Technological Challenges on the Path to ~3.0 MW at the SNS Accelerator

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For the SNS team

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

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Outline

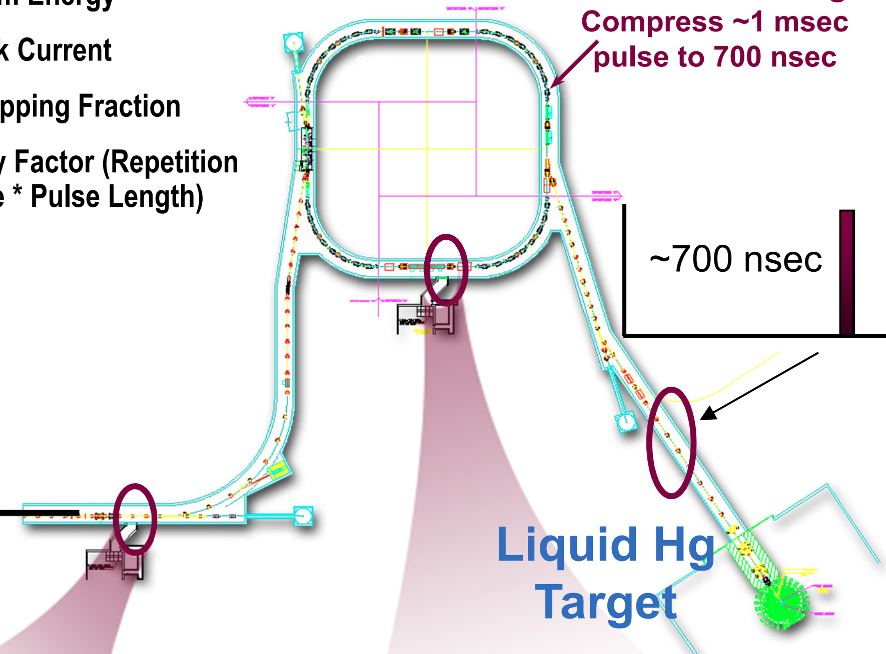
- **What is the SNS?**
- **Current Machine Performance**
- **Second Target Station Capabilities / Proton Power Upgrade**
- **The Path to ~3.0 MW**
  - **Sustainable operation at 1.4 MW**
  - **Ion Source**
  - **RFQ**
  - **Beam Energy**
  - **Ring Injection**
  - **Modulators and RF**
  - **Targets**
  - **Activation**
- **Summary**

The SNS is a ~1 GeV pulsed linac and accumulator ring capable of delivering ~23.3 kJ proton pulses at 60 Hz

- **Power (and base neutron flux) is the product of:**
  - Beam Energy
  - Peak Current
  - Chopping Fraction
  - Duty Factor (Repetition Rate * Pulse Length)

