SNS Lessons Learned

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SANG-HO KIM
SNS, ORNL

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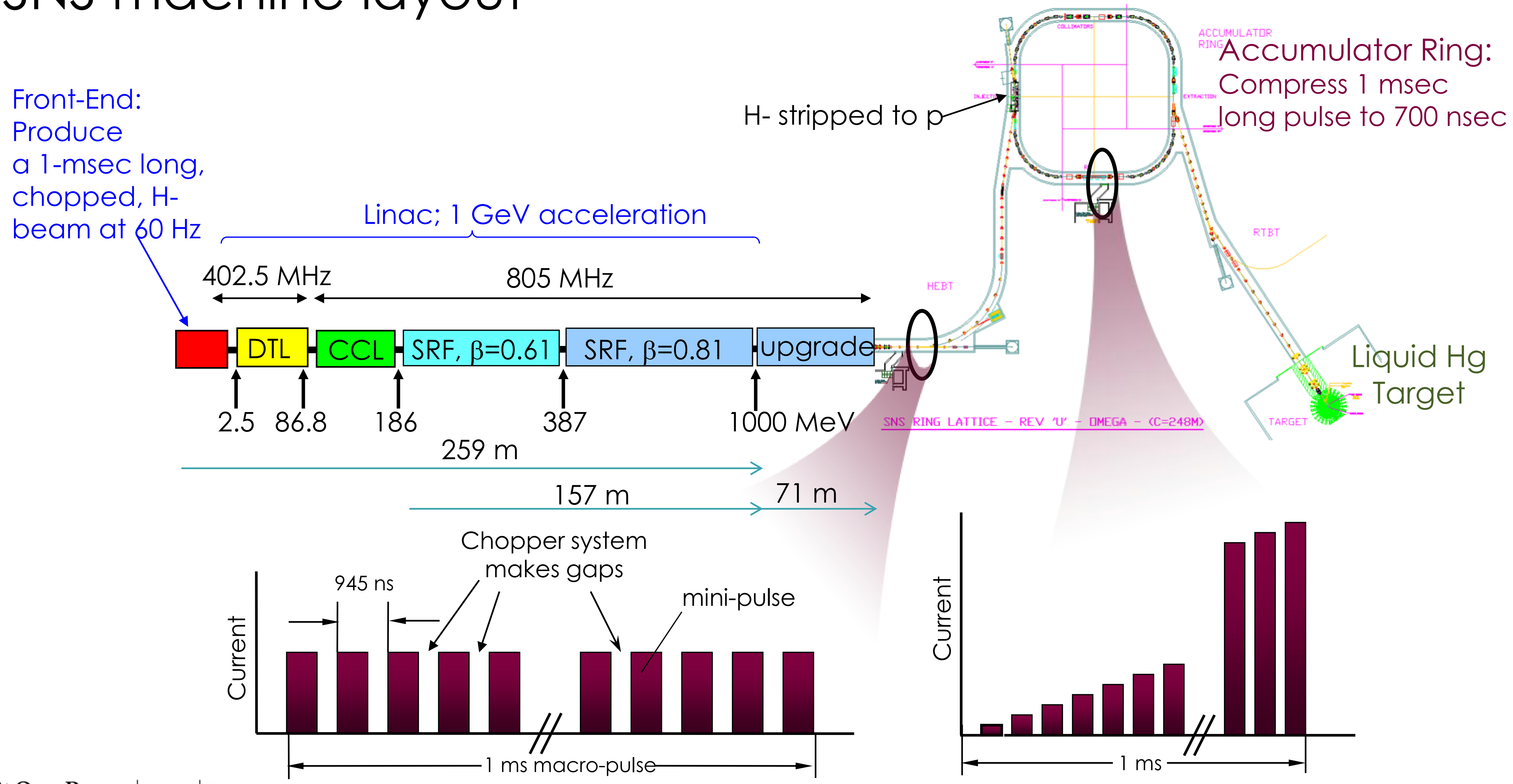
Outline

- Introduction
- SNS SCL operational status
- Design changes for proton power upgrade project
- Summary

