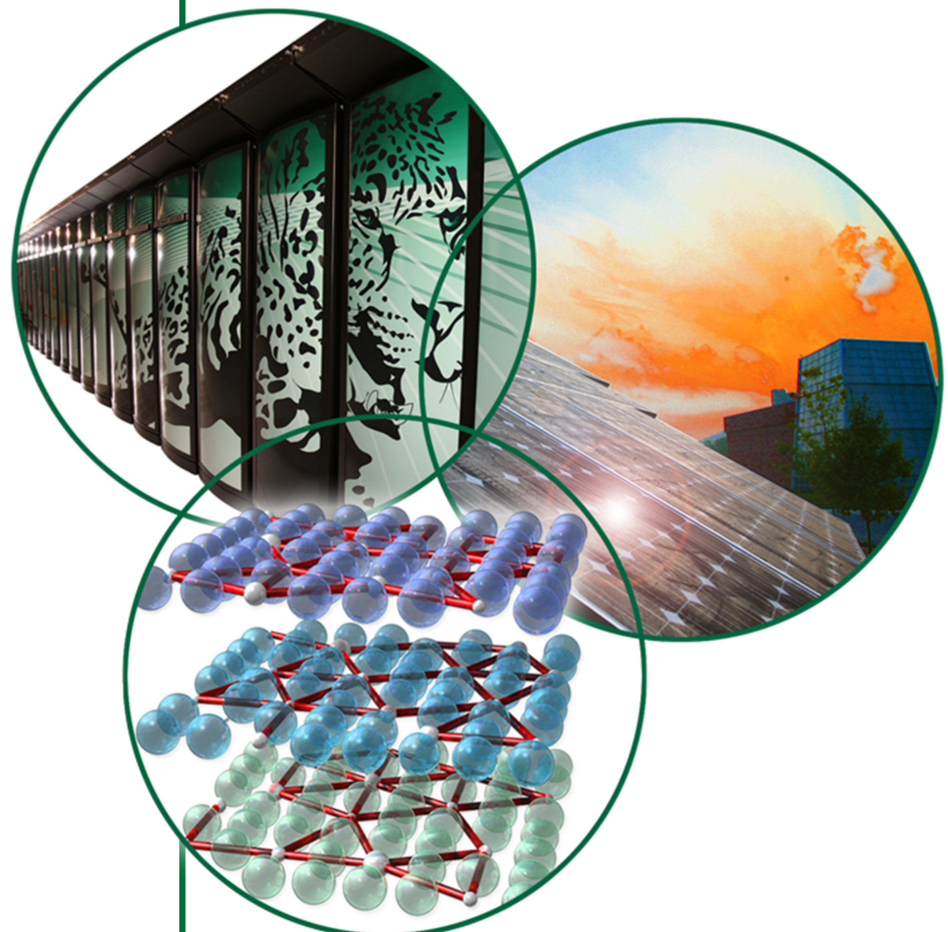
Operational Experience for High Power Spallation Targets



John Haines, Bernie Riemer (ORNL),
Masatoshi Futakawa (JAEA),
Werner Wagner and Michael Wohlmuther (PSI)

4th High Power Targetry Workshop

Malmö, Sweden

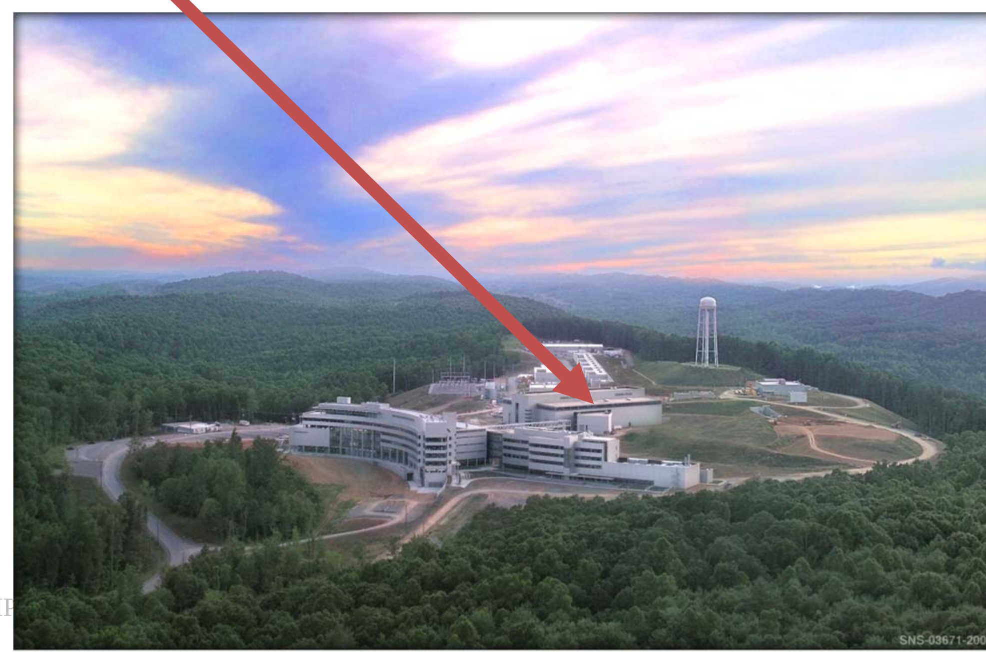
May 2, 2011

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

MW-Class Spallation Targets

- SINQ at the Paul Scherrer Institut (PSI)
- SNS at the Oak Ridge National Laboratory (ORNL)
- JSNS at the Japan Atomic Energy Agency (JAEA)

