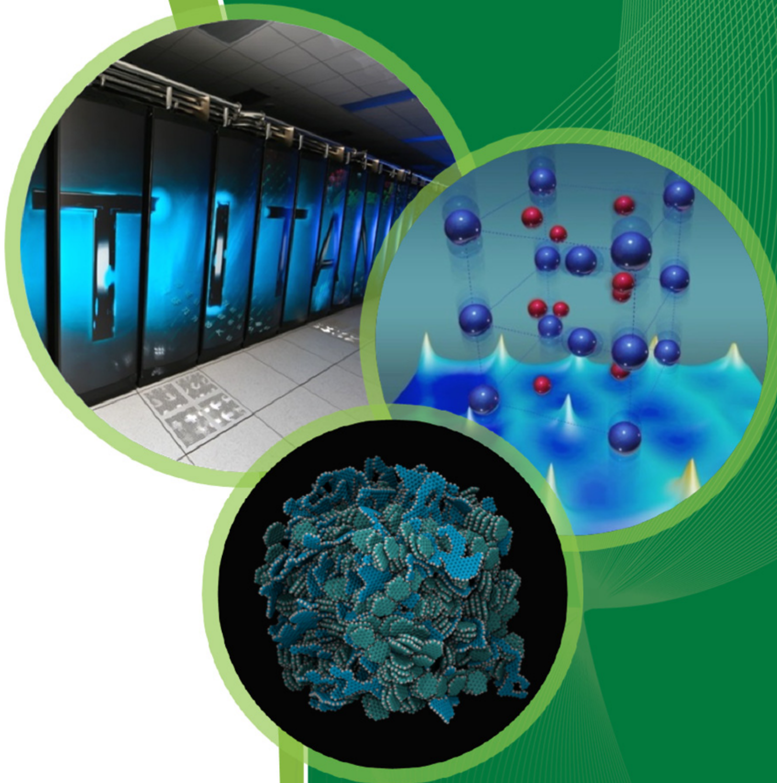
SNS Commissioning and Operations, the first 10 Years.

An overview of the components status after high intensity beam running experience



George Dodson
Deputy Division Director
Research Accelerator Division
Spallation Neutron Source

High Brightness 2016

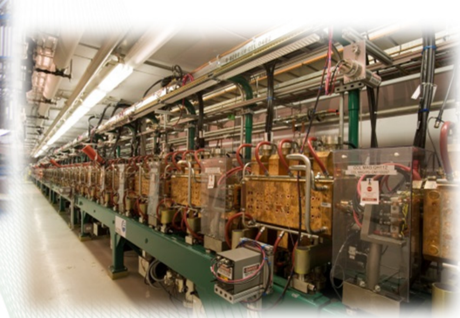
ORNL is managed by UT-Battelle
for the US Department of Energy

Introduction

- The SNS Construction Project produced a first of a kind facility and achieved CD-4 ten years ago in April 2006.
- Since then we have made considerable investments to improve availability and beam power on target, and now routinely achieve accelerator performance expectations:
  - >4000 user hours per year
  - >90% accelerator availability against schedule
  - Operation at 1.3 - 1.4 MW beam power on target
- The suite of instruments has expanded from three at CD-4 to 19, and the scientific productivity and impact is steadily increasing.
- These accomplishments have enabled sponsor and user support for the Proton Power and Second Target Station upgrades now underway.

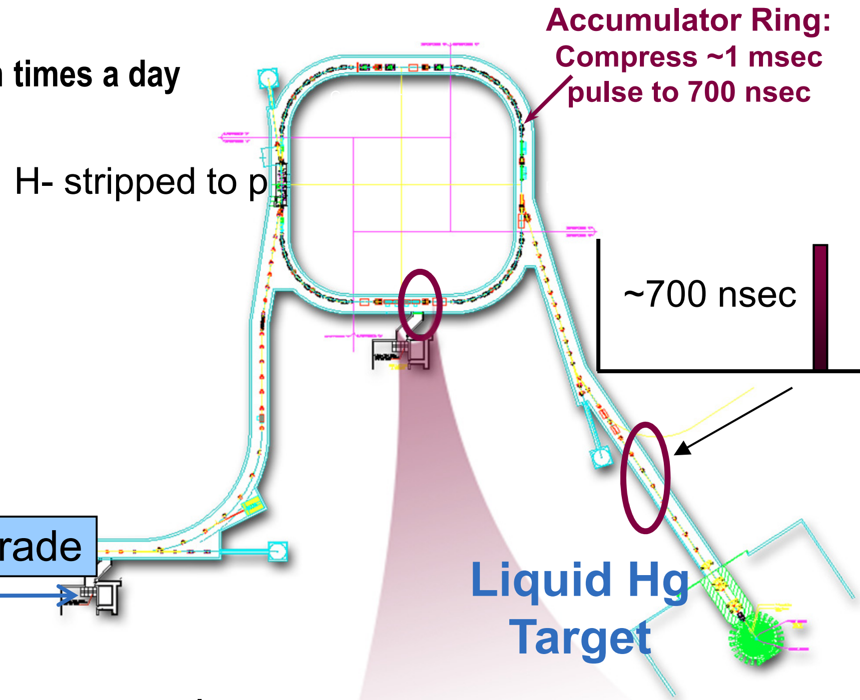
The SNS: The world's most intense pulsed neutron beams for scientific research

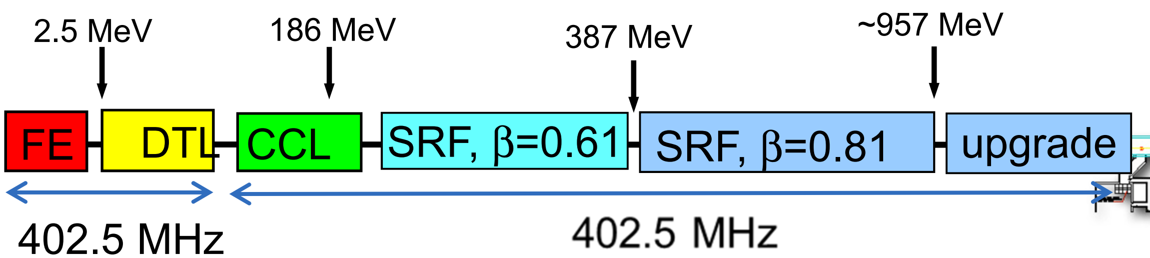
- Designed for 1.4 MW proton beam power at 60 Hz; constructed for 1 MW proton beam power
- Constructed from 1998 to 2006
- First beam on target on April 28, 2006
- First neutrons for science FY 2007
- Achieved 1 MW capability in 2009;
  1.4 MW demonstration in 2014
- Annually schedule 5,000 hours of user operation
- 18 neutron scattering instruments in the User Program, and 1 beam line for fundamental nuclear physics
- Designed to accommodate upgrades for capability and capacity (accelerator and second target station)

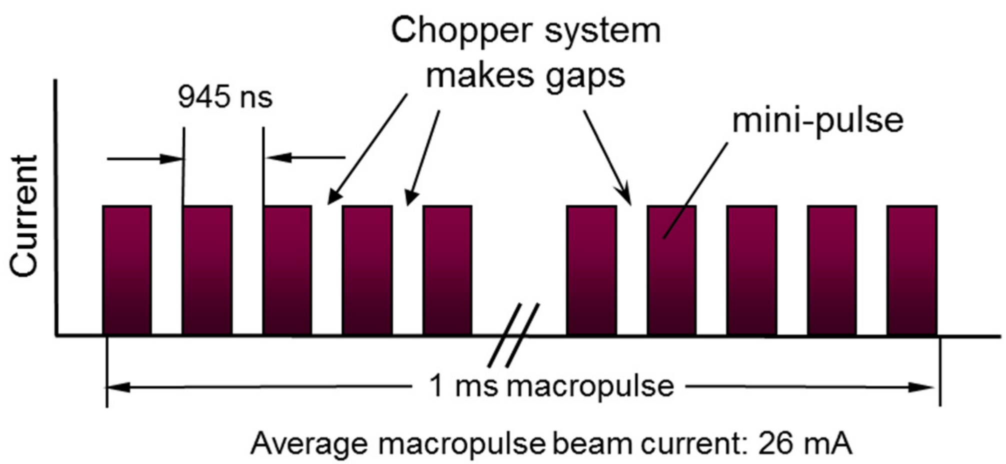


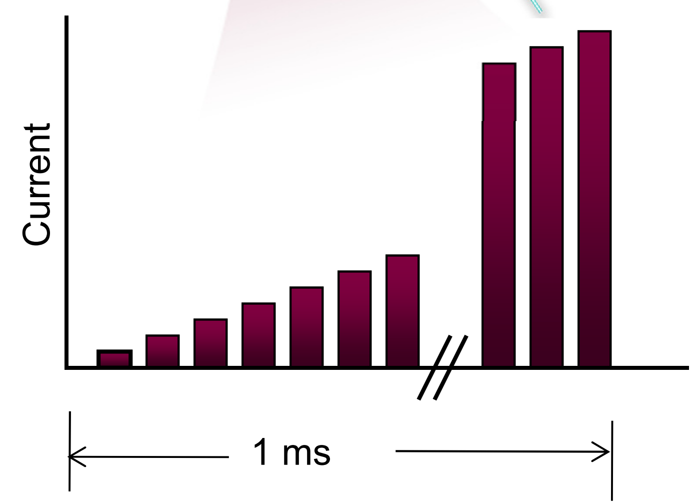
The SNS accelerator provides the world's most powerful pulsed proton beam to enable neutron science

- The machine has over 100,000 control points and cycles ~5.2 million times a day
- Power (and base neutron flux) is the product of:
  - Beam Energy 957 MeV
  - Peak Current 36mA
  - Chopping Fraction .81% (52/64)
  - Pulse Length 975 μSec
  - Repetition Rate 60 Hz







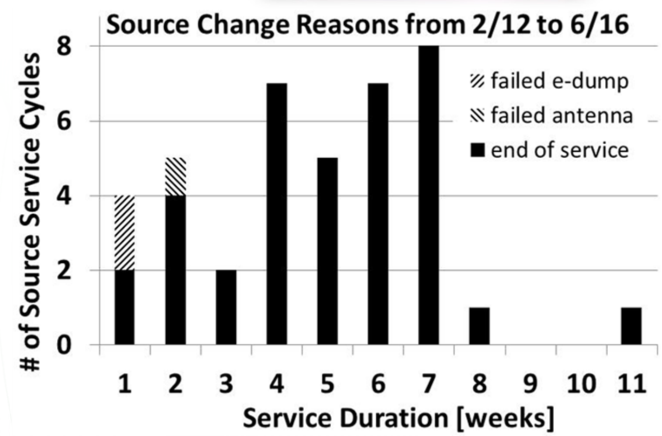


The SNS accelerator, accumulator and transport systems perform very well relative to design requirements

