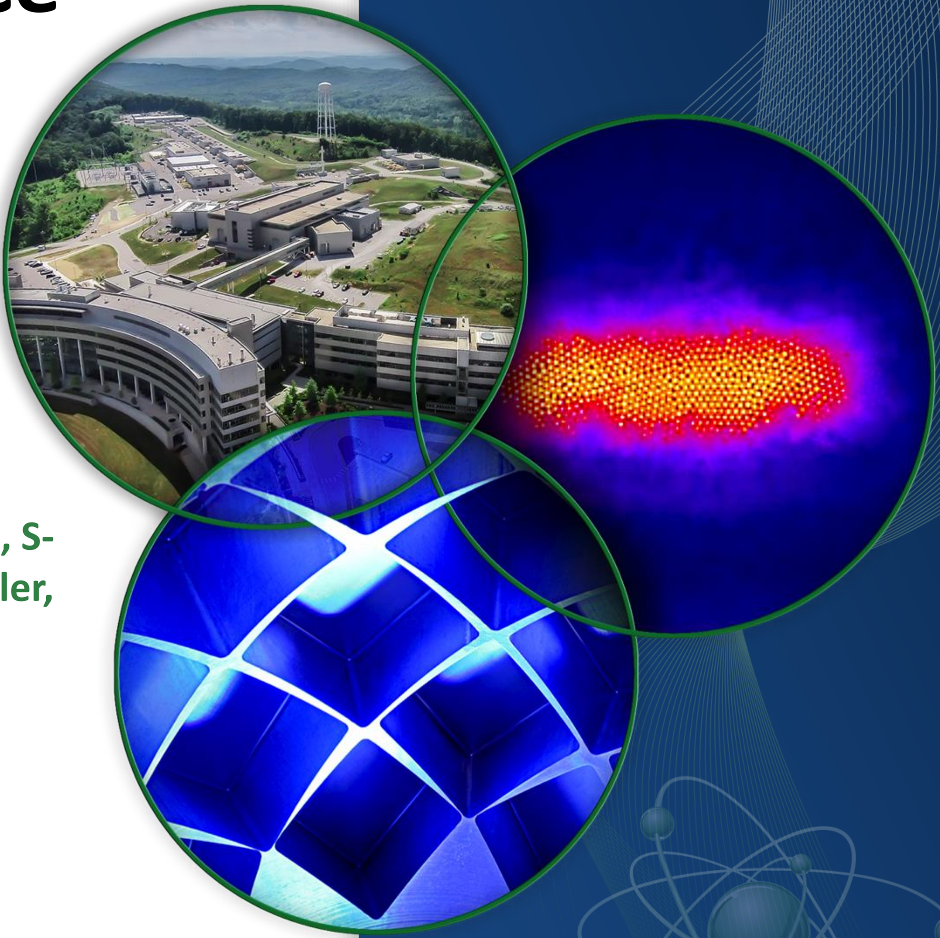
Status and Performance of RF Linac in ORNL Spallation Neutron Source



Y. Kang,

D. Anderson, M. Champion, M. Crofford, S-H. Kim, S-W. Lee, L. M. Middendorf, J. Moss, V. Peplov, C. Piller, R. Saethre, J. Saunders, M. Wezensky

Research Accelerator Division

Spallation Neutron Source

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CWRF2016 Workshop

Grenoble, France

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

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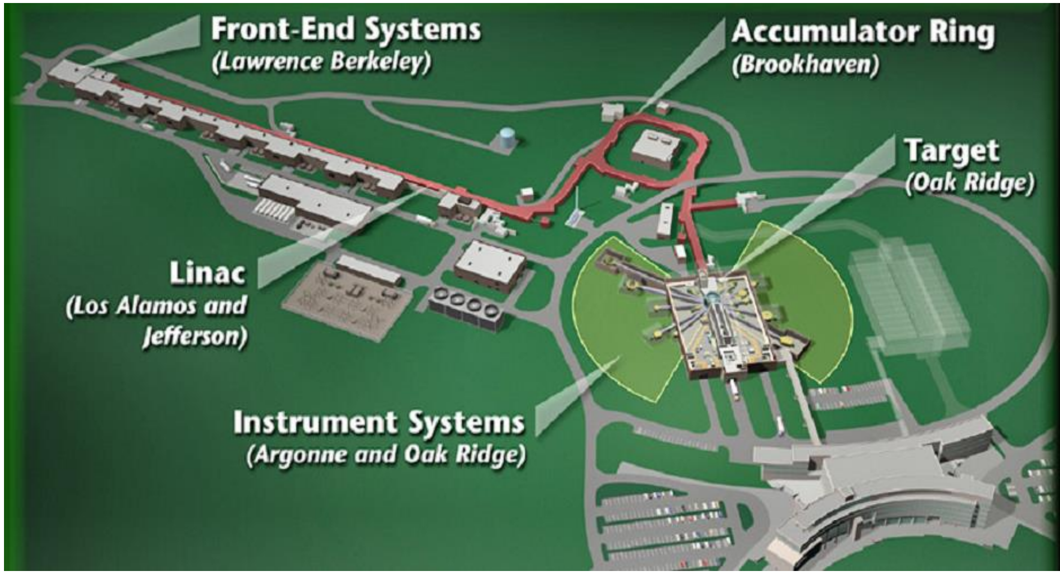
OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

Outline

- **SNS Overview**
- SNS Accelerator Complex Operation and Performance
- Accelerator Systems and Subsystems
  - Ion Source, RFQ, MEBT, DTL, CCL, and SCL
- Performances, Issues, and Improvements of RF Components
  - Klystron, Circulator,
- RF Power Couplers and Windows
  - RFQ, DTL, CCL, and SCL
  - RF Processing of Couplers and Windows
- New Beam Test Facility
- Summary

Spallation Neutron Source

- SNS is a pulsed neutron source, driven by a 1.4 MW SRF proton accelerator to be the leading facility for neutron scattering research
- SNS was funded through DOE-BES at a cost of 1.4 B$ and constructed with a collaboration of six US DOE laboratories
- Since accelerator complex was fully commissioned in 2006, operation has been ramping up to 1.4 MW beam power and 1GeV beam energy, the design goals
- Future upgrades of the beam power and the energy of the accelerator have been planned with the addition of the second target station



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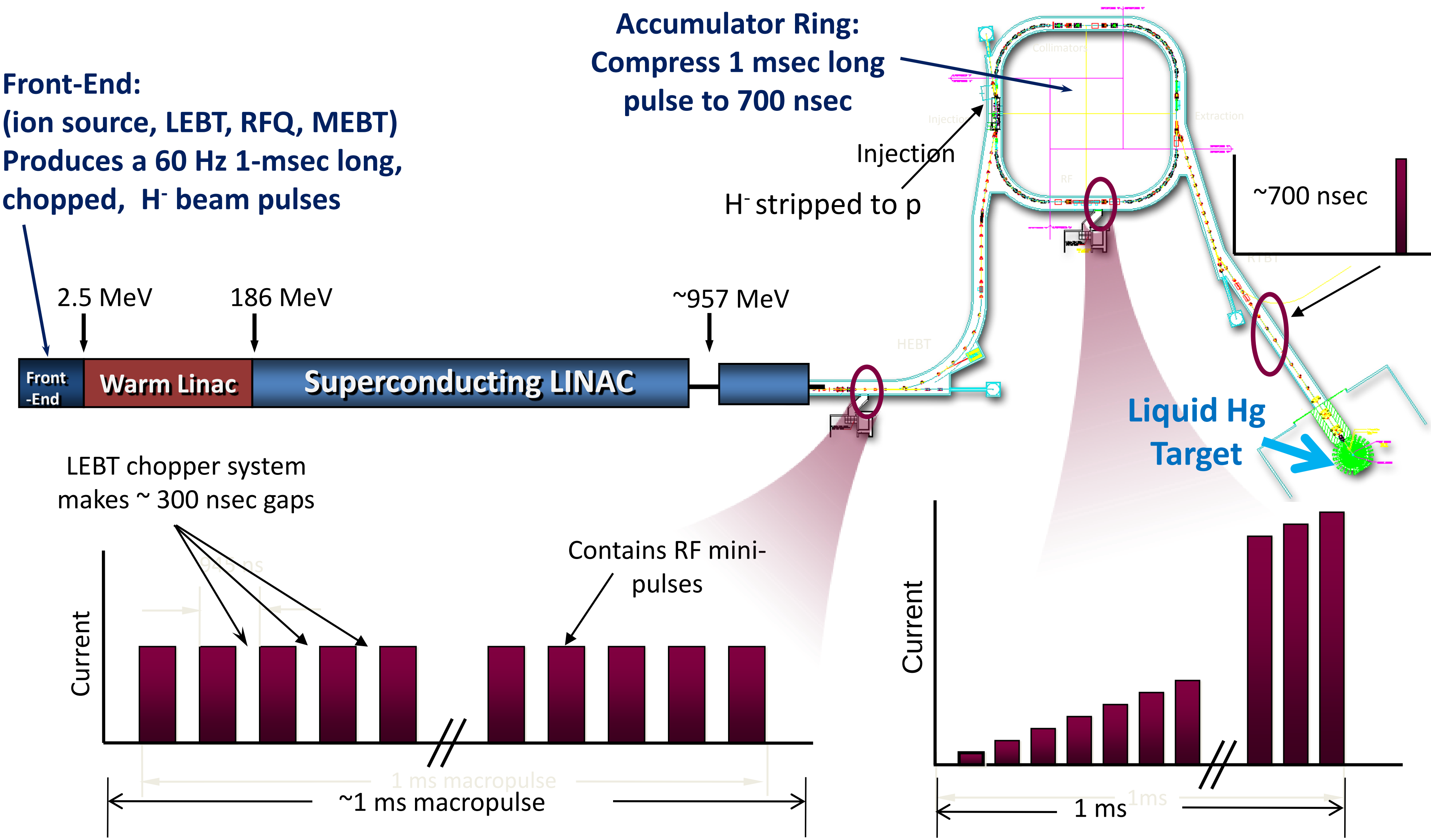
The SNS Provides the Most Intense Pulsed Neutron Beams



