Oak Ridge National Laboratory

High power operation, upgrade and R&Ds at Spallation Neutron Source

Presented at the

FRIB/MSU APES

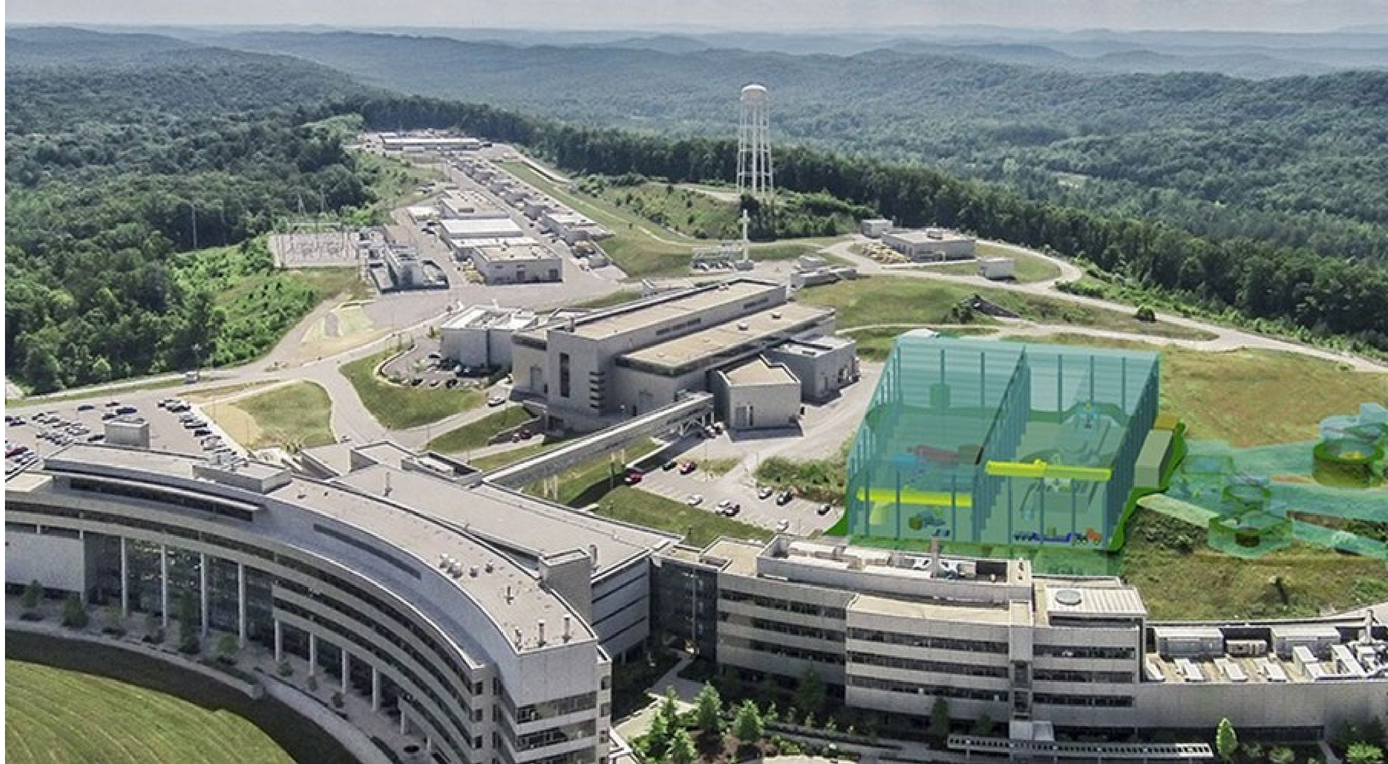
September 22, 2023

Sang-ho Kim
On behalf of the SNS and PPU project team

U.S. DEPARTMENT OF ENERGY

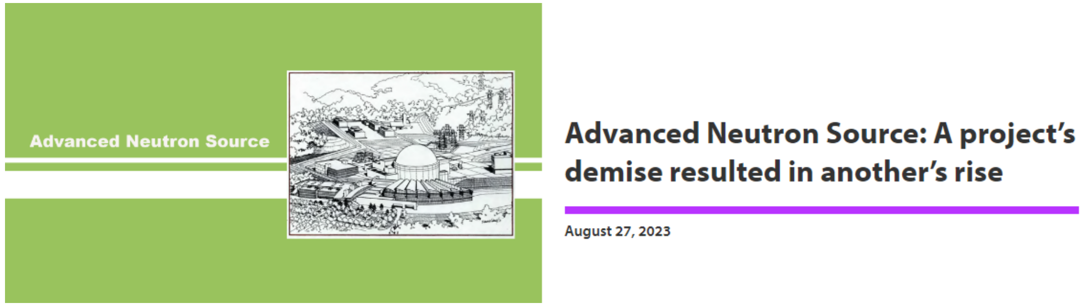
Outline

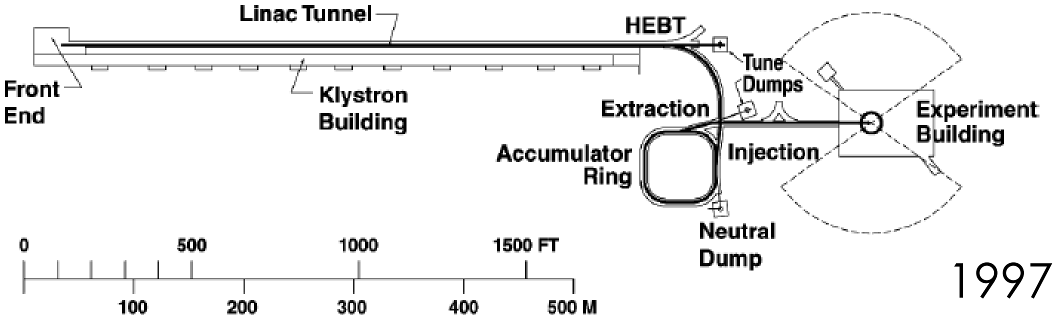
- Introduction and status of SNS accelerator
- PPU project and power ramp-up
- R&D topics (current and future) at SNS



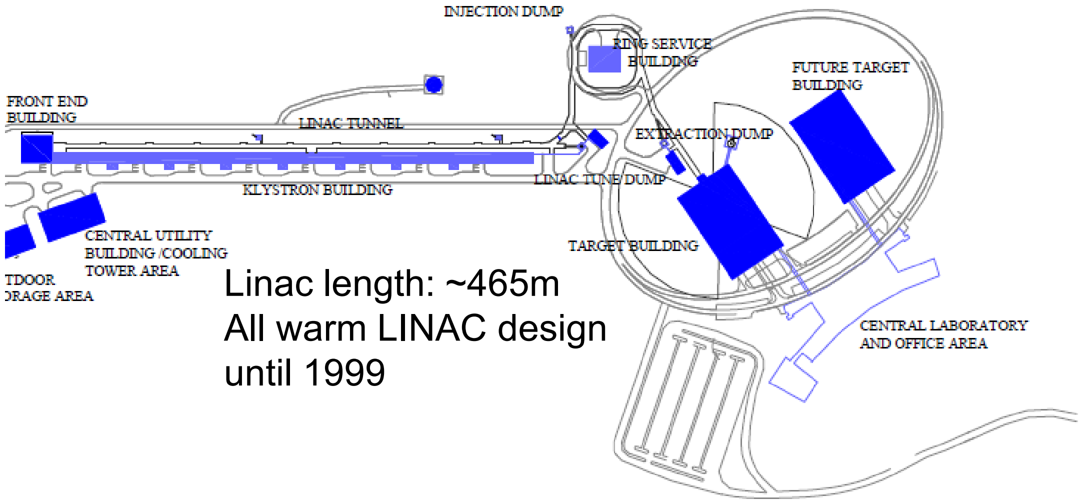
History of SNS

- 14th reactor (ANS) at ORNL for neutron scattering, isotope production and material irradiation was proposed in early 1990s
  - But cancelled
- Accelerator based neutron source was proposed, along with extension of HFIR reactor operation
  - National Spallation Neutron Source (NSNS)
- Spallation Neutron source received CD-2 approval in 1997
  - 1-GeV warm linac + accumulator ring
- After CD-2, adopted SRF in 2000
  - Warm linac up to 186 MeV + Superconducting linac up to 1000 MeV (+ room for upgrade)