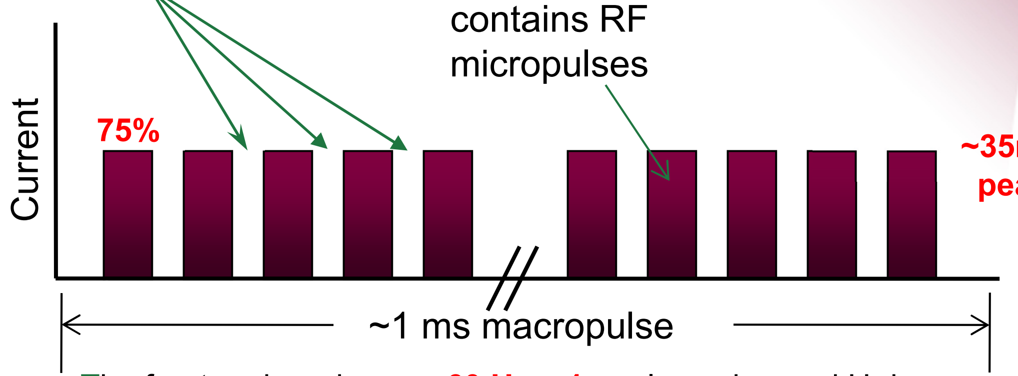
2.5 MeV | 186 MeV | **~972 MeV**

Front-End | Warm Linac | Superconducting LINAC

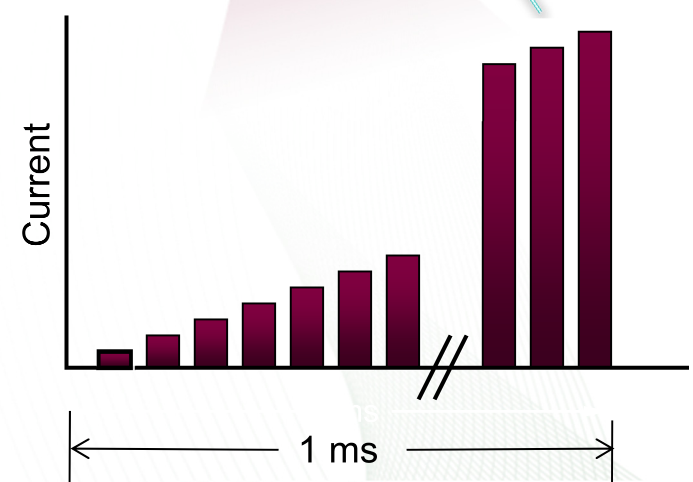


LEBT chopper system makes gaps **(25%)** between minipulses

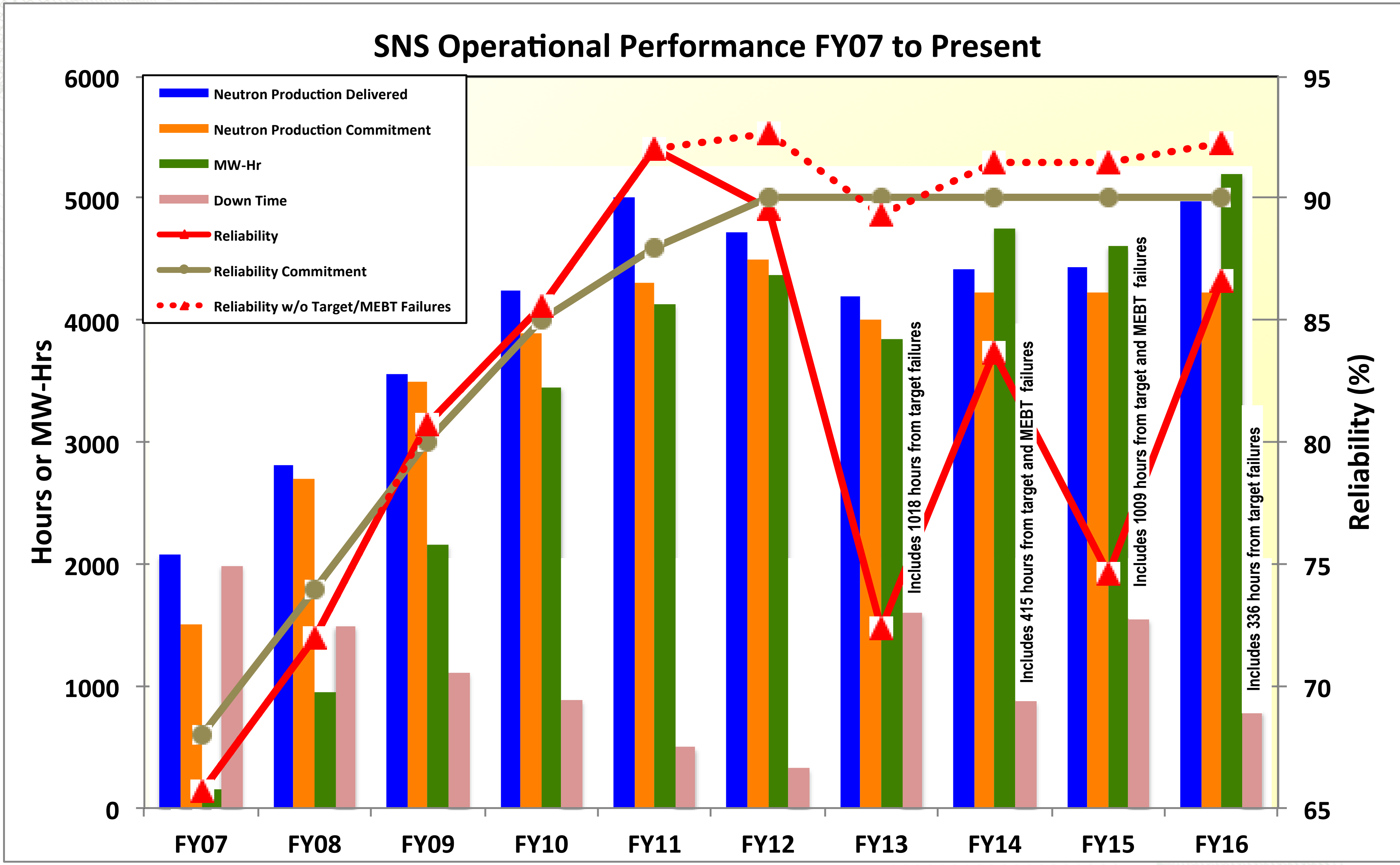
Each mini-pulse contains RF micropulses



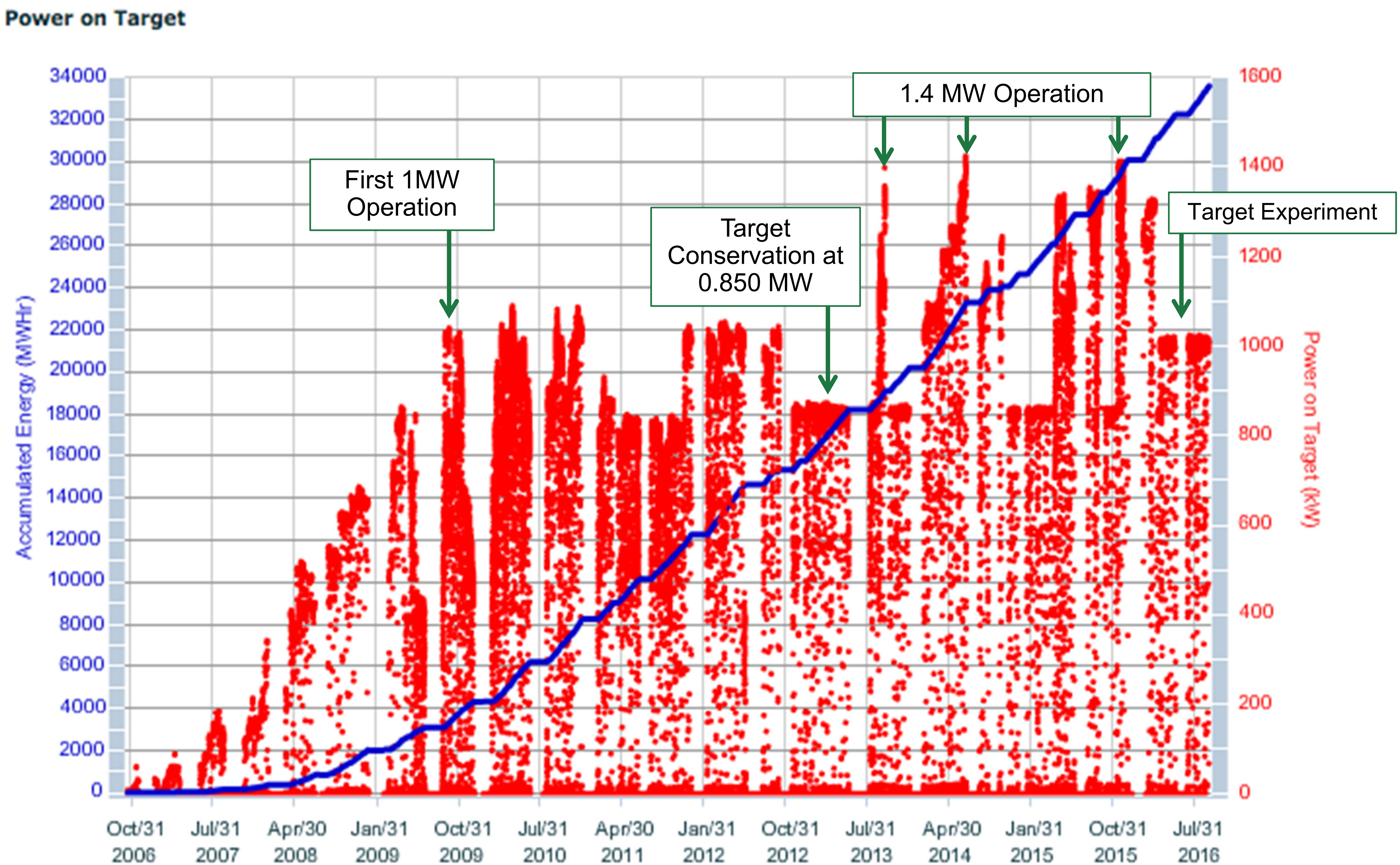
The front end produces a **60 Hz, ~1 ms** long chopped H- beam



The SNS is capable of sustained operation at power levels up to 1.4 MW but overall reliability has been affected by target performance



SNS has delivered almost 34 GW-Hr of proton beam to target over 10 years and delivers 700-800 experiments/year



ORNL/SNS proposes to build an innovative Second Target Station (STS) at SNS to meet the US demand for neutrons

STS capabilities

High peak neutron brightness
- High-throughput – in situ sample synthesis
- Out-of-equilibrium behavior phenomena
- Kinetics: Time-dependent phenomena
- Small samples – microspot scanning
- Parametric studies

Cold neutrons
- Nano- to mesoscale phenomena
- Slow dynamics
- Neutron spin manipulation
- Beam focusing

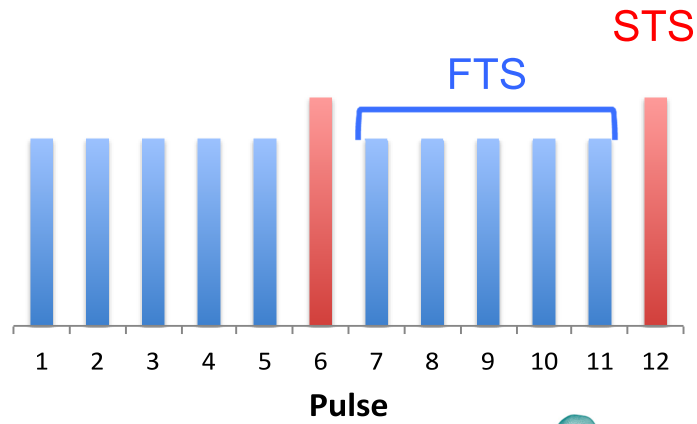
10 Hz operation
- Simultaneous access to wide range of length/time scales
- Wavelength dispersive methods
- Extreme sample environments (limited angular access)
- Limits heat deposition in compact target

High-performance computing
- Real-time manipulation/visualization of massive data sets
- Combine and interpret multi-technique data
- Linking experimental data and theory
- Unified reconstruction of imaging and scattering data

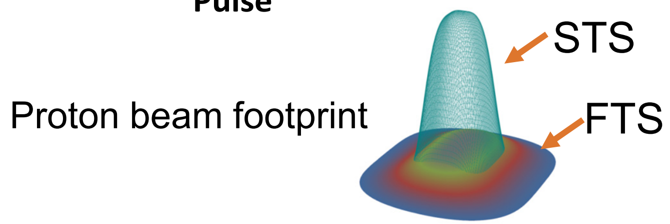
Innovative instrument concepts
- Orders of magnitude performance gains
- Integrated polarized neutron capabilities
- Manipulate sample nuclei and electron spin in situ
- Multimodal and flexible reconfiguration
- Beam line as a lab

The STS is the driver for the technical requirements – but the existing target station can benefit
(Technical Design Report Jan. 2015)

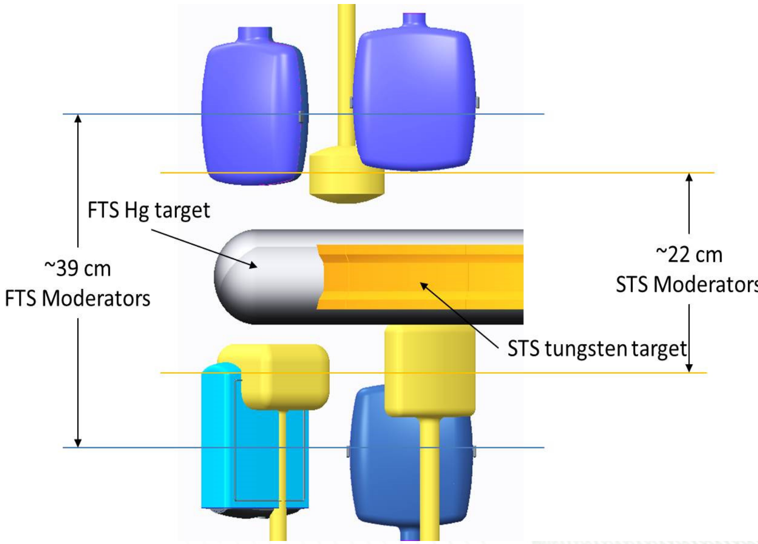
- **10 Hz**
  - Redirect 1 of 6 pulses to STS
  - First Target Station (FTS) still receives 50 Hz



- **High Brightness**
  - Double accelerator intensity per pulse
  - Make neutron source more compact

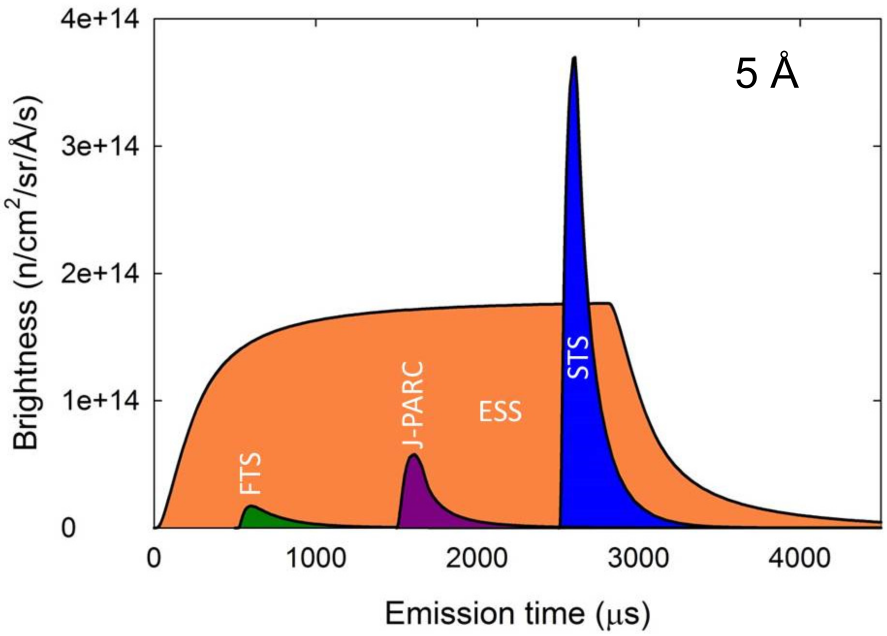


- **Cold neutrons**
  - Optimize cold coupled moderator
  - Provisions for long beam-lines



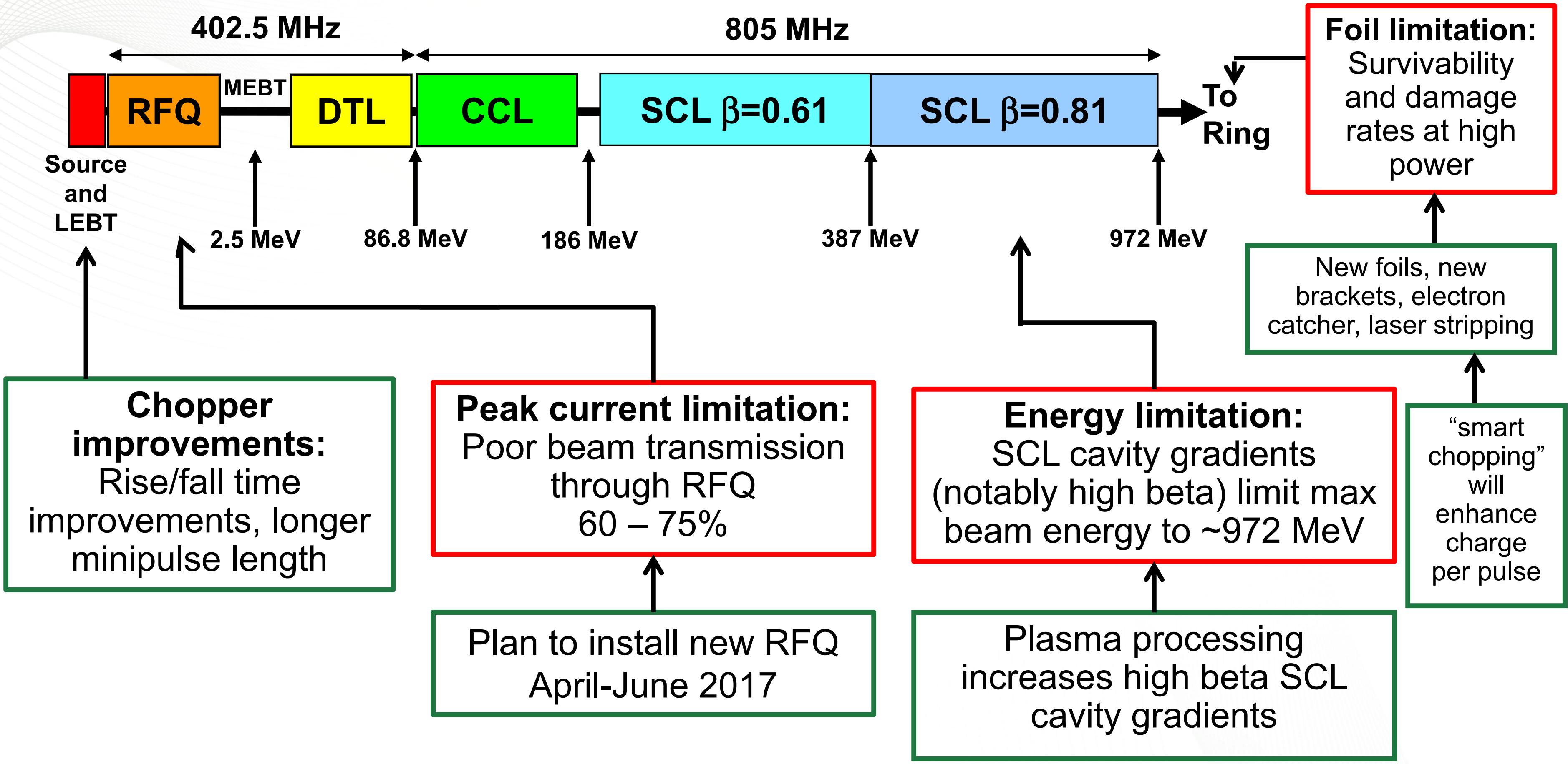
STS will be world's highest peak brightness neutron source

