Status and Future Directions for High Power Neutron Production Targets

Charlotte Barbier

09/04/2019

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

What is a High-Power Neutron Source?

- Accelerators
  - kW-MW
  - High power density (MW/m^3)
  - High energy density per pulse (J/m^3/pulse)
- **Targets**
  - **Heavy metal (High Z: Ta, W, Hg, Pb-Bi, U)**
  - **neutron production roughly proportional to power deposited**
- Beam lines
- Detectors
- Civil construction

Key Parameters

- Proton energy E: between 1 and 5 GeV for neutron production
- Beam intensity N: nb of proton per pulse (~10^{14})
- Repetition rate f

- Then the power can be computed with :

$$P(MW) = 1.6 \times 10^{-16} \times E(GeV) \times N \times f(Hz)$$

High Power Neutron Sources

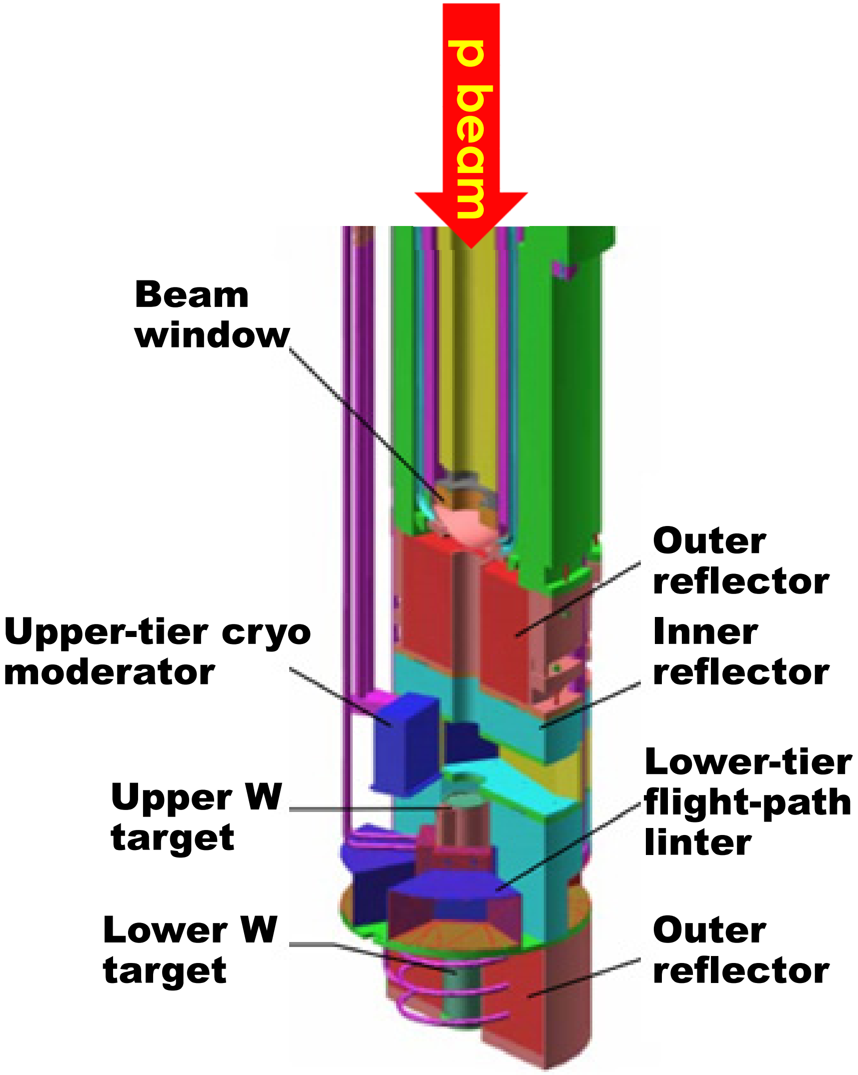
	Starting Operation	Target material	Power [MW]	Proton Energy [GeV]	Pulse type	Repetition [Hz]
LANSCE-Target 1	1977	Tungsten	0.1	0.8	Short	20
ISIS TS-1	1984	Tungsten	0.16	0.8	Short	40
LANSCE-Target 4	1986	Tungsten	0.1	0-0.6	Short	100
SINQ	1996	Lead	1	0.57	continuous	N/A
SNS-FTS	2006	Mercury	1.4	1.0	Short	60
ISIS TS-2	2008	Tungsten	0.032	0.8	Short	10
J-PARC	2009	Mercury	1	3.0	Short	25
CSNS-I	2018	Tungsten	0.12	1.6	Short	25
ESS	**2023**	**Tungsten***	**5**	**2**	**Long**	**14.7**
SNS-FTS	**2025**	**Mercury**	**2.0**	**1.3**	**Short**	**60 (45*)**
SNS-STS	**20??**	**Tungsten***	**0.7**	**1.3**	**Short**	**15**
CSNS-II	**20??**	**Tungsten**	**0.5**	**1.6**	**Short**	**25**

Main Challenges in Designing Targets

- Harsh environment
  - High radiation
  - High Temperature
- Fast deposition of energy
  - Complex dynamic ➔ metal expands rapidly leading to strong pressure waves.
- Material properties not very well known, especially once exposed to radiation
  - Harder to predict accurately temperatures and stresses
- Gigacycle fatigues
- Fabrication
  - Weld are the weakest point

LANSCE – Lujan Center Target (0.8 GeV, 0.1MW)

- Beam injection form above
- Tungsten target
  - MK I (1991-1998)
  - MK II (1998-2010)
  - MK III (2010-2020)
- Water cooled
- MK I target design with bare, thick tungsten cylinder suffered severe corrosion and fracture
- MK I&II experienced:
  - Highly activated water systems
  - Degradation in neutron performance
- Successive designs were segmented into plates and clad with tantalum using HIP (Hot Isostatic Pressing) process



R. Werbeck / LANL

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A.T. Nelson / LANL

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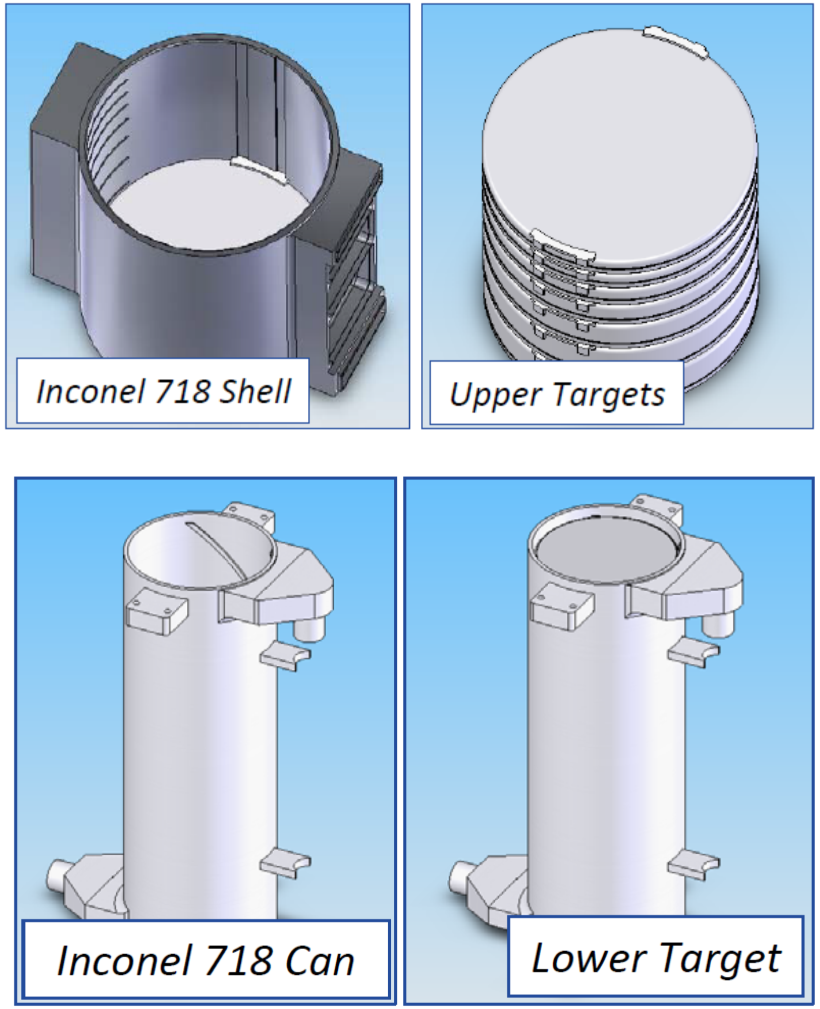


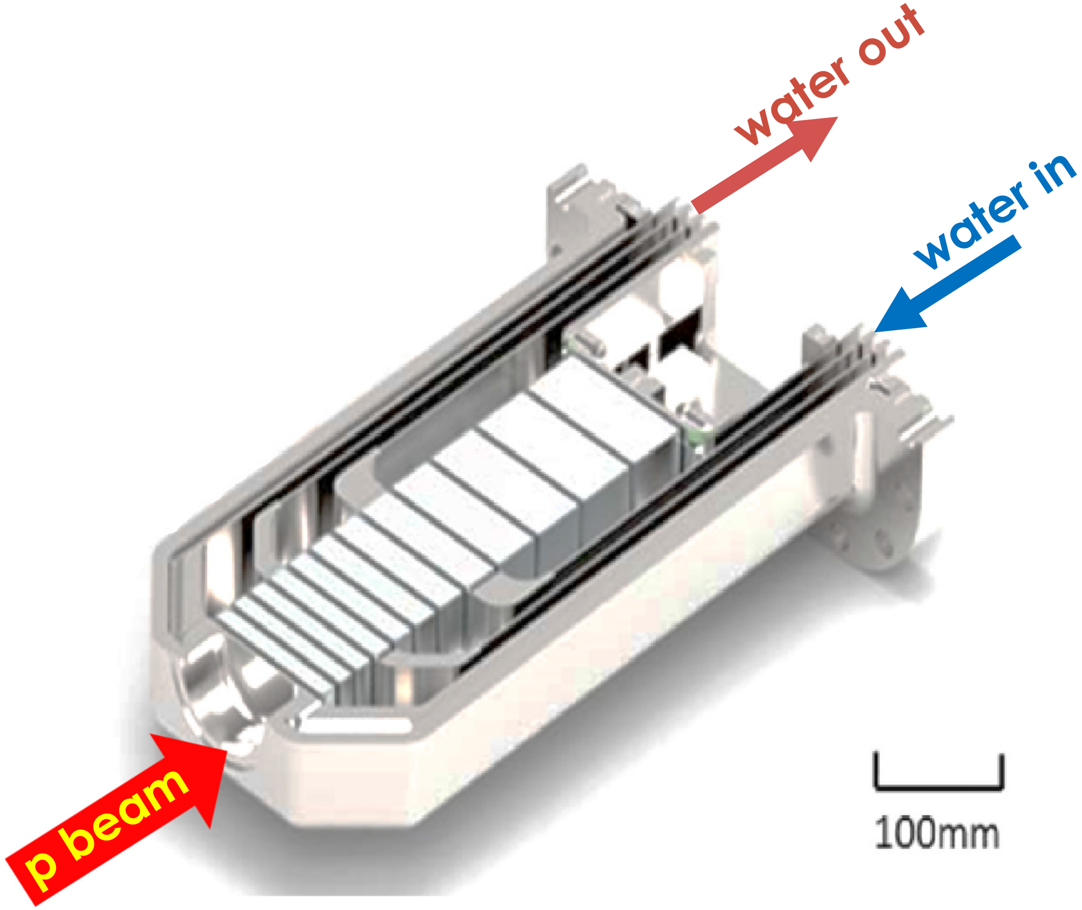
A.T. Nelson / LANL

ISIS

- Two target station
  - Target Station 1 (TS1)
  - Target Station 2 (TS2)
- Operation for more than 30 years
- Highest power short-pulse spallation source prior to SNS at ORNL
  - Plate target design with water cooling
  - Uranium targets tried initially but abandoned because of short life
  - Tantalum target plates worked well but had very high activation & decay heat levels
  - Currently using tungsten with a tantalum clad
- Many features from TS1 were adapted in SNS, JSNS, CSNS…

Target Station 1

- Initial target material: uranium
  - radiation damage failures
- Reliable operations with tungsten targets
- Rely on thermocouples to detect plates failure
- Design upgrade planned for 2020
  (TS1 Project):
  - 60% lighter in mass
  - neutron output improved



