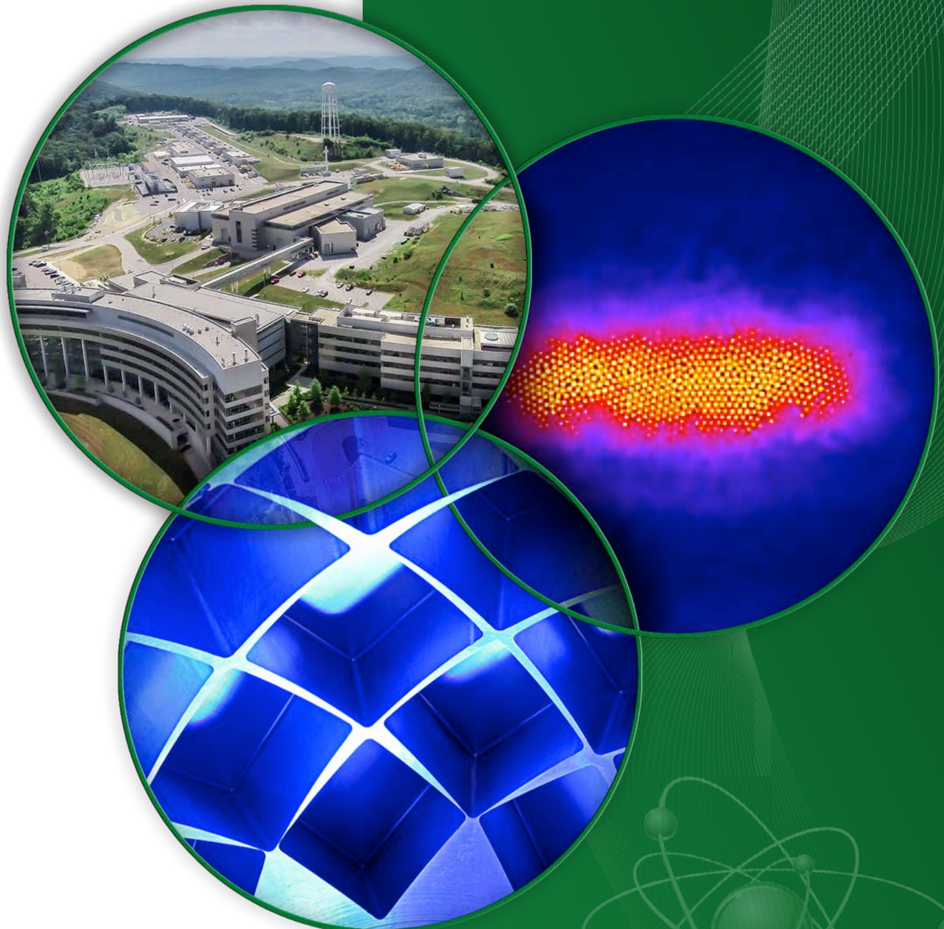
Superconducting RF Strategy STS Strategy



Presented at:

Accelerator Advisory Committee Meeting

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Scope Overview

- Seven new high beta cryomodules will be fabricated and installed to increase beam energy to 1.3 GeV
  - Nine empty slots available
  - A design gradient of 16 MV/m is specified
  - Improvements will be incorporated in the cavity design to enhance performance

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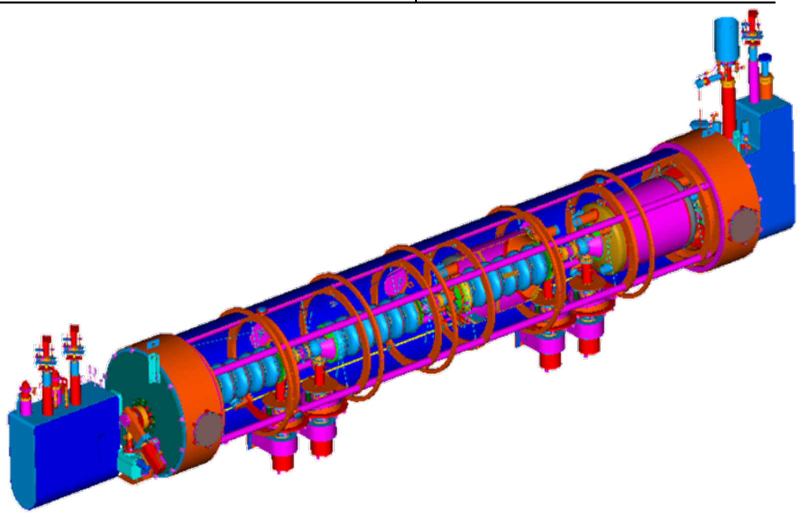
Outline

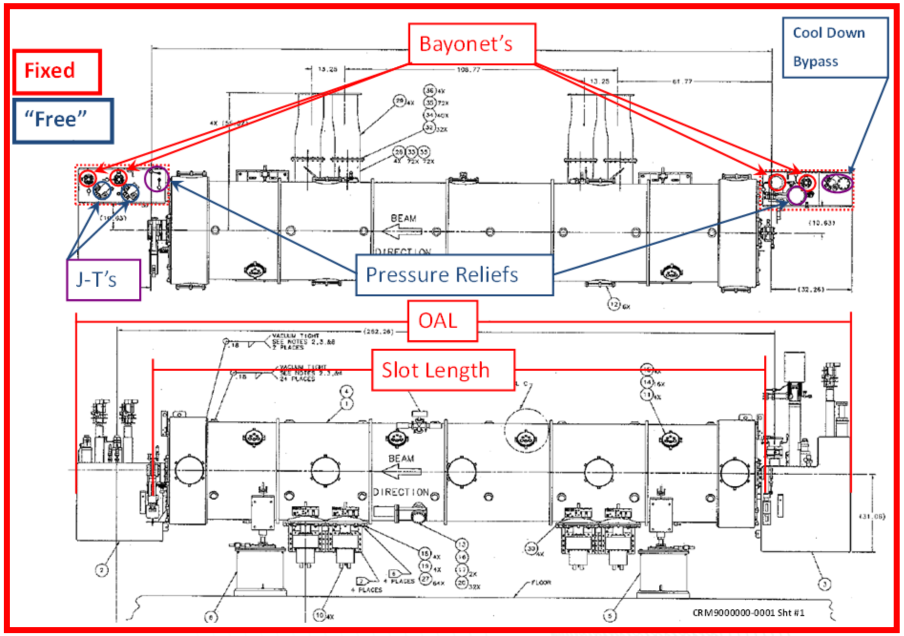
- Design constraints of cryomodules
- Issues leading to design changes
- Spare high beta cryomodule
  - Multiple improvements made and tested
  - A good intermediate step between the original cryomodules and STS cryomodules
- Additional improvements are still required for the STS cryomodules
- Plan for the STS SCL
  - High Power RF and High Voltage Converter Modulators (David Anderson)
- Summary