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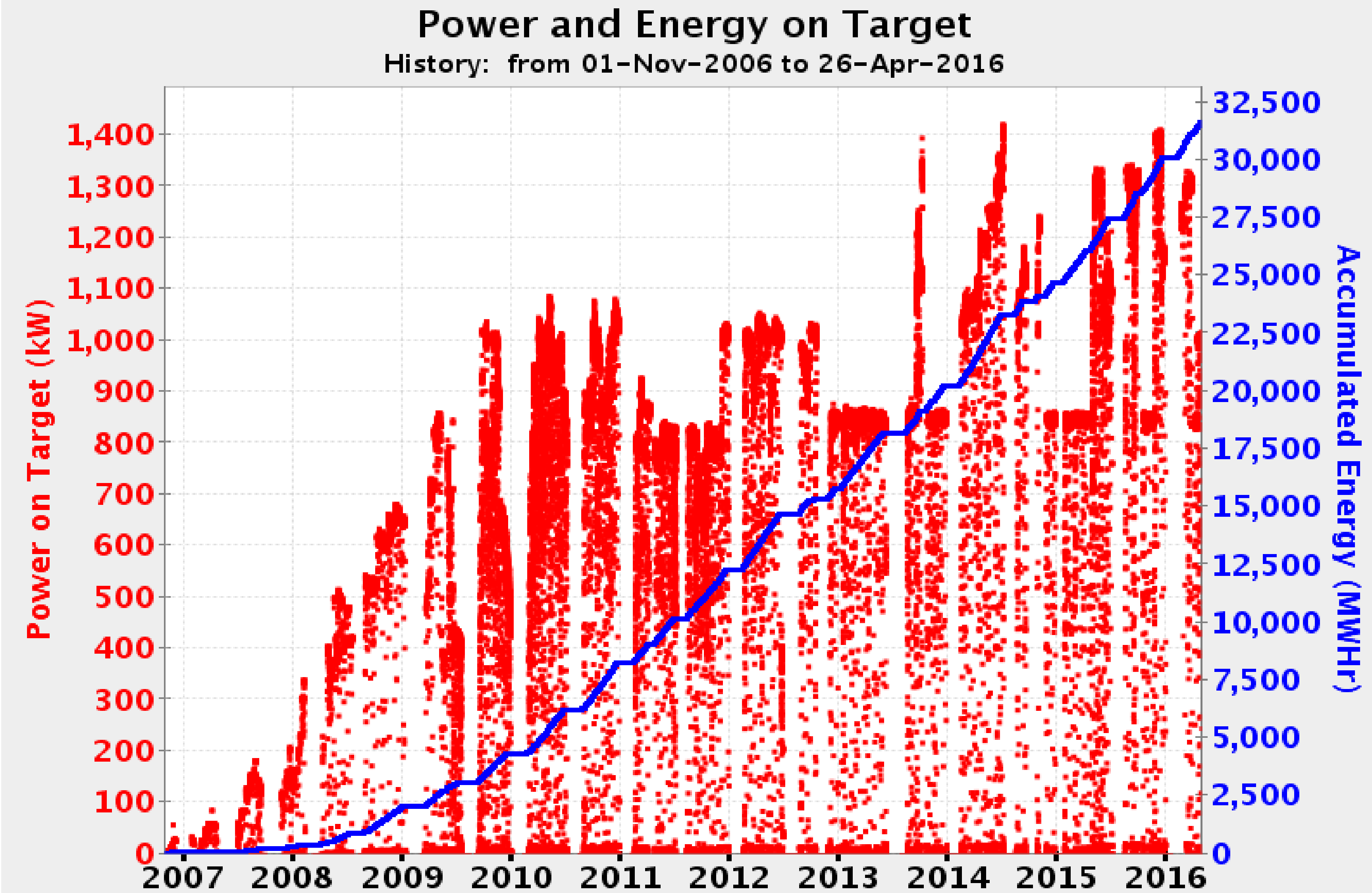

- SNS has demonstrated it is capable of sustained operation at power levels up to 1.4 MW
- Failures of the Target and the MEBT systems lowered the system reliability

SNS Performs Well Relative to Design Parameters

	Design	Best Ever	Routine Operation
Kinetic Energy [GeV]	1.0	1.07	0.957
Beam Power [MW]	1.4	1.427	0.8-1.40
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

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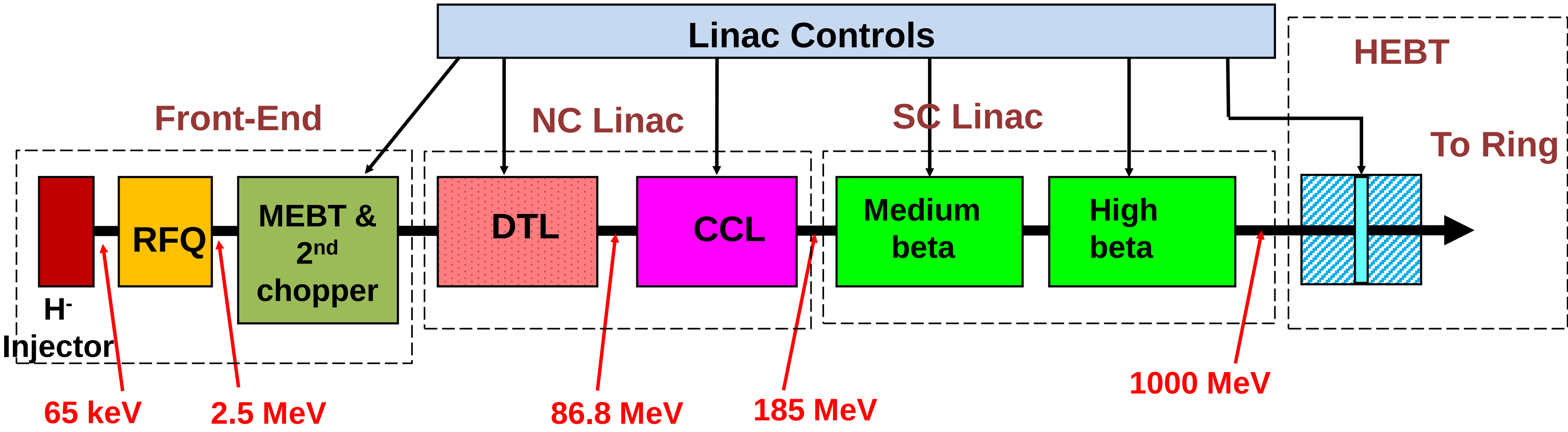
SNS RF Linac Systems

- Ten years of operation reveals some increases of component failures. Most of the 92 klystrons have exceeded the specified life of 50,000 operational hours. Operational management of klystrons is now focused on promoting long tube life for the aging.