Comparison with ESS and J-PARC



SNS ring compresses proton pulse to form sharp neutron pulse

SNS has identified and is addressing barriers to routine operation at 1.4 MW with ~10% margin



Accelerated peak current and beam energy limitations have been offset by LEBT chopper improvements, but we need more margin

The path to increased power at SNS is through the Proton Power Upgrade (PPU) project

Accelerator power =	Energy ×	Current ×	Pulse length ×	Repetition rate
1.4 MW	0.97 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

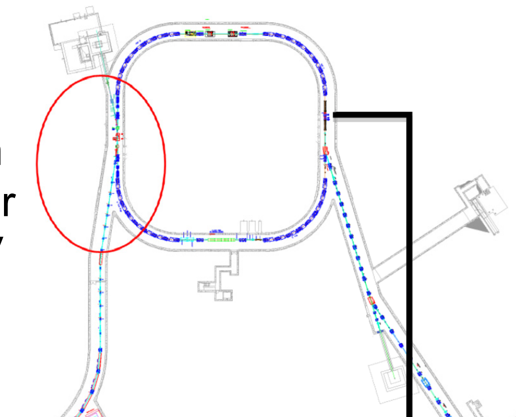
The key objective is to increase the available energy per pulse from ~23.3 to ~47kJ

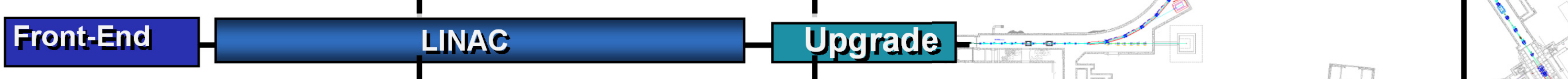
The SNS machine was built to accommodate certain upgrades

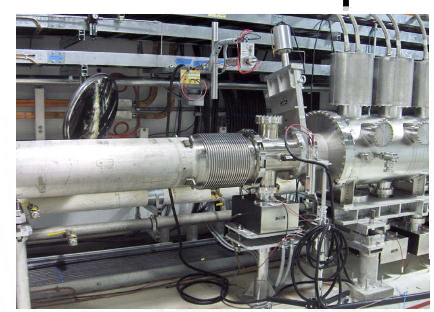
Tunnel: Fill 7 empty drift sections with cryomodules (space available for 9)

96% Ring + transport line magnets are 1.3 GeV ready

Must rebuild injection region for 1.3 GeV







Beam extraction:
Fill empty space with kickers

Klystron gallery: fill empty area with high power RF equipment

SNS has established test facilities and processes to ensure we can achieve the PPU technical basis

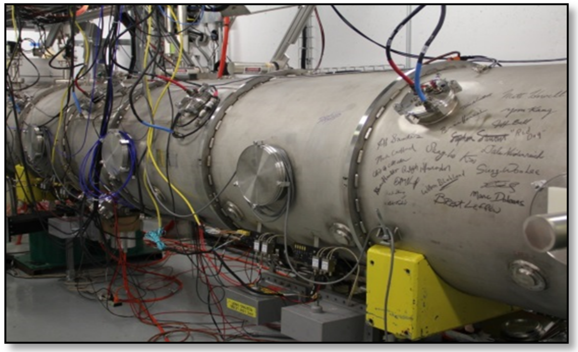
Ion source test stand has led to current increases, demonstrating capability required for PPU

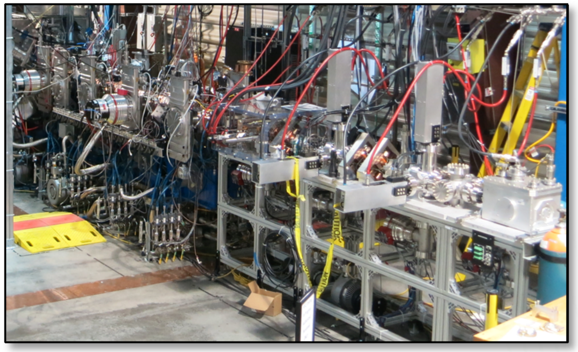
Ring damper system is operational, providing insurance against instabilities at higher PPU intensities

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

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

Plasma processing for in situ cavity gradient improvement of installed cryomodules has been demonstrated





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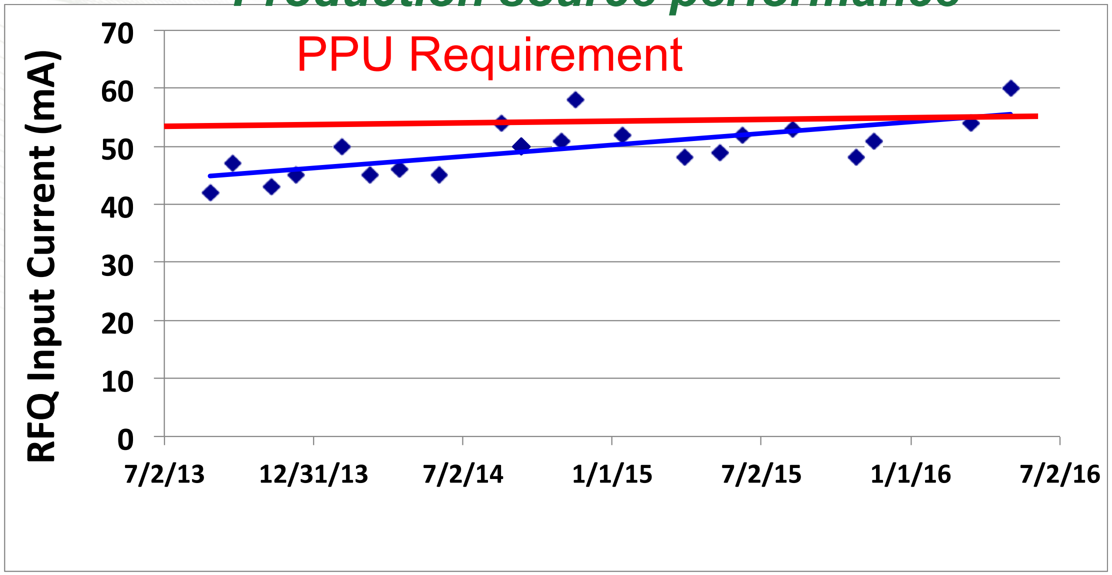
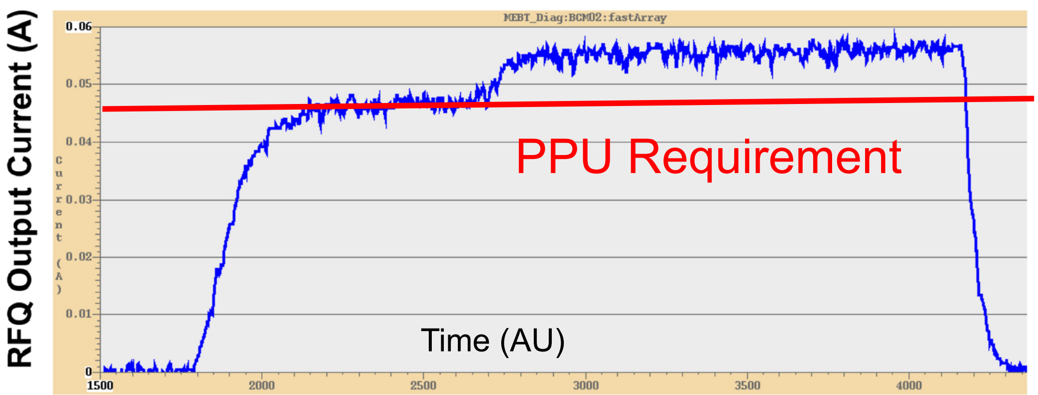
The SNS H- ion sources have consistently demonstrated performance that supports PPU requirements

Production source performance



Nov. 3, 2008: RFQ output current

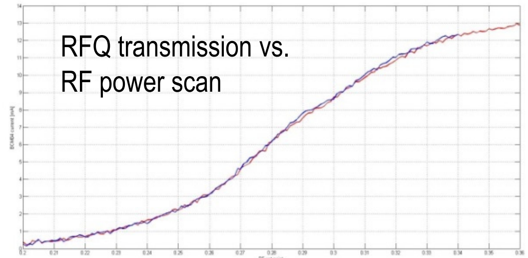


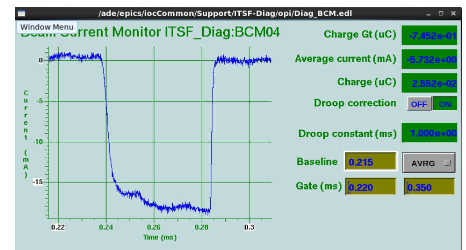
- Current PPU approach eases ion source requirements but we would like 10% margin: keep improving
- Need ~ 46 mA out of RFQ, 55 mA into RFQ
- Utilize new Beam Test Facility and existing ion source test stand to increase margin

Existence proof: RFQ design can transmit PPU beam current

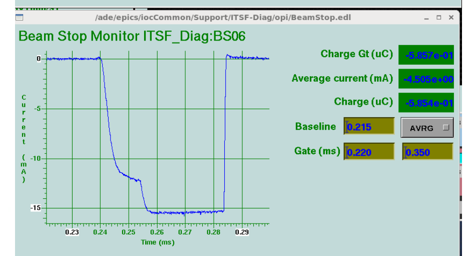
We are making very good progress on commissioning the Beam Test Facility and spare RFQ

- Achieved 20mA RFQ output peak current required by low power commissioning plan
- Commissioned all beam diagnostics
- Measured RFQ transmission of ~90% at 20mA is close to design expectation
- Measured RFQ output energy of 2.5 +/-.02 MeV is close to design expectation and well within DTL acceptance
- Measured transmission through MEBT of >98% is determined by BCM accuracy and acceptable for beam power ramp-up
- All low current commissioning plan task are complete
- Ion source is being tuned to provide nominal RFQ output current of 40mA

