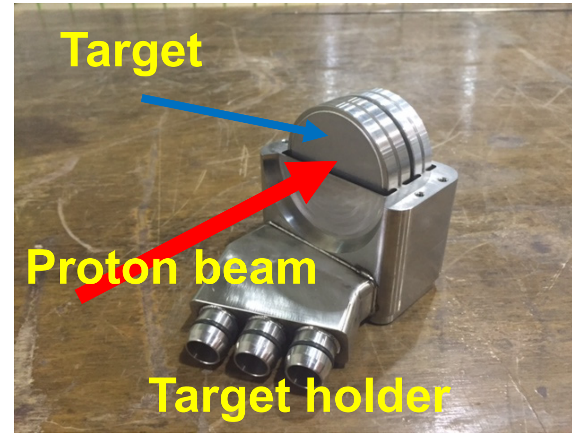
# PSI: SINQ Target
## *(Courtesy B. Blau)*

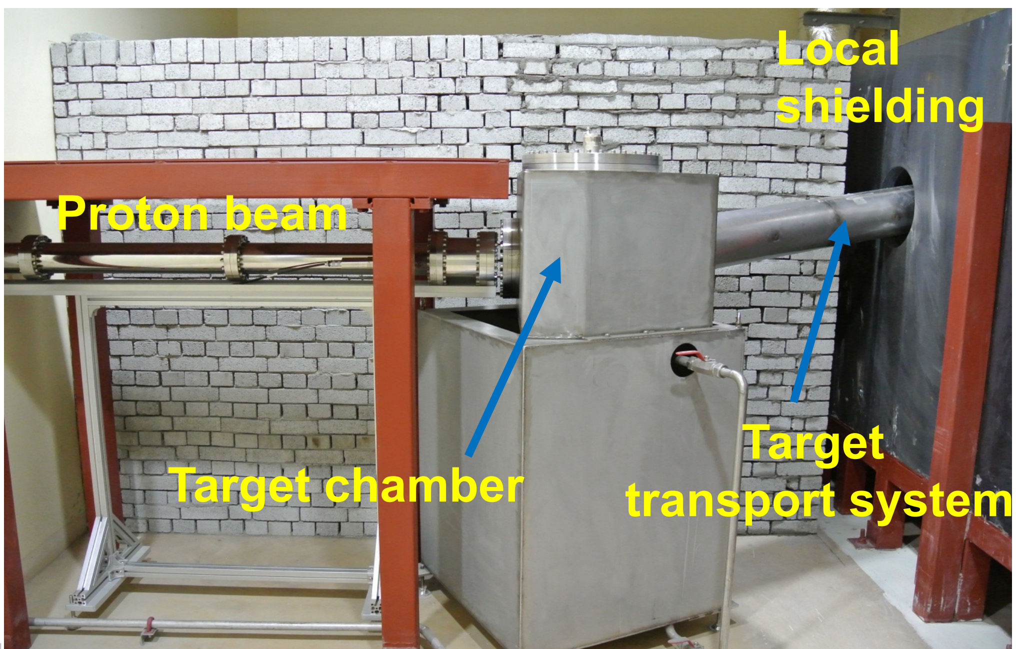


- Purpose: Neutron scattering
  - ~ 1MW on target
  - 0.59 GeV, CW @ 1.6 mA
- Solid target
  - Cannelloni target:
    - Pb in Zircalloy tubes
    - Pb blanket
    - Water cooled
  - Some tubes contain irradiation samples
- Operations never stopped prematurely  for target failure

# KOMAC High Power Target
## *(Courtesy Yong-Sub Cho)*

- Purpose: Isotope production, multi-purpose
  - 30 kW, 100 MeV, 30 Hz
  - Long pulse, 0.5 ms
  - Solid (RbCl and Zn, SS clad) water cooled
  - RI production commissioning ongoing
  - Maintenance with high activation a challenge