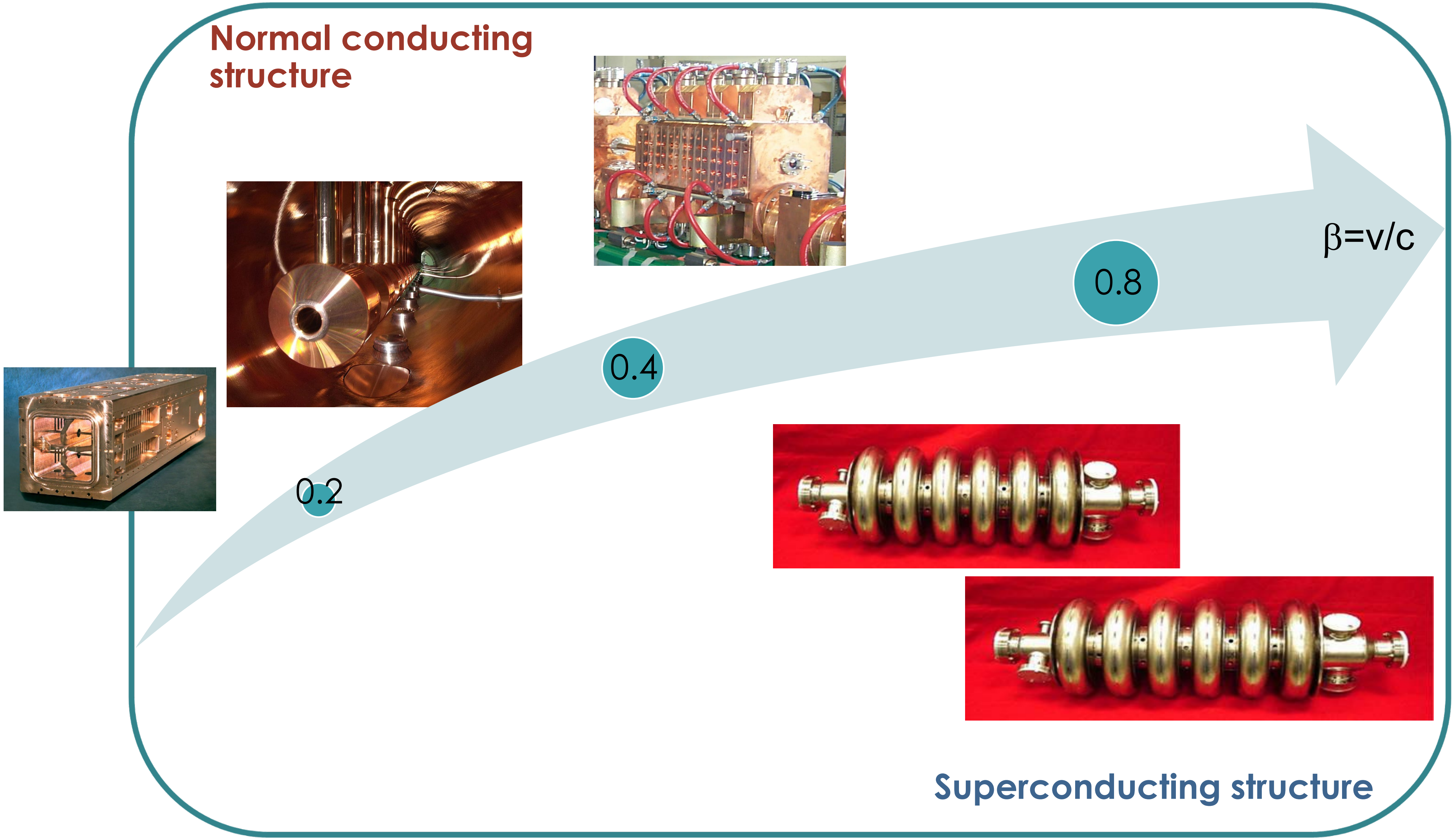


1997

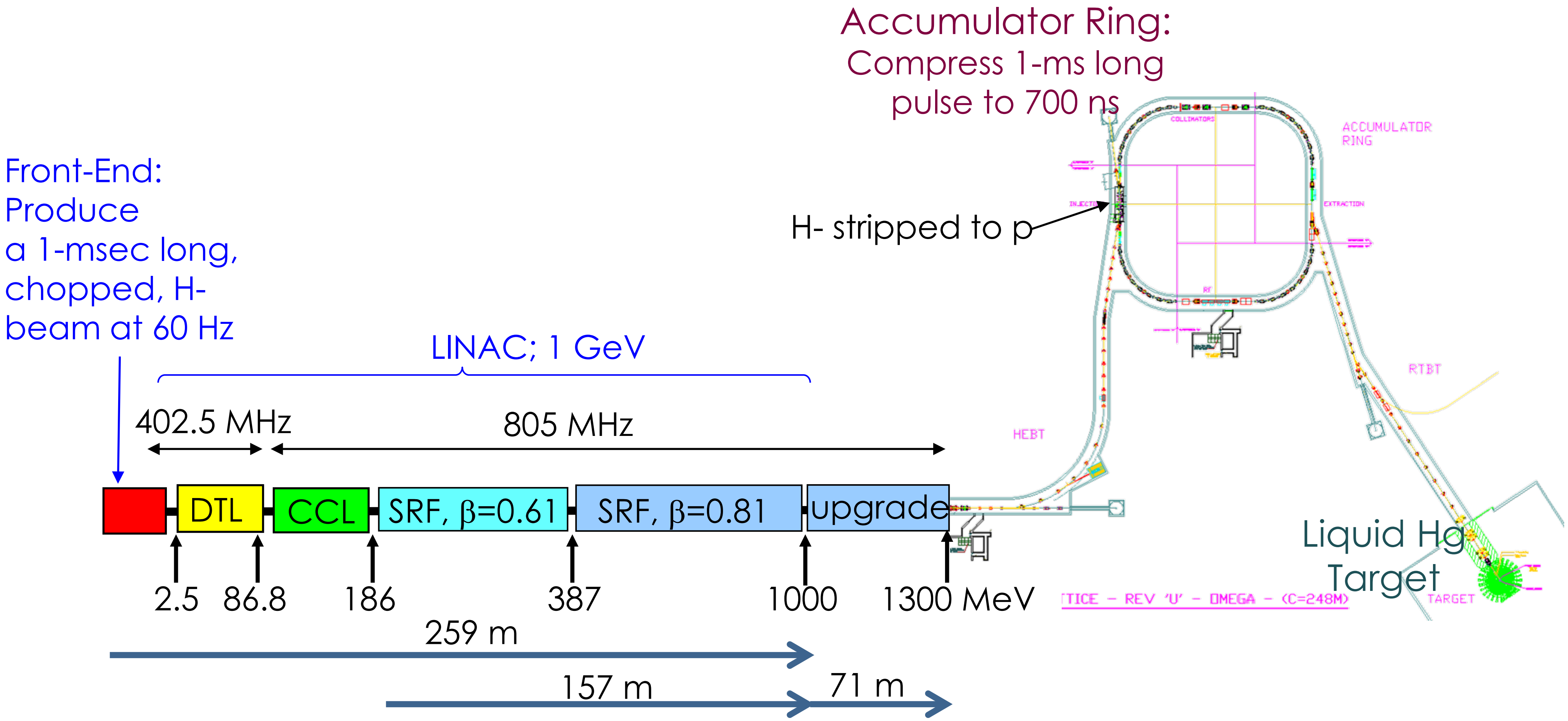


Linac length: ~465m
All warm LINAC design until 1999

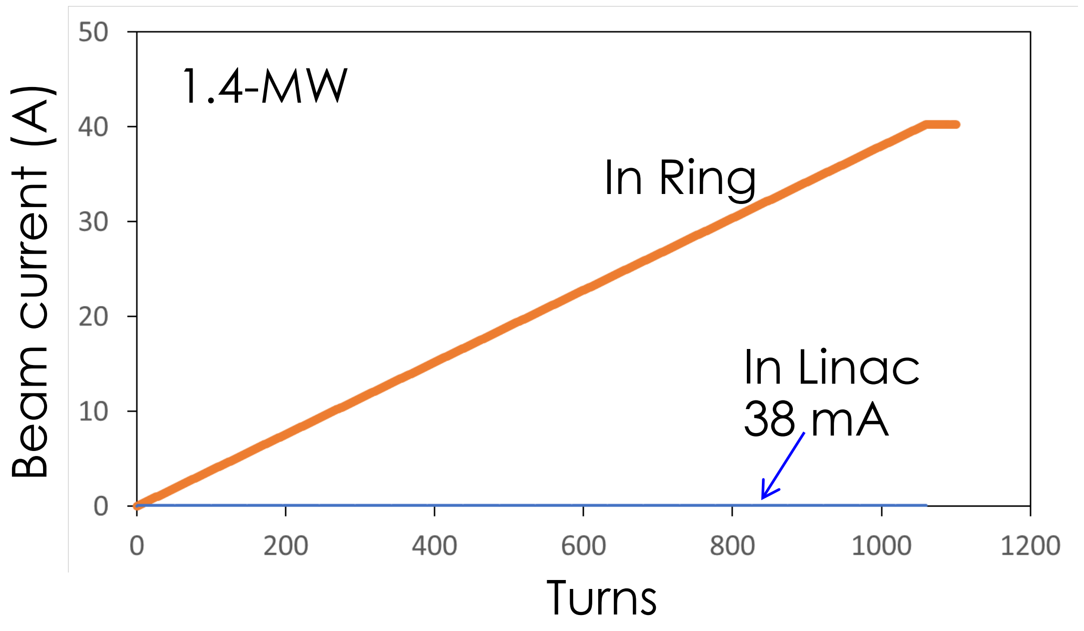
RF structures in SNS linac



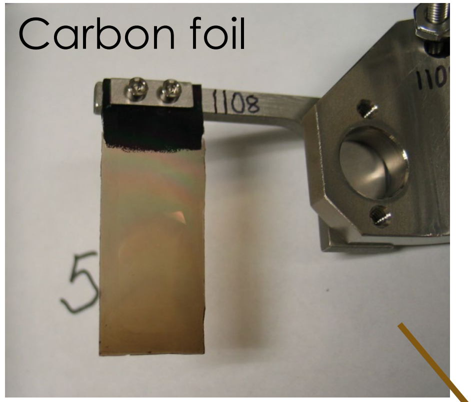
Final layout of SNS

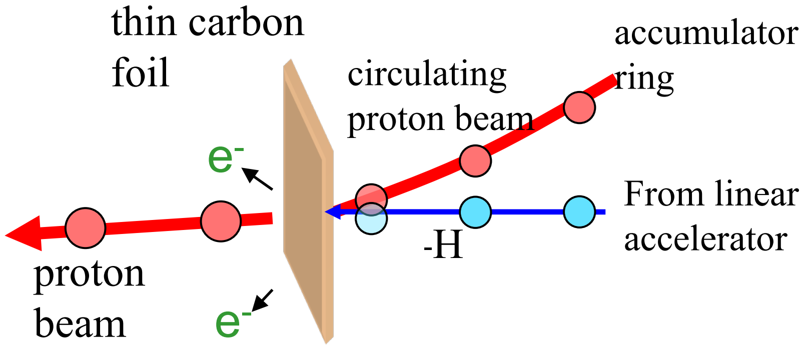


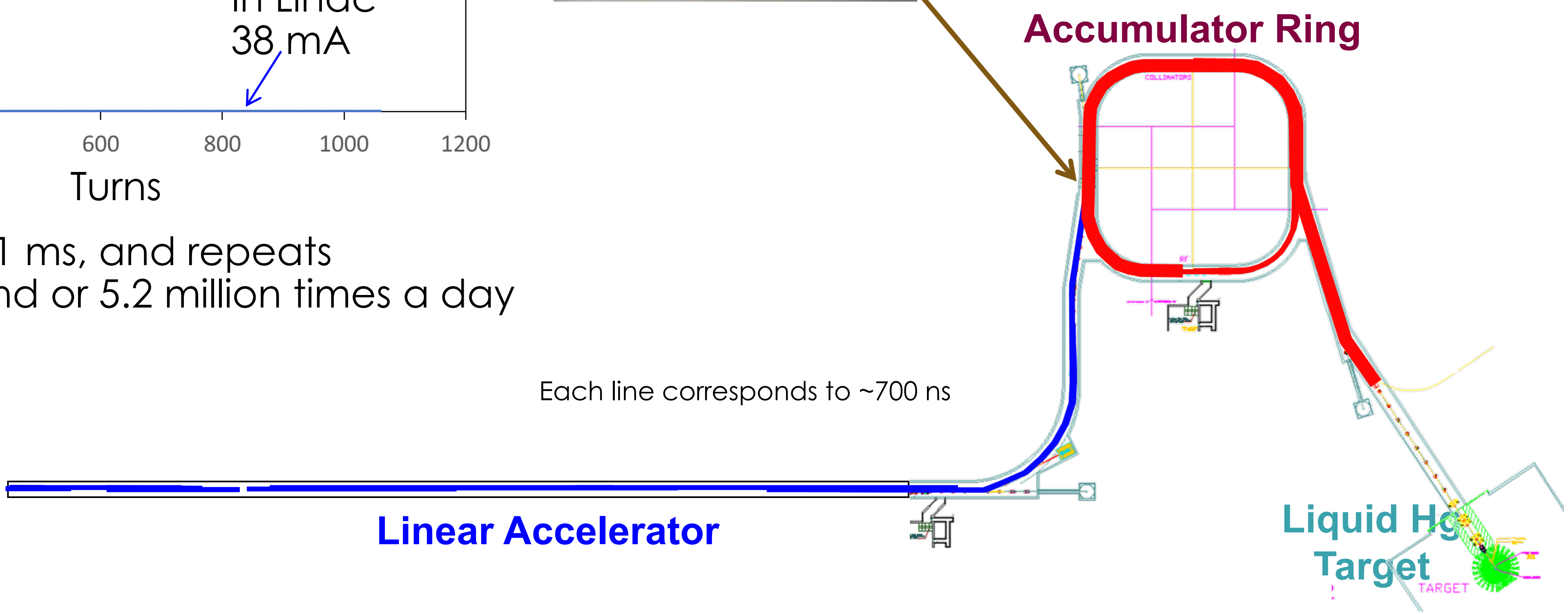
Acceleration, accumulation, and extraction