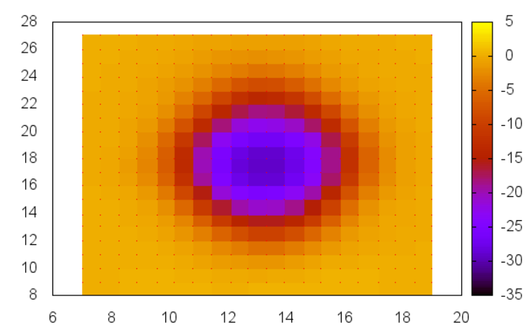




Beam current at RFQ exit

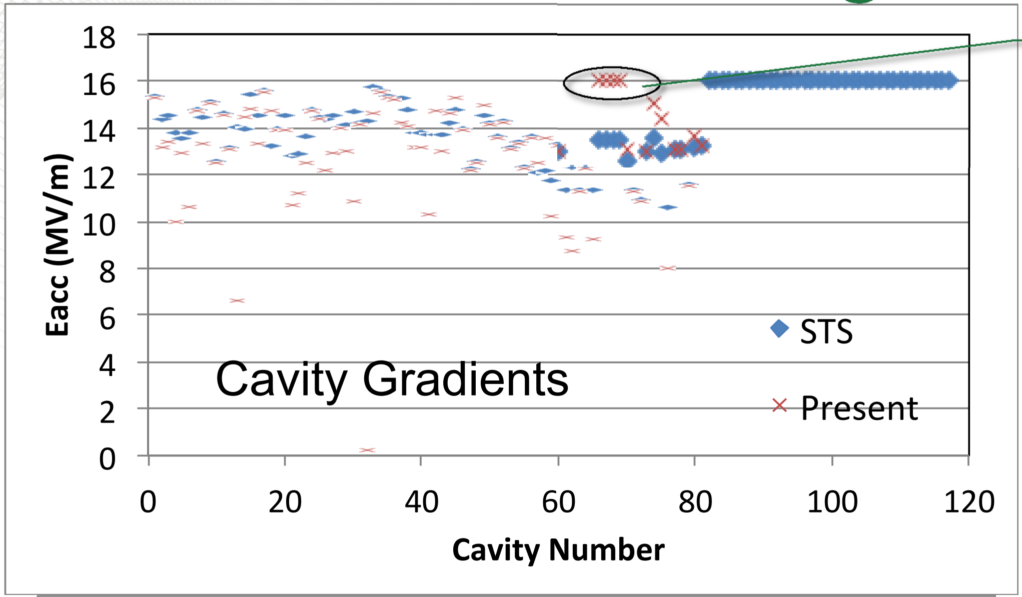


Beam current at beam stop



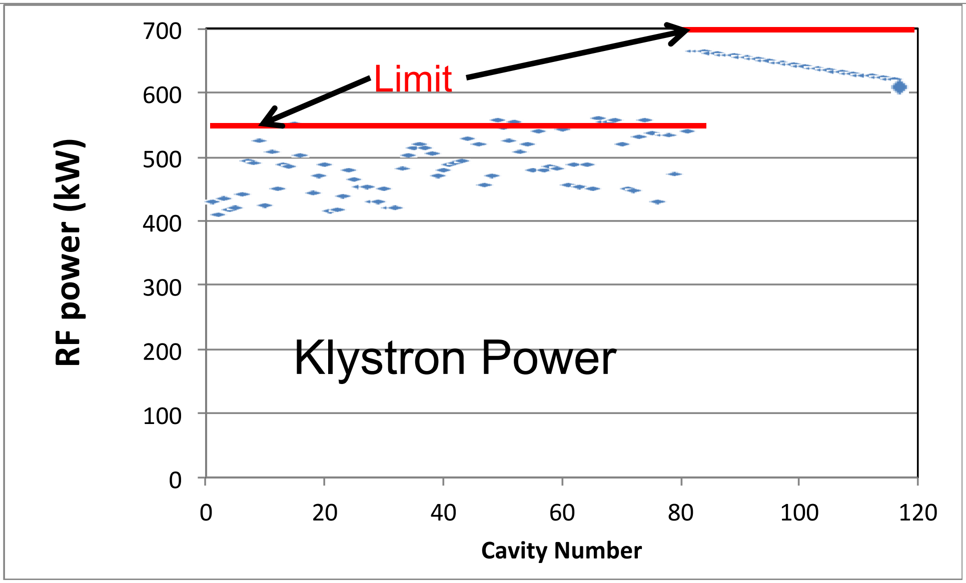
Transverse beam profile measured with 2-d slit scan

The SNS spare high-β cryomodule has demonstrated the PPU gradient requirement



Gradients are reasonable:

- 16 MV/m for new CMs
- Same as spare CM built in 2012
- ESS: 18.5 MV/m
- LCLS-II: 16 MV/m



RF power:

- Existing cryomodules limited to 550 kW/ klystron
- New ones will be 700 kW capable (off-the-shelf)
- Couplers are adequate to support higher power

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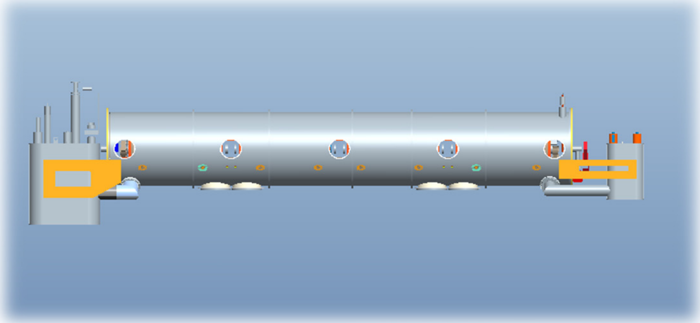
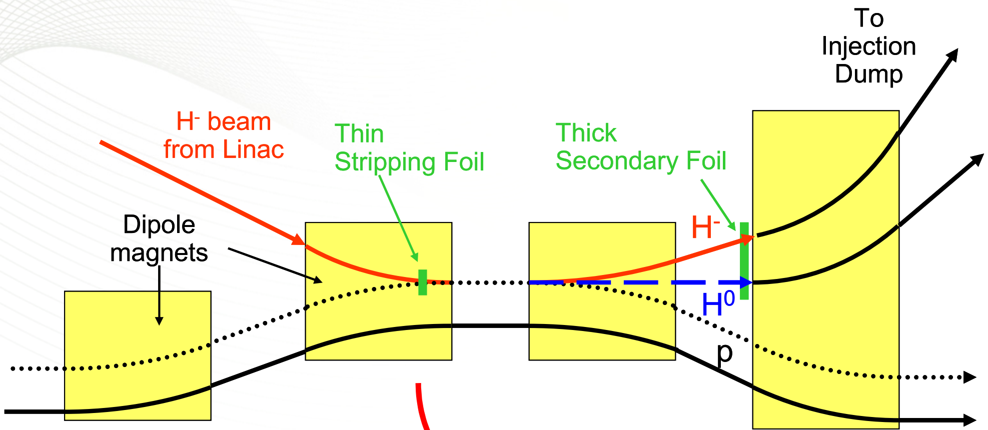
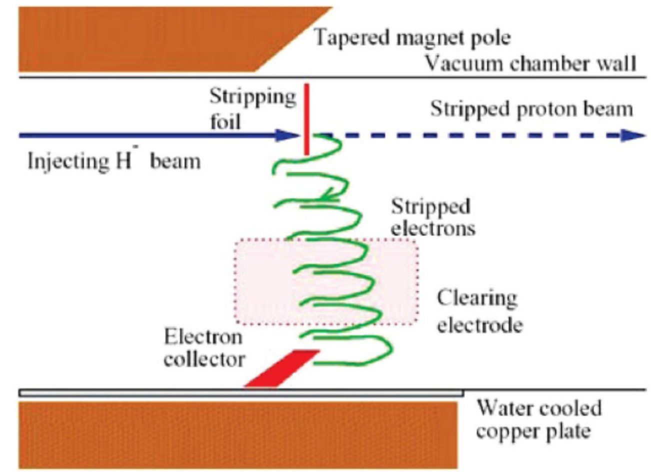
PPU strategy to achieve 1.3 GeV

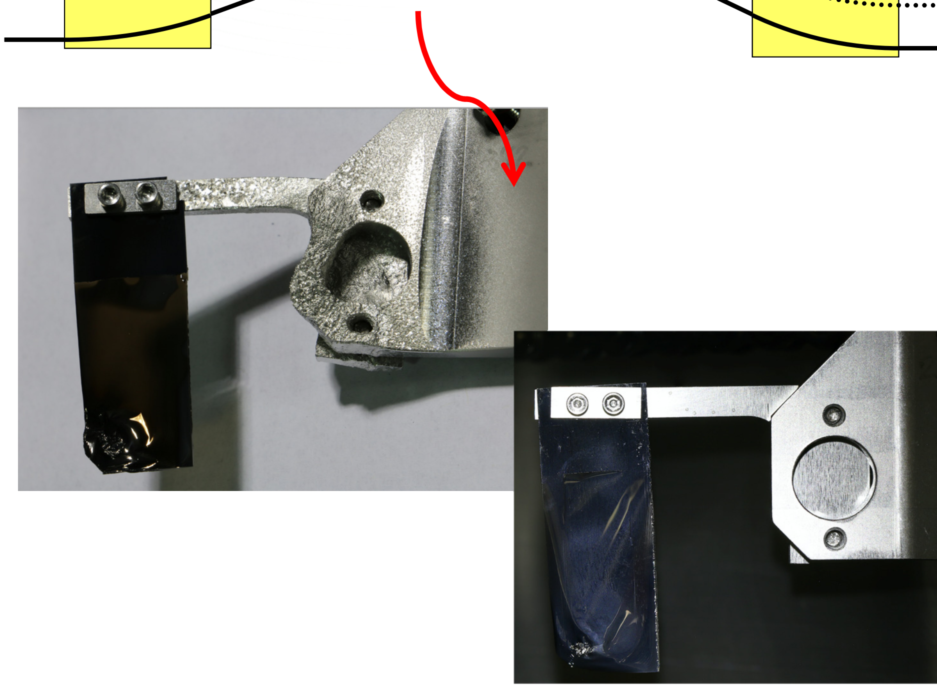
- Fabricate seven new high beta cryomodules in-house and install to increase beam energy to 1.3 GeV
  - A design gradient of 16 MV/m is specified
  - Improvements will be incorporated in the cavity design to enhance performance
  - Nine empty slots available
- Utilize experience from high beta spare cryomodule
  - Maintain certain design interface points for ease of integration of new cryomodules into the existing tunnel
  - Meet the pressure requirements set forth in 10 CFR 851
- Build a medium beta spare cryomodule
  - Start in 2017
- Expand the plasma processing technique for medium beta cavities