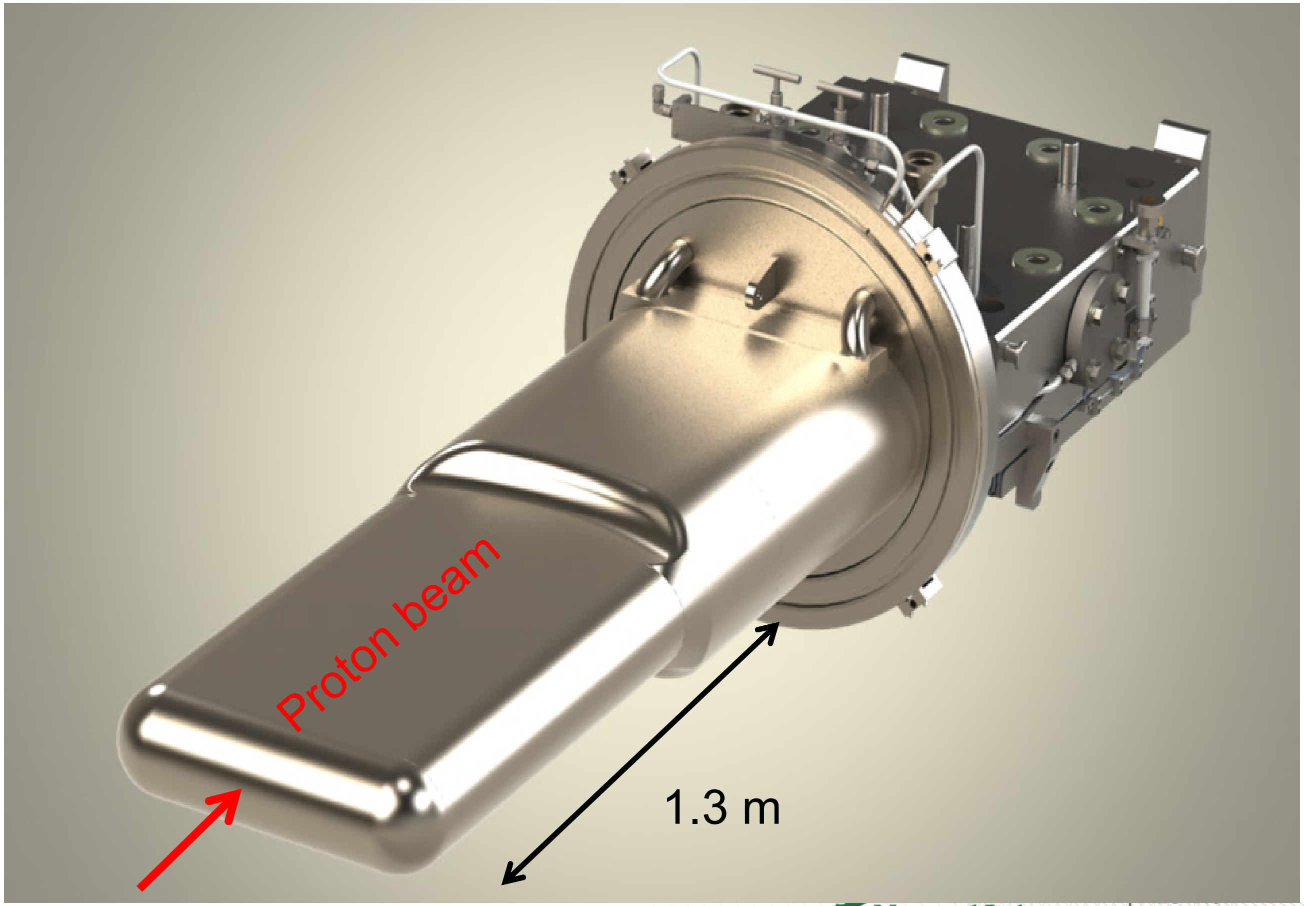



# Second Generation: Liquid Metal Targets

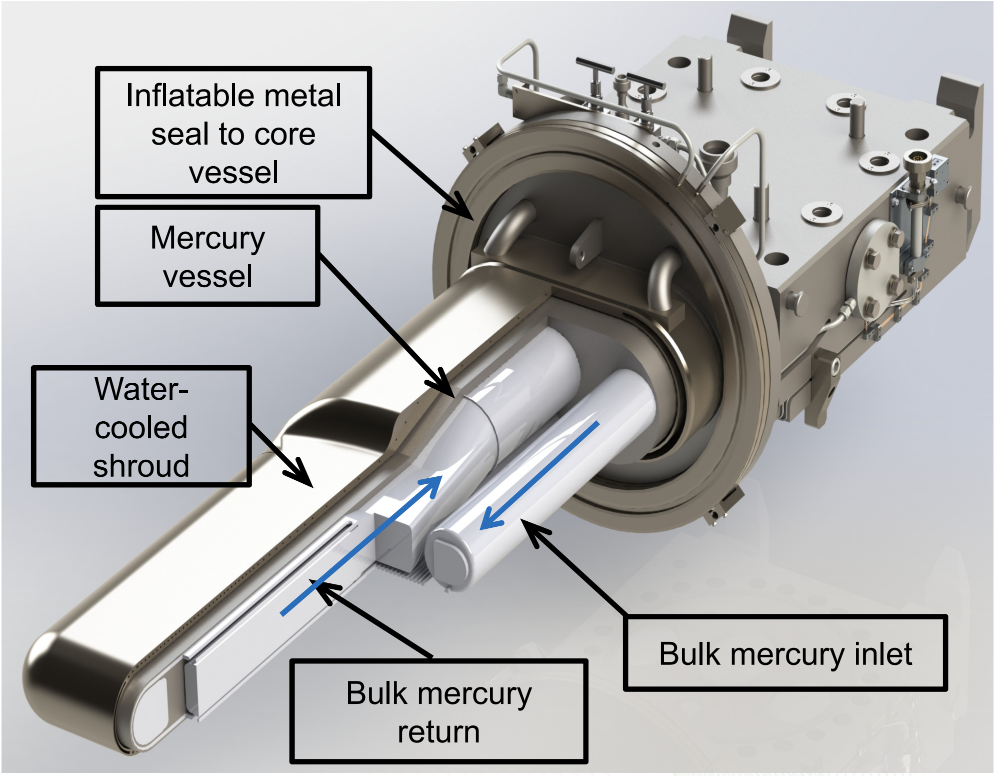
- Advantage: combine secondary (neutron) production material and coolant
  - Hg is high Z and liquid