This happens in 1 ms, and repeats
60 times a second or 5.2 million times a day







Each line corresponds to ~700 ns

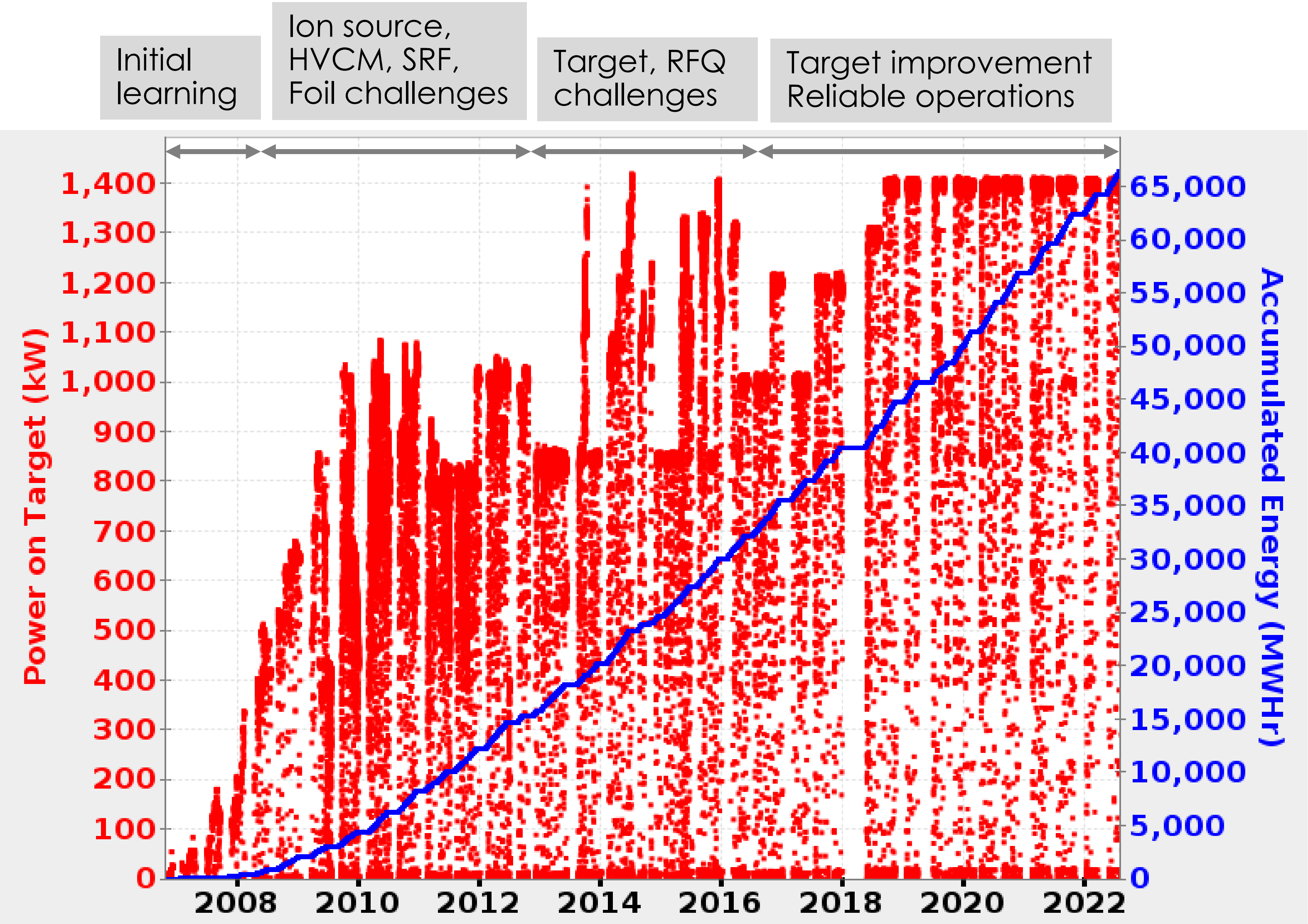
Challenges of the original SNS project

- 1.4 MW, pulsed spallation neutron source; about 7~8 times bigger beam power than any existing machines ✓
- Low beam loss at 1.4-MW operation for hand-on maintenance ✓
- 1.4-MW beam accumulation (~1.5e14 ppp) in the ring & stripper foil ✓
- Superconducting RF technology for high energy proton acceleration ✓
- Liquid mercury target ✓
- IGBT based compact High Voltage Convertor Modulator (HVCM) ✓
- Machine availability goal >90 % (typically 4,500 production hours per year) ✓

All these challenges required significant R&D.

All challenges were overcome and SNS achieved stable/reliable operation at 1.4 MW operation

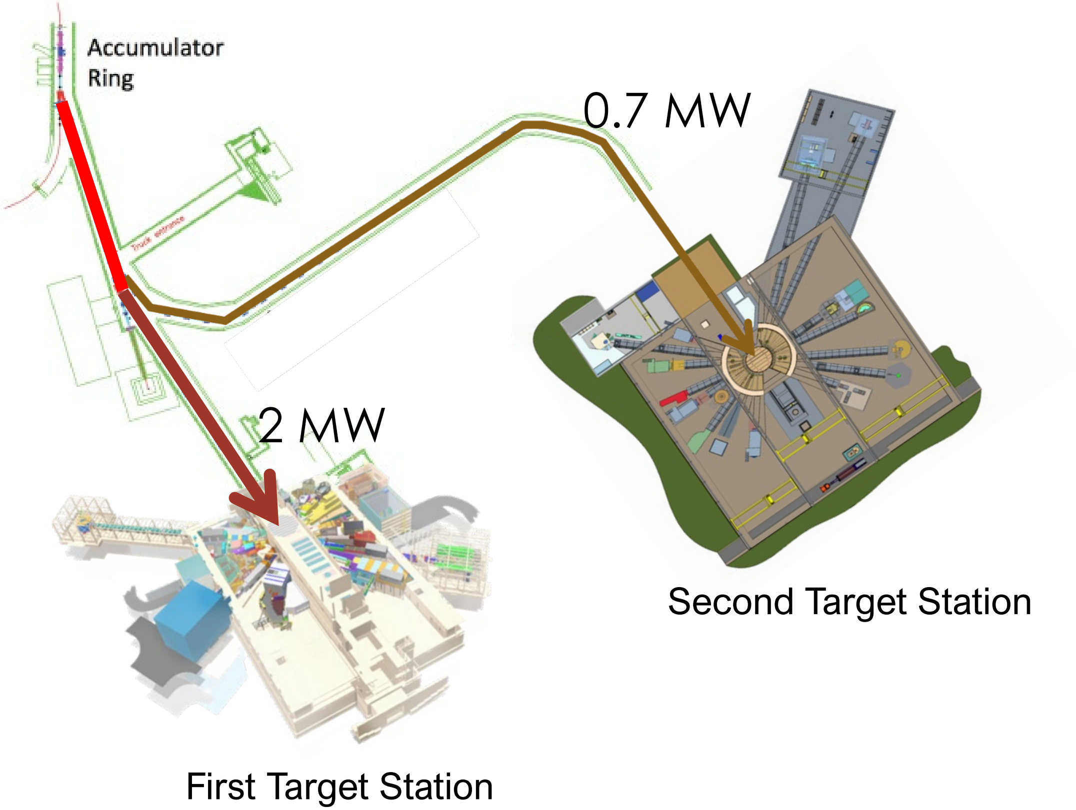
Beam power history



Proton Power Upgrade (PPU) Project

Proton Power Upgrade Project

- Accelerator: upgrade or replace components to enable 2.8 MW beam operation
- First Target Station: upgrade for 2-MW beam at 1.3 GeV, 60 pps



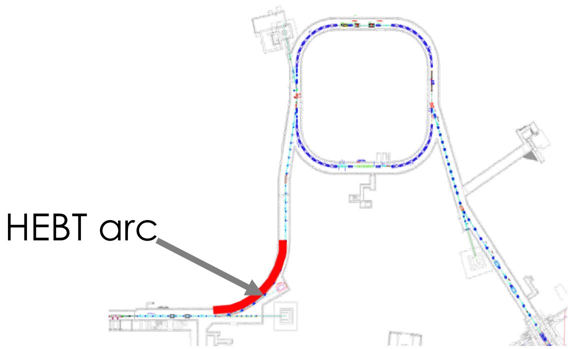
- Second target station (STS) is a separate project (received CD-1)
- Beam distribution after STS
  - 45 pps to First Target Station (2.0 MW)
  - 15 pps to Second Target Station (0.7 MW)
  - Beam energy per pulse ~ 47 kJ

PPU approach for 2.8-MW accelerator capability

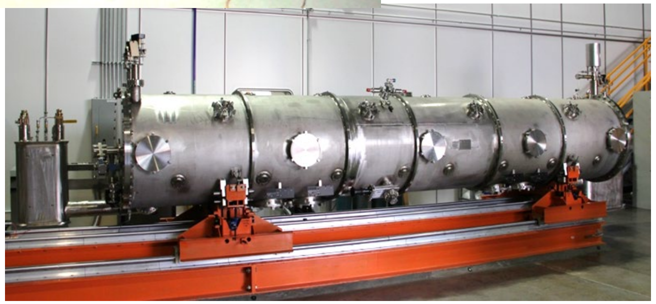
- Optimization between built-in upgrade provisions, Cost effectiveness and Technical aspects

- Beam energy upgrade to 1.3 GeV
  - At H- beam >1.3 GeV, Lorentz Stripping would cause increased beam loss at HEBT arc
  - All existing magnets in HEBT and ring are capable for 1.3 GeV except injection and extraction regions
  - By adding 7 PPU cryomodules and associated RF/HVCM systems
    - PPU cryomodule design based on in-house built spare high beta cryomodule

- Beam current increase by 50%
  - All existing systems are capable or adjustable using operational flexibility (e.g. SCL)
    - Except three DTL high-power RF systems and associated HVCM (out of ~100 existing RF systems)



Empty slots at the end of linac tunnel

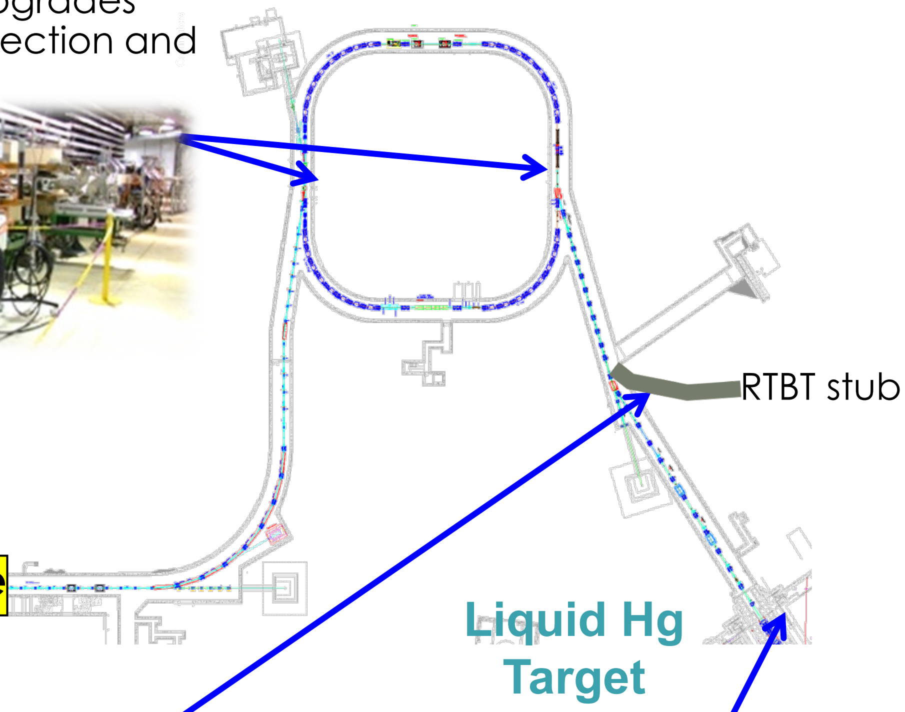


Spare HB cryomodule in production since 2012 demonstrates PPU gradient

PPU scope

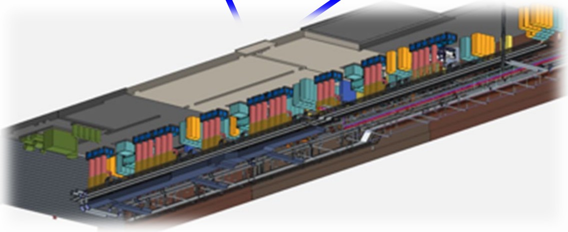
Superconducting Linac upgrades
- Add 7 new cryomodules

