OAK RIDGE National Laboratory

Oak Ridge National Lab SNS Lab Talk - Status of the Proton Power Upgrade Project at the Spallation Neutron Source

Mark Crofford

LLRF Systems Manager

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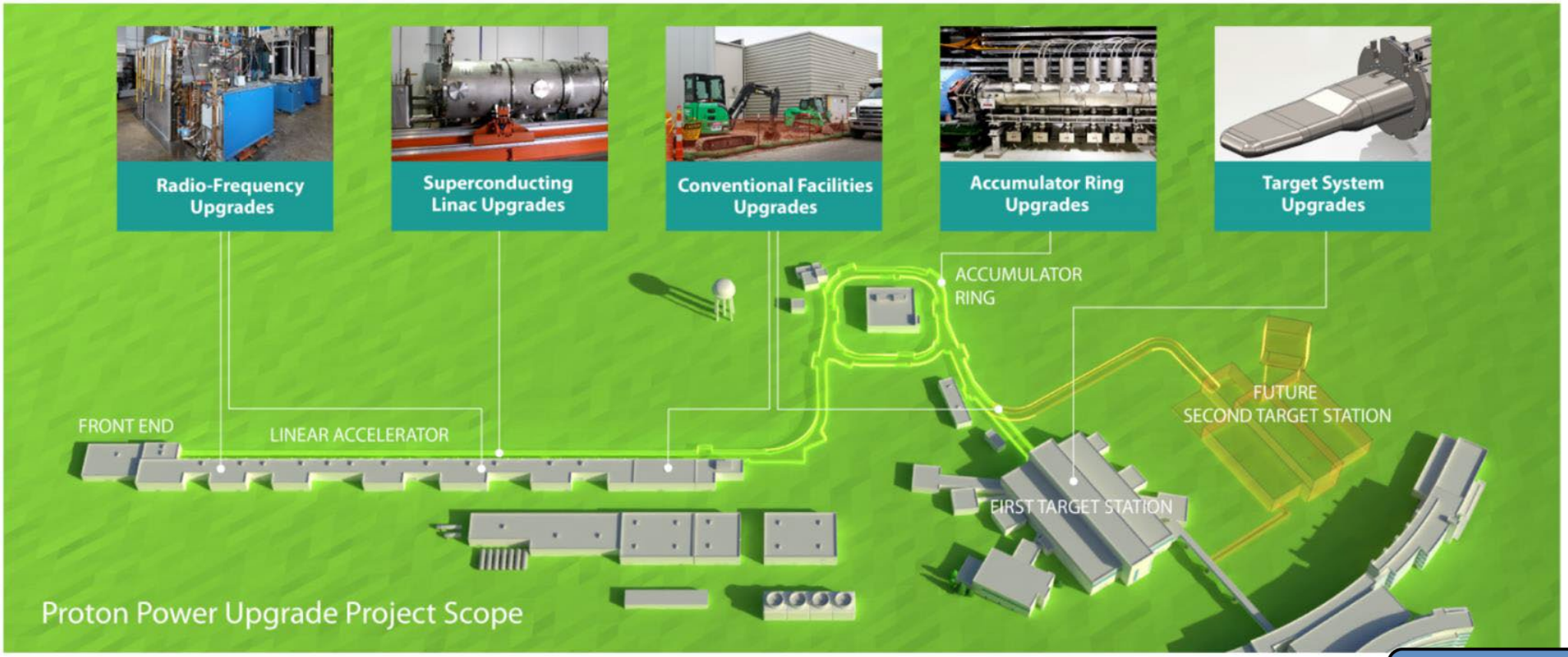
Since LLRF Workshop 2022

- At the 2022 workshop, Phase 1 equipment installation for the Proton Power Upgrade (PPU) was nearing completion
  - Phase 1 - two cryomodules (8 cavities)
    - Operation from December 2022 to February 2023
- Phase 2 installation was completed in June 2023
  - Phase 2 – two cryomodules (8 cavities)
    - Operation from June 2023 to August 2023
- Phase 3 installation is ongoing
  - Three cryomodules (12 cavities)

Proton Power Upgrade project scope

- Upgrade the SNS accelerator beam power capability from 1.4 MW to 2.8 MW
  - 30% beam energy increase: 1.0 GeV → 1.3 GeV
  - 50% beam current increase: 26 mA → 38 mA