- Disadvantage: cavitation damage

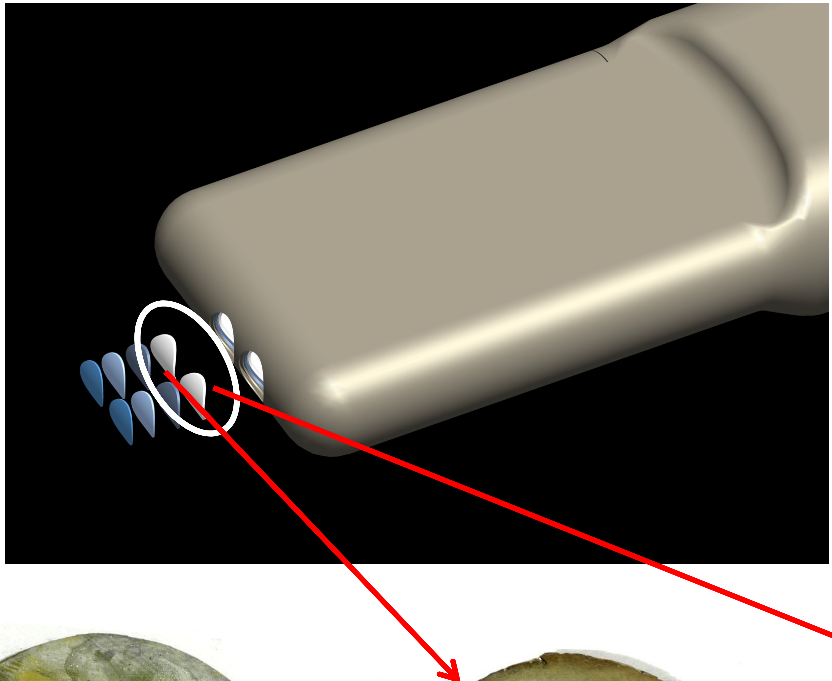


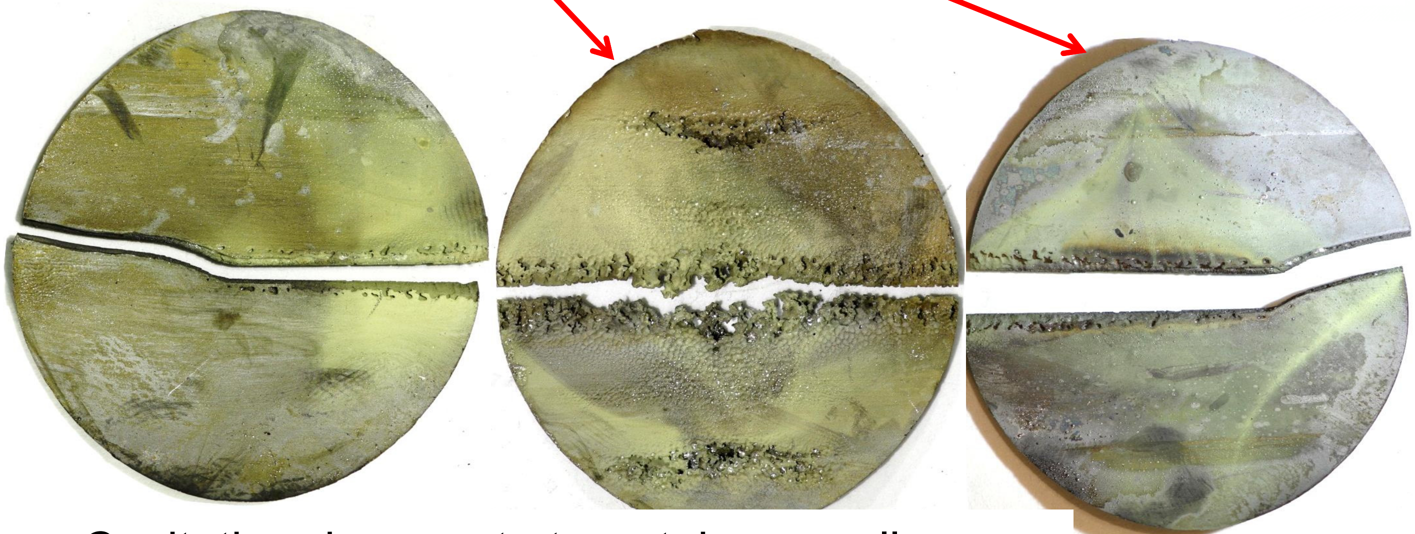
# ORNL: Spallation Neutron Source

- Purpose: neutron production
  - 1.4 MW, 940 MeV, 60 Hz
  - Short pulse (700 ns)
  - Hg target
  - Horizontal rail system / hot-cell
- Lessons
  - Weld failures and cavitation erosion pitting
  - Directed flow adjacent to vessel inhibits cavitation damage



# Cavitation Induced Pitting



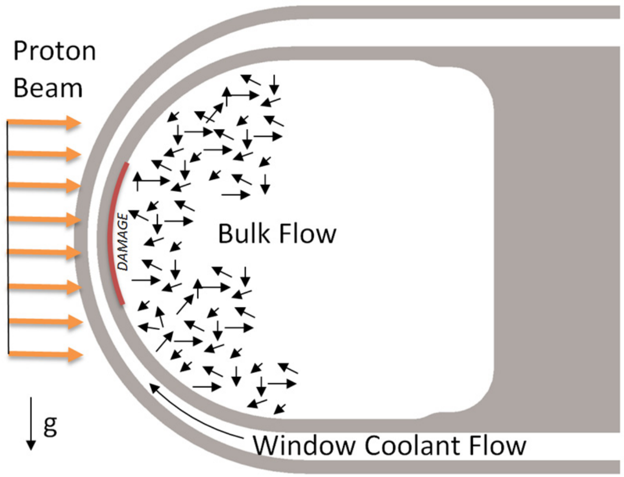


Cavitation damage to target inner wall

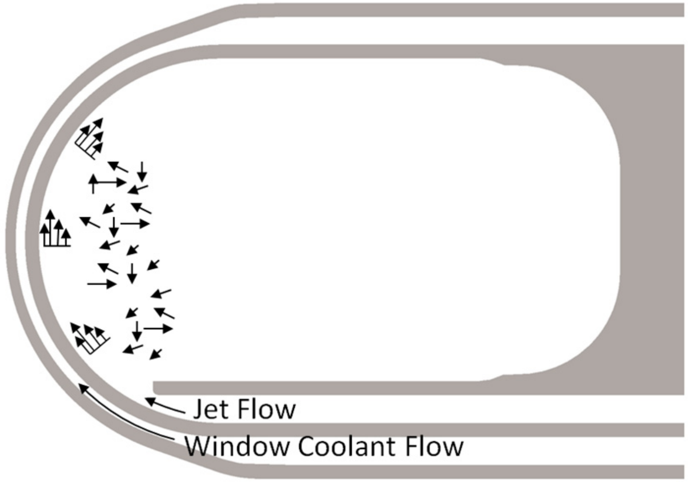
- Vessel wall facing the Hg has pitting damage in nose area

# Directed Hg Flow Mitigates Pitting

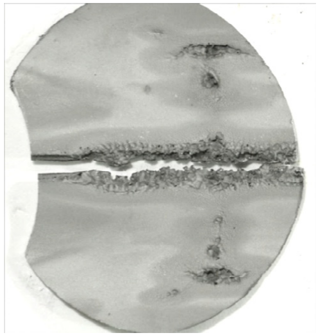
<u>Nominal target, poor flow at nose wall</u>

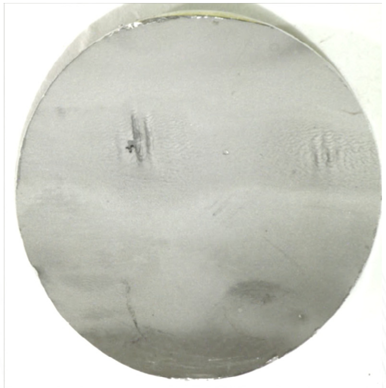



<u>Direct flow along wall at target nose</u>




Extracted inner wall cores:





- Both cases: 1MW x 600 hours
- Dramatic effect!