SNS machine layout



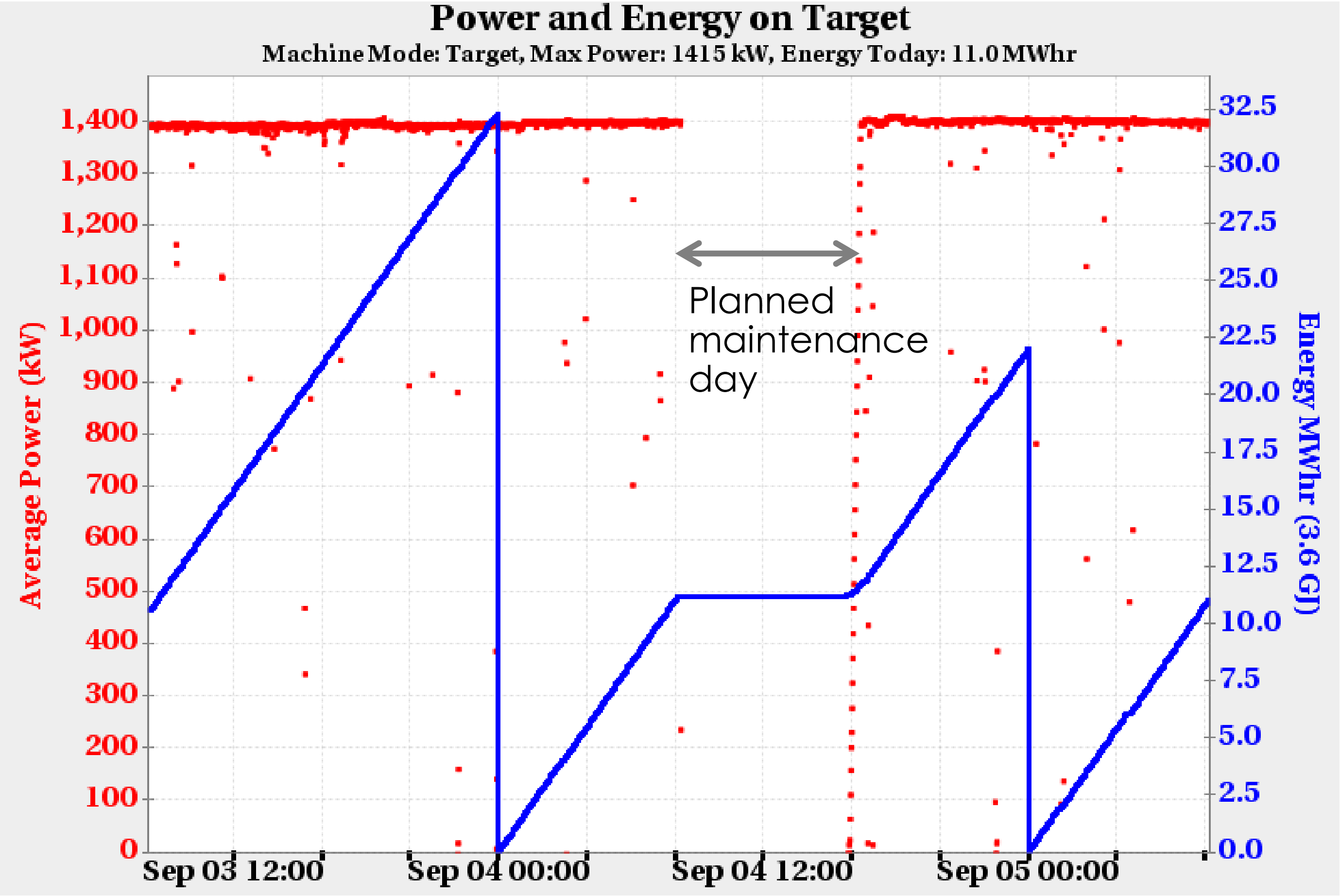
Average macro-pulse beam current:
26 mA

SNS cryomodule design basis

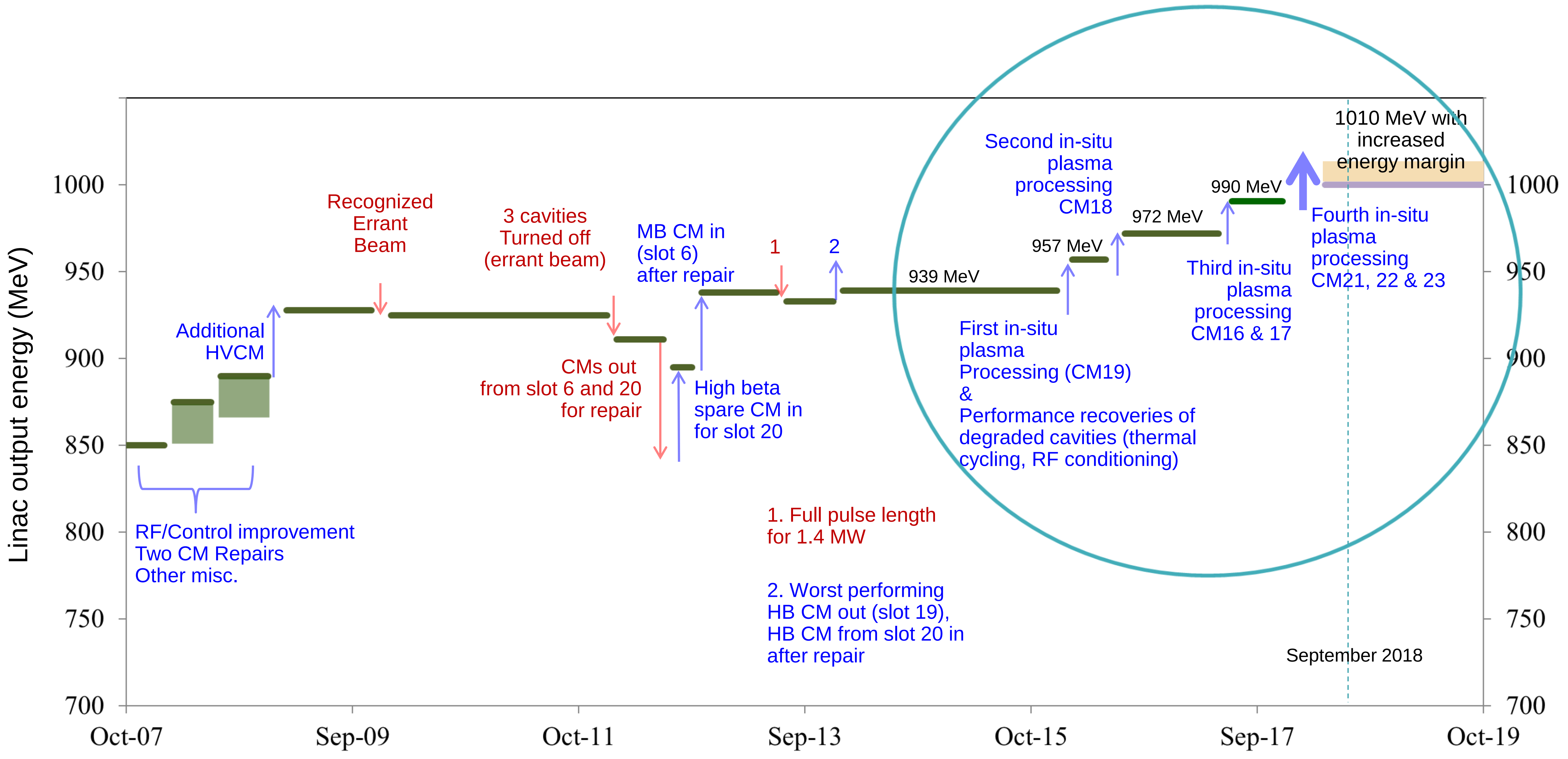
- Cryomodule: similar construction arrangement employed in CEBAF (space frame, end-cans, heat exchanger in return end can)
- Fundamental power coupler: scaled from KEK 508-MHz coupler
- HOM coupler: scaled from TTF HOM coupler
- Mechanical tuner: adapted from Saclay-TTF design
- Piezo tuner: adapted later on. Integrated into one of legs for unexpected large LFD
- Cavity end-group: built with reactor grade niobium