Ring system upgrades
- Primarily injection and extraction



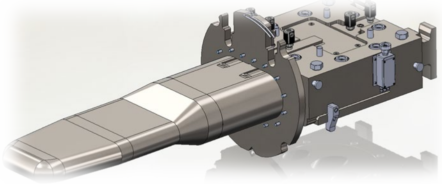
FE | DTL | CCL | SRF, β=0.61 | SRF, β=0.81 | **upgrade**

Radio Frequency (RF) system upgrades
- Additions for new cryomodules
- Upgrades for existing systems



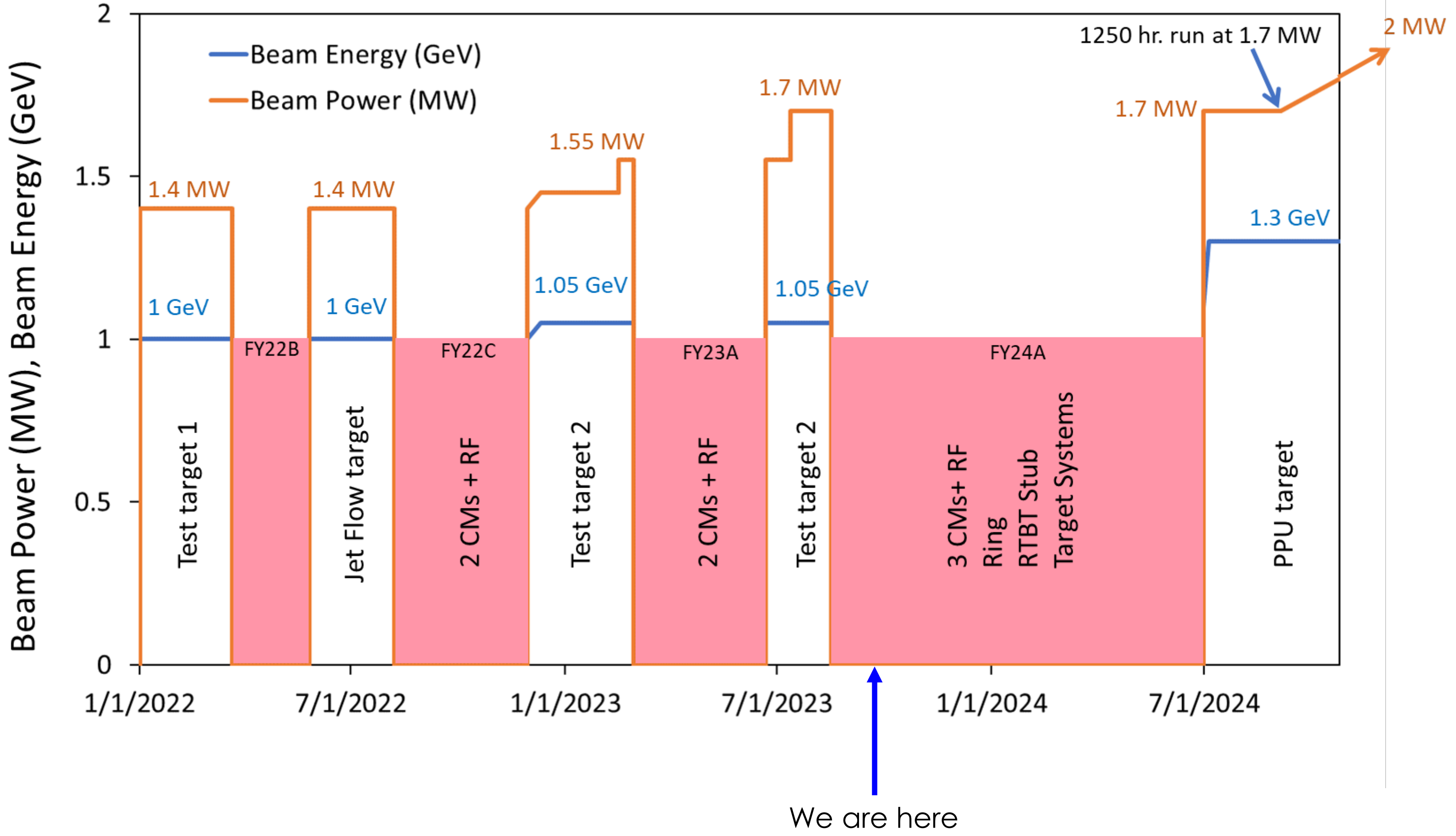
Conventional facility upgrades
- Klystron gallery extension
- RTBT stub

First Target Station upgrades
- 2 MW, at 1.3 GeV, 60 pps

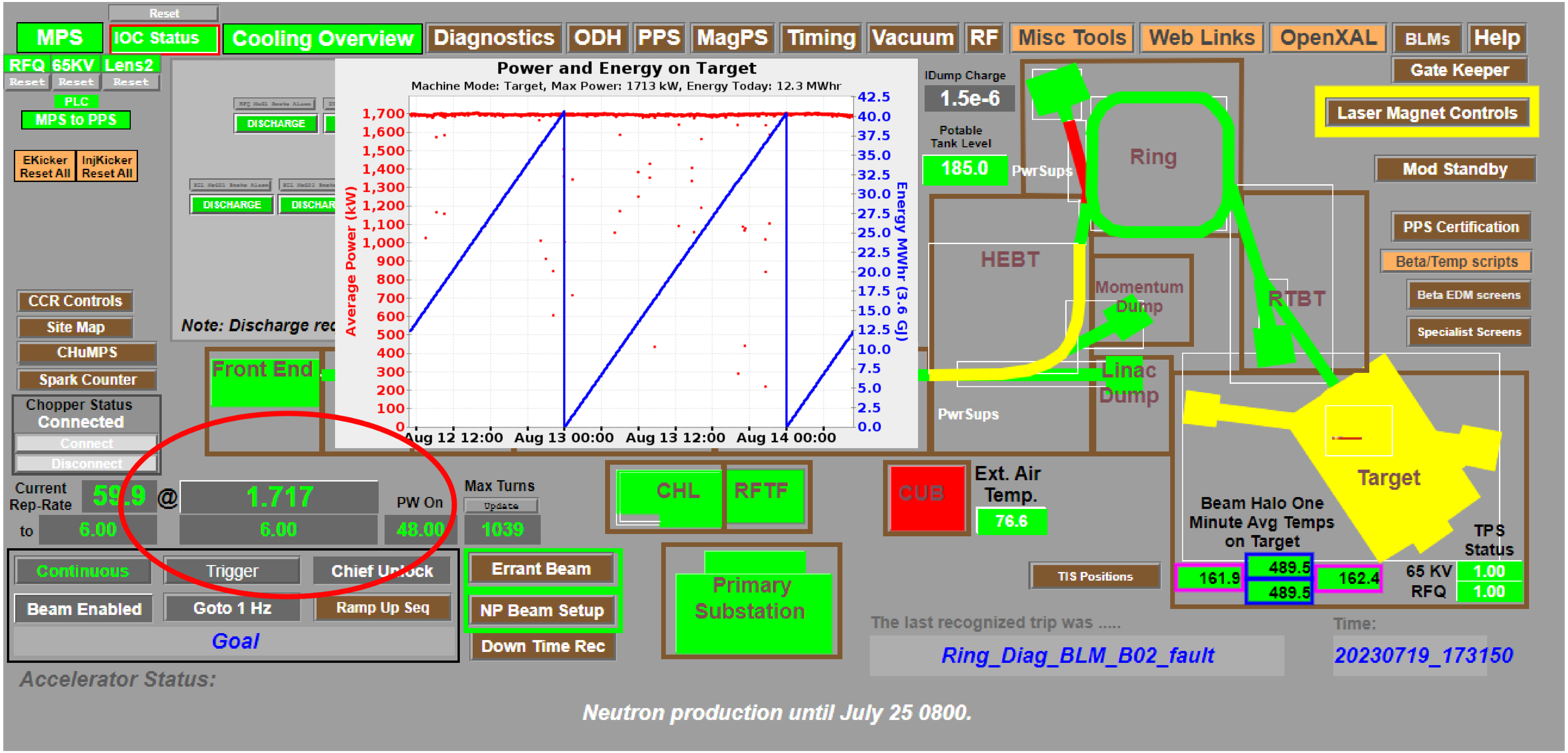


Power Ramp-up plan

- Performance verification of new equipment as they are installed
- Increase neutron flux to users more quickly than would waiting until project completion
- Last run SNS achieved a stable operation at 1.7 MW

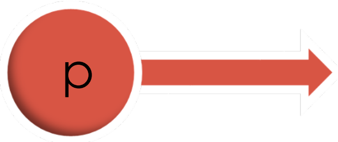


1.7MW at 1.05 GeV – equivalent to 2.1 MW at 1.3 GeV



Beam power

- A single proton at 1.3 GeV → 2.1 x 10^{-10} J



- For 2.8 MW average beam power at 1.3-GeV protons
  - Number of protons per second : 1.35 x 10^{16}
  - Number of protons per pulse at 60 pps : 2.24 x 10^{14}
    - Charge per pulse : 36 μC
    - Energy per pulse : 46.7 kJ, Energy per second: 2.8 MJ

(for comparison)

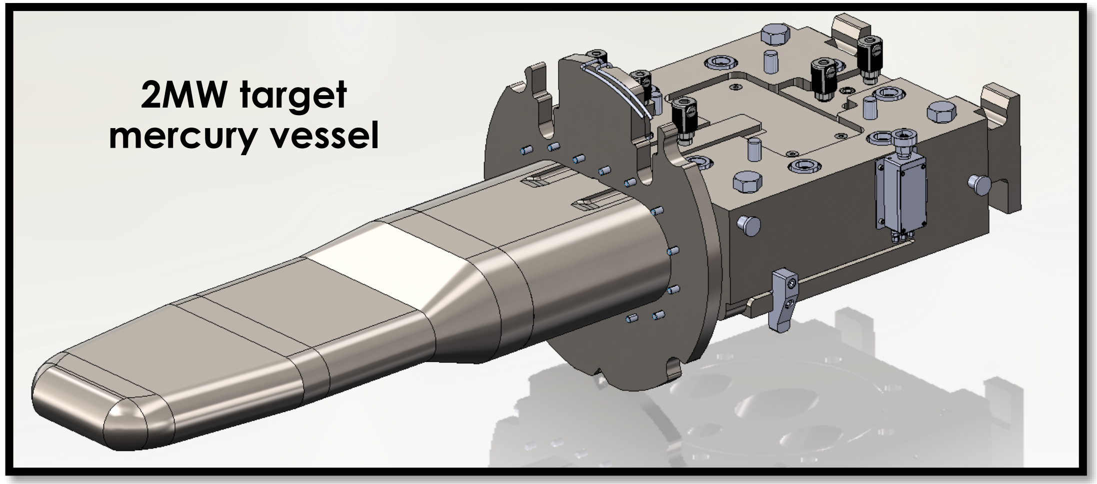
– 500 kg object at 50 km/h: 48 kJ

– 100 g projectile at (3 × speed of sound): 53 kJ

– One stick of dynamite: ~ 1 MJ

First Target Station (B. Rimmer, C. Barbier, D. Winder et. al.)