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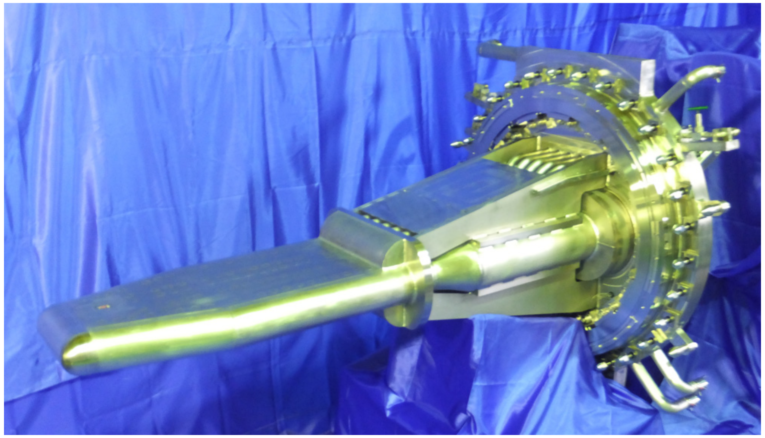
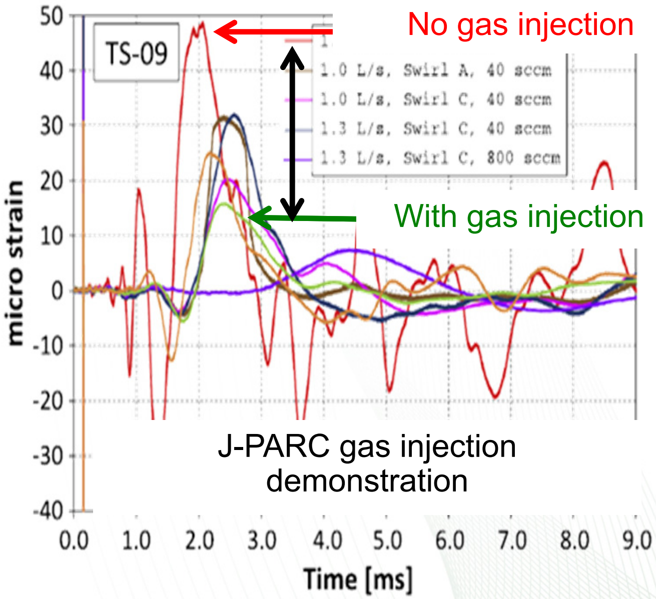
# J-PARC: Material Life Science Facility
***(Courtesy H. Katsuhiro)***

- Purpose: neutron production
  - 1 MW, 3 GeV, 25Hz
  - Short pulse (2 x 150 ns)
  - Hg target
  - Horizontal rail system / hot-cell
- Lessons
  - He gas injection mitigates pressure pulse intensity
  - Weld failures