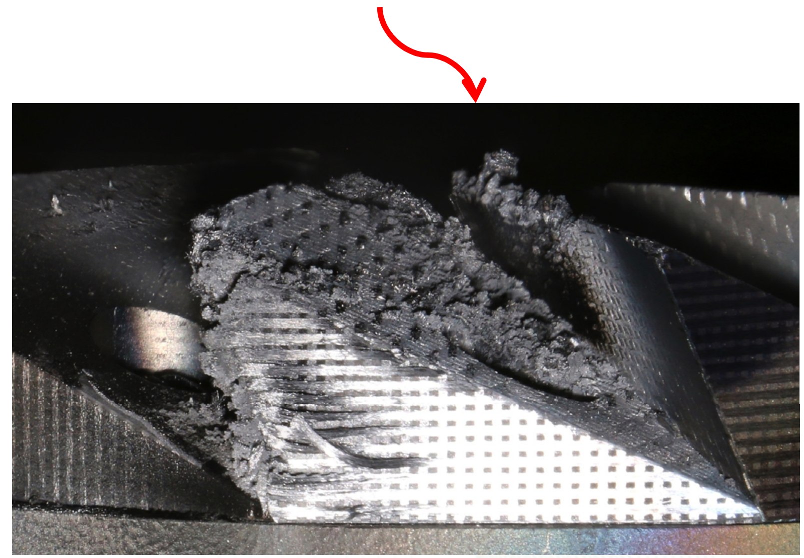
SNS accumulator ring injection at high beam power presents several challenges







Stripper foil mount and bracket damage



Electron collector damage

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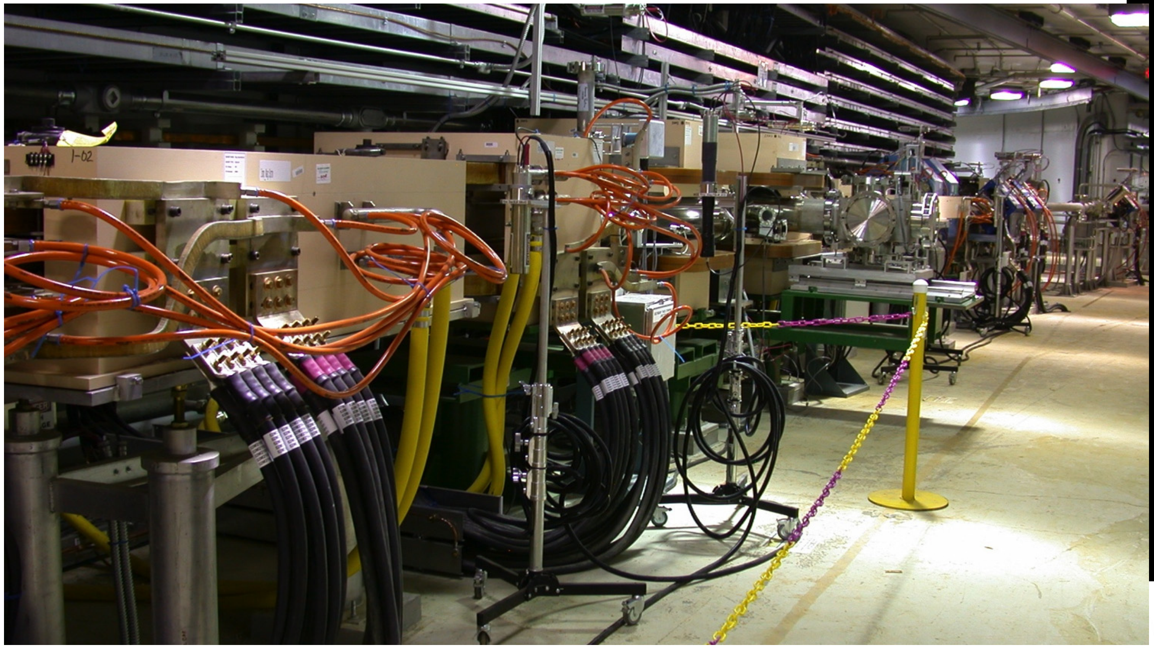
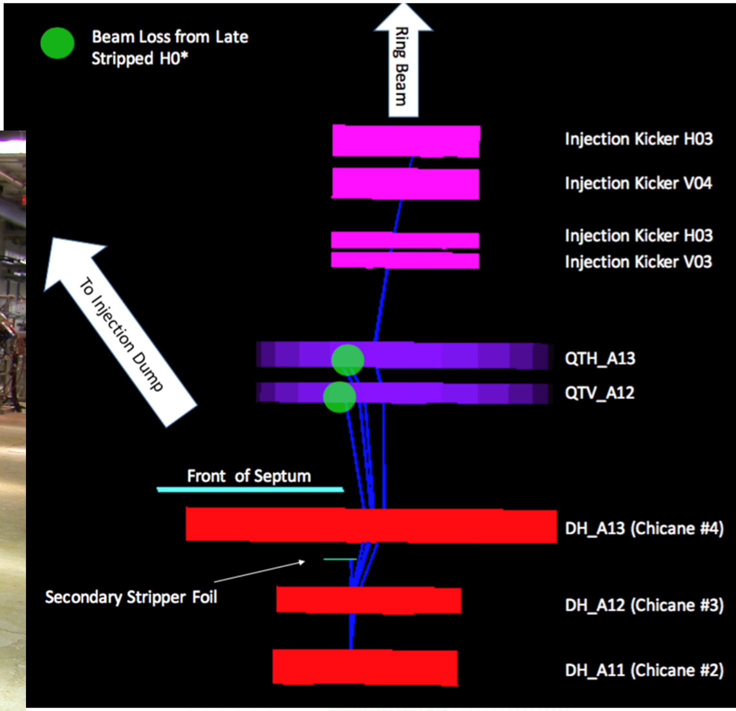
The ring injection system will have to be replaced to accommodate the PPU beam energy of 1.3 GeV and manage stripping of excited neutron hydrogen atoms

- Ring injection is the most complicated part of the SNS accelerator complex – also the most activated
  - Most injection magnets are replaced in PPU
- Magnet requirements continue to be refined
  - “Exotic” beam loss mechanism drives magnet size

Excited state neutral H transport





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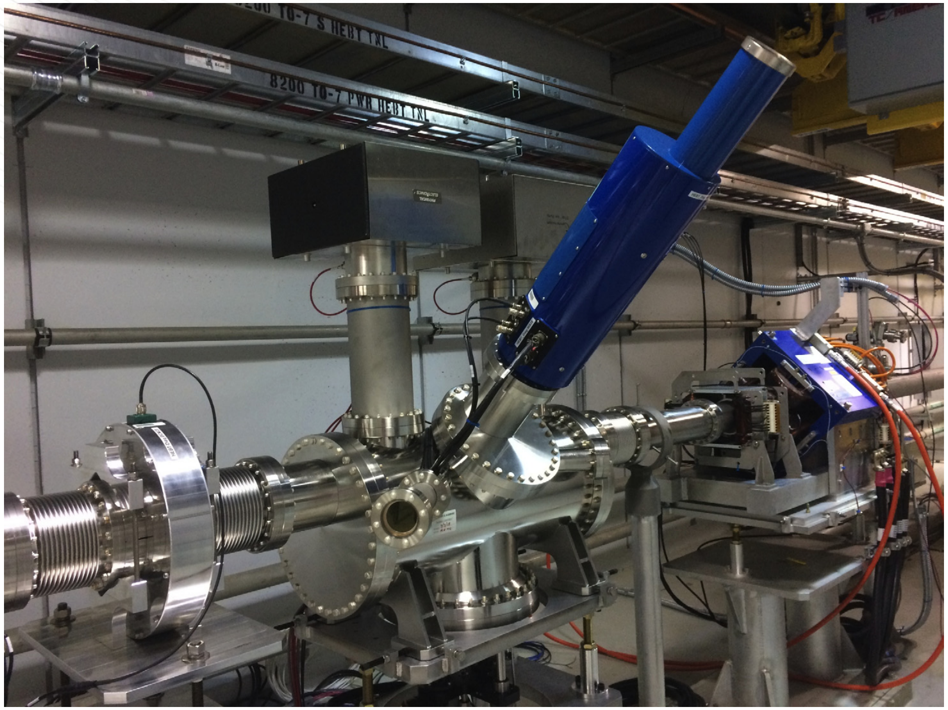
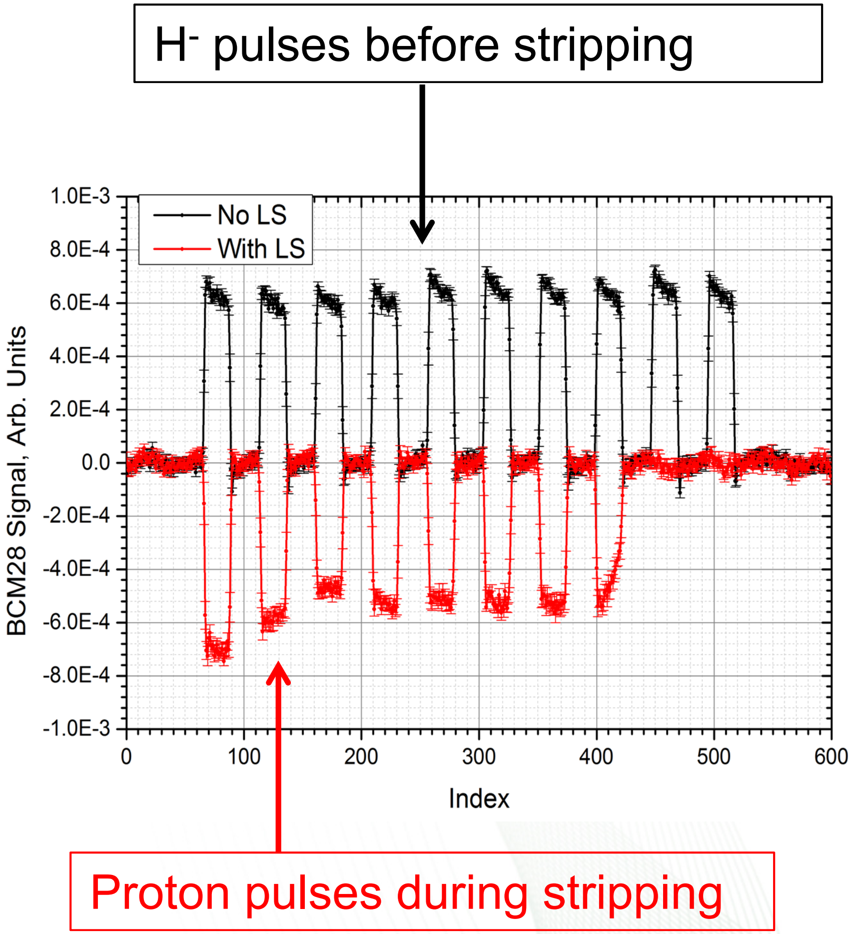
SNS has successfully demonstrated ~10 μs laser- assisted stripping