- Includes scope across much of the neutron source

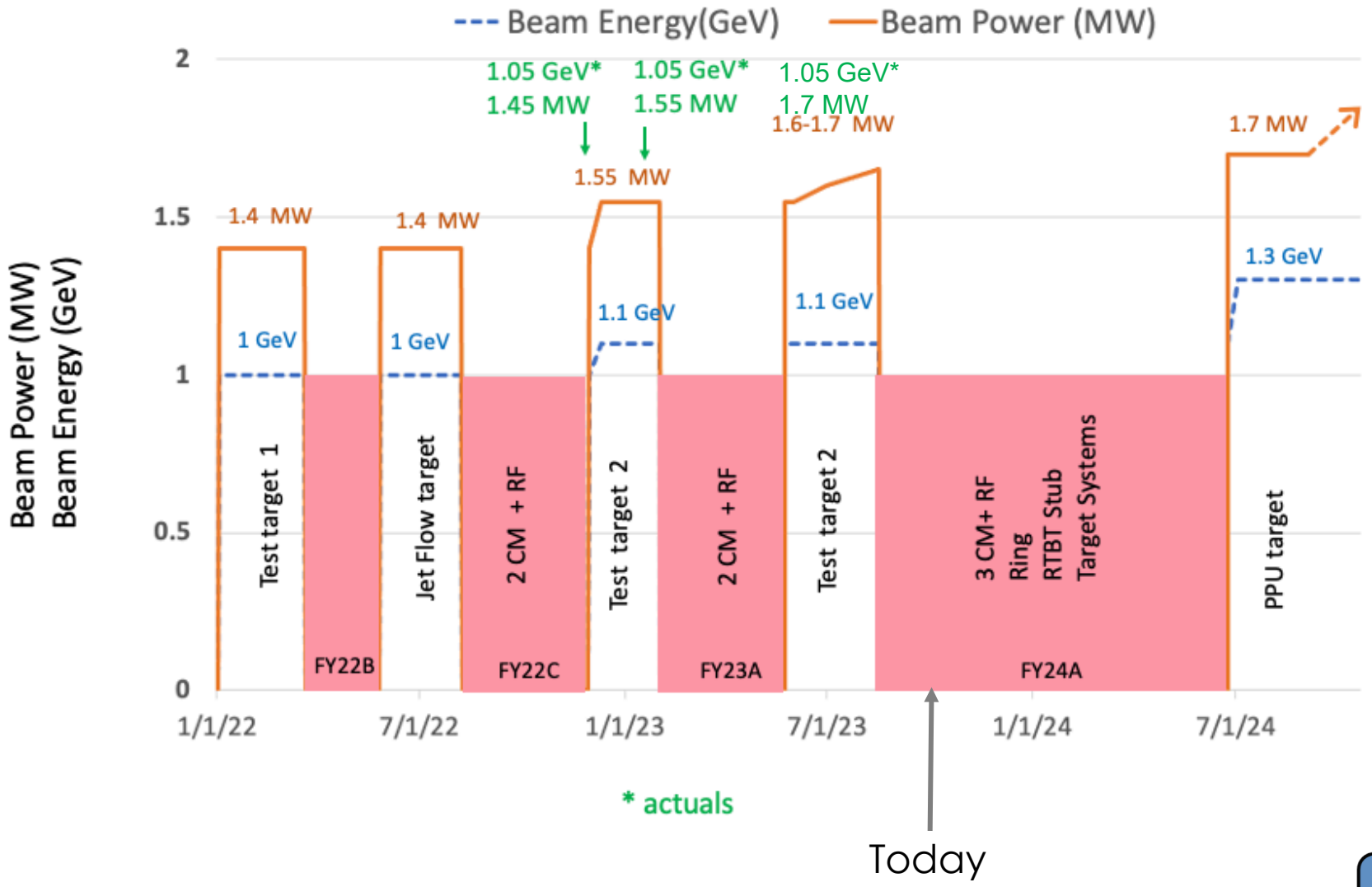


Slide courtesy of M. Champion

Completed Phase 1and 2 installation

- Four cryomodules and associated equipment installed
  - CM31 and 32 – Phase 1
  - CM29 and 30 – Phase 2
- Operating equipment as it becomes available
  - Power ramp-up plan
- This was the most fun…
  - First tests of multiple new MicroTCA.4 LLRF control systems
  - Determined energy limits of what existing magnets can support
  - Challenges tuning beam with a large drift space