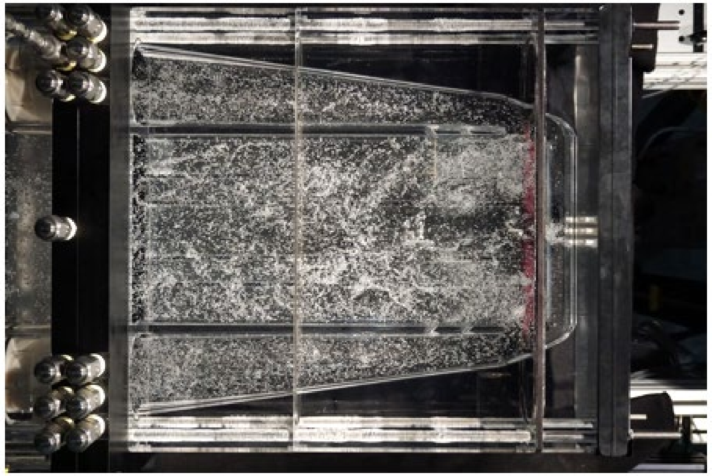
- 2-MW target design
  - All available means of leverage are sought (gas injection, years of operational experience, post irradiation exam, strain measurement, fabrication, collaboration, modeling/simulation, etc.)
  - 10 + 10 slpm gas injection capability
- Successful R&D for high-rate gas injection
- PPU test target 2: Record high operation 4400 MW-hour running at 1.4 – 1.7 MW

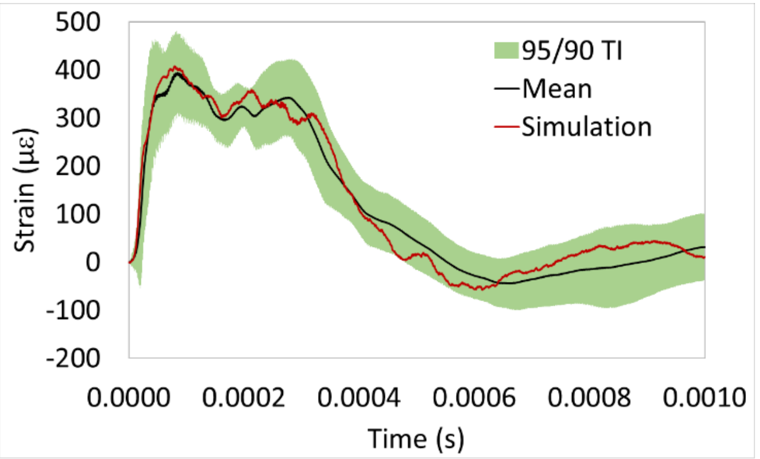


w/ no gas
target16

w/ gas
Target 29

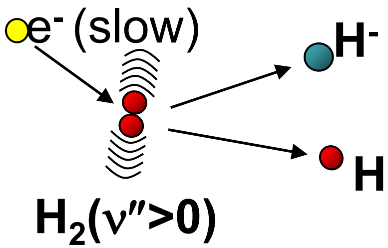
Post Irradiation Examination

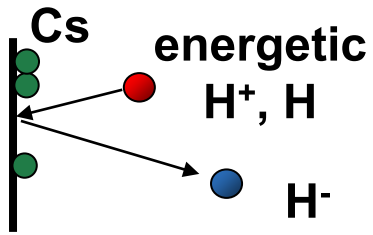




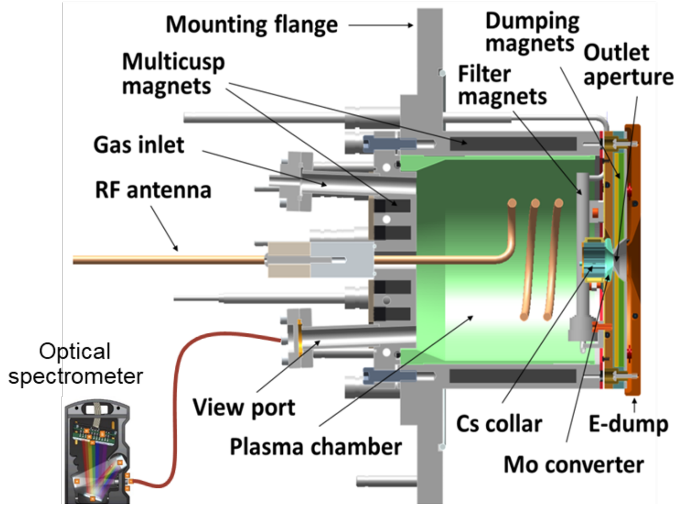
Accelerator R&D topics at SNS
multi-faceted efforts for near term, medium term and long term

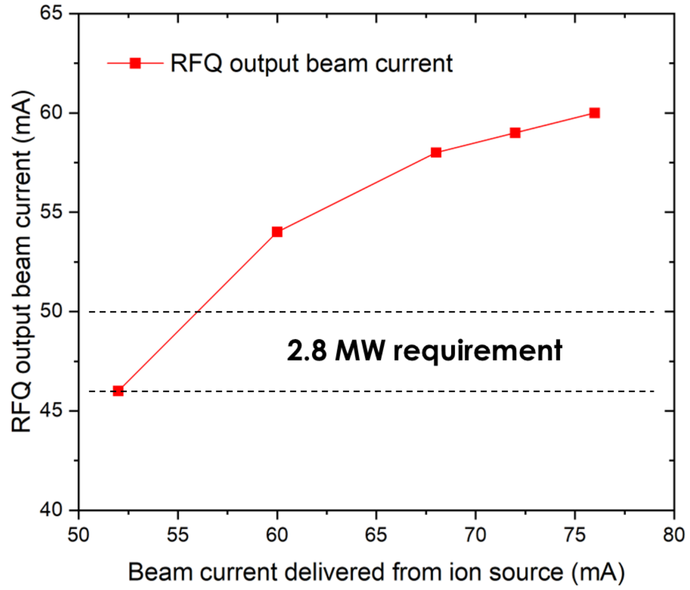
H- ion source R&D (B. Han et. al.)





- Goals: Higher current, good beam quality, long lifetime running at lower hydrogen gas, lower RF power
- Achieved a single source per run cycle (~4 month long) with output beam current 50-55 mA
  - Total extracted H- charge per source is ~ 10 A-hours, this is the world record (a few times higher than any other H- sources)
- Tested much higher beam current with advanced beam extraction and background RF system
  - Sufficient margin even for 2.8 MW operation
  - Same beam current at much reduced hydrogen gas

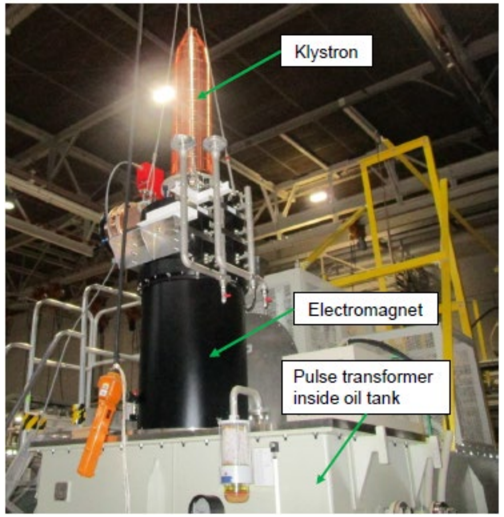




Development for long-term sustainability of warm linac

5-MW Klystron

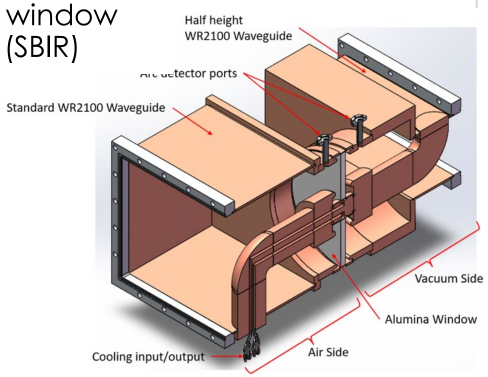
- This project is to develop a new vendor to secure a supply chain and quality of products for this critical component
- Successful factory acceptance test with the first production article

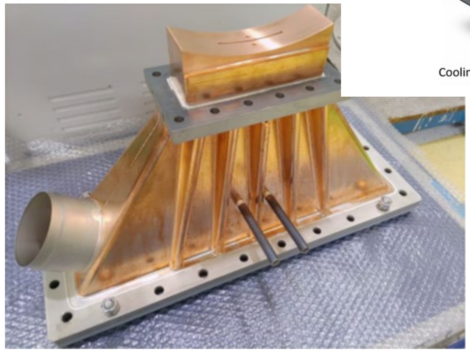


DTL Iris coupler & new 3MW window

- Occasionally showing vacuum activities causing RF truncations: One of single point failures
- Working group updated design and developed spares iris coupler
- RF structure team is working with a company (SBIR) for new 3-MW window

New high power window development (SBIR)

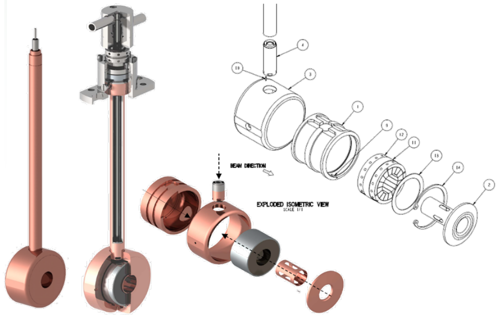


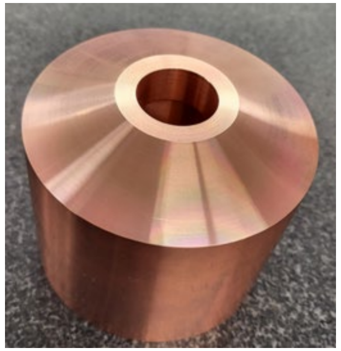


3 MW iris coupler

Drift tube engineering

- SNS DTL has 210 unique drift tubes (DTs): four types (empty drift, beam position monitor, permanent magnet quadrupole, electromagnet dipole)
- Recently (October 2020, and March 2023), one DT with electromagnet in DTL2 and DTL3 each showed cooling water leaks (water line to air)
- Working group (RF and mechanical engineering) was formed in FY2021, refined engineering and is developing a vendor

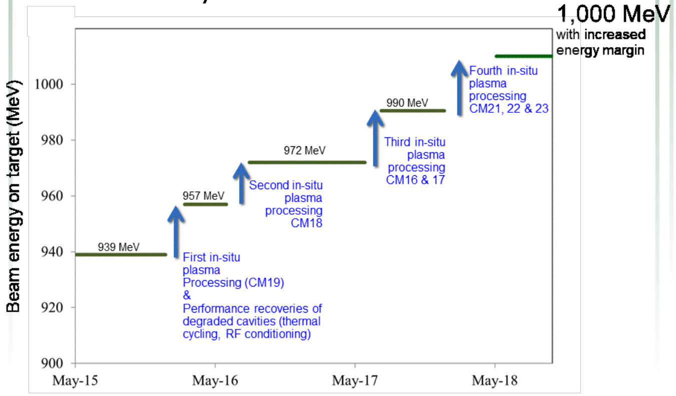




Developments for long-term sustainability of SCL

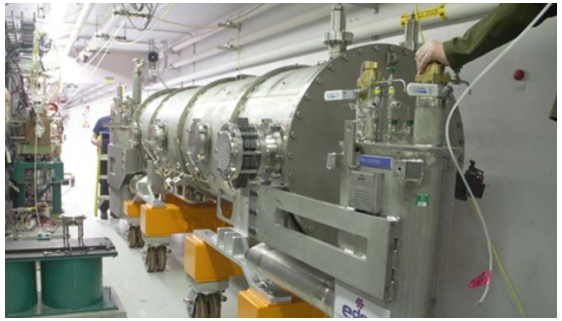
Plasma boosts to 1 GeV

- Cryomodule/SRF has achieved its stable operation since 2010, but
- Beam energy was limited at 940 MeV until deployment of plasma processing
- Total 10 cryomodules have been successfully plasma processed
  - 8 high beta cryomodules
  - 2 medium beta cryomodules