New cryomodule design constraints at SNS

- Use original design where possible to minimize spares requirements
- Incorporate lessons learned from original 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

Parameter	Value
Slot Length	7.891 m
CM length (bore tube)	6.291 m
# of bayonets	4
# of control valves	5



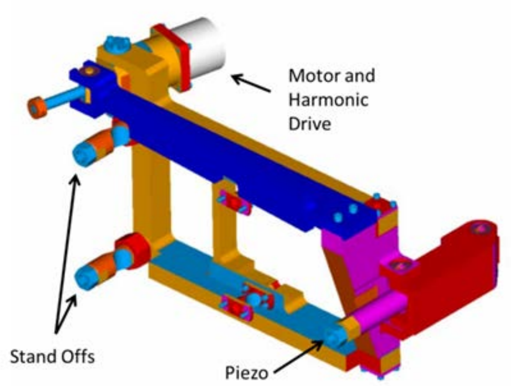


Issues leading to design changes

- Cavity performance
  - Most exhibit field emission below design gradient
    - Limits gradient in normal operation through heating of the end group
    - Collective effects also exist
    - Field emission limits the final output energy of the linac
  - Each cavity set at a maximum gradient based on collective limits
    - Determined from performance testing
  - HOM coupler system performance issues even when operating RF only
  - Piezo tuners have had mechanical failures
- Pressure vessel code compliance required
  - 10CFR851 enacted in February of 2007
    - Requires meeting the ASME Boiler and Pressure Vessel Code or equivalent
  - Original cryomodules designed utilizing “good engineering practice”

Example of a demonstrated improvement

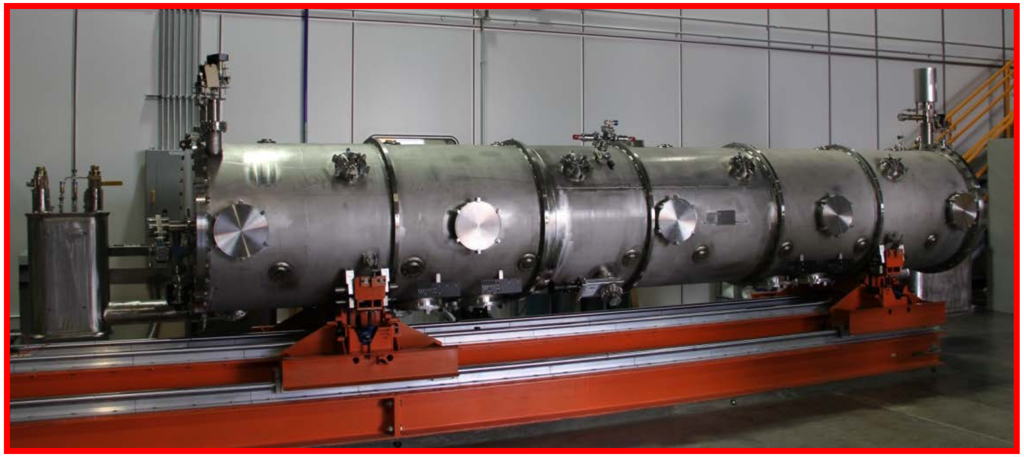
- Tuner Improvement
  - Original tuner incorporated a Piezo tuner
    - Accounts for Lorentz force detuning of cavities
    - Large unexpected mechanical resonance has not been observed at SNS
    - Cavity phase and amplitude have been within compensation range of RF system
    - Piezo tuners have had mechanical failures
  - Piezo tuners removed from STS cavities and replaced with a standard stand off



Spare High Beta Cryomodule

High beta spare cryomodule was developed and fabricated in-house at SNS to be code compliant

- First code stamped cryomodule in the world
- This spare allows removal of operating high beta cryomodule for repair
- High beta spare cryomodule serves as prototype for STS
- Set the baseline design for a medium beta spare cryomodule



High beta spare has been in service since the summer of 2012 and all four cavities reached 16 MV/m, STS specification

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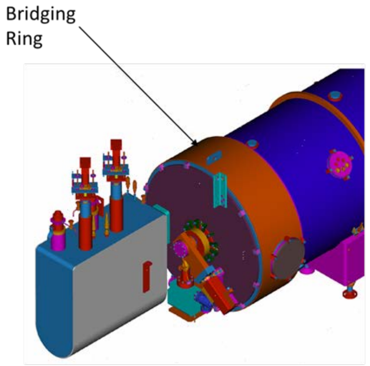
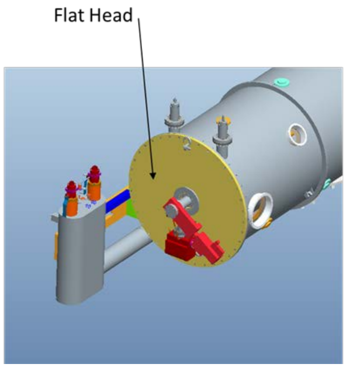
SNS approach to meet 10CFR851 (1)

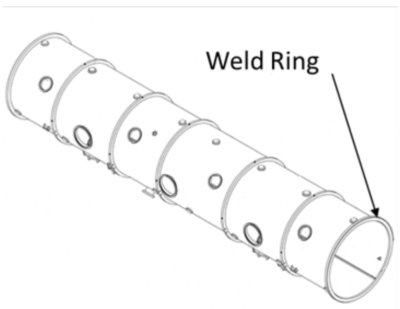
- Cryomodule
  - Apply Section VIII of the ASME Boiler and Pressure Vessel Code to the vacuum boundary
  - Make use of interpretation VIII-1-89-82
    - This interpretation deemed it acceptable to stamp the exterior vessel of a heat exchanger if the tube side exceeded the rated operating pressure provided the shell and associated relief devices are designed to withstand the highest design pressure associated with the tube side.
  - Deviation from typical approach of making the helium circuit the pressure boundary
    - Certain materials integral to our system not considered code materials
    - Other materials not code certified at operating temperatures
  - Good engineering practice was applied to the internal components of the cryomodules

