OAK RIDGE National Laboratory

Status Update of the Spallation Neutron Source

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RaDIATE 2018 Collaboration Meeting
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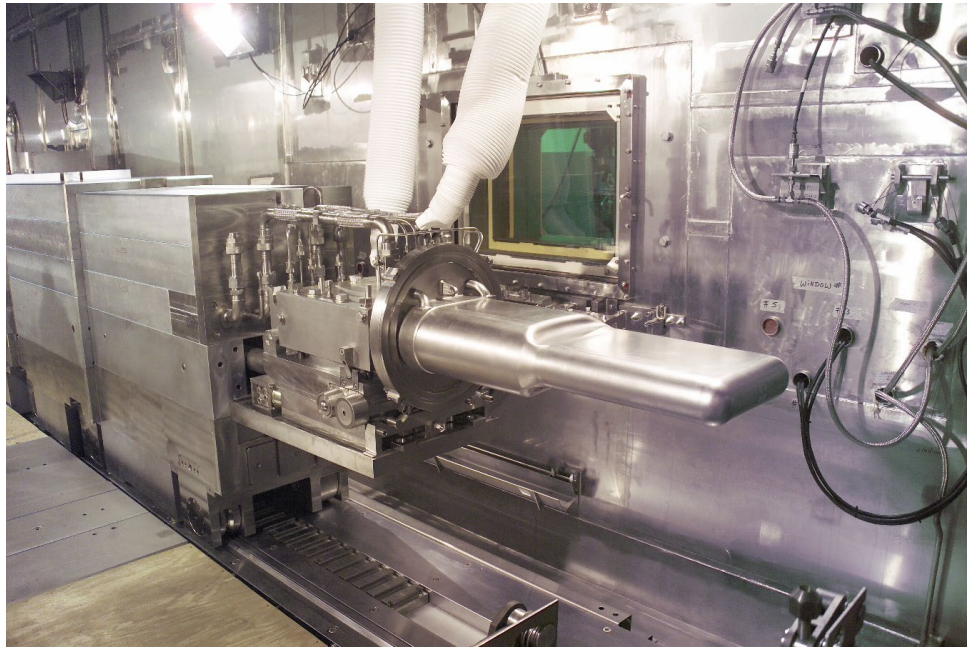
CERN

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

U.S. DEPARTMENT OF ENERGY

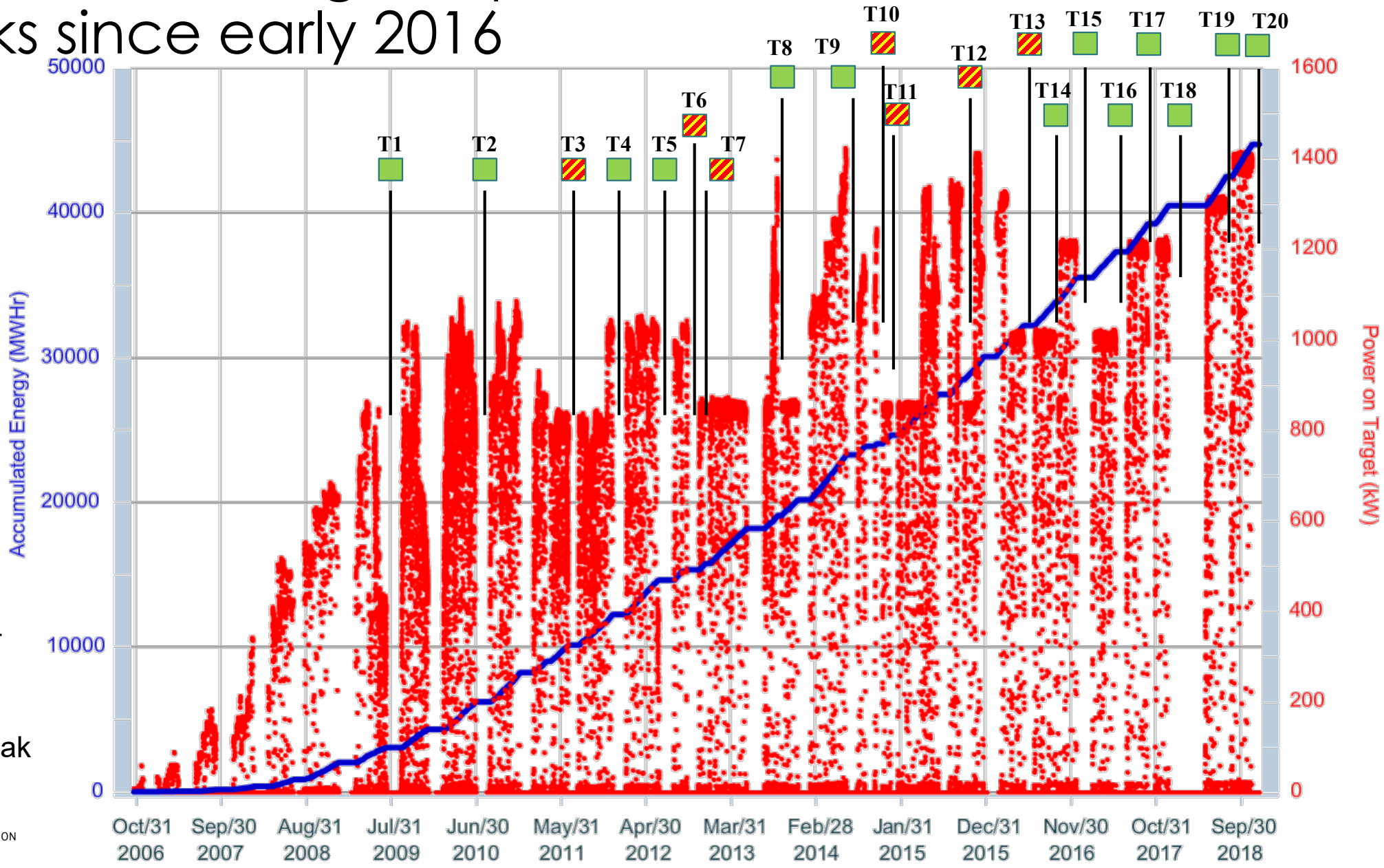
Over the past 2-1/2 years at the SNS

- No target leaks
- Power on target now steady at 1.4 MW
- Replaced Inner Reflector Plug
  - Coolant loop #4 upgraded to heavy water
- Radio Frequency Quadrupole (RFQ) was replaced
- Routine operation of gas injection in SNS mercury target
- Mercury target vessel strain measurements
- First SNS aluminum proton beam window
- Upgrades will bring 2 MW to the SNS mercury target



Beam power & target replacements
No leaks since early 2016

Target #20 operated with gas injection @ 1.4 MW

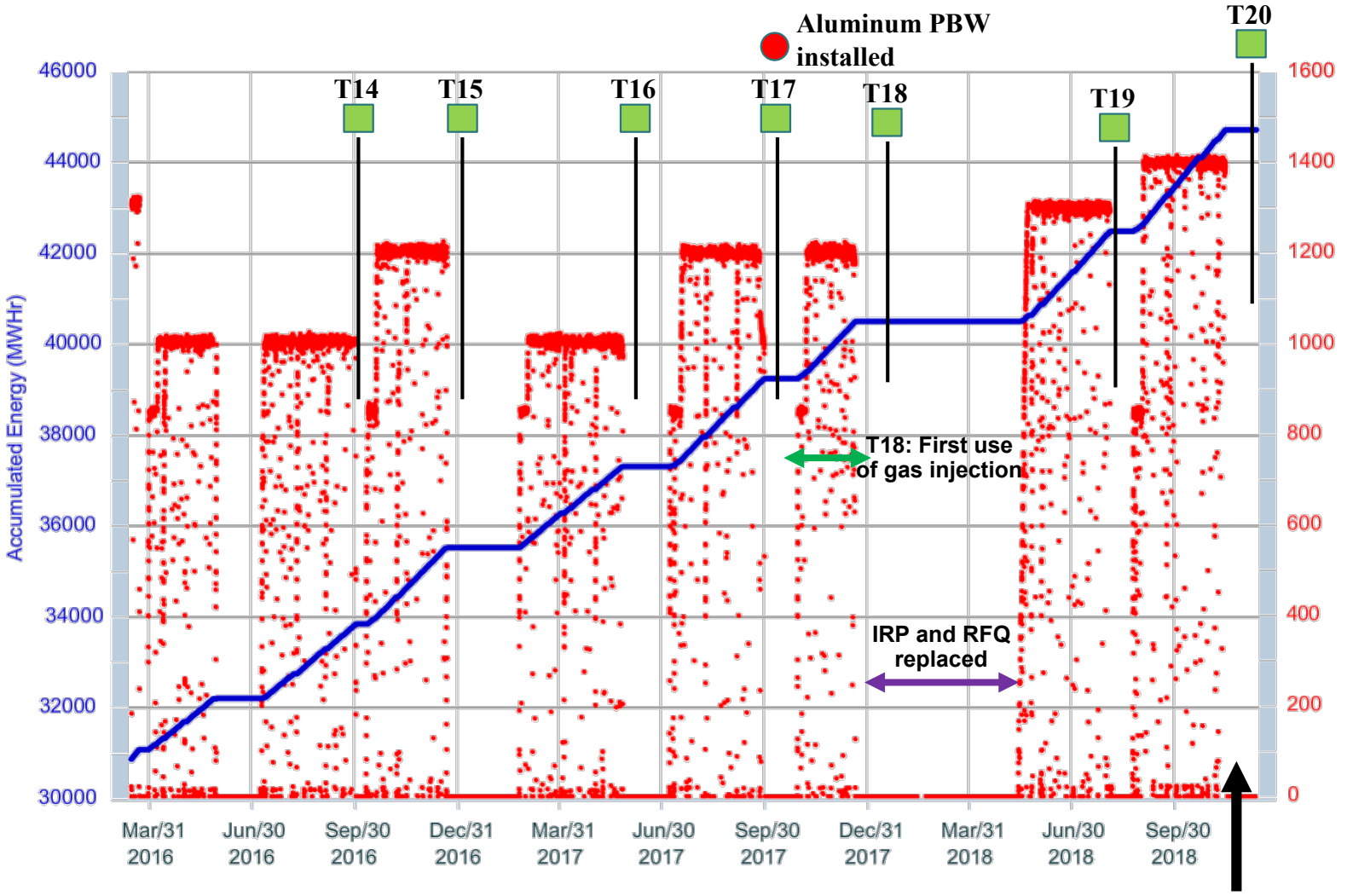


Target removal

- Scheduled
- Hg vessel leak

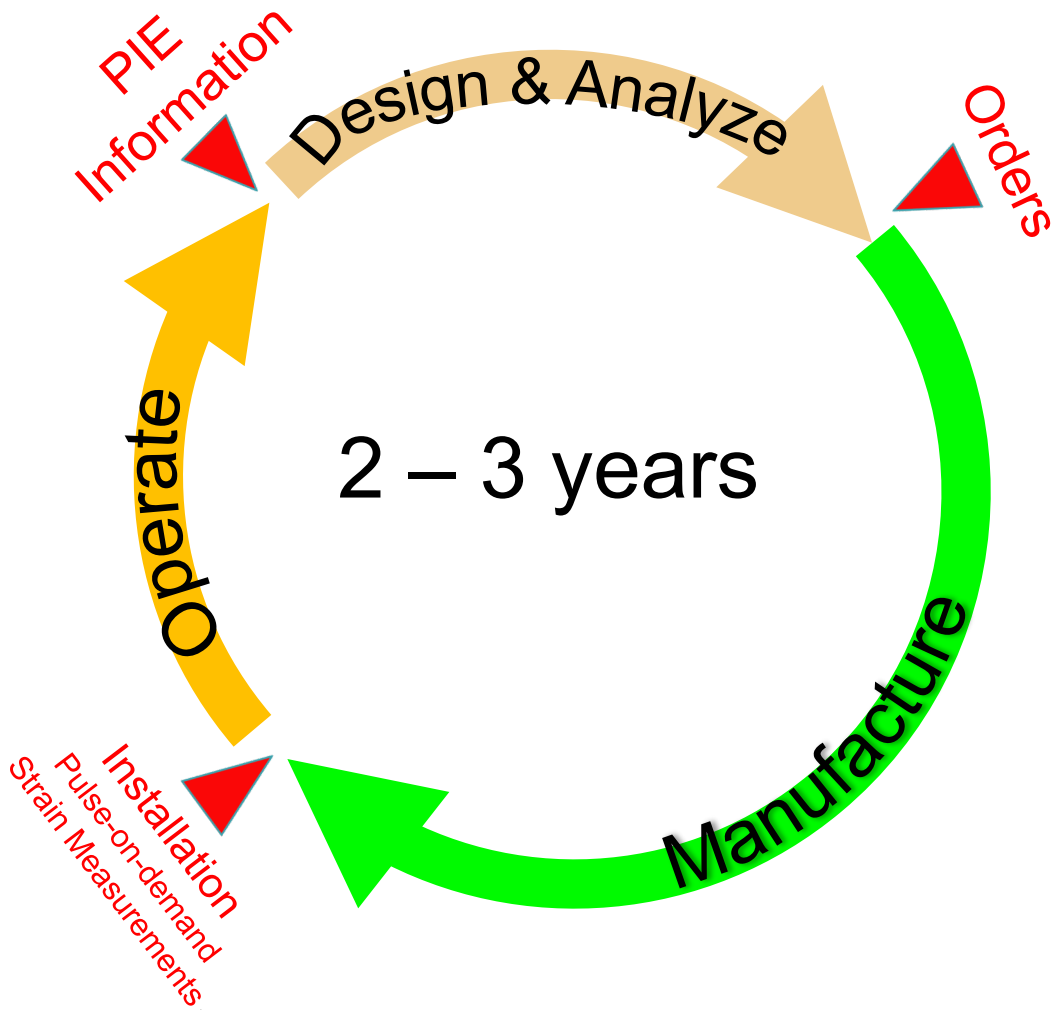
Target operations are following a step-wise, data-driven plan for reliable operation at 1.4 MW

- Three targets per year
  - Opportunities to deploy changes in design and operation faster
  - Mitigating risk of leaks
  - Managing supply and fabrication time
  - Supports development
- Stable power operation aides understanding of cavitation erosion rates



Nov. 15: RFQ failure!