SNS machine status

- SNS is running reliably at or above design spec.
  - Beam power on target: 1.4 MW
  - Beam energy: 1,010 MeV
  - Ion source beam current: >38mA (achieved 53 mA)
  - RFQ transmission: > 90 %
  - Availability: 94 % in FY18
  - Accelerator is running with much improved margin
  - Operation is on track according to Target management plan



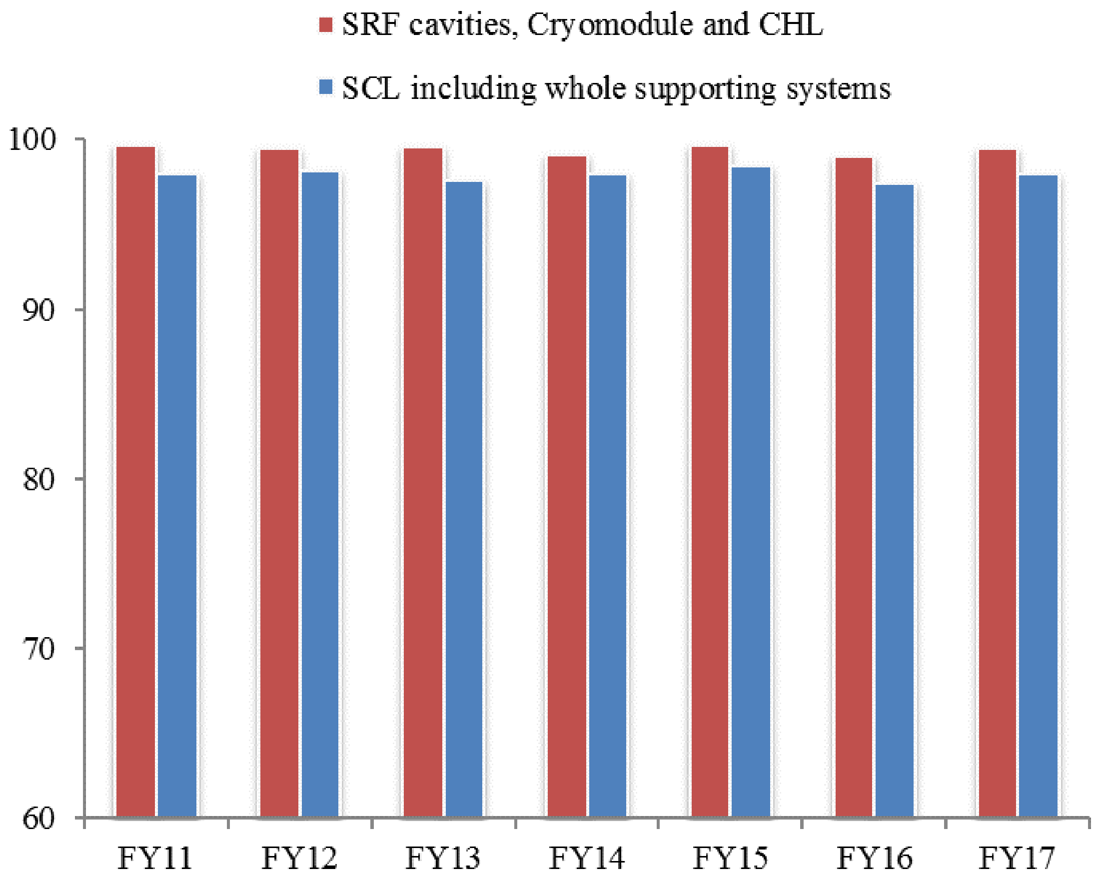
Plasma boost to 1 GeV



Oak Ridge National Laboratory | High Flux Isotope Reactor | Spallation Neutron Source

SCL operation has been stable and reliable

- Availability last 8 years:
  - Whole SCL including RF, HVCM, Control, Vacuum, etc.:~98 %
  - SRF cavities, cryomodules, and CHL: >99%
    - Average trip or downtime: <1 trip/day corresponding to <5 min./day
- Sustainability for the future
  - Developed spare high beta cryomodule
  - Developed CHL spare carbon bed
  - Developing spare medium beta cryomodule
- Improving performance
  - Deployment of in-situ plasma processing



Cavity performance recovery and improvement

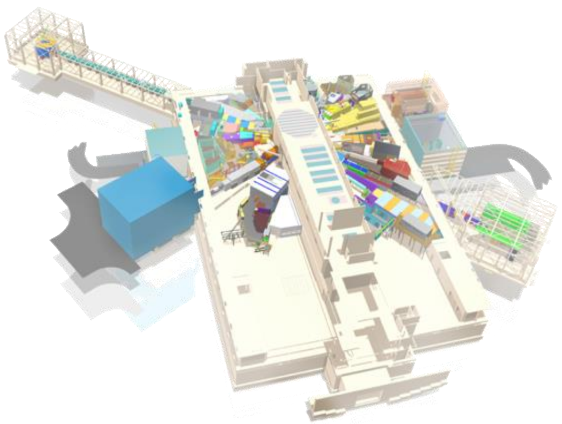
- Recovery of cavity performance to previously attained operating gradients
  - A few cavities in each operating period show a slight performance degradation (lower operating gradient slightly, typically 1 MV/m) due to beam, electron activities, etc.
  - Recovery during maintenance period: RF conditioning and thermal cycling
- Improvement to new higher operating gradients by in-situ plasma processing
  - So far, in-situ plasma processing deployed to 8 HB CMs
  - Main driving force to bring SNS beam energy to 1 GeV