Spare cryomodule development

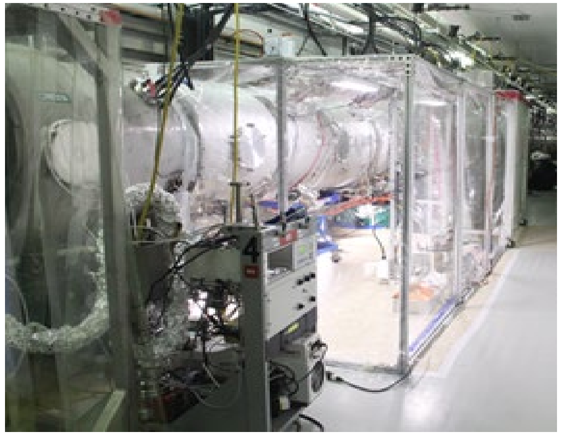
- Both medium- and high-beta cryomodules fabricated in-house by SNS personnel
- Allows off-line cryomodule repair while maintaining the same beam energy



Installation of the spare medium beta cryomodule in the slot 1 in February 2020

In-situ replacement of beamline components

- Established class 100 or better environment in the local clean room
- Better maintenance efficiency



Local clean room setup for cryomodule repair and installation of new power couplers

Repair of internal leak

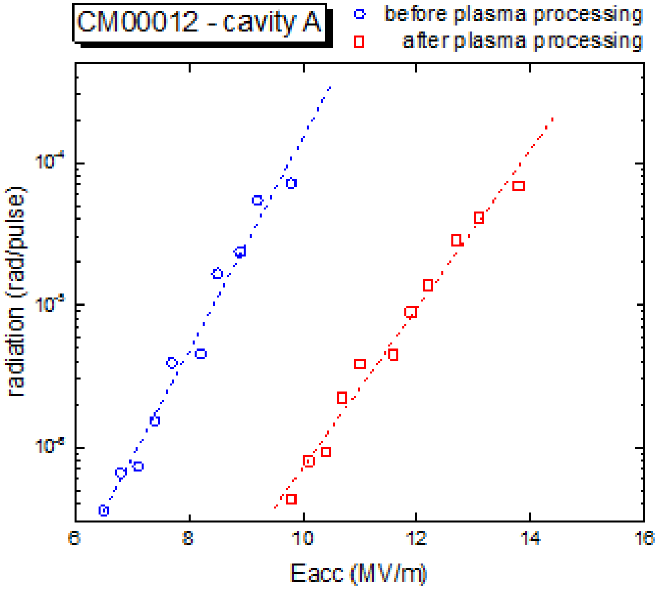
- Leak is THE biggest enemy
- Developed engineering, procedures, work control, training for contaminated cryomodule maintenance

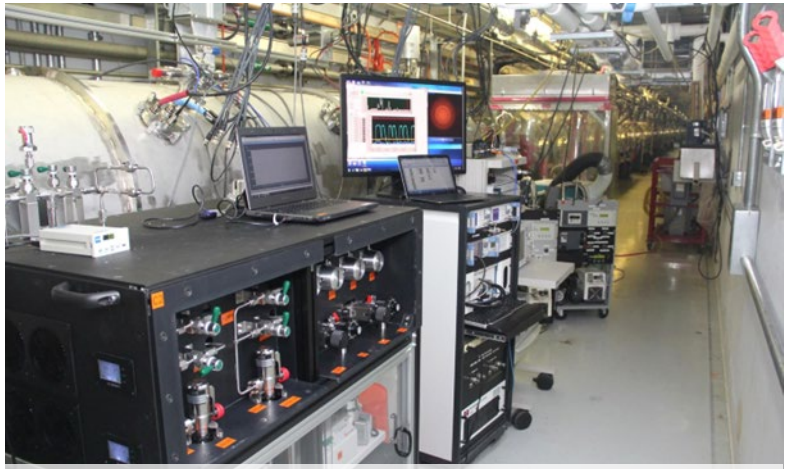
Cutting/grinding of cryomodule end-can in decontamination tent

Plasma processing for SRF cavities at SNS (M. Doleans et.al.)

- SNS developed a novel in-situ method, plasma processing using Ne-O_2 plasma to reduce electron activities (field emission, multipacting) for both medium- and high-beta cryomodules
  - Oxygen plasma mainly removes hydro-carbons
  - gathering lots of interest in the community leading to collaborations for technology transfer to other laboratories
- 'Ex-situ' method is being investigated
  - More aggressive method than oxygen plasma aiming at mild dry etching


Ignition of plasma in SRF cavity

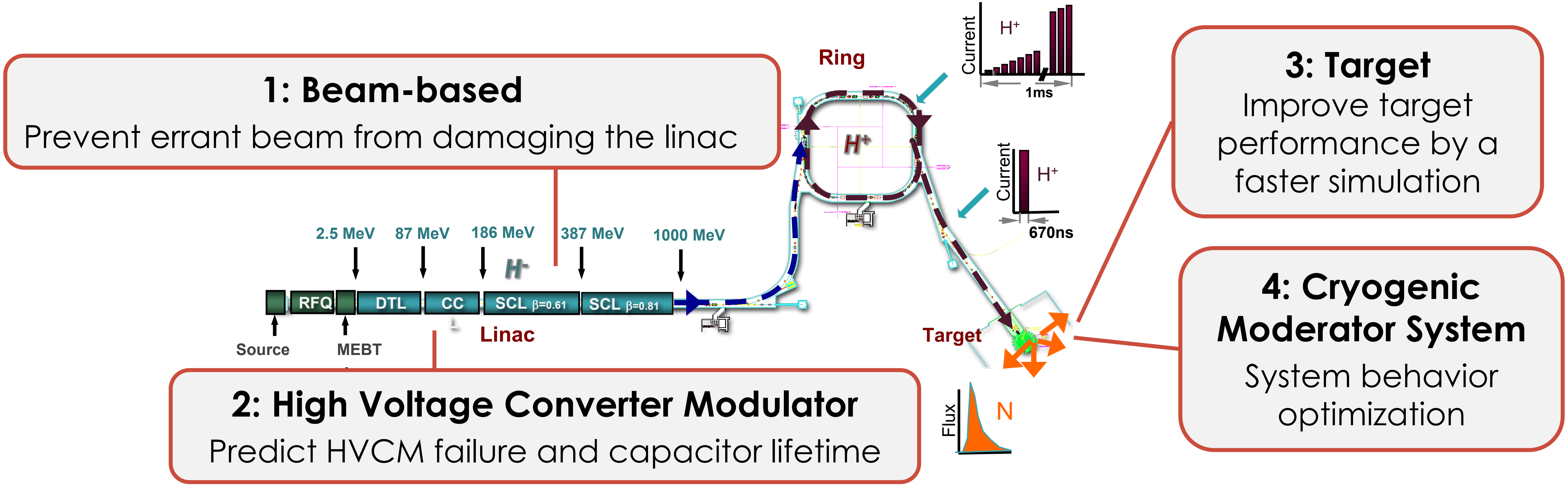



In-situ plasma processing in the tunnel

Machine Leaning R&D (W. Blockland et.al.)

Can we leverage Machine Learning advantages?

- Automatic Learning process
- Ability to model complex non-linearities
- Ability to process big data efficiently

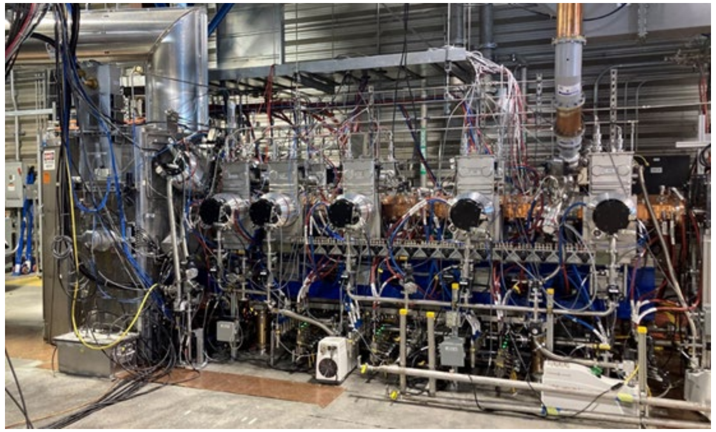


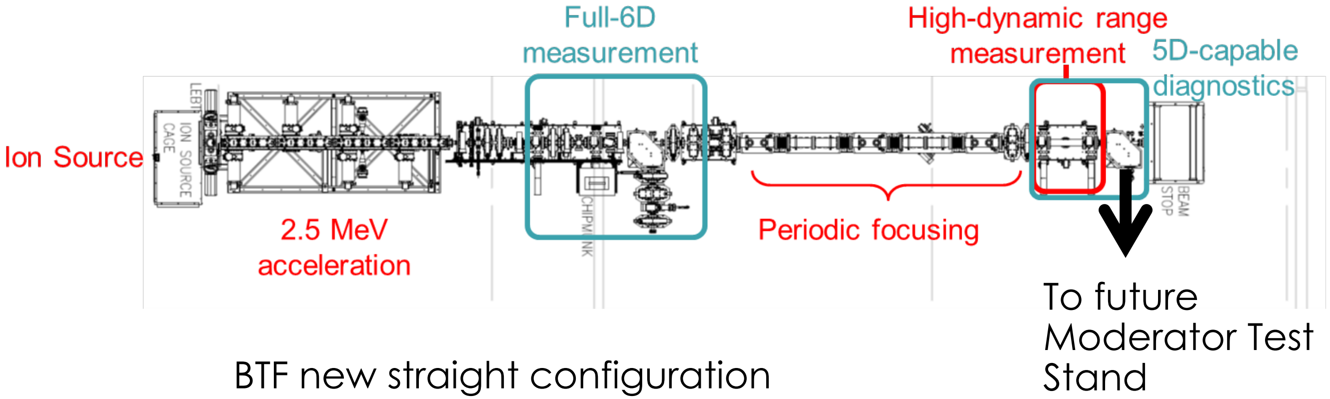
OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Beam Test facility (K. Ruisard, A. Aleksandrov)

- To understand beam dynamics better
  - Enable development and measurement that cannot be done in the main machine
- Dedicated to research: Beam is available 24/7 for research
- Advanced diagnostics development
  - 6-D, 5-D beam distribution measurements
  - Large dynamic range diagnostics (one part per million)
- Being upgraded for straight configuration
- New user will join soon: Future neutron moderator test stand (funded) will be attached to the BTF for future neutron moderator designs

RFQ in BTF





BTF new straight configuration

Self-consistent beam distribution (SCBD) in the ring (N. Evans)

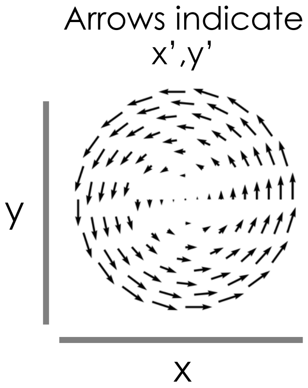
- Can we uniformly stack beam from linac in ring?
- Goal: Proof-of-principle painting of a uniformly filled, elliptical bunch in the SNS ring (the Danilov distribution)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **6**, 094202 (2003)

Self-consistent time dependent two dimensional and three dimensional space charge distributions with linear force