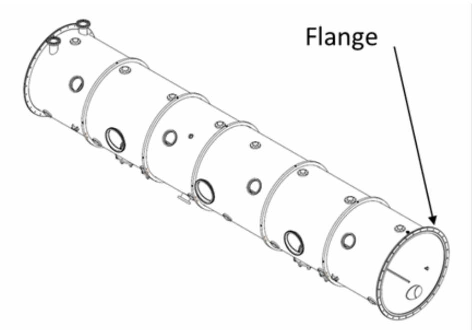
SNS approach to meet 10CFR851 (2)

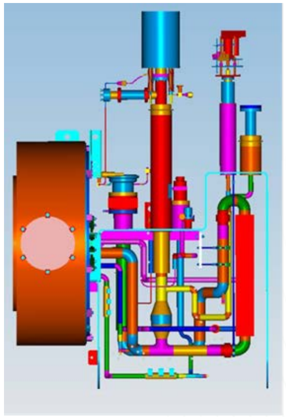
- Vacuum Vessel
  - Bridging ring removed from cryomodule design
  - Vacuum vessel was lengthened
  - Changes were incorporated in spare high beta cryomodule and methodologies developed
- End Cans
  - Pressure stamped on vacuum shell
    - Thicknesses and shape of outer shell had to be modified
  - Allow for pressure testing before integrating with the vacuum vessel
  - Simplify piping where possible

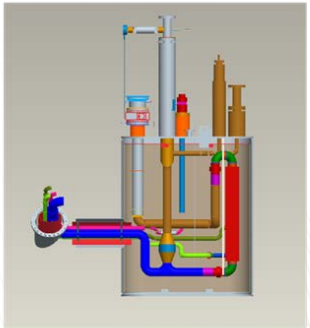


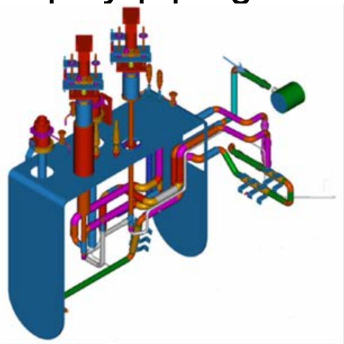


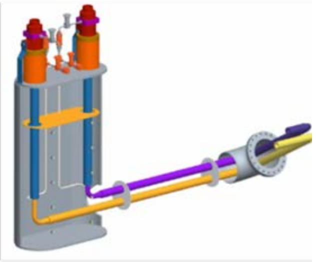






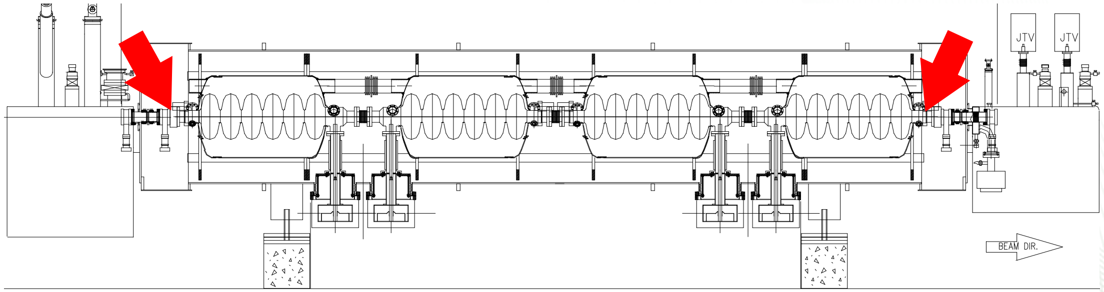






Improvements leading to high beta spare cryomodule cavities meeting gradient specification

- Cavities were processed using EP
- HOM feedthroughs removed and blanked on all cavities
  - HOM couplers were detuned
- Additional Improvements
  - Thermal stationing of outside end groups
    - Install a cooling block to the outside end group end flanges
    - Successfully implemented on the spare cryomodule
    - Was in the original design and eliminated



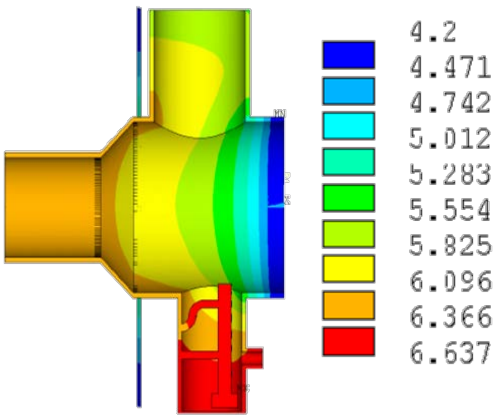
Additional Improvements for STS CM

The spare high beta cryomodule was a stepping stone, additional upgrades are identified for success

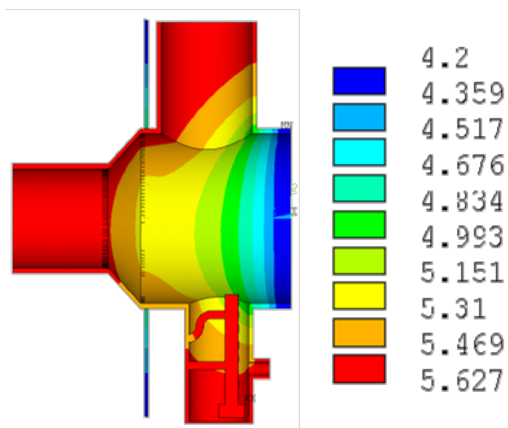
- Spare high beta cryomodule cavities met STS specifications but
  - we have an indication that end group performance is still problematic due to low grade material and complex geometry
  - Cavity 20d (spare high beta cryomodule cavity) has shown degradation since installation in summer of 2012
- Further improvements for STS cavities will improve operational margins and reduces risk
  - Change end group material to RRR to improve thermal stability and increase thermal margin
  - No HOM components
    - Not needed
    - Simplifies geometry and increases effectiveness of processing
  - Fundamental power coupler design slightly modified to reduce thermal radiation to end group
- With these changes, sustainable operation at 16 MV/m is achievable for STS cavities

End group improvements for STS cavities

- End group thermal operational performance is the weakest link for achieving stable higher gradients in installed cavities due to
  - Multiple thermal loads including thermal radiation from FPC, field emission, multipacting, etc.
  - Cooling to the end group is provided only by conduction
- Improving thermal conductivity of end group would provide stability at higher thermal loads
  – High RRR end group improves conduction and increases thermal margin