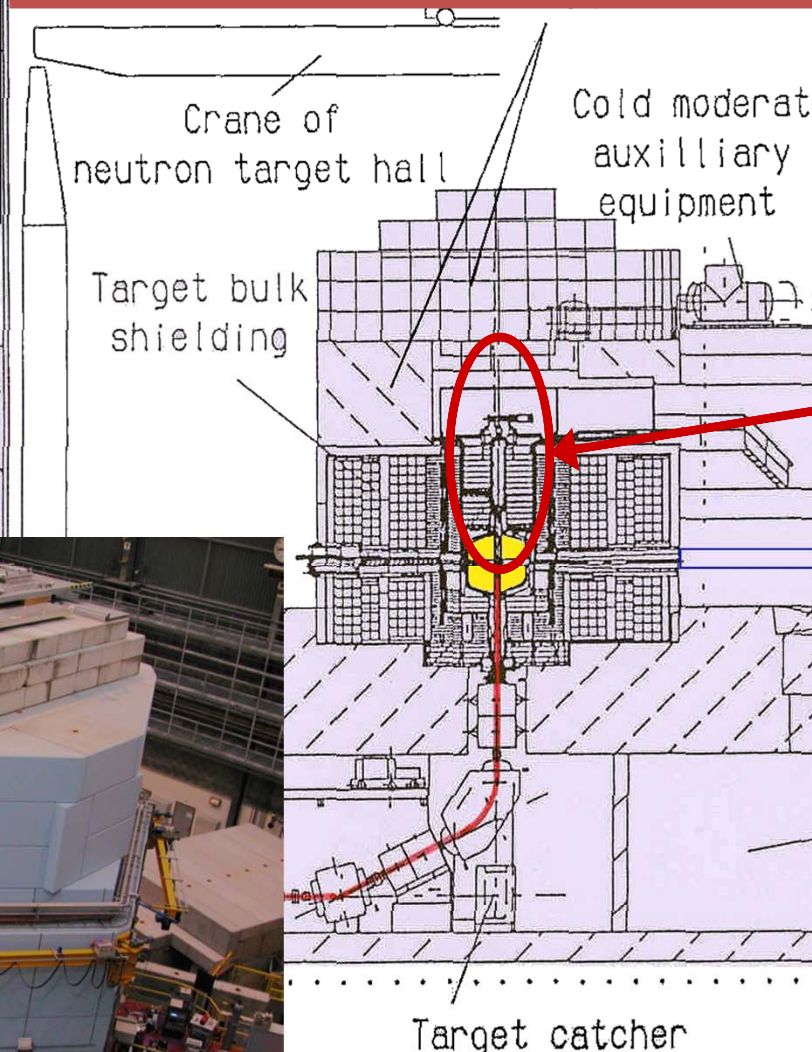


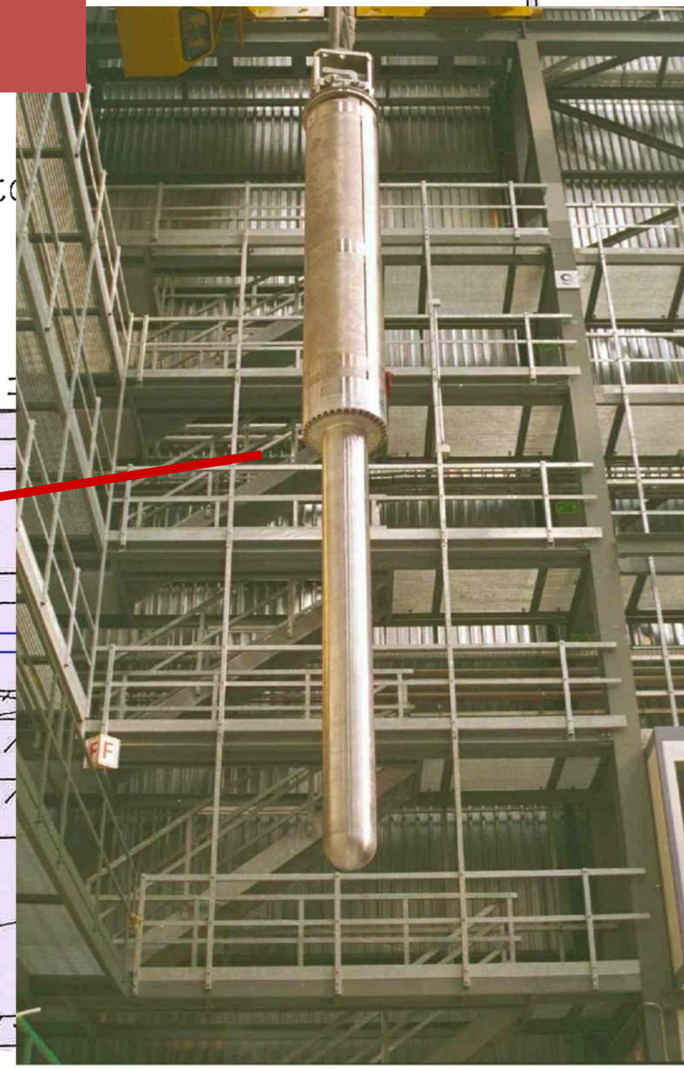
SINQ experience

SINQ Facility

Proton beam:
- **CW**
- **590 MeV**
- **~ 1.5 mA ⇒ 0.9 MW**

SINQ Target Station



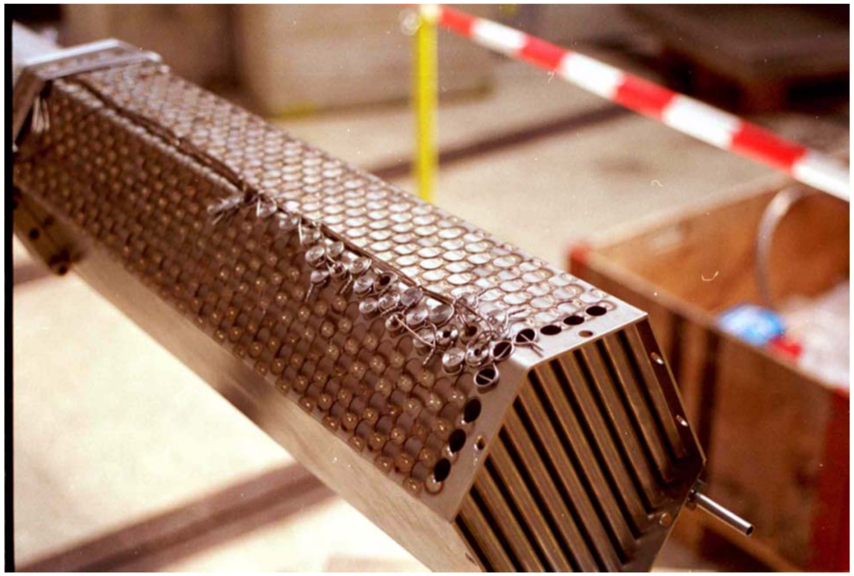


SINQ - Target

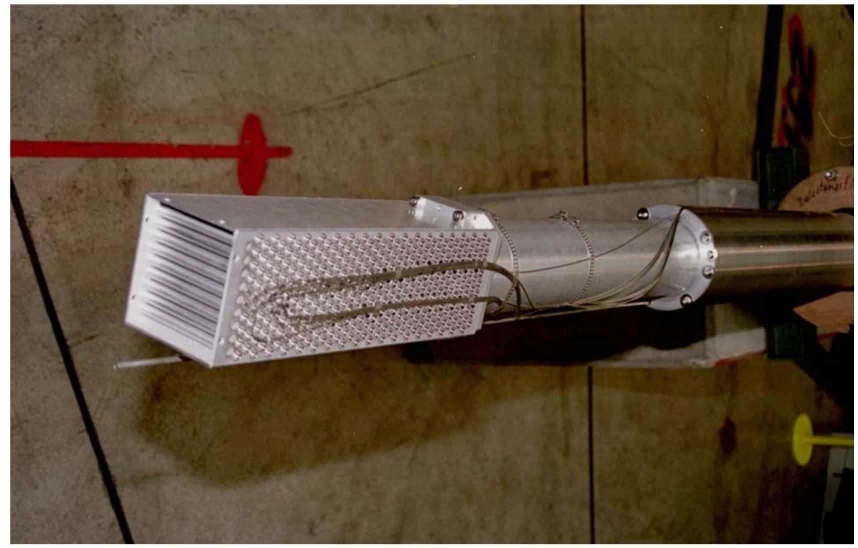
Target-01.jpg
GK87 / 12.05.99

Target Evolution at SINQ

1997-1999: SINQ Target Mark 2
Water-cooled Zircaloy rods



2000 - 2009:SINQ-Target Mark 3:
Lead rods, with steel clad
42% increase in neutron yield



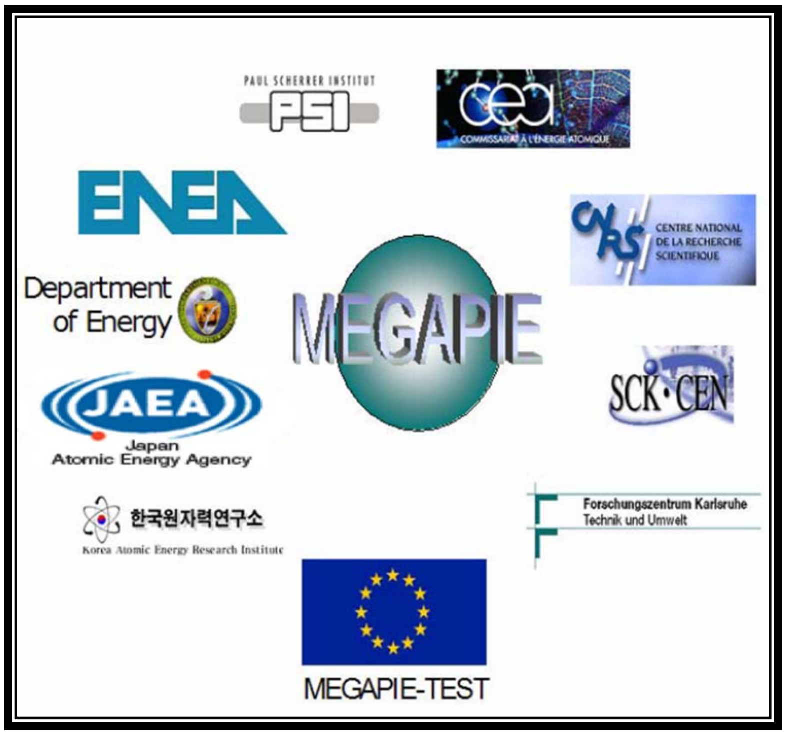
Aug- Dec 2006: MEGAwatt Pilot Experiment:

- **Joint international initiative to design, build, licence, operate and explore a liquid metal spallation target for 1 MW beam power**

MEGAPIE
A liquid metal target for SINQ

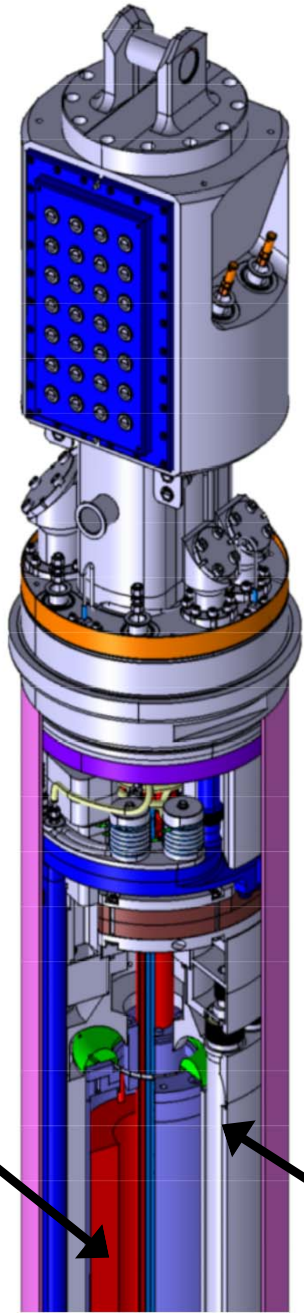
MEGAwatt Pilot Experiment:

- **Lead-Bismuth-Eutectic (LBE, T_m=125°C)**
- **Increase the neutron flux at SINQ**
- **Demonstrate the feasibility of a liquid metal target for high-power spallation and ADS applications**



MEGAPIE (Pb-Bi) Target Features

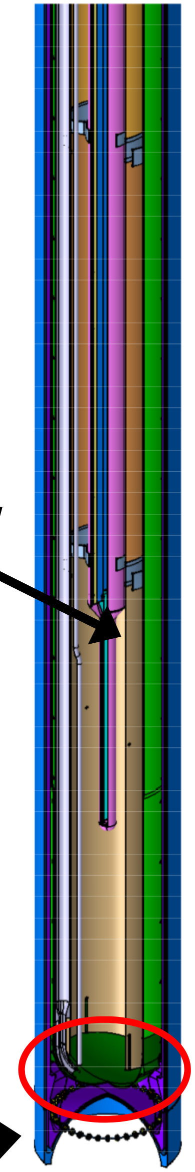
target head



electro-magnetic pumps

heat exchanger

central flow guide tube



lower target assembly

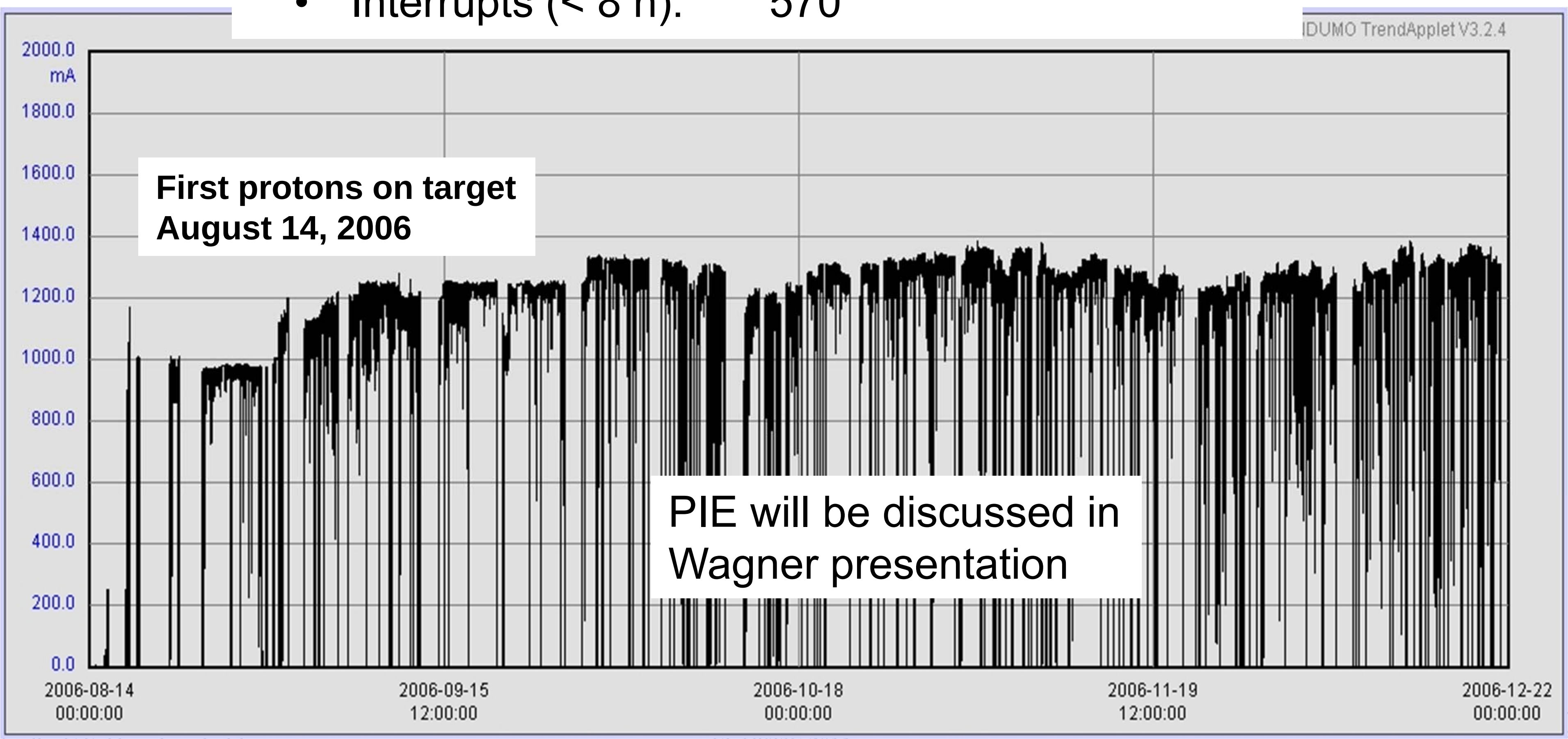
safety hull

beam window

MEGAPIE Target Operated Continuously for Four Months

On beam: August 14 – December 21, 2006

- Accumulated charge: 2.8 Ah
- Peak Current: 1400 μA
- Beam trips (< 1 min): 5500
- Interrupts (< 8 h): 570

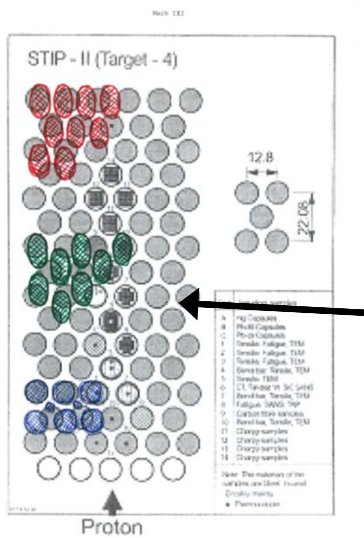


MEGAPIE Target Enhanced SINQ Neutron Flux

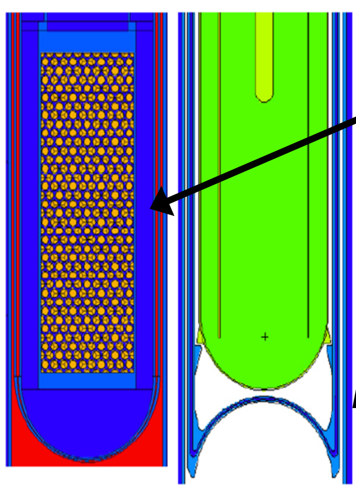
Fluxes measured by Au foil activation (in neutrons/cm^2/s/mA)