V. Danilov, S. Cousineau, S. Henderson, and J. Holmes

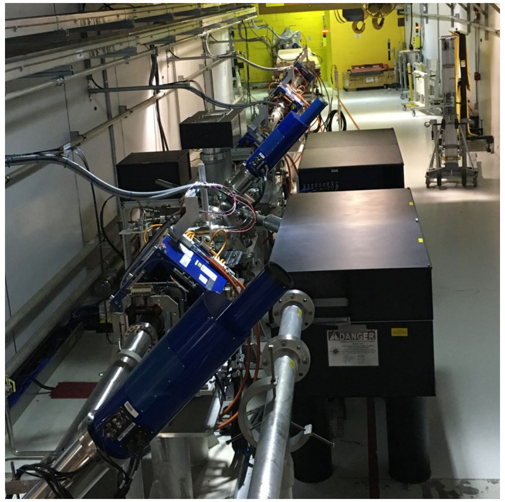
- Benefits of Danilov distribution
  - Uniformity: minimizes space charge tune spread, and shift – providing opportunity to overcome space charge limit at injection
  - Low 4D emittance: increases collider performance for similar beam size

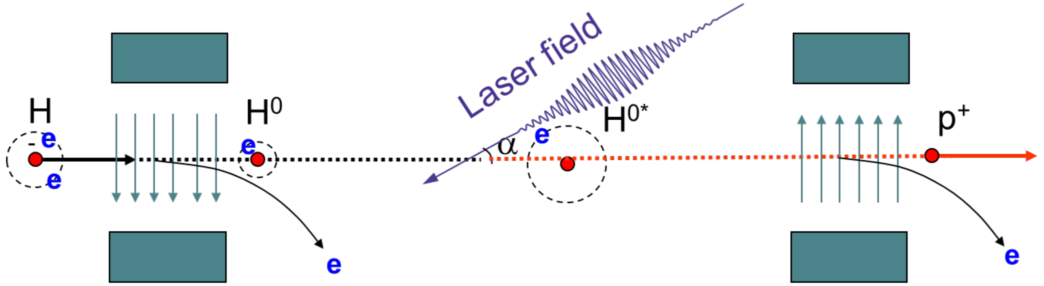


Two solenoids in the SNS ring for SCBD study

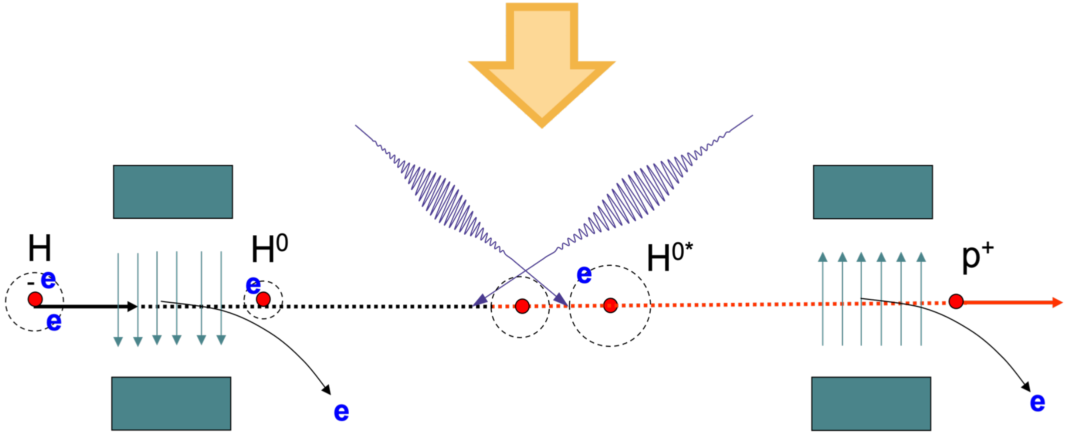
Laser Assisted Charge Exchange (S. Cousineau, A. Aleksandrov, et. al.)

- For higher power H- beam injection into ring
- Recent developments demonstrated proof of concept and laser power requirement of commercially available systems
  - Two step excitation
  - Laser, H- beam manipulations
  - Crab crossing
  - Laser stability improvement
- Engineering development is progressing for
  - Precision alignment
  - Better laser stability





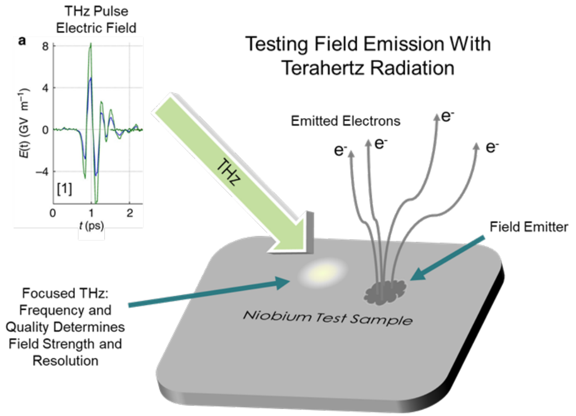
Physics concept (demonstrated in 2006 at SNS)

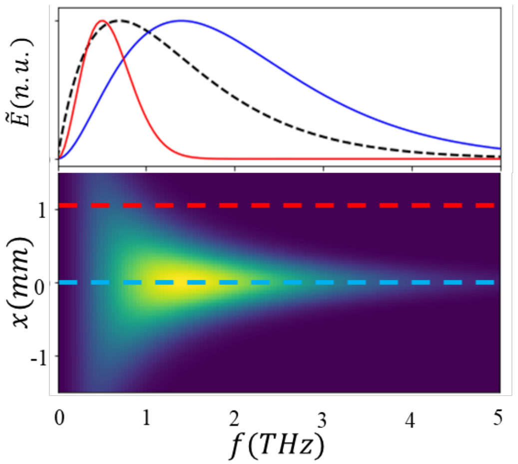


Sequential excitation concept (demonstrated in 2022 at SNS)

R&D using Intense laser-induced THz radiation
(M. Doleans, G. Hine)

- Current effort
  - Achieve intense THz field 100 MV/m – 1,000 MV/m
  - Develop diagnostics
  - Investigating new manipulation method (e.g. meta-surfaces)
- Vision for future
  - Surface study: e.g. field emission without resonant structure
  - THz-based ion acceleration





From DOE BES highlight

Sizing Up Special Light to Downsize Particle Accelerators

Measuring the shape of intense bursts of terahertz light paves the way for future accelerator technologies.

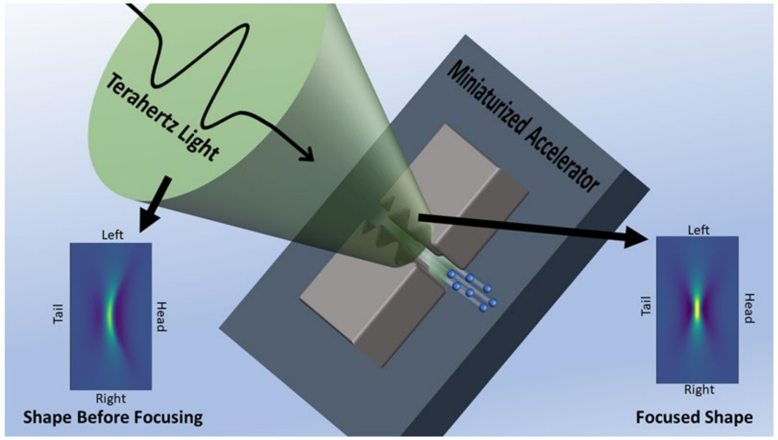
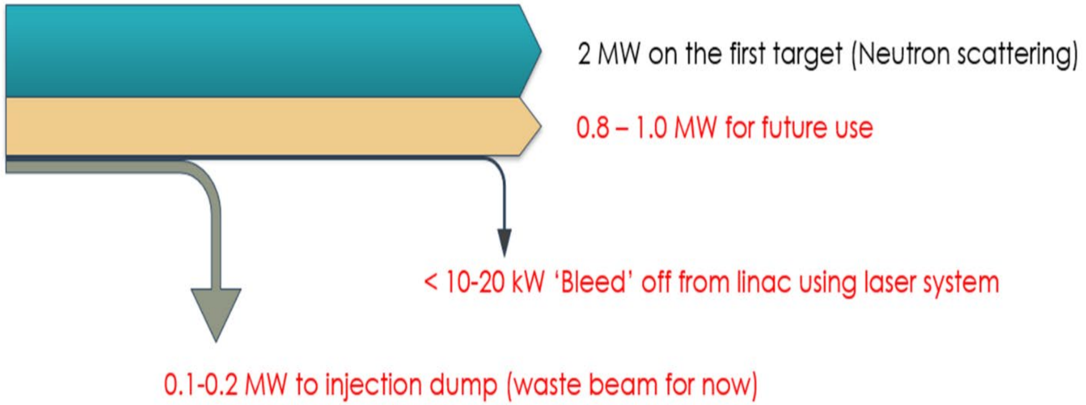


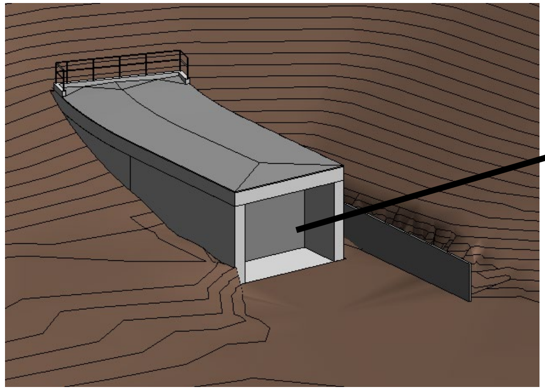
Image courtesy of Oak Ridge National Laboratory

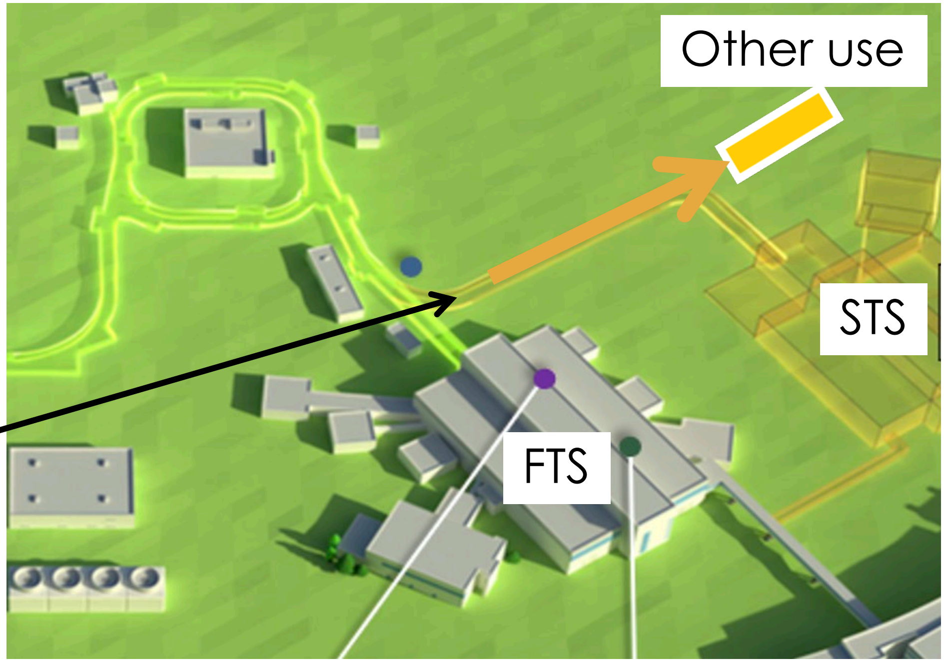
Opportunities for new science capability using SNS beam

- After the completion of PPU, 2.8 MW capable accelerator
  - FTS: 2 MW, STS: 0.7 MW
  - 2 or 3 pps can be distributed for other uses
    - Single pulse beam energy: 47 kJ
  - Requires control/LLRF for 3 flavor beams



- Opportunities
  - Medical isotope production
    - Feasibility study is being initiated
  - Material irradiation
  - Muon source
  - Fundamental physics
  - Basic study for ADS