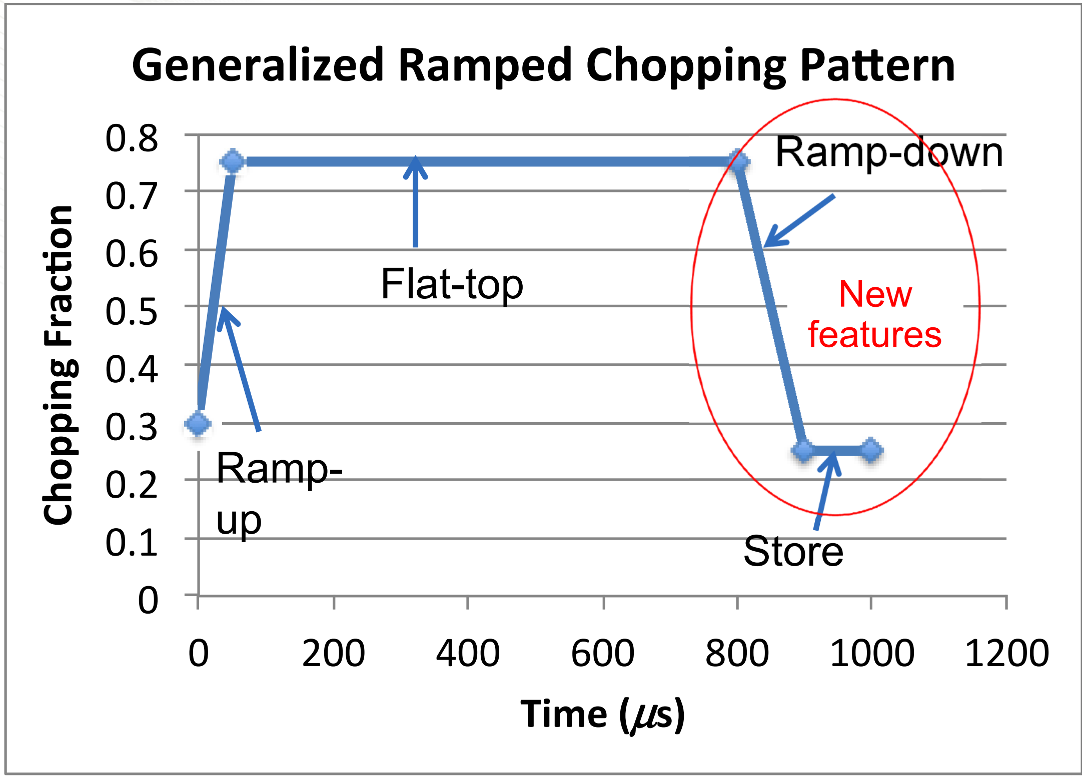
- First microsecond-long laser-assisted H^- stripping.
- Demonstrated stripping for 8 μs long pulse with ≥ 98% efficiency.

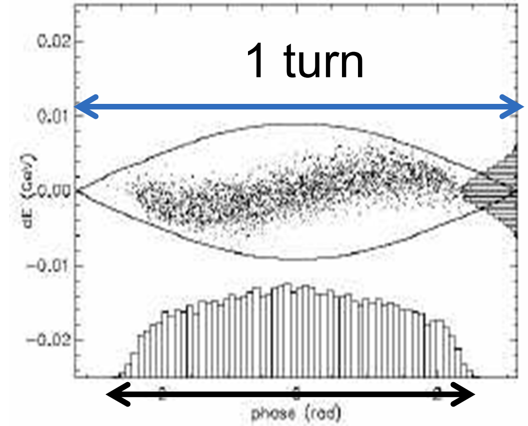




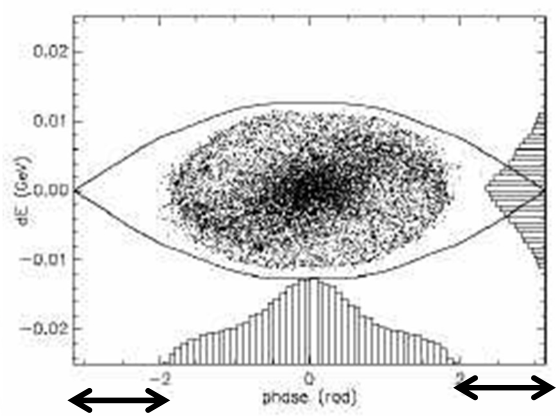
* Funded in part by a DOE HEP grant through University of Tennessee, with ORNL and Fermilab partnership.

Smart chopping using RF gymnastics at the end of accumulation could allow increased charge per pulse





Relatively large un-chopped flattop most of injection



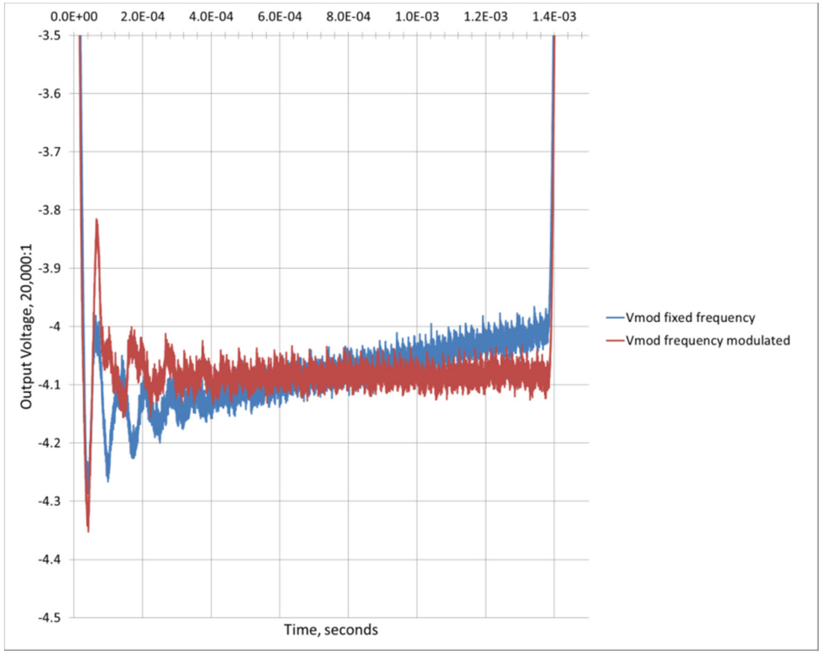
Longitudinal “tricks” to recover big gap at extraction time

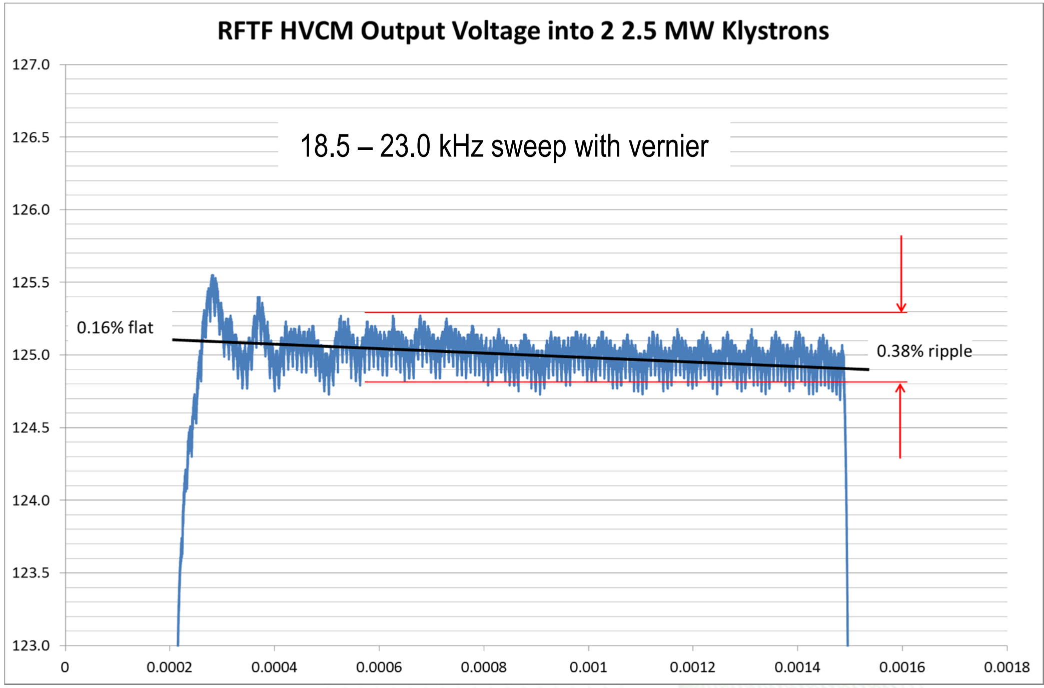
A 5-10% increase in “average un-chopped” fraction may be possible – testing planned for Fall of 2017

Pulse flattening to achieve reliable 1.4 MW operation, provide additional LLRF control margin and support PPU

- Klystrons are at saturation at the end of the pulse with no remaining control margin
- Pulse flattening for improved LLRF control margin demonstrated and currently running on DTL-Mod5, SCL-Mod18 and test modulators
  - Utilizing frequency modulation
  - Comparable LLRF regulation error
- IGBT commutation currents increase by 40% but still acceptable

SCL-Mod18 Output Voltage with 17.8 to 23.0 kHz frequency modulation





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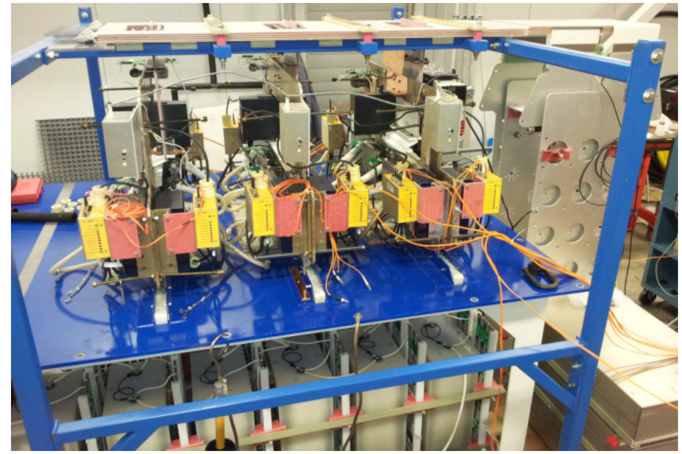
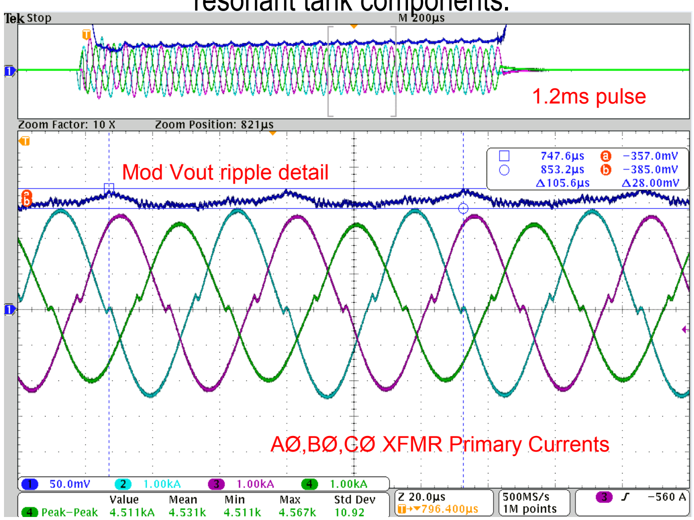
The Alternate Topology Modulator (ATM) shows promise for PPU and other applications