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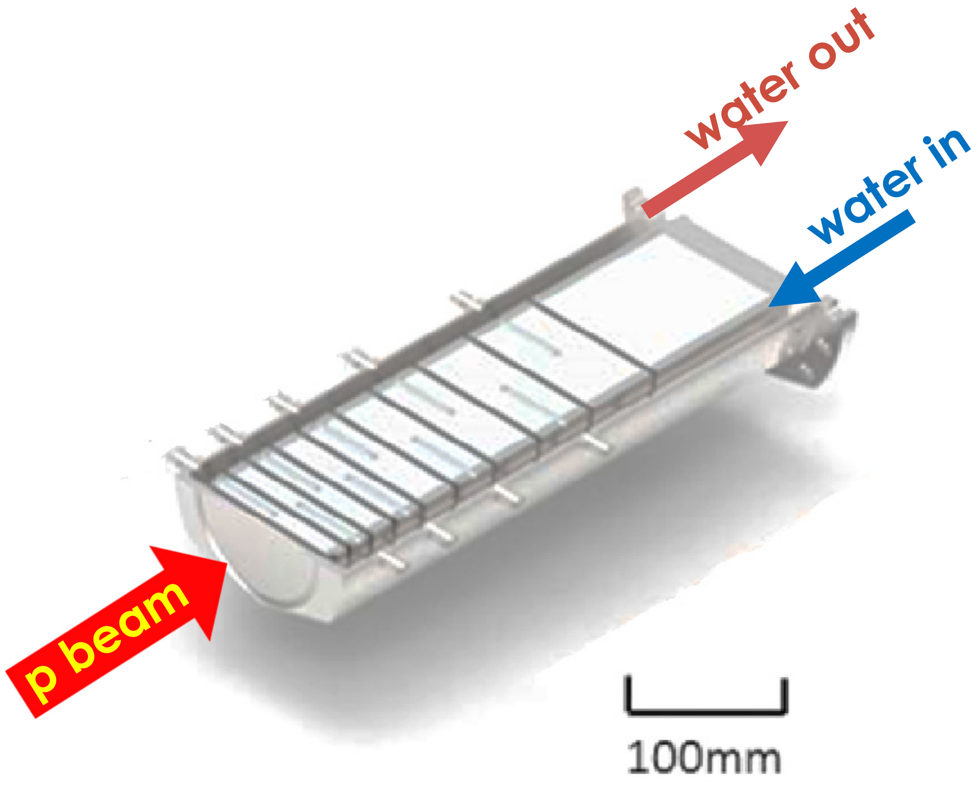
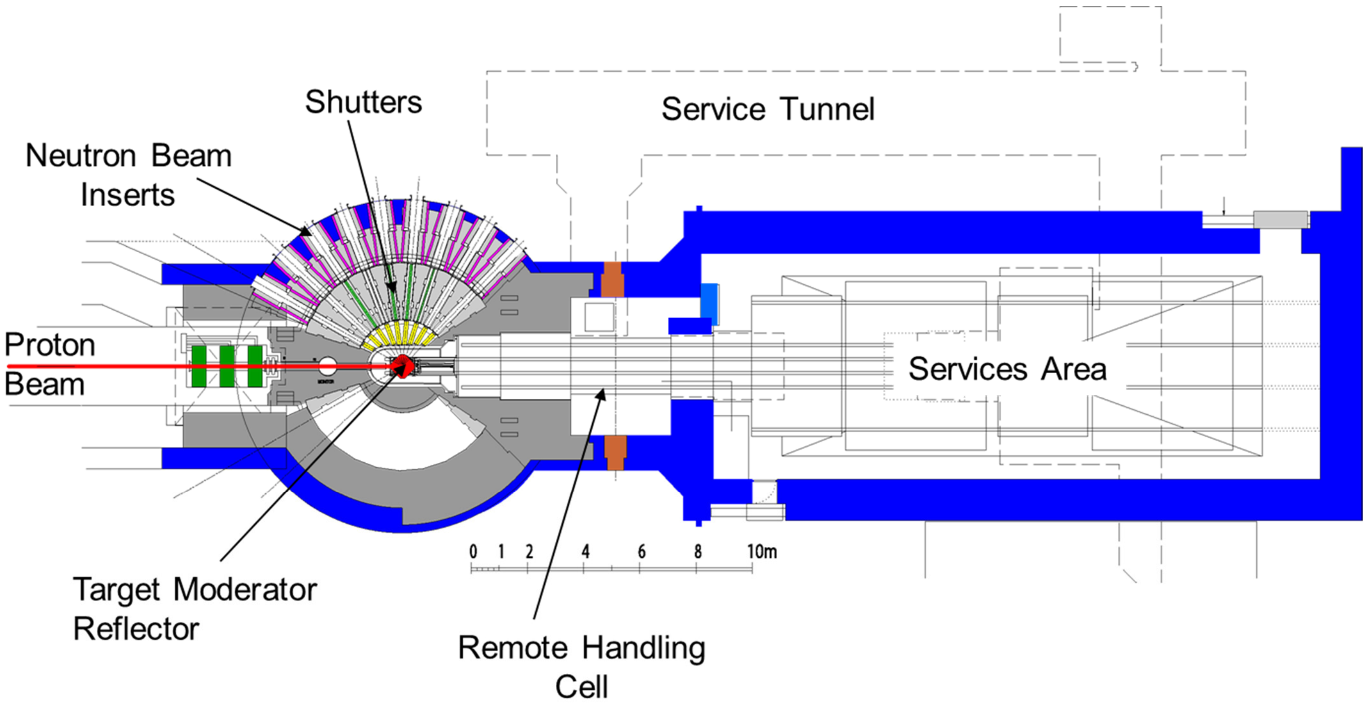
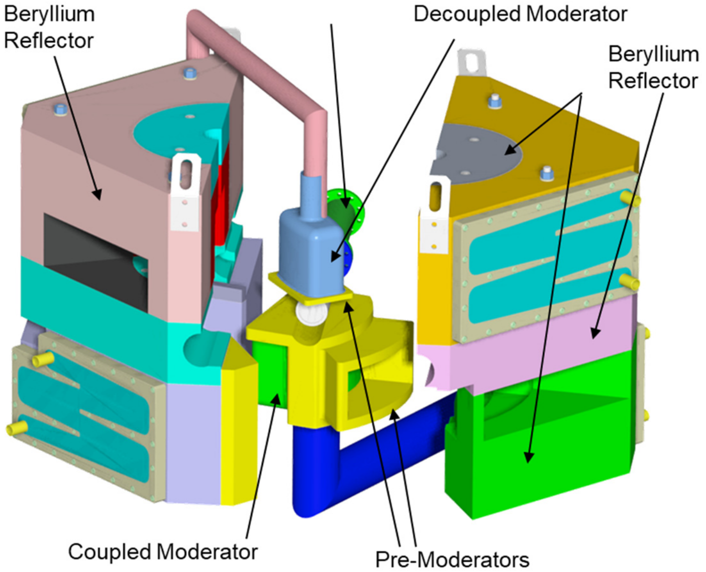
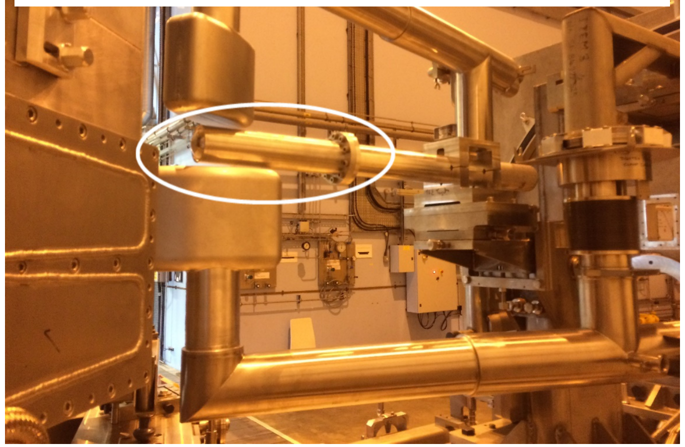


ISIS Target Station 2





ISIS TS-2 water-cooled tungsten target

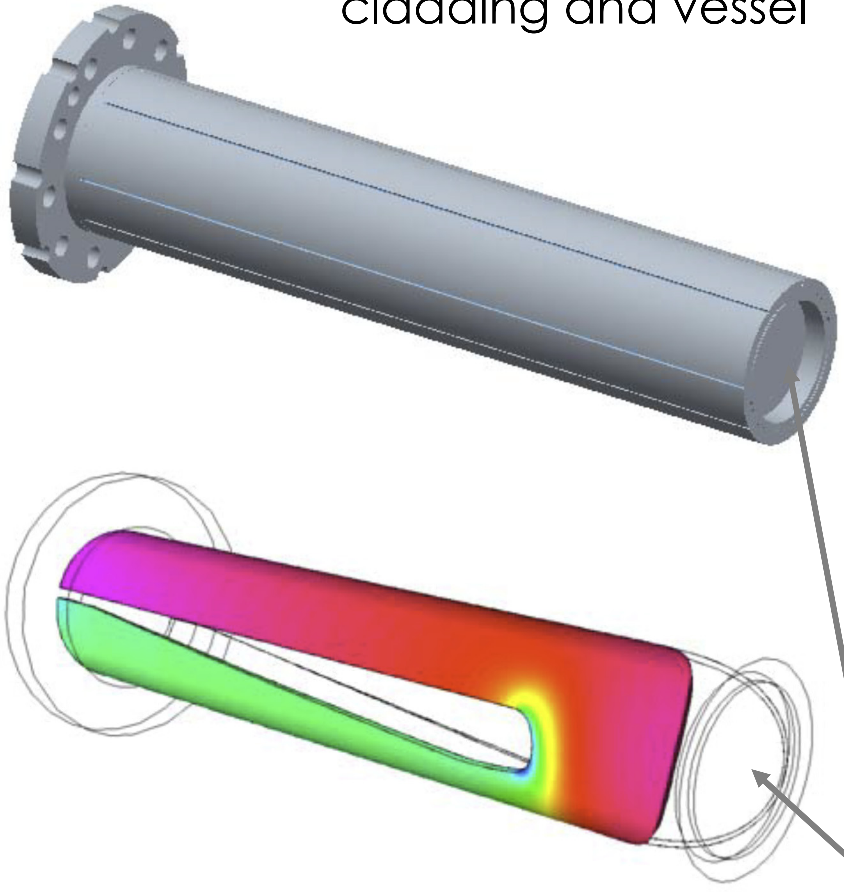


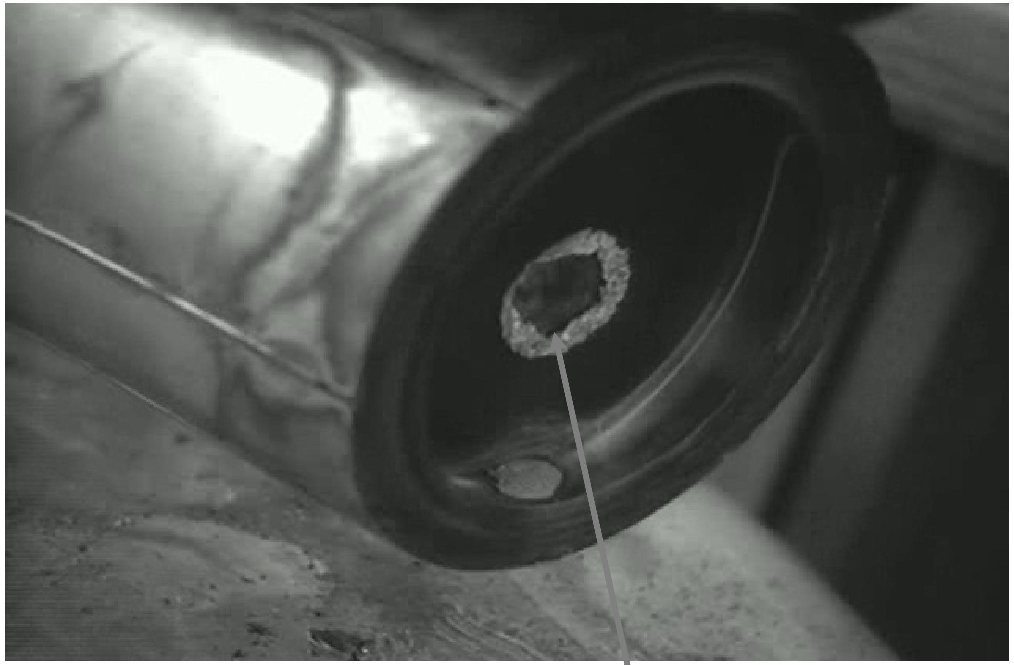
- Moderators very **close** to target:
  - Improved efficiency of neutrons to instrument
  - Possible because of low power
- Design oriented for **rapid** and **flexible** maintenance

Pictures from T. Broome

ISIS-TS2 original design (Mk I) – Clad failure

Tungsten rod with tantalum cladding and vessel





No cooling at beam entrance and design assumed a flatter and larger beam profile than actual

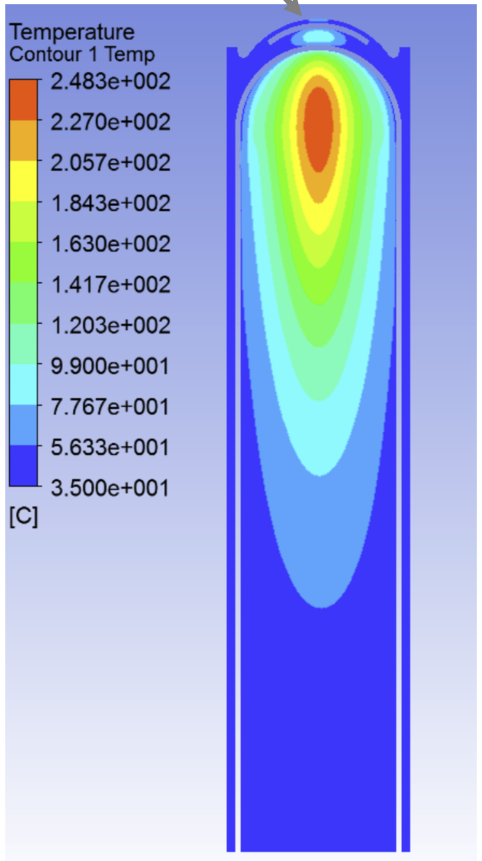
Intergranular corrosion of tantalum cladding due to lack of cooling at beam entrance % moisture in He vessel

ISIS / STFC

TS2 Target Design Evolution

- Added a water patch at the beam entrance
- Some problems at cap weld: W activation products got into cooling water
  - Weld redesign
  - Clad thickness adjusted

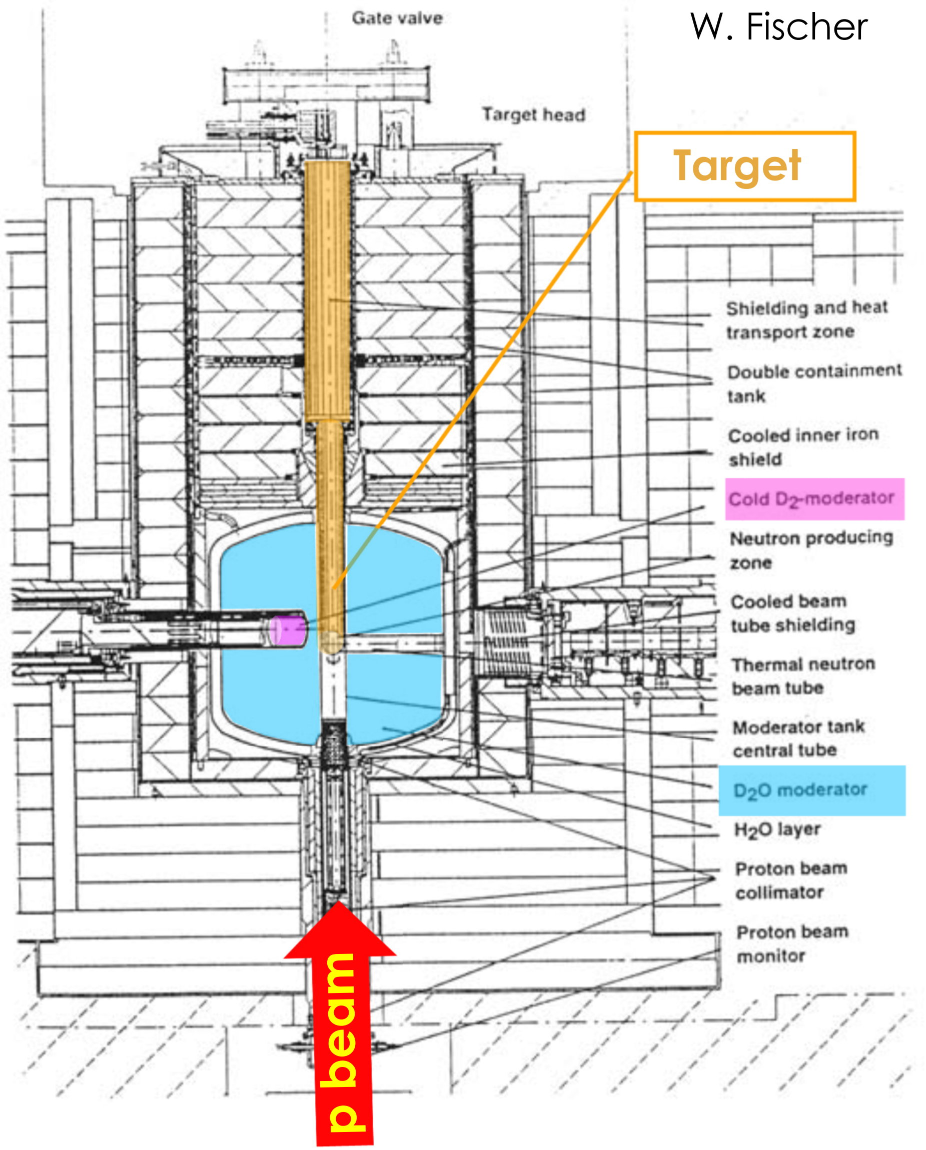
Extra cooling at beam entrance



D. Wilcox

Swiss Intense Neutron Source - SINQ
Paul Scherrer Institut

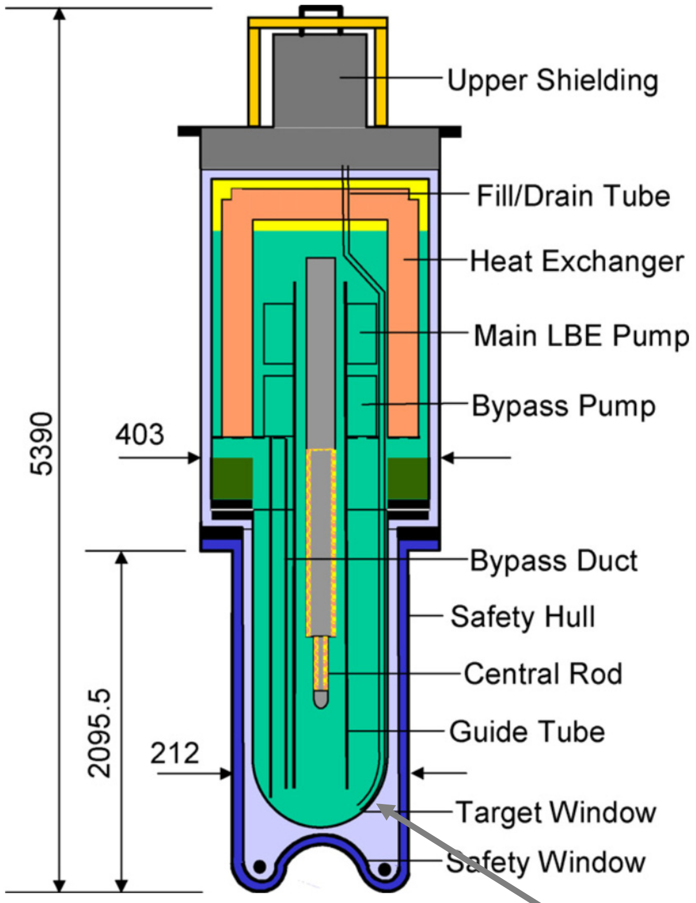
- Continuous beam with injection from below
- Solid lead target rods inside SS or Zircaloy tubes
- One liquid metal target was operated
  - MEGAPIE – 1MW Pilot Experiment
- Solid lead target design evolution strove to reach MEGAPIE performance
- 11th target suffered cascade rupture of target tubes
  - Power has since been limited