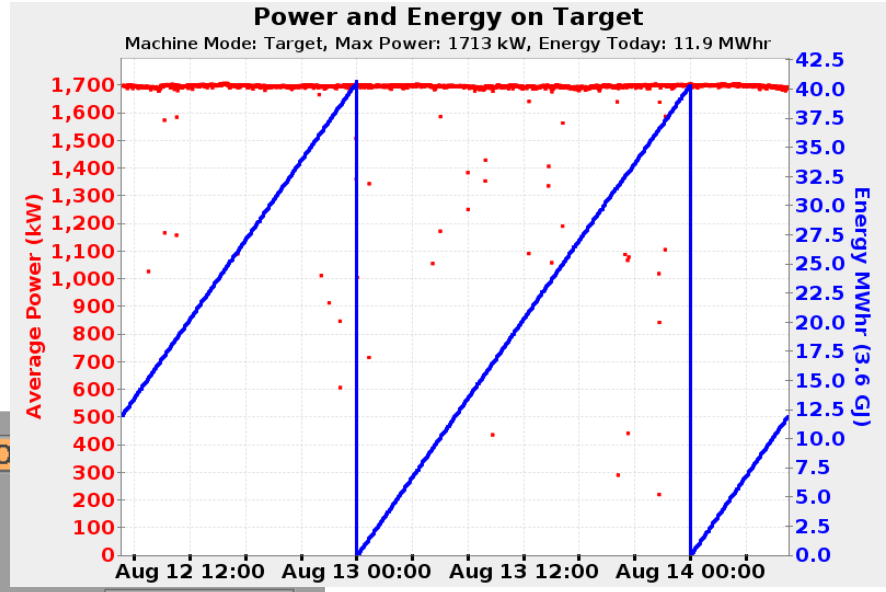
Power Ramp-up Plan



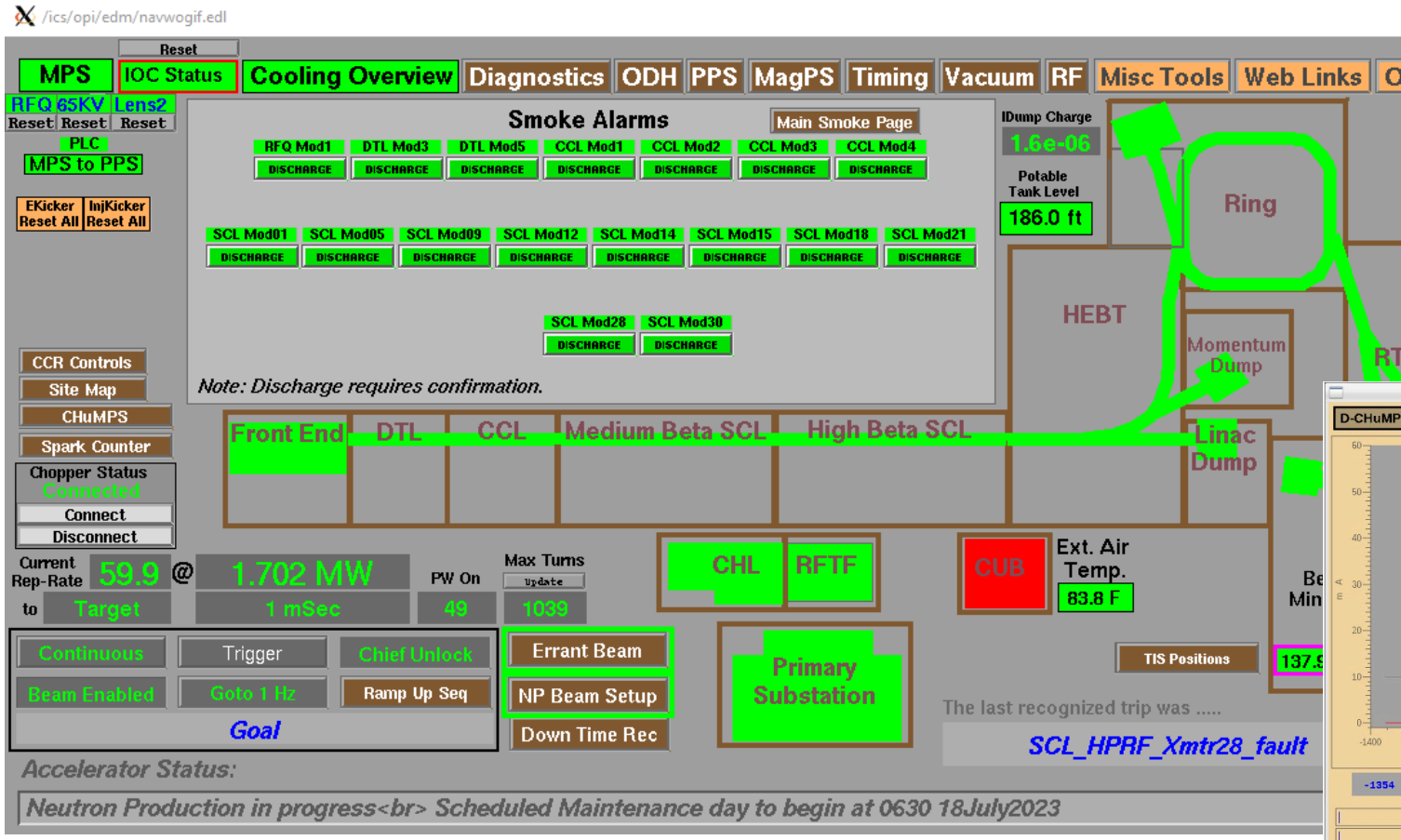
Slide courtesy of M. Champion

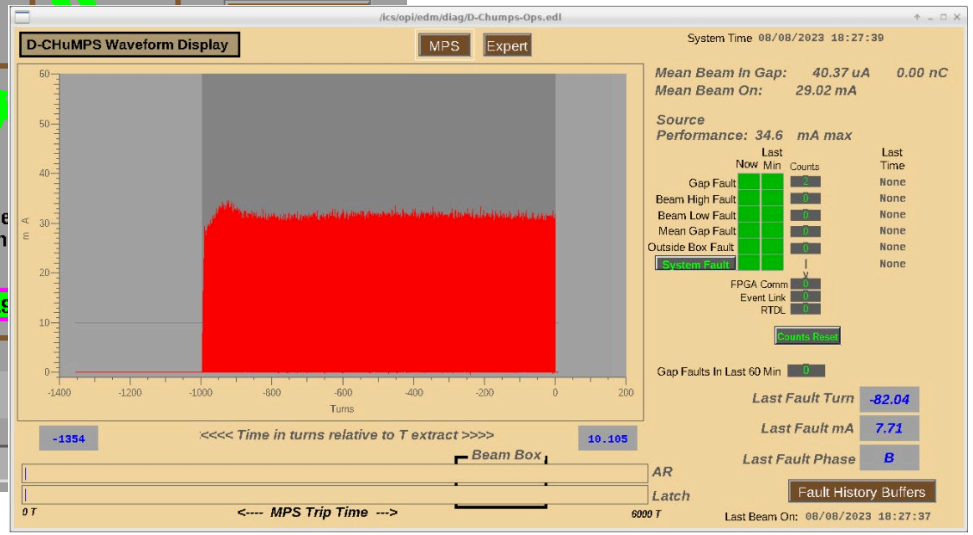
Successful 1.7 MW beam operation

- New equipment operates reliably
  - Trip rates comparable to 1.4 MW runs



Scheduled NP availability for:	Last 24 hrs.	Last 7 days	FY23-2	FY23
MWhr:	40.5	233.4	1452.2	3850.4
Avg MWhr/day:	40.5	36.9	32.9	32.9
NP Hrs. delivered:	23.8	137.1	928.5	2577.8





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Phase 3 installation started August 17, 2023

- Longest outage ever for SNS ~11 months
- LINAC
  - Install three new cryomodules
  - Complete installation/commissioning of RF stations
  - Upgrade two DTL high-voltage converter modulators to support 3 MW klystrons