(a) RRR=70



(b) RRR=150

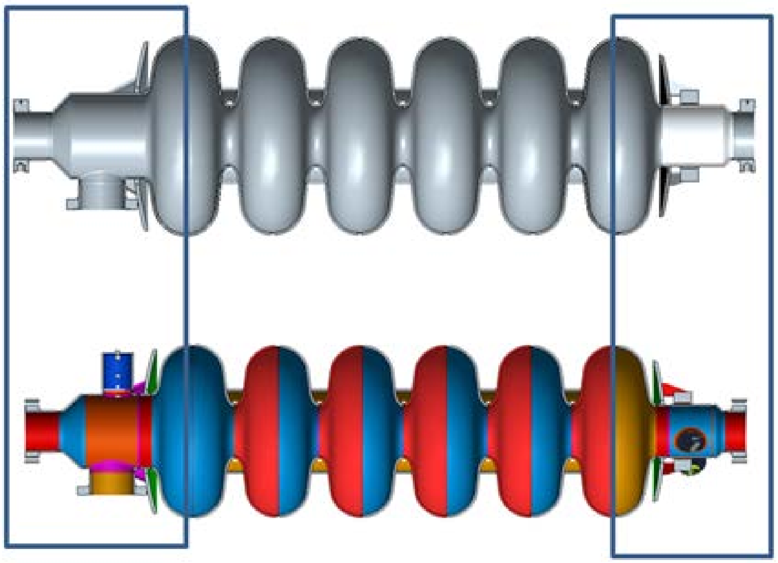
- With a distributed thermal load, an end group with a RRR of 150 would operate 1K colder than the original end groups.
- For a localized thermal load, thermal margin increases significantly.

Eliminate HOM couplers for STS cavities

- Issues with HOM couplers at SNS
  - About 15% of SNS cavities display abnormal signals through the HOM feedthroughs
  - All attenuators for the HOM signals were damaged within one year of operation
  - Two cavities were not operational due to these issues (one was repaired)
- HOM couplers are not needed for SNS linac operation
  - Probability of cavity frequency falling on a significant beam power spectral line at any instant in time is very small
  - HOM couplers were included in original design as insurance against unknown parameters
  - After operation and additional studies of HOM couplers, it was decided that HOM couplers are not needed for SNS (March 2007 SRF review)
  - HOM feedthroughs have been removed from four cryomodules during repair (leaks were detected in approximately half of the HOM feedthroughs)
- The STS cavities will not have HOM couplers
  - Eliminates the possibility of damage to the HOM due to high or abnormal power loading
  - Eliminates a complex geometry

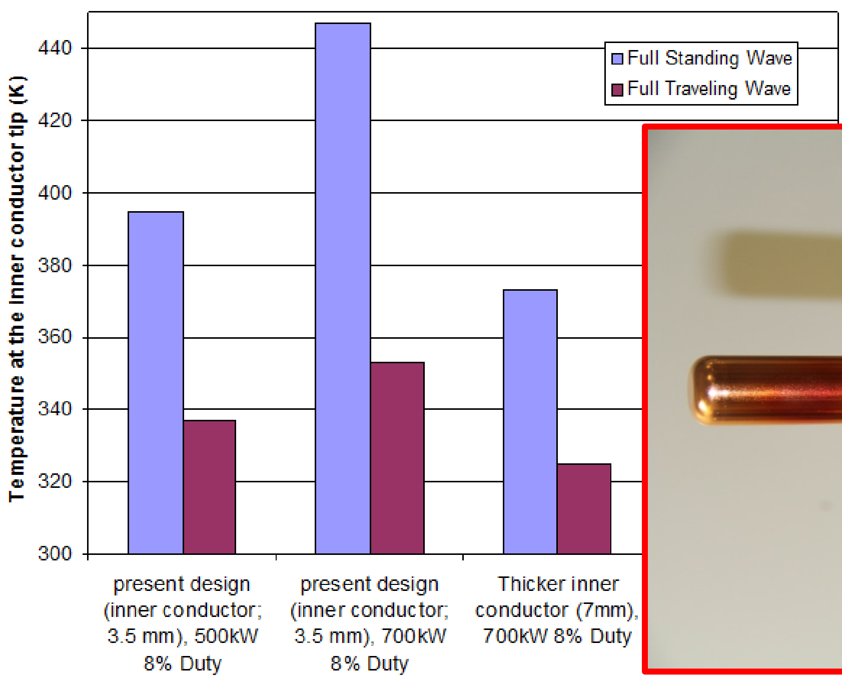
Two spare cavities from the original production were modified to study the end group design for STS

- Manufacturing scheme of end group replacement was developed
- End groups removed and replaced with high RRR end groups
- HOM coupler removed from end groups
- Chemical processing was completed at Jefferson Laboratory
- Cavities have been delivered and ready for test

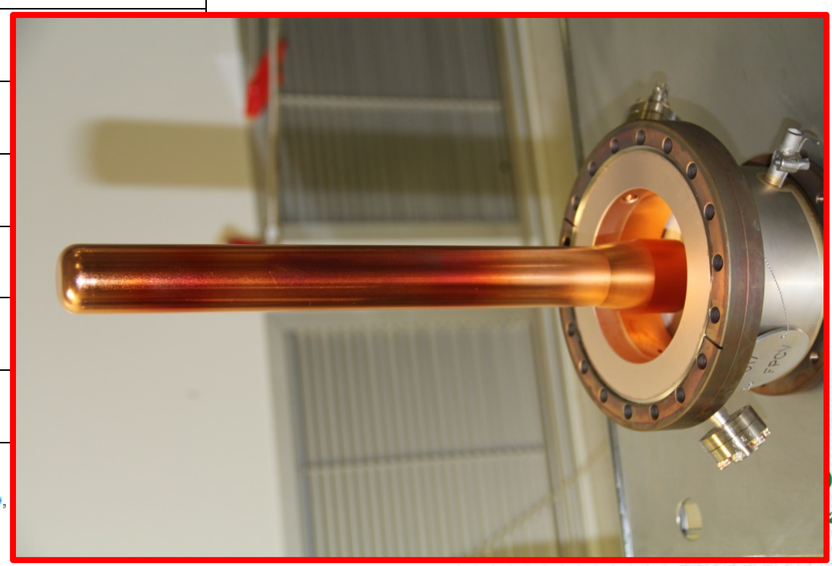


Fundamental Power Coupler (FPC)

- Installed FPCs
  - Scaled from KEK 508.8 MHz coupler
  - Designed for peak power of 550 kW (~8% duty factor: average power 47 kW) and tested up to 2MW in full travelling wave on test bench
- STS FPCs
  - Designed for 700 kW peak and 65 kW average power providing operational margin
  - Only design change: utilizes a thicker inner conductor wall (7mm vs 3.5mm) to operate at a lower tip temperature
  - Prototyped and full power testing under way