RF Generation

	H^- Injector	MEBT	RFQ & DTL	CCL	SCL	Ring
Frequency (MHz)	2 /13.56	402.5	402.5	805	805	1.05/2.1
Amplifiers	1/1	4	7	4	33/48	3/1
RF Power (kW)	120 /1	25	2500	5.0	550	500
Efficiency (%)			>46	>50	>50	
Device	Tetrode, SSA	SSA	Klystron	Klystron	Klystron	Tetrode
Power supply (kV/A)			120 / 33.2	135 / 88	75 / 11.2	

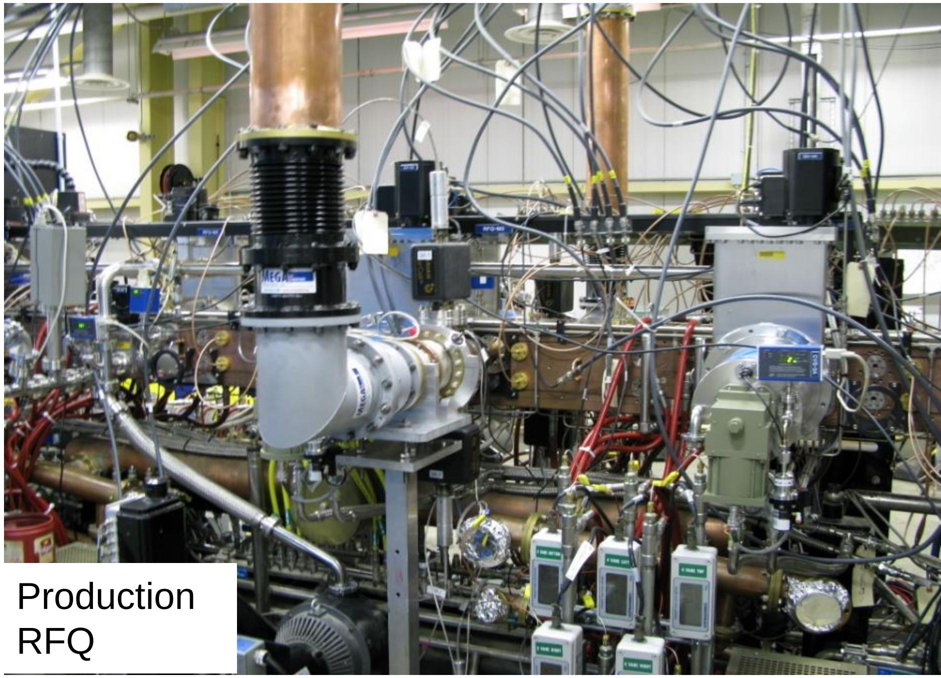
Ion Source (H^-) and LEBT

Production Ion Source

- The SNS H^- ion source is a cesium-enhanced, multicusp RF plasma ion source generates 65 keV H^- Ions to the RFQ with an internal antenna.
- Updates and corrective maintenance of the front-end systems on the ion source, LEBT, RFQ, and MEBT have been significant since commissioning.
- The beam current from the ion source has increased steadily (~20 mA -> ~60 mA)
- 2 MHz pulsed tube amp running at > 60 kW capable of up to 80 kW 6% duty cycle is used with 13 MHz 300 W CW SSA to the antenna for ignition of plasma
- Antenna failures practically eliminated due to cleaner fabrication, thinner porcelain coatings and improved quality control; there has been no antenna failure for over 3 years.
- The two-lens, electrostatic LEBT is 12-cm long. The second lens is split into four quadrants to steer, chop, and blank the beam. The short electrostatic LEBT has been operating reliably with a routine change-out of LEBT that is done twice a year due to insulator coating which seems to be a good plan to maintain the reliability.

RFQ

- 3.7 m long 4 vane type structure operating at 402.5 MHz and 550 kW structure power delivers 2.5 MeV H^- Ions to the DTL through MEBT
- The beam transmission through the RFQ decreased and has been a concern in the front-end system for the higher beam power operation through the years.
- The beam transmission has been measured lower than the design minimum of 80% lately. In the summer of 2013, the RFQ was retuned after observation of field tilt. Then, the transmission increased from 72% to 77% for a 45 mA input current which was still not satisfactory.
- A new spare RFQ has been built and fully RF tested. After validation of the performance of the new RFQ with beam, the existing RFQ will be replaced with the spare.

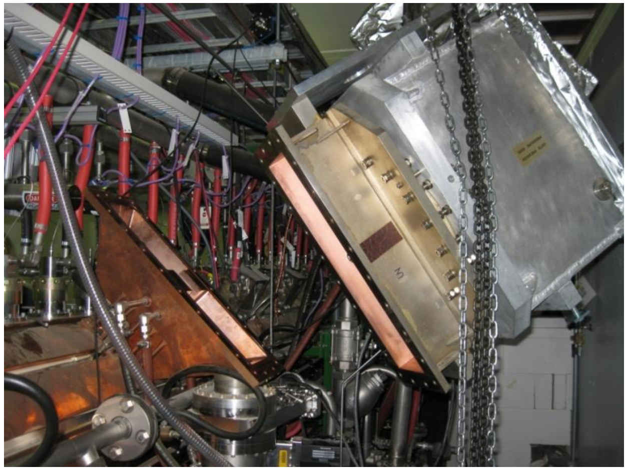


Production RFQ

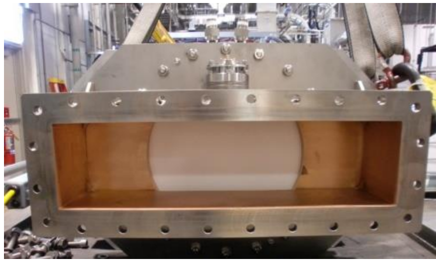
MEBT

- Performs longitudinal beam compression of 2.5 MeV beam with 4 rebuncher cavities
- RF amplifiers were upgraded to SSA each running at 25 kW @ 402.5 MHz, 8% duty cycle (6 modules per amplifier)

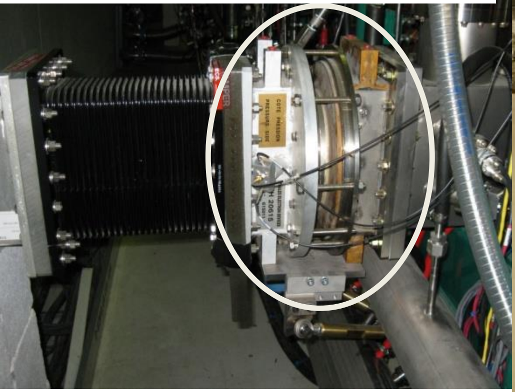
DTL and CCL

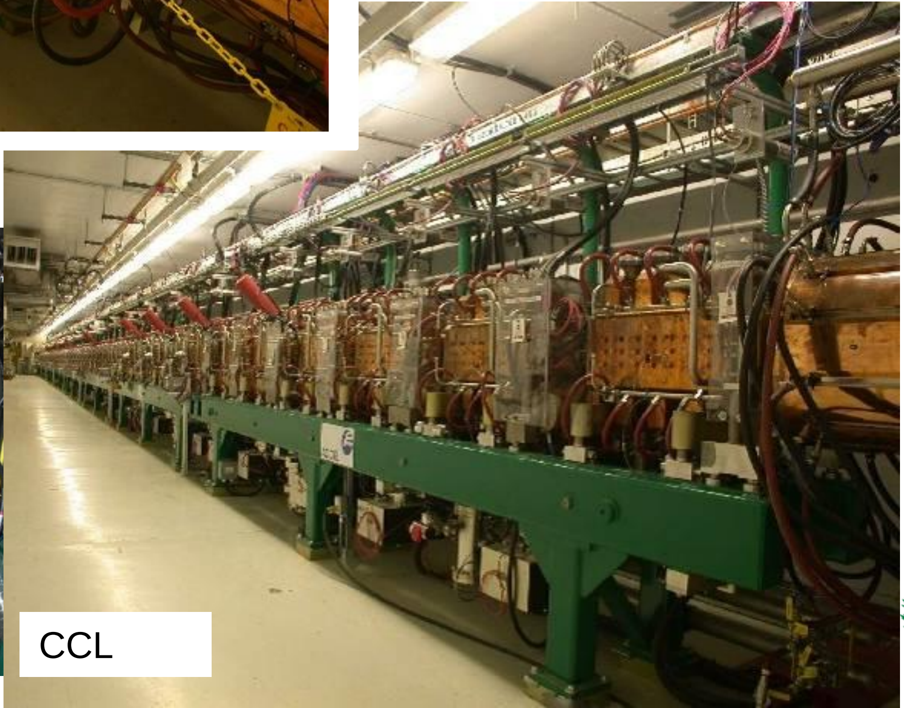


DTL iris coupler and window



CCL window mounted to the cavity structure





CCL

- **SNS linac employs six 402.5 MHz DTL tank accelerating structures**
- **Each DTL tank is fed by a ridge waveguide iris coupler and a waveguide window**
- **SNS linac employs four 805 MHz CCL sections.**
- **Each CCL section is fed at two bridge couplers with two waveguide windows**