Machine Parameter	Design	Best Ever	Routine Operation
Kinetic Energy [GeV]	1.0	1.07	0.957
Beam Power [MW]	1.4	1.427	0.85-1.40
Linac Beam Duty Factor [%]	6	6	5
Modulator/RF Duty Factor [%]	8	8	7
Peak Linac Current [mA]	38	42	36
Average Linac Current [mA]	1.6	1.6	1.1-1.49
Linac pulse length [msec]	1.0	0.98	0.975
Repetition Rate [Hz]	60	60	60
SRF Cavities	81	80	79-80
Ring Accumulation Turns	1060	1020	1008
Peak Ring Current [A]	25	26	14.5-25.8
Ring Bunch Intensity	1.5×10^{14}	1.74×10^{14}	$0.87-1.5 \times 10^{14}$
Ring Space Charge Tune Spread	0.15	0.14	0.09-0.16

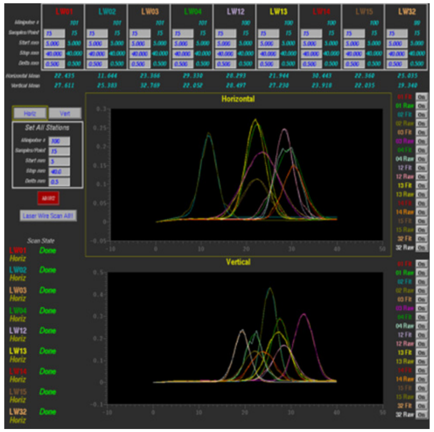
The SNS: A neutron source built with many technological "Firsts" followed by a process of Continuous Improvement

- First (and only) MW-class superconducting Proton Linear Accelerator and Proton Accumulator Ring
- First persistent, high-intensity, long-life, high duty factor negative hydrogen ion source
  - Before 2011, 12 of16 antennas failed in service.
    - Improved manufacturing and inspections all but eliminated antenna failures(90% rejection rate!)
  - In 2006 ion sources had a very short lifetime, Since 2011 ≥6 service weeks became customary:
    - 40 production sources have been replaced
      - 37 at the end of their service cycle
      - 2 prematurely after e-dump failed
      - 1 prematurely after antenna failed
  - Operated through mid 2012 with source currents from ~42-46mA.
  - Later, as RFQ transmission degraded, operated with ~45-55 mA. At the end of 2015, operated at ~60mA
  - **Only 2 sources were used in run 2016-1 (16 weeks), delivering 5.5 and 4.1 Amp-hours respectively**

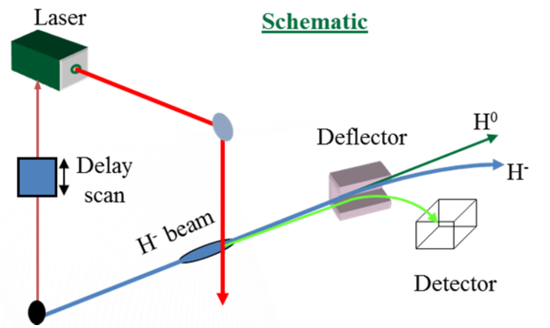


First deployment of laser-based beam diagnostics

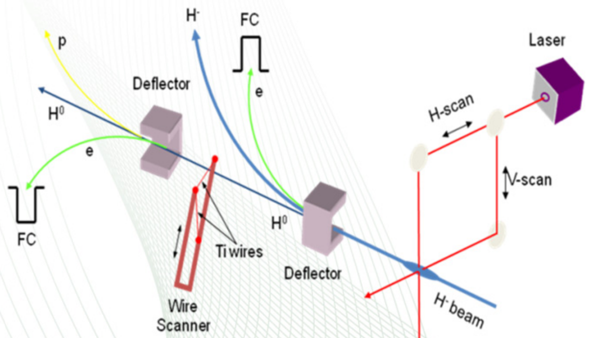
- Laser Profile Monitors at 9 locations in SCL simultaneously, at high beam power
  - Q-Switched Nd:YAG, 7nS pulses
  - Laser strips e, Magnet-Faraday cup detector
  - 10^2 dynamic range and 10ns temporal resolution



- MEBT Longitudinal Profile
  - Ti-Sapphire Mode-Locked to accelerator 80.5MHz. 5'th subharmonic of RF to suppress background
  - Laser strips electron, collected by a Fast Scintillator/PMT
  - 10^2 dynamic range and 10ps temporal resolution expected

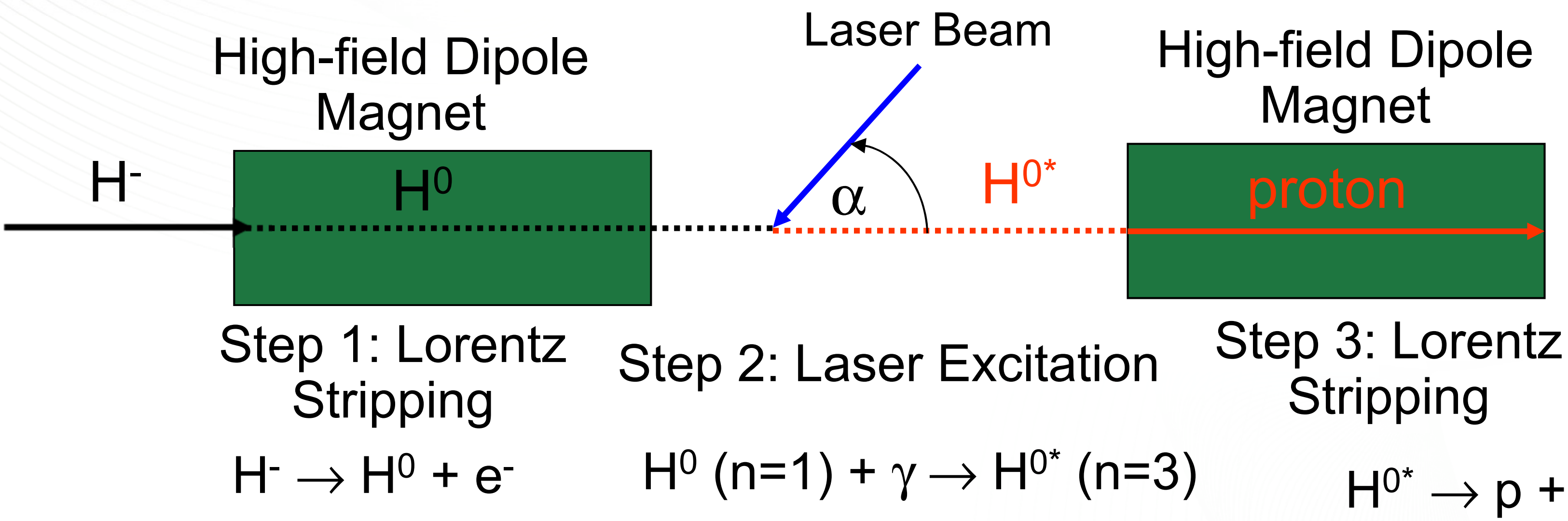


- HEBT Laser Emittance Scanner
  - Laser scan strips narrow channel of H^- beam into H^0 beam
  - Titanium wire scanner measures divergence of the H^0 beam released from laser slit
  - Measurement is nonintrusive
  - 10^3 dynamic range and 10ns temporal resolution

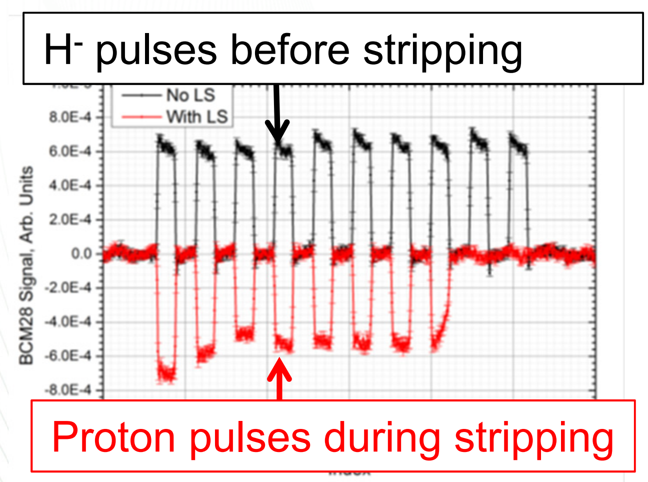


First Tests of Laser-Assisted Ion Stripping

Novel laser based approach of “foil-less” stripping for charge-exchange injection in high intensity proton facilities using a three-step method employing a narrowband laser beam

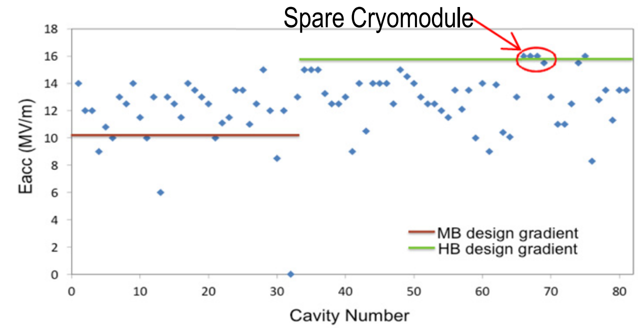


Parameter	Delivered
Remote Station Laser Parameters	
Macropulse length	10 us
Micropulse width	30 – 50 ps (adjustable)
Maximum Peak Power	1.7 MW (limit to 1 MW for experiment)
Pointing stability at IP	±0.10 mm (H) ×±0.11 mm (V)
Horizontal divergence at IP	2.6 mrad
Vertical size at IP	1.1 mm



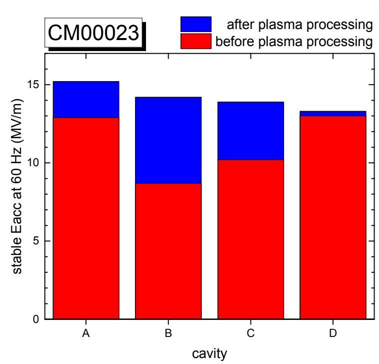
First Deployment of In-Situ Plasma Processing, which will enable higher proton beam energy