STS FPC



Plan for the STS SCL

Design parameter summary of cryomodules

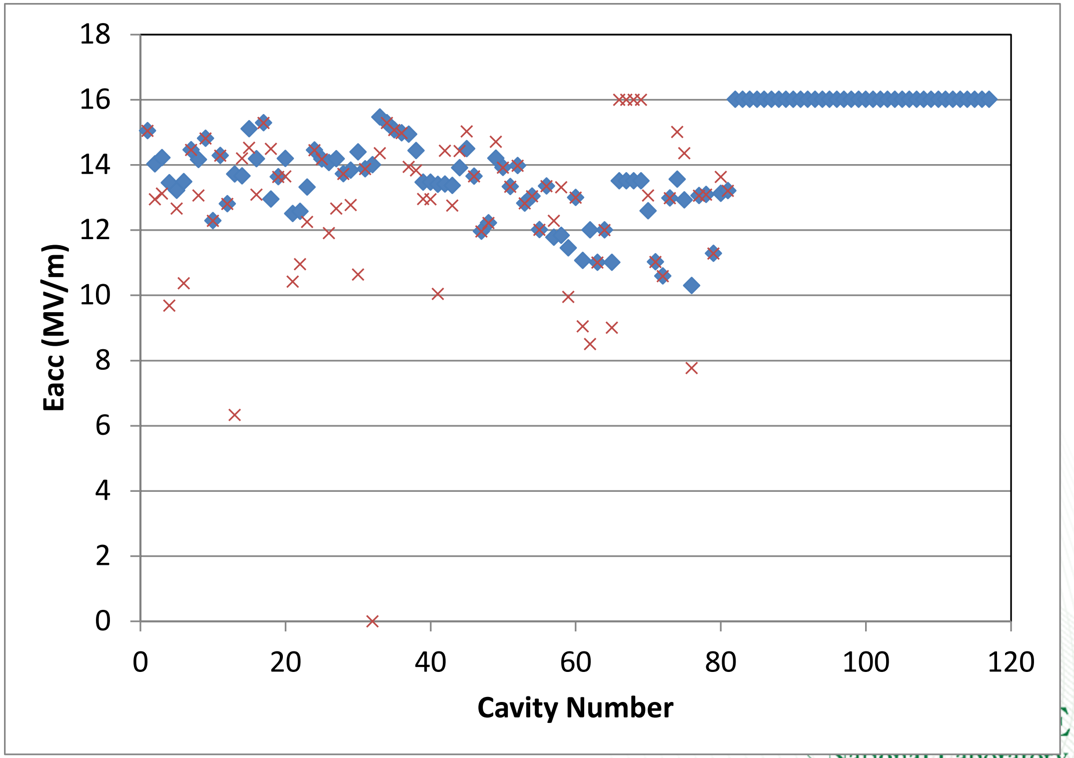
Parameters	Original SNS High Beta Cryomodule	Spare High Beta Cryomodule	STS High Beta Cryomodule
E_{acc} (=E_oT_g, T_g: Transit time factor at β_0.81) (MV/m)	$\boxed{15.8}$	16.0	16.0
Fundamental power coupler (FPC) rating, peak and average (kW)	550, 50	550, 50	700, 65
External Q of FPC, Q_{ex}	7×10^5 (+/- 20%) Fixed Type	7×10^5 (+/- 20%) Fixed Type	8×10^5 (+/- 20%) Fixed Type
Material of cavity	High RRR Nb (>250) for cells. Reactor grade Nb for end groups	High RRR Nb (>250) for cells. Reactor grade Nb for end groups	High RRR Nb (>250) for cells and end groups.
HOM couplers per cavity	2 (one at each end group)	2 (one at each end group detuned with feedthoughs removed)	none
Tuner	1 mechanical tuner, 1 fast piezo tuner	1 mechanical tuner (no fast piezo tuner)	1 mechanical tuner (no fast piezo tuner)
Pressure Vessel	Good engineering practice	Code stamp required	Code stamp required

Original HB CMs are actually operating at approximately 13 MV/m

- Confident in successful STS CM effort
  - Ten years of operating experience with original cryomodules
  - Successful fabrication and operation of spare high beta cryomodule

Plan for STS linac

- Seven new high beta cryomodules are proposed to meet 1.3 GeV with three cavities as energy reserve
  - Assumed improvement is estimated from operational experience and known issues
    - For example, 5a and 11b rework is assumed
    - In-situ plasma processing for Medium beta cavities are assumed
  - Gradients need to be reduced for some high beta cavities due to limited available RF power