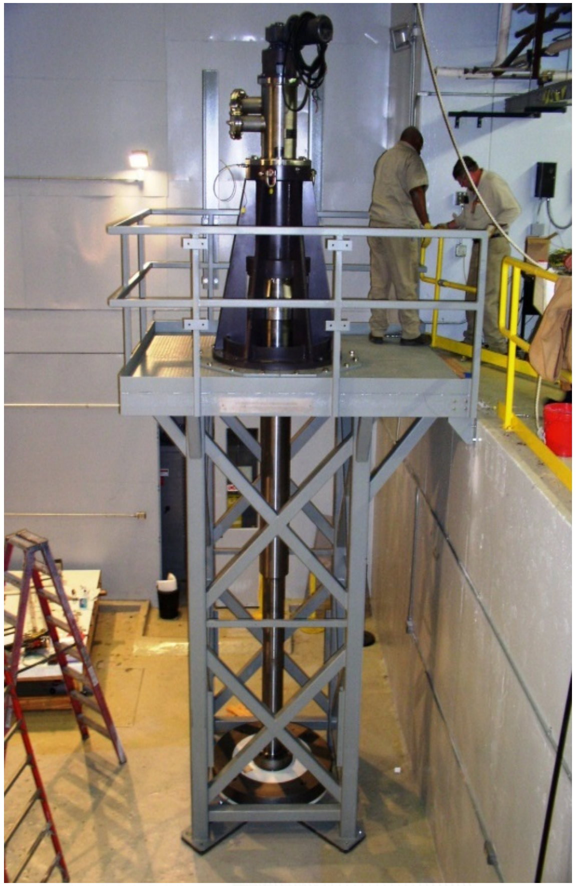


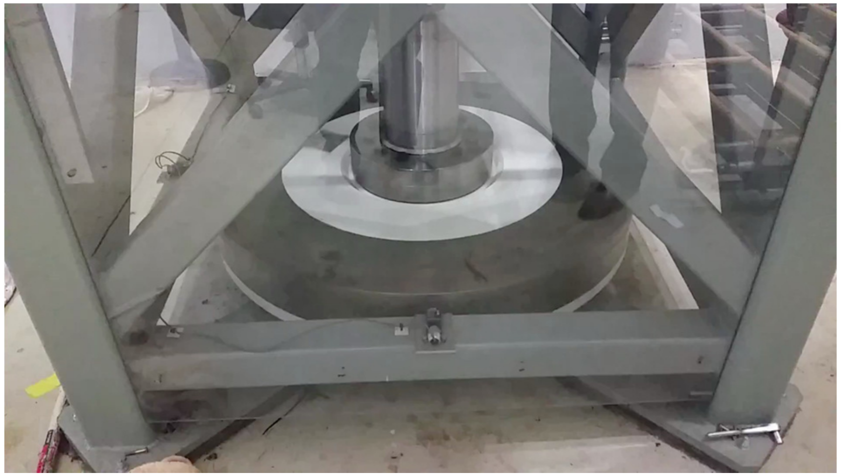



J-PARC gas injection demonstration

# Third Generation Neutron Source Targets: Rotating Target

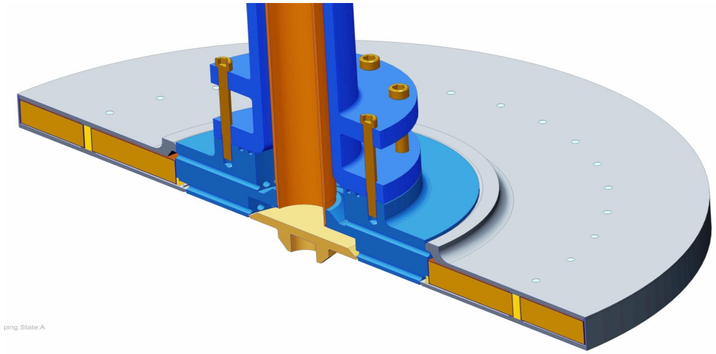
- Future neutron sources are adopting rotating targets
  - Advantages
    - Spread heat load of larger volume
    - Residual activation decay heat issue is also mitigated
  - Disadvantage
    - Moving parts, rotating seals
    - Replacement complicated

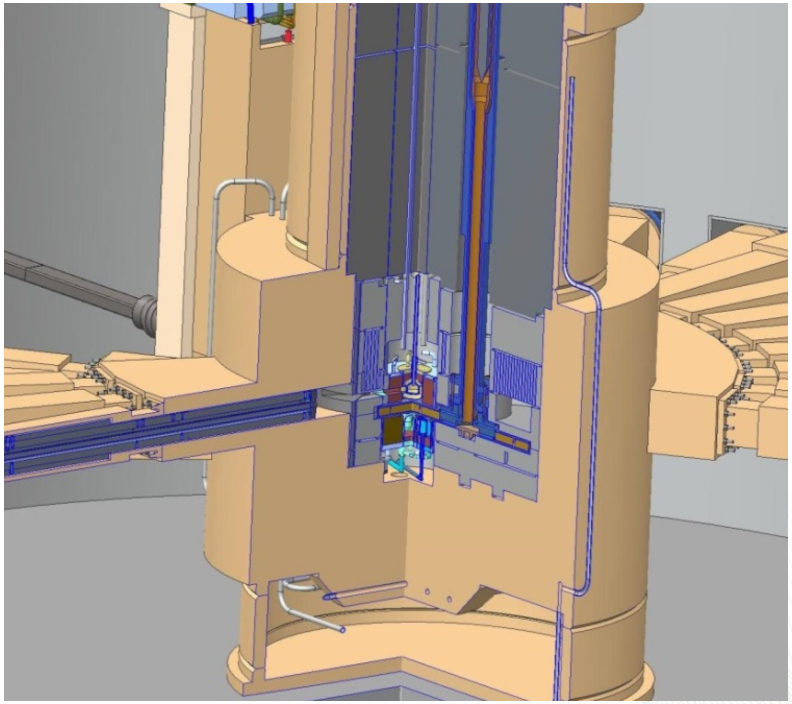




# Second Target Station / SNS

- Purpose: Neutron scattering
  - 467 kW
  - 1.3 GeV, 10Hz
- Rotating target
  - W target, Ta clad
  - Water cooled
  - Vertical access







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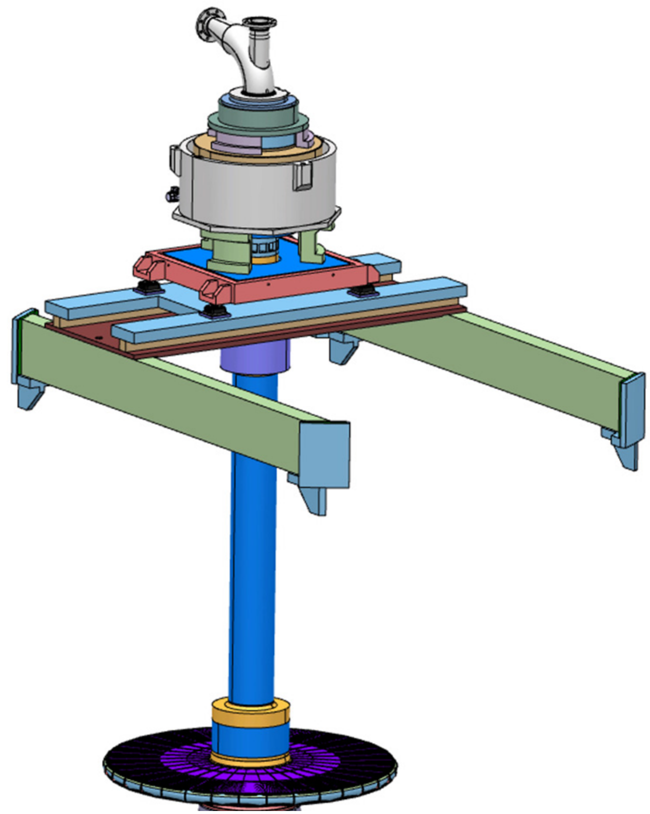
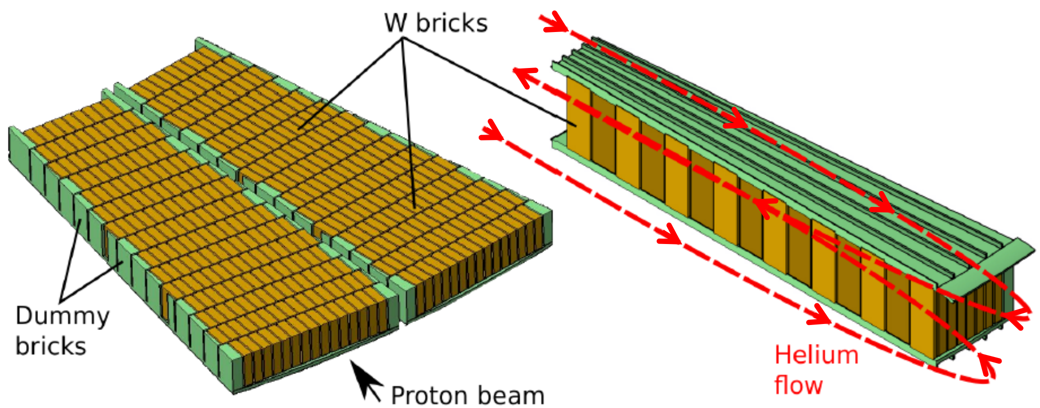
# European Spallation Source
## *(Courtesy E. Pitcher)*