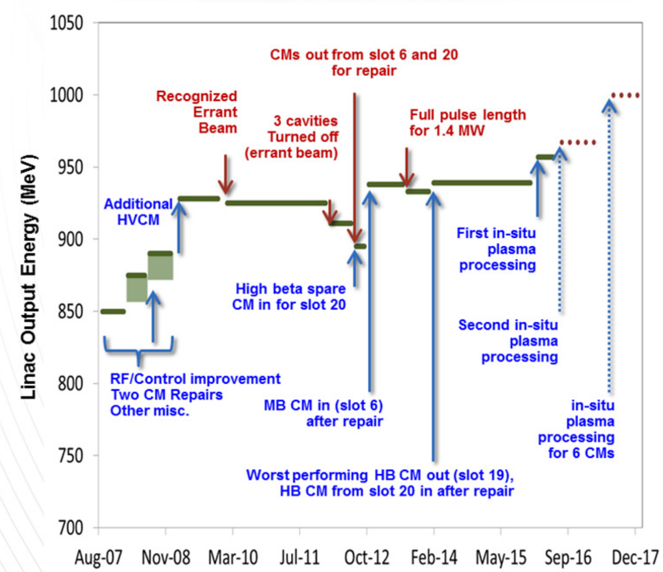
- SNS high-beta superconducting cavities did not performed to design specification, even following installation
  - Performance limited by field emission due to surface contamination
  - Spare cryomodule manufactured at SNS meets specification
- Conducted a R&D program to characterize the surface performance, developed techniques to remove contaminants without taking the cryomodule out of the tunnel
- First deployment in January 2016 – excellent results; will continue to process the rest of the cavities in subsequent outages



SNS Superconducting Cavity Field Gradients 03/2015

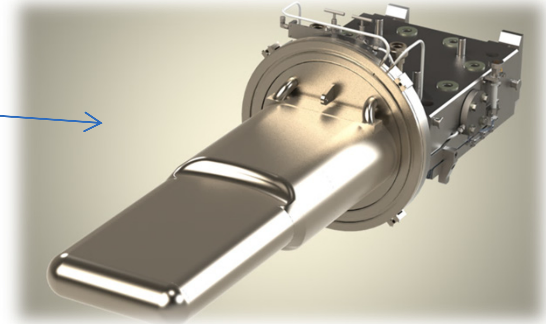
Average Improvement in accelerating gradient of ~25% resulting in beam energy increase of ~11 MeV



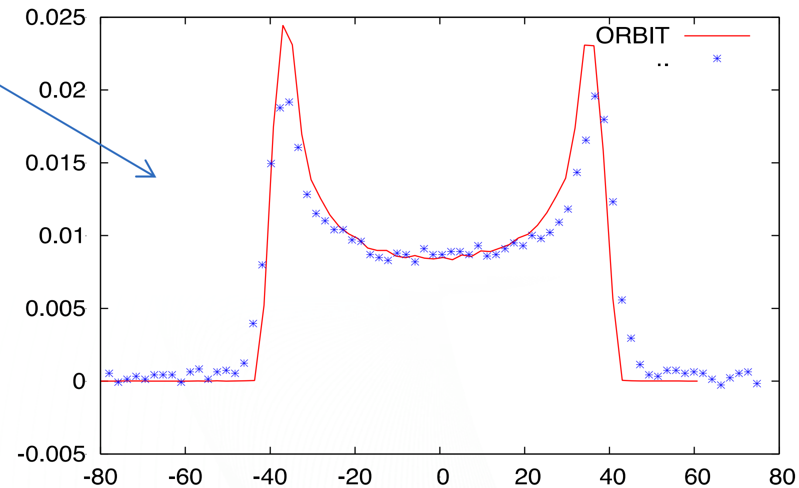


- Goal is to achieve 1 GeV by the end of CY2017

- First use of liquid mercury target to produce high-intensity pulsed spallation neutrons at a user facility



- The development and deployment of the Open XAL suite of tools and the PyOrbit code for on-line accelerator modeling



ORBIT – Measured Profile

- The highest ever beam power to a neutron production target by any accelerator complex 1.427MW

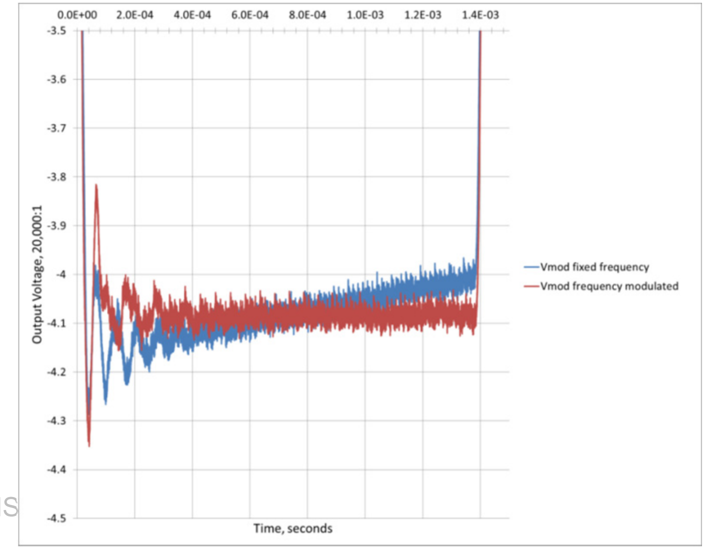
- The highest intensity proton ring on a charge per pulse basis 1.74×10^{14} ppp (27.9μC)

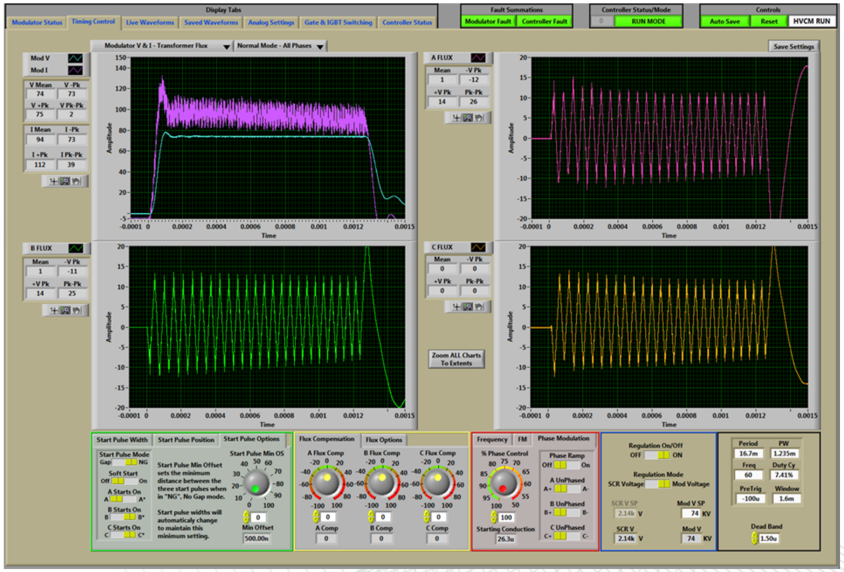
Ring Simulations - Collective Effects:

First large-scale application of new solid-state pulsed high-voltage technology (High Voltage Converter Modulators

- The HVCM did not meet reliability expectations during the ramp up to 1 MW
- Numerous components improved via design changes and selection of alternate vendors
  - Gate drivers, snubbers, capacitors, transformers
- New controller enables pulse flattening, diagnostics, and obsolescence mitigation
- Provides additional RF power margin and reduces wear and tear on klystrons
- Achieved high reliability performance has made this this technology attractive to other accelerator projects
- Development of alternative topology HVCM and

HIGH VOLTAGE CONVERTER MODULATOR



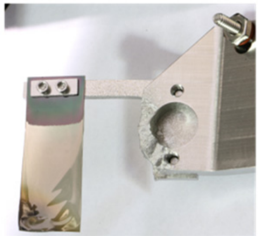


Stripping Foil development capabilities and improvements support operation at 1.4 MW

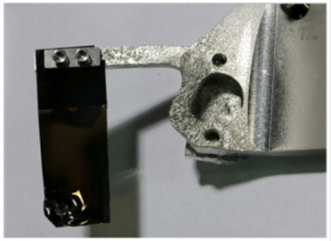
- Lifetime of stripping foils was a concern as the proton beam power increased beyond 1 MW
- Standard corrugated nano-crystalline diamond foils work at 1.4 MW
- Foil holder problems solved
- Foil fabrication has been a successful collaborative effort between the Neutron Sciences and ORNL Physical Sciences directorates

Ti vs TZM bracket comparison

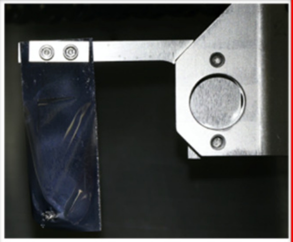
Photos by C. Luck



#BW-18,
~24 days at ~1.2 MW



#1872,
3 months at 1.1 to 1.4 MW.



#2199, TZM bracket,
~16 days at 1.4 MW

All brackets and mounts are Ti except this one

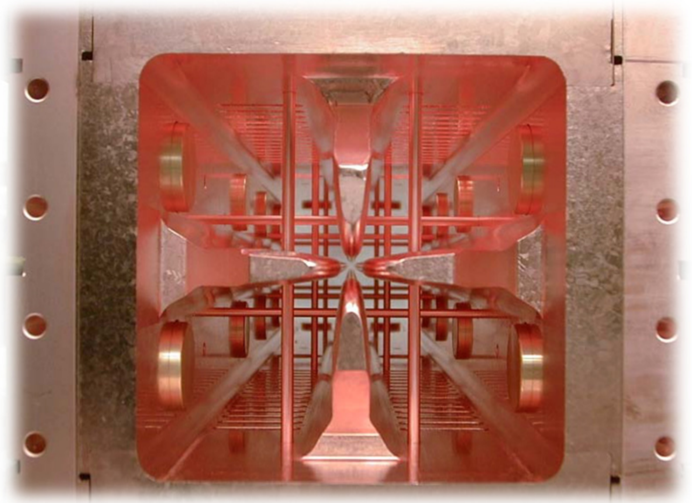
- New TZM bracket tested Nov. – Dec. 2015
  - Almost zero damage at full 1.4 MW beam power
- Advantages: high sublimation temperature, low sputtering yield, high sputtering threshold
- Disadvantages: Heavy, long-lived radio-activation
- Tested three more TZM brackets during Feb – May 2016 run