- Ring
  - Install new injection region magnets
  - Install injection dump imaging system
  - Upgrade extraction kicker power supplies
- Target
  - Install mercury overflow tank
  - Complete the target gas injection system including recirculation
  - Install a new target
- Conventional Facilities
  - Perform Ring-to-Target Beam Transport (RTBT) Stub construction to enable future connection to the Second Target Station while operating the First Target Station

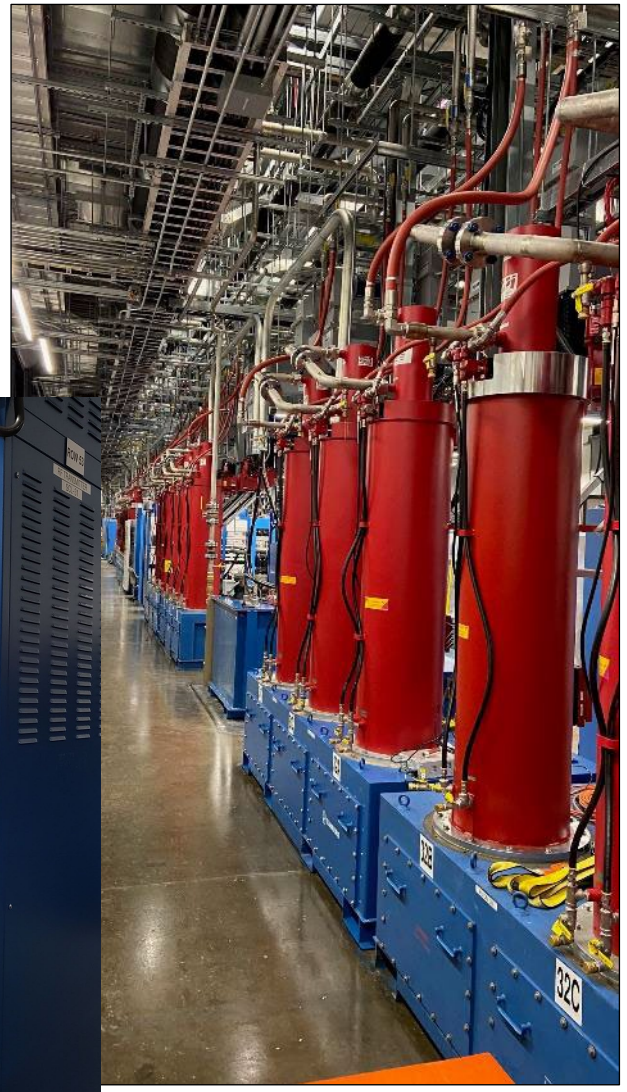
Linac systems installation & checkout

- All transmitters & klystrons are in place
- Seventh cryomodule placed in tunnel on September 28th
  - Cryomodules tested at SNS prior to installation
- Final LLRF systems installed and communicating