- Purpose: Neutron scattering – world' first long pulse
  - 5 MW!
  - 2 GeV: 357 kJ x14 Hz @ 2.9 ms
- Rotating target
  - W: 6700 bricks, 3.5 tonnes
  - He cooled: 3 kg/s
  - Vertical access



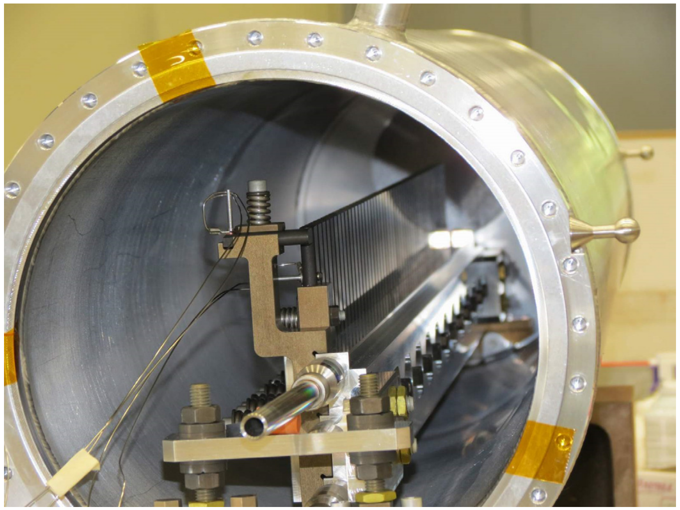


# FNAL NOVA Neutrino Target Used 2013-2016

## *(Courtesy James Hylen)*

P-C interactions produce pions, which are focused, decay to produce neutrinos

*Long, narrow target: pions can escape out sides, reducing pion re-interactions*



**50 Graphite fins: 24 mm long & 7.4mm wide**

***Proton beam spot sigma = 1.3 mm***

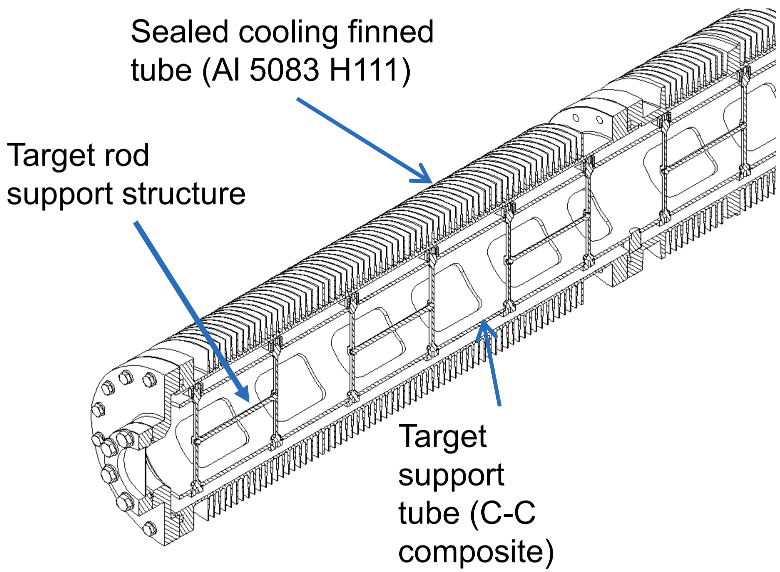
Cooled by water cooled Al pressing plates

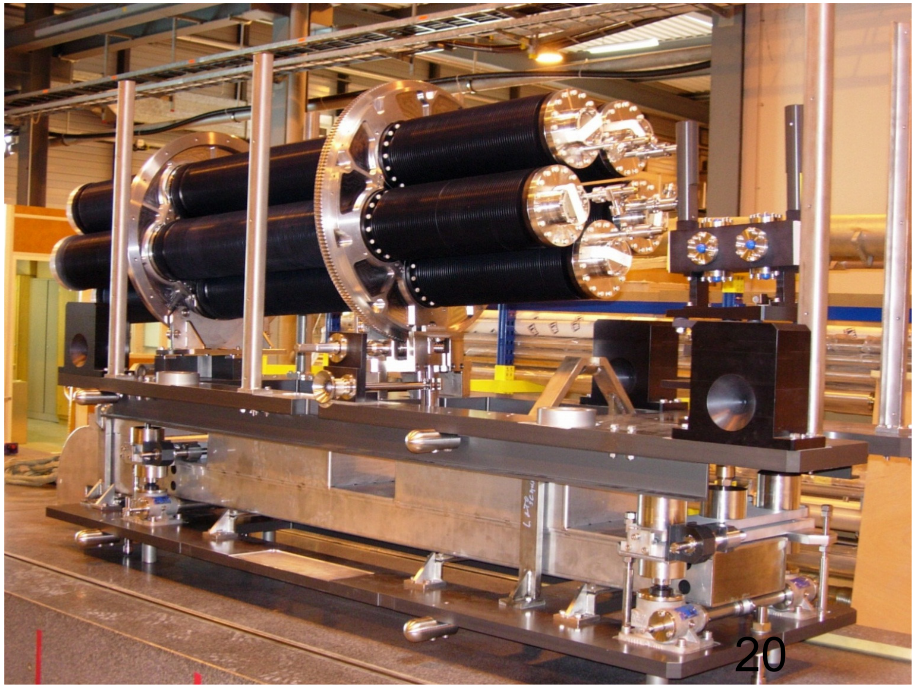
*No operational issues so far, have not replaced target yet*

| | Design | So far |
|---|---|---|
| Beam energy | 120 GeV | 120 GeV |
| POT / 10 micro-second spill | 4.9e13 | 4.4e13 |
| Repetition time | 1.33 sec | 1.33 sec |
| Beam power | 700 kW | 580 kW |