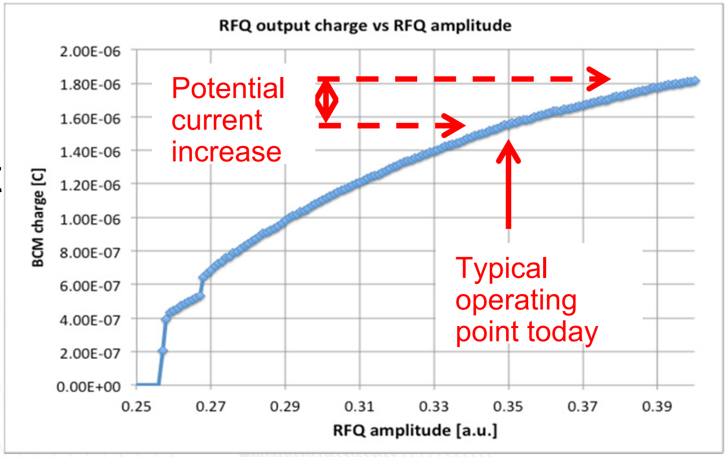
SNS diamond stripper foil production begins at CNMS using new CVD tool

- Replaces capability being decommissioned in Building 4100
- Permits close on-site collaboration for novel foil development
- New commercial hardware with excellent outcomes

New Radio-Frequency Quadrupole to be tested at the Beam Test Facility before installation

- The installed Radio-Frequency Quadrupole (RFQ) that accelerates the beam from 0.065 MeV to 2.5 MeV has suffered three detuning events during its approximately 12-year service life
- In 2012 the RFQ transmission began to drop. It has reduced by about 15% from its previous values, which directly translates into beam lost in the RFQ and lower available beam power
- Possible single point failure mode for the facility
- Vulnerability addressed through the of a spare unit of different mechanical design but equivalent physics design
- Essential to demonstrate proper beam performance before considering installation. We have built a test facility with an ion source, LEBT, and ability to measure accelerated beam. After the RFQ swap the Beam Test Facility will be used for accelerator R&D.

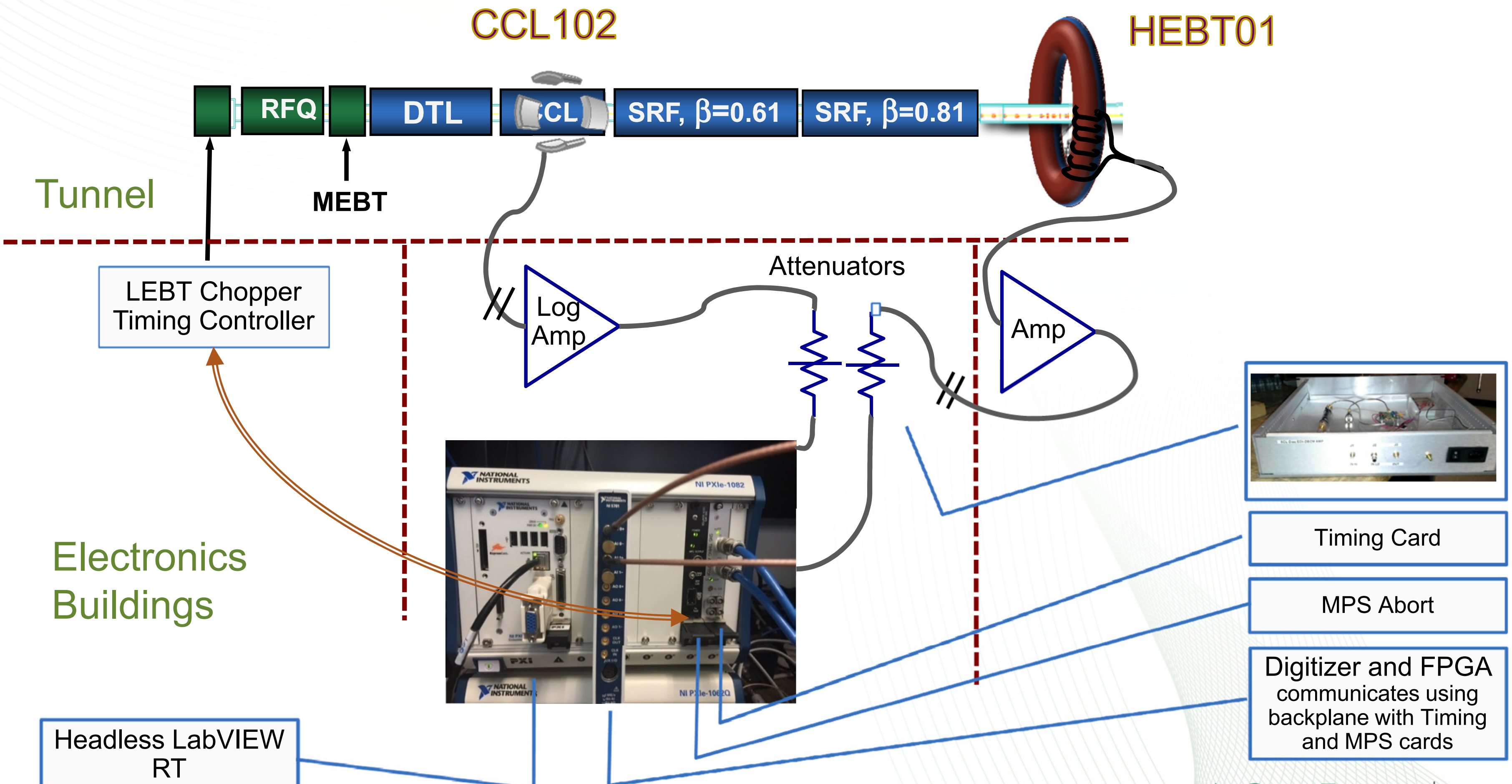




Courtesy A. Shishlo
Oct. 27, 2015

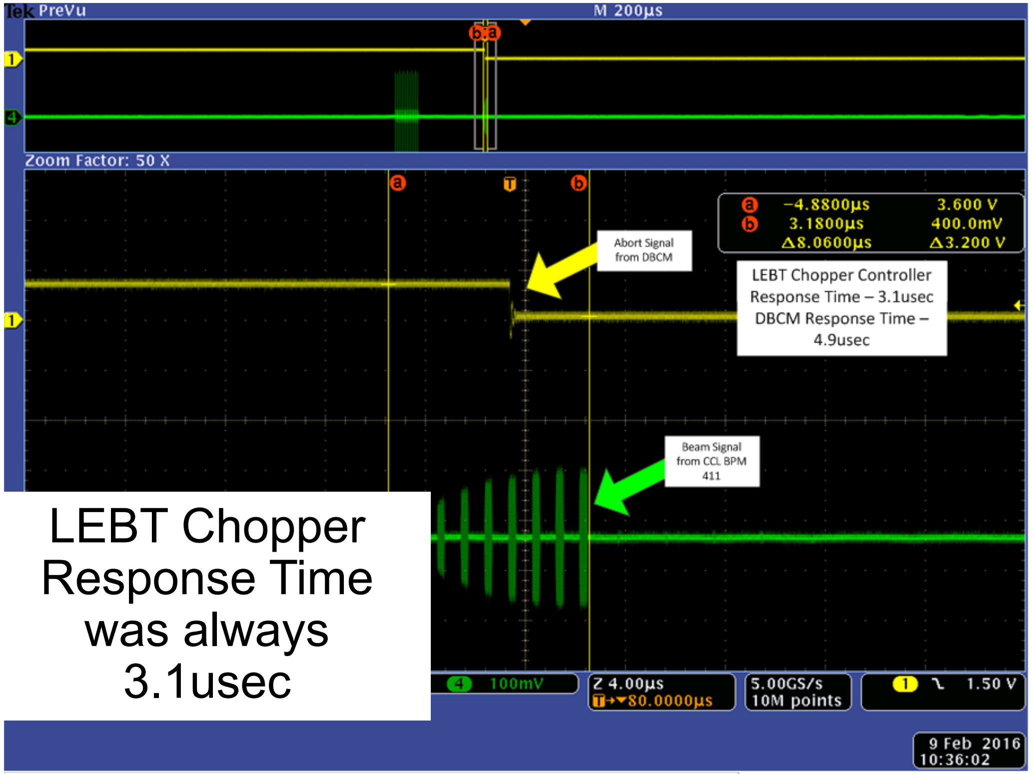
Protect the SCL from Beam Loss Events, the DBCM System

System compares beam in the CCL with beam in the HEBT, differences cause a direct abort signal to be sent on fiber cable to the LEBT Chopper in the Front-End

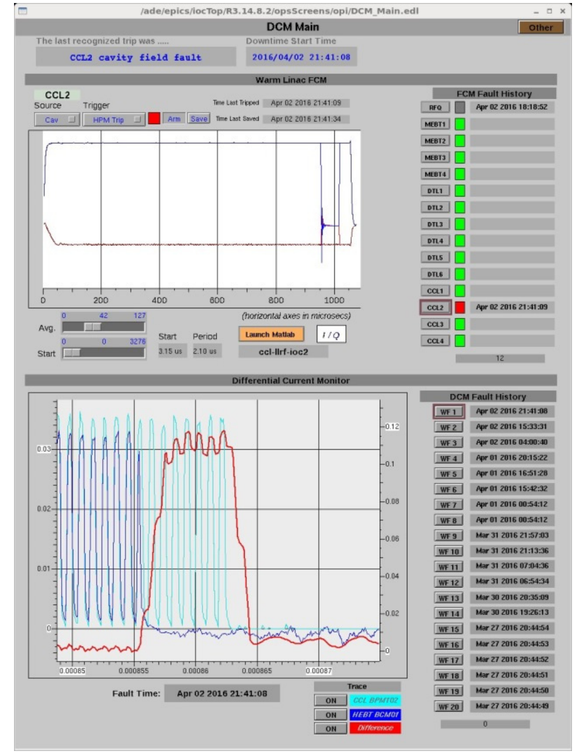


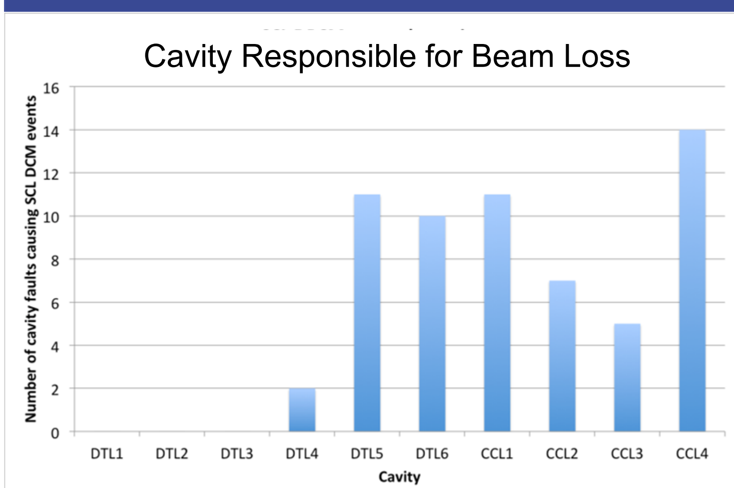
Layout of Differential Beam Current Monitor