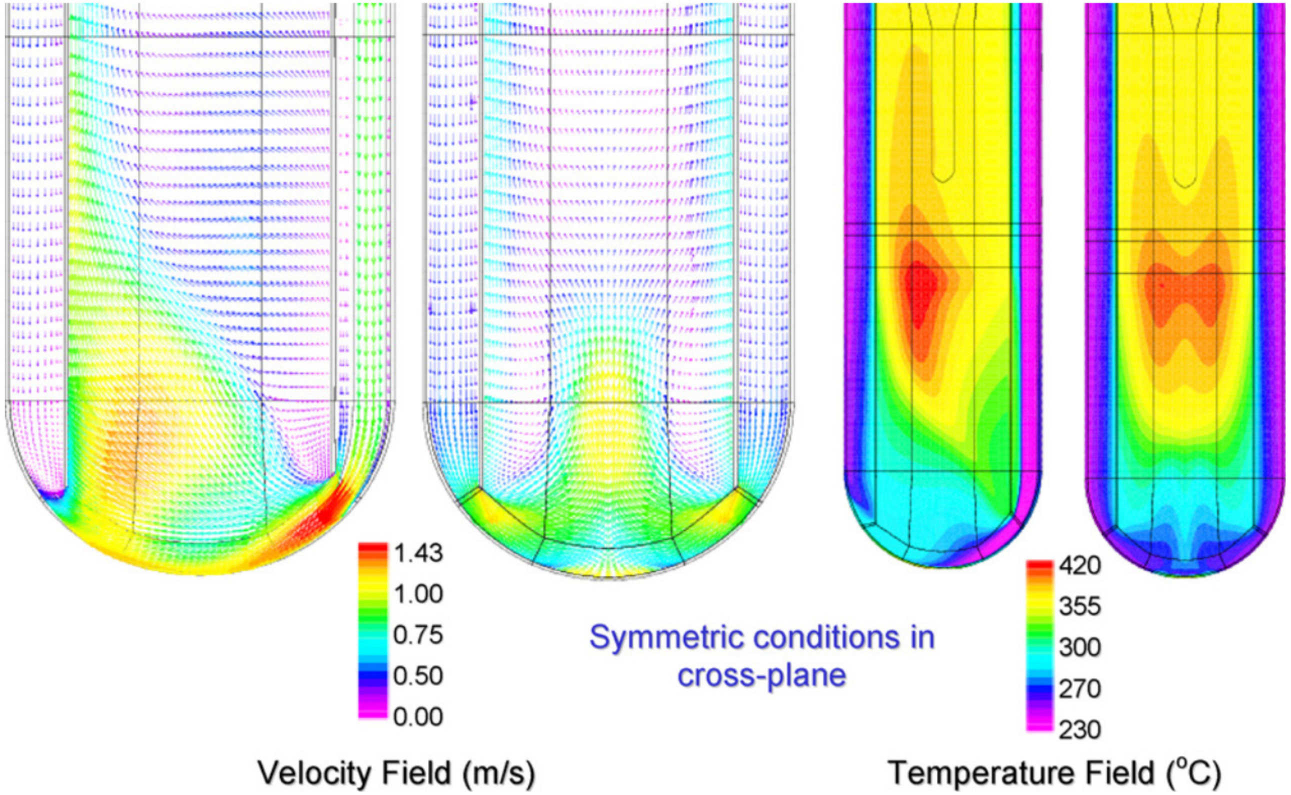


MEGAPIE: Demo. of the feasibility of a liquid metal target @ 1MW

- LBE (Lead Bismuth Eutectic), ~10^4 kg/m^3
- Got great performance: ~70% increase in neutron production
- High melting temperature (125 C)
  - Heating to prevent freezing in piping
  - Freezing in spill accident can be an advantage
- ^{210}Po is produced
  - Decays by α
  - Must be contained (biological hazard)
- Liquid metal corrosion is a serious issue with steels
  - Requires control of the oxygen content within a narrow range

MEGAPIE Design Details



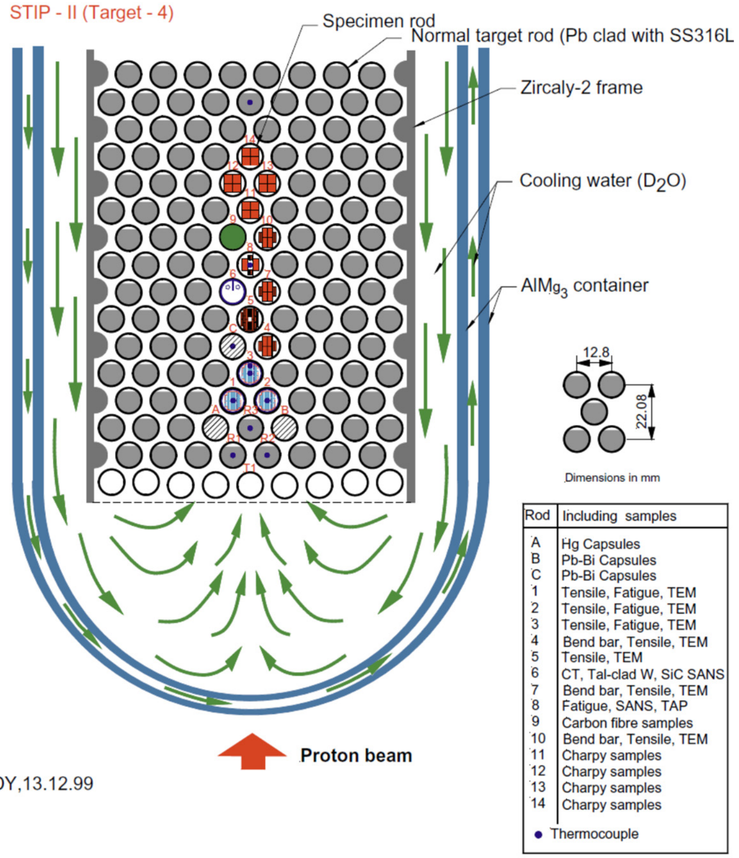


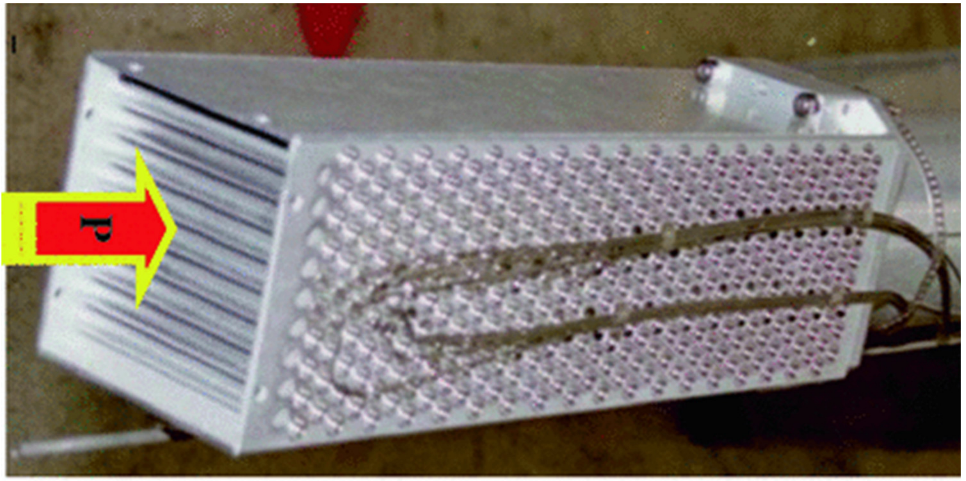
Jet to avoid stagnation at the beam entrance

Fazio et al., Nuclear Eng. and Design 238 (2008) 1471–1495

MEGAPIE Results Leveraged for Designing SINQ lead targets

- Compaction of rod bundle spacing
- D2O cooled

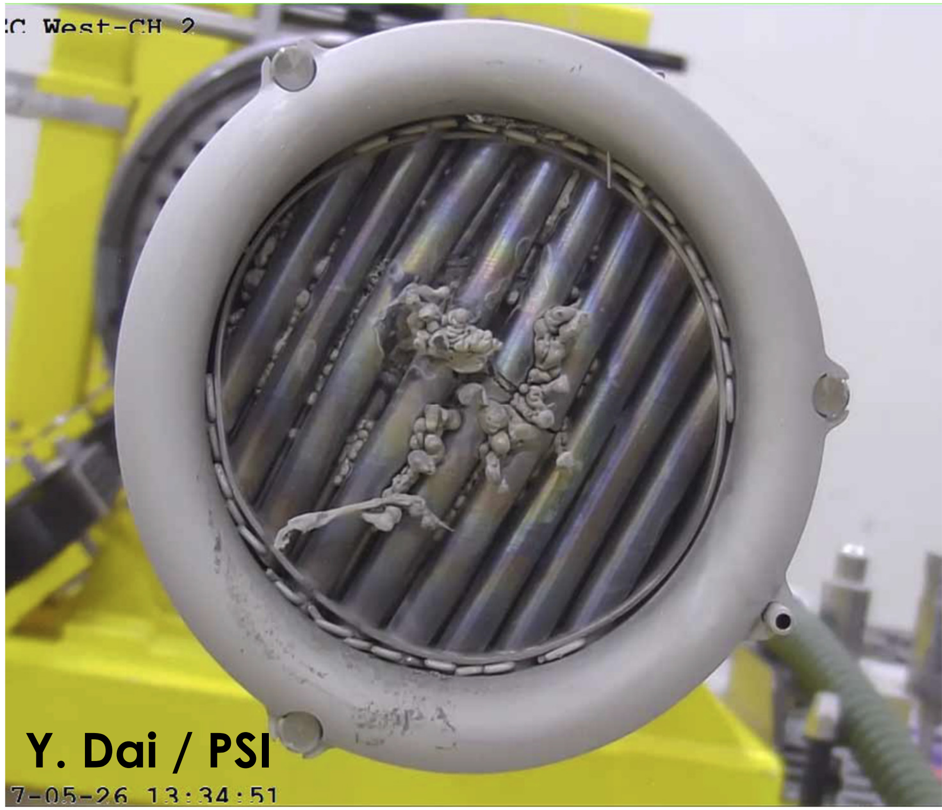




W. Wagner, Y. Dai, M. Wohlmuther

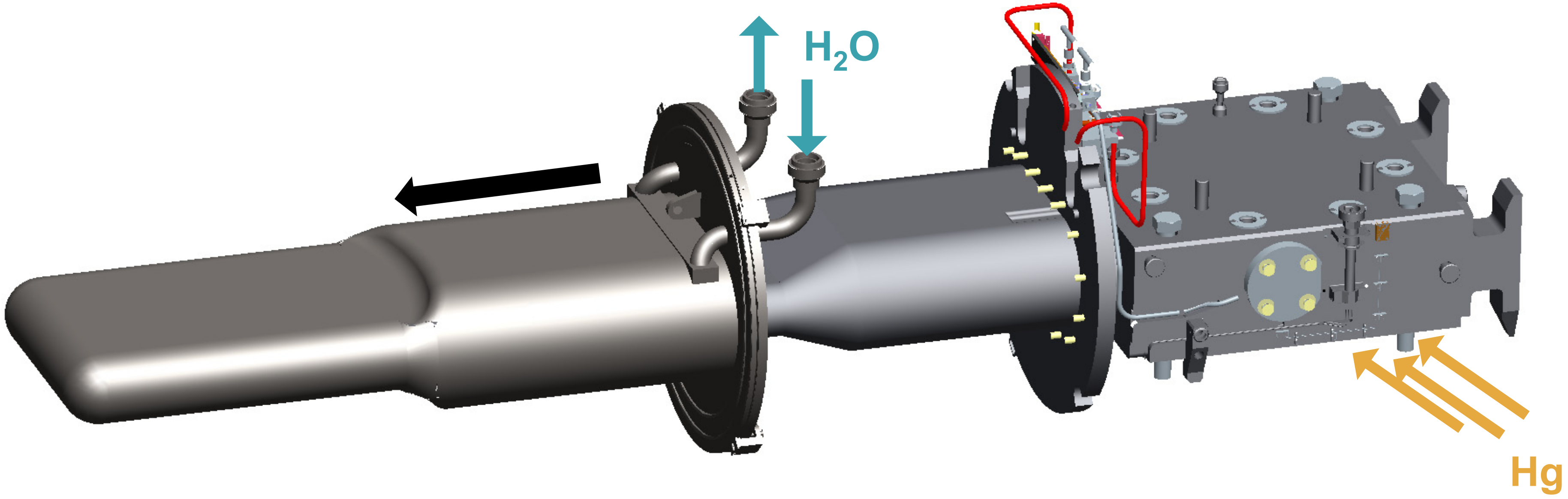
SINQ Target 11 (2016): Cascade of Ruptured Tubes

- Initiating event followed by succession of tube falling and blocking coolant flow
- Earlier detection of an over-focused beam
  - Operations continued after pause
- Later -
  - Water pressure increase detected
  - High activation in water detected
- Power is presently limited to < 800 kW