	SINQ 2005	Err. (%)	MEGAPIE 2006	Err. (%)	ratio
ICON	3.80E+8	~5	6.89E+8	~5	1.81
NEUTRA	2.59E+7	~5	4.80E+7	~5	1.85
EIGER	6.46E+8	~5	1.04E+9	~5	1.61
NAA	5.82E+12*	~5	1.04E+13	~5	1.79

Improvement options for the solid Pb canneloni target



Scetch from Knud Thomsen

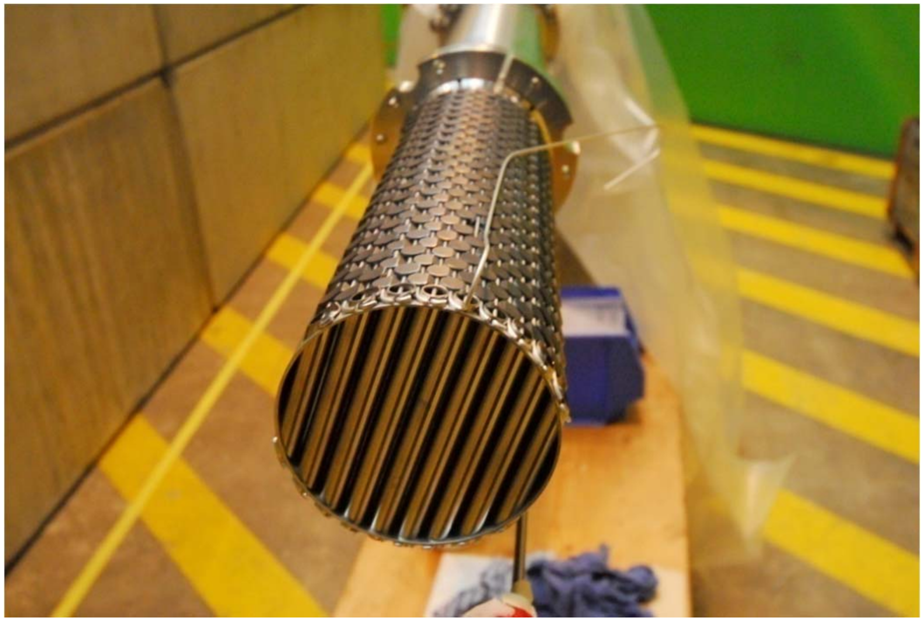


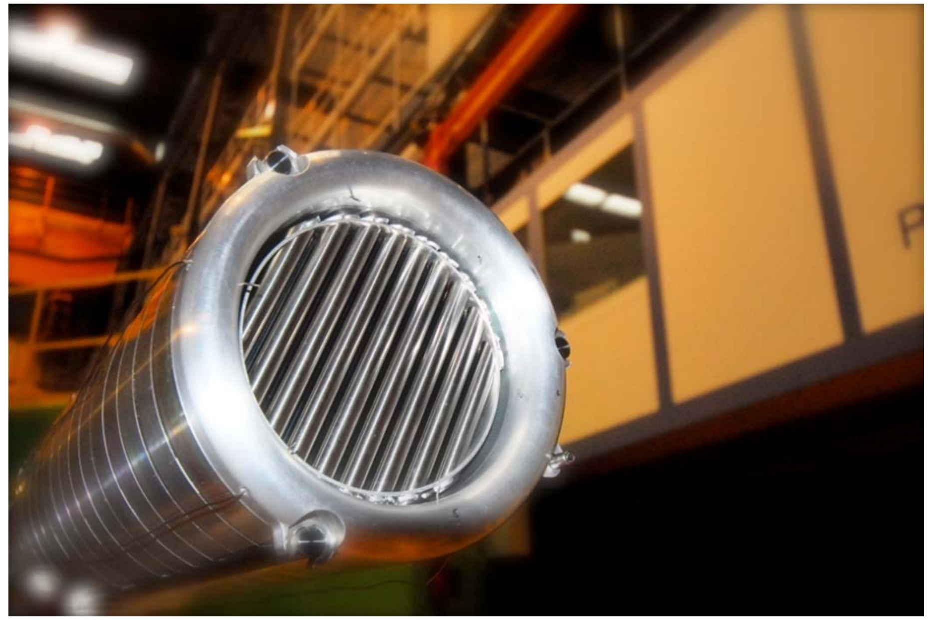
predicted gain

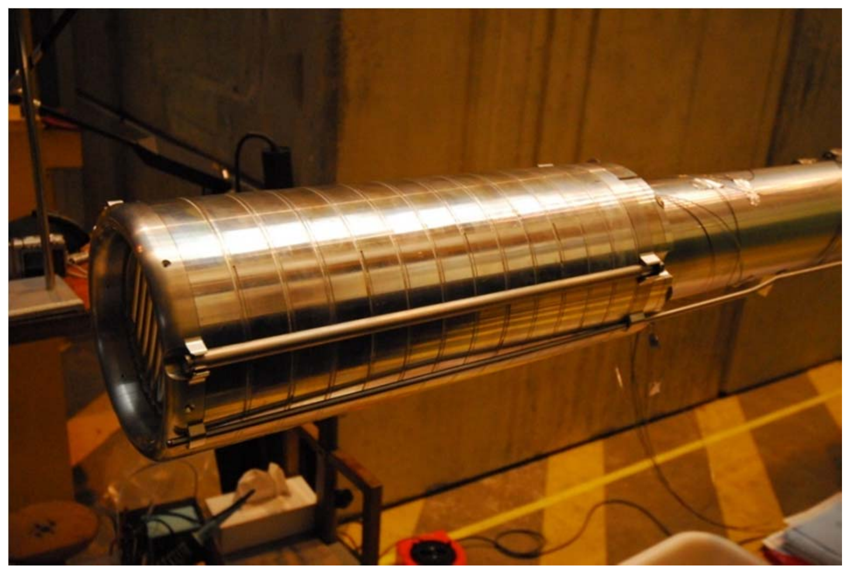
- Zr cladding (replacing steel) → 10-13%
- compaction: closer rod-packing (2 mm gap ⇨ 1.2 mm) → 5%
- thinner tube wall (0.75 mm ⇨ 0.5 mm) → 5%
- Pb-reflectors filling the gap around the canneloni structure → 10%
- inverted calotte of safety hull → 5%
- No (or less) STIP samples → 10%

~50%

The new Zr-Pb cannellomi target for SINQ







Status:

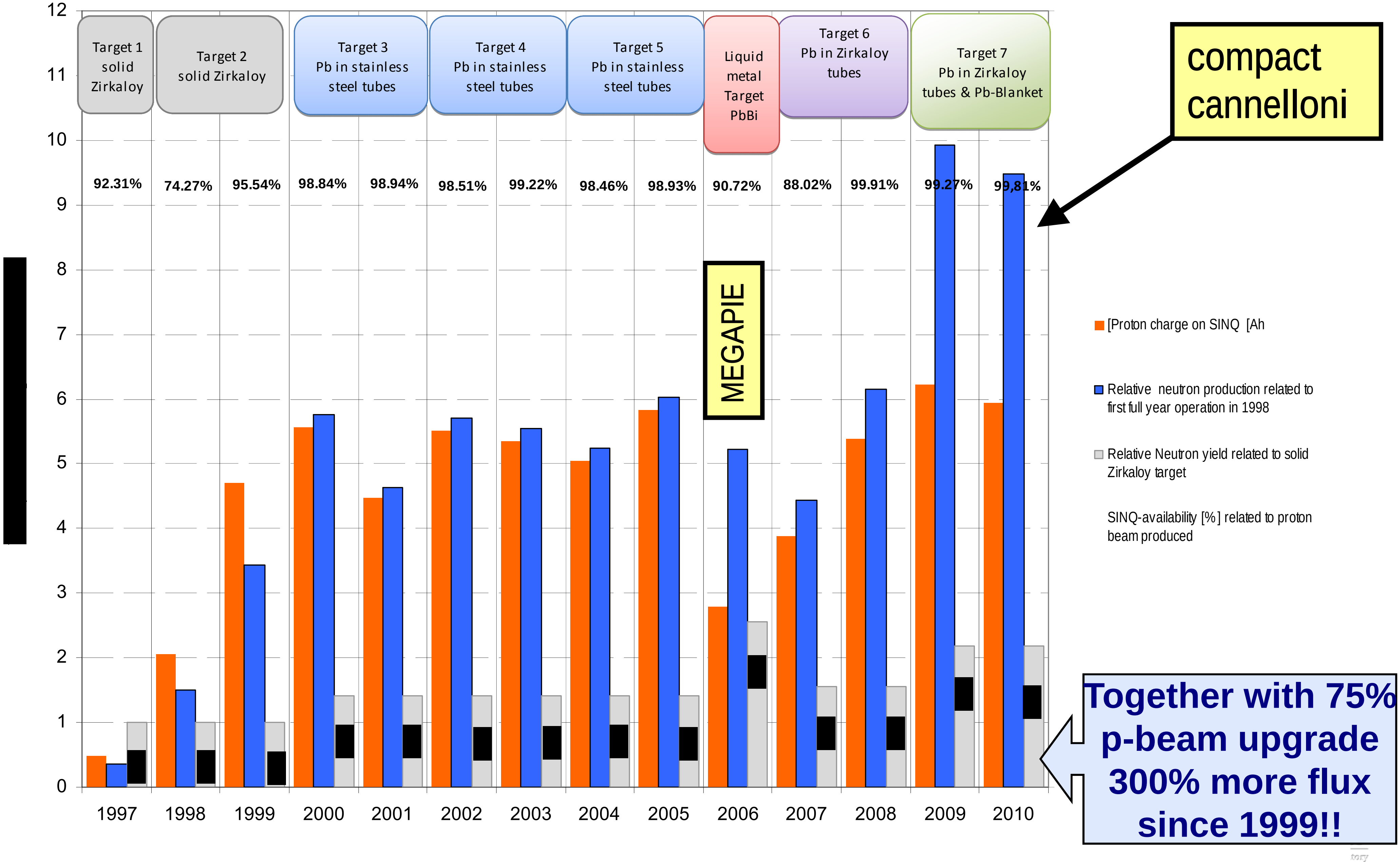
Operated @ 0.9 MW

April 2009 – Dec. 2010

Neutron flux gain:

54% compared to Target Mark 3 (2004 / 2005)

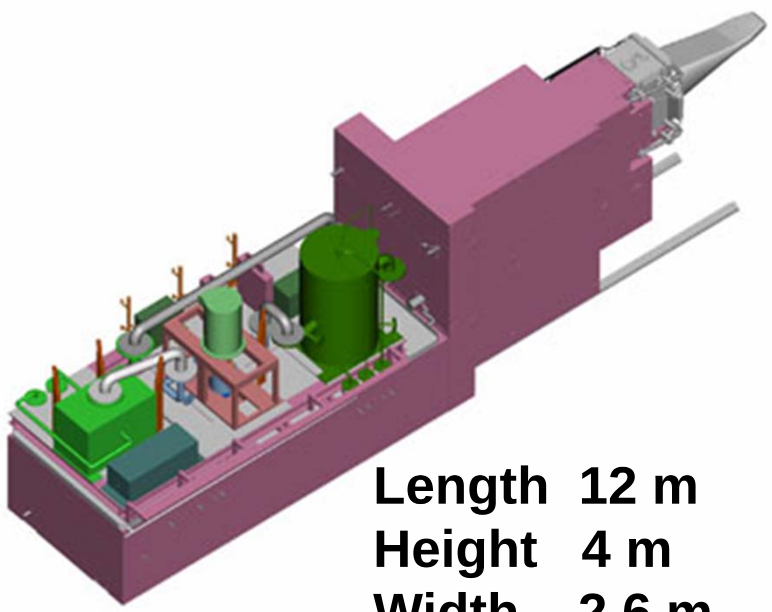
SINQ neutron production statistics 1997-2010