DBCM to LEBT Chopper Controller Results



LEBT Chopper Response Time was always 3.1usec



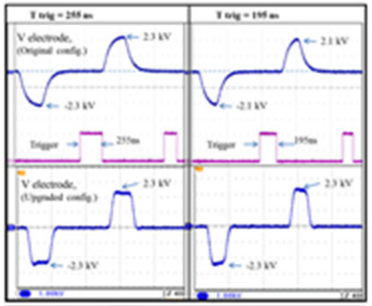


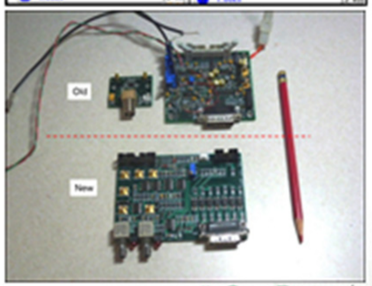
- EDM page shows
  - which cavity faulted
  - time of cavity fault
  - ability to save RF waveforms
  - last 20 DBCM waveforms
  - timestamp for each waveform
- Additional controls for setting thresholds for interlock
- Over ~1 Month:
  - 21 out of 108 aborts are not yet assigned (AP studies, Noise)
- Average Total Shutoff Time down to 8 µsec, previously 16-20 for BLM System

Improvements in the beam chopping system have increased our power margin for operation at 1.4 MW and promise future gains through "smart chopping"

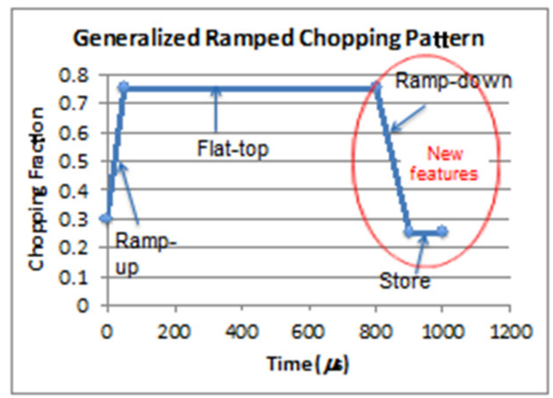
LEBT Chopper Pulser Issues and Development

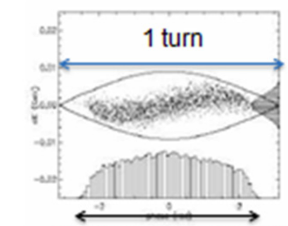
- Better reliability since FY12 due to improved Gate Drive design which limited failure caused by arcs in LEBT structure
- Optical isolation of triggers eliminates recent hot swap failures of input trigger receiver
- Reduced rise/fall times allowed minimum pulse widths to be reduced from 255 ns to 165 ns
- Smaller gaps in the Ring equals higher chopping fraction
- Pulse width reduction is limited to 195 ns by E-Kicker jitter causing losses during extraction



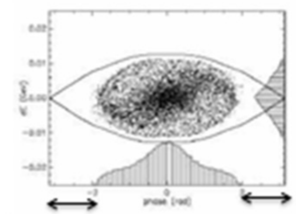


Smart chopping





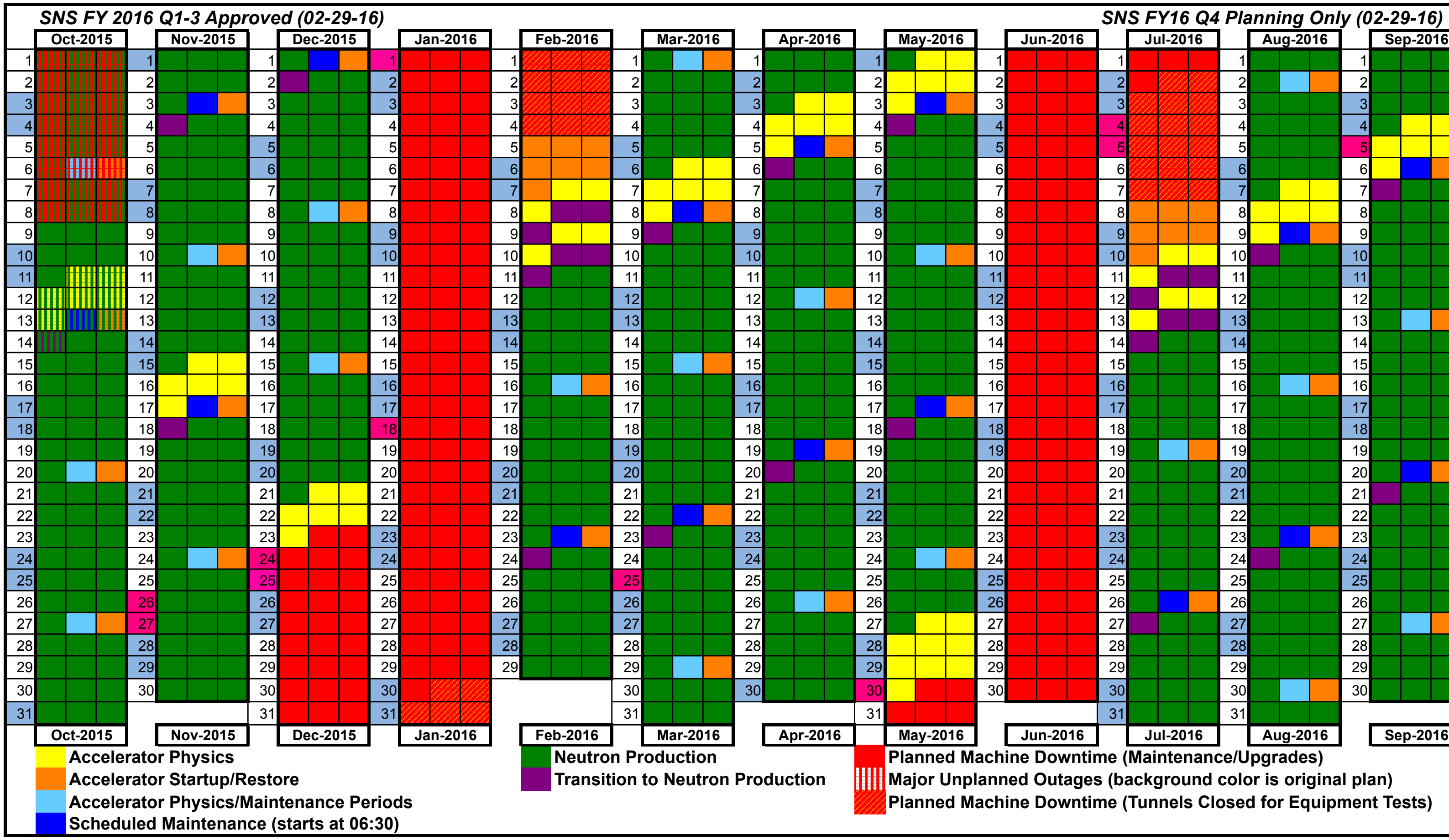
Relatively large un-chopped flattop most of injection



Longitudinal "tricks" to recover big gap at extraction time

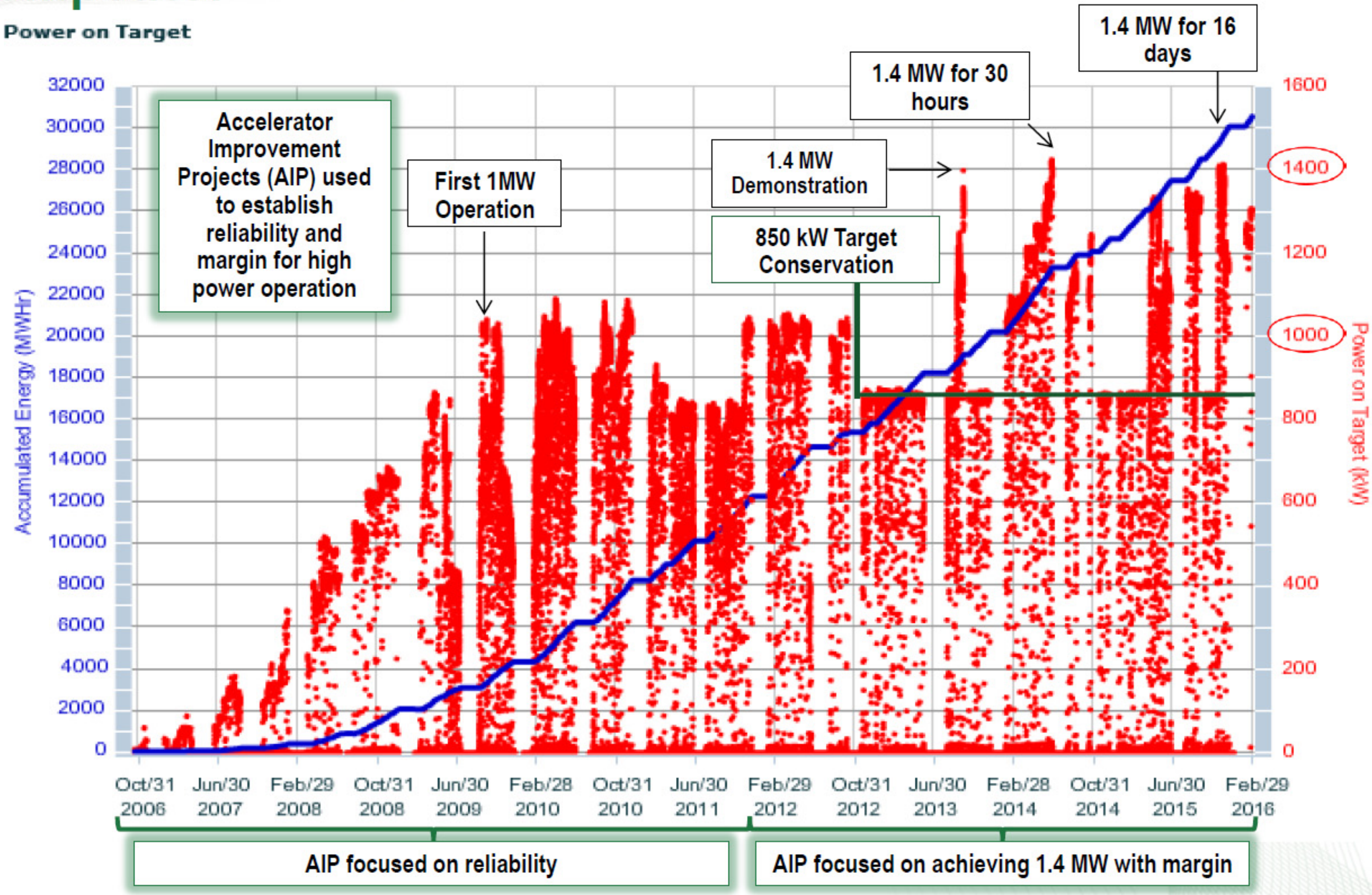
- 10% increase in "average un-chopped" fraction may be possible