Cryomodules 27 thru 32 installed in the SNS Linac

LLRF racks

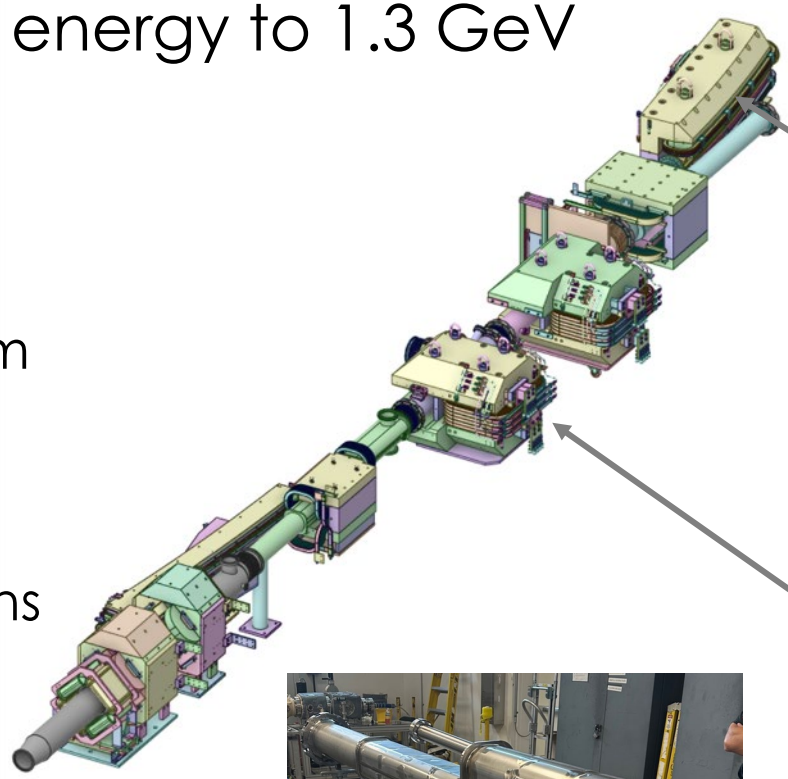
Transmitter racks



Klystron gallery looking upstream from the east end

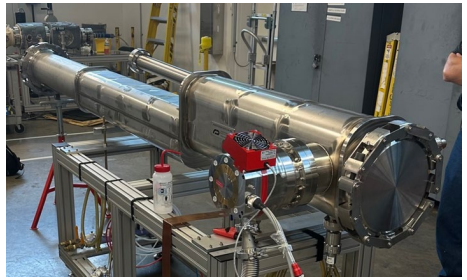
Ring upgrades are underway

- New Ring injection region magnets are required to increase beam energy to 1.3 GeV
- Phase 1 & 2 energy was limited to 1.05 GeV
  - Phase 2 1.7 MW goal was achieved by increasing beam current
  - Good stress test for LLRF adaptive beam loading correction & RF power margins
- Magnets testing complete and now on-site



Injection dump dipole ready for installation

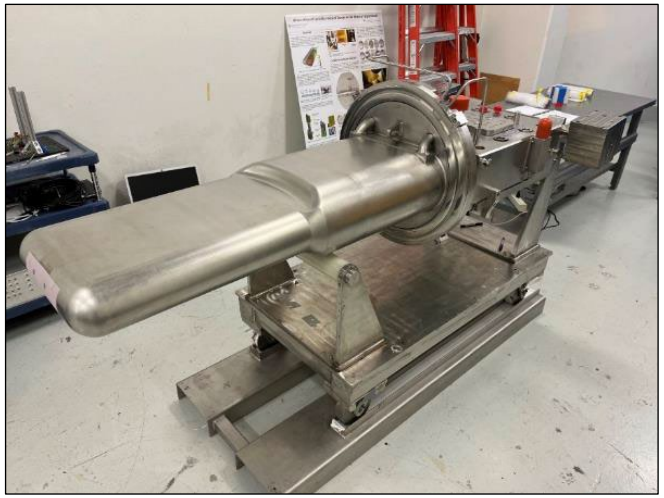
Chicane magnets in the warehouse awaiting installation



Chicane chamber 1 during leak check in SNS vacuum shop

Target Systems

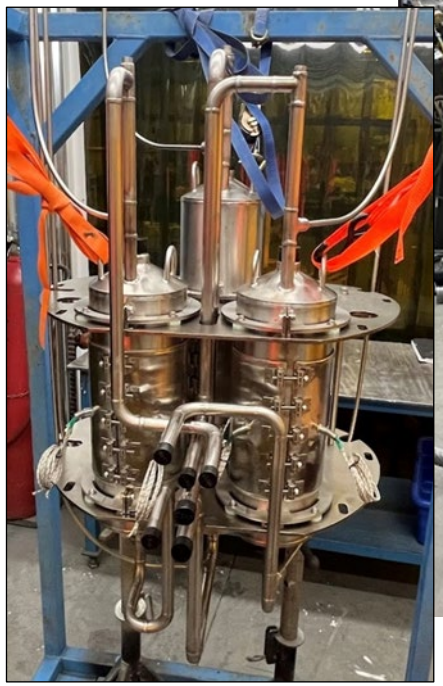
- PPU test target #2 in operation since November 2022
  - Supported 1.55 and 1.7 MW operation
  - >4400 MW-hours to date
  - Target will be replaced during outage
- Considerable work to complete for First Target Systems during outage