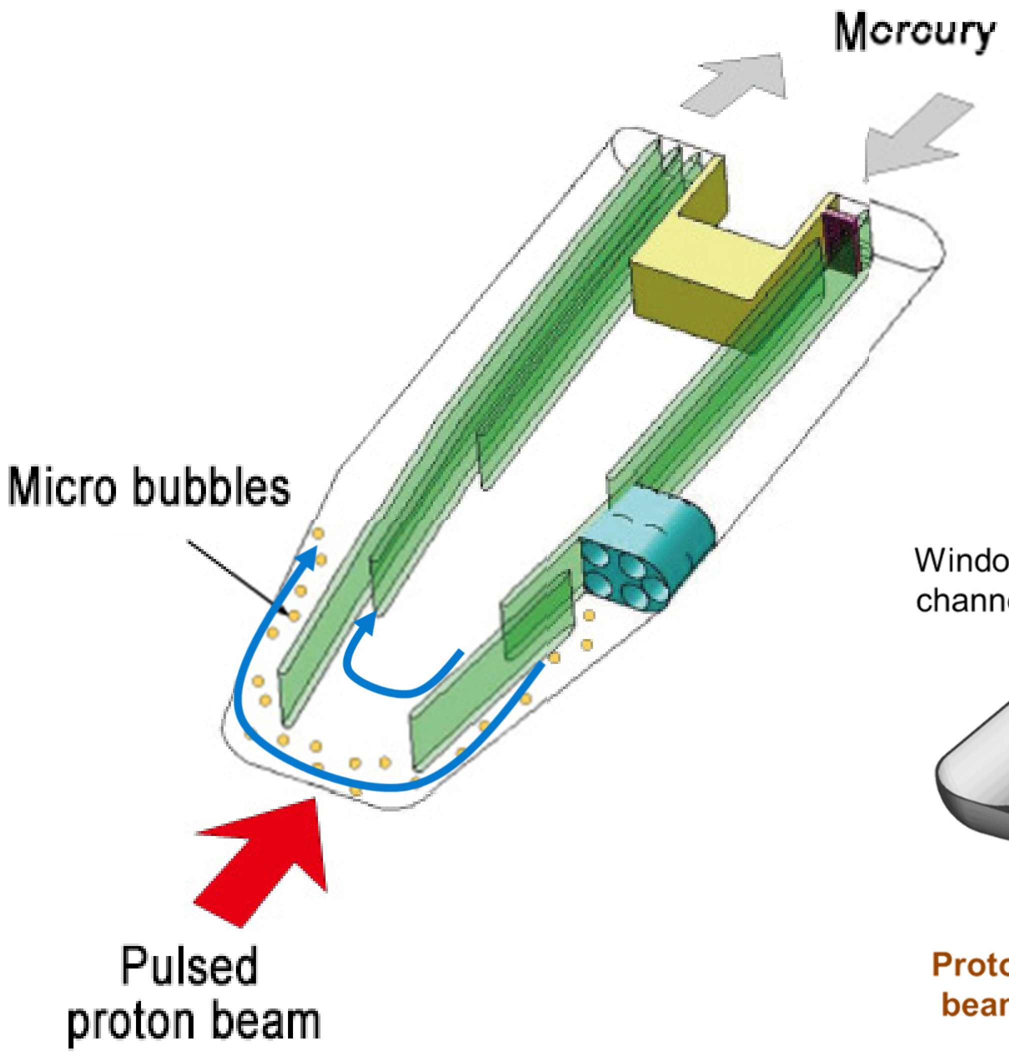
SNS and J-PARC: mercury Target

- Mercury is flowing into a stainless steel vessel
- A cool water shroud is used to contain potential leak

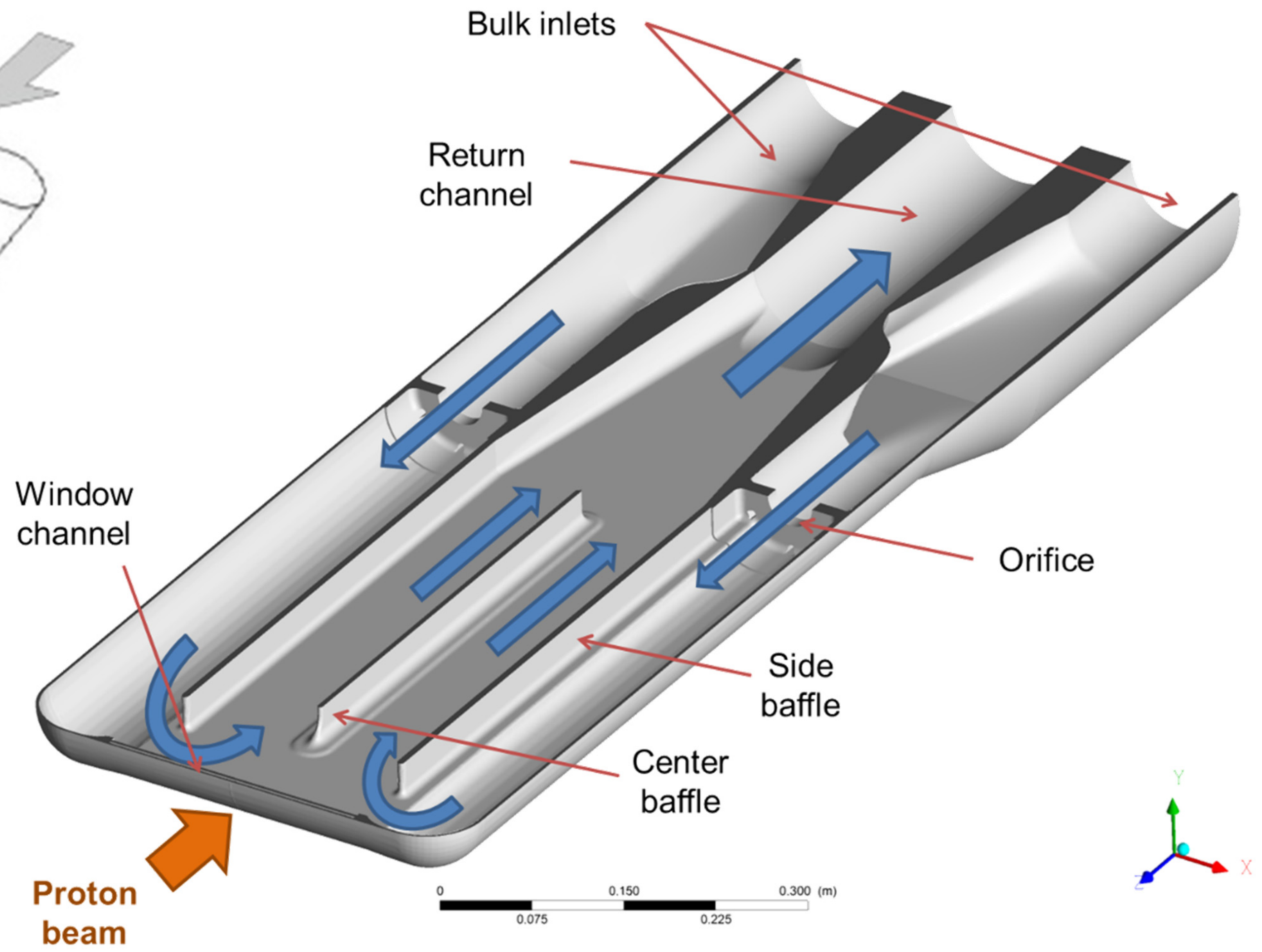


SNS Target module

Different Flow Paths

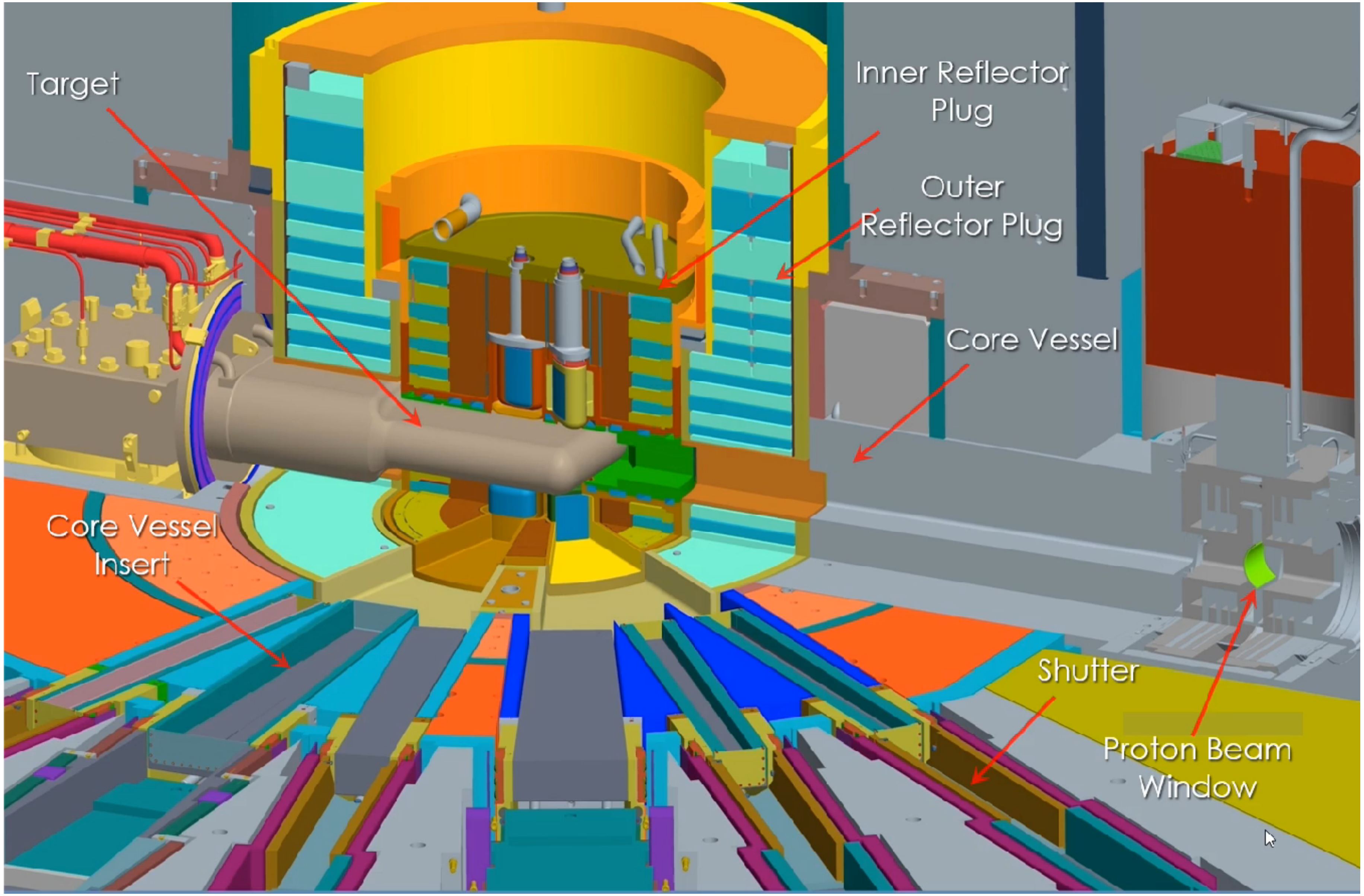


J-PARC, non-symmetric flow



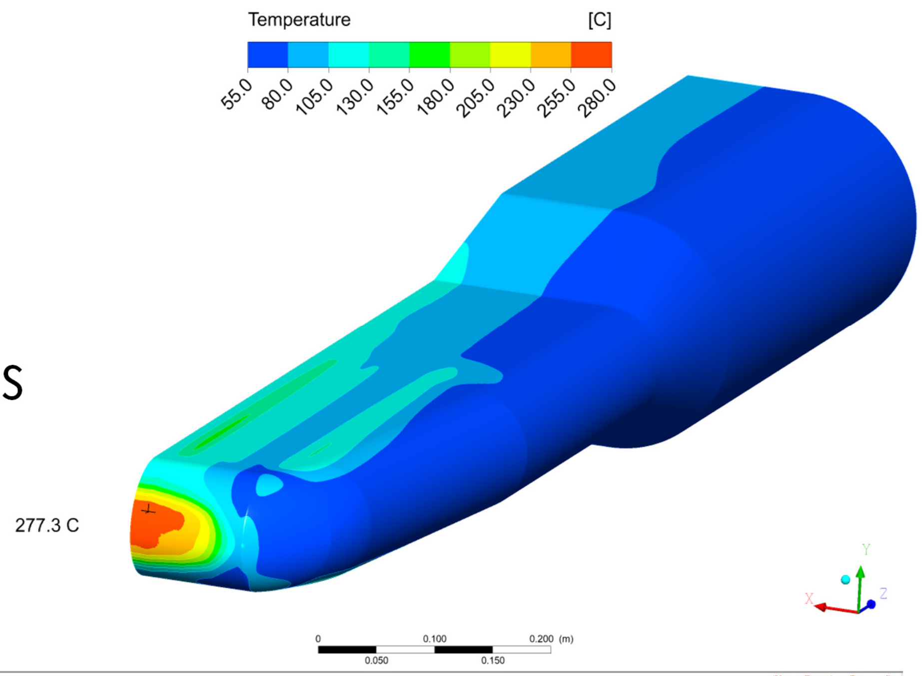
SNS, symmetric flow with stagnation region at the beam entrance

Components & interfaces at the core of the SNS source

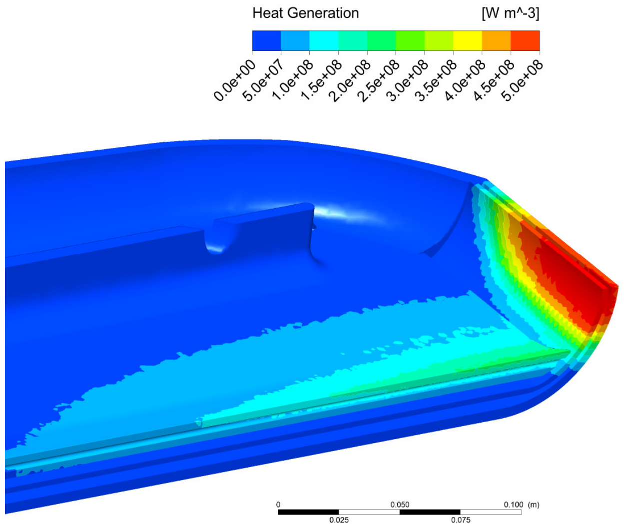


Challenges with Mercury Target

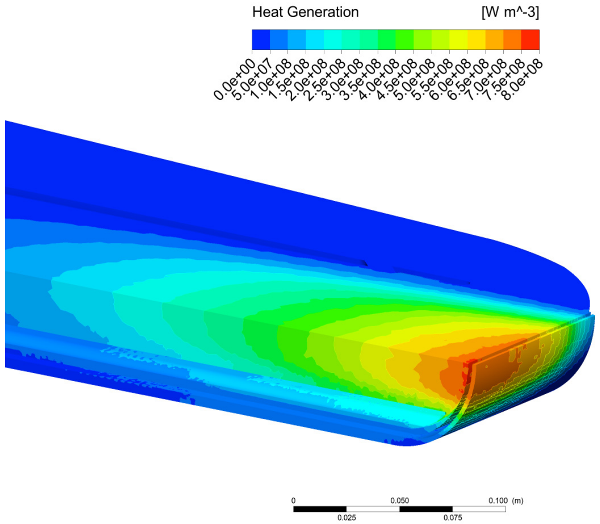
- Complex transient dynamics
- Cavitating mercury
- Addition of bubbles ➔ hard to quantify benefits
  - Lifespan (and failure) hard to predict
- Uncertainty with the beam