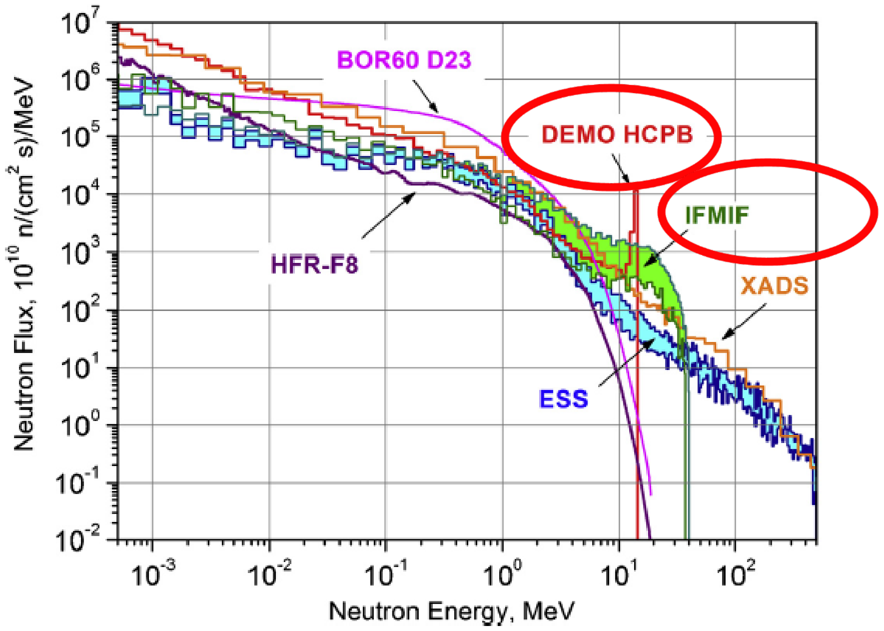


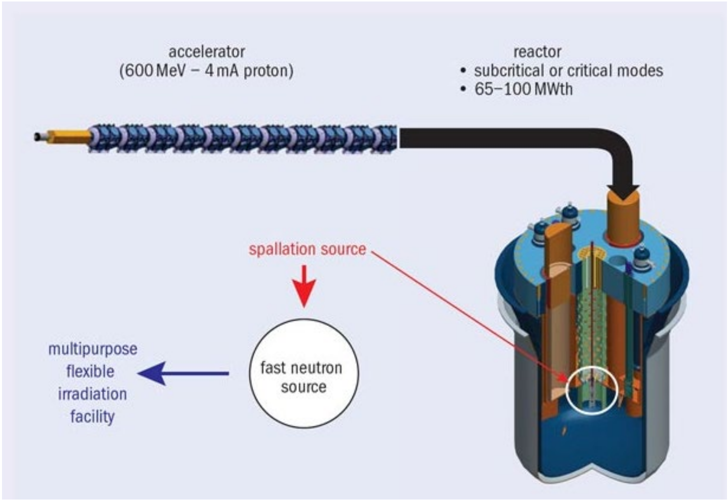


Future high-power machines – FPNS, ADS

- Recently there were DOE RFIs for
  - Fusion Prototypic Neutron Source (FPNS)
  - Nuclear transmutation including ADS
- Fusion Prototypic Neutron Source (FPNS)
  - To understand degradation of material exposed to 14.1 MeV neutrons
  - Li (d, xn): deuteron energy 30 – 40 MeV
  - Very high-current CW accelerator + very high-power lithium target (5 – 10 MW)
- Accelerator Driven System (ADS)
  - Nuclear transmutation, energy production
  - 800 – 1500 MeV, 10-30 mA CW proton beam
  - Very tight beam interruption requirement

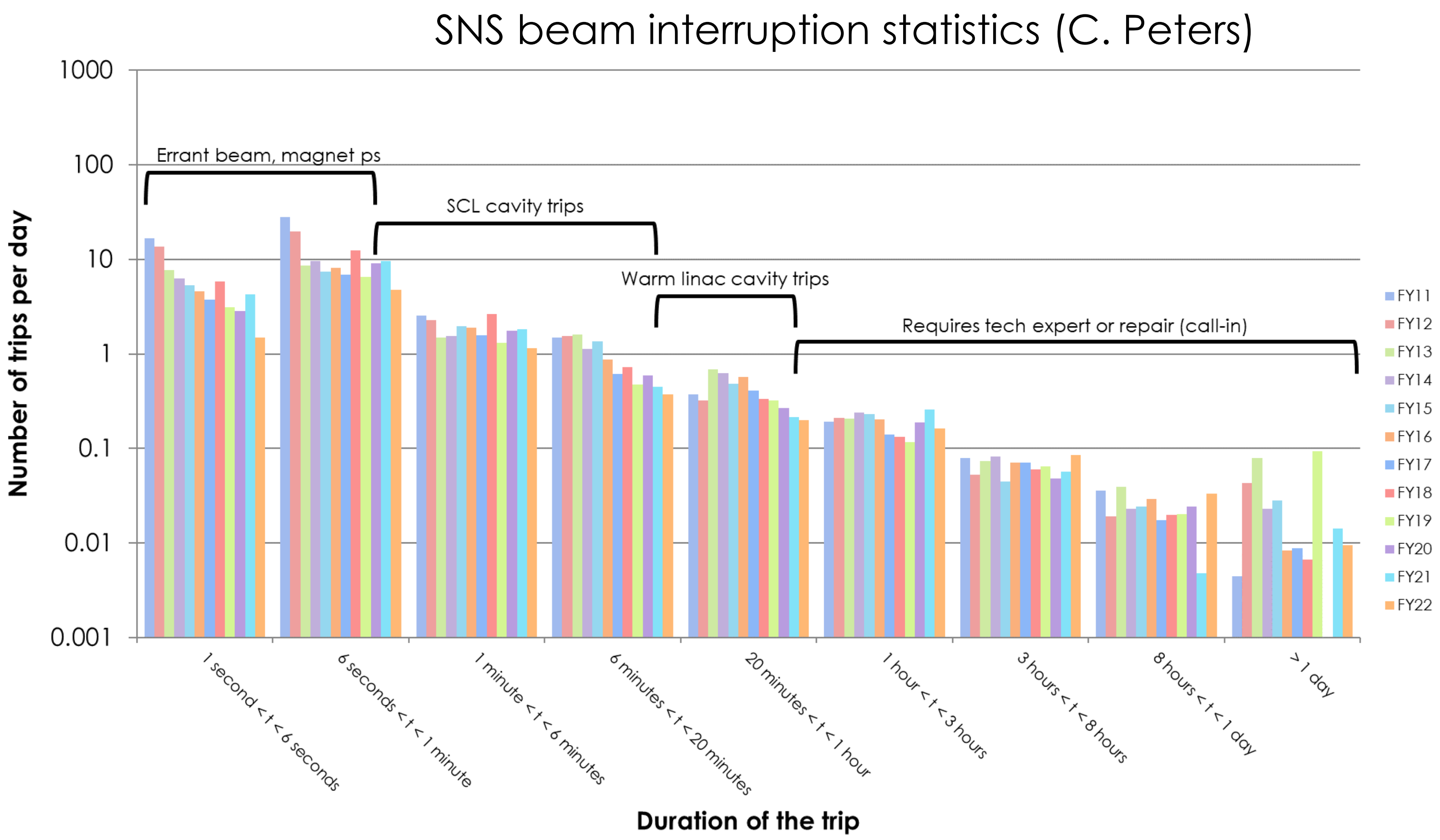
S.J. Zinkle, A. Möslang / Fusion Engineering and Design *88 (2013) 472– 482*

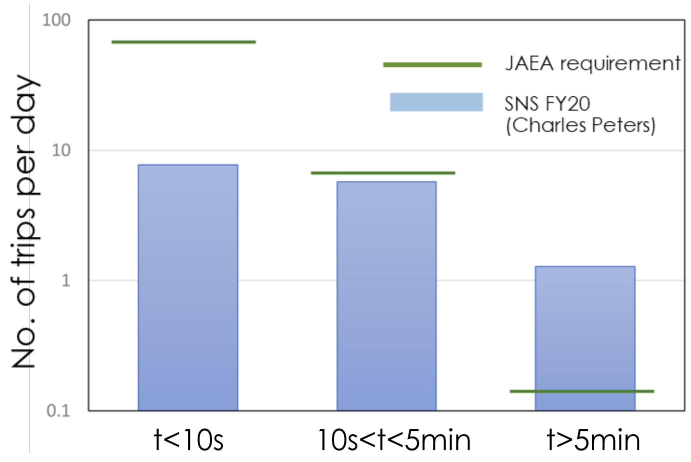


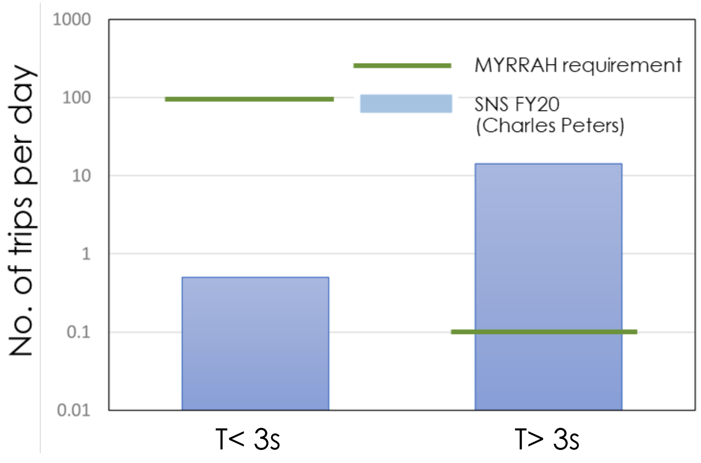


MYRRHA

Beam interruption requirement



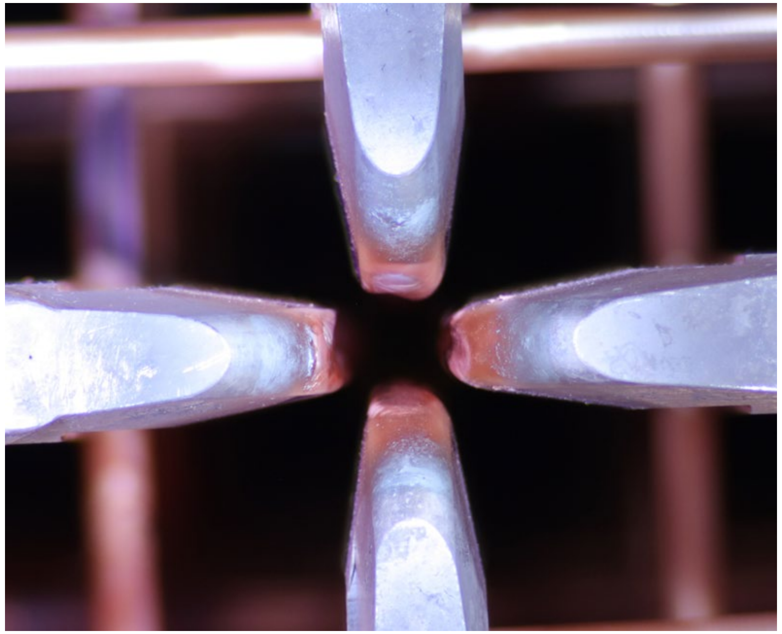




Future high-power machines – research topics

new regime and new requirement need new design philosophy and new development

- Uncontrolled beam loss
- Beam scraping/collimation
- Sustainable RFQ with relevant beam power
- High power CW coupler
- High-power solid-state RF amplifier
- Accelerating structure with larger bore radius
- Fast compensation of faulted cavities
- Recovery of faulted cavity while running beam
- Robust control system



SNS RFQ01 vain erosion after 16 years of operation

Thanks for your attention!