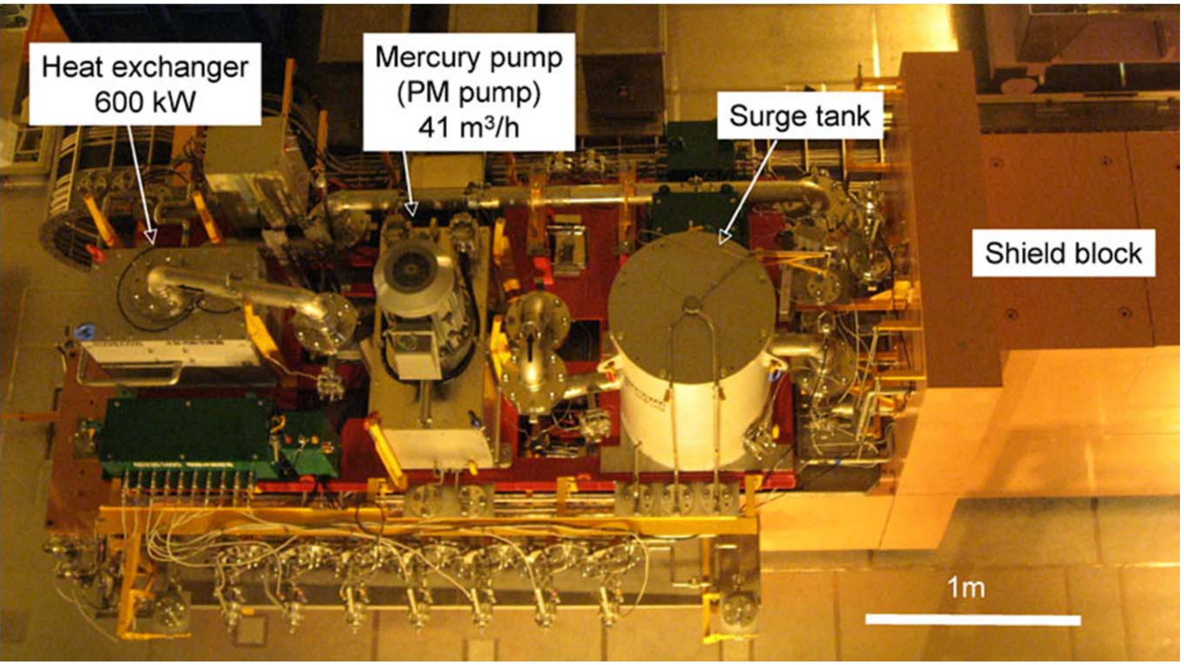
JSNS mercury target

JSNS Hg Target

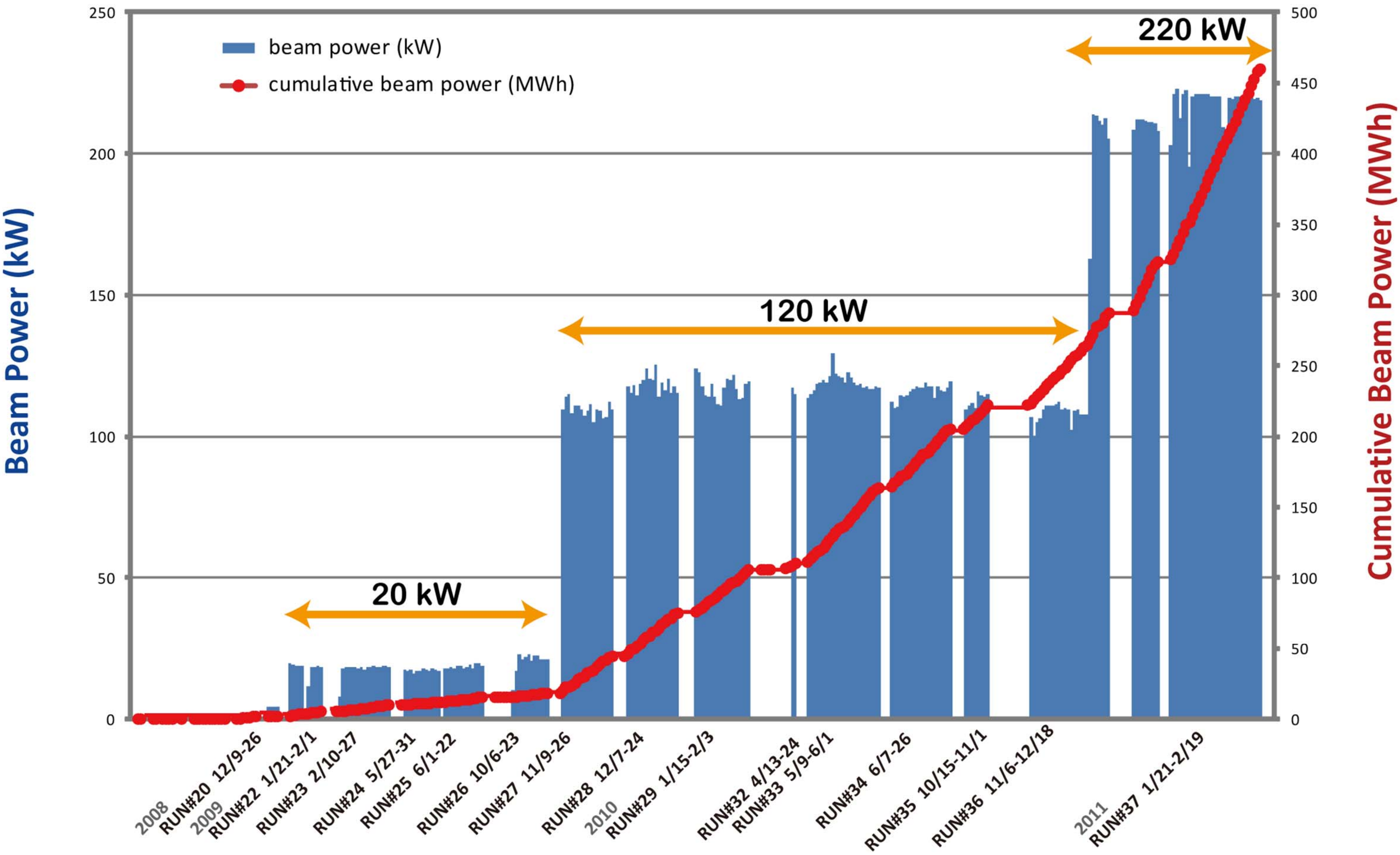
- Proton Beam (design parameters):
  - 3 GeV, 25 Hz rep rate, 0.33 mA ⇒ 1 MW
- Hg Target:
  - Cross-flow type, with multi wall vessel
  - Hg leak detectors between walls
  - All components of circulation system on trolley
  - Hot cell : Hands-on maintenance
  - Vibration measuring system to diagnose pressure wave effects



Length 12 m
Height 4 m
Width 2.6 m
Weight 315 ton

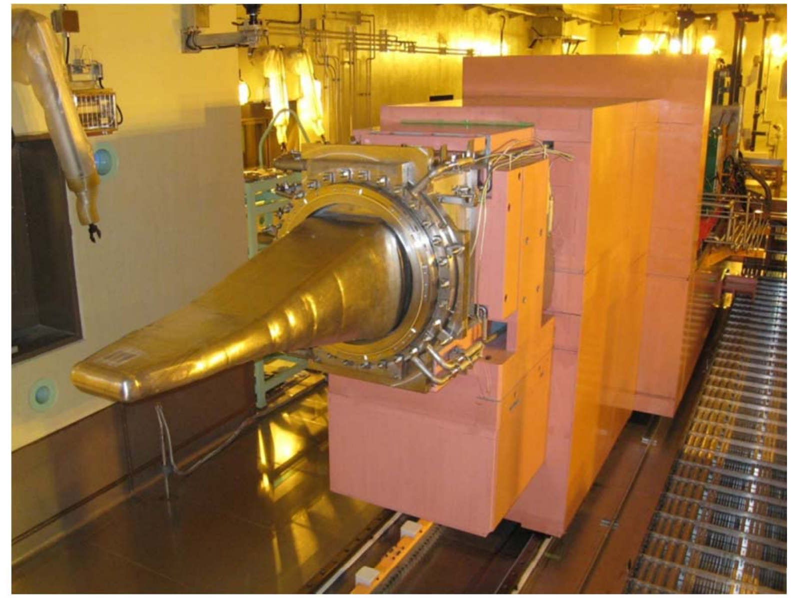


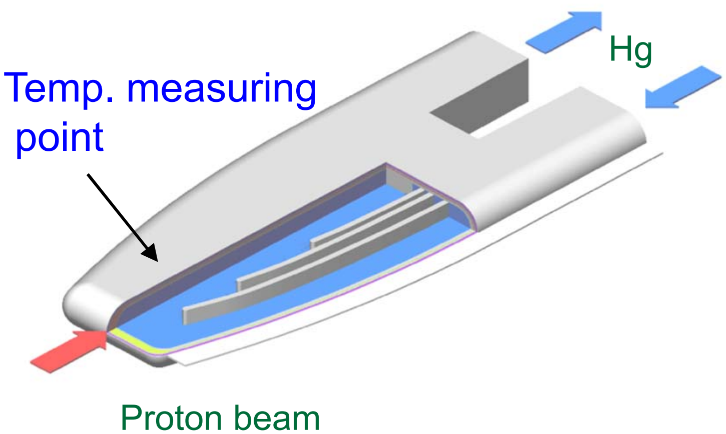
Beam power on JSNS target

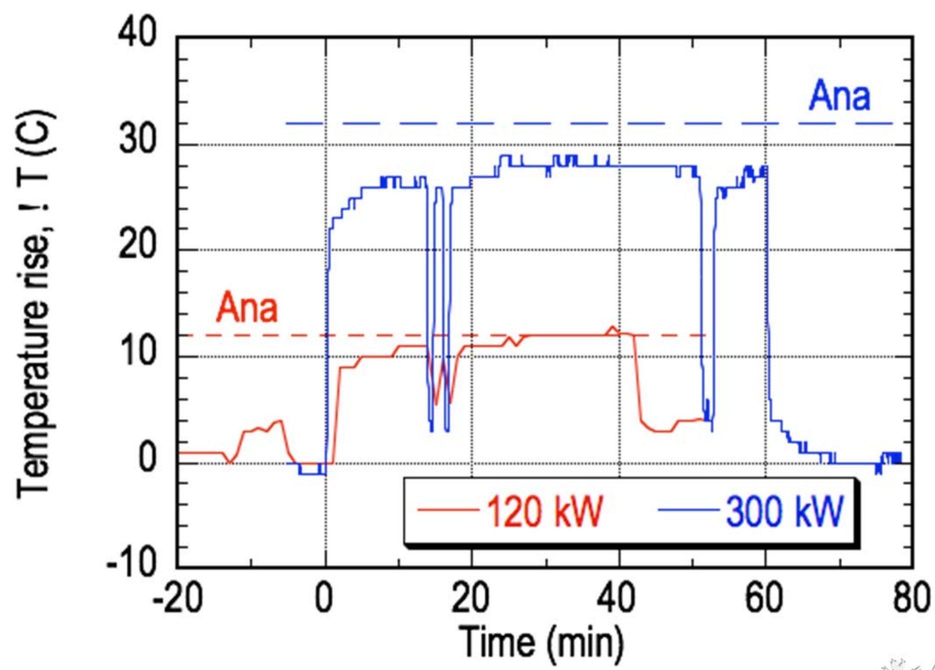


Confirmation of target system design

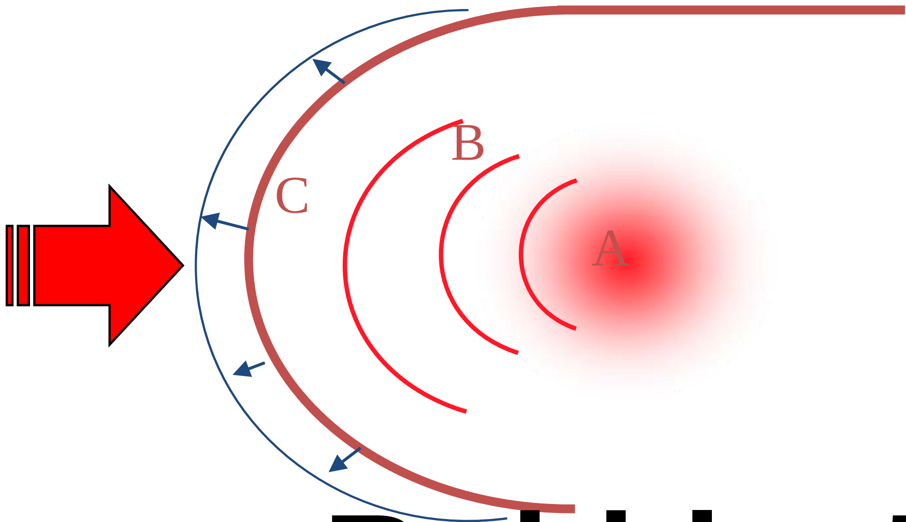
- **Temperature rise of mercury vessel for 120 kW & 300 kW beam power agreed with estimates**
  - **Confirmed operation of the mercury circulation system ; EM pump, heat exchanger, etc.**