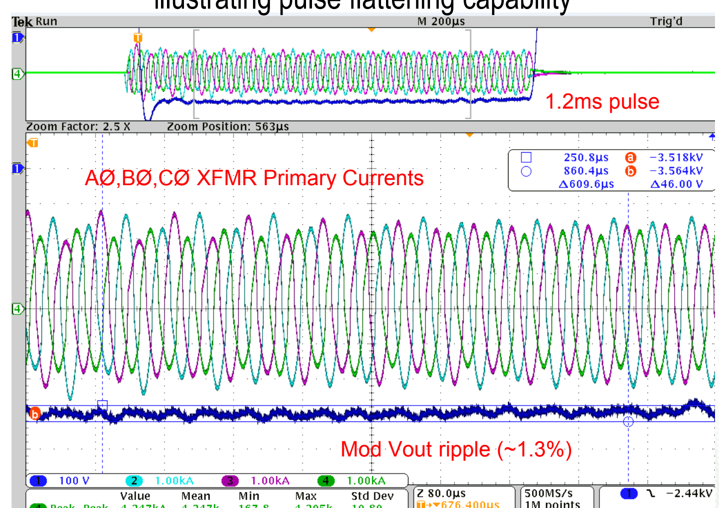
- Presently installed in HEBT test stand.
- Delivering 1.2ms 70kV 100A pulse at 60 Hz.
- 92% efficient ZVS/ZCS power conversion.
- Thermal run completed. Maximum temperatures recorded transformer (76 °C), rectifier (72 °C) and resonant capacitor (39 °C) are well within safe operating margins.
- Plan to operate at levels required for PPU after verifying safe for beam stick loads (shorted wire test)



Fixed frequency operation: output regulation 0.7% pp presently limited by phase to phase imbalance in resonant tank components.



Variable frequency operation: 24kHz-19kHz sweep illustrating pulse flattening capability



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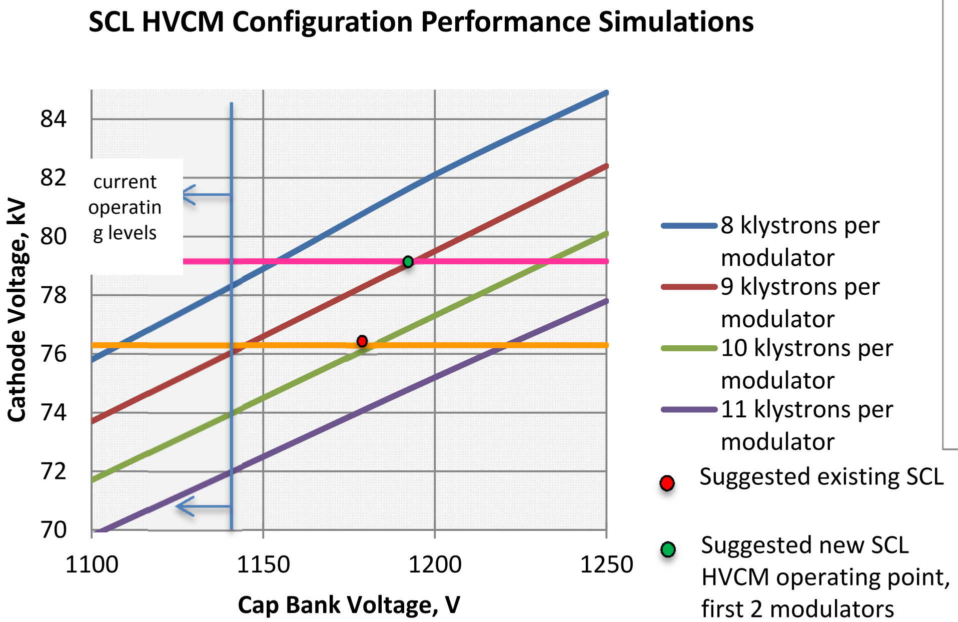
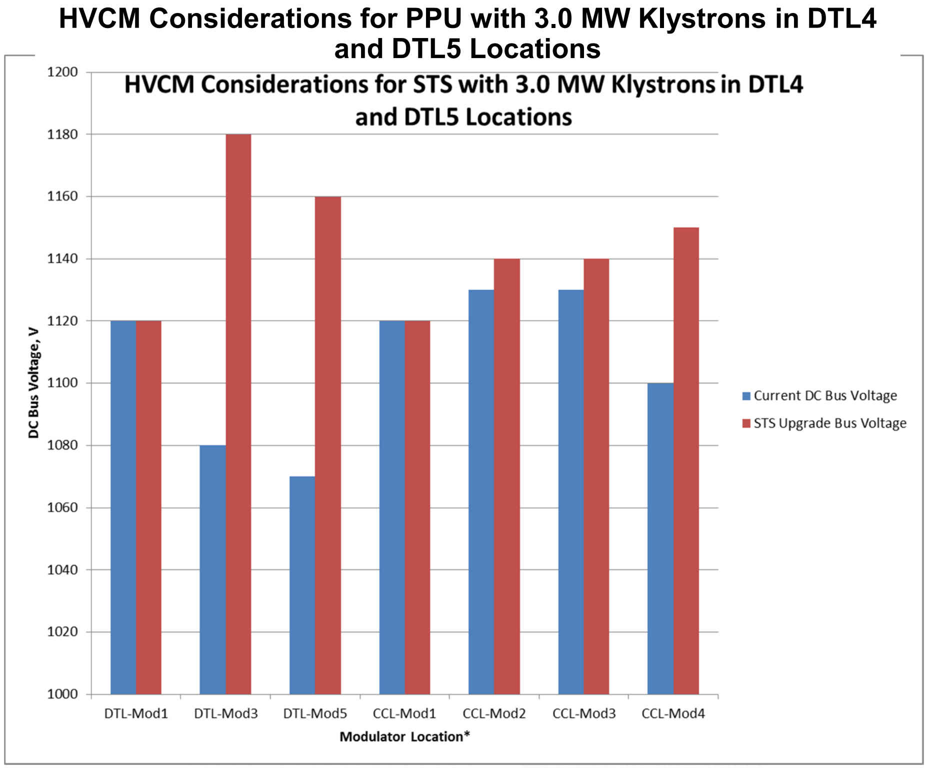
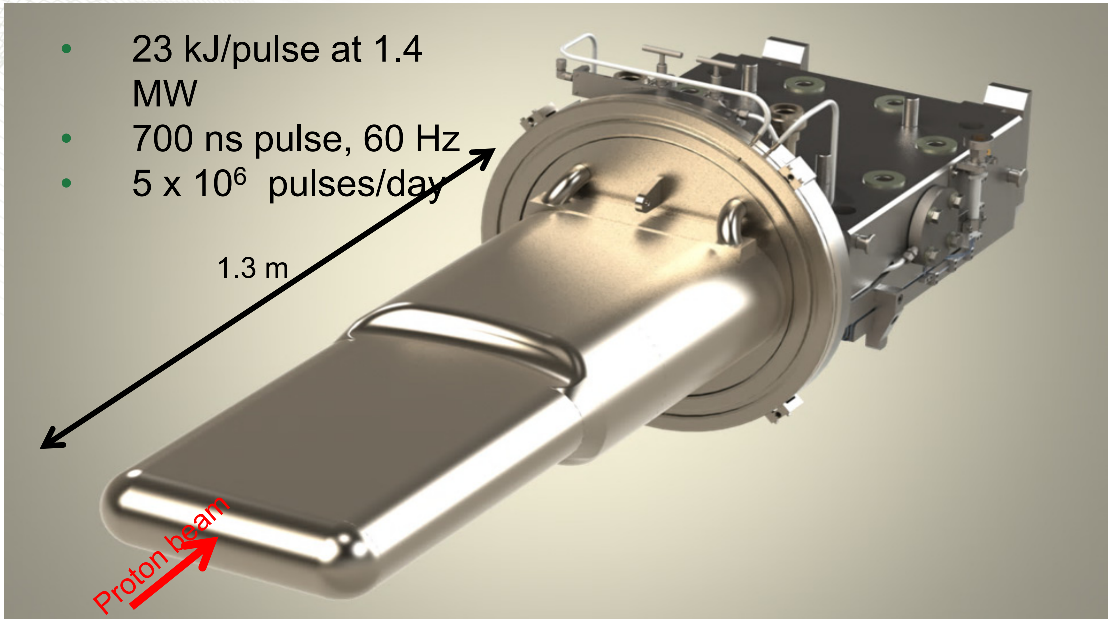
Modulators require some development for PPU but should achieve reliability comparable to existing modulator performance

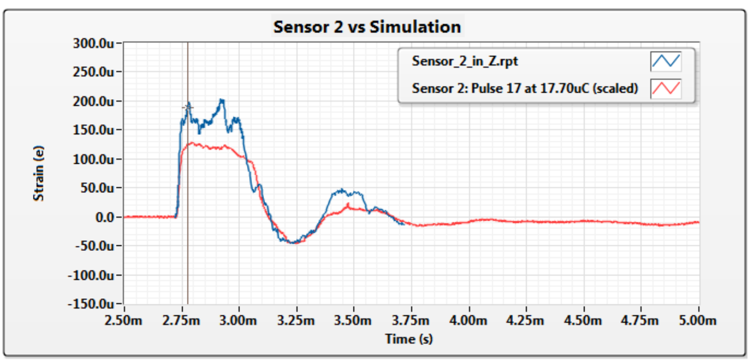
- Modify boost transformers in warm linac to achieve required higher output voltages, esp. for 3.0 MW klystrons
- Existing medium/high beta cavity klystron:modulator ratio of 10:1 forces higher DC bus voltage for additional power
- Reduction to a 9:1 klystron:modulator ratio for first 18 new cavities (2 HVCMs), 10:1 ratio for the last 10 new cavities at reduced power levels
- **3 additional modulators required for PPU upgrade**

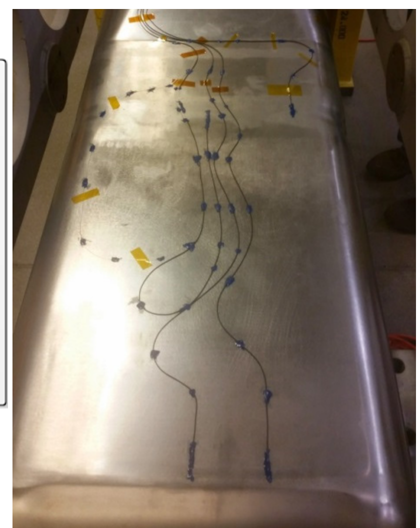




The SNS mercury target module remains a barrier to sustainable operation at 1.4 MW but we are learning rapidly







- Continue target reliability approaches
  - Gas bubble injection
  - Target redesign for higher power
  - Strain measurements on a target
  - Improved Post Irradiation Examination
  - Fabrication improvements
- FTS Systems
  - Re-evaluate 2 MW safety-envelope limit