Repairs since FY07

- Instruments (PT, CCG, TC, TD): >100
- Leaks in helium line: ~10
- JT valve actuator: ~20
- Thermal cycling to remove gaseous contamination: ~12
- Tuner repair: >20 (mostly between FY06 and FY13)
- Insulating vacuum repair/upgrade: 10 CMs require pumping
- RF component (water condensation at coupler air side, loosen connectors in CM): 3
- HOM couplers: removed feedthroughs from 7 CMs
- Coupler window (10-7 torr l/s scale leak): 4

SNS upgrade plans

Today



First Target Station
- 24 instrument positions
- 19 instruments built

1.4 MW

Accelerator today

Future

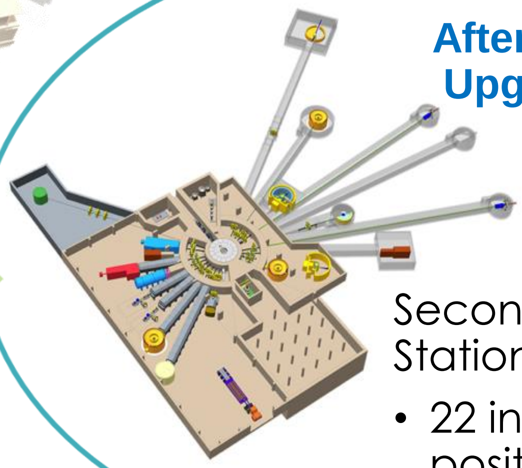
First Target Station
- 24 instrument positions
- 21 instruments built

2 MW

0.8 MW

Accelerator after PPU project

After STS Upgrade



Second Target Station
- 22 instrument positions
- 8 initial instruments

- PPU delivers 2.8 MW capable accelerator
  - Beam energy 30 % increase
  - Beam current 50 % increase

PPU SCL scope

- Increase beam energy from 1 GeV to 1.3 GeV
- Ensure 38-mA (macro-pulse average) beam loading
- Seven new high beta cryomodule
  - Nine empty slots are available
  - Warm sections and magnets are already in place

Design specifications

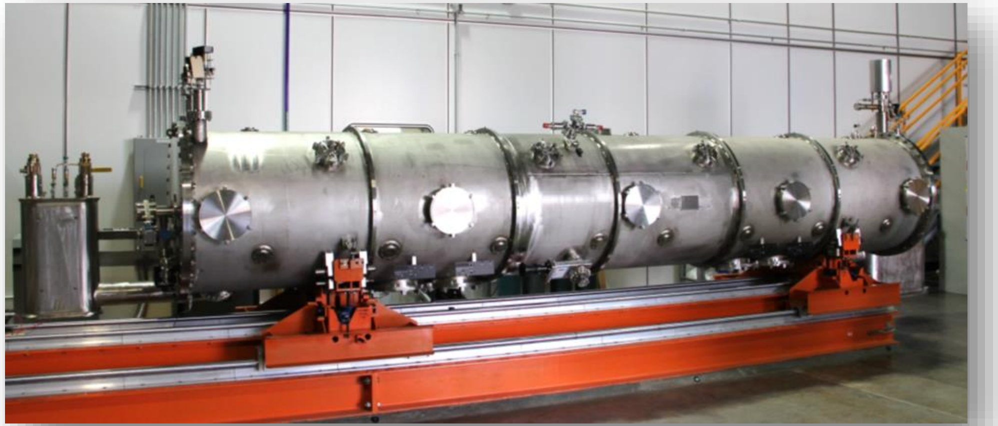
- Lessons learned are incorporated into the design

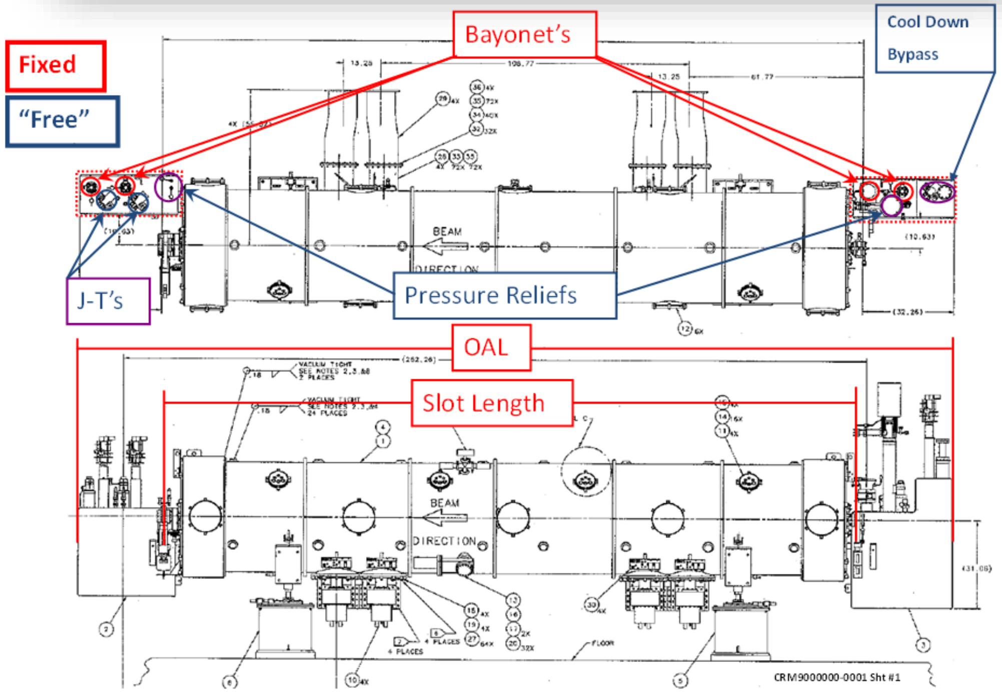
Parameters	Original SNS high-beta cryomodule design	PPU high-beta cryomodule	Demonstration of Performance
E_{acc} (MV/m)	15.8 (14.8*)	16.0	Demonstrated with spare HB CM in operation since 2012
FPC rating. Peak, Average (kW)	550, 50	700, 65	Demonstrated with FPC qualification on test stand
Q_0	$> 5 \times 10^9$ at 2.1 K	$> 5 \times 10^9$ at 2.1 K	No change
External Q of FPC, Q_{ex}	7×10^5 (±20%), fixed type	8×10^5 (±20%), fixed type	Verified on test bench
Material of cavity	RRR>250 for cells, RRR~70 for end groups	RRR>250 for both cells and end groups	Developed 3 new medium beta cavities with RRR>300
Higher-order mode coupler	Two (one at each end group)	None	Demonstrated through HOM measurement and operation
Tuner	One mechanical tune, one fast piezo tuner	1 mechanical tuner (no fast piezo tuner)	Demonstrated through operation
Pressure vessel	Good engineering practice	Code stamp required	Developed spare HB CM