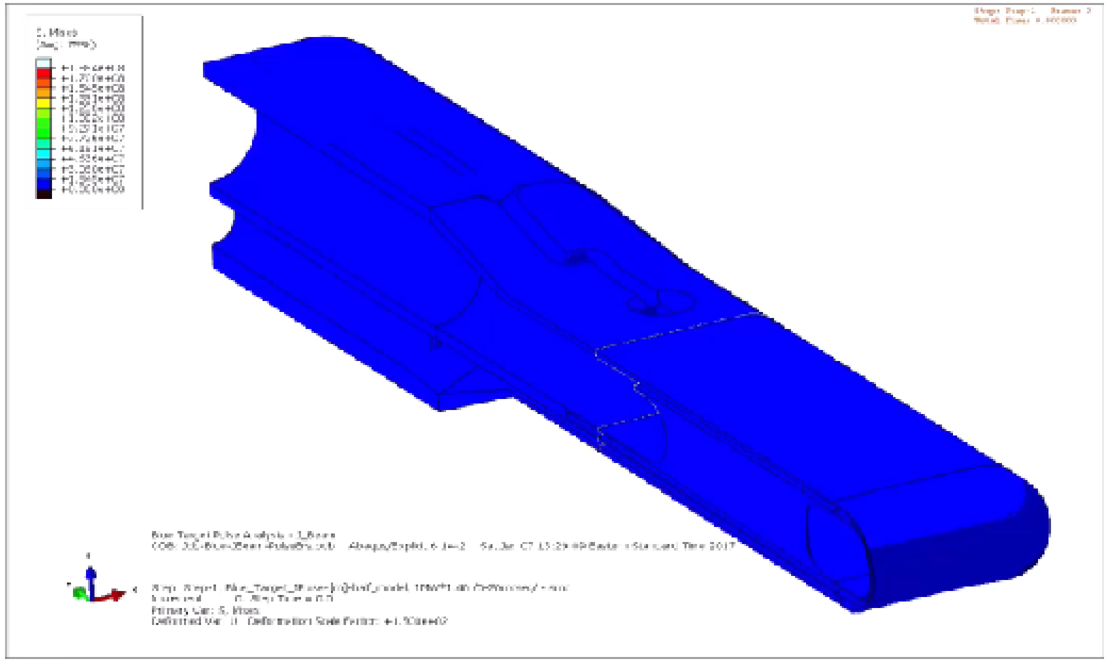


Heat deposition in SS

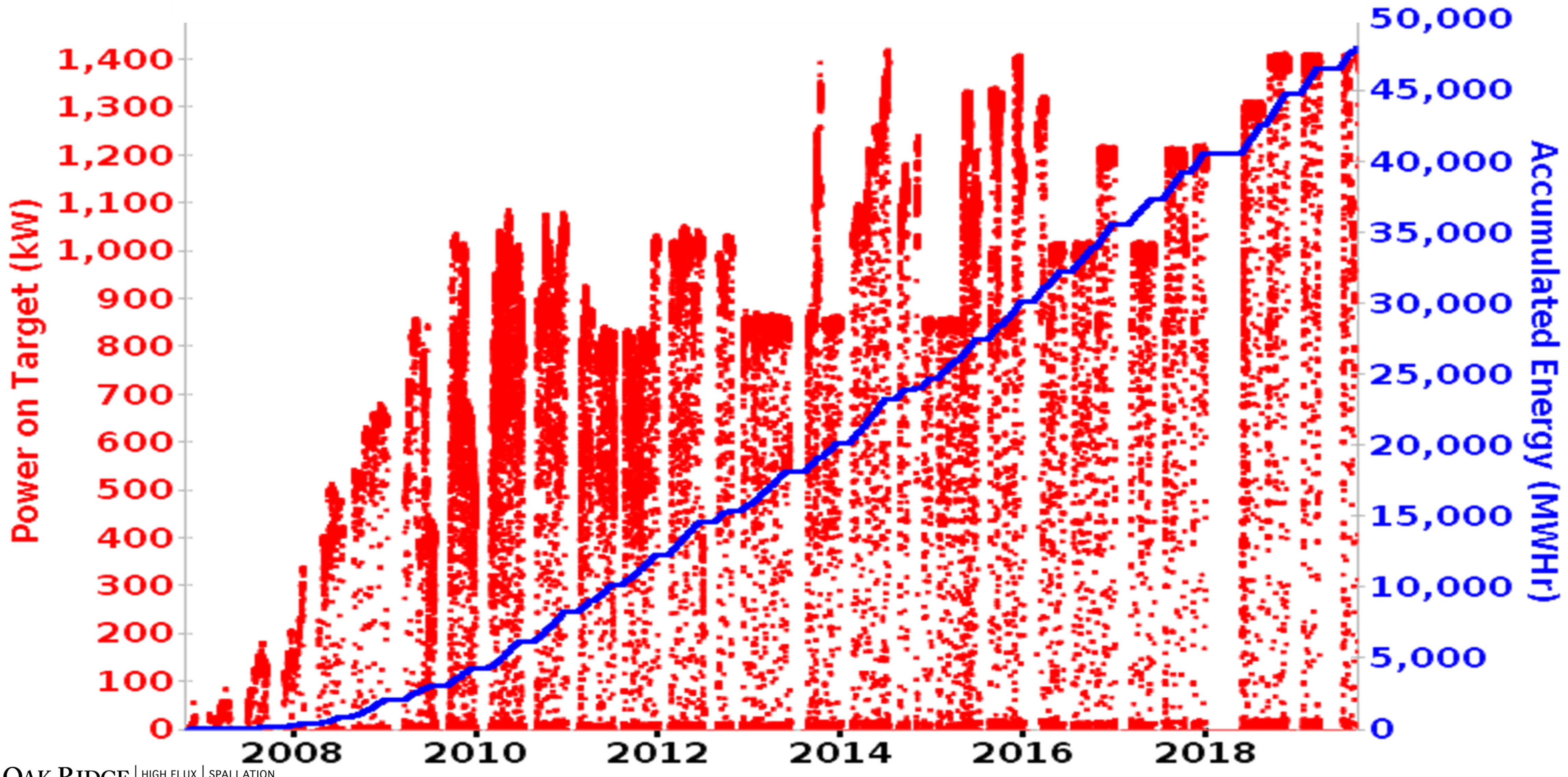


Heat deposition in HG

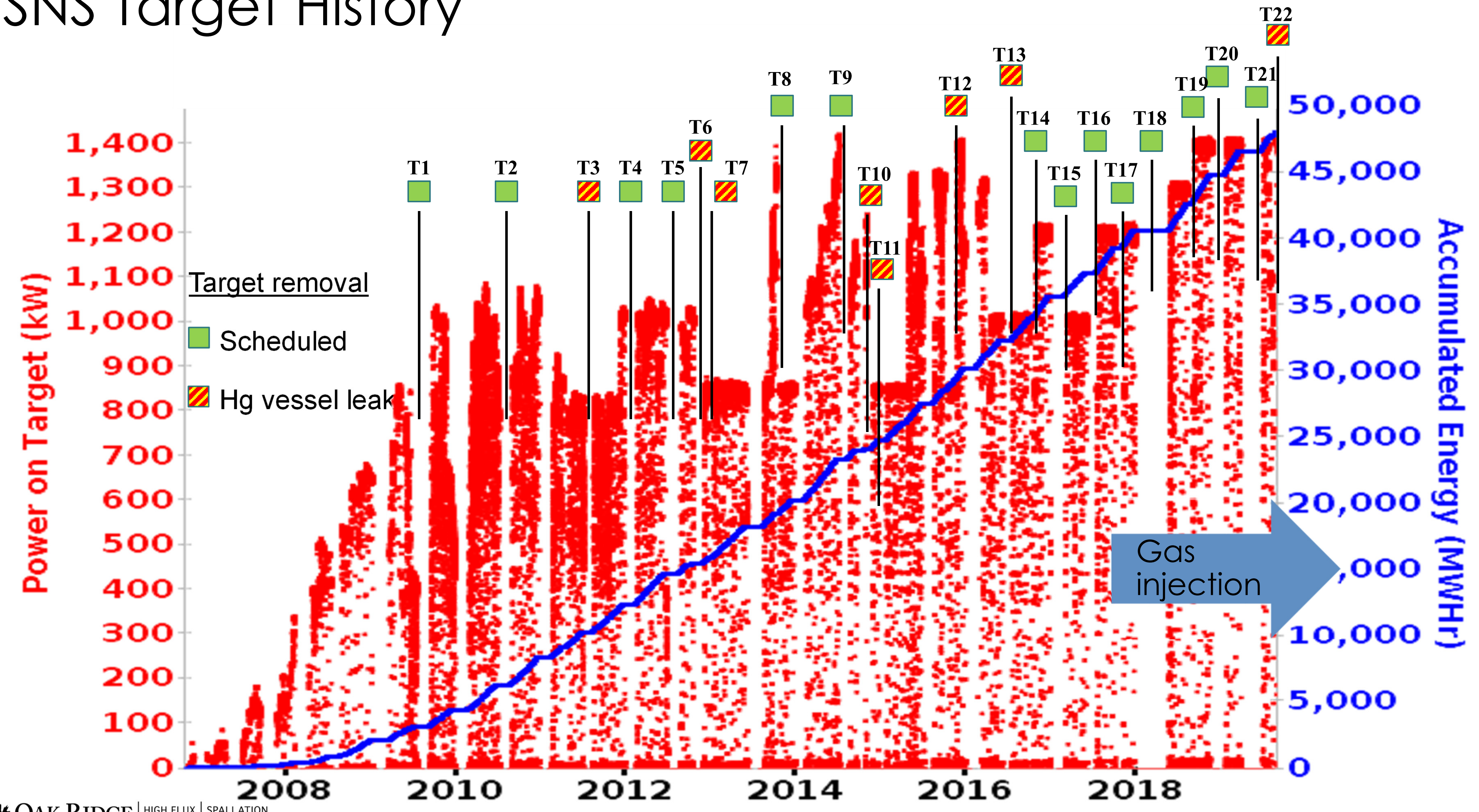




SNS Target History



SNS Target History



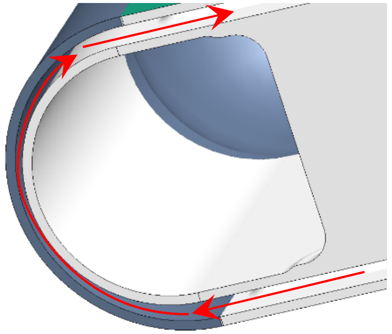
Oak Ridge National Laboratory | High Flux Isotope Reactor | Spallation Neutron Source

Frequent Target Failure

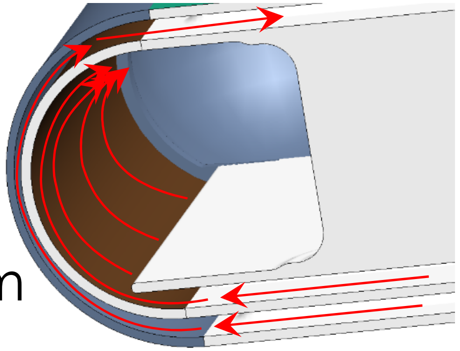
- Target design has evolved to address each failure
  - T03: could not determine leak location ➔ shroud is not removable
  - T07, T08, T11: leak at a weld at the bottom of the target ➔ weld section has been removed.
  - T10: leak at a weld ➔ more QA during fabrication
  - T12, T13 : nose leak due to cavitation erosion ➔ gas injection in the target to mitigate pressure wave and cavitation erosion
  - T22: new target design ➔ leak location and cause TBD
- It takes ~2-3 years to design a new target (from design to delivery) ➔ benefits of improved design take some time.
- A Target Management Plan has been developed to ensure we have always enough spare and a consistent strategy in improving our target

Types and Recent History of Target Modules

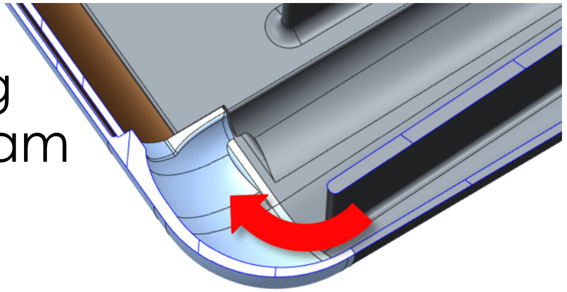
Target Types



- Original flow
  - Many upgrades in newer targets



- Jet-Flow
  - Sweeping flow at beam



- Blue
  - Jet-flow + sweeping flow away from beam

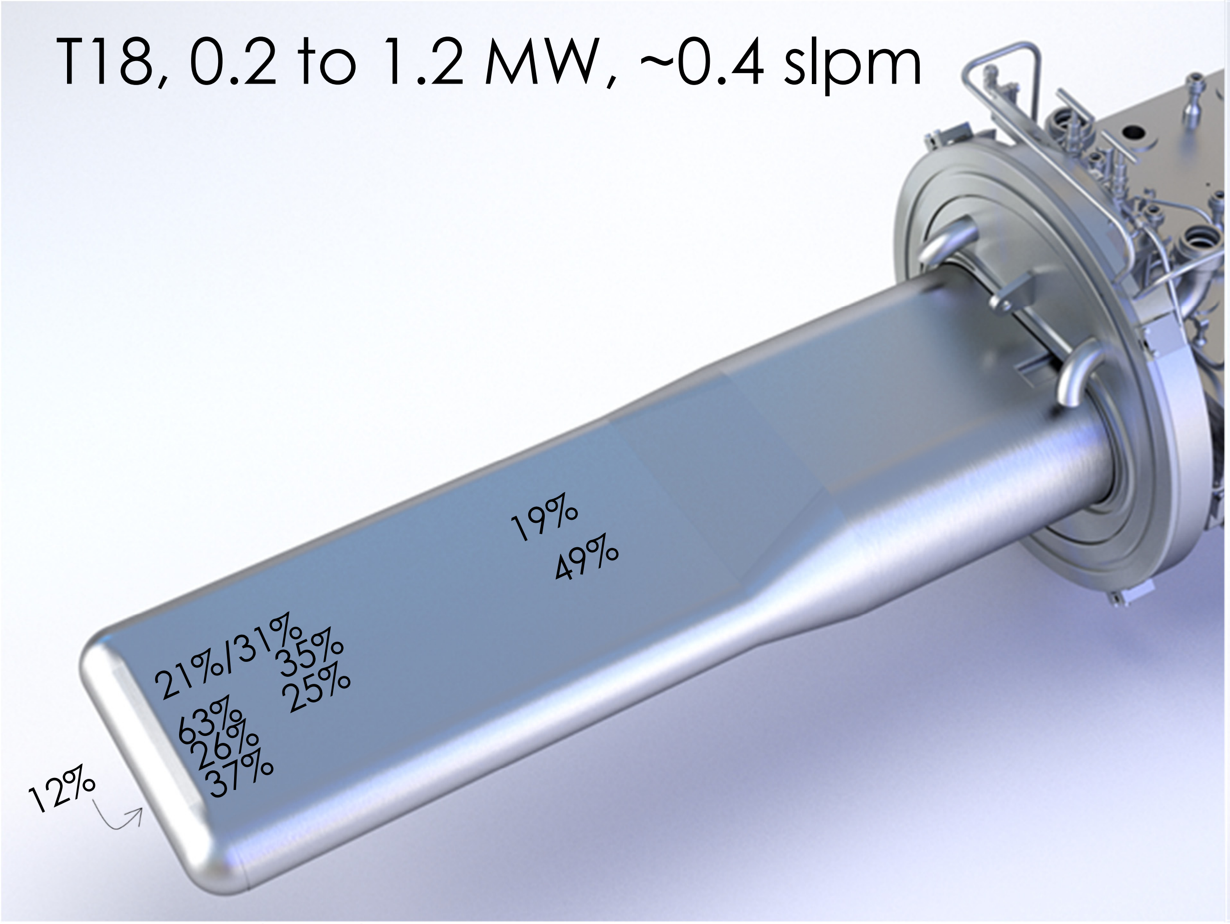
Target History

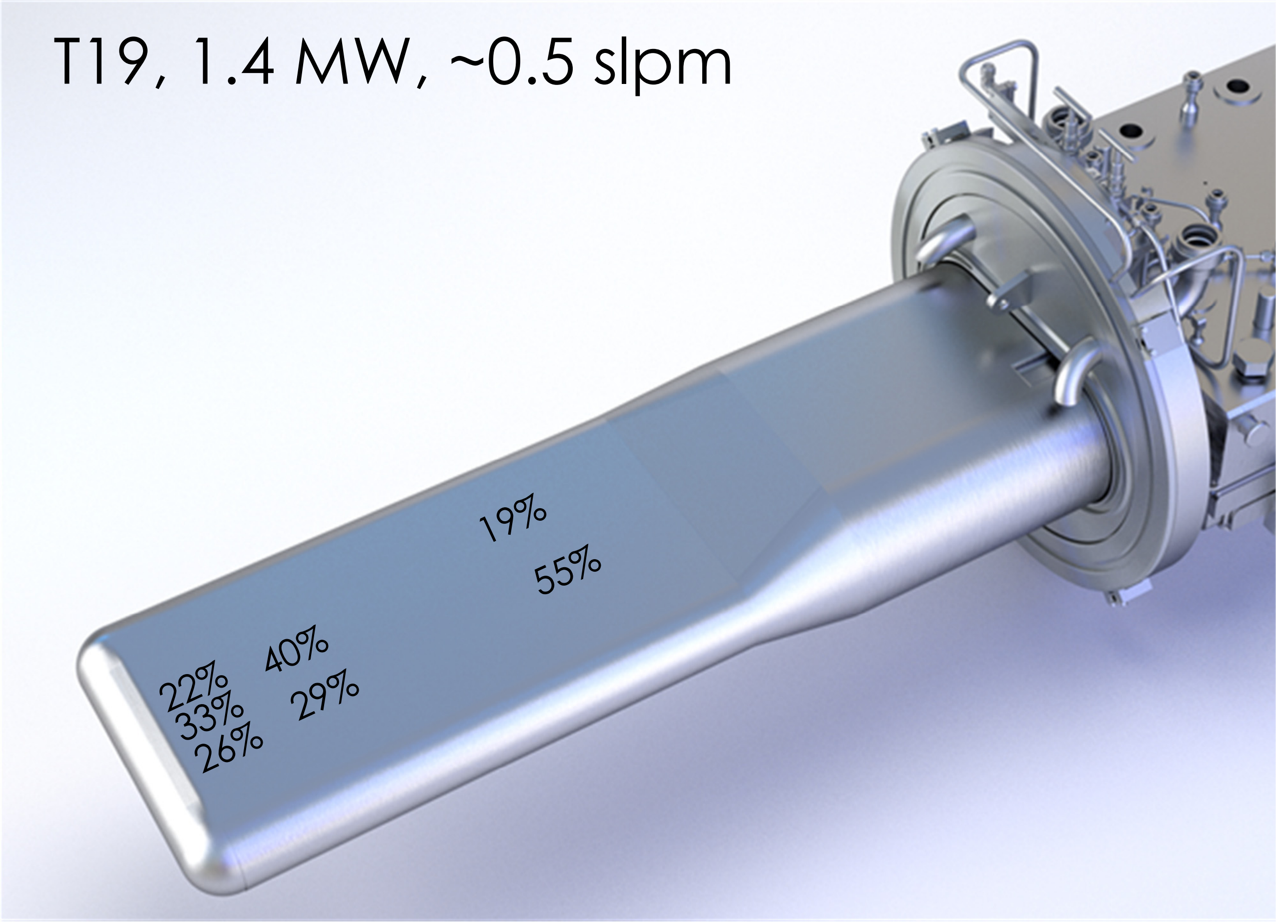
- T1-T9, T11, Original flow targets
  - Three leaked at trapezoidal cover plate
- T10, First jet-flow
  - Leaked at weld away from beam
- T12-T15, Original flow targets
  - T12 and T13 had leaks from cavitation erosion outside of beam spot
  - Moved to steady power / Target Management Plan
- T16-T17, Jet-flow
- T18-T20, Jet-flow with gas injection
- T21, Original flow with gas injection
- T22, Blue design with gas injection