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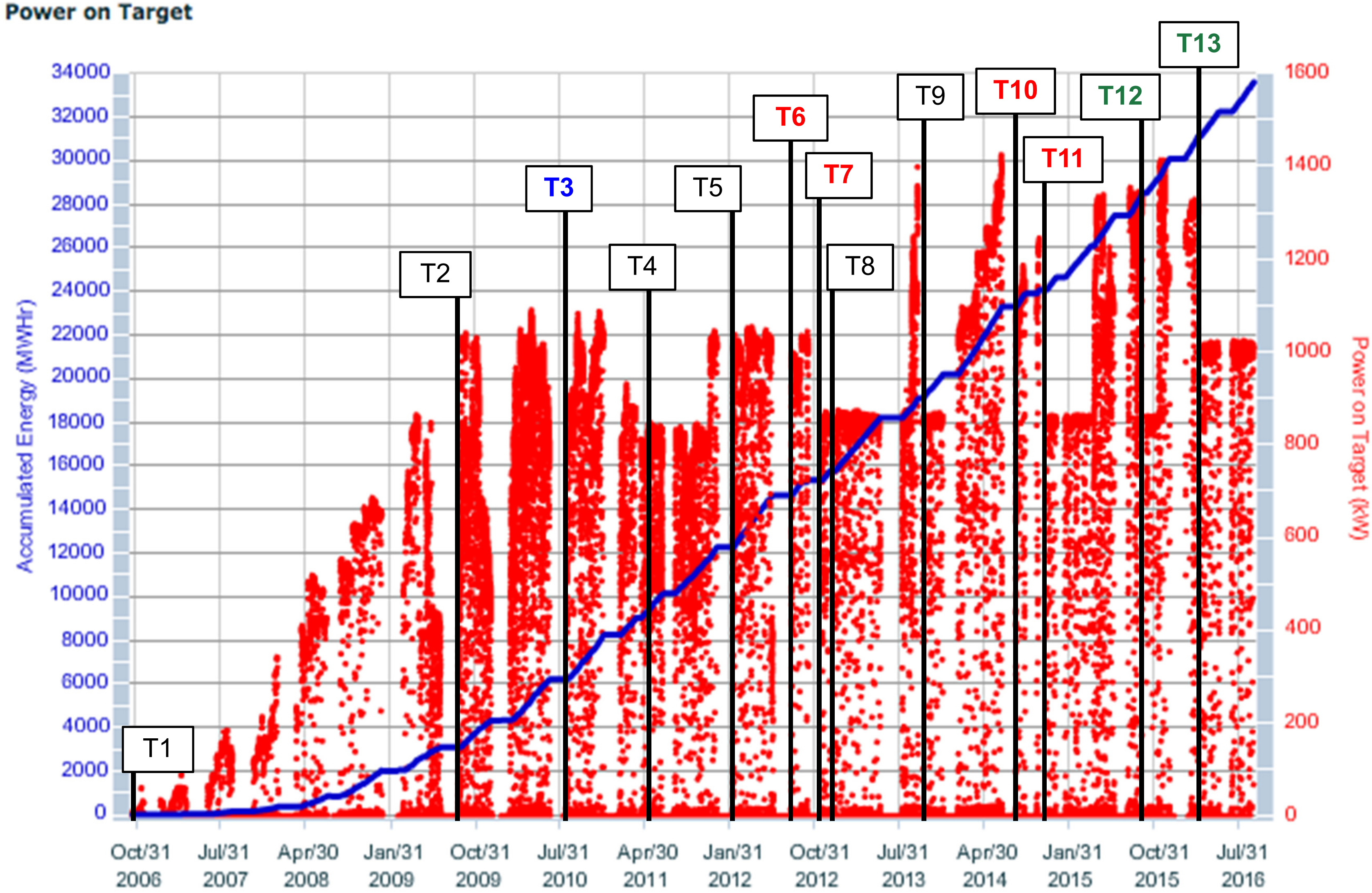
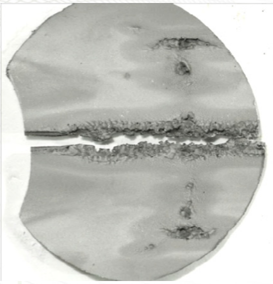
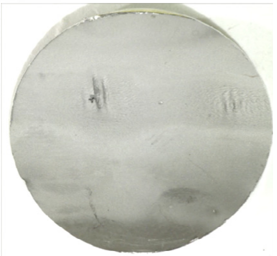
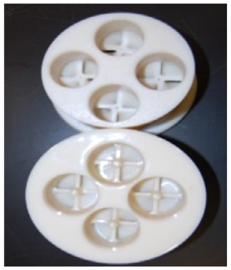
We've addressed target vessel structural challenges but high-power cavitation damage erosion remains an issue

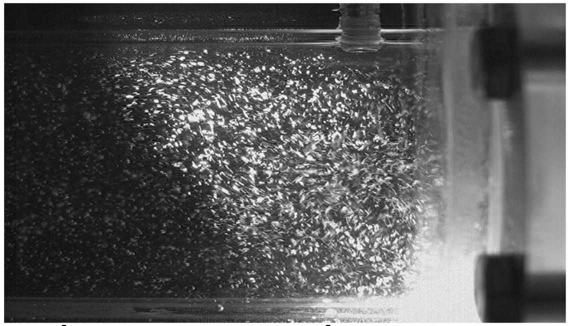


The target plan for PPU builds on current activities and focuses on gas bubble/wall injection and system upgrades









Ongoing target post irradiation examination, instrumentation

2016 | 2018 | 2020 | 2021 | 2023

FTS Target Reliability
- Structure/fabrication
- Gas injection
- Flow

1.4 MW reliable operations

Final target design

Initiate target fabrication

PPU complete

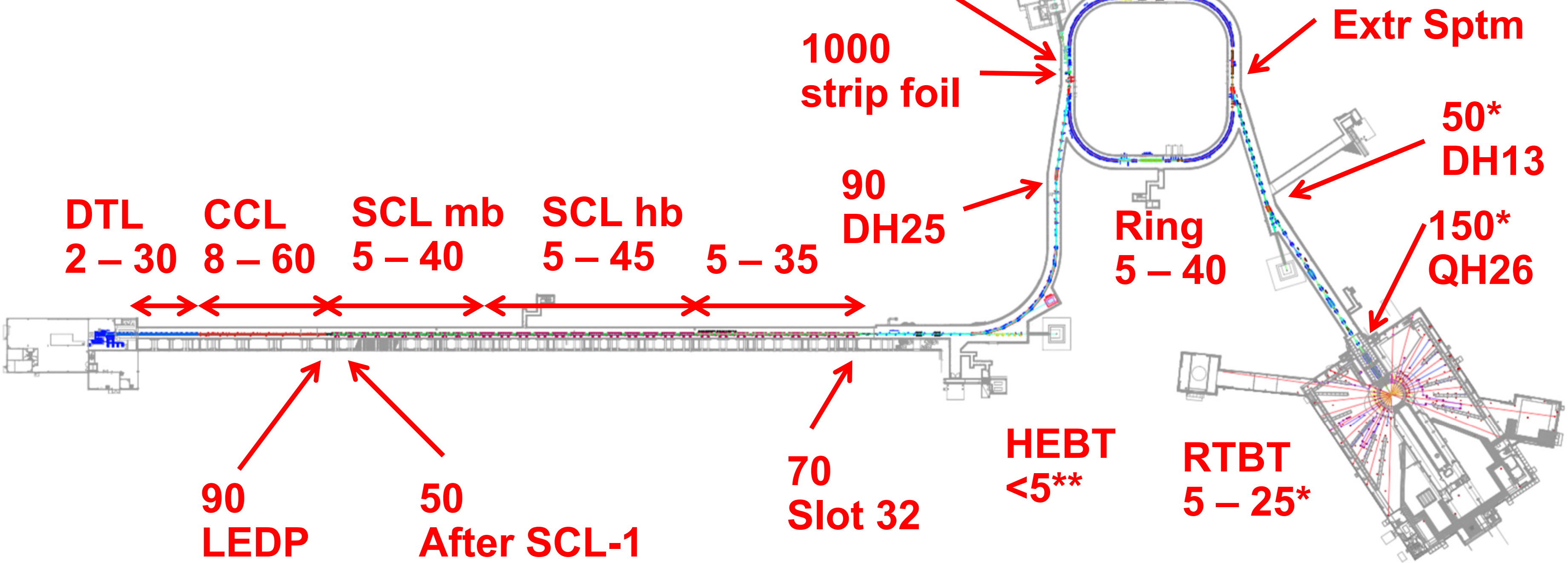
Gas wall injection development

Evaluation of auxiliary target systems (shielding, cooling, …)

Red = PPU Activities

Activation levels in the SNS complex are manageable but some areas may challenge 1 W/m design loss at ~3 MW

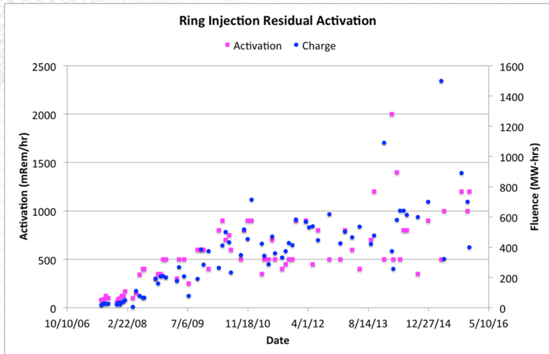
1.3 MW until 3 to 5 hours before survey
Sept. 22, 2015
All numbers are mrem/h at 30 cm
100 mrem/h = 1 mSv/h



Except for a few hot spots, the dose rates are relatively low

* 3 days after 1.3 MW
** No survey near this time, indicated does rates are typical

SNS is actively pursuing measurements and modeling necessary to support low-loss operaiton at ~3.0 MW



Simulation determines parameters for minimum beam loss

Need accurate input distribution for simulation codes

Need good linac simulation code

Need accurate SNS linac lattice

6D phase space measurement on Beam Test Facility

Add linac simulation capability to PyORBIT

Benchmark simulations with measurements

Beam-based measurement of lattice parameters

B. Cathey FRA1CO04

Summary

- The SNS machine is capable of routine, highly reliable operation at 1.4 MW but margin is needed
- Replacement of the RFQ, additional plasma processing, and modulator upgrades will provide margin for 1.4 MW operation by late 2017
- Understanding of mercury target structural issues is much improved, but cavitation damage erosion at beam powers above 1.2 MW still requires mitigation techniques to be developed
- The Proton Power Upgrade project to double the charge per pulse to ~47 kJ is well defined
  - New RFQ and incremental ion source improvements will provide the required peak current
  - 7 high beta cryomodules at 16 MV/m will raise the beam energy to 1.3 GeV
  - Ring injection modifications and extraction kicker upgrades are well in hand with robust designs
  - An aggressive target improvement plan is in place to design and build a 2 MW capable target

Thank you for your attention!