* Average HB cavities in operation as of Sept. 2018

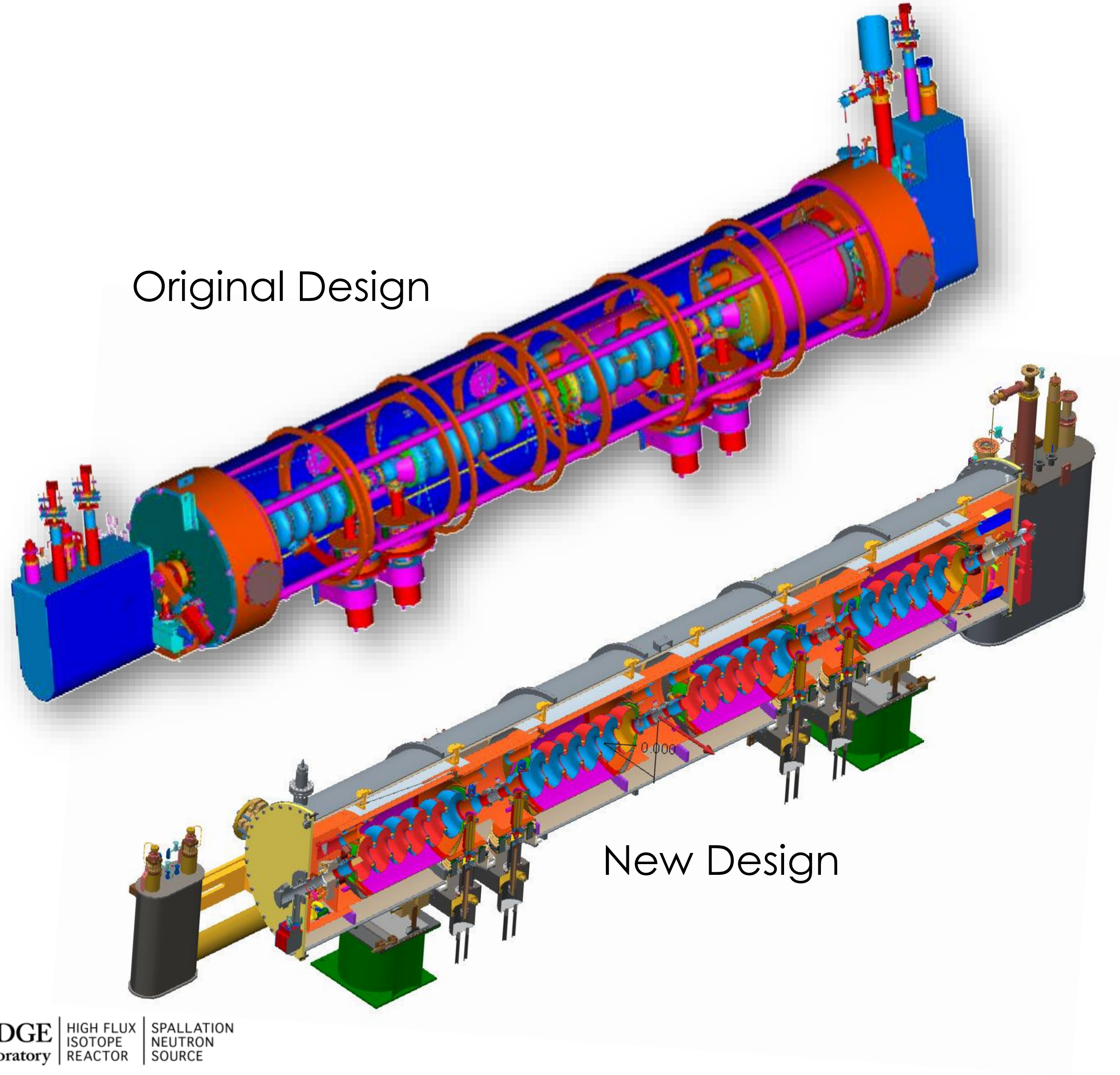
Design principles for PPU cryomodules

- Pressure boundary is compliant with 10CFR851
  - Conducted internal and external reviews
  - Vacuum boundary built to ASME BPVC Section VIII (code stamps)
  - Helium piping built to ASME B31.3
  - All welding conducted in accordance with ASME code
  - The spare high beta cryomodule was built accordingly in 2012: design standard for PPU cryomodule
- Interface point are the same as previous design
  - U-tube connections held constant
  - Slot length held constant
  - Waveguide connections held constant
  - Instrumentation connections are very similar