Our challenge is to improve targets while encumbered by a ~3 year time lag

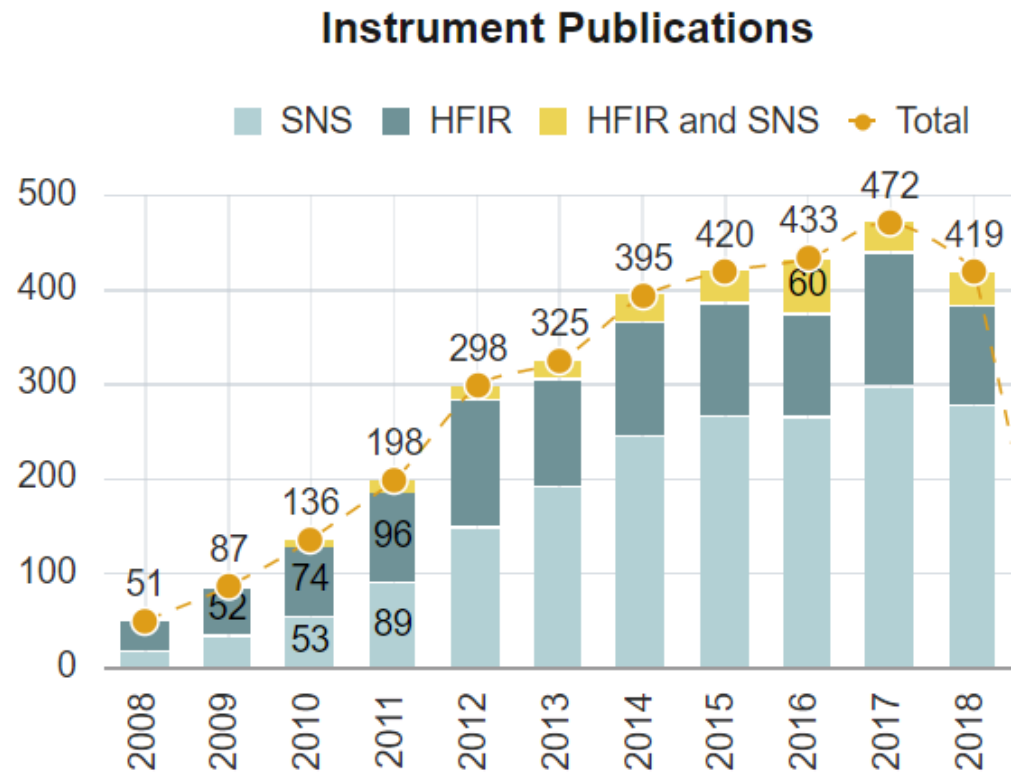


Strategy of Target Management Plan

- Leverage information to improve design
  - Predictive models
  - Engineering judgments
- Remain versatile (allowing for contingencies)
- Maintain spare inventory

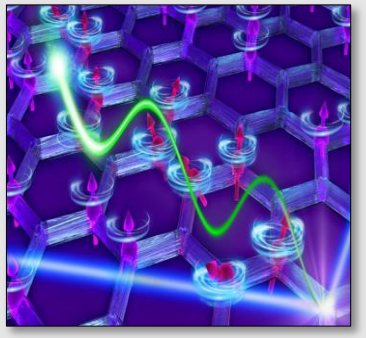
The scientific productivity and impact of the user program continues to grow

Percentage of papers in journals with impact factors >7 increased from 19% in Calendar Year (CY) 2015 to 25% in CY 2017



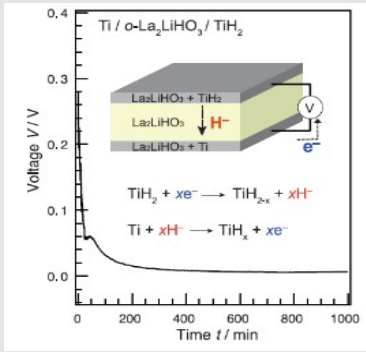
Neutrons reveal Majorana fermions in a Kitaev quantum spin liquid

Banerjee et al., *Science* 2017



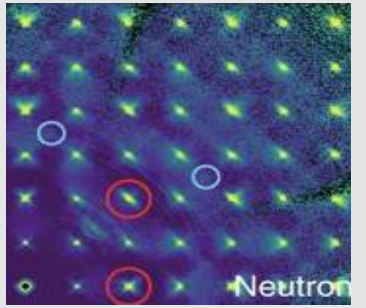
Neutrons validate novel proton conducting solid state battery materials

Kobayashi et al., *Science* 2016



Neutrons relate ultrahigh piezoelectricity and multiscale structure in relaxor ferroelectrics

Krogstad et al., *Nature Mat.* 2018



SNS: Snapshot of the User Program

FY 2015

- Unique Users: 845
- Total Users: 1675
- First-Time Users: 354
- Experiments: 773
- Instrument Publications: 300

FY 2016

- Unique Users: 893
- Total Users: 1809
- First-Time Users: 344
- Experiments: 854
- Instrument Publications: 324

FY 2017

- Unique Users: 764
- Total Users: 1679
- First-Time Users: 305
- Experiments: 794
- Instrument Publications: 331

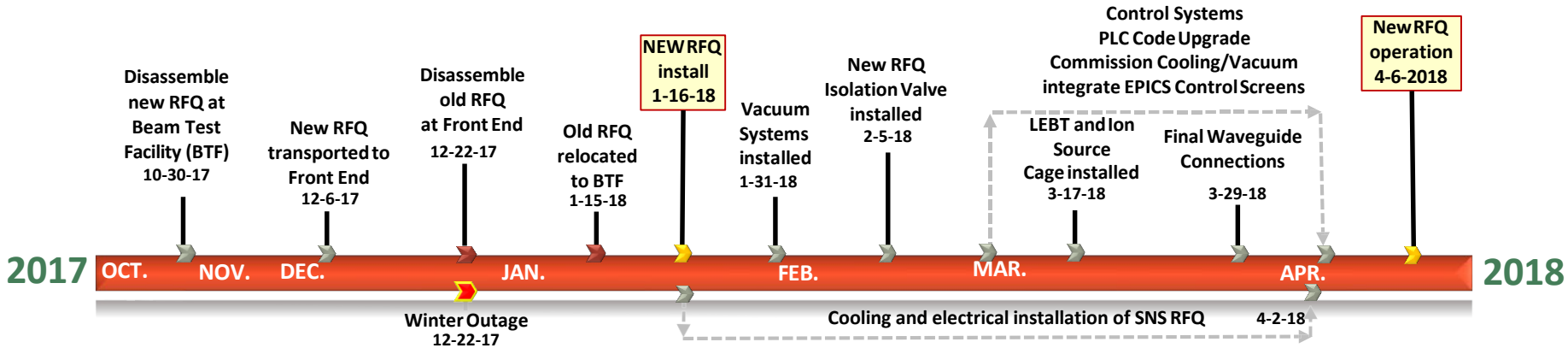
FY 2018

- Unique Users: 644
- Total Users: 1307
- First-Time Users: 281
- Experiments: 600
- Instrument Publications: 314

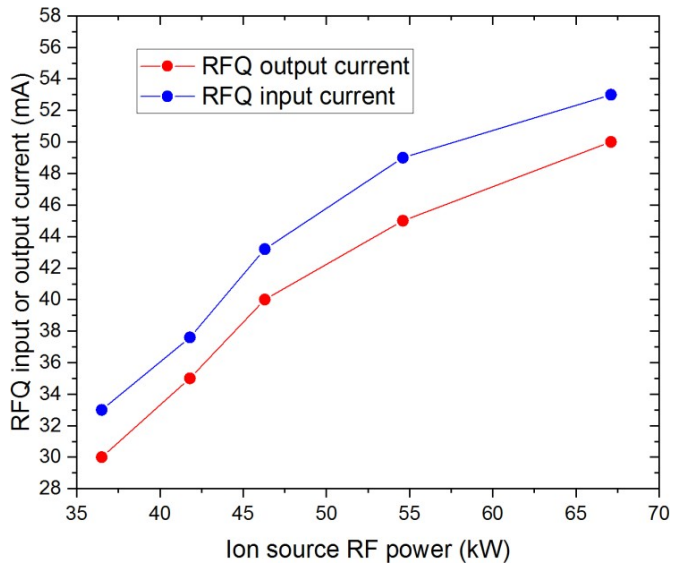
As of Oct. 25, 2018

Average days/experiment: 4.2 days

Installation of the new RFQ is the key to operational power margin and a milestone for upgrade projects



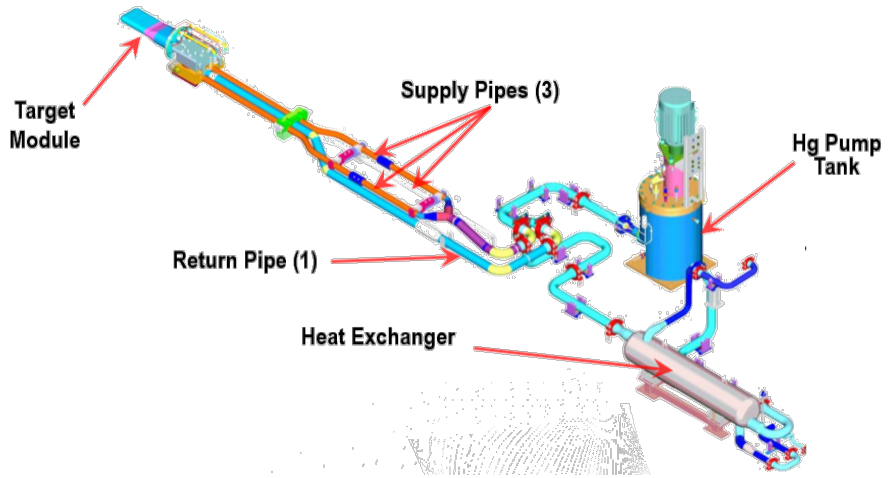
RFQ input current (mA)	RFQ output current (mA)	RFQ transmission (%)
33	30	91.0
37.6	35	93.1
43.2	40	92.5
49	45	91.8
53	50	94.3
53	50	94.3



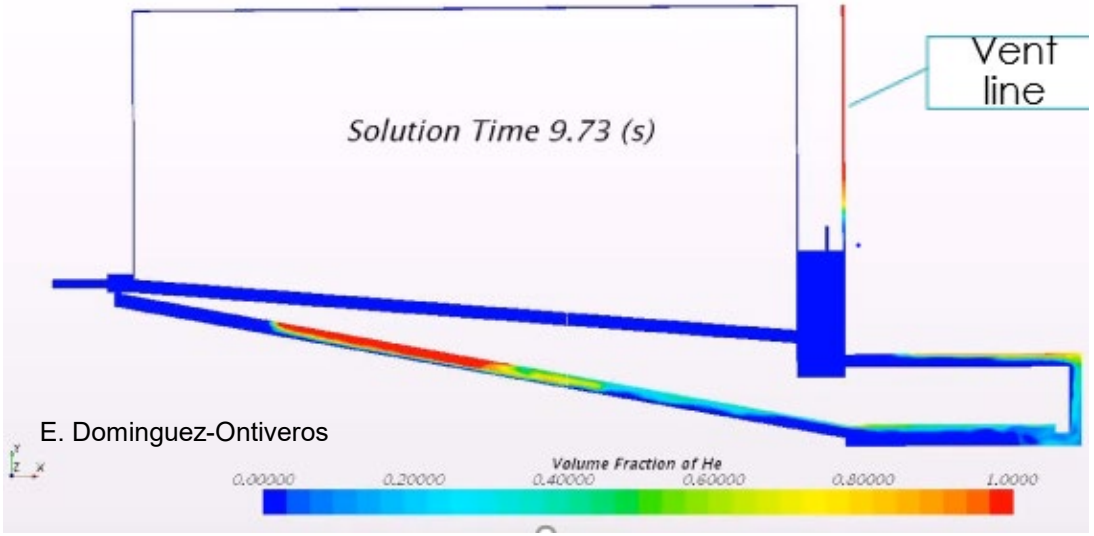
November RFQ failure was due to broken RF "C" seal at an end plate
Seal has been replaced and RFQ is ready for operation

Target gas injection initiated in the SNS mercury target

- Essential for reliable, long-lived high-power operation of SNS targets
- Small gas bubbles reduce pressure waves caused by pulsed beam
  - The pressure waves drive high-cycle fatigue of the mercury vessel and erosion damage from mercury cavitation
- While gas injection is good for the target vessel, it poses a risk that mercury could escape from the hot-cell