Bubble Injection Needed to Mitigate Cavitation Damage



3 mechanisms for each region

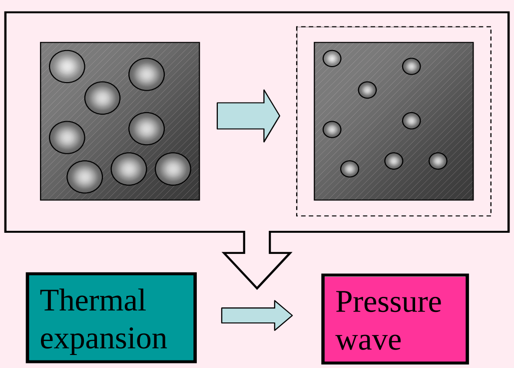
Center of thermal shock : A
Absorption

Propagation path : B
Attenuation

Negative pressure field : C
Suppression

Bubble<50 μm

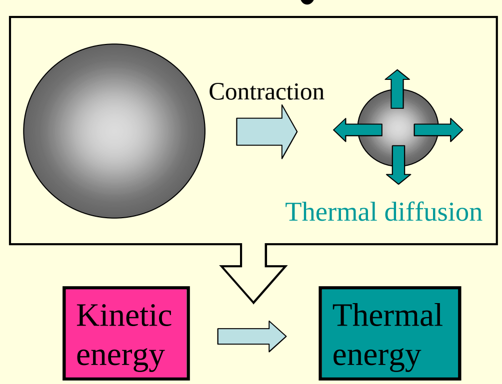
A



Absorption **of the thermal expansion of mercury due to the contraction of micro bubbles**

Absorption

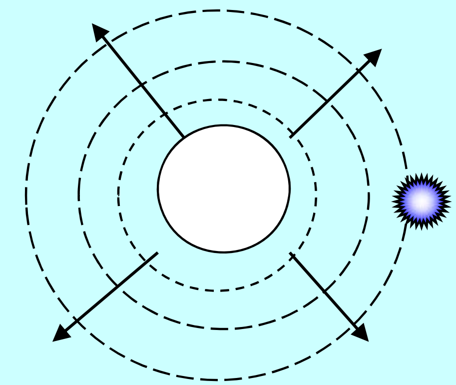
B



Attenuation **of the pressure waves due to the thermal dissipation of kinetic energy**

Attenuation

C



Suppression **against cavitation bubble by compressive pressure emitted from gas-bubble expansion.**

Suppression

Bubblers applicable to target

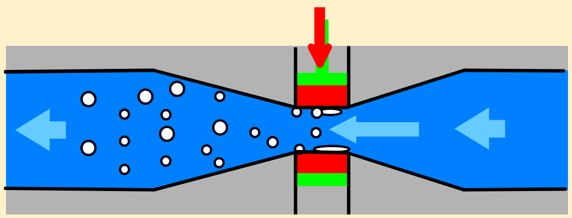
What bubbler is the most suitable under mercury target condition ?

Venturi

Difficult to cont., D>50 μm

High erosion risk

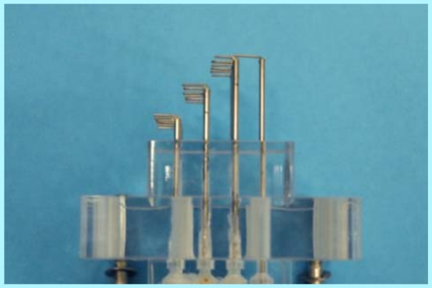
High pressure drop



Needle

Controllable, D>500 μm,

Flow induced vibration, Erosion



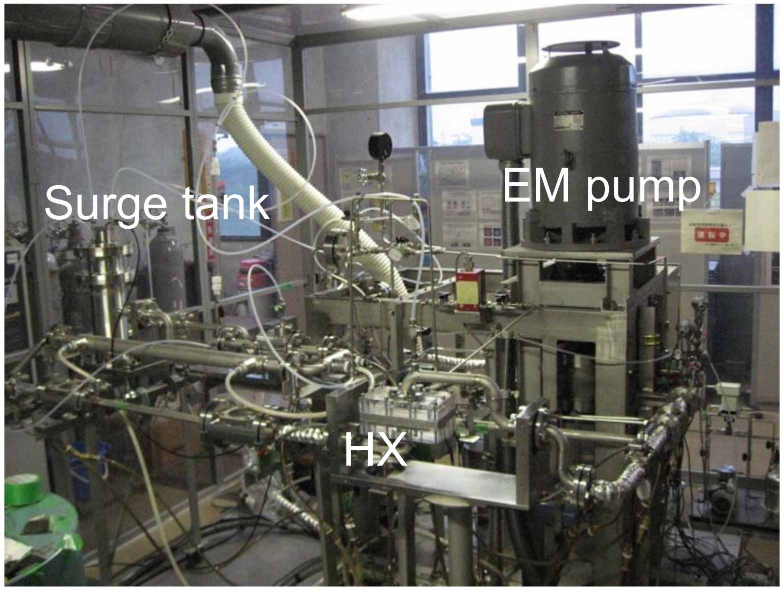
Swirl

Controllable, D<50 μm,

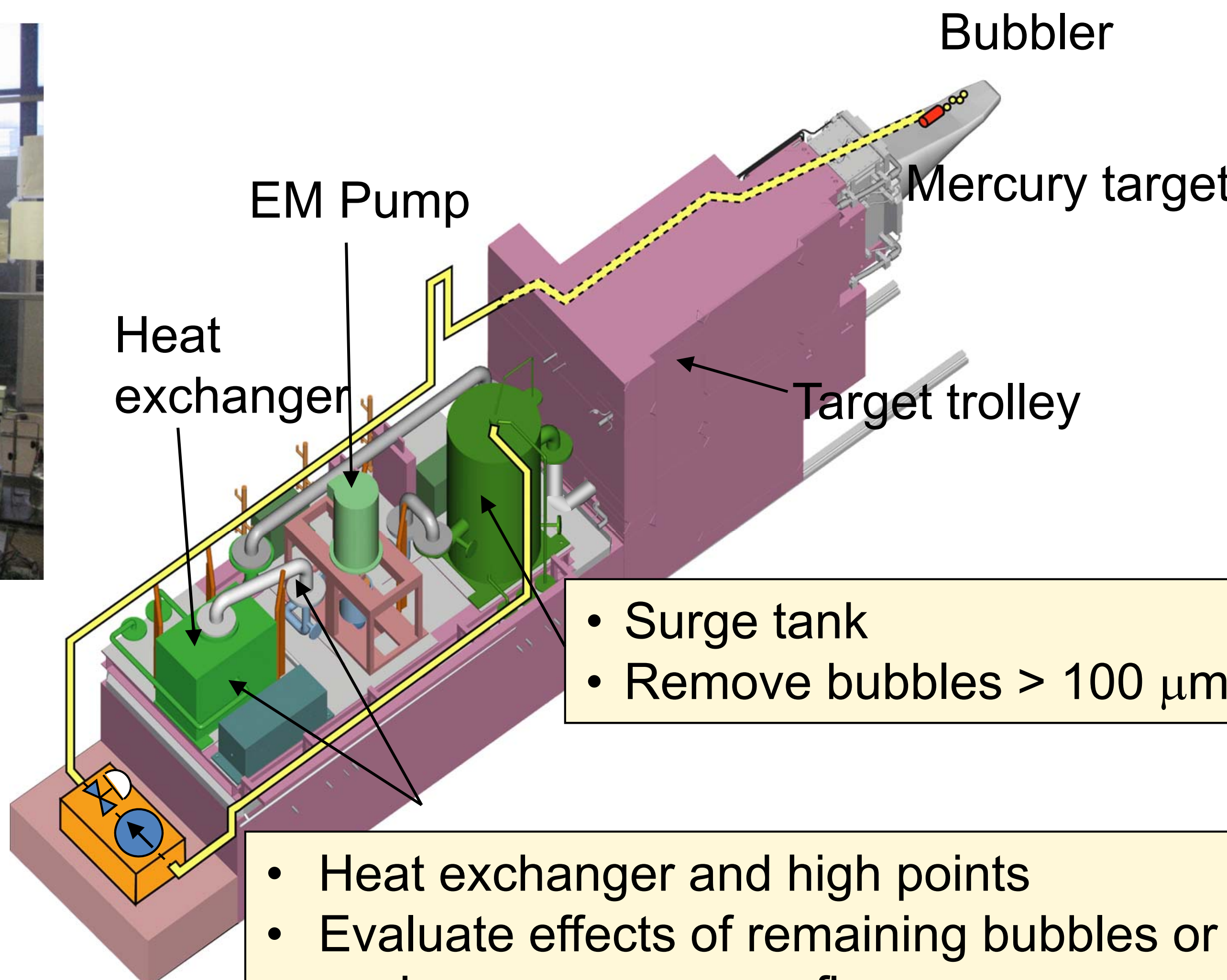
Acceptable pressure drop

Gas supply system for bubblers

- Component tests are being carried out in water and mercury loops
- Conceptual design is being made by a company



Mercury loop



- Surge tank
- Remove bubbles > 100 μm

- Gas supply system
- Control gas pressure and flow rate

- Heat exchanger and high points
- Evaluate effects of remaining bubbles or gas layers on mercury flow

Strong Collaboration Between JSNS and SNS on Hg Target Development

- Facilities for cavitation damage characterization and mitigation tests:
  - Off-line tests
    - JAEAs impact testing apparatus (MIMTM)
    - ORNLs full-scale Hg loop (TTF)
  - In-Beam Tests at LANLs WNR facility
- Characterize bubbles, measure mitigation effects, etc.