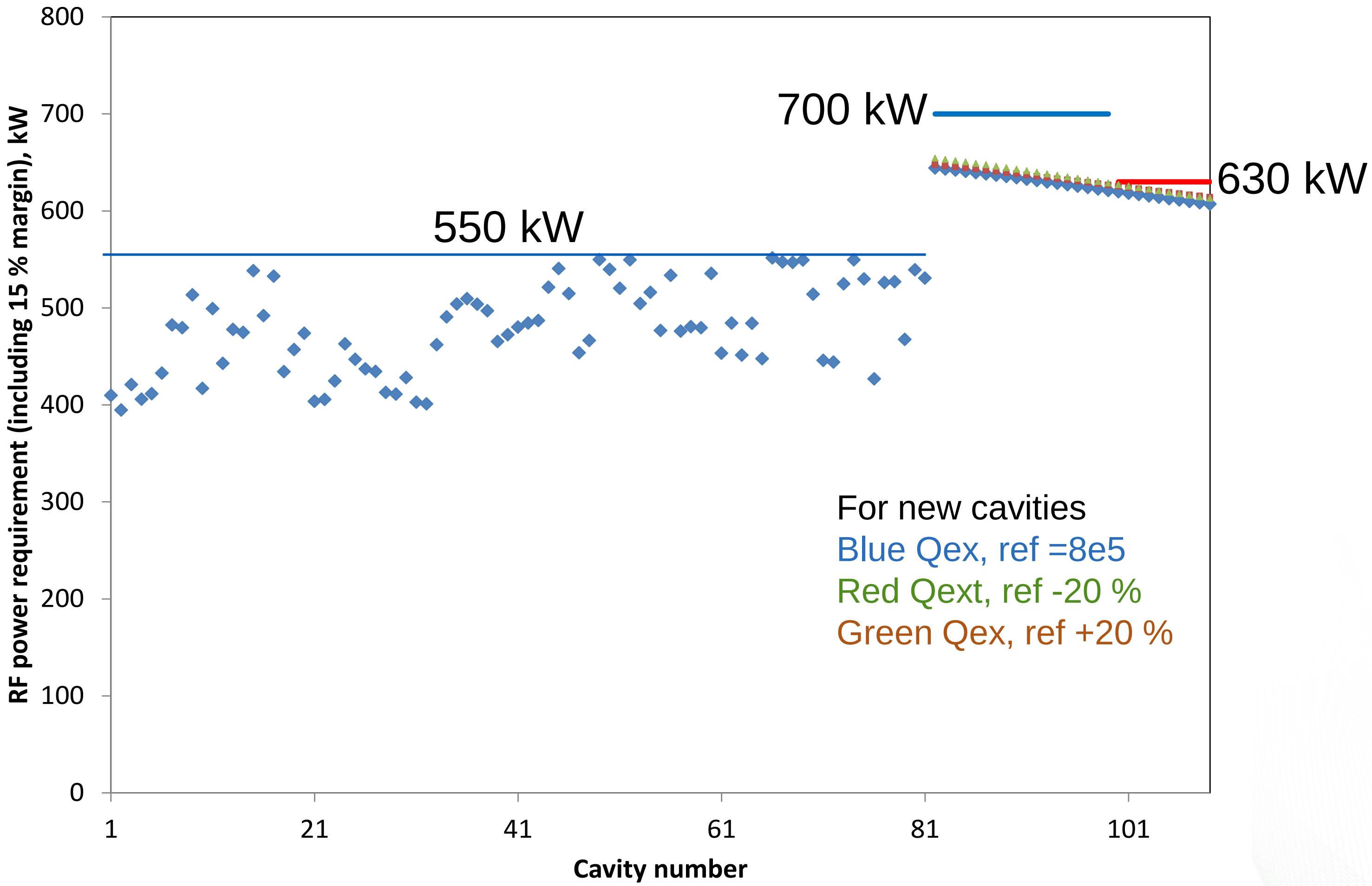
X Present operating gradients

◆ STS operating gradients

HPRF and HVCM

Utilization of HPRF for STS

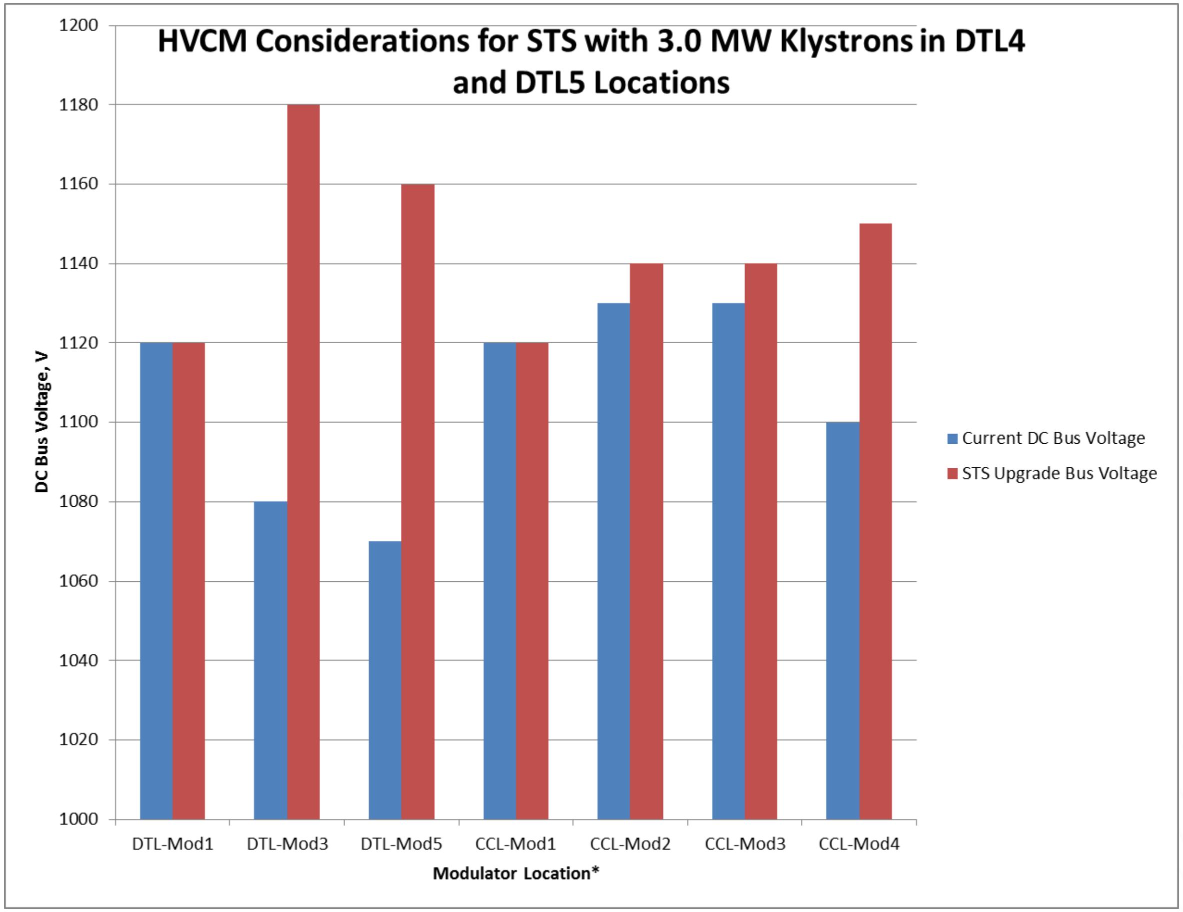
38 mA, -50 Hz detuning at the end of pulse for STS cavities



- No changes of HPRF for existing CMs
- STS portion → 700 kW klystron, 65 kW avg. FPC

Warm Linac HVCMs with Alternate 3.0 MW Klystron Appears Feasible with Current Modulators