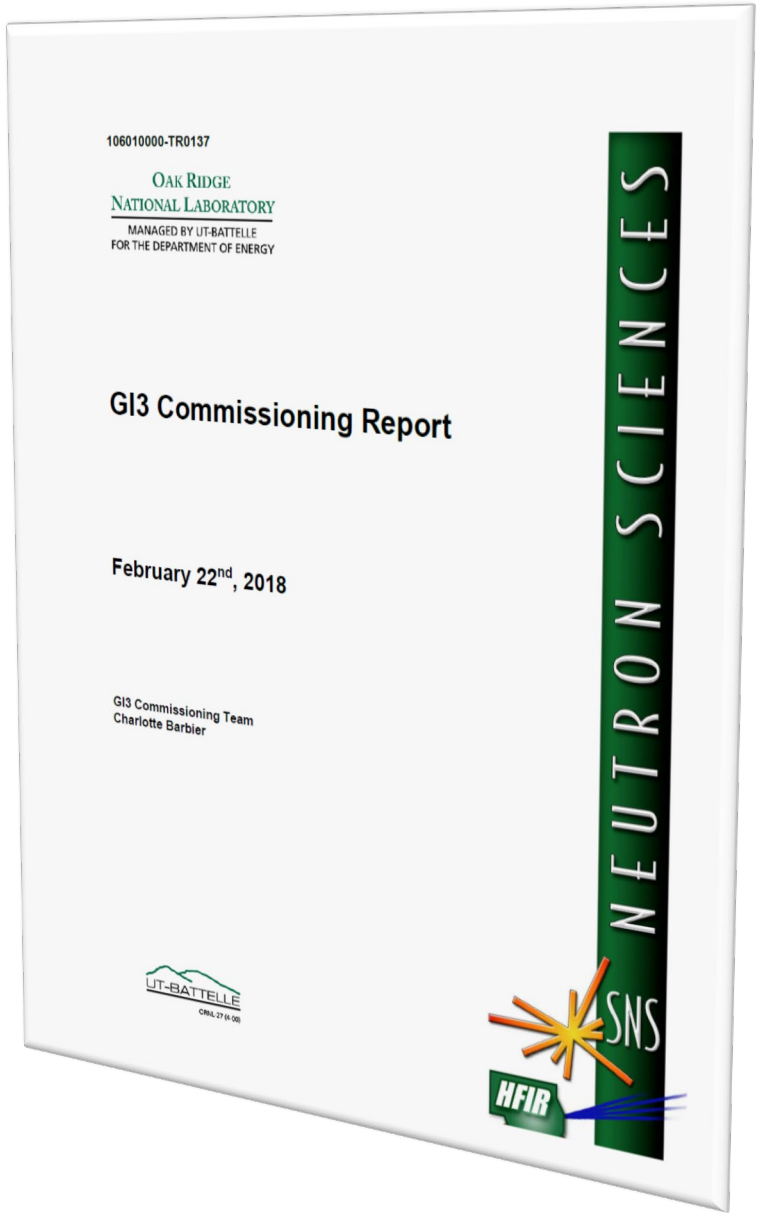


Bounding event for safety analysis

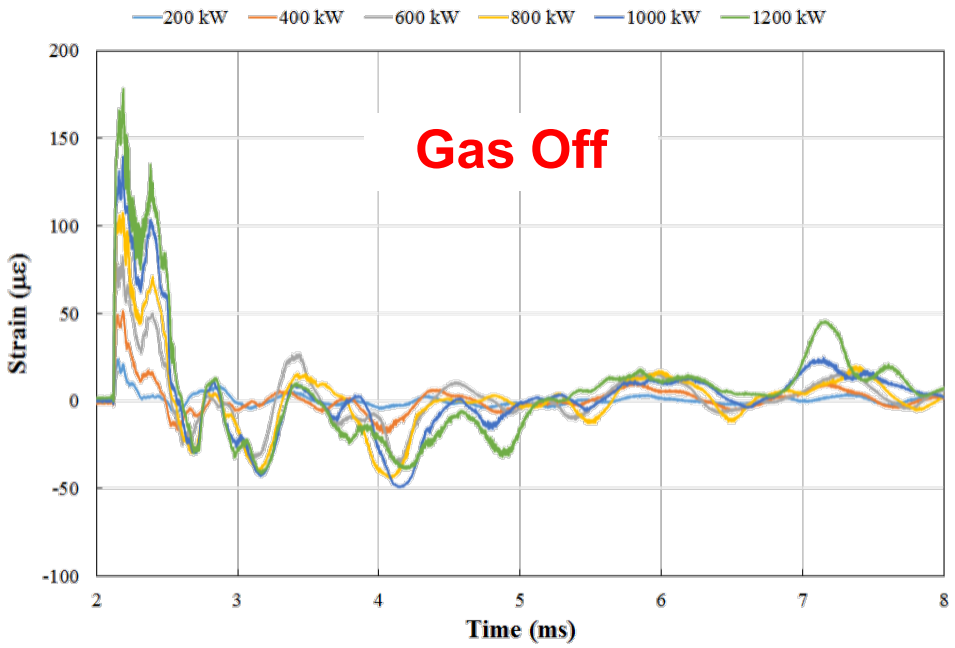


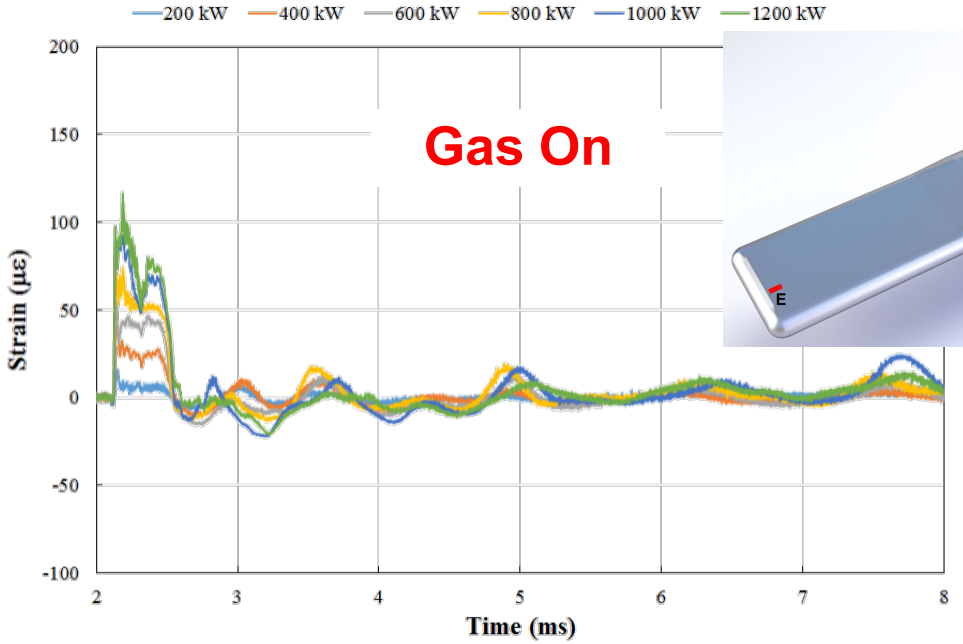
Gas injection results are positive

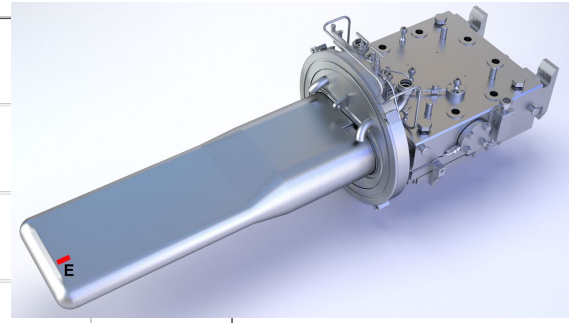
- Significant strain reductions are being achieved
  - Indications are that more gas will be better
- Gas injection is reducing cavitation damage significantly
- Gas flows used to date have not interfered with loop operation or site emissions
  - However, higher radiation dose rates are observed at the mercury pump
- Approval to routinely operate gas injection was granted
- Increasing the gas rate is planned
  - Greater and more uniform strain reductions
  - Further reduction in damage as power increases

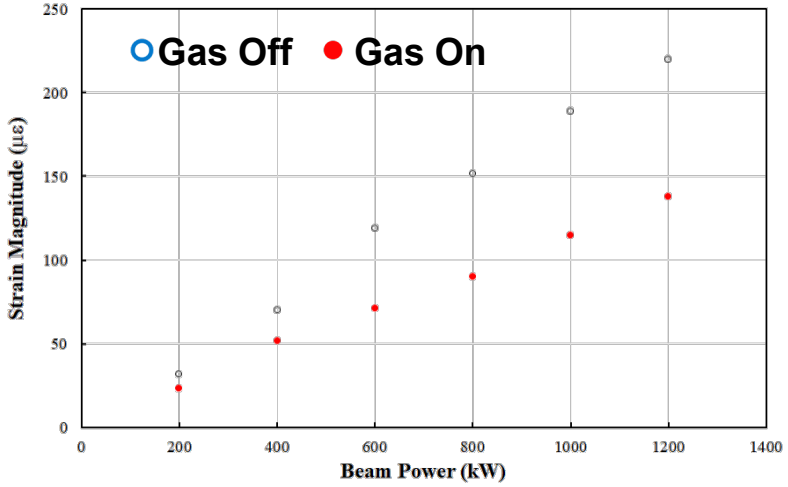


Sensor “E” results: up to 40% reduction with gas on





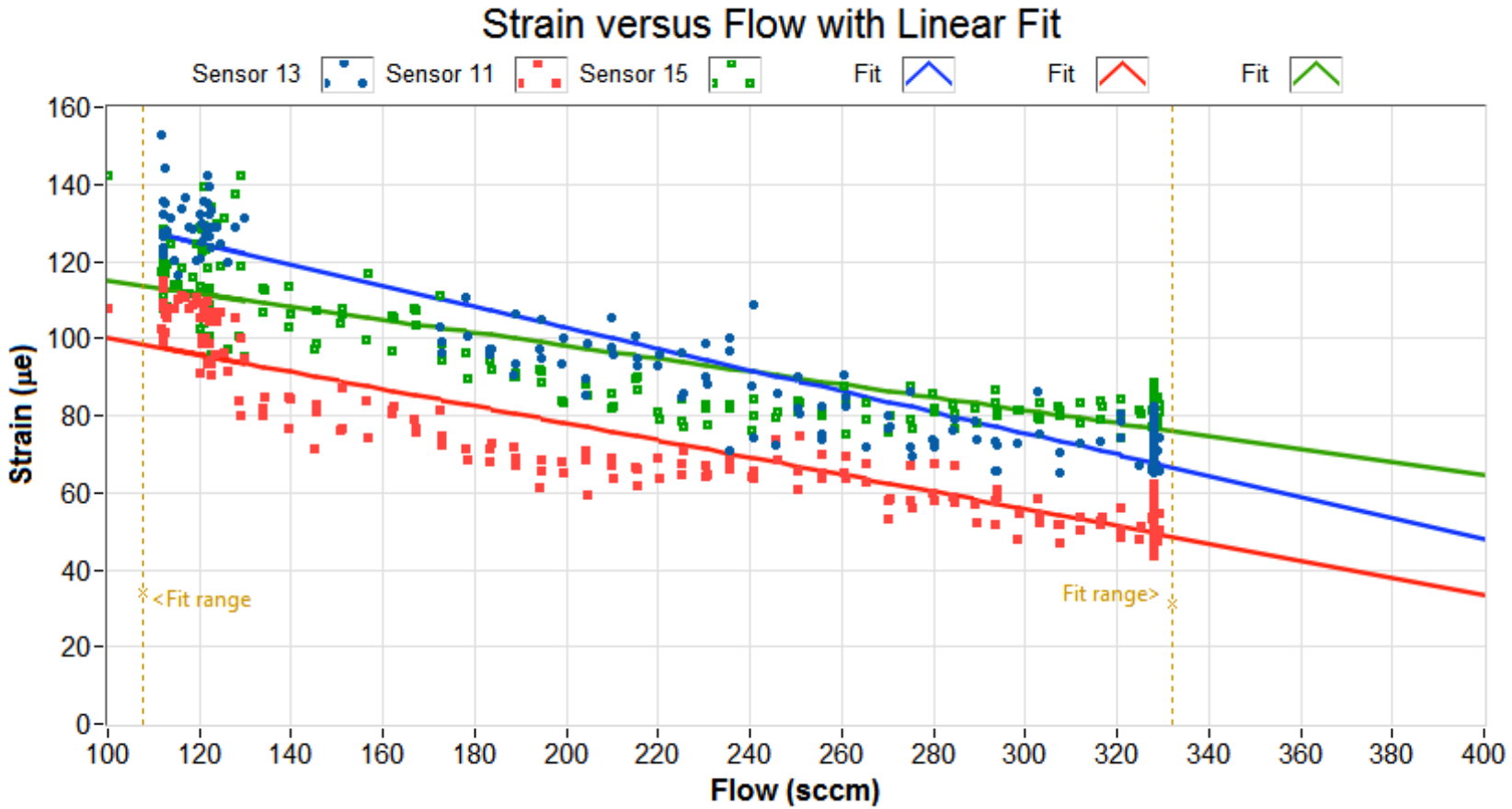




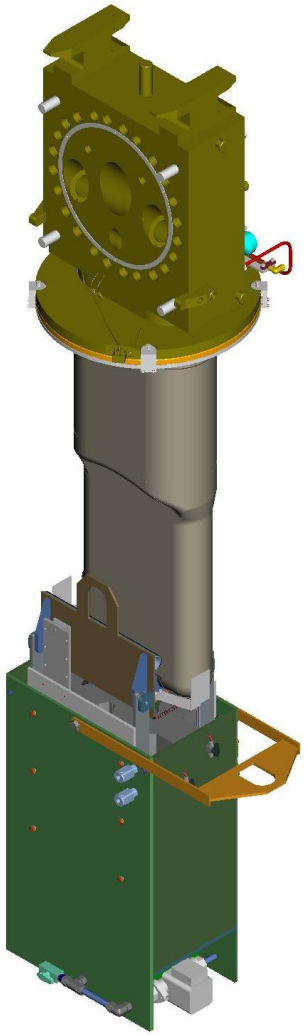
Beam Power (kW)	Strain Magnitude (με)		Strain Reduction (%)
	Gas injection off	Gas injection on	
200	31.73	23.06	27.3
400	70.06	51.50	26.5
600	118.76	70.95	40.3
800	151.79	90.09	40.6
1000	189.04	114.75	39.3
1200	219.97	137.64	37.4

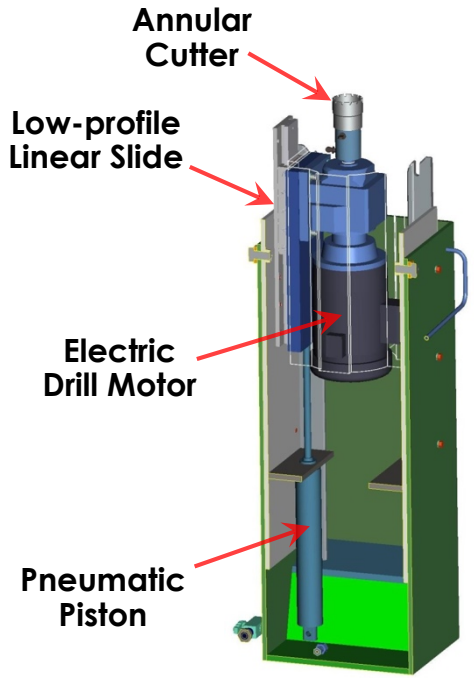
Testing indicated strain dependence on gas flow rate