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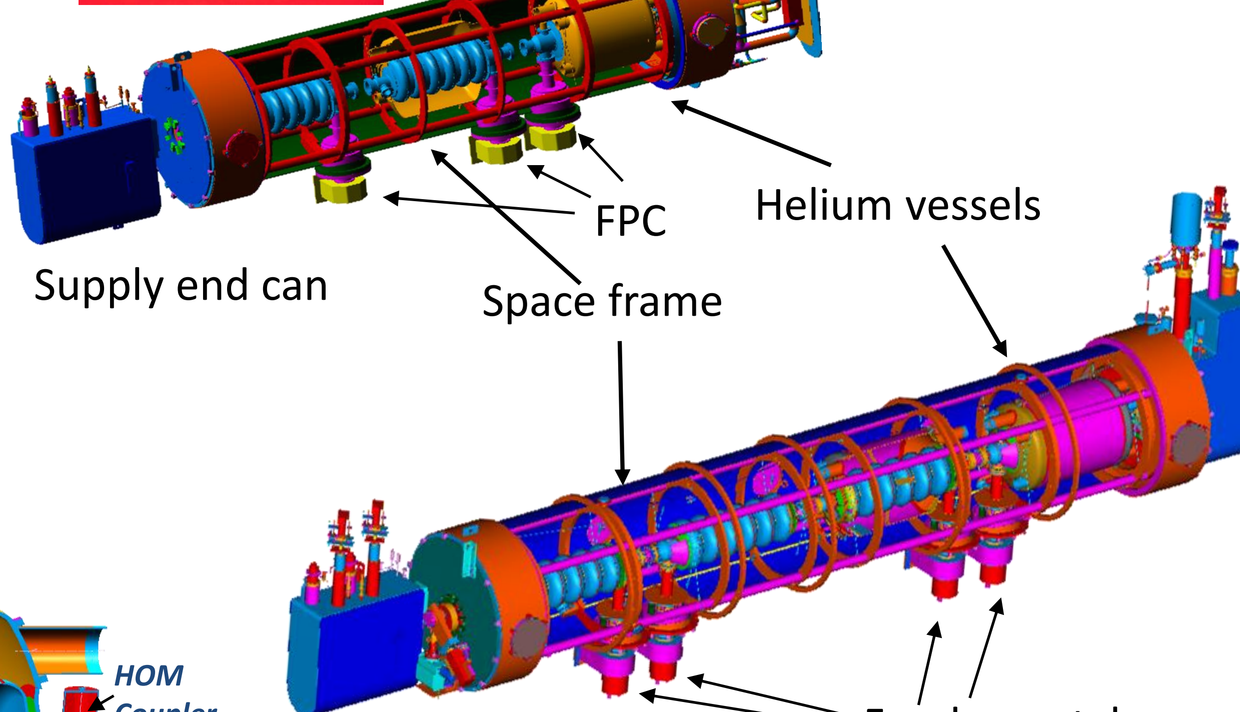
SCL Cavities and Cryomodules

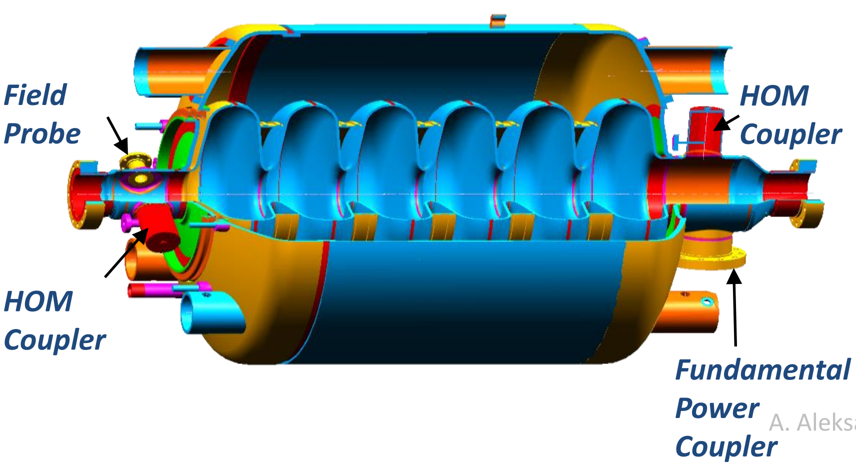
- 81 6-cell cavities in 23 cryomodules
  - 11 medium-beta CM
    (33 β=0.61 cavities)
  - 12 high-beta CM
    (48 β=0.81 cavities)
- E_a=15.9 MV/m at β=0.81 & Q_o> 5E9
- One klystron per one 6-cell cavity operation
- SNS has built first own high-β cryomodule commissioned in March 2012

Designed to operate at 2.1 K (superfluid helium)

Medium beta, b=0.61



High beta, b=0.81



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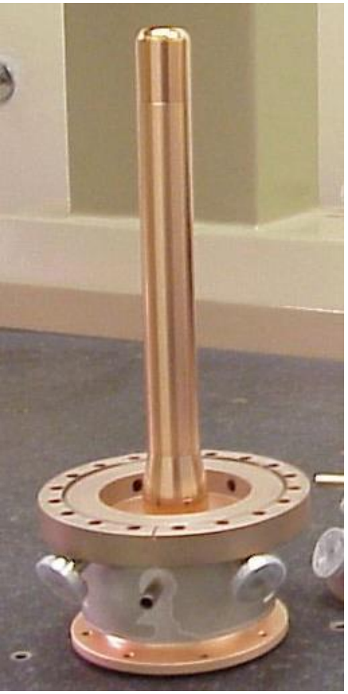
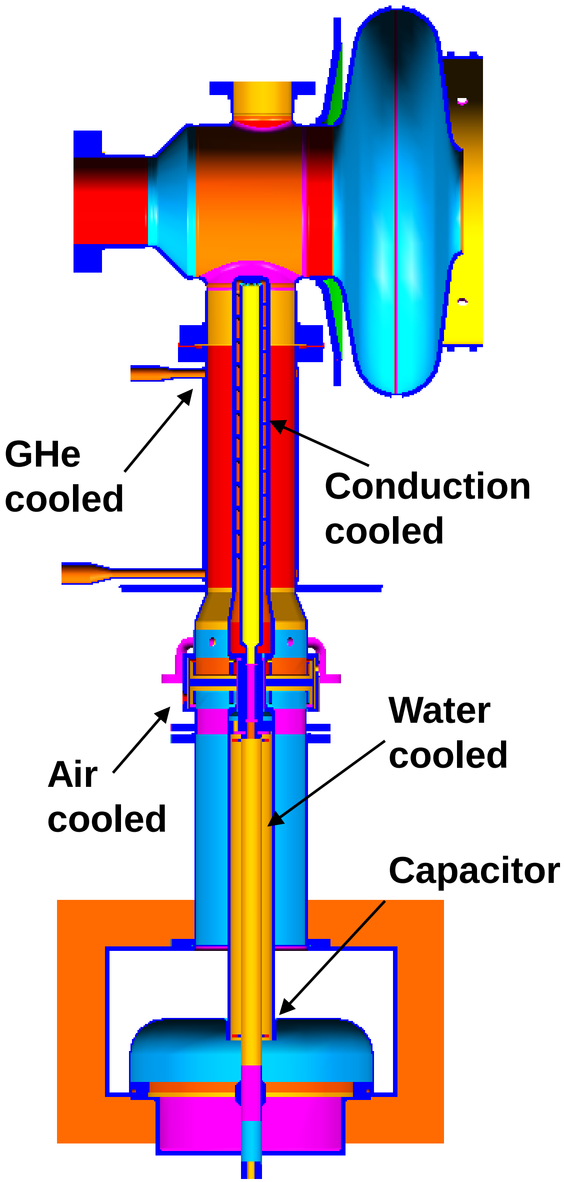
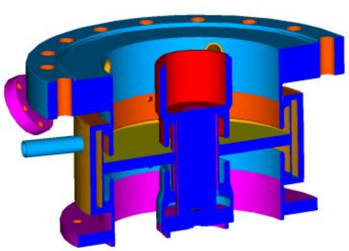
SNS SCL Coupler