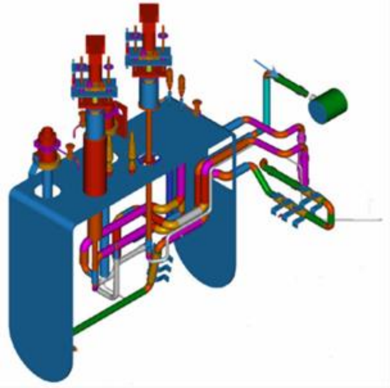


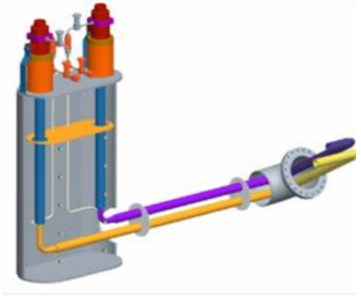
Vacuum vessel and end cans



Return End Can

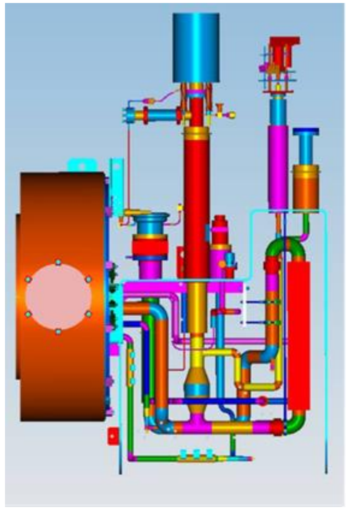
Original Design | New Design

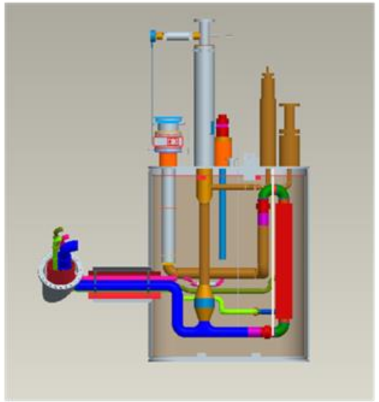




Return End Can

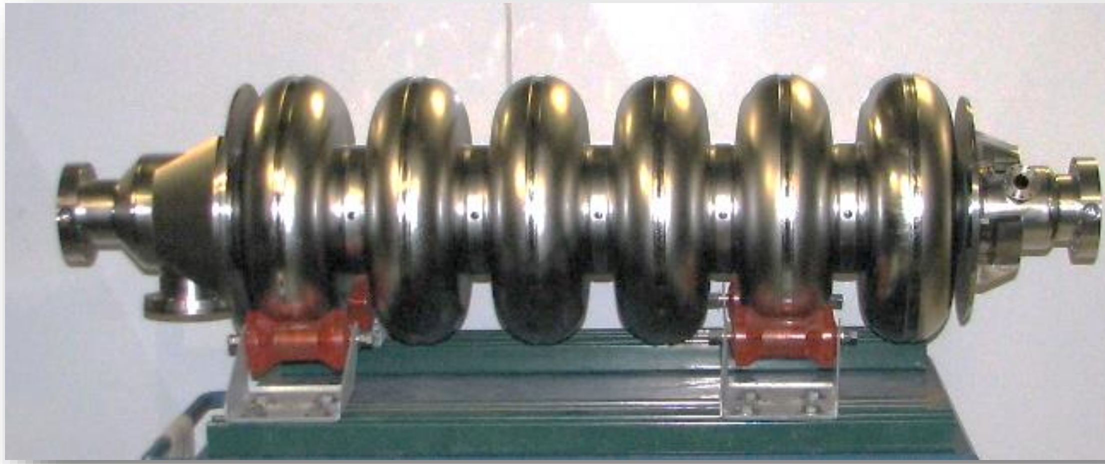
Original Design | New Design

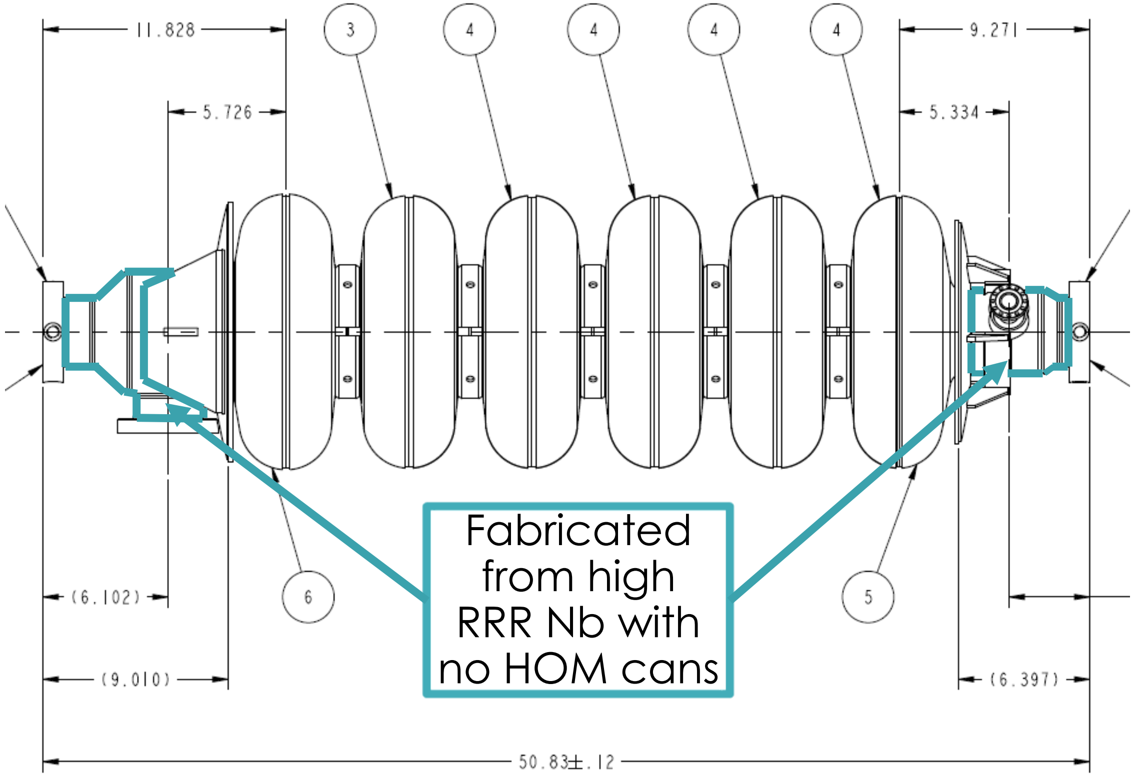




Design changes - Cavity

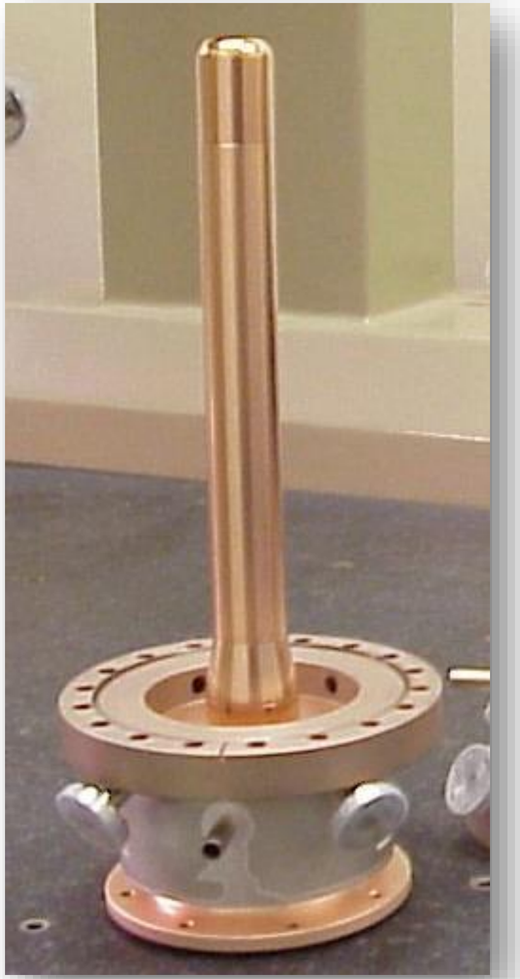
- Minor changes will be incorporated in the fabrication of new PPU cavities: Changes demonstrated with new MB cavities