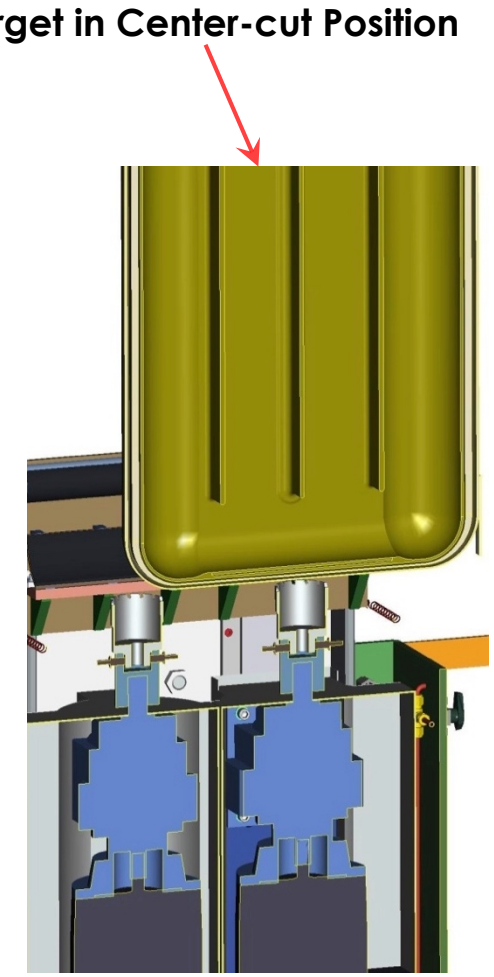
- Increasing gas flows are planned



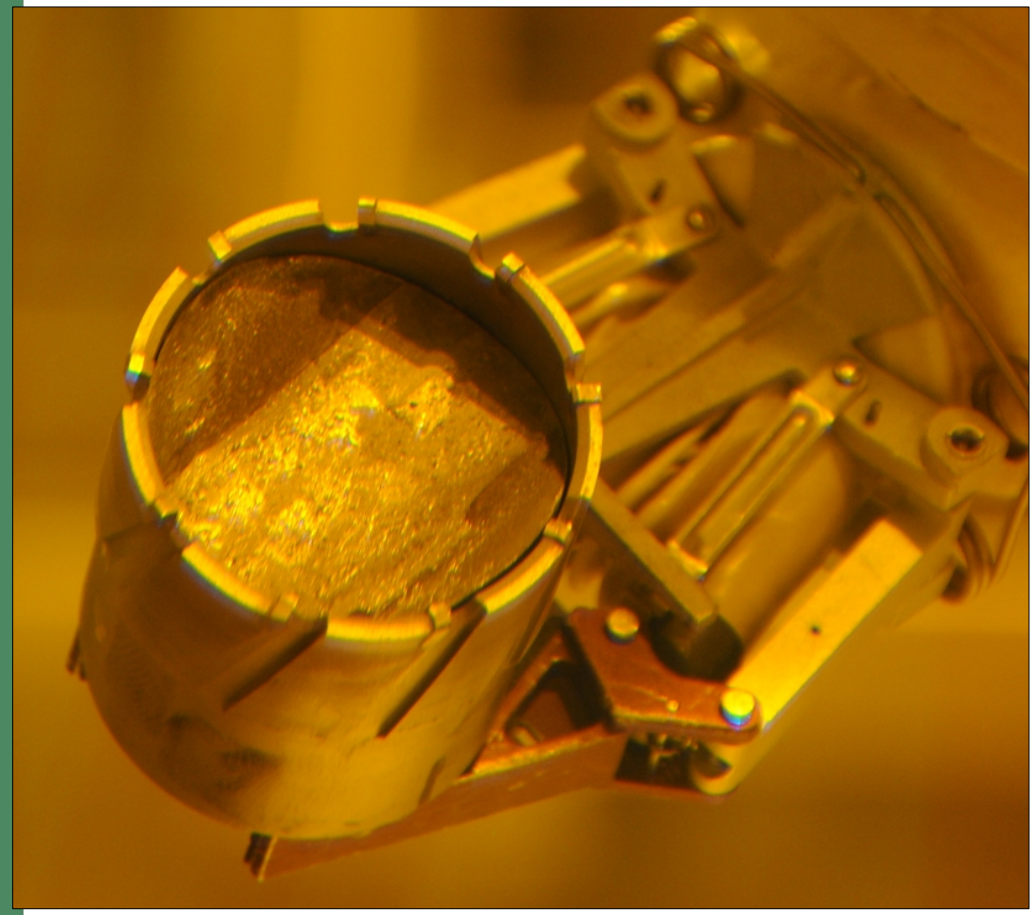
Disk-shaped specimens are routinely sampled from the beam entrance region of SNS targets after service

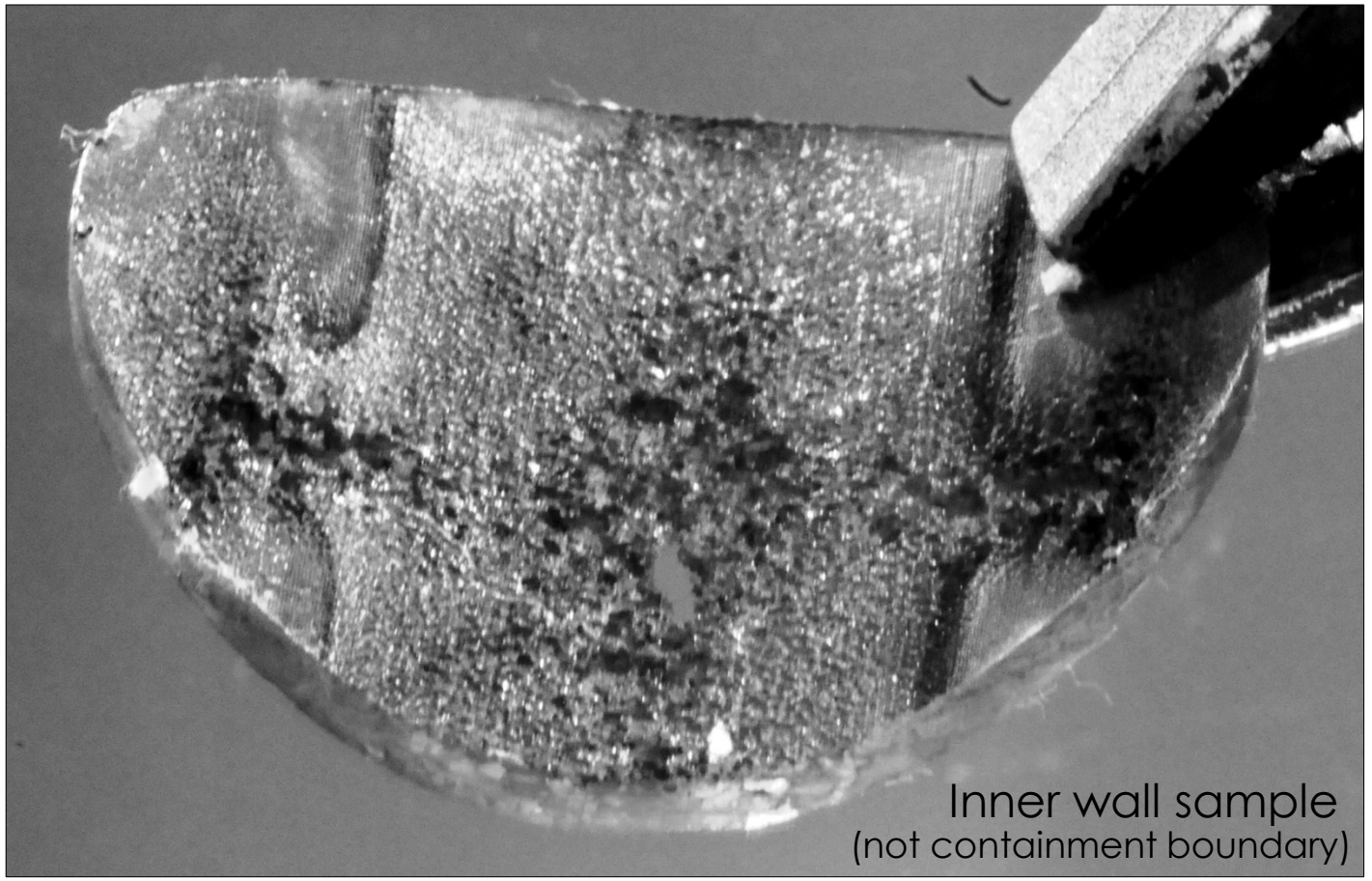






Target sampling with annular cutters

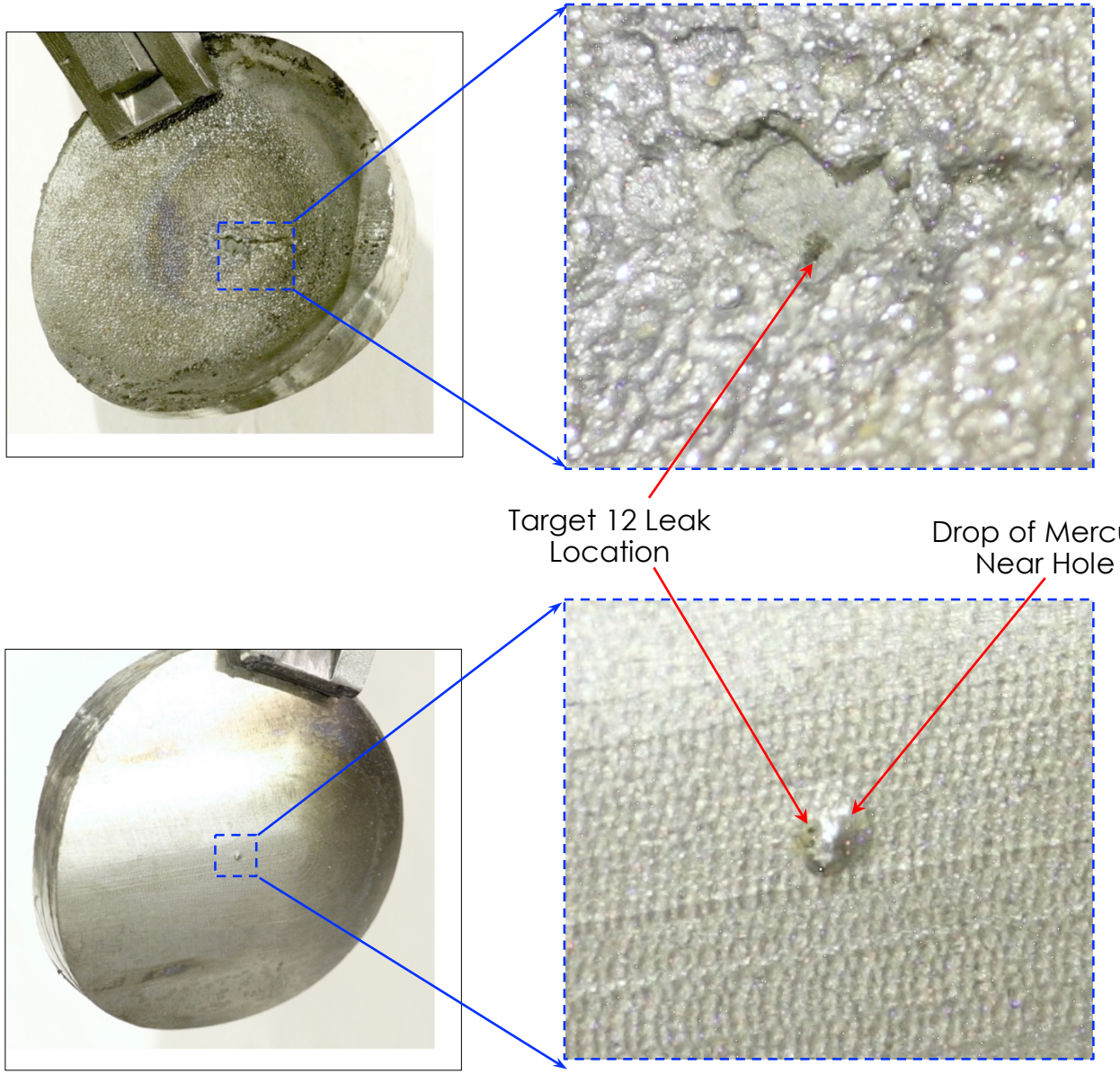




Sample diameter: ca. 60 mm

Leaks in Target 12 (2015) and 13 (2016) were caused by cavitation-induced erosion

- No gas injection
- The leaks were caused by cavitation erosion at the front of the mercury vessel
  - *Outside* the proton beam path
  - At the end of a bulk inlet supply
- The holes were small, the diameter of Target 12 hole was estimated to be 125 – 250 µm (0.005-0.010 in)



Target 12
original design
no gas Injection
P_{avg} = 964 kW
E_{total} = 4,460 MWh

Target 13
original design
no gas Injection
P_{avg} = 1,075 kW
E_{total} = 2,588 MWh

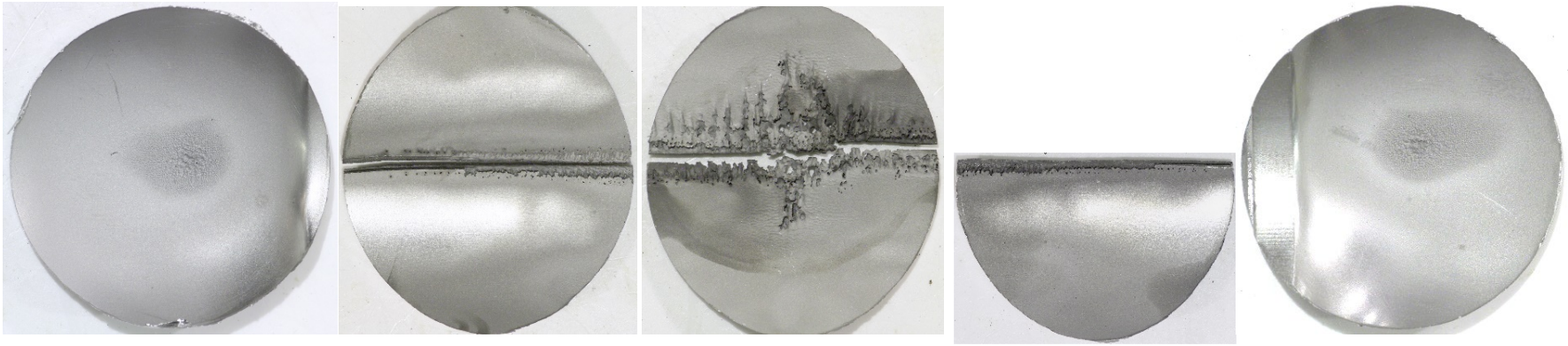
Targets 17 and 19 provide a comparison between targets operated with and without gas injection