Coupler antenna assembly



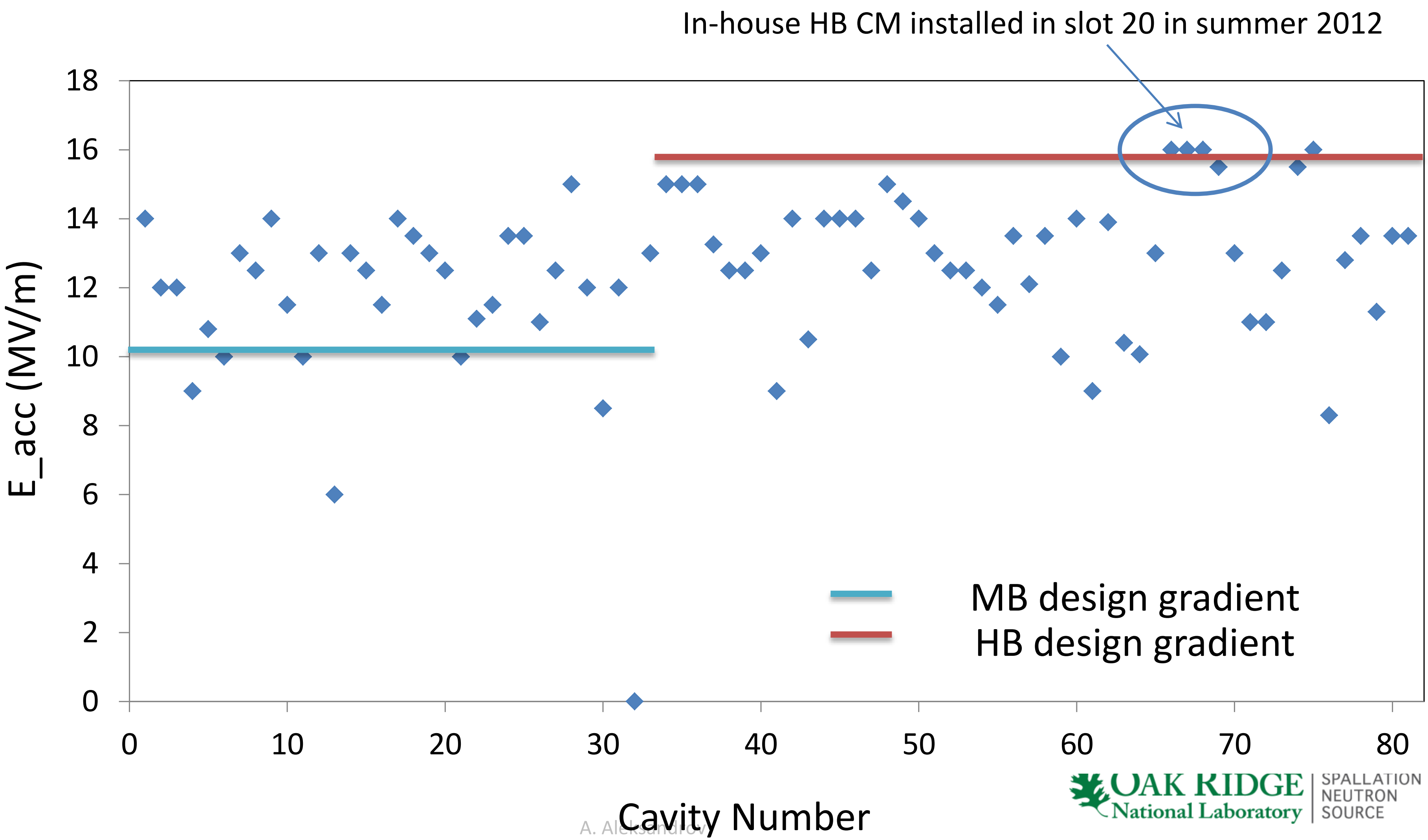


Ceramic window

- Peak power in operation up to 550 kW (45 kW ave)
  - 1.3 msec RF on @ 60 pps
  - tested up to 2.4 MW peak in standing wave
- Q_{ext} ~ 7E5 with the SNS 6-cell cavities
- 300° K coaxial window and antenna
- Vacuum, arc interlocks
- Electron probe pickup
- Center conductor biased up to 2.5 kV
- PPU specifications:
  - 700 kW peak, 56 kW average
  - Higher average power for the upgrade & more stable operation at 60 Hz has additional cooling

Current SCL Operating Gradients

- Average E_acc of medium and high beta cavities are 12 MV/m and 13 MV/m respectively
- HB CM developed and manufactured in-house showed satisfactory E_acc.



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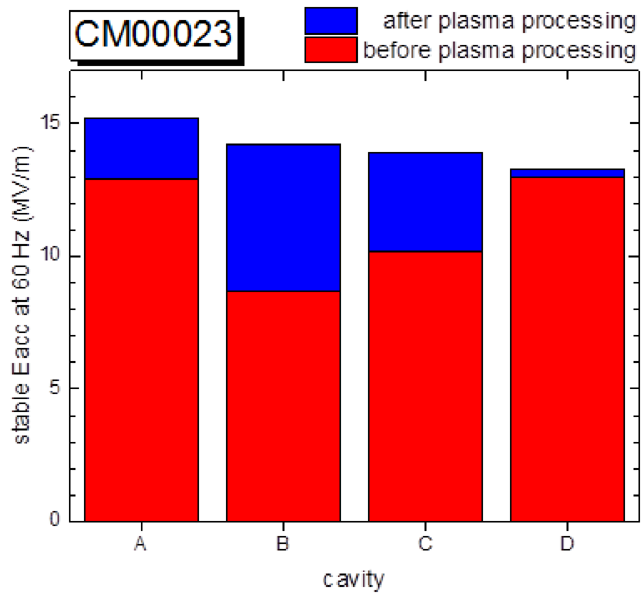
SCL Performance and Improvements

- The availabilities have been 99.5% for the SRF system alone and 98% for the SCL including RF, HVCM, control, vacuum, etc. during the last 5 years. Average trip (downtime): < 1 trip/day (<5 min./day)
- Some cavities have shown performance degradation in FY15 and FY16-1. Recovery of cavity performance to previously attained operating gradients was successful in several cavities with
  - RF conditioning starting from low repetition rate and
  - Thermal cycling
- The HOM couplers originally installed in the cavities against the potential interference of HOMs with the beam were found unnecessary in SNS. The HOM couplers have been either disabled or removed from the cavities since they presented difficulties in cavity processing and in operations at SNS.
- DC-biasing has been added on the input power couplers for better operational stability with suppression of multipacting.
- After studies with the plasma processing, in-situ plasma processing technique has been developed and being performed in the linac tunnel starting with the medium beta cavities. The processing has delivered positive results with increased field gradient.



Performance improvement for the four cavities in cryomodule after in-situ plasma processing.