In recent years the schedule has two outages each year for major maintenance and has been sufficiently flexible to accommodate much of the unplanned major downtime

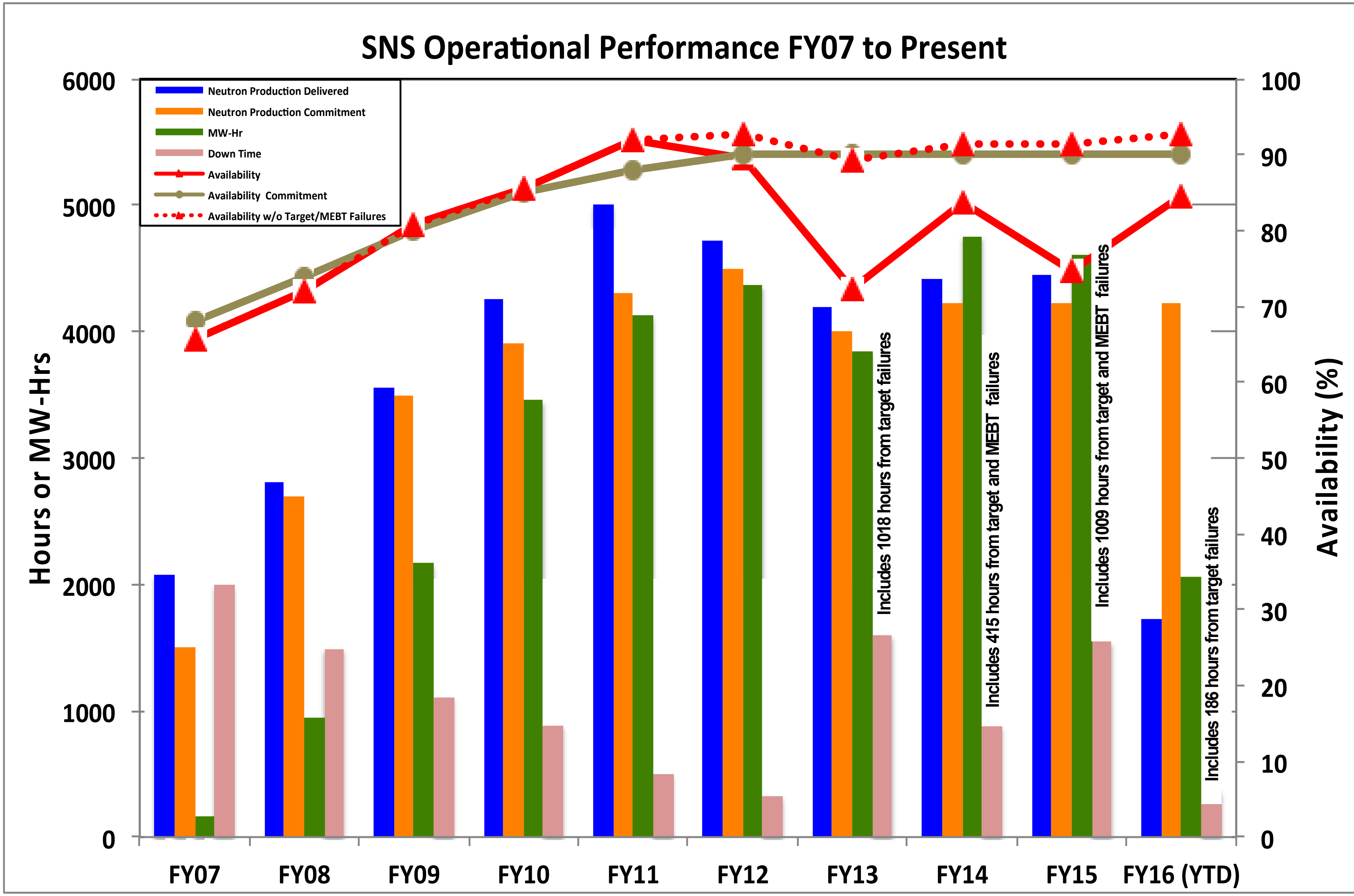


- Definitions:
  - Predictability: Is the facility configured for the planned work that day?
  - Availability: How well do we deliver against the plan for that day?

SNS has delivered over 30GW-Hrs to target since 2006 – this is a factor of 6 more than our nearest international competitor

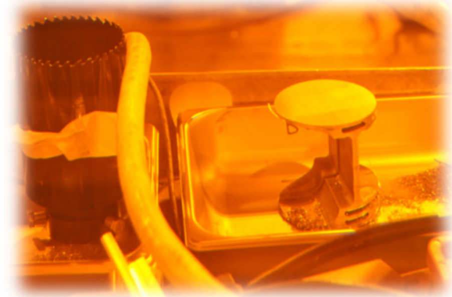


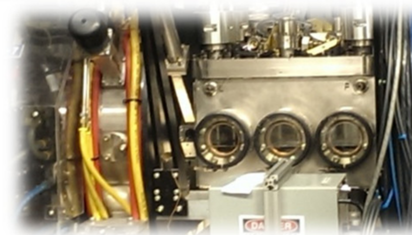
SNS has always exceeded commitments for hours delivered



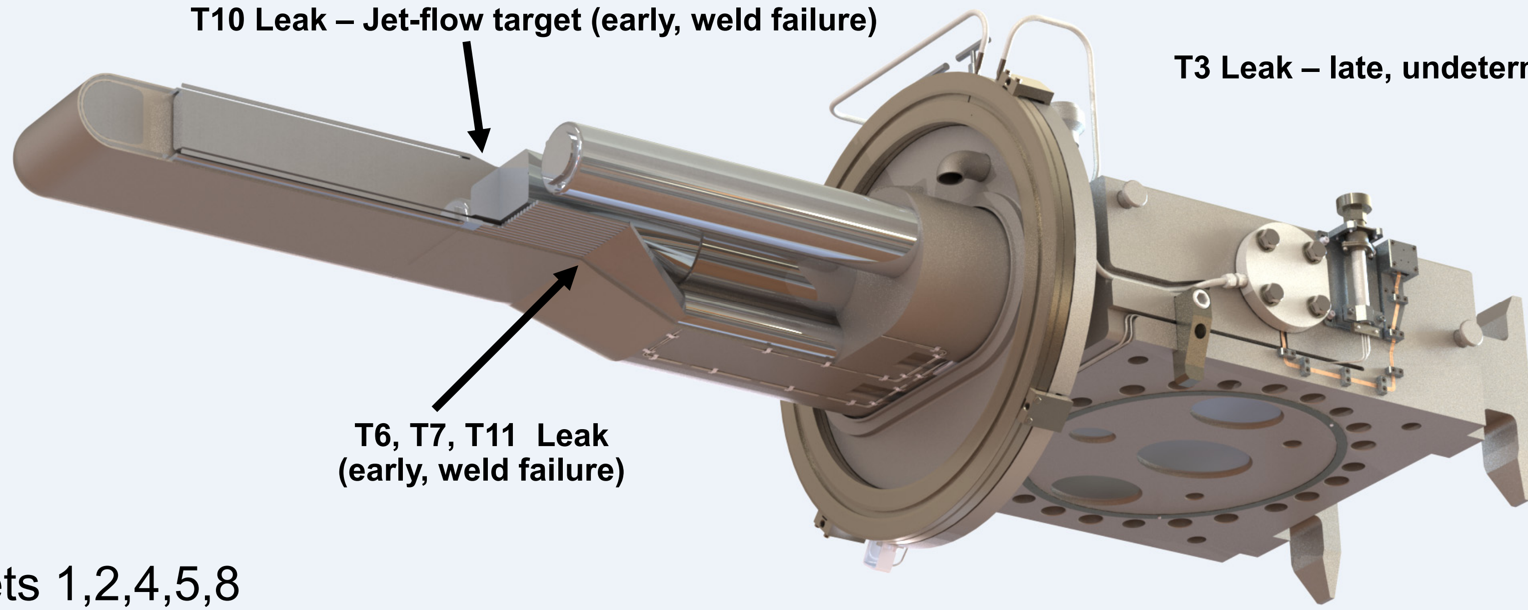
Long unplanned down times can be particularly disruptive to the SNS user program

- Since 2006, the facility has experienced eight major unexpected equipment failures:
  - Seven in-service target end-of-life events
  - One unexpected fracture of the water-cooled chopper scraper in the vacuum envelope of the Medium Energy Beam Transport (MEBT) that filled the vacuum envelope with water
  - One unexpected non-operable condition for the Personnel Protection System (PPS) during certification testing
- The MEBT device was removed to prevent recurrence – it was not needed for normal operation
- Permanent approved modifications have addressed the PPS inoperability condition