- 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

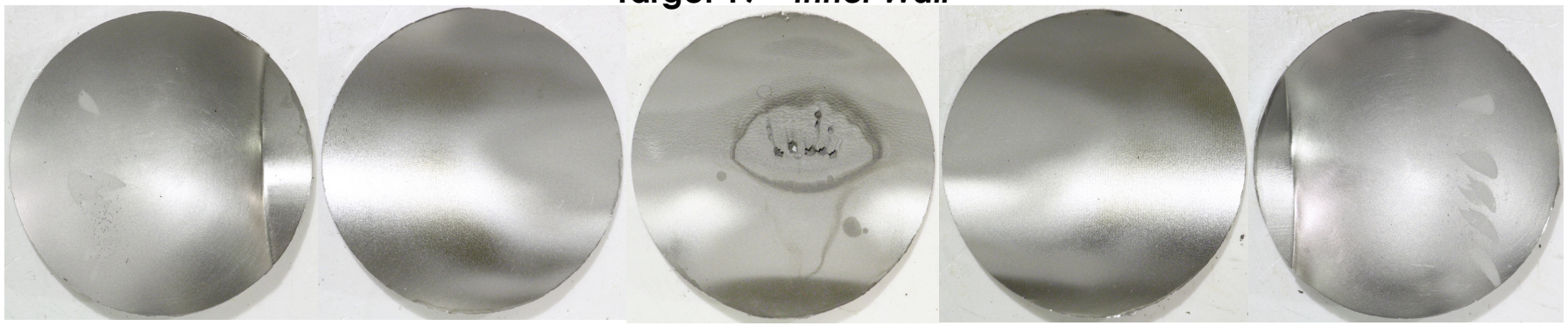
Target 17 – *Inner Wall*



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*

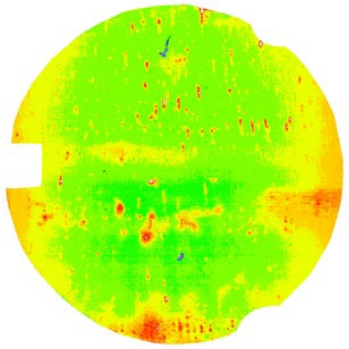


Erosion to *outer wall* characterized using laser scanning
These are center samples – on the beam axis

Original Target Design → Jet-Flow Target Design →

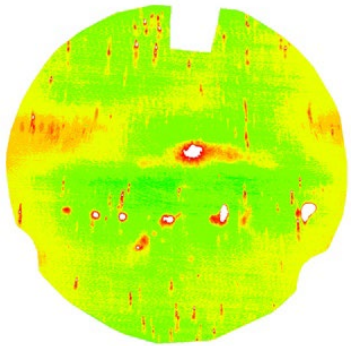
Gas Injection →

Target 12
No Gas Injection
E_{total} = 4,460 MWh
P_{avg} = 964 kW



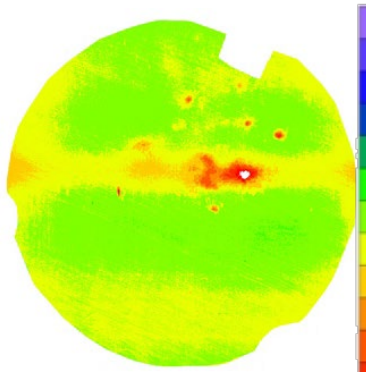
Max Erosion
0.012 in

Target 13
No Gas Injection
E_{total} = 2,589 MWh
P_{avg} = 1,075 kW



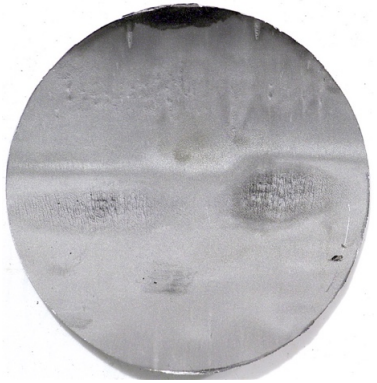
Max Erosion
0.052 in

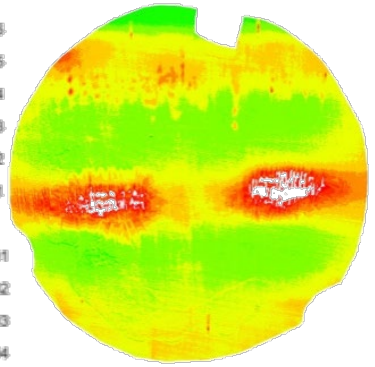
Target 16
No Gas Injection
E_{total} = 1,780 MWh
P_{avg} = 968 kW



Max Erosion
0.008 in

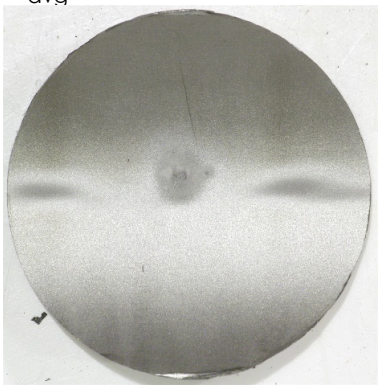
Target 17
No Gas Injection
E_{total} = 1,936 MWh
P_{avg} = 1,127 kW

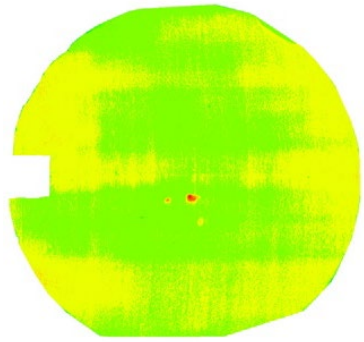




Max Erosion
0.022 in

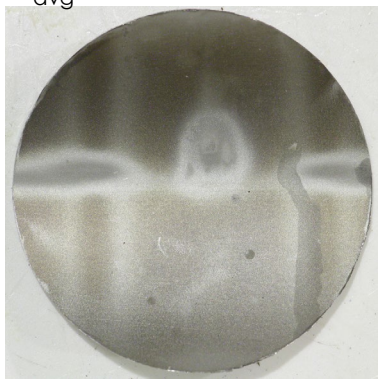
Target 18
Q_{avg} = 0.45 - 0.25 SLPM
E_{total} = 1,261 MWh
P_{avg} = 1,128 kW

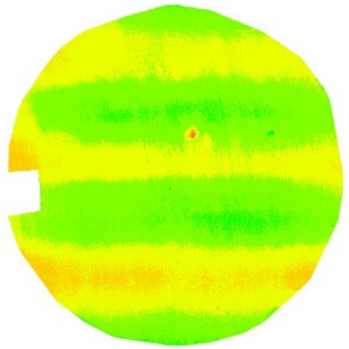




Max Erosion
0.006 in

Target 19
Q_{avg} = ~0.45 SLPM
E_{total} = 1,987 MWh
P_{avg} = 1,207 kW





Max Erosion
0.004 in

Erosion color scale fixed

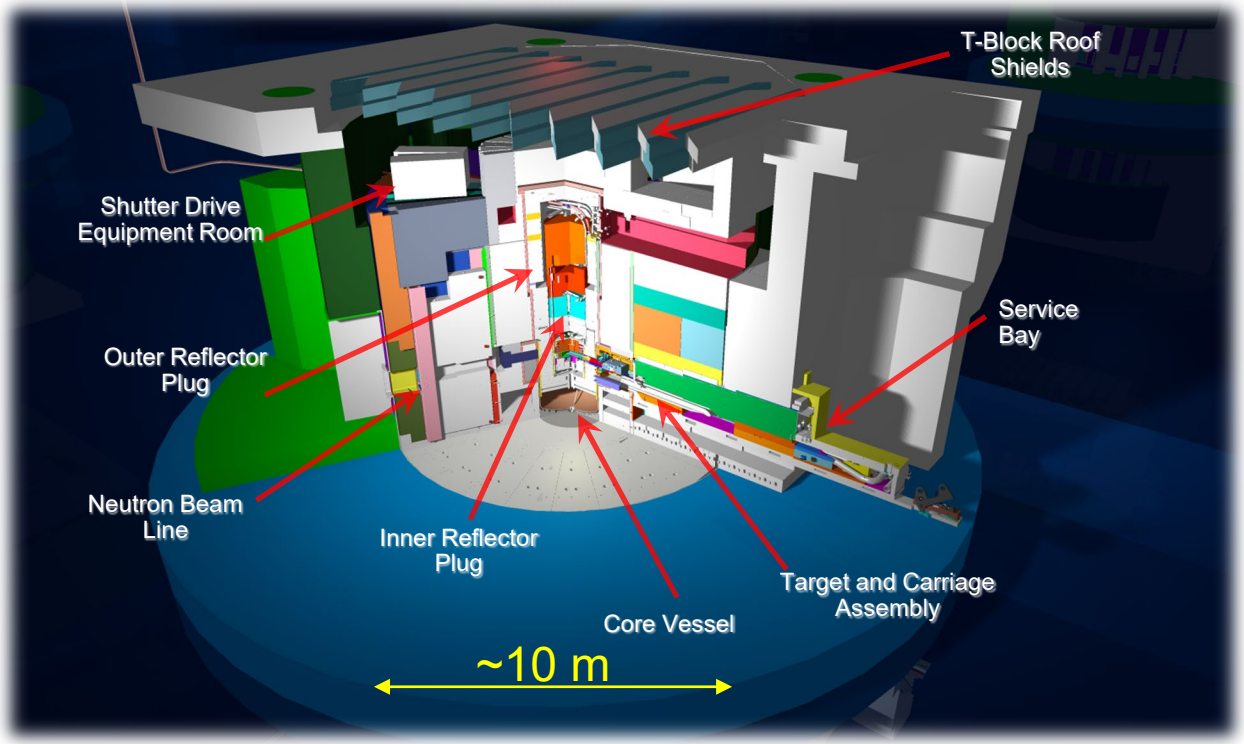
Gas rates will be raised to extend 1.4 MW target lifetime and to support development for the 2 MW upgrade

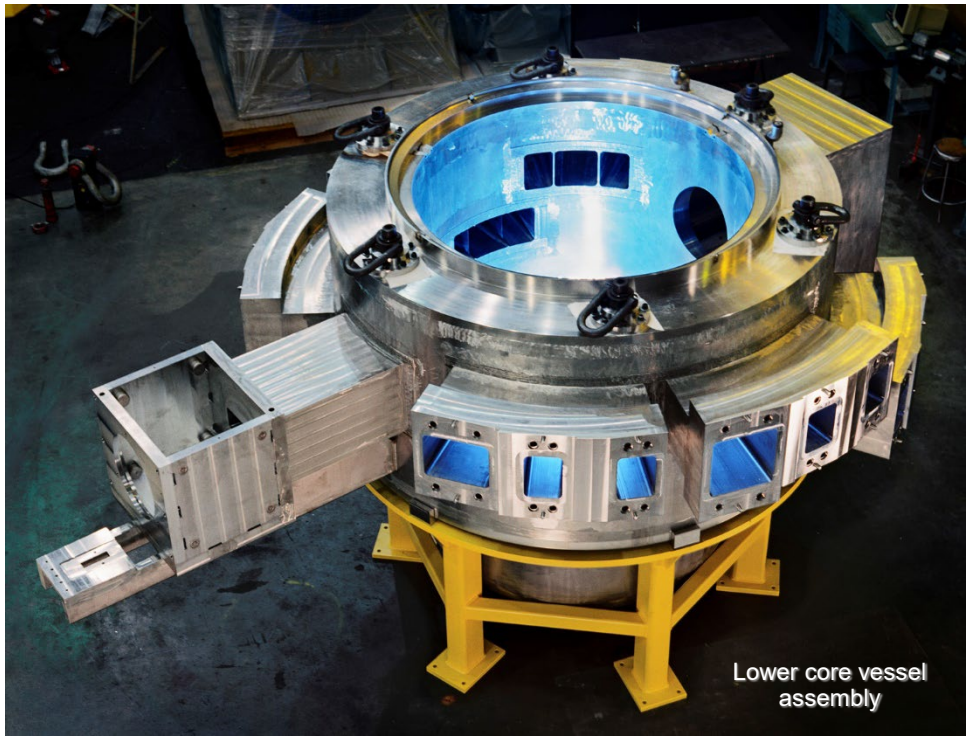
- Over the next few years we intend to raise the gas rate to bubblers to several SLPM
  - Safety demands a cautious approach
  - Method will remain a “once-though” helium gas supply for several years

- The Proton Power Upgrade Project (PPU) will maximize target life margins with even more gas injection and will recirculate gas

Operational difficulty: water inside the core vessel

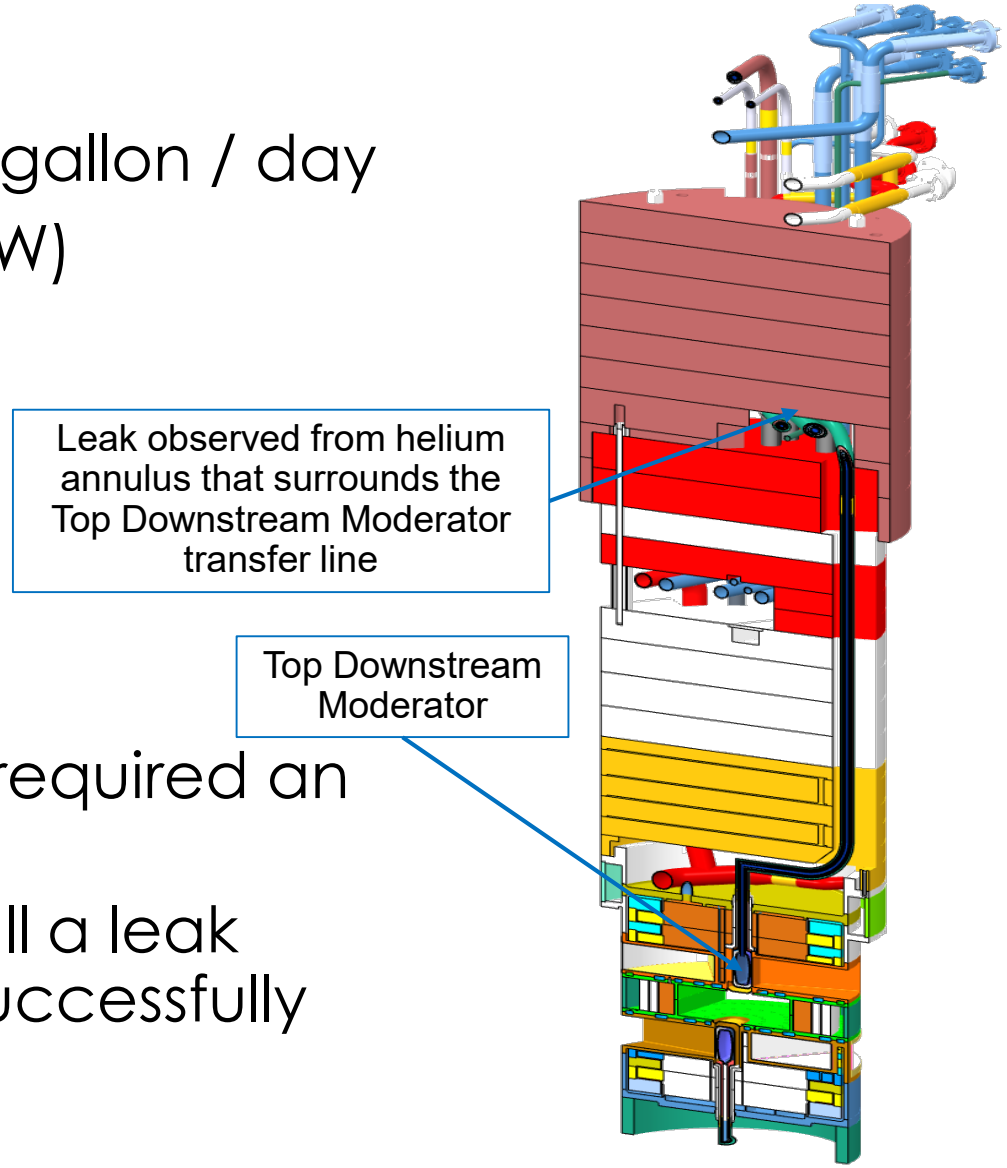
- The core vessel contains the inner and outer reflector plugs, neutron moderators, core vessel inserts, and interfaces with the target and proton beam window seals