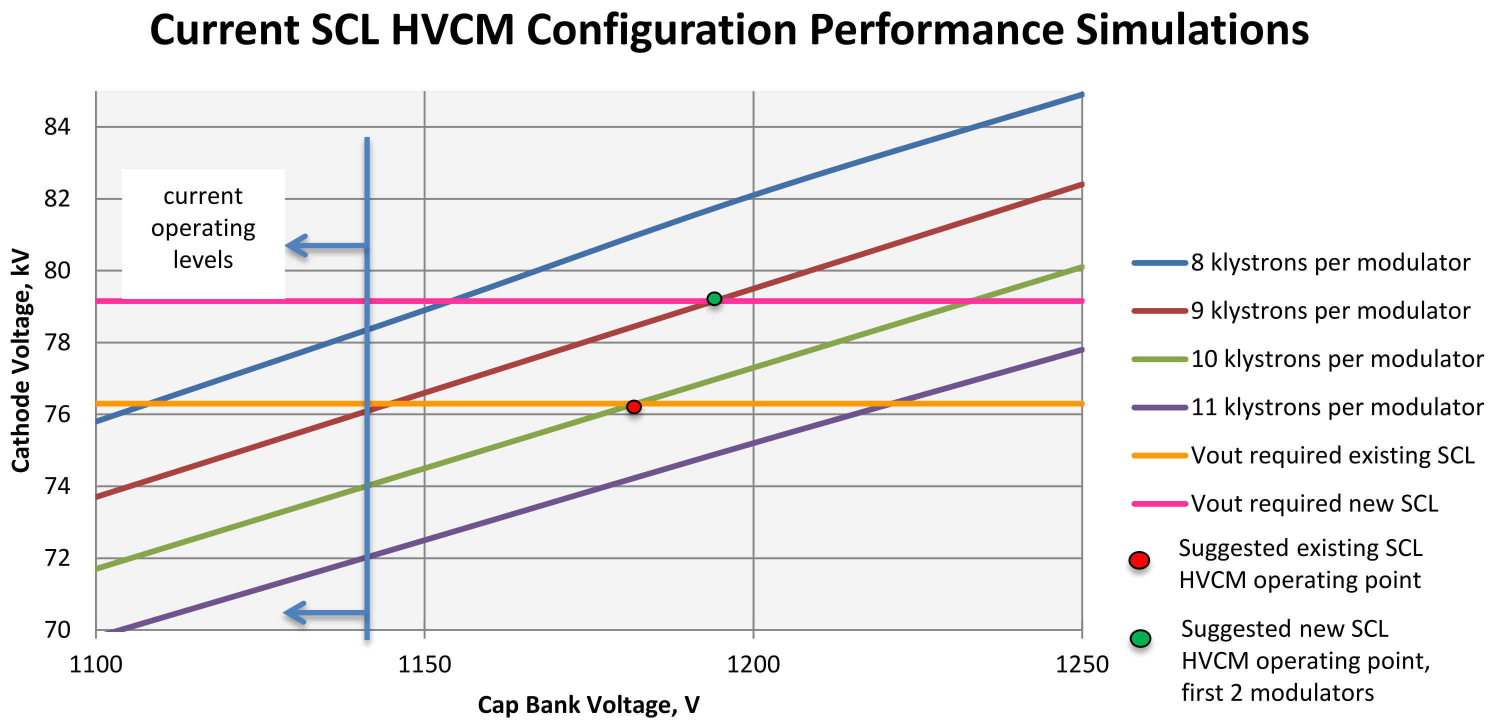
- HVCM DC Bus Voltage is a leading indicator of system reliability
- DTL4 and DTL5 operate off of DTL-Mod5 with two 3.0 MW klystrons
- DTL3 and DTL6 operate off of DTL-Mod3 with existing 2.5 MW klystrons
- Other klystrons unchanged but require more output power



- Operation to ±1250 V for hundreds of hours demonstrated on HEBT HVCM with snubbers
- Anticipate comparable reliability to current performance at up to ±1200 V
- Need better performance parameters for 3.0 MW klystron

Constraints of Current HVCM Systems Dictate the Ratio of Klystrons to Modulators in the SCL (new and existing)

- Existing medium/high beta cavity klystron: modulator ratio of 10:1 forces higher DC bus voltage to provide required additional power
- Reduction to a 9:1 klystron: modulator ratio for first 18 new cavities (2 HVCMs) to achieve the required power reliably
- 10:1 ratio for the last 10 new cavities at reduced <630 kW power levels still maintains proper gradients and reliable HVCM operation
- **3 additional modulators required for STS upgrade**



Summary

- The cavity specification gradient of 16 MV/m is achievable and sustainable and has been demonstrated in the spare high beta cryomodule
- Lessons learned from the operation of the original cryomodules and the fabrication and operation of the spare high beta cryomodule
  - Multiple cavities have had electron loading within the end group
    - Changing the end group to high RRR niobium will improve the thermal stability of the cavity
    - Removing the HOM filter will eliminate issues associated with this system
    - Spare high beta cavities have been modified to study the new end groups
  - The spare high beta cryomodule provides an important milestone to developing the STS cryomodule