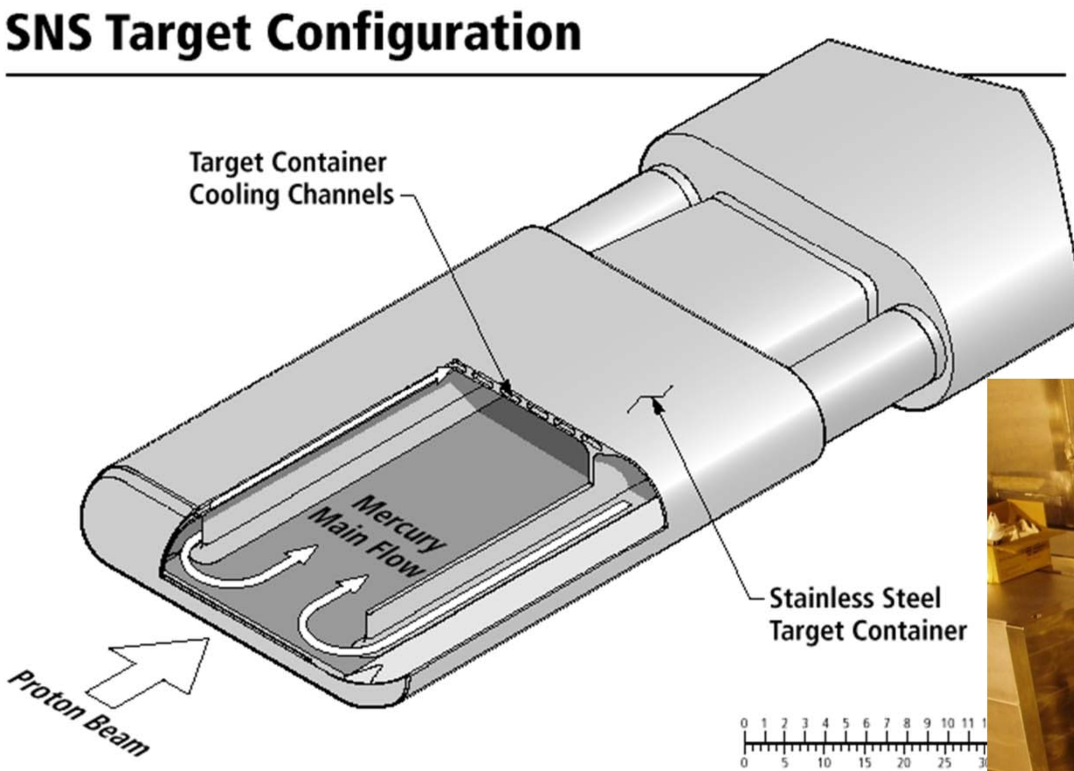
MIMTM

WNR

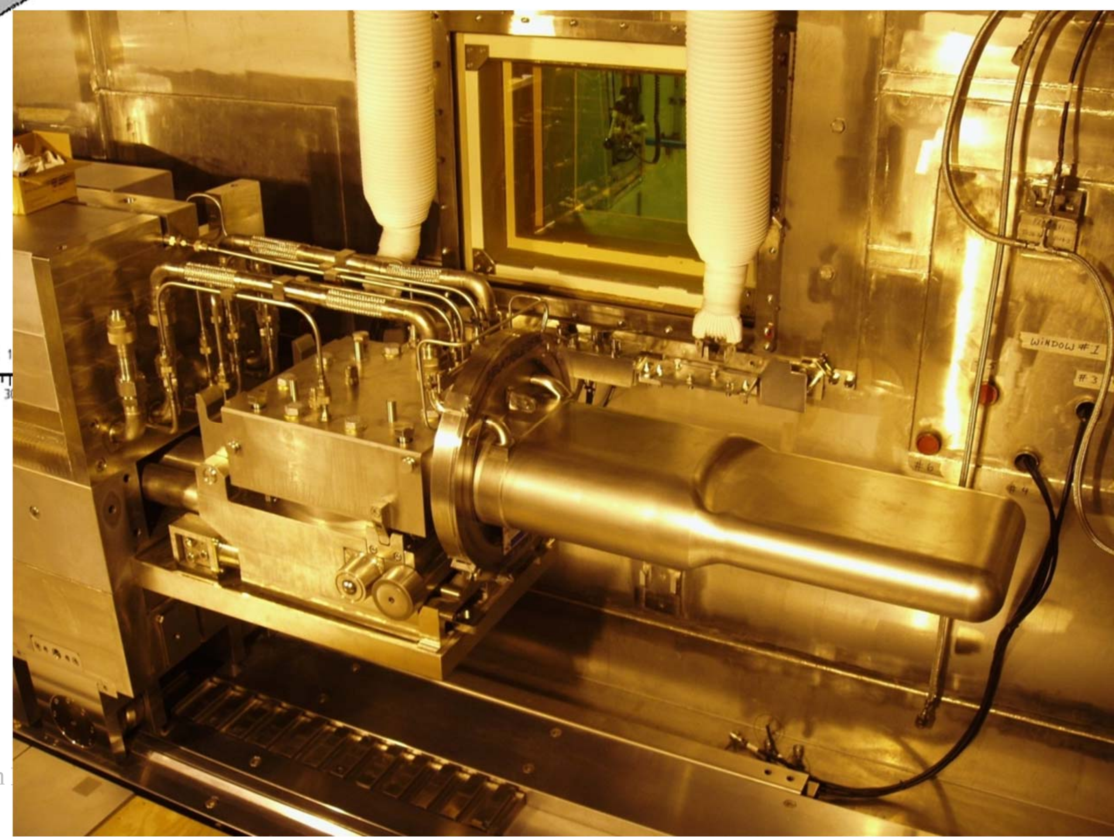
TTF

SNS mercury target

SNS Mercury Target



SNS Ultimate Parameters
- 1 GeV protons
- 2 MW average beam power
- Pulse duration ~ 0.7 μs
- 60 Hz rep rate

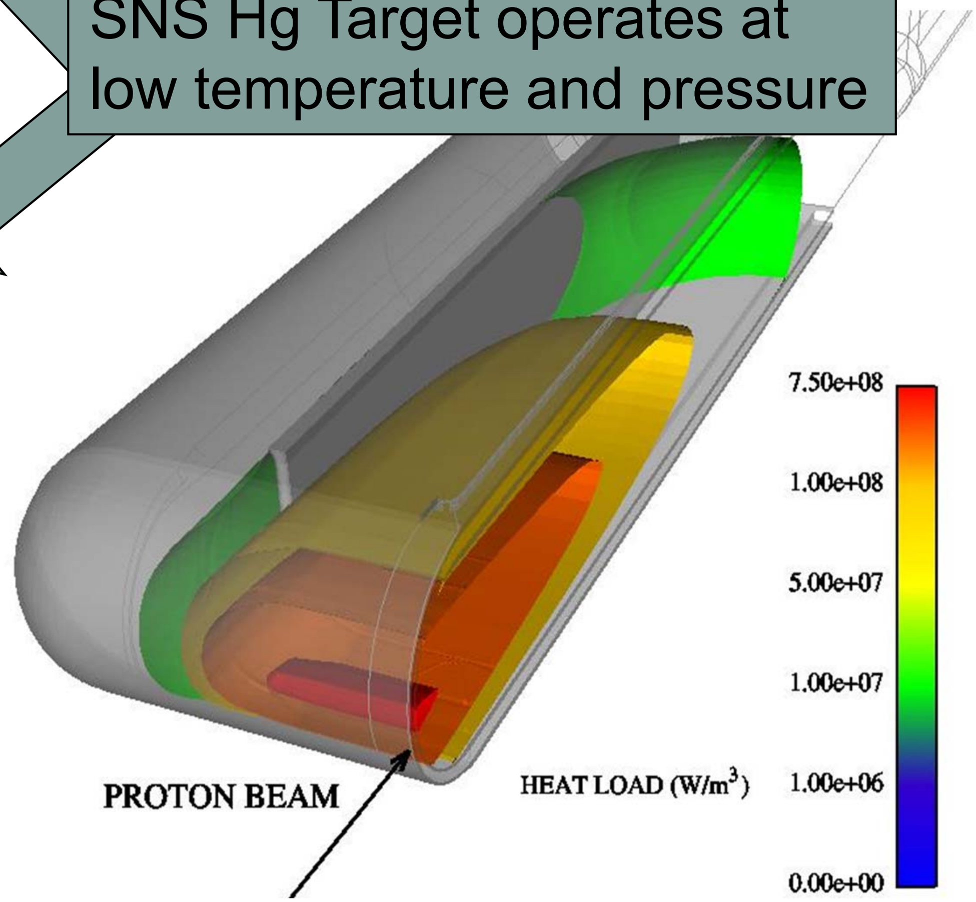


Mercury Loop Parameters @ 2 MW

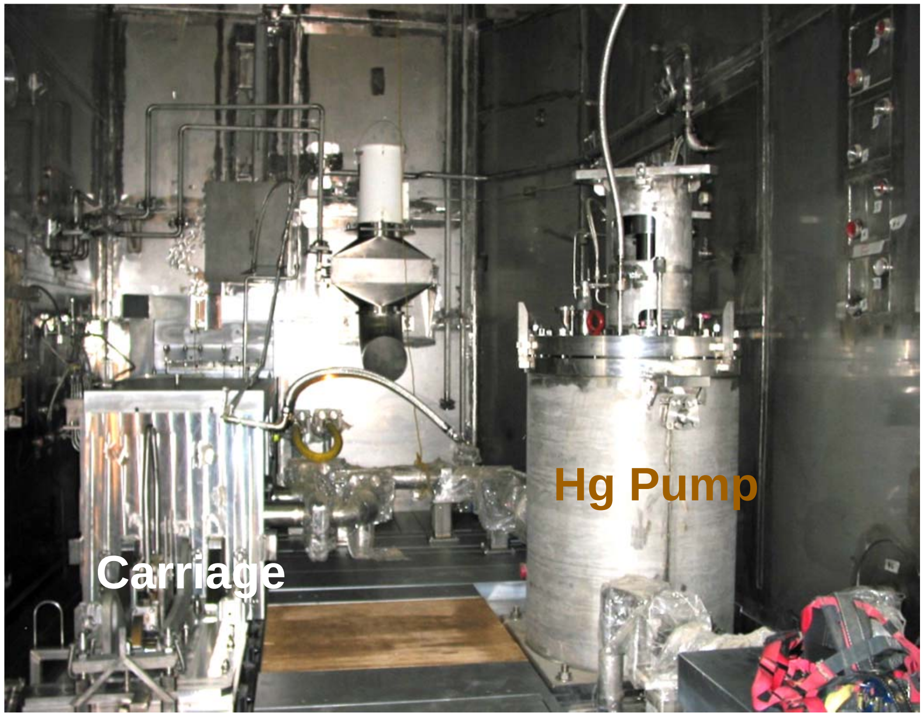
• Power absorbed in Hg	1.2 MW
• Nom Op Pressure	0.3 MPa
• Flow Rate	340 kg/s
• V_{max} (In Window)	3.5 m/s
• Temperature	
– Inlet to target	60ºC
– Exit from target	90ºC
• Total Hg Inventory	1.4 m^3
• Centrifugal Pump Power	30 kW

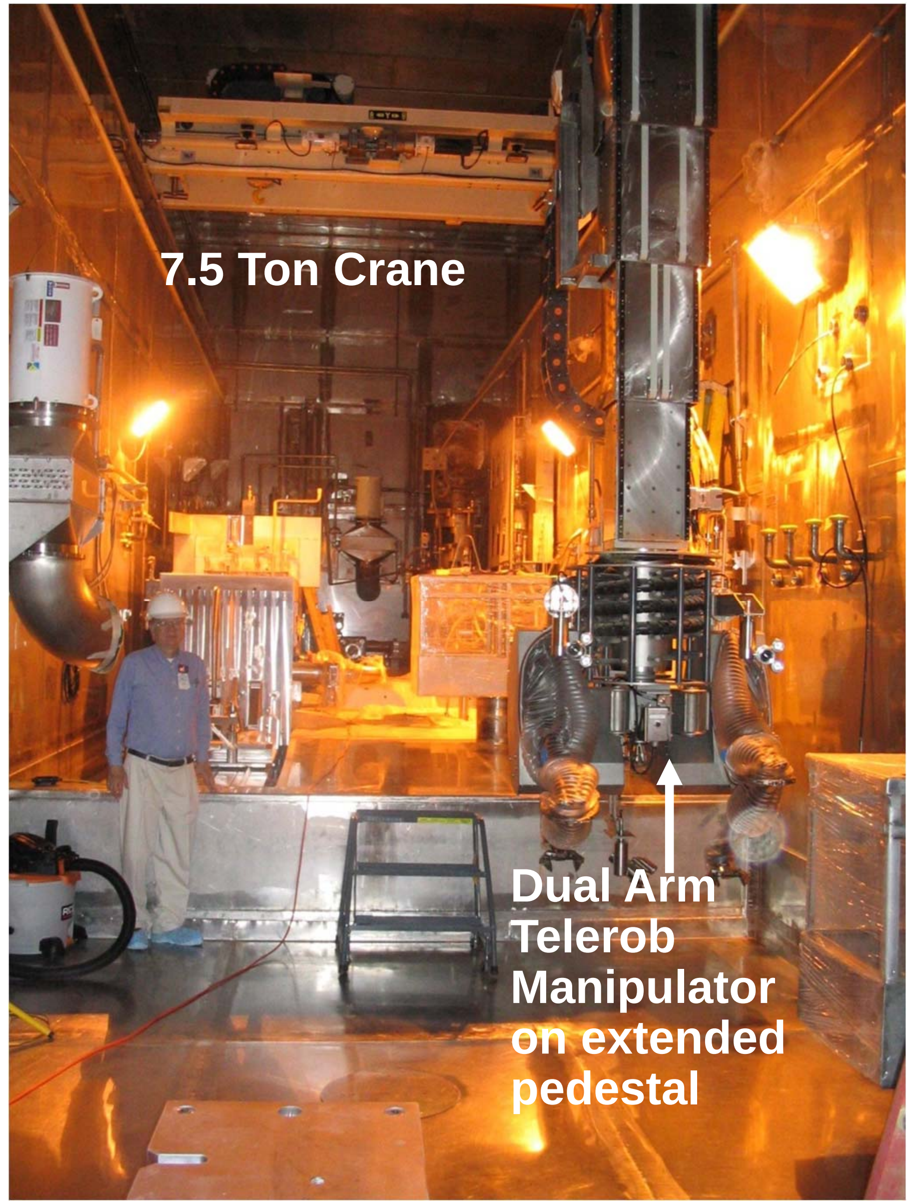
SNS Hg Target operates at low temperature and pressure