  - End-group base material will be high RRR and not reactor grade material to increase thermal stability
  - No HOM cans are in design, which will reduce complexity and improve cleaning of cavities

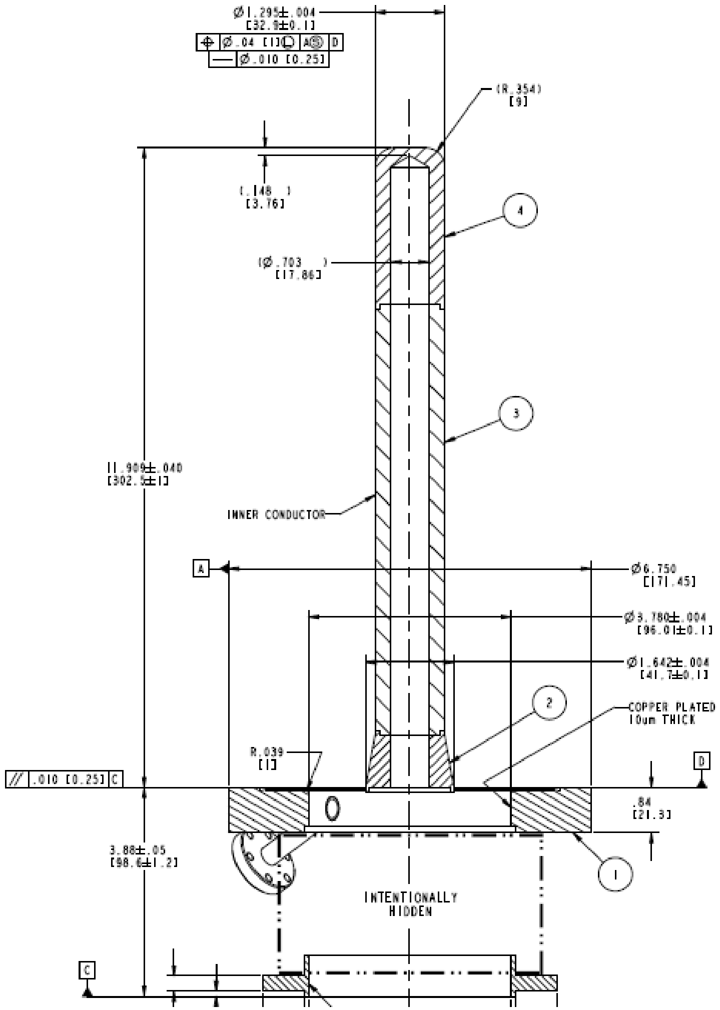




Design changes – Fundamental power coupler

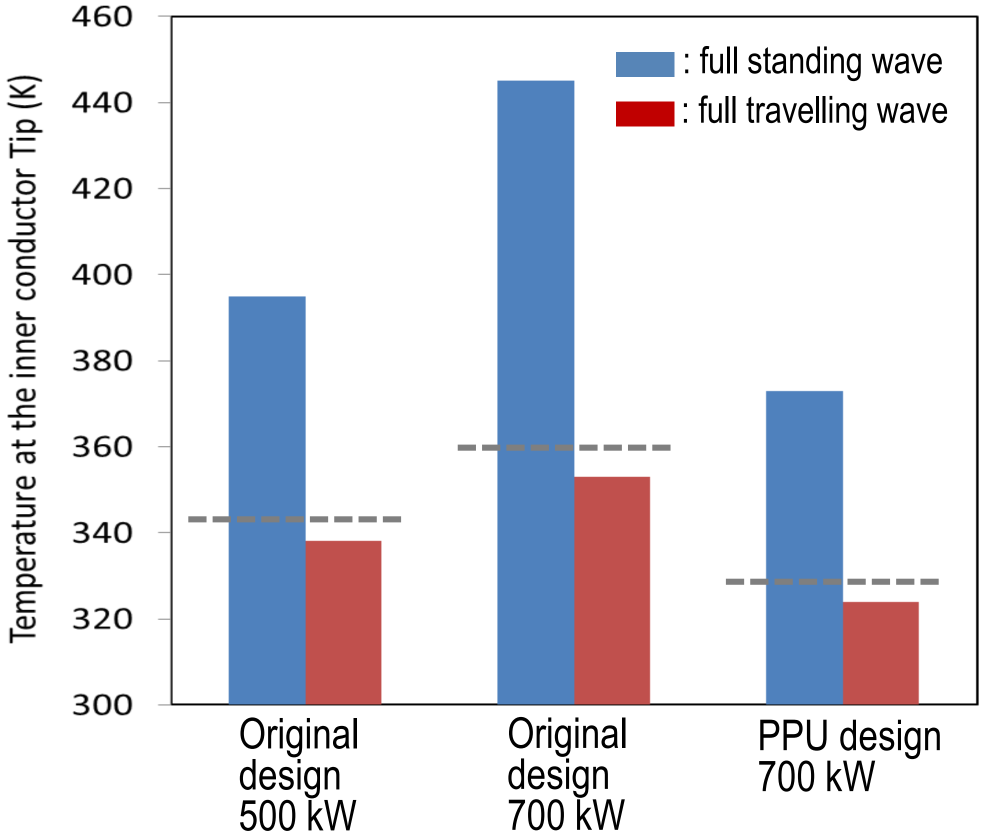
- Two minor changes for the fabrication of new FPCs
  - The inner conductor wall thickness will increase lead to an operating temperature below the ones currently in operation
  - The inner conductor length will be reduced by 1.5 mm for better matching to the beam loading