D. Winder

Benefits of Gas Injection in Mercury

- Strain decrease relative to without gas injection
  [1 – (µL/L with gas / µL/L without gas)]



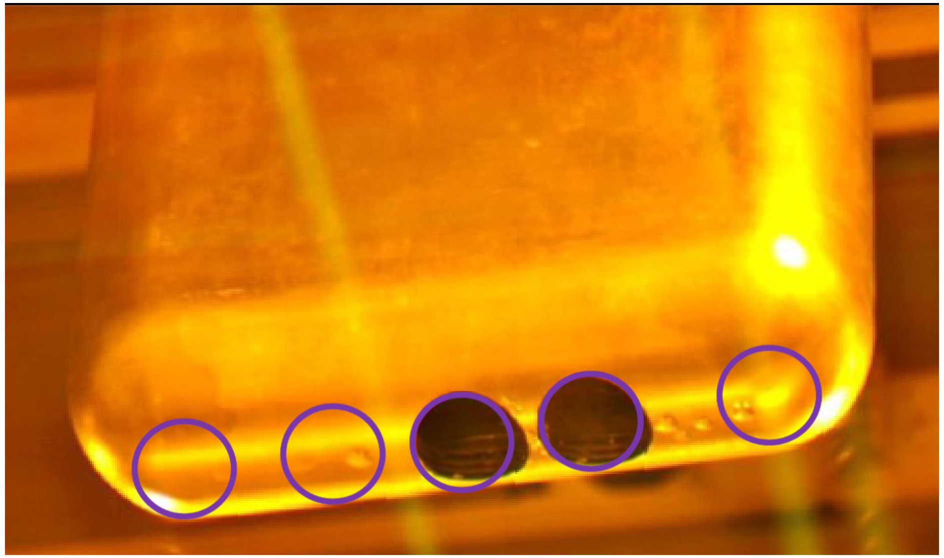


OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR | SPALLATION NEUTRON SOURCE

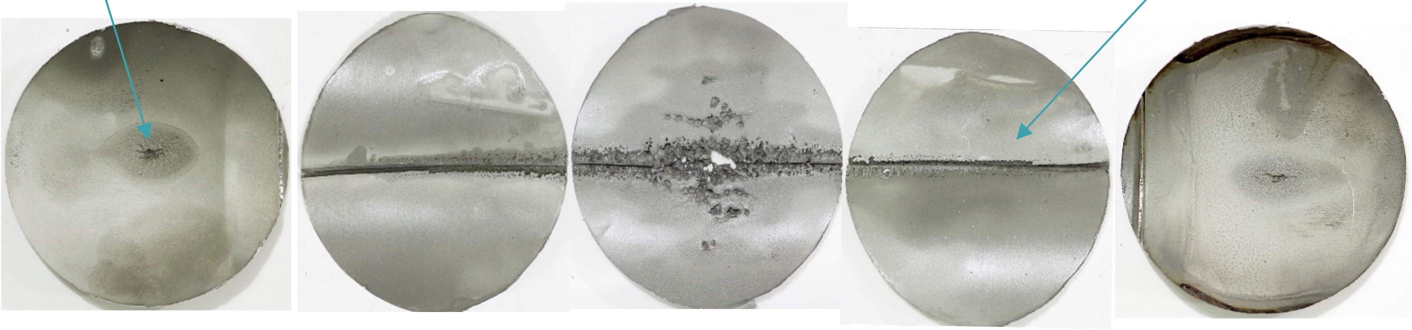
D. Winder

Post Irradiation Examination

Cavitation erosion at the end of the bulk inlets



at one point, the window breaks into 2 pieces.



Target 15 (original)
P_{avg} = 1133 kW
E_{total} = 1667 MWh

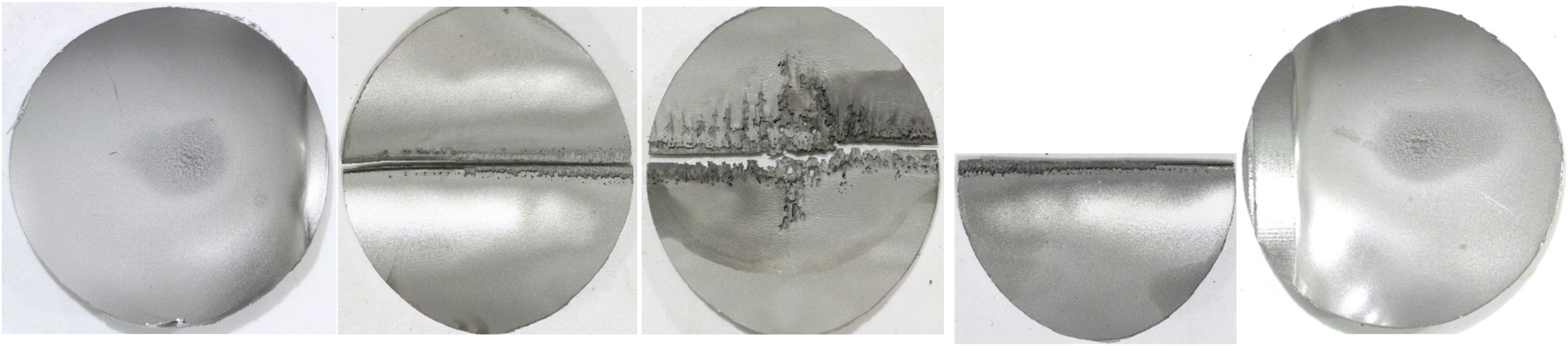
Clear Benefits of Gas Injection

- Target 17 and 19 were both ‘jet-flow’ targets with similar operational histories
- The Target 19 inner wall was not fractured and had little erosion damage compared to Target 17

Target 17
(Jet-flow Design)

No Gas Injection
P_{avg} = 1,127 kW
E_{total} = 1,936 MWh

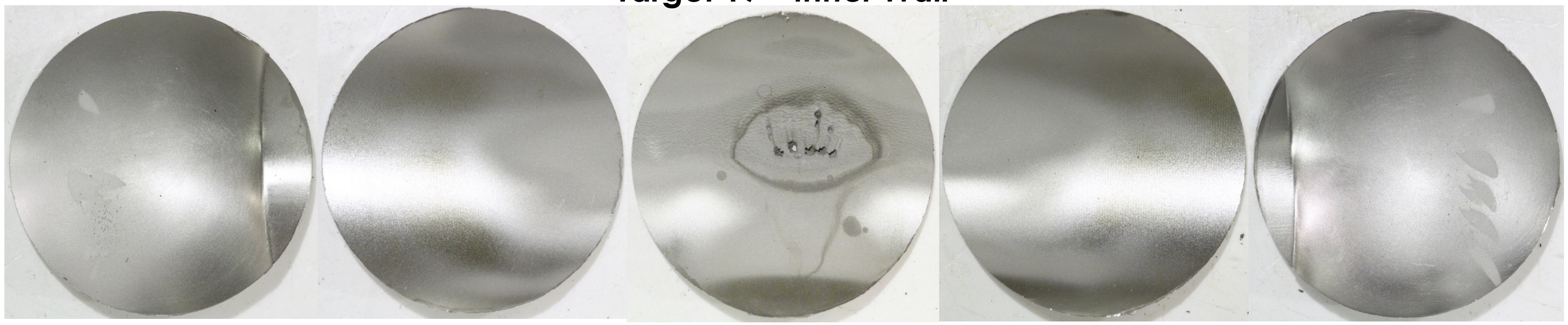
Target 17 – *Inner Wall*



Target 19
(Jet-flow design)

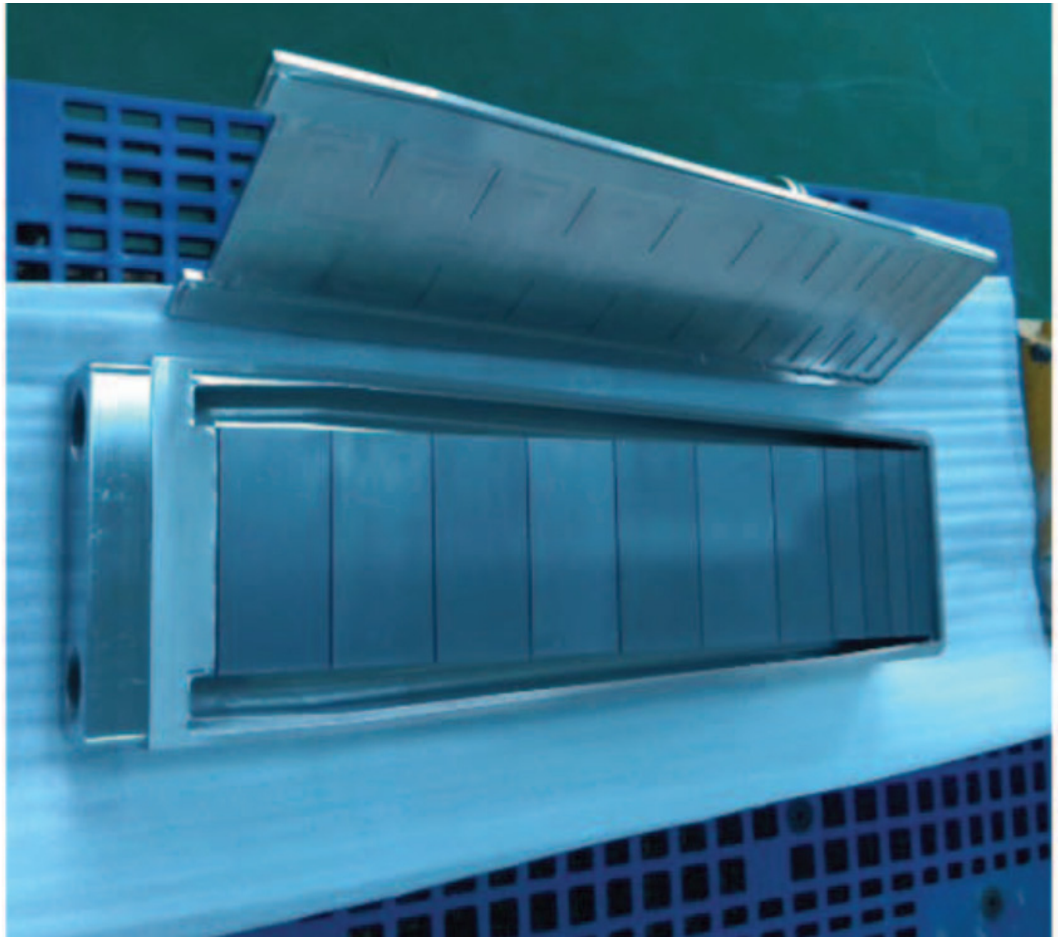
Gas Injection On
Q_{avg} = ~0.45 SLPM
P_{avg} = 1,207 kW
E_{total} = 1,987 MWh

Target 19 – *Inner Wall*



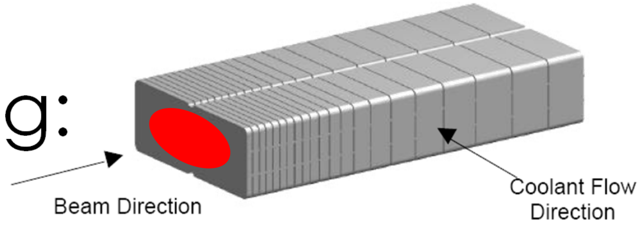
CSNS

- Considered a rotating target for a while
- Final design is a fix segmented W target: 11 tungsten plate with 0.3mm tantalum cladding
- D2O cooled
- Goals:
  - Stabilizing power to 0.1 MW
  - Replacing light water to heavy water in moderators
  - Upgrade the power to 0.5 MW

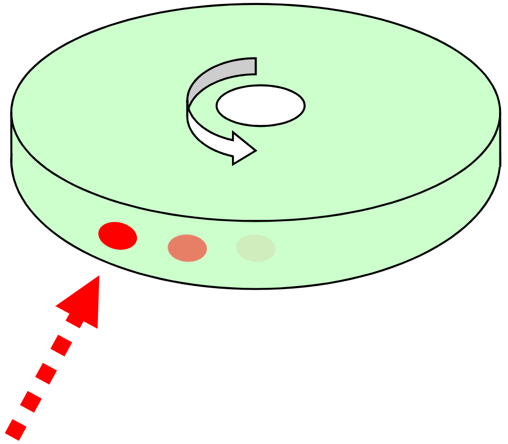


Rotating Targets

- Fixed solid target at MW power are challenging:
  - Need a lot of water cooling
  - In case of a clad failure ➔ high activation
  - Short life due to vessel radiation damage