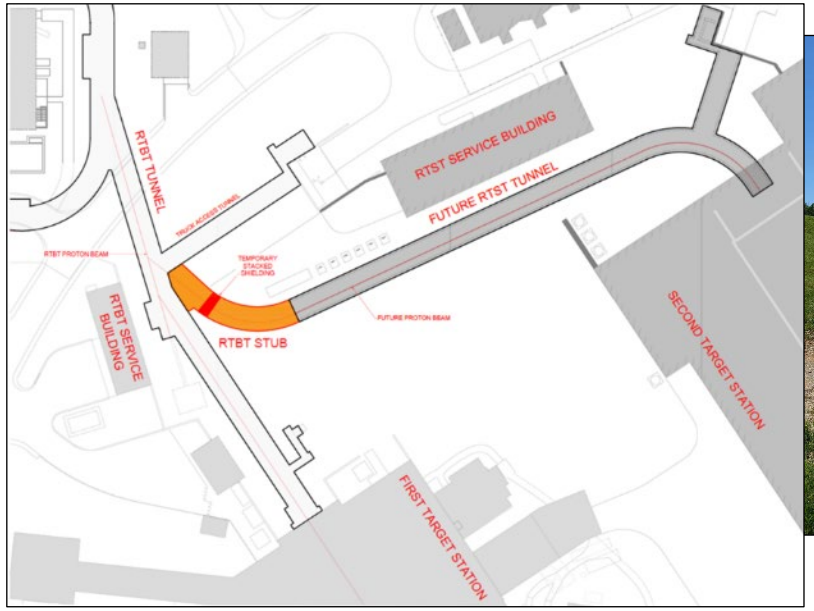
Test Target #2 prior to installation

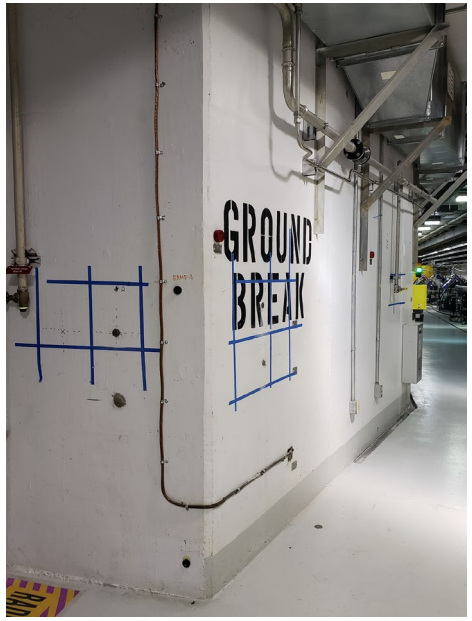
Mercury overflow tank

Ortho/para catalyst beds and vessel



RTBT Stub construction has begun



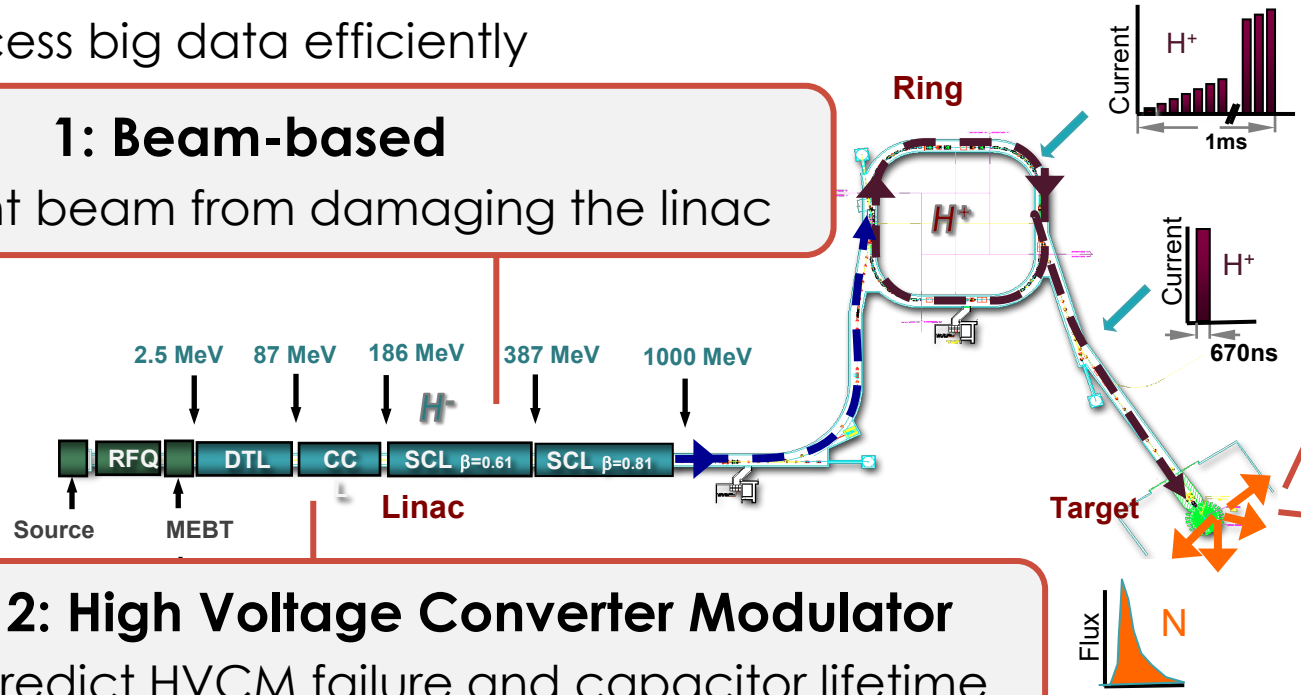


- Pre-outage site preparation excavation completed
- Excavation of the RTBT berm completed
- Rebar install started October 2023
  - Concrete pour
- Plan to finish in Feb. 2024