Peak power density in mercury ~ 800 MW/m^3



Target Service Bay



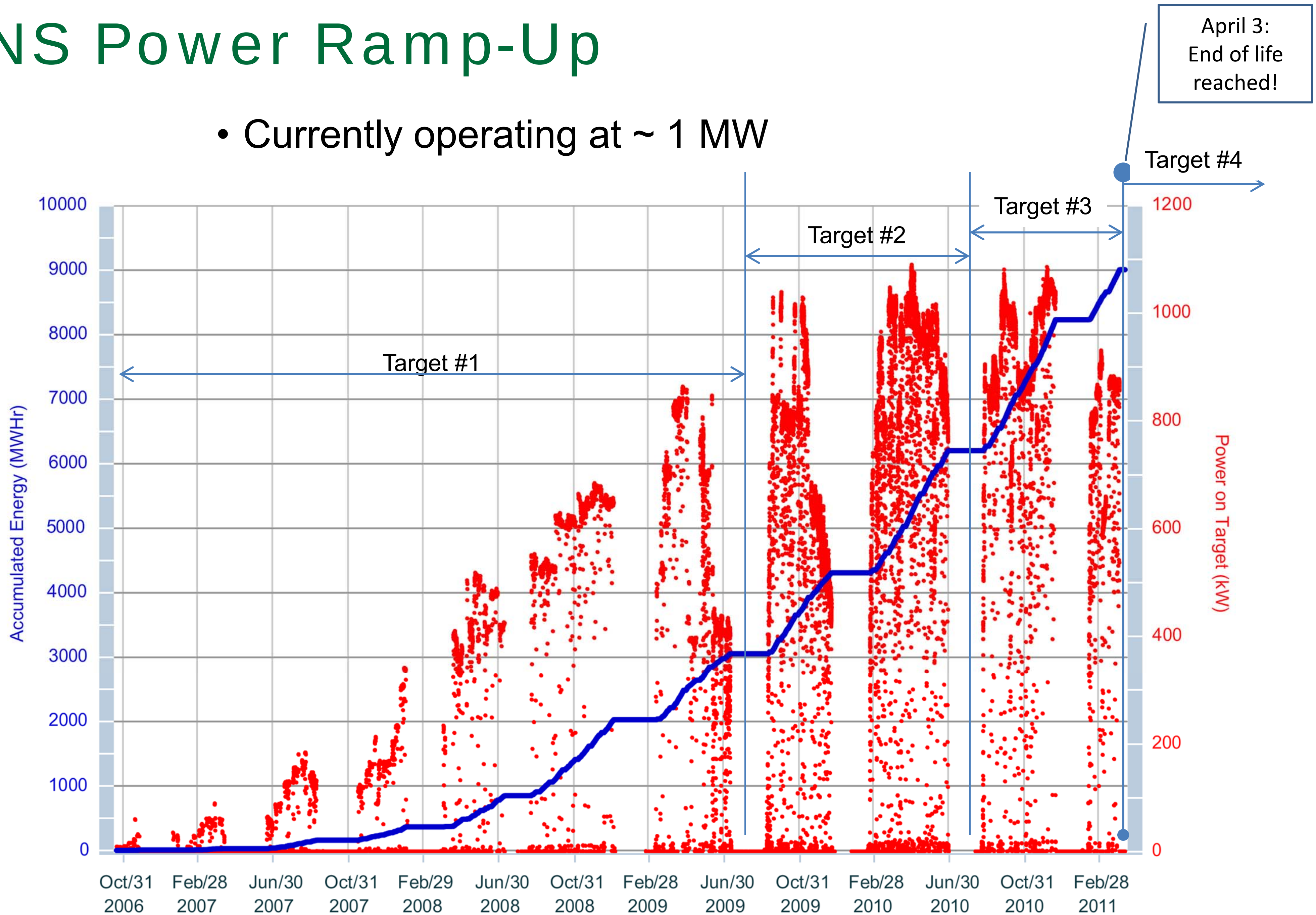


Target Service Bay

- **Stainless-steel lined**
- **4 window workstations**
- **8 through-the-wall manipulators**
- **7.5 ton crane**
- **Pedestal mounted manipulator**
- **Shielded transfer bay**

SNS Power Ramp-Up

- Currently operating at ~ 1 MW



OAK RIDGE National Laboratory

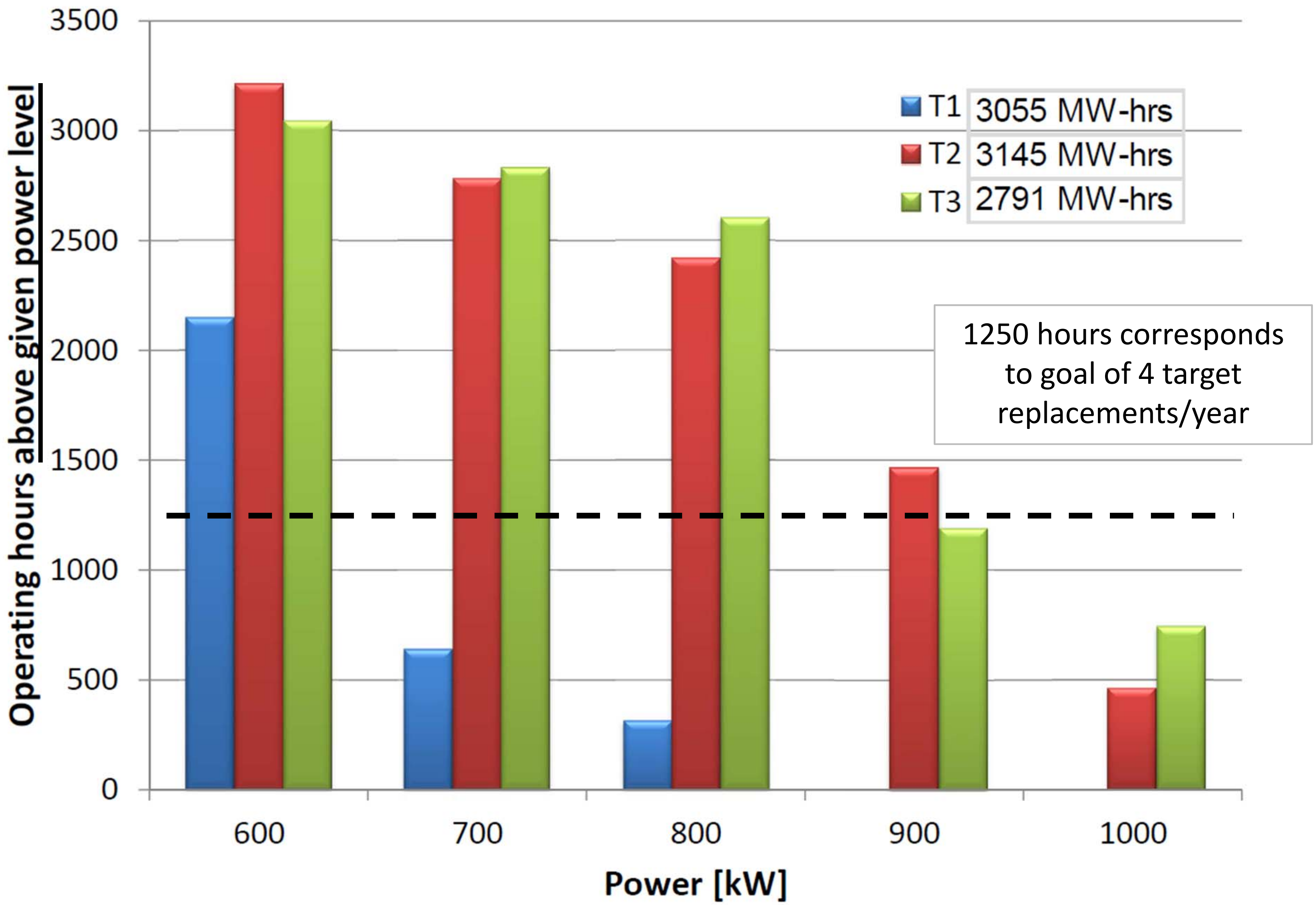
Mercury Target Status

- 1st target module replaced July 2009; 2nd target replaced July 2010
  - Both during planned extended maintenance periods
  - Both exceeded original goal of 5 dpa (reaching almost 8 dpa)
- Plans are still to run the next few targets to end-of-life, i.e. mercury leaks from primary container to its water-cooled shroud (or 10 dpa)
  - If cavitation damage limits lifetime, will operate at a power level consistent with using four targets/year (~ 1250 hour lifetime)
- Three spare target modules on-site; five more by 2012

3 April 2011:
Target #3 reached an early end of life

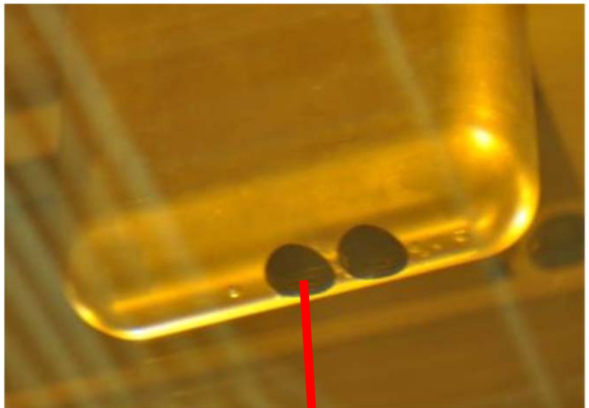
- Leak detectors in interstitial space between mercury vessel and shroud gave unanimous indications of a leak
- Plan was to replace T3 during summer maintenance period
  - It would have reached ca. 10 dpa by that time
- Target replacement to be completed by 17 April
- Investigation / PIE now under way
  - Must locate and characterize the leak
  - It is not confirmed that cavitation is the cause

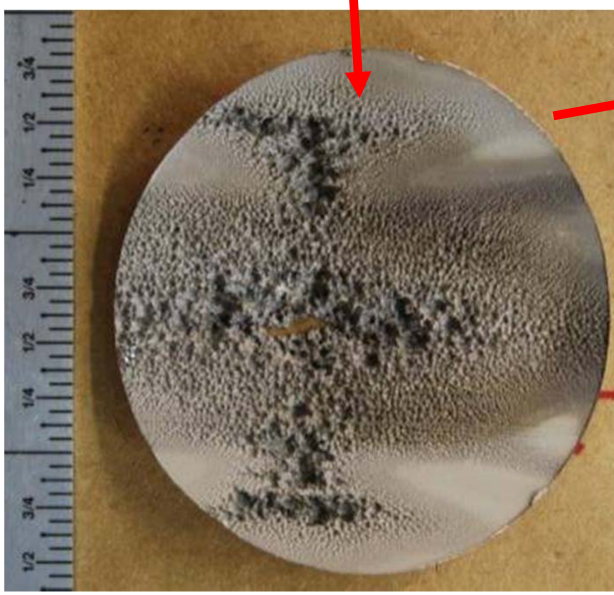
Mercury target module lifetime remains uncertain