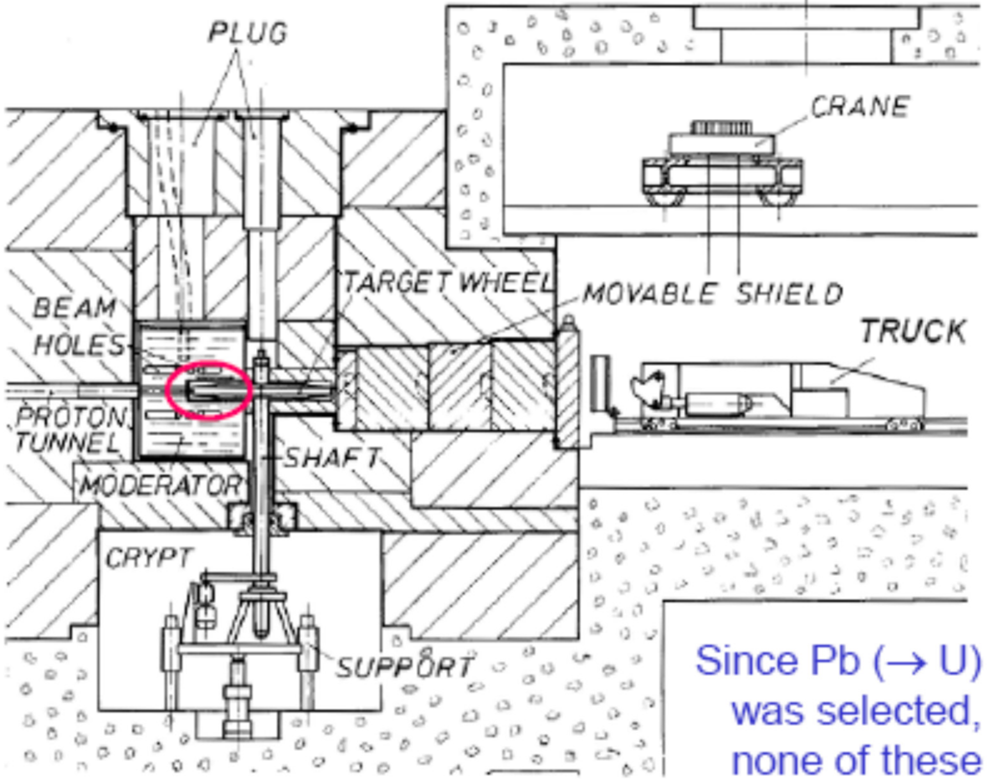
- Rotating solid target designs offer the potential of better neutronic performance because of higher spallation target density compared to fixed targets, and longer lifetimes

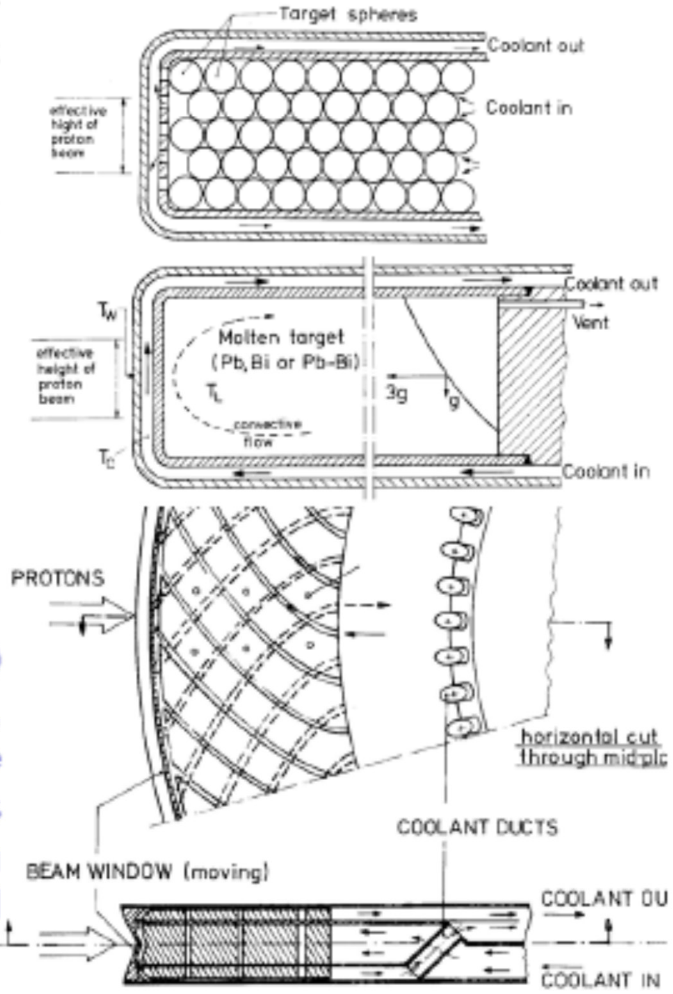


- ESS (European Spallation Source)
- SNS Second Target Station (STS)

Rotating targets idea has been around for a while …

Early Considerations for the Rotating SNQ Target





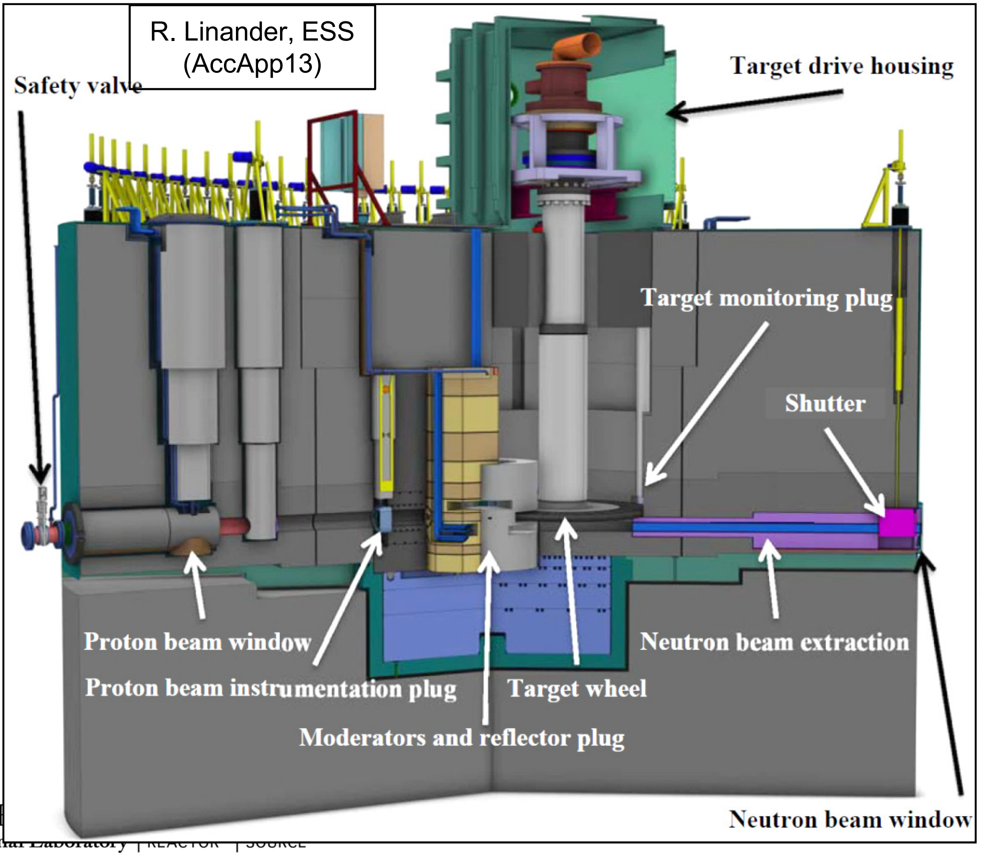
SNQ-rotating target studies as presented in a 1979 workshop at Jülich (Jül-Conf-34)

Since Pb (→ U) was selected, none of these options was followed up in greater detail

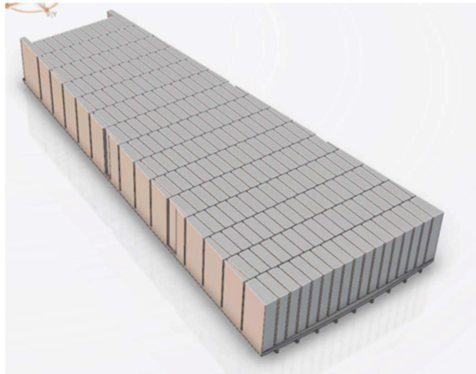
ESS: a rotating, **helium-cooled** target design

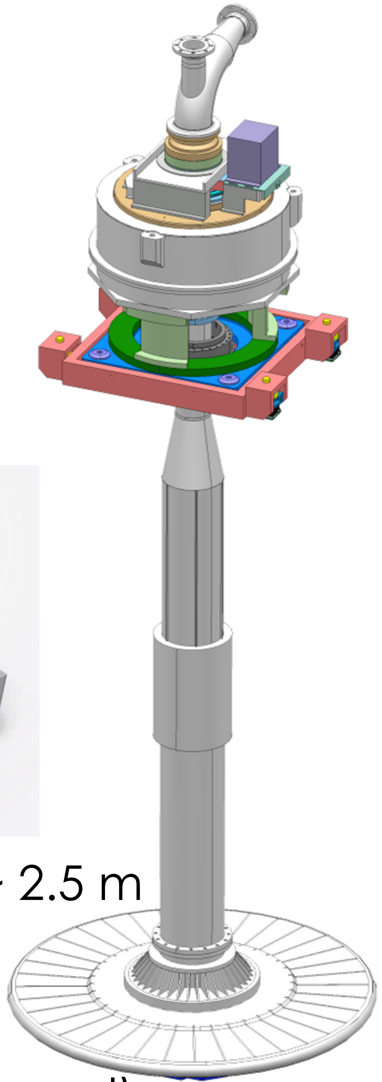
- 2 GeV, 5 MW long-pulse (2.86 ms), 14 Hz beam
- **Bare** tungsten bricks; 100°C rise/pulse

R. Linander, ESS (AccApp13)



3 kg/s helium mass flow rate





ϕ ~ 2.5 m

36 sectors of W-brick filled cassettes
Rotation speed ~0.4 Hz
Lifetime of 5 yeas at 5 MW (10 dpa to vessel)

First beam on target expected 2023

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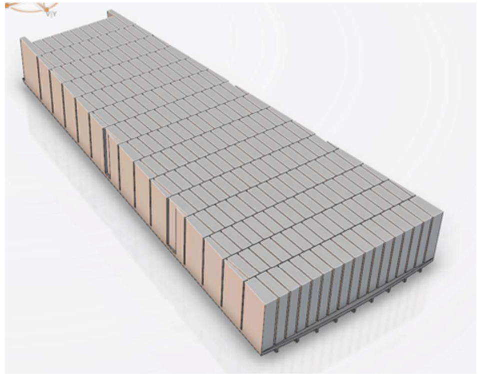
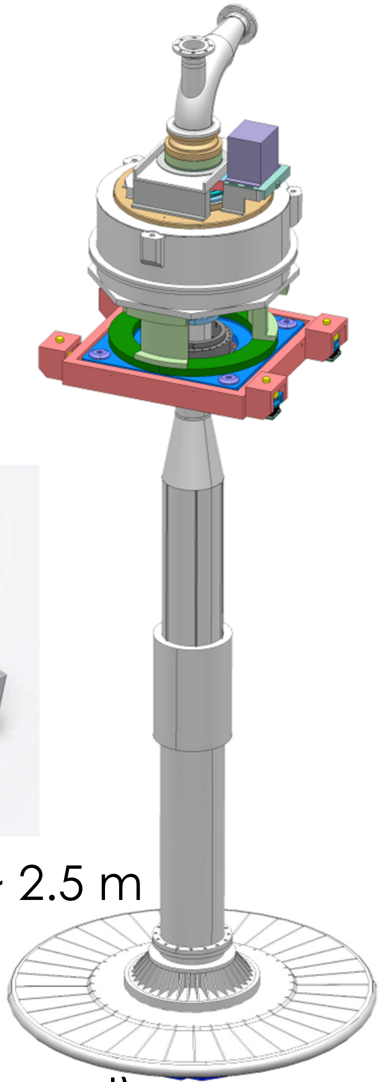
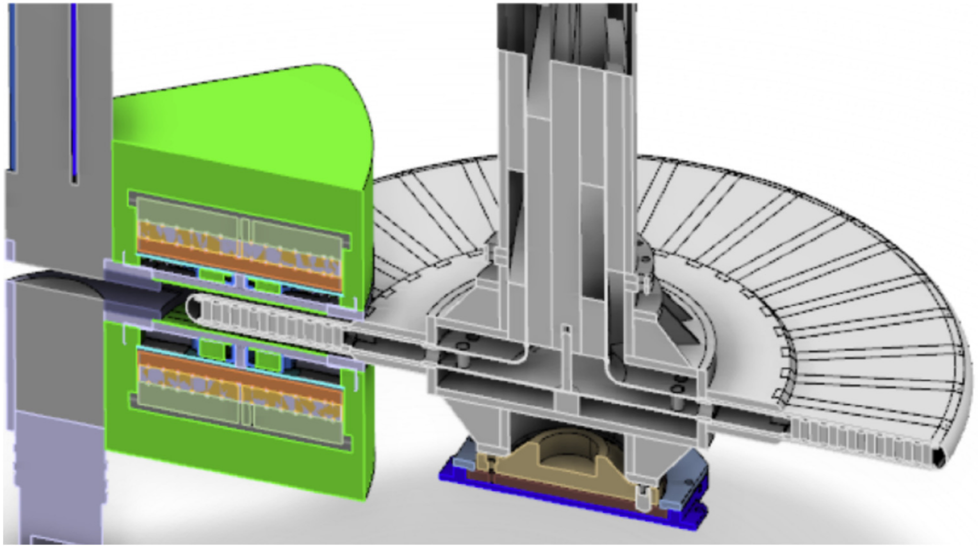
3 kg/s helium mass flow rate







ϕ ~ 2.5 m

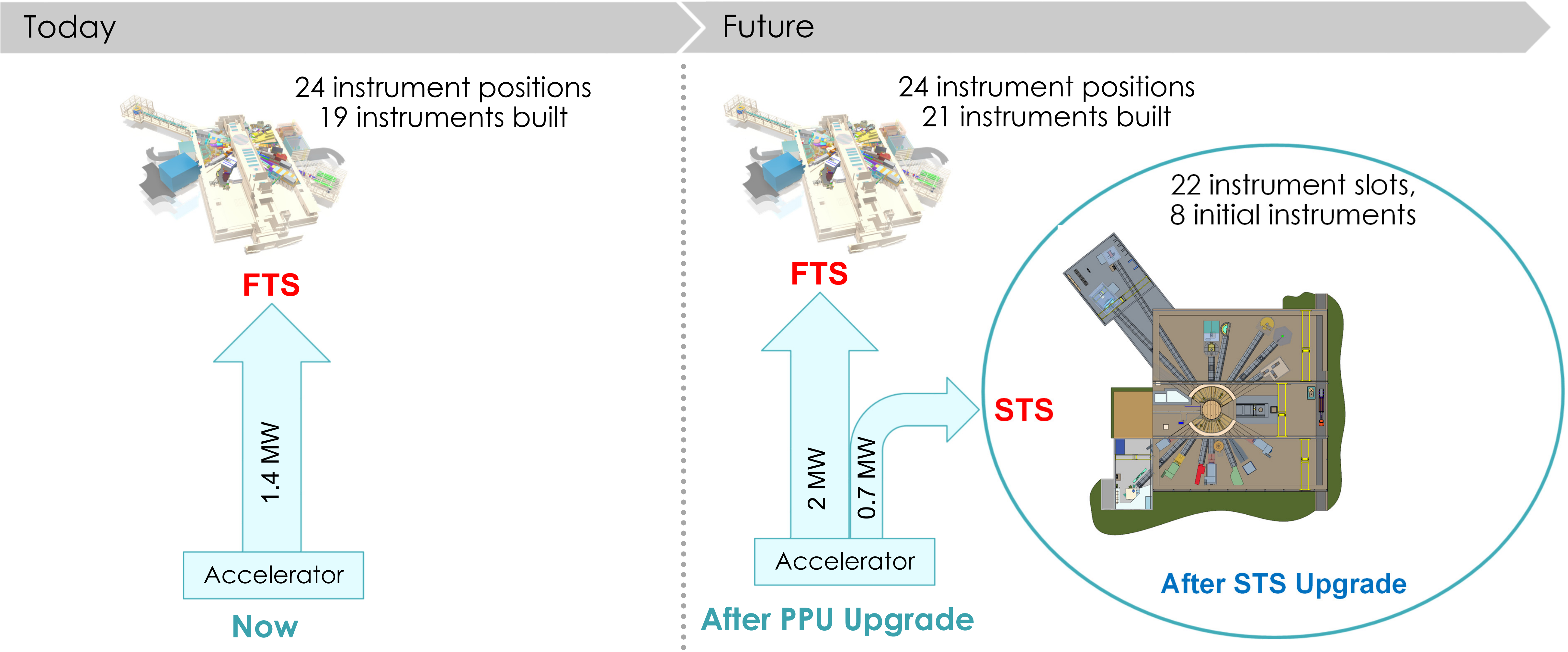
36 sectors of W-brick filled cassettes
Rotation speed ~0.4 Hz
Lifetime of 5 yeas at 5 MW (10 dpa to vessel)