Machine learning and automation initiatives

- The Beam Diagnostics, Physics, and Operations Groups are active in developing ML applications
- Can we leverage Machine Learning advantages?
  - Automatic Learning process
  - Ability to model complex non-linearities
  - Ability to process big data efficiently

1: Beam-based
Prevent errant beam from damaging the linac



2: High Voltage Converter Modulator
Predict HVCM failure and capacitor lifetime

3: Target
Improve target performance by a faster simulation

4: Cryogenic Moderator System
System behavior optimization

Slide courtesy of W. Blokland

#4: Cryogenic Moderator System has been improved

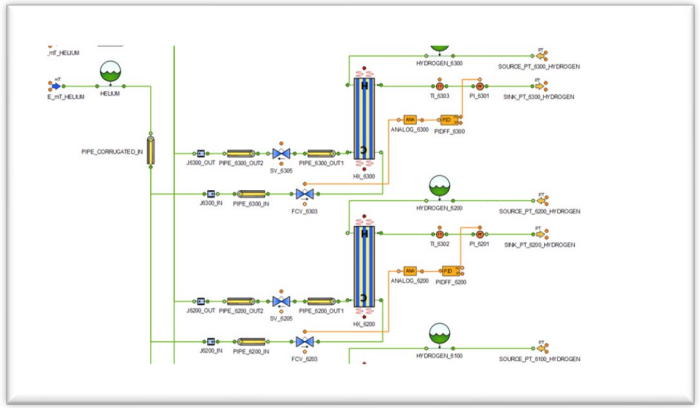
Problem

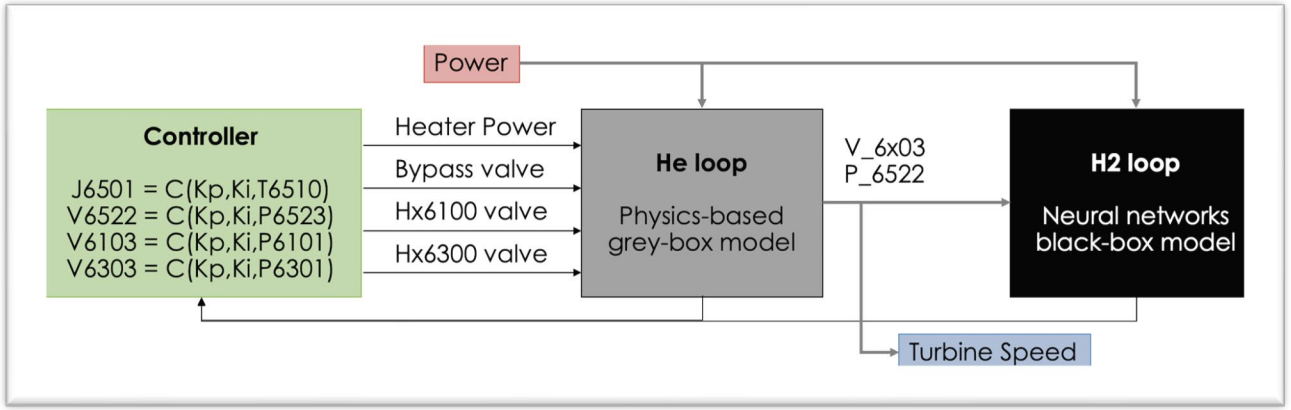
Undesirable behavior during transients, can be a problem after PPU. The system is complicated and not well modeled

Method

Construct models of subsystems

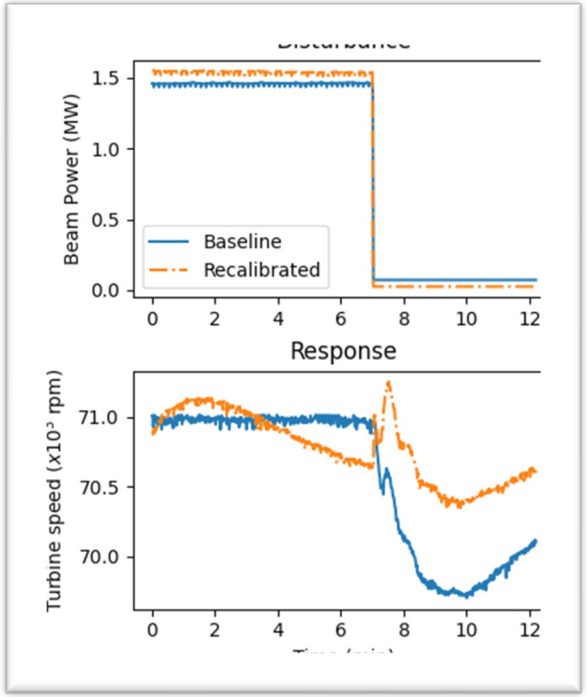
Use ML to augment models and use simulation to retune controllers





Results

Reduced turbine transients by 50% and factor of ten reduction in time for the system to return to desired state. The CMS will continue to operate with these improvements.