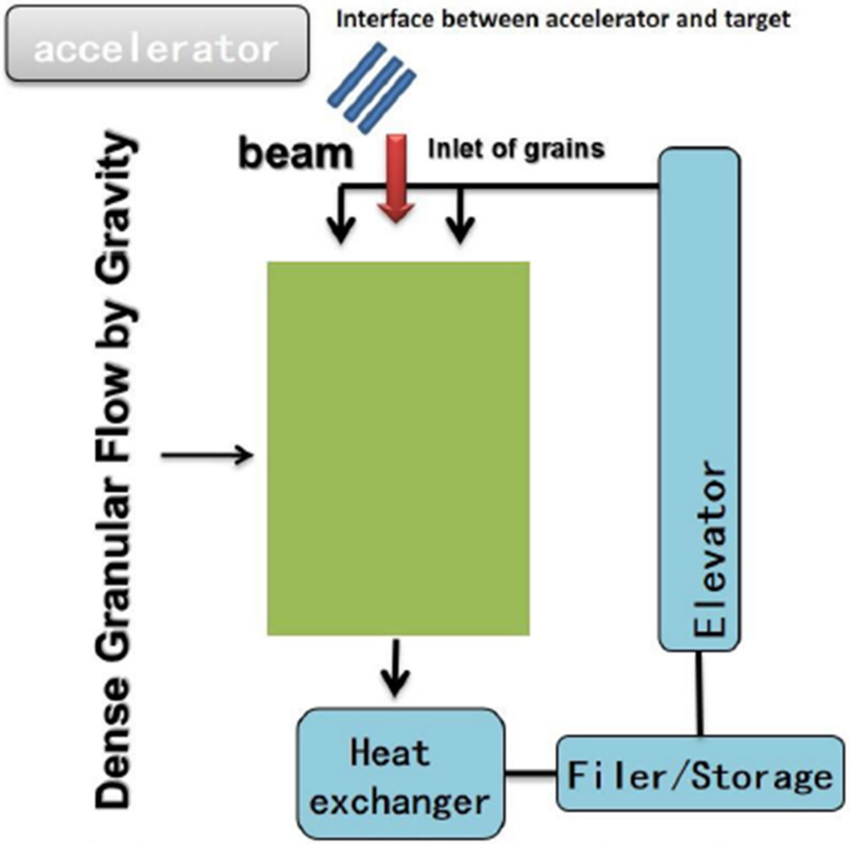
# CERN CNGS engineering challenges *(courtesy M. Calviani)*

- CNGS target unit conceived as a static sealed system with 0.5 bar of Helium
  - 130 cm long graphite target (~3$\lambda$)
  - Radiative-cooled target, ~1200 °C
  - Run at 500 kW



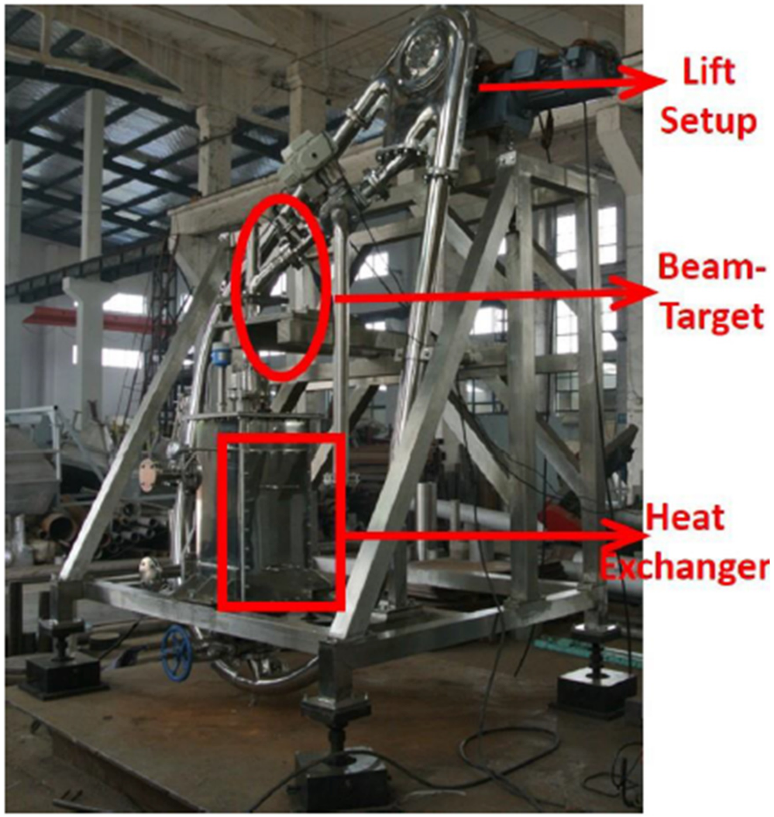



# China- ADS: Gravity fed granular target *(courtesy Lei Yang, IMP)*




Yang L, Zhan W. *Sci China Tech Sci* October (2015) Vol.58 No.10 P1705

Prototype test setup




- Combines solid / liquid target attributes

# High Power Proton Targets Take a Beating

| | Power on Target (MW) | Peak Power – Time Average ($MW/m^3$) | Peak Power – Instantaneous $MW/m^3$) |
|---|---|---|---|
| *Neutron Sources* | | | |
| ISIS TS1 | 0.14 | 400 | |
| Lujan | 0.1 | 250 | 50,000 |
| PSI | 0.94 | 820 | NA |
| SNS | 1.4 | 552 | 10,000 |
| J-PARC | 1.0 | 430 | |
| ESS | 5 | 90 | 80,000 |
| SNS-STS | 0.47 | 18 | 20,000 |
| *Isotope production* | | | |
| KOMAC | 0.03 | 350 | |
| *Neutrino Production* | | | |
| FNAL NOVA | 0.75 | 470 | $10^5$ |
| CERN CNGS | 0.4 | | $10^6$ |