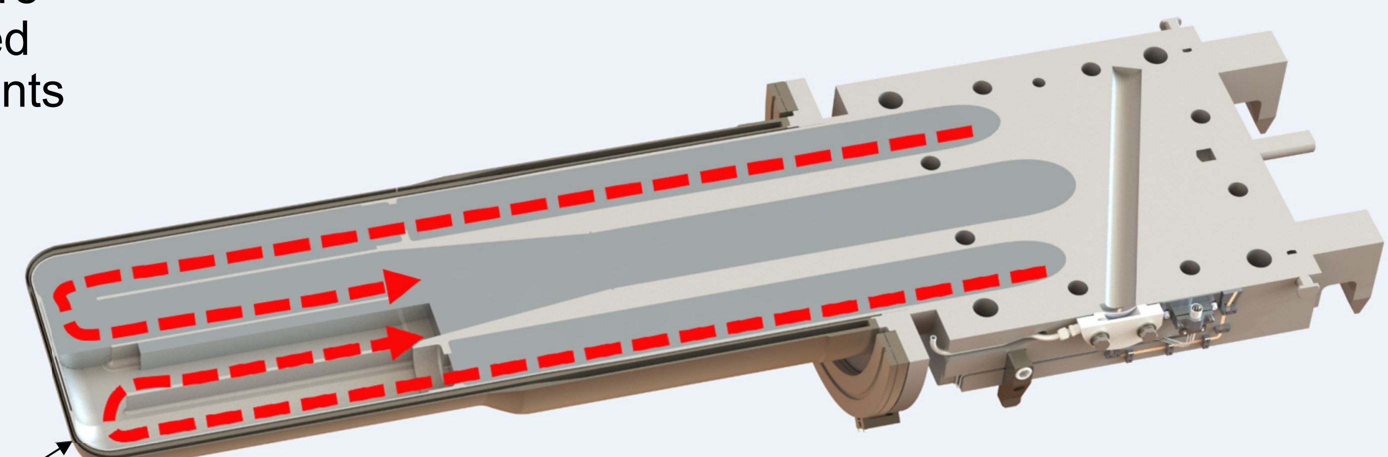




We have identified the leak locations for all but one of the 7 targets that leaked



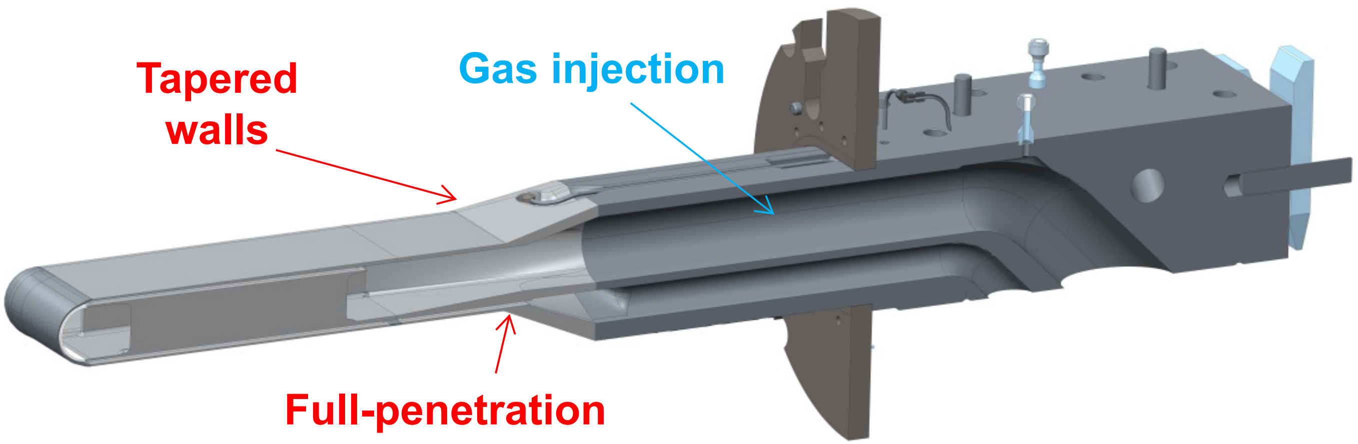
Targets 1,2,4,5,8 and 9 were scheduled replacements



Target Goal: Reliable 1.4-MW Operation

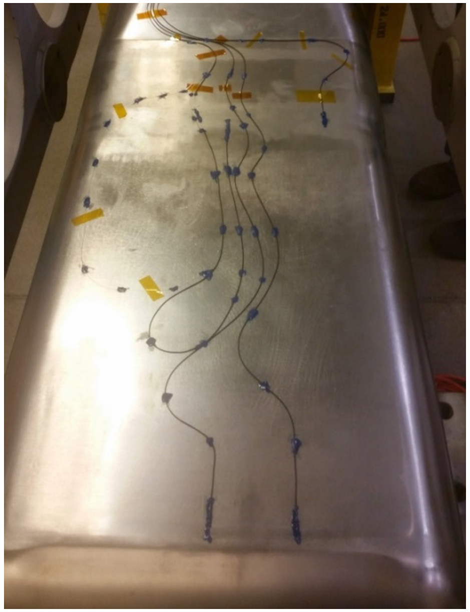
No more than two predictable target change-outs per year

- Multiple failure modes interact through non-linear relationships
  - High-cycle fatigue (~$5.2X10^6$ pulses/day)
  - Corrosive/erosive actions of mercury
  - Beam-induced cavitation
- Re-Design of Targets and Fabrication Improvements

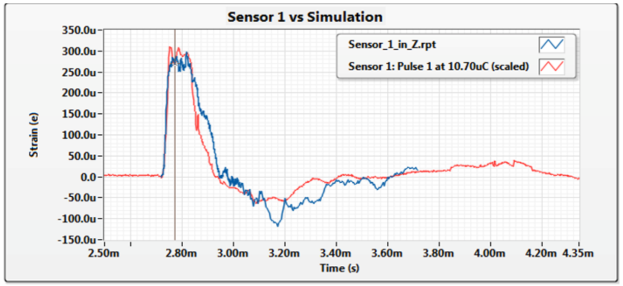


Target Developments

Eight strain sensors on the target vessel



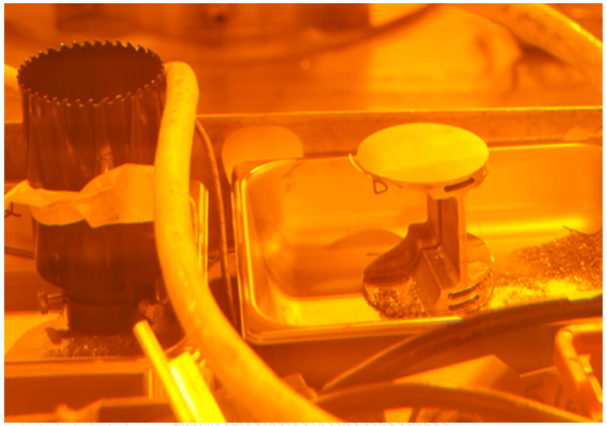
- In situ strain measurements



- Improvements in Post-Irradiation Examination

High resolution photographs of Target 12 coupon at suspected leak showing erosion damage and pinhole leak location

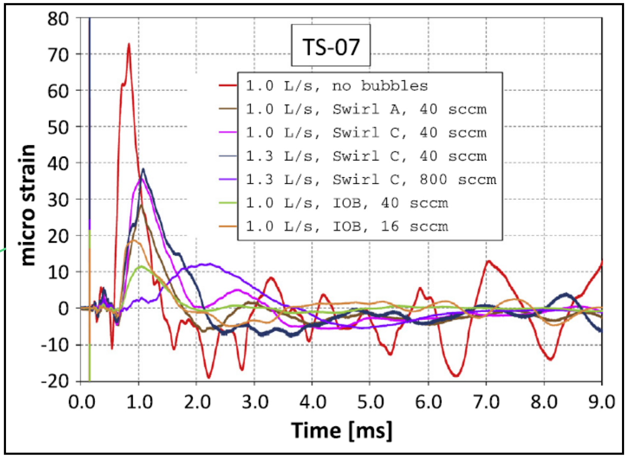
Leak on E-beam weld



Microscopy and metallurgical testing

Evidence for fatigue reduction by Small Gas Bubble Injection LANSCE/WNR and J-PARC

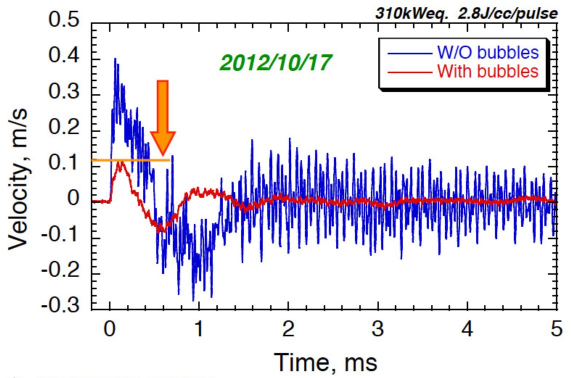
Gas bubbles reduced strain magnitude and cycles



B.W. Riemer et al. / Journal of Nuclear Materials 450 (2014) 192–203

J-PARC

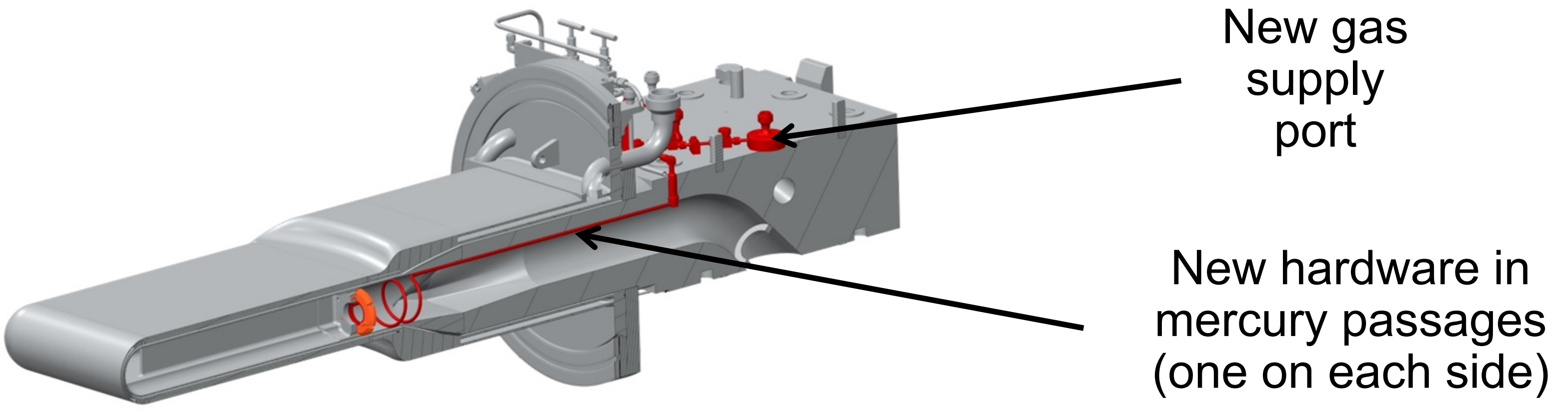
Bubbling effect on vibration



* First peak is reduced
high-frequency components resulting from mirror ringing is reduced by bubble injection