First beam on target expected 2023

ESS helium-cooled rotating tungsten target (P. Nilsson)

Second Target Station

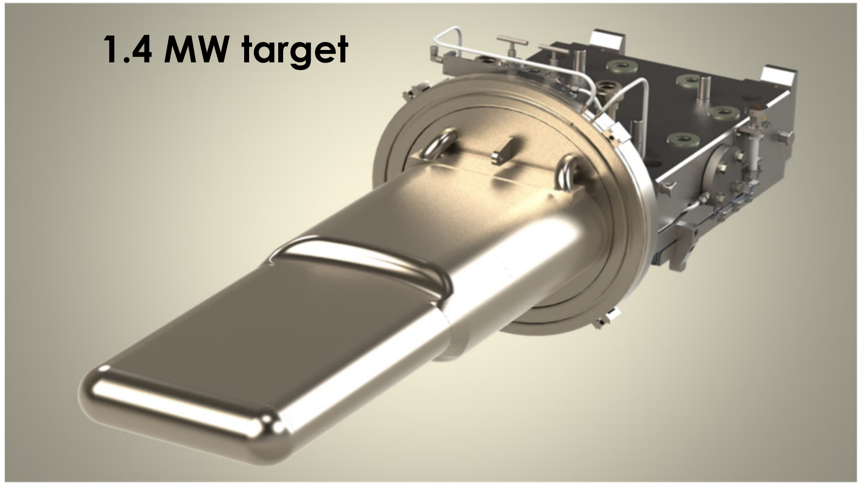
- Second Target Station : rotating Target

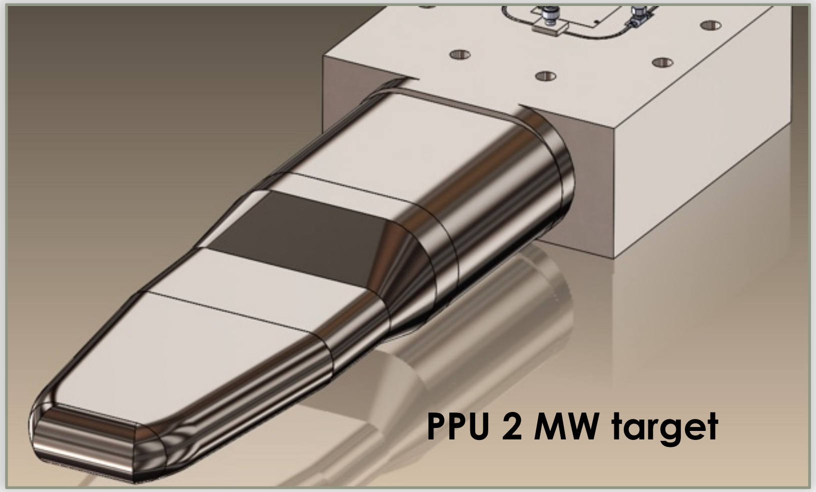


G. Murdoch

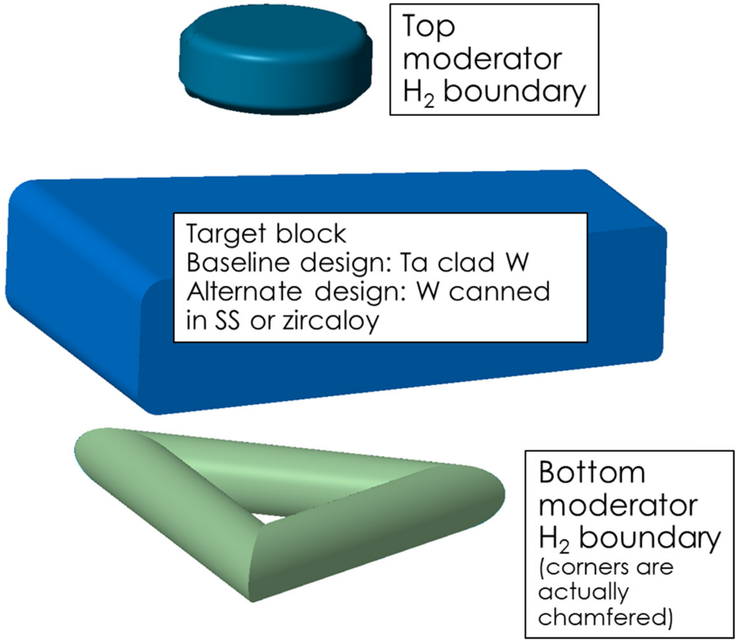
PPU Upgrade for FTS

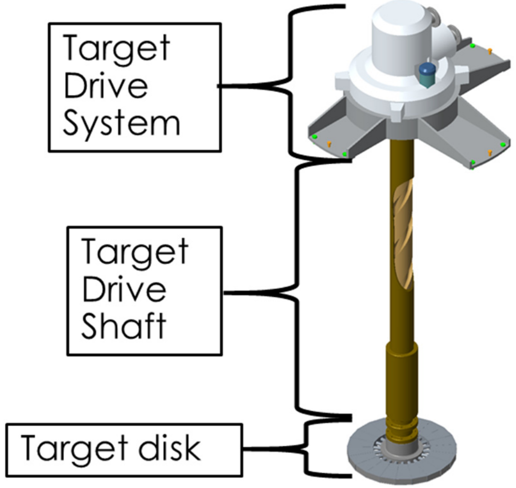
- Accelerator is being upgraded from 1.4 MW 1 GeV to 2.8 MW 1.3 GeV
- FTS power will be limited to 2MW:
  - Increase gas injection in the target
  - Gas protection layer at the nose
- FTS hg process loop upgraded to accommodate more gas injection

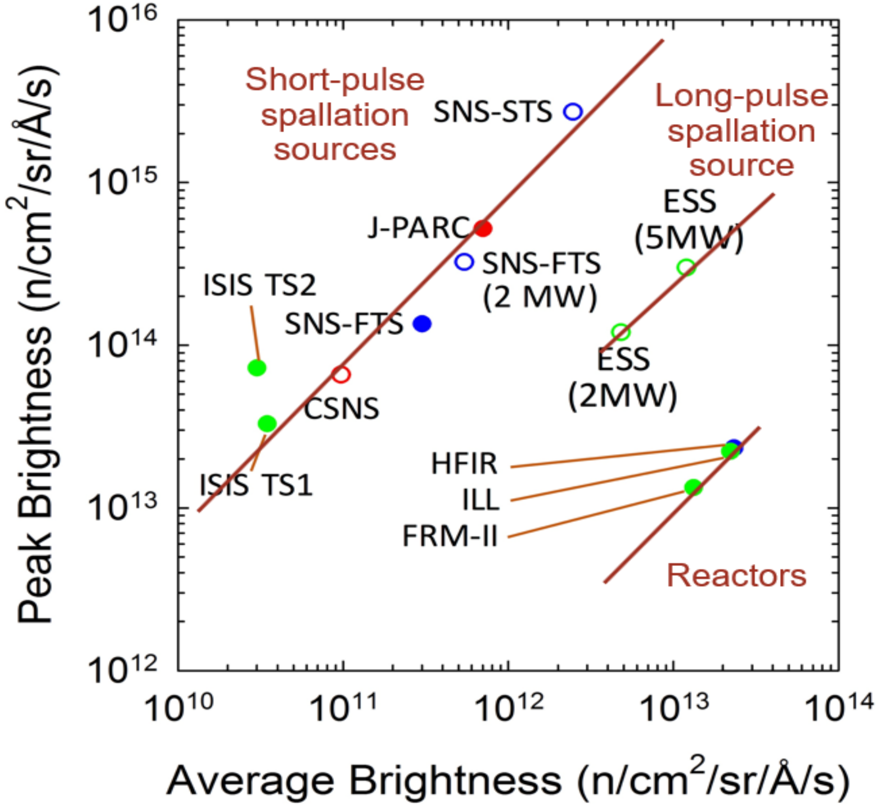




STS Goal: a very bright source

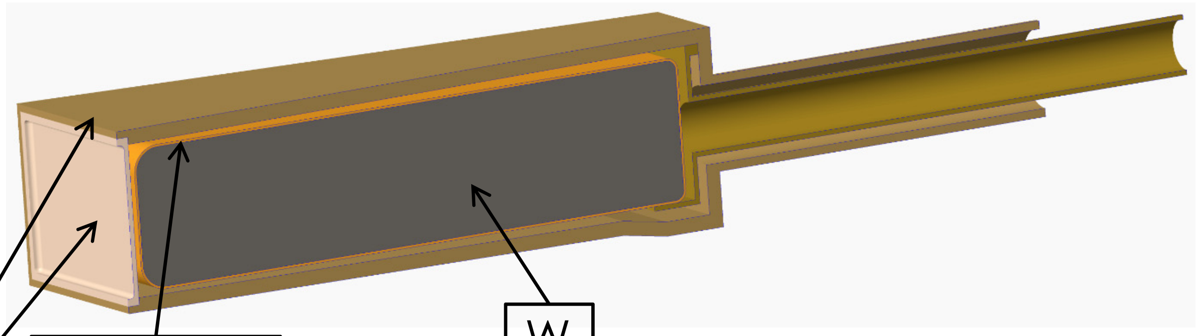
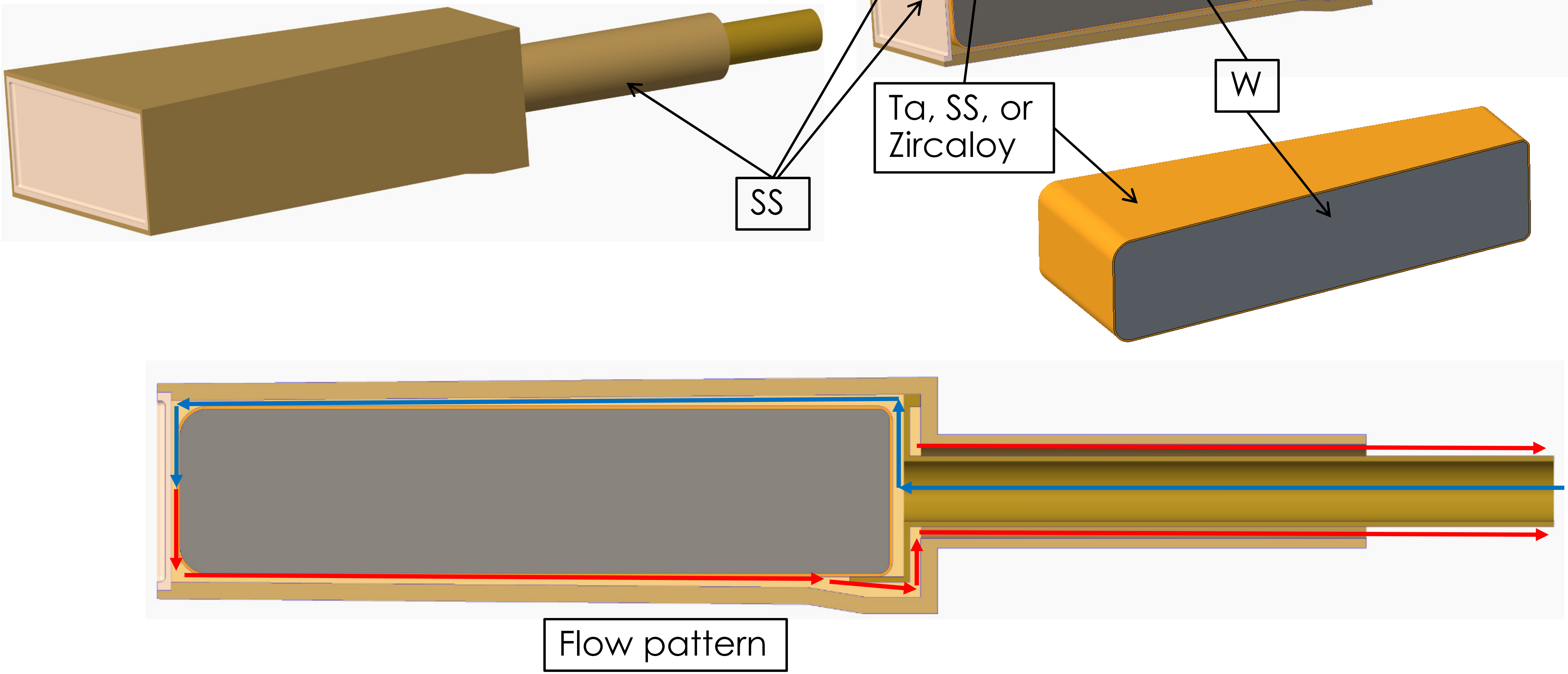






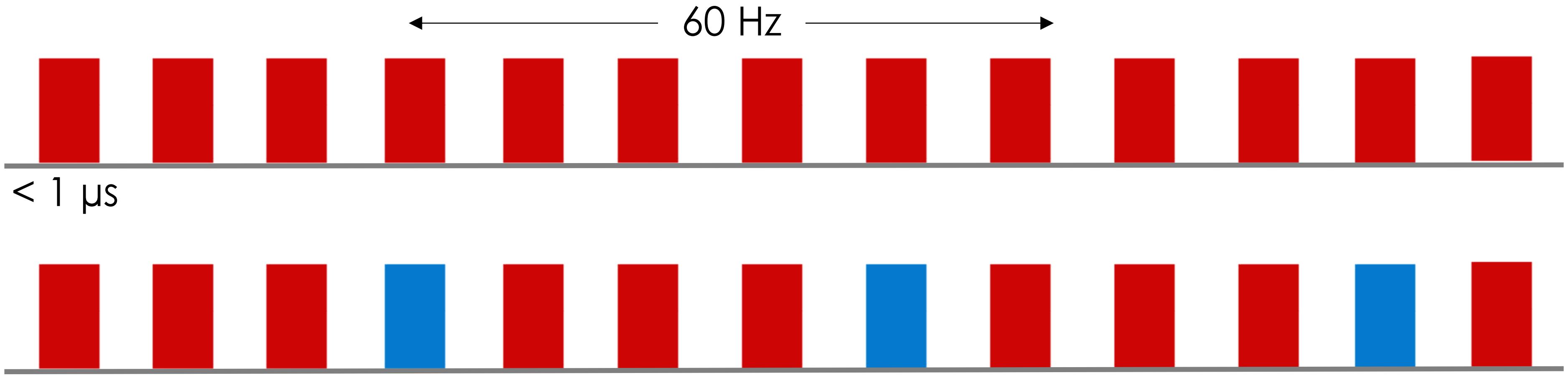
- W to get better brightness
- Rotating because of high power (0.7MW)

Tungsten requires casing to prevent corrosion with water/radiation

Pulse Patterning with Independent Power Knobs

- 60 Hz is maintained, but is parsed for delivery to two targets
- STS will support independent power control to each target



SNS Today – FTS Only:
60 pulses at 60 Hz spacing to FTS

2.8 MW Power FTS/STS:
45/60 pulses to FTS,
15/60 pulses to STS

40% more intense pulse on FTS!
Mercury Target will need to be upgraded again

Additional Thoughts

- Higher beam power is an effective approach to producing more neutrons, but has several challenges:
  - Heat removal
  - Pulse effects
  - Component (radiation) lifetimes must be manageable
- Simulations can be more and more leveraged to optimize moderators and target shape:
  - Neutronics models are closer and closer to reality
  - CFD and structural analysis much faster (HPC)
- Quick target change to make target failure less inconvenient.
- Instruments must be taken into consideration!