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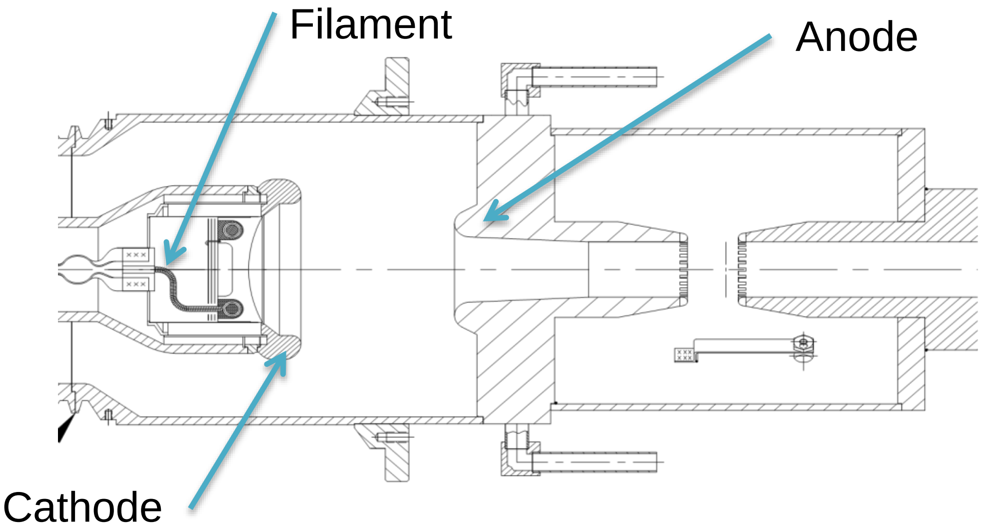
Linac RF Performance and Availability

- May 2013 through December 2015:
  - Total Machine operation time – 13,110 hours out of 16,161 requested operation hours for neutron production and accelerator physics
  - Total RF system downtime – 413 hours
    - Total includes non-beam downtime and cavity vacuum trips
  - Major contributors of downtime:
    - DTL High Power RF
      - 28 hours for two DTL6 circulator replacements
      - 114 hours for DTL5 window replacement and conditioning
    - CCL High Power RF
      - 36 hours for CCL3 klystron replacement
      - 14 hours for CCL2 klystron replacement
    - SCL High Power RF
      - 20 hours for SCL-1C klystron replacement
  - Most trips are in the DTL and CCL and ~ 20 – 30 minutes in duration

Klystron Failures

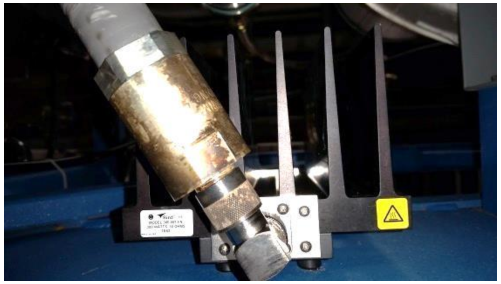
- From March 2013 to October of 2014 six klystrons were replaced
  - Two DTL klystron failures due to the second cavity load.
    - DTL -2 March 2013
    - DTL-4 July 2013
  - Two CCL klystron failures due to the electron gun filament circuit
    - CCL-2 May 2014
    - CCL-3 October 2014
  - One CCL klystron failure due to reduced cathode emission (cathode end of life)
    - CCL -4 January 2014
  - One SCL klystron failure due to the electron gun filament circuit
    - SCL-1C September 2013
- Operational management of klystrons is now focused on prolonging tube life



Picture courtesy of Ed Eisen, CPI

Klystron Management Process

- After six klystron failures in 18 months, there have been no failures in 15 months
  - Second Cavity Load Failures:
    - Speculate that water chemistry is causing contact failure.
      - Record load impedance every six months and replace the load when readings are over 50 ohms.
      - Results of impedance measurements show a life of approximately three years
      - Currently testing an air cooled load on DTL-5
  - Record klystron emission data annually
    - Look for decreasing emission as an end of life indicator
    - Decrease filament current set point in order to achieve full cathode emission at a lower temperature
      - Current rule of thumb is one ampere above the filament current at which the cathode is operating at 98 percent emission
    - Reduce filament on-off cycles
      - Leave filaments warm during maintenance days
      - Reduce set point to 50 percent when not operating cathode for more than 24 hours



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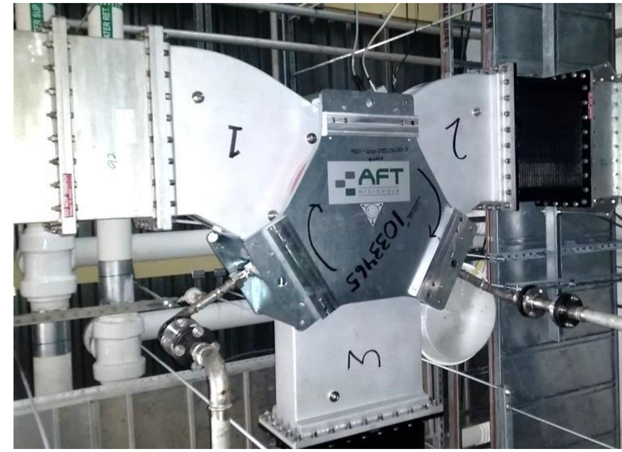
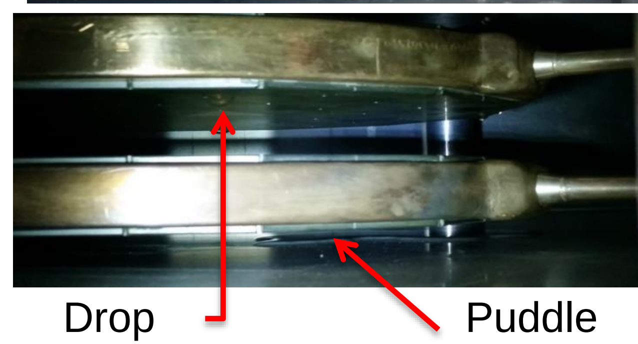
High Power Circulators

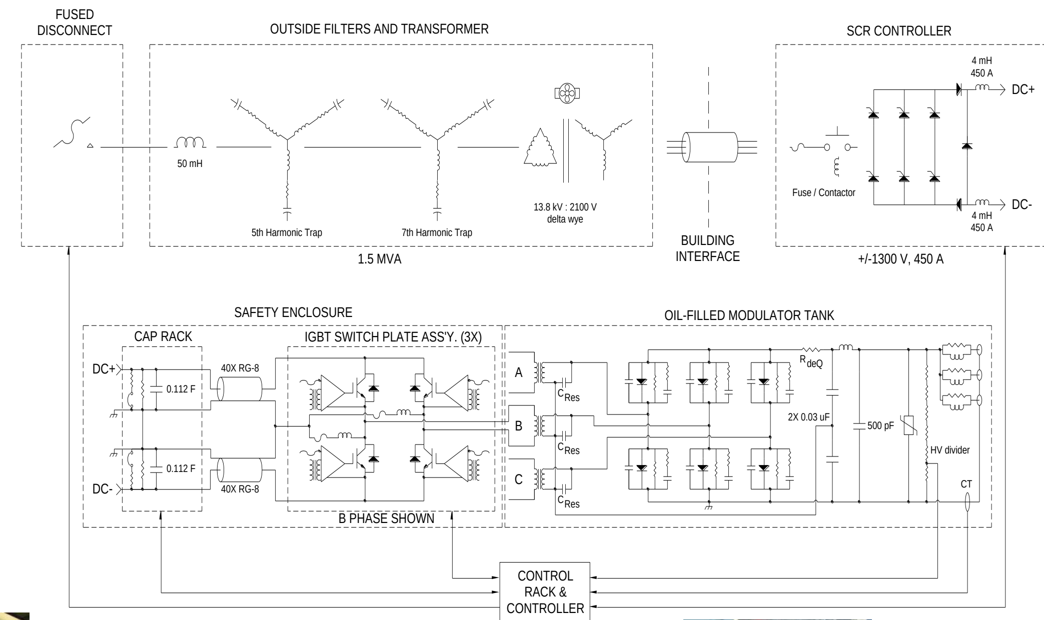
- Arcing was detected in the DTL-6 circulator on June 16th, 2014
- A water leak was detected on the bottom pancake of the circulator assembly
- Leaks were attributed to a failed gasket in the connection between the cooling manifold and the pancake cooling channels
- A spare circulator was removed from the RF Test Facility (RFTF) and installed to allow for continued operations
- The manufacturer sent a field engineer to repair the defective gasket
  - The SNS RF structures technician was trained in making the same repair
- Arcing was detected again in the replacement DTL-6 circulator on November 24, 2015
- A leak was detected on the center of the top pancake of the circulator assembly
  - Location prevented in-place repair
  - Refurbishment required by the manufacturer
- Another spare circulator was removed from the RFTF and installed to allow for continued operations
- Under power since mid January 2016 and has had no operational problems
- Two other 402 MHz circulators showed the similar leaks with failed gaskets





High Voltage Converter Modulators (HVCM) provide pulsed power to high power RF klystrons using 20 kHz switching with IGBTs

- Provides up to 135 kV, 1.35 ms pulses at 60 Hz to amplify RF to 5 MW
- 3 phases employed to increase output ripple frequency
  - Minimizes output filter requirements
  - Minimizes fault energy available to klystron
- Powers multiple klystrons up to 11 MW peak power
- Currently there is ≤5% pulse droop operating in open-loop