Demonstrated power limit is now > 900 kW

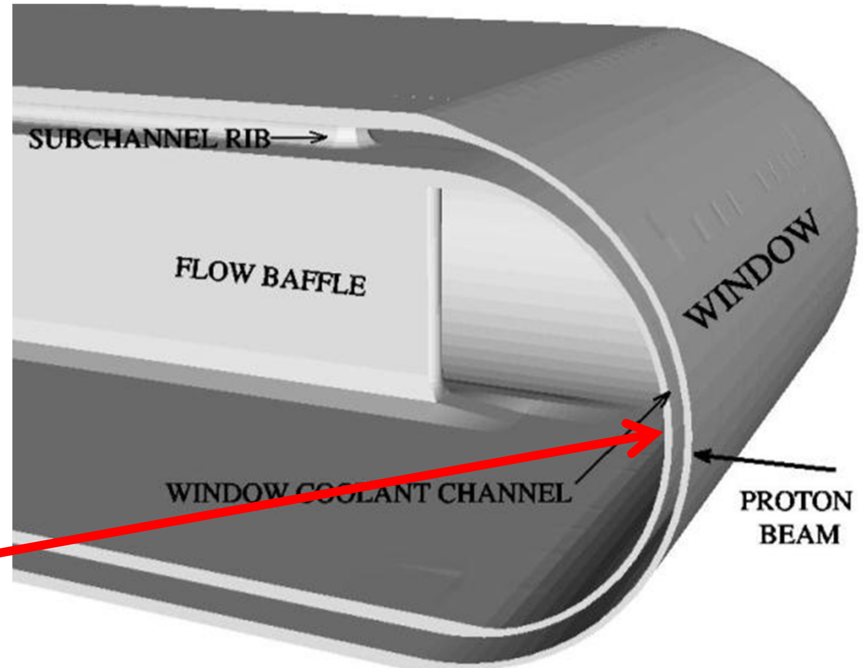
Results of Post-Irradiation Examination of Hg Target Module #1





60 mm

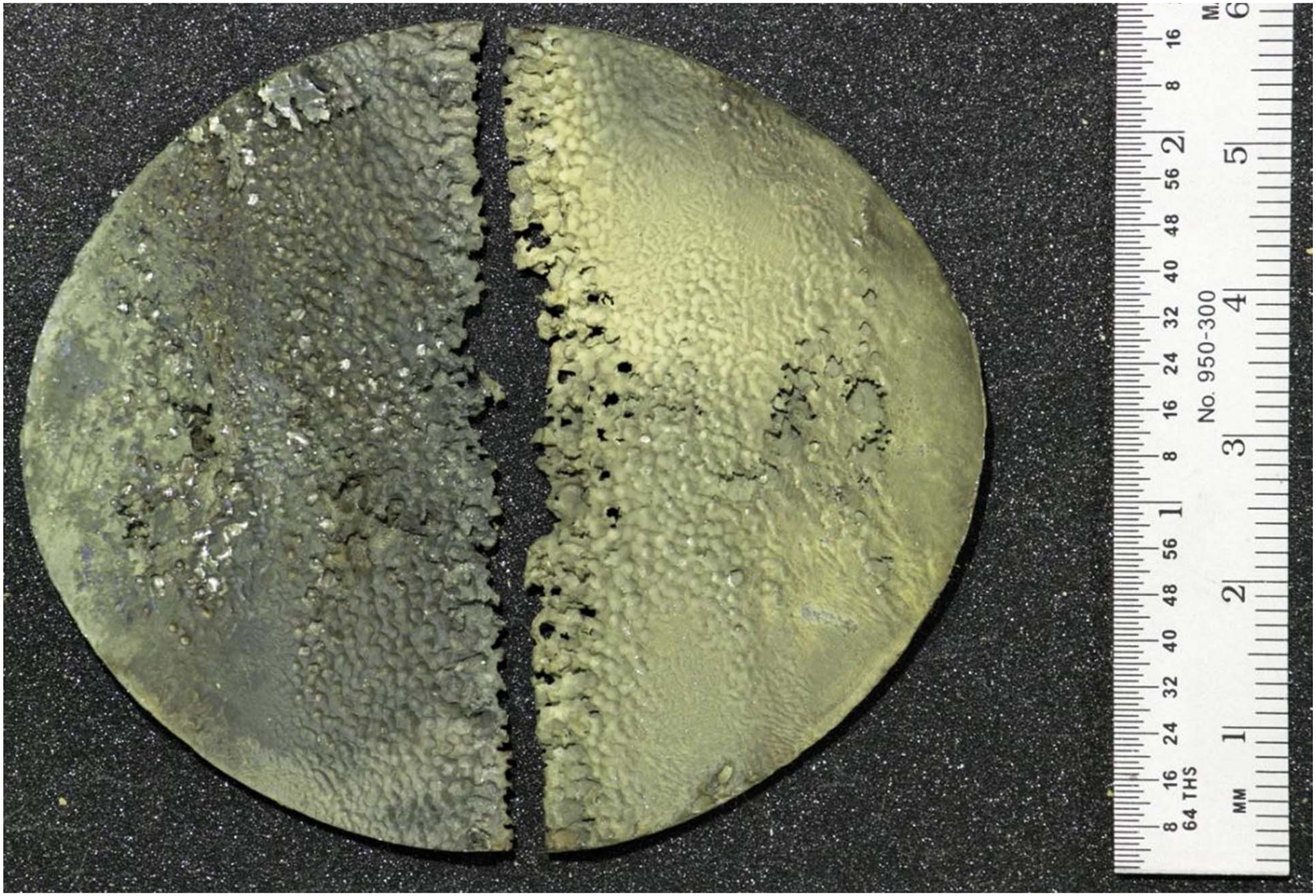
Inner surface of wall between bulk Hg and small channel



- Target #1:
  - Cavitation damage phenomenon confirmed on inner wall at center of target
  - Outer wall fully intact; inner wall at off-center location shows little or no damage
  - Damage region appears to correlate with regions of low Hg velocity, but not such a clear distinction on Target #2

Target #2 survived through planned operating period but inner wall suffered more damage

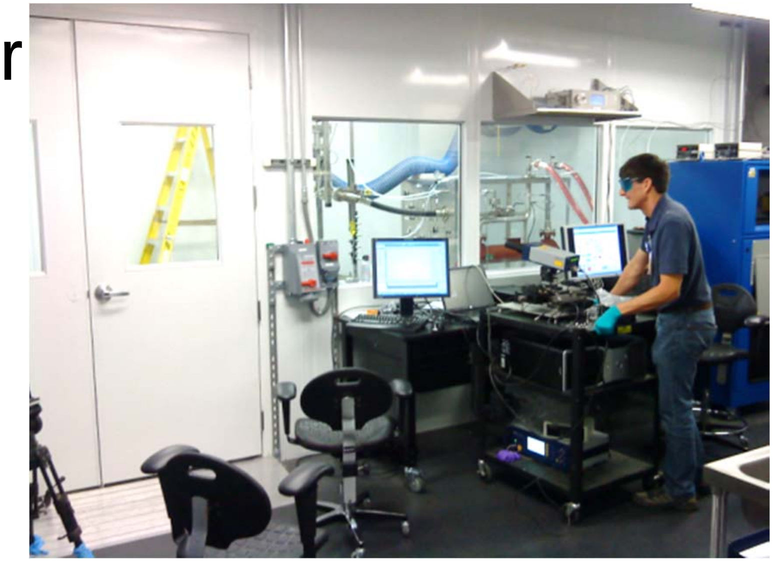
Horizontal operating orientation

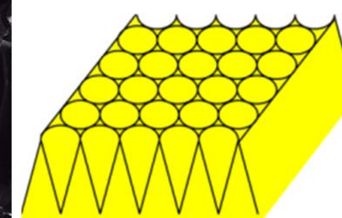


Bulk Hg Flow Surface - UNCLEANED

Hg Target Development Plans

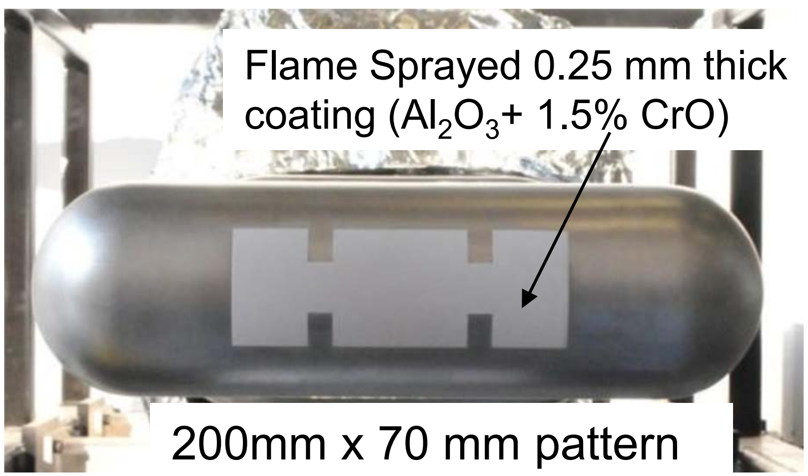
- New mercury laboratory now operational in SNS Experiment Hall
- Continue to pursue gas injection schemes for mitigating cavitation damage
  - Gas injection looks promising, but work remains to optimize and implement
    - Small gas bubbles and/or gas curtain near wall
    - Collaborating with JAEA, RAL, and several university and industrial partners
- More detailed PIE of samples from first ~~two~~ *three* spent target modules will be conducted

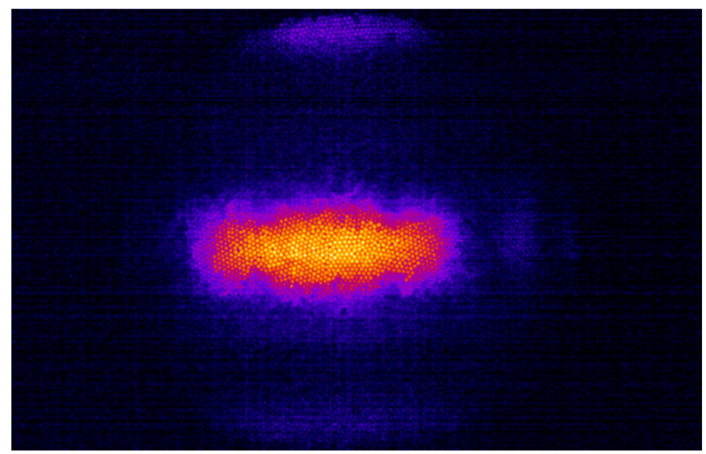




Target Imaging System

- Implemented Target Imaging System on second target
  - System was functional for full life of 2nd target (3200 MW-h)
  - 3rd target installed with enlarged and improved coating pattern
  - Improved resolution system was installed with 3rd Proton Beam Window in December 2010





Target Imaging System

Concluding Remarks

- MEGAPIE, SNS, and JSNS projects successfully implemented liquid metal targets designed for ~ 1 MW
  - MEGAPIE experiment completed in 2006; demonstrated ~ 1 MW reliable operation
  - SNS operating reliably at 1 MW; *3rd target end of life*; ramp-up to 1.4 MW may be impacted
  - JSNS was operating reliably at 220 kW; plan to ultimately achieve 1 MW
- SINQ is pursuing more optimal solid targets
  - Liquid metal target is not being pursued in view of cost and effort, and because the neutron flux of new solid targets is within 15% of MEGAPIE
  - Next generation Pb-Bi target (LIMETS) being pursued as an experiment
- Cavitation damage remains a concern for pulsed sources with liquid metal targets
  - Target lifetime uncertain but reasonably long lifetime established for SNS at 1 MW
    - Cause of target 3 end 0f life not yet determined; ultimate power / lifetime limit remains to be discovered
  - Strong R&D collaboration between SNS and JSNS
- Future projects considering target alternatives
  - SINQ upgrades, CSNS, ESS, SNS-STS, MTS
  - Both liquid and solid target options under consideration