# RaDIATE Collaboration

## *Radiation Damage In Accelerator Target Environments*

Broad aims are threefold:

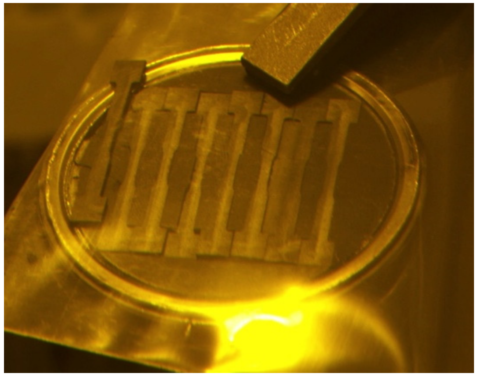
www-radiate.fnal.gov

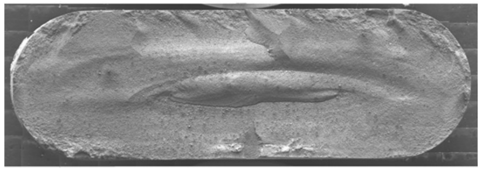
- to generate new and useful materials data for application within the **accelerator** and **fission/fusion** communities
- to recruit and develop new scientific and engineering experts who can **cross the boundaries** between these communities
- to initiate and coordinate a **continuing synergy** between research in these communities, benefitting both **proton accelerator applications** in science and industry and **carbon-free energy technologies**

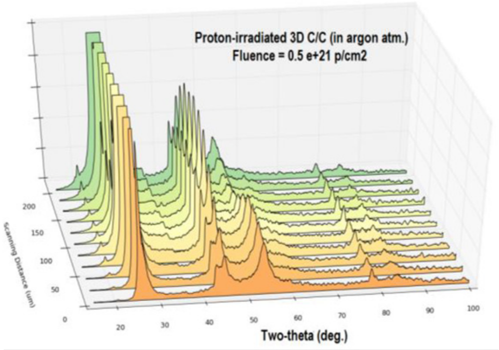
Fermilab · University of Oxford · Brookhaven National Laboratory · European Spallation Source · Argonne National Laboratory · Science & Technology Facilities Council · FRIB · Pacific Northwest National Laboratory · Oak Ridge National Laboratory · Los Alamos National Laboratory EST. 1943 · Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas · Oak Ridge National Laboratory Spallation Neutron Source

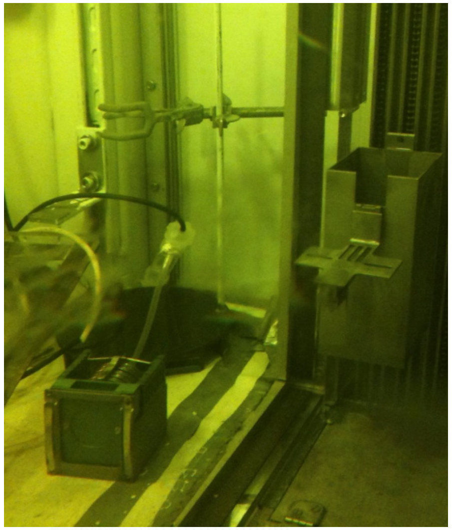
# RaDIATE Current Activities
## *(Courtesy P. Hurh)*

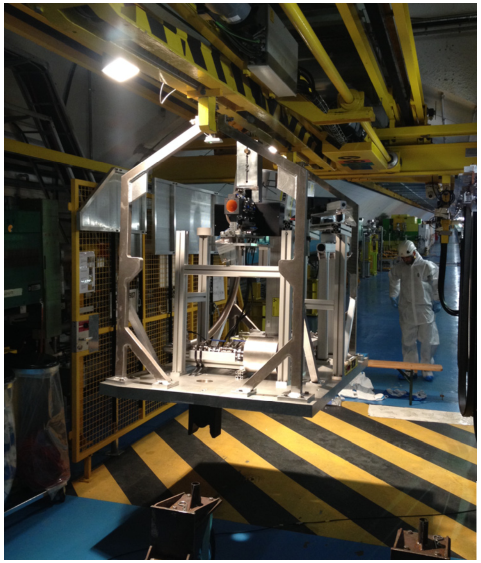
- **HE proton irradiations & Post-Irradiation Examinations (PIE)**
  - **Many materials of interest from Be to Ir!**
- **LE ion irradiations & PIE**
  - **Utilize advanced techniques to correlate damage to HE proton regime**
- **PIE of spent targets/windows**
- **Thermal Shock studies**

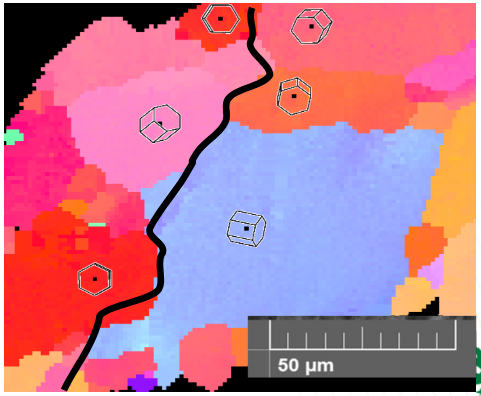


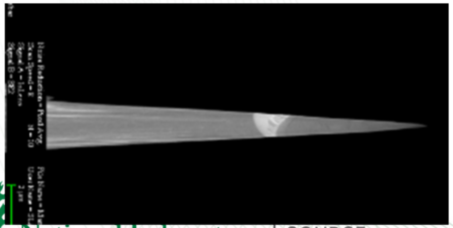










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# Outlook

- 1st generation: Stationary Solid Targets
  - Works well for 100 kW class applications
  - Higher power demonstrated for neutrino applications
- 2nd generation: Liquid Hg targets
  - Targets accepting ~MW beam for short pulse beams
  - Upgrades for robust operation under development
- Moving forward
  - Rotating targets look good
  - Granular-flow target