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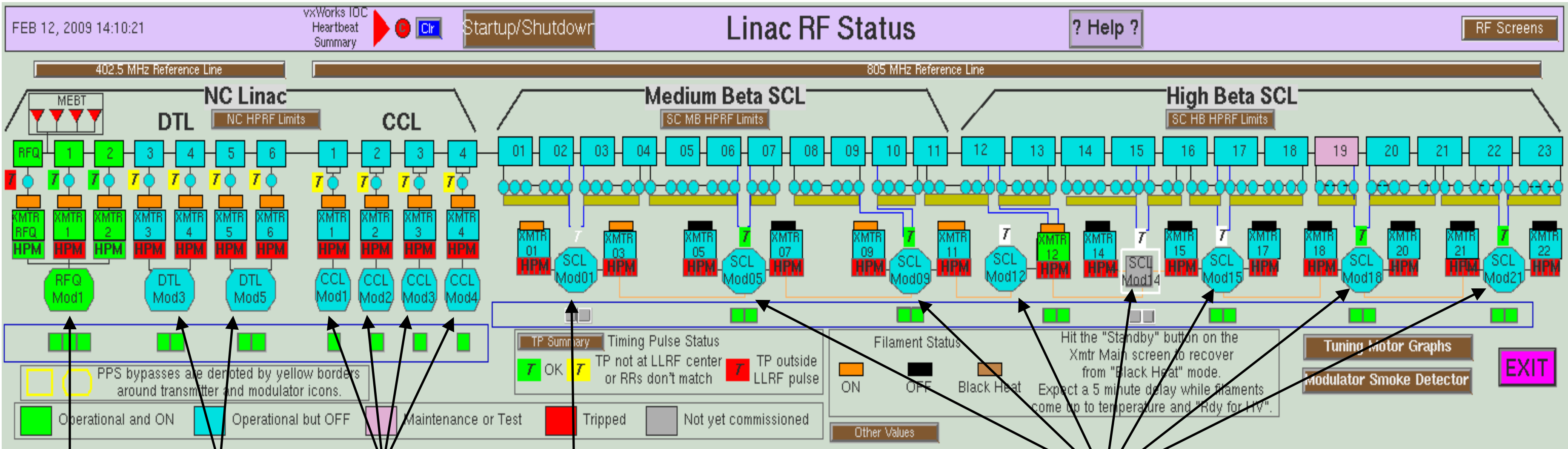
15 HVCMs in 3 Different Configurations Power 92 klystrons in the Linac



115 kV (30 A) | **125 kV (30 A)** | **≤135 kV (70 A)** | **71 kV (9-11 A)** | **75 - 80 kV (9-11 A)**

DTL (8.5-10.6 MW peak) | **CCL (8.4-9.1 MW peak)** | **SCL (8.0-8.8 MW peak)**

Some of the many HVCM improvements:

- Improved boost capacitor performance by finding better capacitors and 12 – 18 month scheduled replacements (the failures of boost capacitors have been a key vulnerability of HVCM)
- The pulse flattening developed with 17.8 to 23.0 kHz frequency modulation is to be deployed (Currently ≤5% pulse droop operating in open-loop)
- New IGBT gate driver circuits improve reliability, lower losses, enhance IGBT protection and reduce ripple
- Adding IGBT snubbers permits higher voltage operation, reliable higher current IGBT operation & eliminates fault over-voltage problem

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RF Windows and Couplers in the Linac

All RF systems operate @ ~ 8% duty cycle

Subsystem	Max Power	Q'ty	Ceramic Window	Issues
RFQ	650 kW	2	Coaxial loop antenna	coupler heating
DTL	2.5 MW	6	WR 2100 with circular Alumina disk	severe arcing with vacuum activities, cracked ceramic disk, water leak
CCL	2.5 MW	8	WR 975 with circular Alumina disk	severe arcing with vacuum activities, cracked ceramic disks
SCL	550 kW	81 (+28)	Coaxial E antenna	antenna cooling improvement for power upgrade

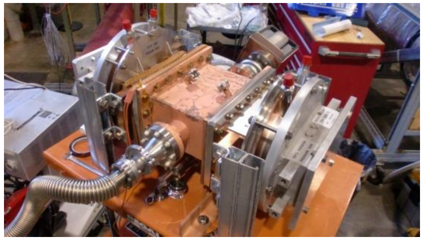
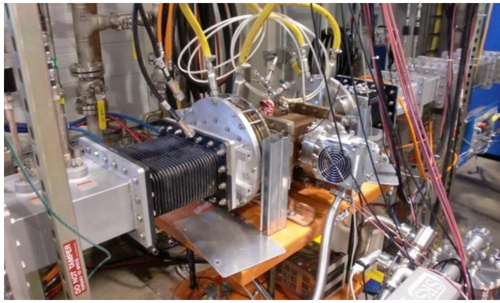
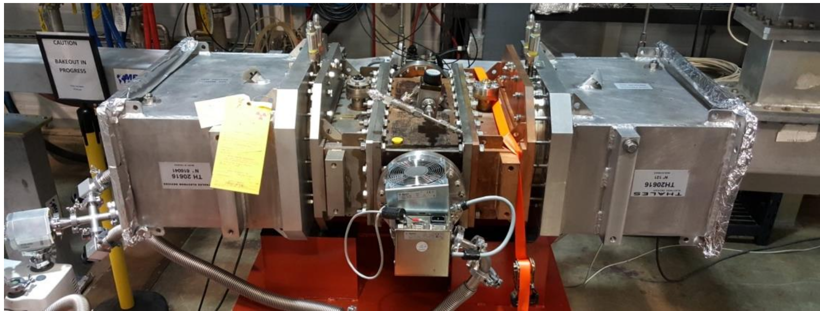
- All windows and couplers are processed by baking and full RF conditioning to the maximum power ratings
- The windows mounted on the cavity structures were initially processed carefully to be good performing devices and usually trouble free for several years when mounted
- Problems arise during operation on the cavities in the accelerator with vacuum and beam
- Experiences show that poor vacuum and poor cooling around the window ceramic may be the culprits of the catastrophic failures of the windows
- The failure modes of the windows with vacuum leaks, or cooling water leak may be regarded as the result of defective material and/or the product assembly

RF Processing of Couplers and Windows in SNS RF Test Facility

- RF testing and processing of High power RF components can be performed in SNS RF Test Facility at up to 8% duty cycle (1.3 msec 60 Hz)
  - 805 MHz, up to 5 MW peak power
  - 402.5 MHz, 2.5 MW max. peak power
  - Complete low-level RF control and monitoring for reliable processing and operation in EPICS environment
- A compact bridge waveguide is used for conditioning of two windows or couplers mounted back to back on it at a time
- The conditioning setup is baked for 48 hrs at 150 °C with 12 hrs ramp-up and 12 hrs cool down before RF processing
- Conditioning setups for the DTL and CCL windows are similar except the dimensions of the waveguide