FPC inner conductor

- Original SNS FPC was tested at > 1 MW during the SNS project
  - There's no concern on power handling capability
- PPU requires the FPC to handle up to 700-kW peak over a 1.3-ms pulse at 60 Hz (65-kW average)
  - Increased inner conductor temperature would result in higher thermal radiation on the end-group
  - Thick inner conductor will lead to an operating temperature below the ones currently in operation

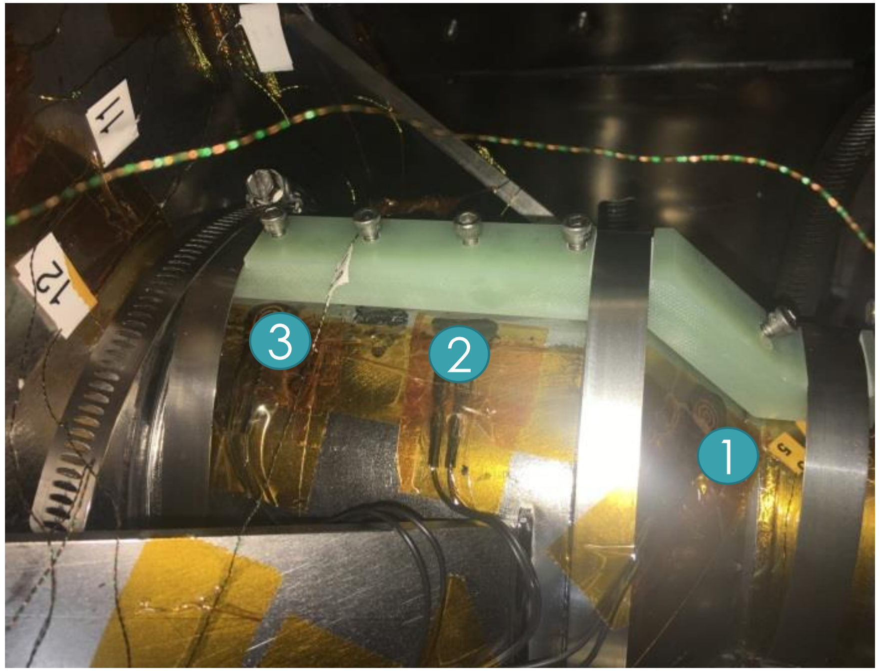


End group thermal stability

- Achievable accelerating gradients of existing cavities are limited due to poor thermal conductivity of end-group
  - End-group heating occurs due to electron activity (Field Emission and Multipacting)
- Several cryomodules in the Linac have shown sudden large increases in JT Valve Position during normal operation indicating partial quench in end-group
  - Initial seed point thermal load is estimated to be < 1 Watt
  - Interaction with stray RF field creates meta stable condition with an increased normal conducting region in end-group
  - Heat loads to 2-K circuit as much as 40 – 50 W observed

End-group thermal stability test

- Cavity SNS MB01 with high RRR end-groups was tested in the Horizontal Test Apparatus (HTA) to check thermal stability of FPC end-group
  - Small area heaters were mounted onto the end-group at three locations
  - Tested performed at design gradient
- An improvement in thermal stability by a factor of ten from the original cavity simulation model for point heat load



FPC end group stability test	Distance of heater from Helium Vessel (cm)	Heater Power	Cavity on
Heater 1	13.2	> 3W	Stable
Heater 2	7.0	> 3W	Stable
Heater 3	2.3	> 3W	Stable

HOM couplers

- During the design phase of the SNS project
  - No beam dynamics issues were identified if Q_{ext} of HOMs < 10^8
  - HOM induced thermal load was estimated with very conservative assumptions for HOM frequency spread and HOM centroid error
    - There will be non-zero chance for this concern and decided to have HOM couplers as an insurance
- HOM coupler operational problems in the past (MP, detuning, large fundamental mode coupling)
  - In 2007 HOM spectrums were measured for all installed cavities to verify HOM frequency spread and HOM frequency centroid error to simulations
    - HOM damping of the SNS cavities is not necessary
    - New SNS cavities in the future will not have HOM couplers
    - HOM feedthroughs will be removed whenever a cryomodule is taken out for repairs
- So far, 7 cryomodules had HOM feedthroughs removed
- PPU cavities will be fabricated without HOM couplers

Summary

- Significant testing and operational experience has led to a better understanding of systems
  - There will be always machine-specific issues and nuisances especially in ‘first of a kind’ machine:
    - keep design simple, keep enough margin, keep room for upgrade
- Lessons learned for reliable operation and high performance
  - Operational flexibility is one of the critical aspects for high availability of SNS SCL
    - Run with adequate energy margin to shorten downtime
  - Balanced performance between all sub-systems, lead to the most reliable and efficient system
    - Weakest-link limits overall performance