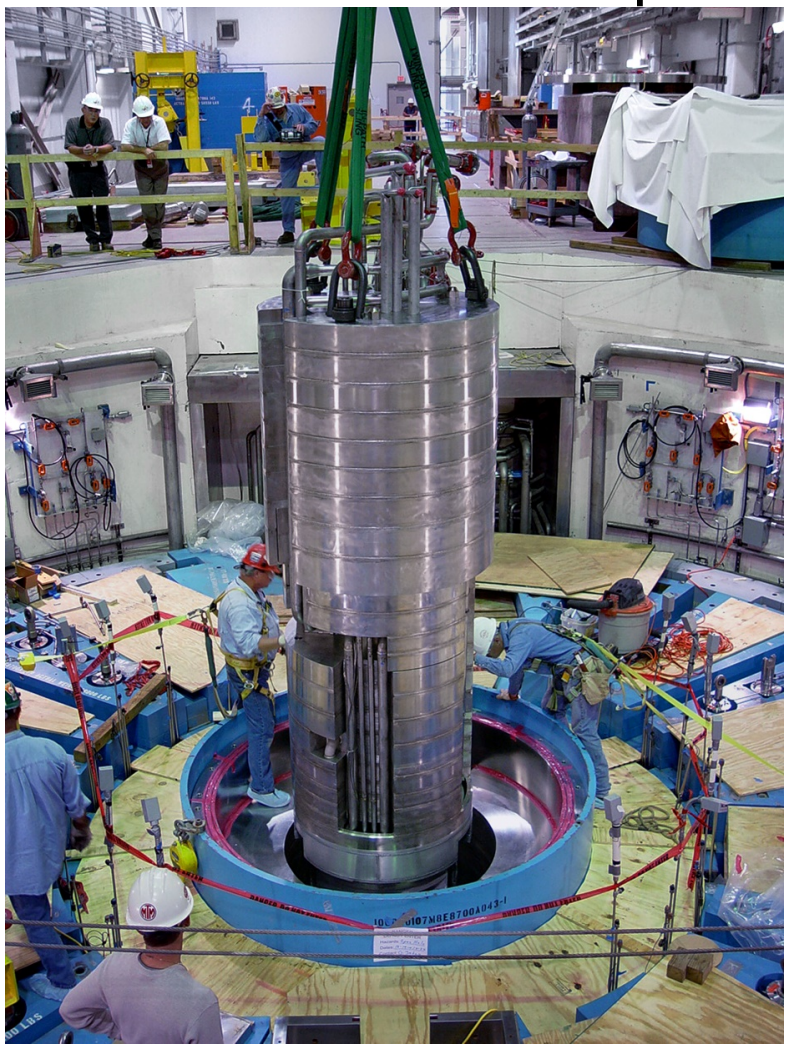
Water leaks inside core vessel were identified in Fall 2016

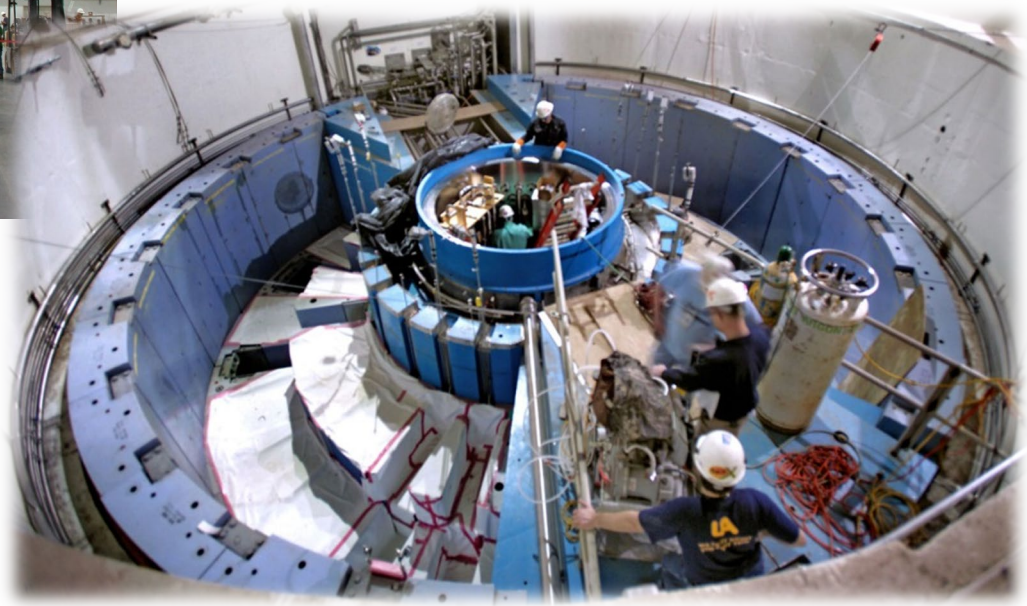
- The first leak was small at approximately 0.5 gallon / day
  - Located in the proton beam window (PBW)
  - Issue was resolved after PBW changeout



- A second leak was identified in November
  - The leak rate continued to increase and required an engineering solution
  - After an intense effort to design and install a leak collection system, the second leak was successfully managed

The Inner Reflector Plug (IRP) is a large, complex and limited-life component of the neutron source





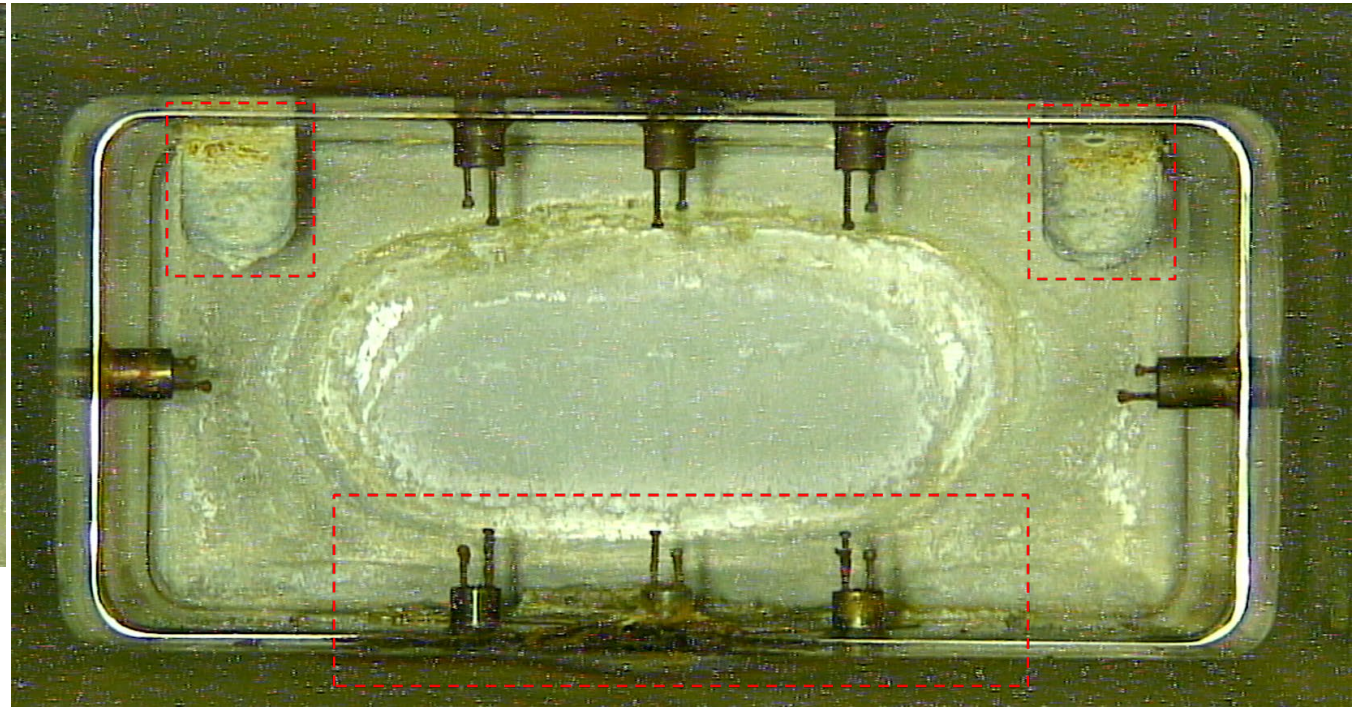
Photos of the original IRP-1 installation

- Planned lifetime was 32 GWh
  - ~early 2016
- Delivery of replacement was delayed
- Replacement completed early 2018
  - 40 GWh
- Coolant changed to D_2O

Operation with water in the core vessel corroded the aluminum proton beam window

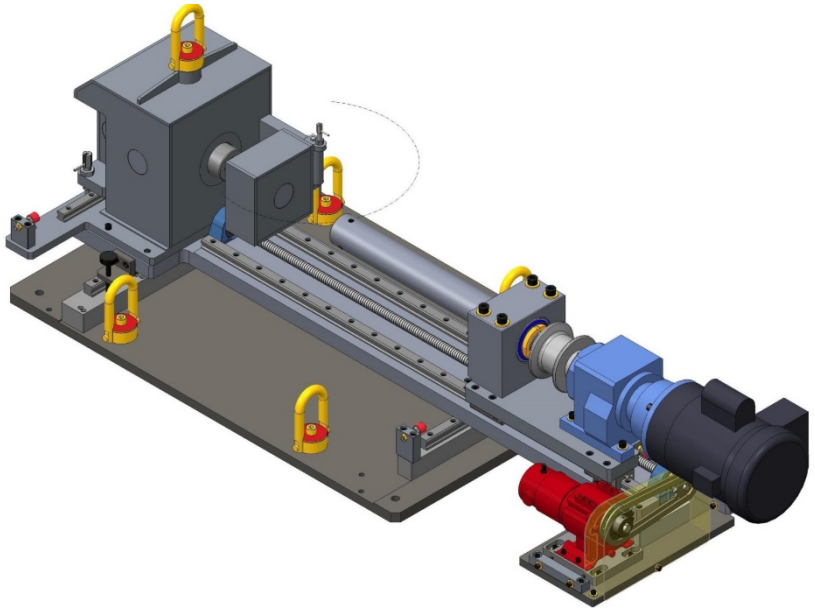
- During the IRP replacement process an inspection camera was positioned inside the core vessel to inspect the neutron and proton beam windows
  - Both are made from aluminum
- While the neutron windows appeared in good shape, corrosion of the PBW was apparent
- This PBW remains in service
  - Spare Inconel PBW will be ready when needed
  - PIE will be conducted to characterize corrosion

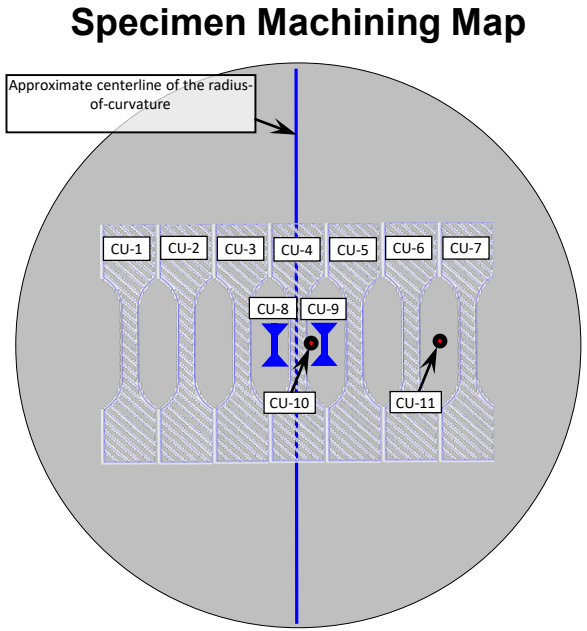
Close-up views of the aluminum PBW and target imaging system mirrors corrosion



Efforts are underway to sample and test material from the aluminum PBW currently in operation

- Currently, the administrative dose limit for the SNS aluminum PBW is based on He concentration generated during operation:
  - 2,000 appm-He
- Strong desire to assess corroded depth
- Opportunity to better understand mechanical properties of Al-6061-T51following high-energy proton irradiation
- Work on a sampling device for the aluminum PBW is underway