Backup slides

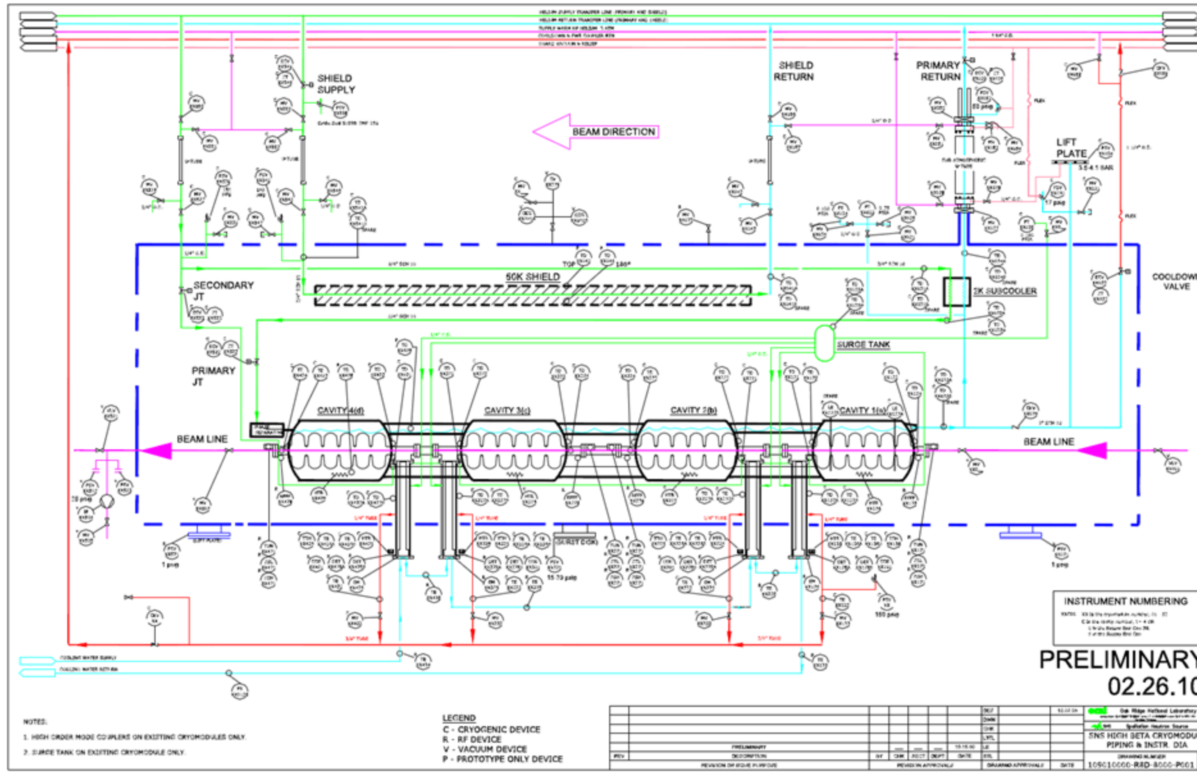
Cavity Parameters

- Cavity RF parameters remain the same

Frequency (MHz)	805
Type	Elliptical
Operating mode	pi
Geometric beta	0.81
Equivalent cavity length (mm)	906
Bore radius (mm)	48.8
Inter-cell coupling (%)	1.6
r/Q at geometric beta (Ohm)	483
Epeak/Eacc	2.2
Bpeak/Eacc (mT/MV/m)	4.75
Wall thickness (mm)	4 (~3.8 after chemical processing)
Operating temperature (K)	2 K
Q_o	$>5 \times 10^9$ at 2 K
Number of cells per cavity	6
Stiffener	Yes (at r=80 mm)
Fundamental power coupler per cavity	1

Heat Loads and Helium Circuits

- 3 helium circuits
  - Shield cooling
  - Primary helium
    - Provides helium to helium vessels
  - Secondary helium
    - Cools couplers and outside end groups
  - Heat Loads
    - Adjusted for STS based on experience with the Spare high beta cryomodule
    - Original cryogenic plant design had 100% margin on primary and 35% on shield
    - Adding seven new high beta cryomodules is well within cryo system capabilities

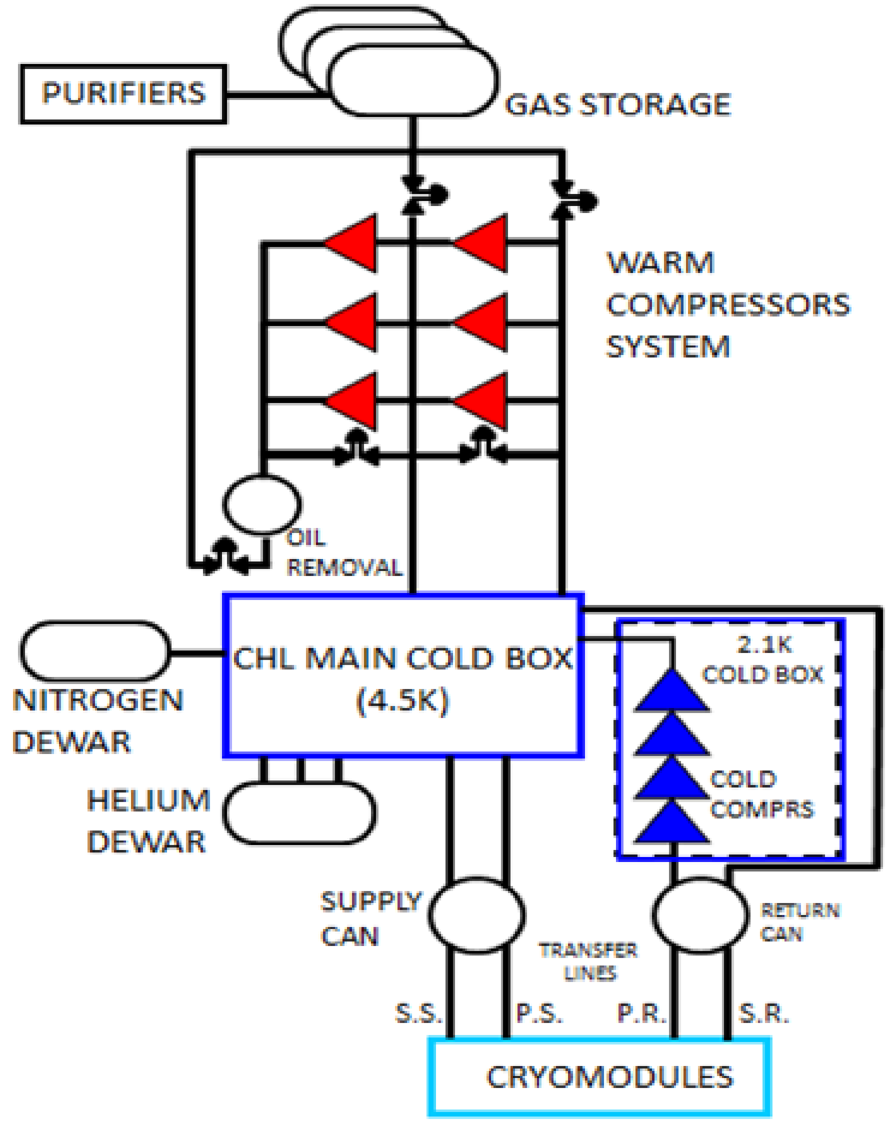


Based on the operating experience

Parameter	Original cryomodule	STS cryomodule
2K heat load (static/dynamic)	28 / 20 W	25 / 40 W
Coupler flow	0.075 g/s	0.067 g/s
Shield load including transfer line	200 W	200 W

Cryogenic System

- **Cryogenic plant has adequate capacity for added STS cryomodules**
- **Sequence development**
  - Each time cryomodules are added to the machine, sequences have to be amended
  - 2K pump down will change (may require additional development)
  - Sequence development is tied to a few key individuals
- **Turn down studies have been conducted to run the system as efficiently as possible**
- **Cryogenic distribution system is designed to accept nine additional cryomodules**
  - Bayonets and valves are already in place



Chemical Processing Development

Processing of STS high beta cavities

1. Ultrasonic Cleaning
2. Bulk BCP
3. Receive from Vendor
4. Ultrasonic Cleaning
5. High Pressure Rinse
6. Vacuum Bake
7. Tune
8. Ultrasonic Cleaning
9. EP
10. Ultrasonic Cleaning
11. He Vessel Welding
12. Ultrasonic Cleaning
13. High Pressure Rinse
14. Low Temp Bake
15. RF Test
16. High Pressure Rinse
17. String Assembly

- Requires process development
  - See SRF activities presentation
  - Development reduces process steps
- Makes use of lessons learned internally and externally