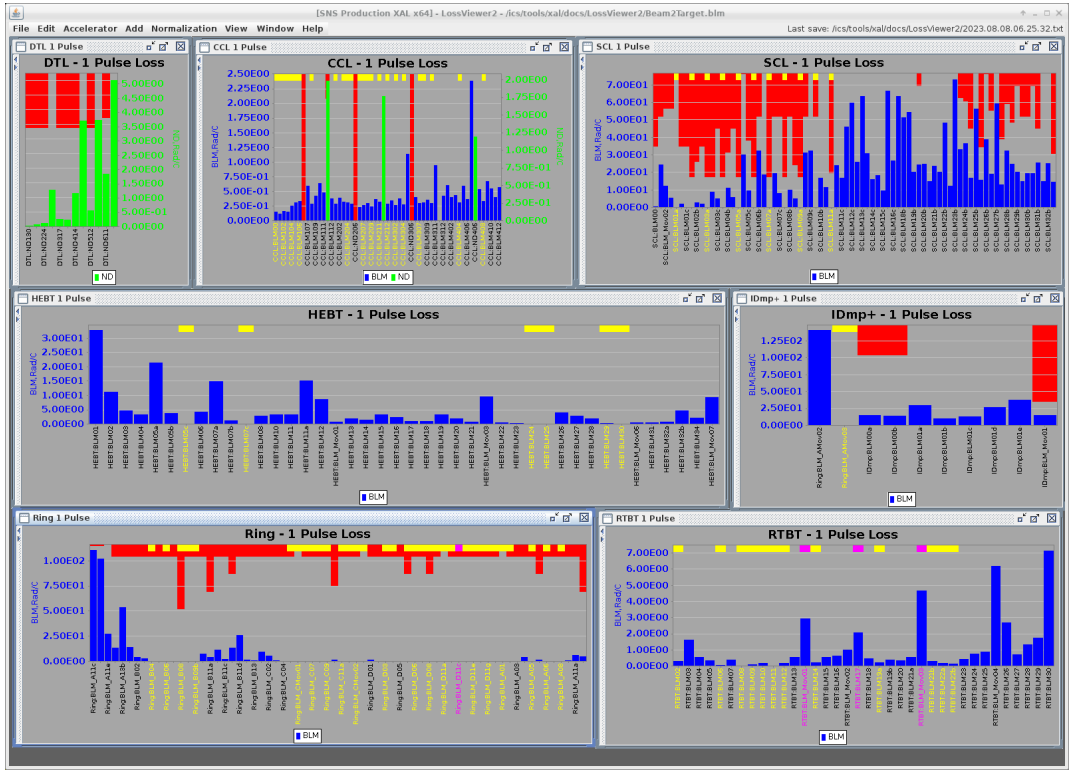


Turbine fluctuation reduced by 50%

Slide courtesy of W. Blokland

Motivation for Automated Beam Loss Tuning (ABLT)

- Minimize radiation exposure
- Maintain uptime through Proton Power Upgrade (PPU)
- Maintain losses due to:
  - Beam halo
  - Day-to-day variances
- Find optimum loss profile with ML



LossViewer application showing all **B**eam **L**oss **M**onitors

Slide courtesy of C. Elliott

Objectives

1. Maintain *and* Optimize Beam Loss

- Tune like an operator first, then explore alternative methods
- Shift RF cavity phases, amplitudes, and quadrupole magnet currents
- Save knob settings & diagnostics to HDF5 file
- Maintain beam & centering on injection dump, beam size and centering on target, power on target, orbit, etc.
- Correlate loss with activation using survey data

2. Run Application during NP

- Test and verify behavior during Accelerator Physics periods
- Receive approval from SNS Accelerator Configuration Control Committee (ACCC)
- Implement safeguards for reliability
- Feed data to ML for future

- The algorithm was successfully tested and allowed to operate for 24 hours with no MPS trips

Slide courtesy of C. Elliott

Summary

- The Proton Power Upgrade project has dominated our efforts during the last year
  - Required to meet the power, availability, and reliability goals during phased power increases
- Phased installation has performed as planned
  - Phase 1 achieved power increase to 1.05 GeV @ 1.55 MW
  - Phase 2 achieved power increase to 1.05 GeV @ 1.70 MW
- Redesigned LLRF control system has met all performance goals
- Phase 3 installation is underway with a planned return to operations date of July 2024
- ML is proving to be a useful tool with achievable applications
- Automation improvements show promise to reduce workload

Acknowledgement

- Thanks to the extensive team for their dedication and hard work. None of this would be possible without the help of everyone involved.
- *LLRF Development Team*
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- *PPU Project Office*
  - John Galambos, Mark Champion
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- Automation slides courtesy of Carrie Elliott
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