10

Retrofit orifice bubbler assembly installed in jet-flow target – under development



SNS Upgrade is packaged as 2 projects: SNS Proton Power Upgrade and Second Target Station

SNS-PPU upgrades the existing accelerator structure

Increases neutron flux to existing beamlines

Provides a platform for SNS-STS

SNS-STS constructs a second target station with an initial suite of 8 beam lines

Mission need and science case for SNS-PPU and SNS-STS are the same

SNS Proton Power Upgrade and Second Target Station: Our operational improvements ensure a firm technical basis

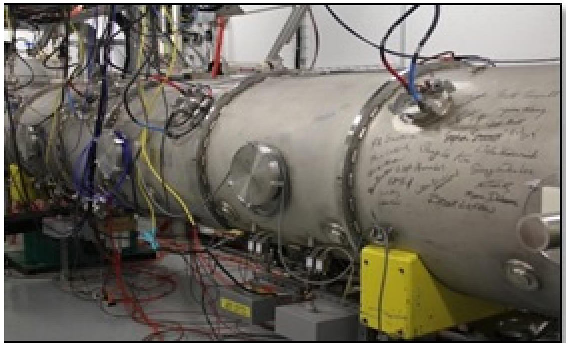
Ion source test stand has led to beam current increases, demonstrating capability required for PPU

Ring damper system is operational, providing insurance against instabilities at higher PPU beam intensities

Spare SRF cryomodule operational since 2012, demonstrating PPU required cavity gradient

Spare RFQ is ready for beam tests and is expected to provide required PPU beam transmission

Plasma processing for in situ cavity gradient recovery, needed to improve poorly performing installed cryomodules, has been demonstrated



SNS-PPU: Path to increased accelerator power

Accelerator power =	Energy ×	Current ×	Pulse length ×	Repetition rate
1.4 MW	0.94 GeV	26 mA	1 ms	60 Hz
2.8 MW	**1.3 GeV**	**38 mA**	1 ms	60 Hz

SRF linac

7 new SRF cryomodules

Associated RF support equipment

→

Copper linac

Upgrade some RF equipment

→

Ring

New injection magnets

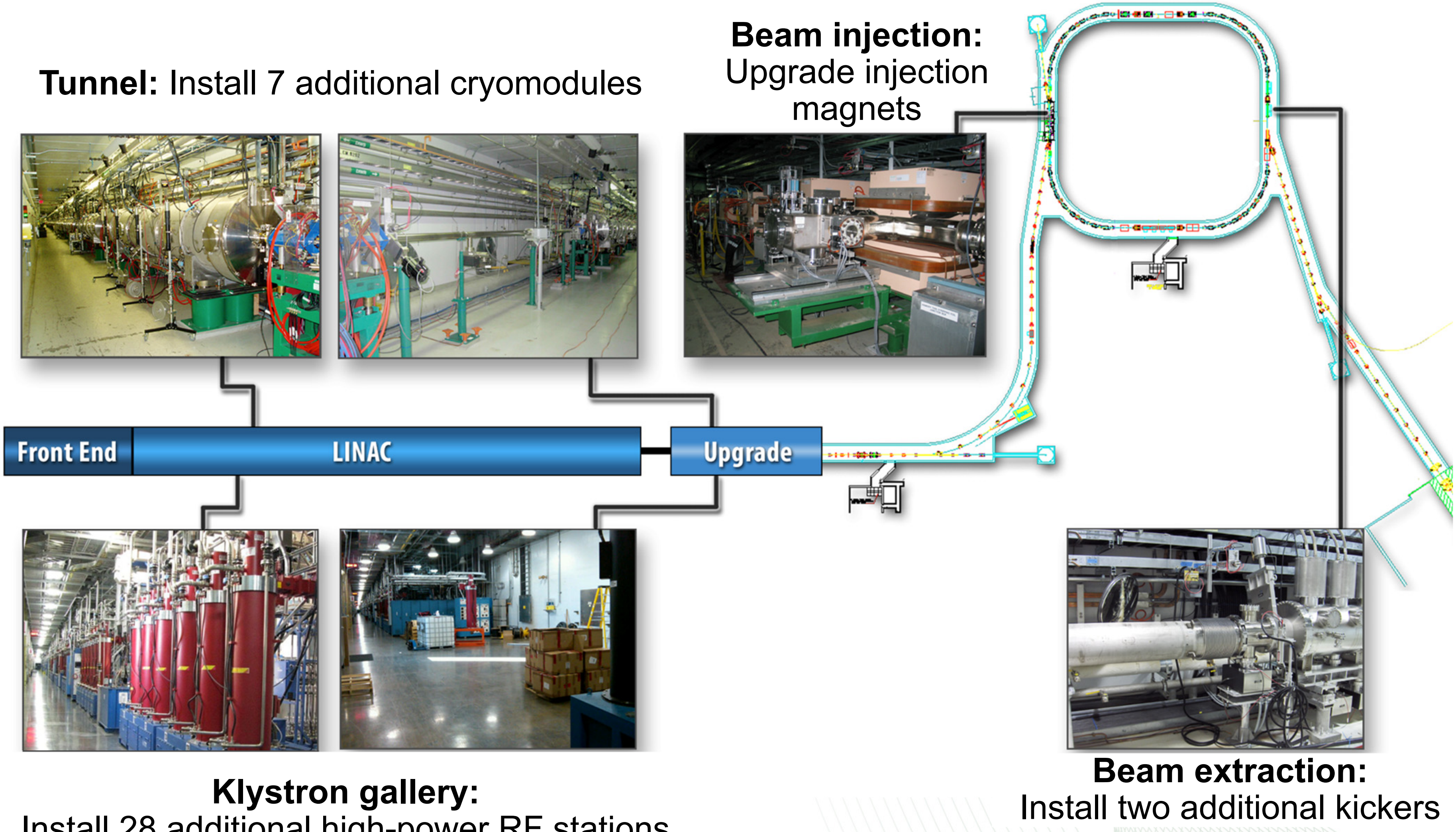
2 new extraction kickers

→

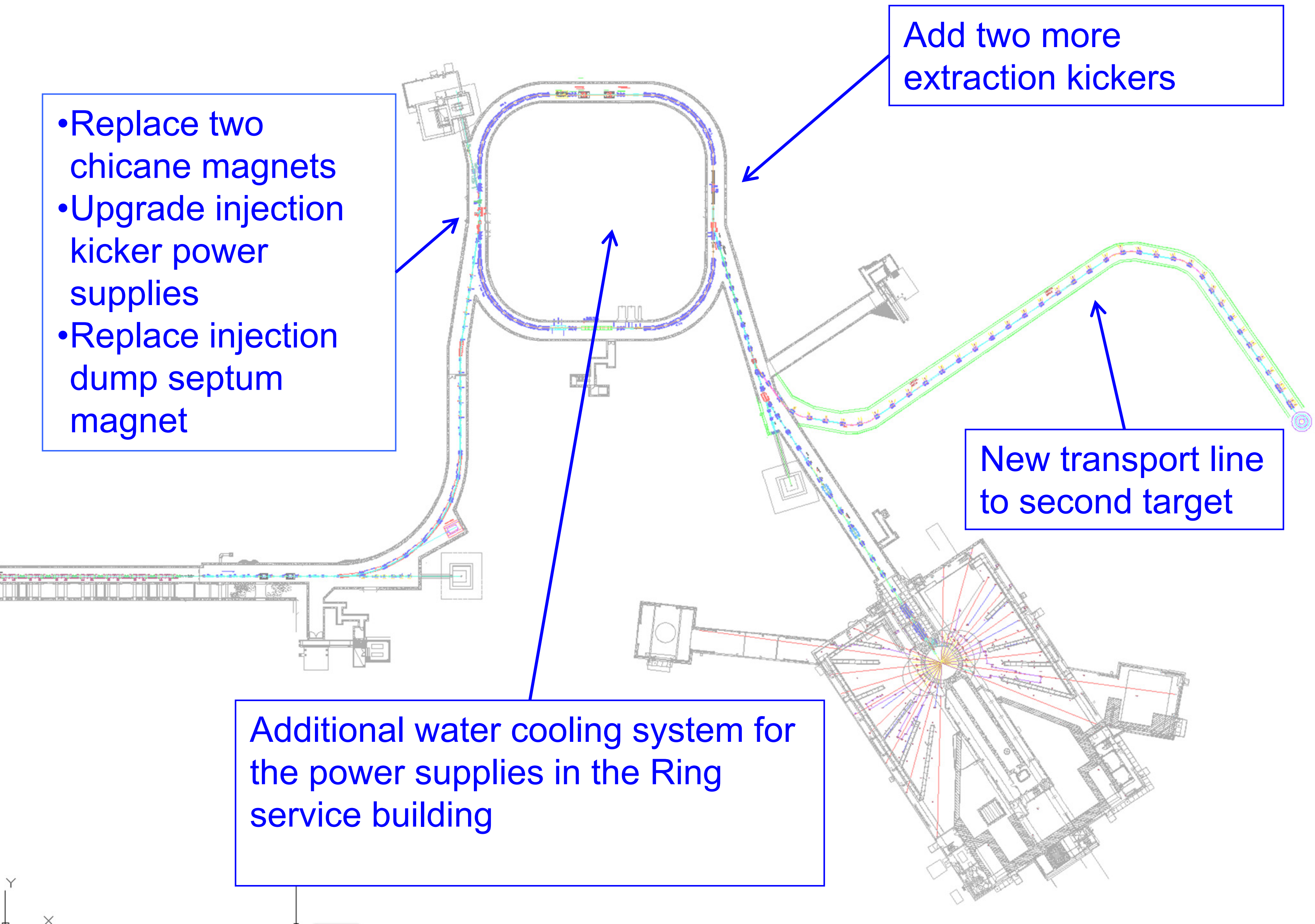
Target

2 MW capable target

Ready to proceed: Accelerator provisions exist for beam energy increase



The PPU + STS Ring Beam Transport



Summary

- The SNS Construction Project achieved CD-4 ten years ago in April 2006.
- Since then we have made, and continue to make, considerable investments to improve availability and beam power on target through a process of continuous improvement. The SNS now routinely achieves accelerator performance expectations:
  - >4000 user hours per year
  - >90% accelerator availability against schedule
  - Operation at ~1.4 MW beam power, limited only by target lifetime
- Working hard on improving the Target to achieve the goal of reliable 1.4-MW Operation with no more than two predictable target change-outs per year
- These accomplishments have enabled sponsor and user support for the Proton Power and Second Target Station upgrades.

Special Thanks

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