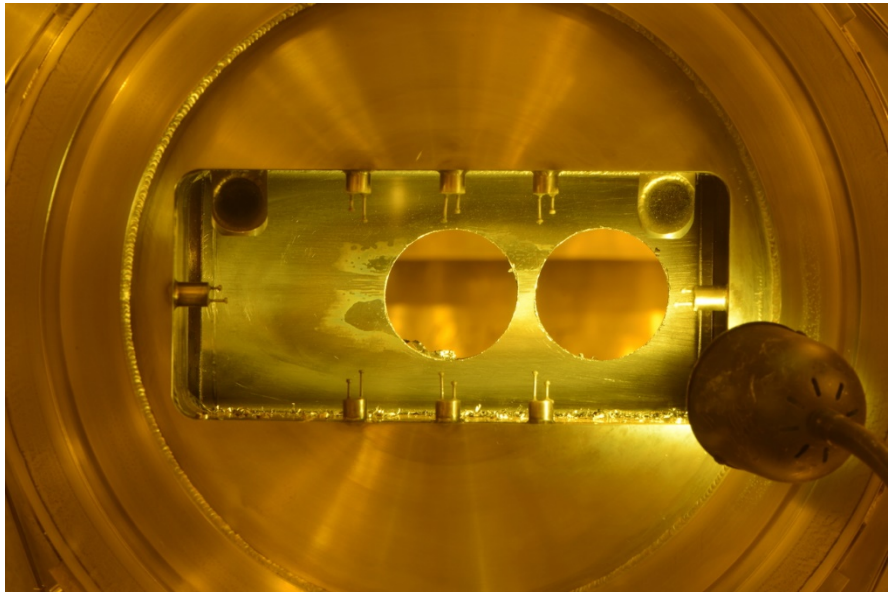




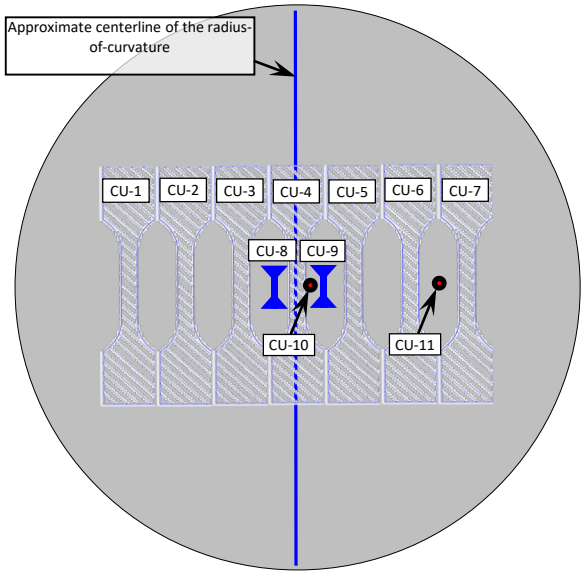
We had previously sampled an Inconel 718 PBW (#4)

- Specimens were machined from samples and tested
  - Tensile specimens to characterize irradiated tensile properties using digital image correlation
  - Micro-tensile specimens to characterize deformation behavior
  - Specimens to measure helium content (at ORNL) and data to benchmark neutronics codes
- Micro-tensile and gas measurement specimens need to be tested

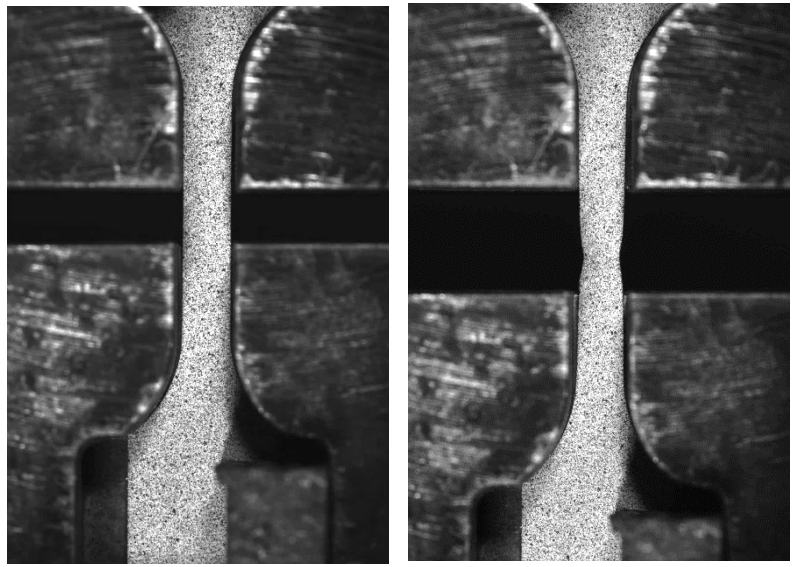
PBW #4 After Sampling



Specimen Machining Map



Specimen CU4-3



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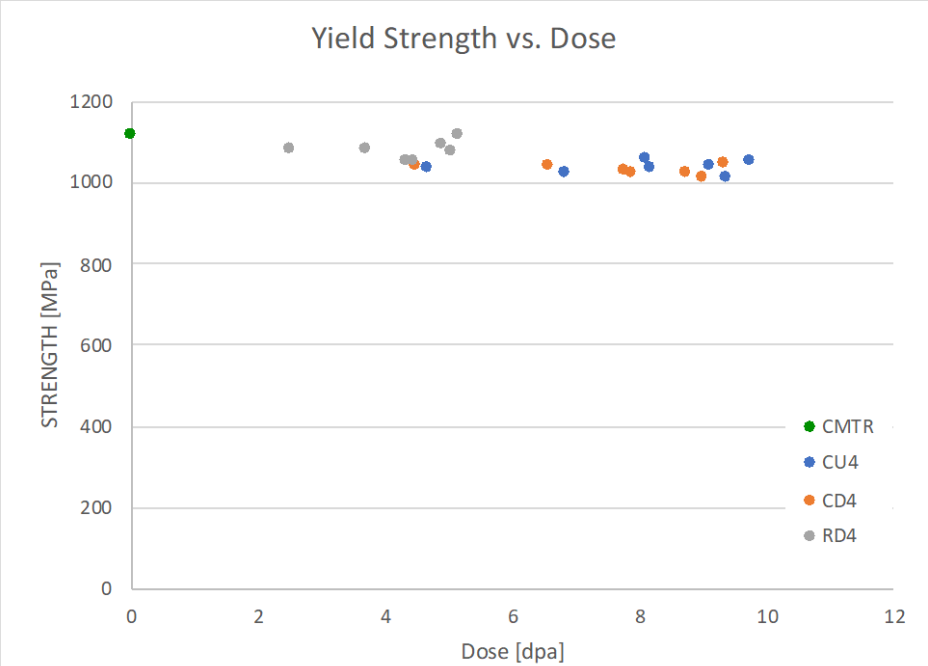
PBW 4 tensile testing results showed the Inconel 718 had appreciable ductility remaining after irradiation

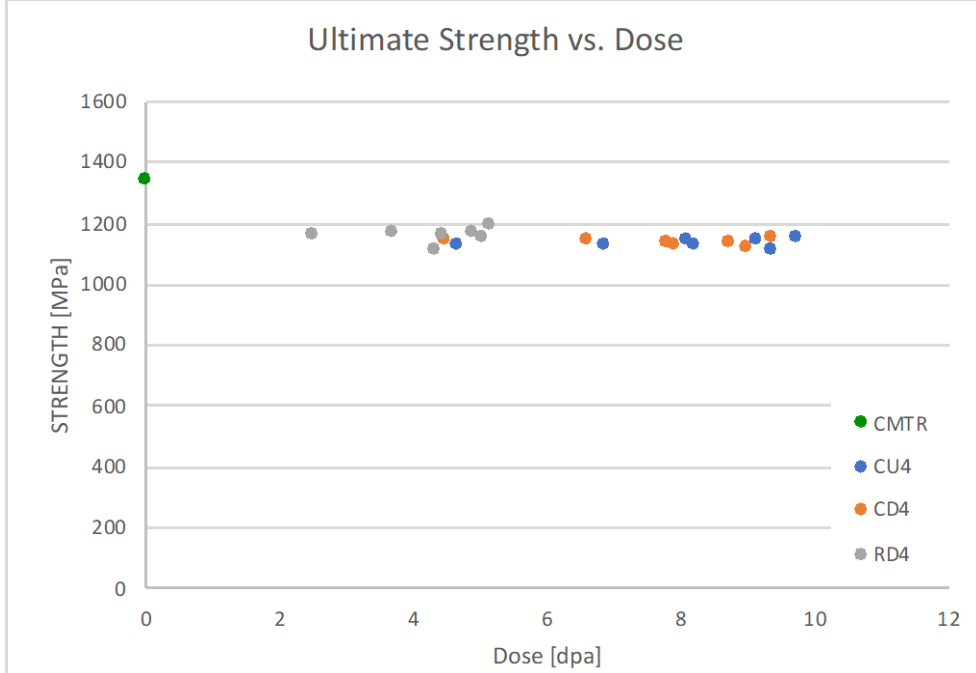
- The Inconel 718 for PBW 4 was supposed to be in the solution annealed condition

from the CMTR:

SOLUTION ANNEAL 1700-1850 DEG F FOR 1HR PER INCH OF THICKNESS & AIR COOL/DESCALE OD DIM TOL +/-.08" PLAIN ENDS
********** MADE IN THE USA **********

- PBW 4 tensile specimens irradiated from 2.5 to 9.7 dpa were tested





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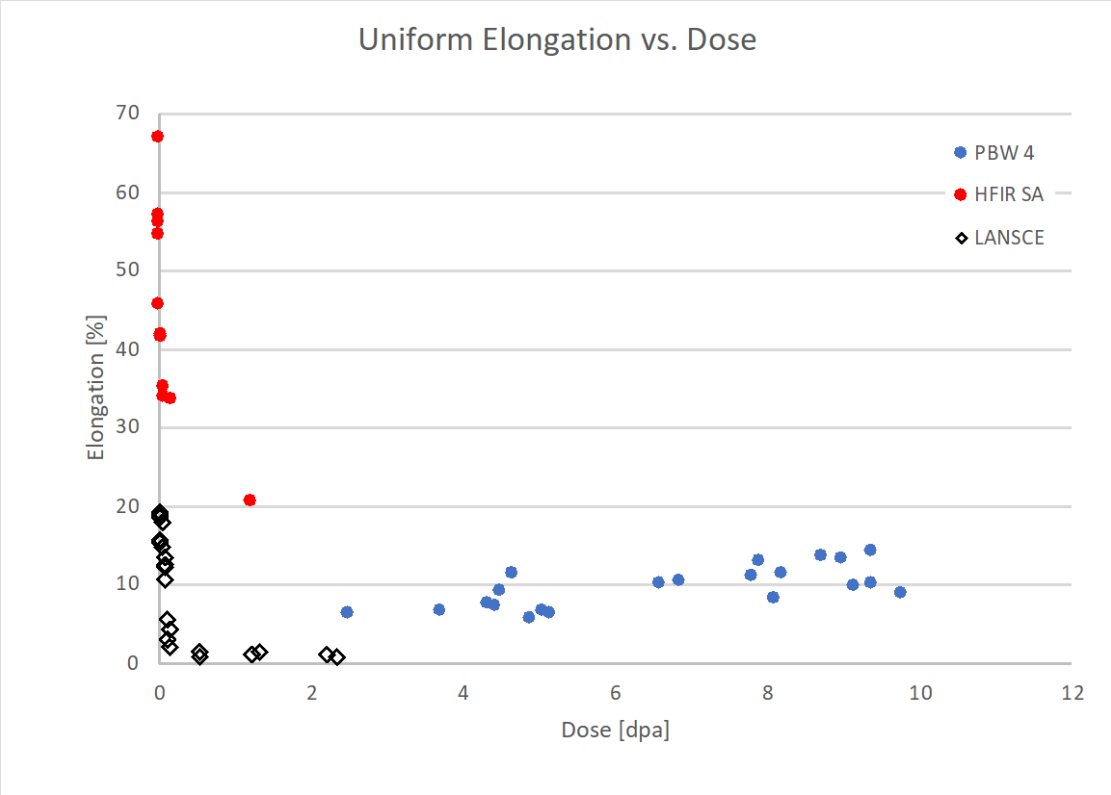
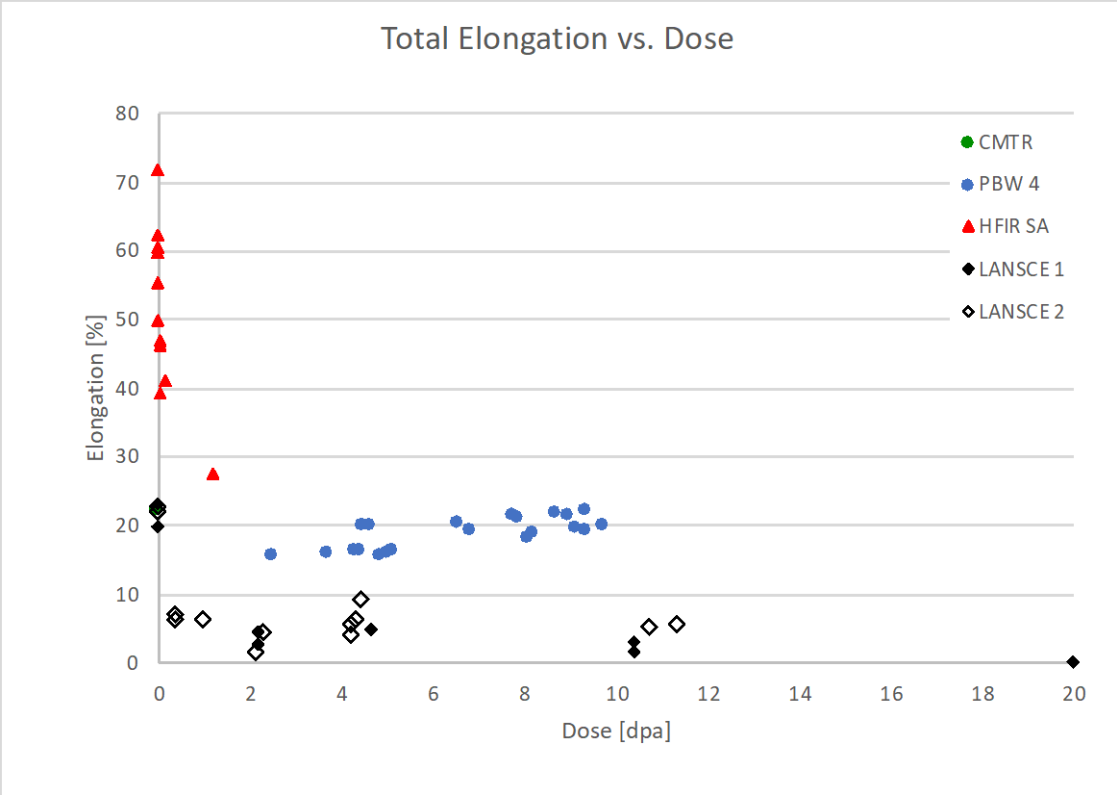
The tensile properties measured from PBW 4 are unique and have not been previously reported in the literature

- No data in the literature is directly comparable to the SNS PBW, but some comparisons can be made
- While strength values were similar to previous studies, the PBW 4 elongation values were greater than previous reports





HFIR – T.S. Byun, K. Farrell Journal of Nuclear Materials 318 (2003) 292-299
LANSCE 1 – S.A. Maloy et al., Journal of Nuclear Materials 296 (2001)119-128
LANSCE 2 – M.R. James et al., Journal of Nuclear Materials 296 (2001) 139-144