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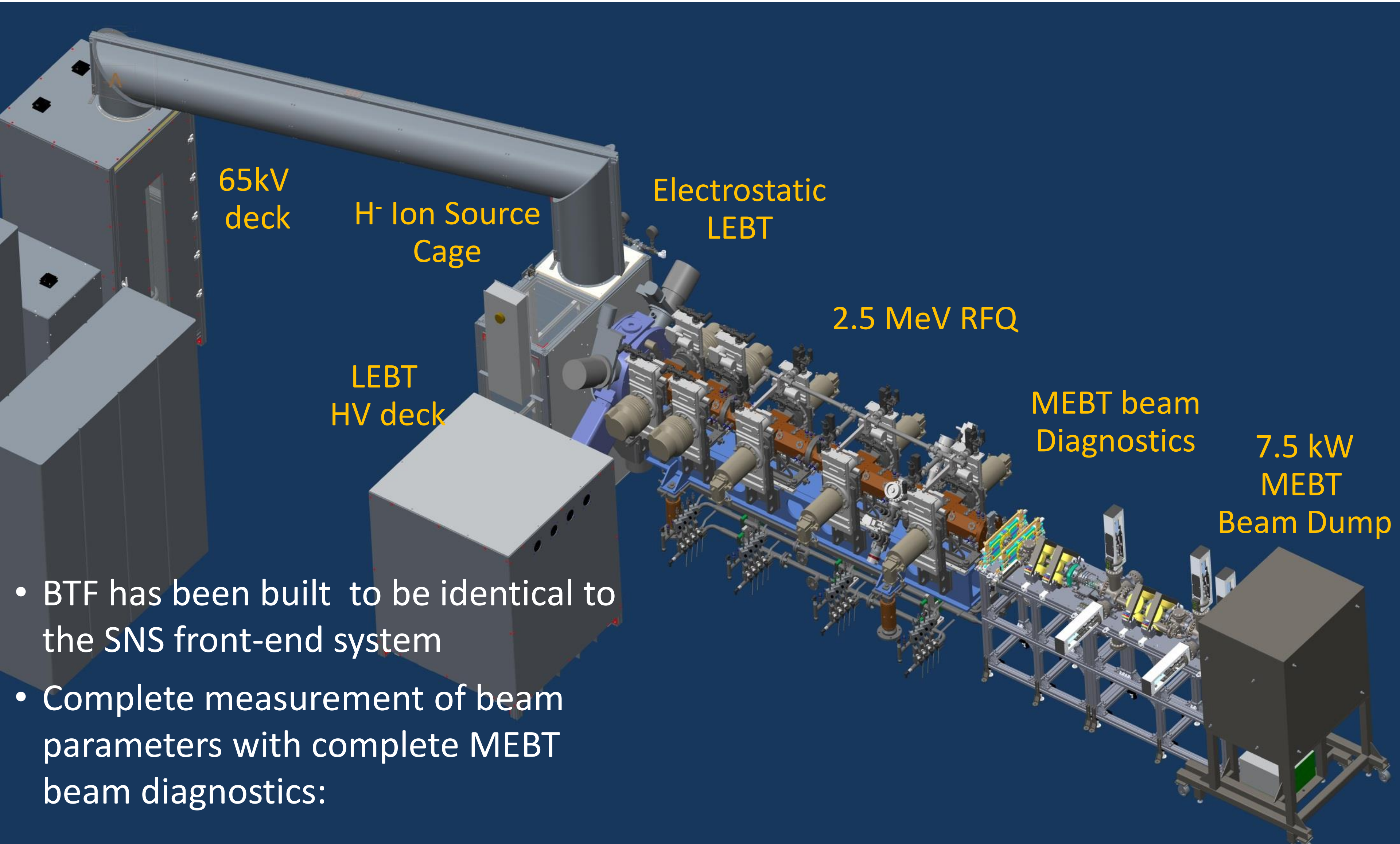
SNS Beam Test Facility (BTF) Layout



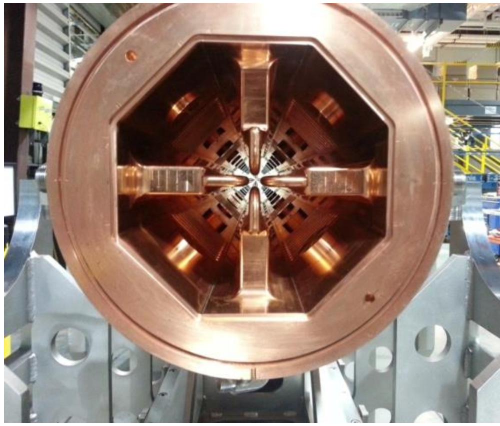
- BTF has been built to be identical to the SNS front-end system
- Complete measurement of beam parameters with complete MEBT beam diagnostics:

Beam Test Facility (BTF) Construction Completed

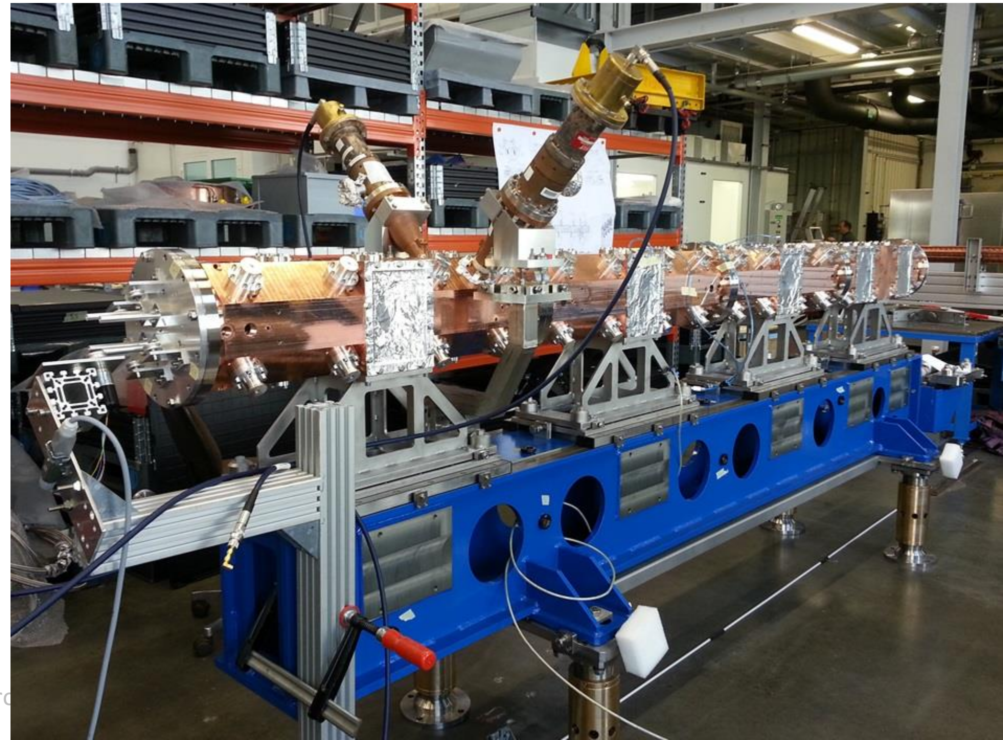
- The BTF has been built with the beam properties identical to the SNS front-end system
- Ion source, LEBT, and MEBT beam diagnostic systems have been added for BTF toward full beam test
- The BTF will be used to validate the performance of the new spare RFQ, to study ion source improvements, and to support neutron moderator development and six-dimensional phase space beam measurements for SNS.
- Future SNS Front End Systems development with diagnostics and MEBT systems (re-bunchers, choppers, etc.)
- 2.5MeV proton beam source can be used for Moderator Demonstration Facility and High intensity beam dynamics study
- The new spare RFQ will be tested with beam parameters measurements full power beam test (5kW)
- The new RFQ will be installed in the SNS linac after validation in the BTF with beam.

New Spare RFQ

- Beam dynamics design is identical to the design used in the existing RFQ by employing the same vane tip modulations
- Single layer Copper structure RFQ with octagonal cross section on robust uniformly supporting structure for stability (in contrast to old RFQ in two layer copper structure with GlidCop exoskeleton for strength needed to use minimally supporting kinematic design)
- 4 vane type with end wall rods for dipole mode stabilizing; Q factor is slightly improved
- 3.7 m length in 4 sections
- 64 slug tuners (1.4” dia each) and 48 field probes
- 2 coaxial input couplers



RF Properties	
Frequency (quadrupole mode)	402.5 MHz
Vane-vane voltage (peak)	83 kV
Max. surface fields	1.85 Kilpatrick
Max. pulse power (rms)	630 kW
Max. duty cycle	8.0 %
Pulse length	1.3 ms
Repetition rate	60 Hz
Min. mode separation	2 MHz
Coupler pulse power (rms)	1.0 MW max



Summary

- After 2006 commissioning, SNS accelerator systems have been being tuned up for sustained operation at 1.4 MW beam power
  - SNS showed its capability of sustained operation at power levels up to 1.4 MW
  - System availability goal > 90% is still to be achieved with improvement of Target
- Ion source and LEBT in the front-end have been significantly updated to deliver more beam current with improved reliability
- Reliability of HVCMs have improved significantly
- SCL is providing a very reliable operation for neutron production following SNS power ramp-up
  - SNS has built own high-β cryomodule (March 2012) successfully
- Maintaining system performance with aging RF components becomes a priority
- Improvement of RF conditioning and performance of windows and couplers is progressing
- New BTF has been built and ready for test with beam through the new spare RFQ
  - Perform full beam test to validate the performance of the new RFQ, to study ion source improvements, and other developments for SNS
  - The new RFQ will be validated in the BTF with beam and will be installed in the SNS linac.
  - BTF has been set up for full beam test with an RFQ for ion source development and performance improvements of SNS