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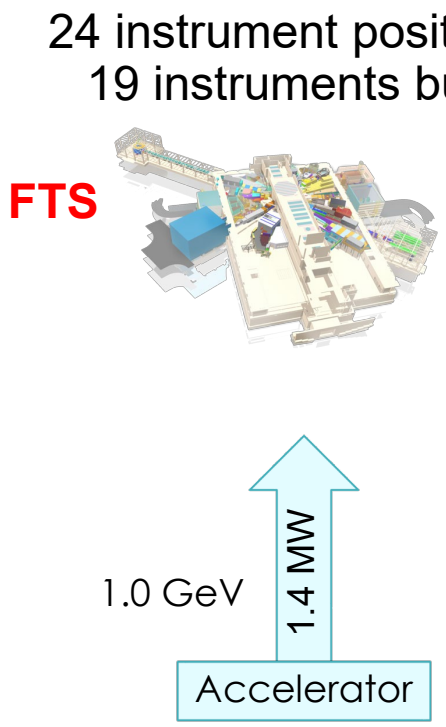
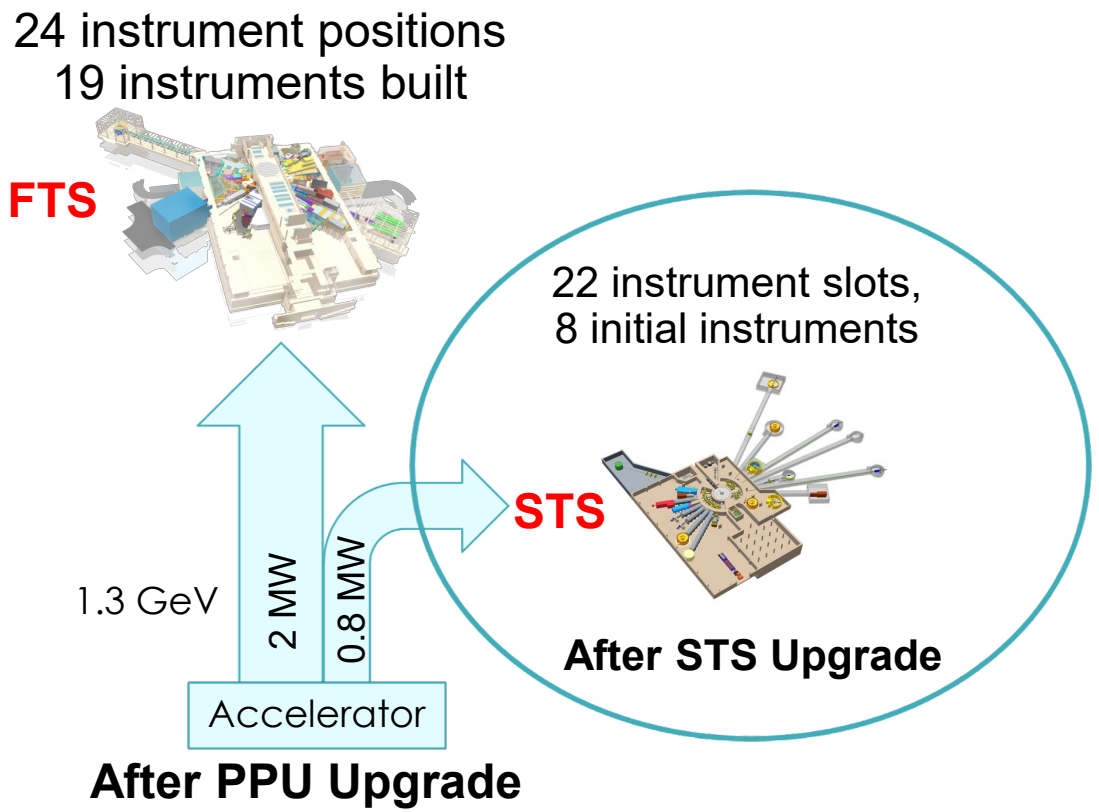
SNS Upgrade Plans

- **Proton Power Upgrade** project **doubles accelerator power** capability to 2.8 MW
  - CD-1 granted April 2018; total cost ~$240M; pursuing CD-2 in FY2019; project completion in 2024
  - Provides accelerator basis for STS
  - **Increases FTS power to 2 MW and extends life 20 more years**
- **Second Target Station** provides new instrument hall with world class cold neutron brightness
  - Pursuing CD-1 in in FY2019; total cost ~$1.5B



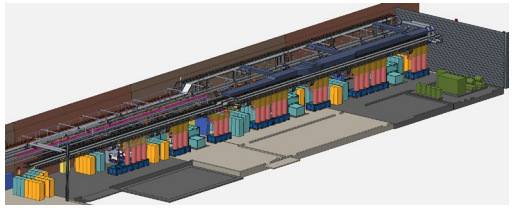


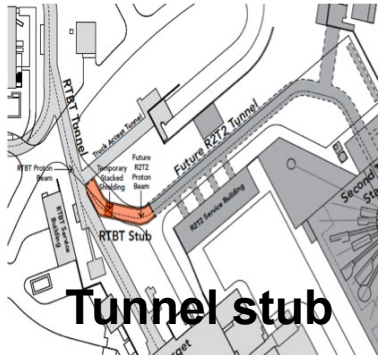
Proton Power Upgrade Technical Scope

30% increase in proton energy

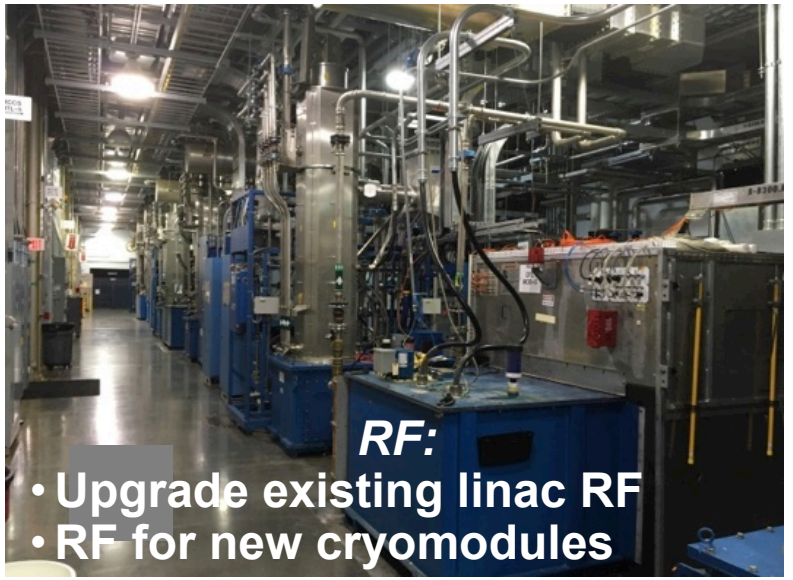
Conventional Facilities:

Klystron gallery

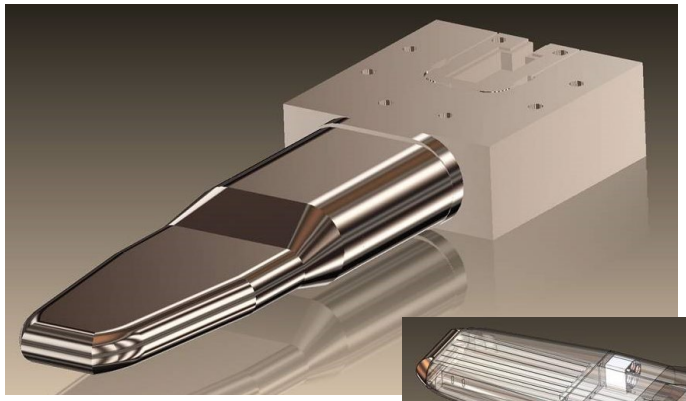


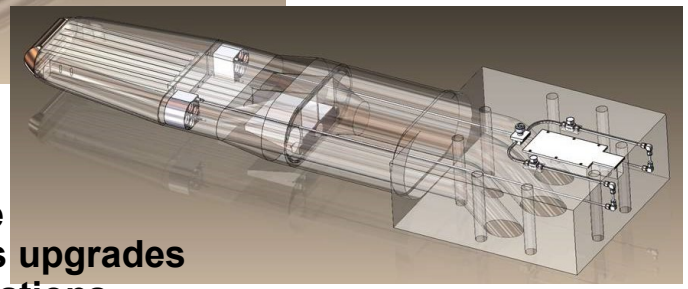


Tunnel stub

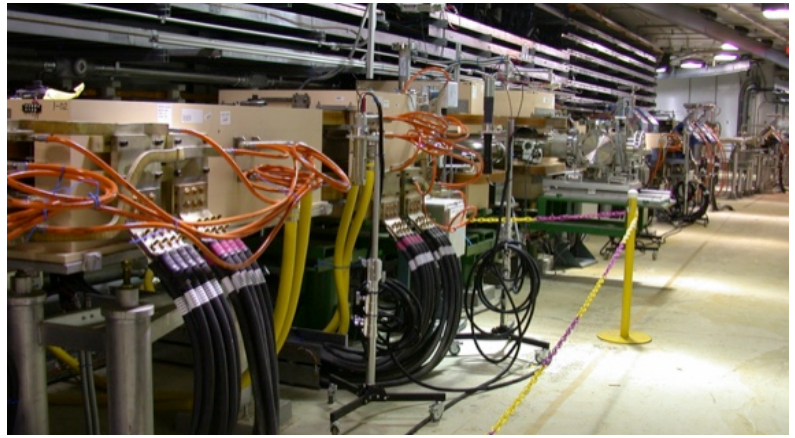


Basis for WBS Structure





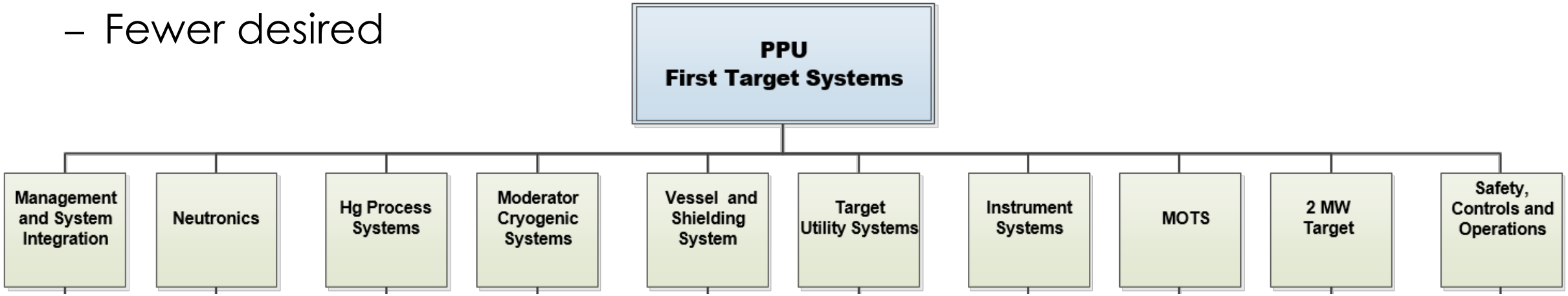
Target systems:
- **2 MW target module**
- **Supporting systems upgrades**
- **Target station evaluations**



Ring:
Injection / extraction regions

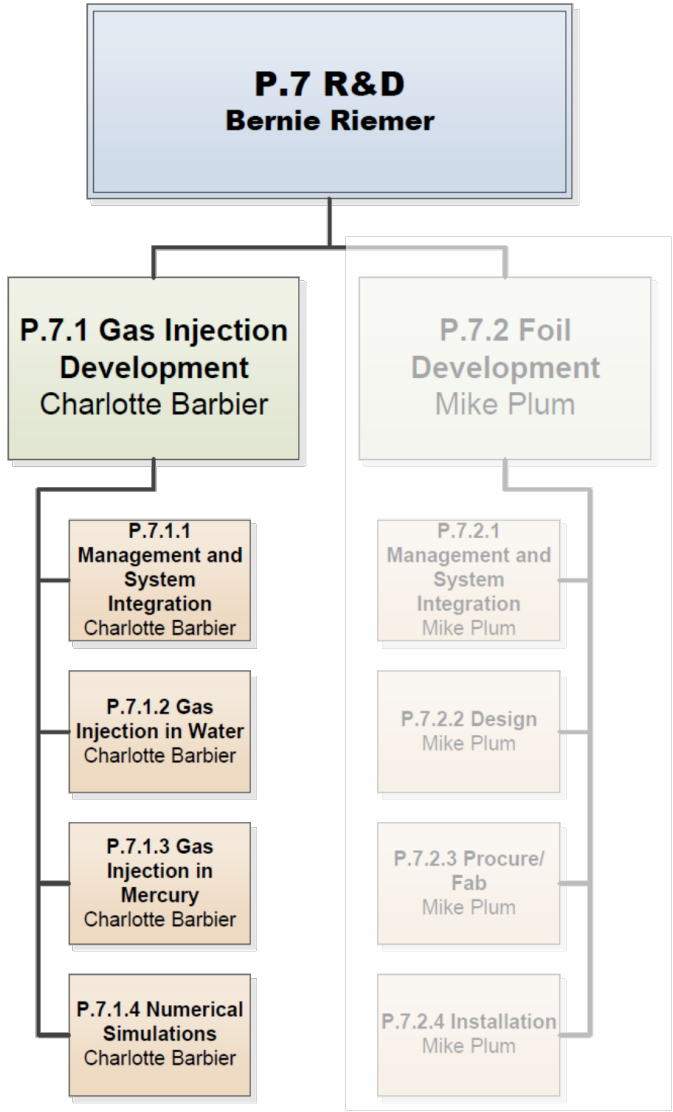
PPU FTS Systems scope is more than the target

- Requirement is to assure reliable operation of the First Target Station at 1.3 GeV, for at least 2.0 MW, at 60 Hz
- FTS lifetime extended to 60 years
- Target consumption rate of no more than 4 per year
  - 1,250 hours per target
  - Fewer desired



PPU R&D for target gas injection

- PPU gas injection R&D is addressing:
  - Swirl bubbler design & performance
    - Technology from J-PARC
  - Bubbler gas rate
  - Gas wall design & gas rate
  - Gas hold-up characterization in mercury loop
  - Gas gas-liquid separator design
- A combination of experiments and simulations is being employed
- Up to 20 SLPM for target gas injection



Record power levels and improved reliability at the SNS Upgrades are underway

- No target leaks have occurred at the SNS since early 2016
- Steady operation at 1.4 MW has started
- Target gas injection is now routine operation
  - Significant pulse strain reductions achieved
  - Cavitation damage is significantly reduced
  - Increasing gas injection is planned
- Water leaks inside the core vessel posed operational difficulties but were successfully managed
- First replacement of the inner reflector plug was completed
- The Proton Power Upgrade project will enable operation of two target stations and send 2 MW to the mercury target