SPALLATION NEUTRON SOURCE CRYOMODULE HEAT LOADS AND THERMAL DESIGN

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ABSTRACT

When complete, the Spallation Neutron Source (SNS) will provide a 1 GeV, 2 MW beam for experiments. One portion of the machine's linac consists of over 80 Superconducting Radio Frequency (SRF) 805 MHz cavities housed in a minimum of 23 cryomodules operating at a saturation temperature of 2.1 K. Minimization of the total heat load is critical to machine performance and for efficient operation of the system. The total heat load of the cryomodules consists of the fixed static load and the dynamic load, which is proportional to the cavity performance. The helium refrigerator supports mainly the cryomodule loads and to a lesser extent the distribution system loads. The estimated heat loads and calculated thermal performance are discussed along with two unique features of this design: the helium heat exchanger housed in the cryomodule return end can and the helium gas cooled fundamental power coupler.

INTRODUCTION

The cryomodules supplied to the SNS[1] by Jefferson Lab must facilitate reliable 2.1 K operation of the superconducting cavities and minimize the heat load to the refrigeration system. The design of the SNS cryomodule (CM), described in [2], is largely based on the proven CEBAF CM design [3] but also integrates technology from the 12 GeV Upgraded CM as well as proven designs from machines at DESY, CERN and KEK. There are two distinct cavity designs [4] housed within the cryomodules, a $\beta = 0.61$ (medium β) cryomodule (MBCM) and a $\beta = 0.81$ (high β) cryomodule (HBCM). Where possible, common designs have been developed for some of the CM subsystems such as end cans, helium vessels, and fundamental power couplers in an effort to minimize manufacturing costs by obtaining economies of scale.

Two key elements of the SNS cryogenic system design were adapted from existing machines. The more efficient concept of providing 5 K supercritical helium gas and then producing superfluid helium in the CM rather than supplying 2.2 K supercritical helium

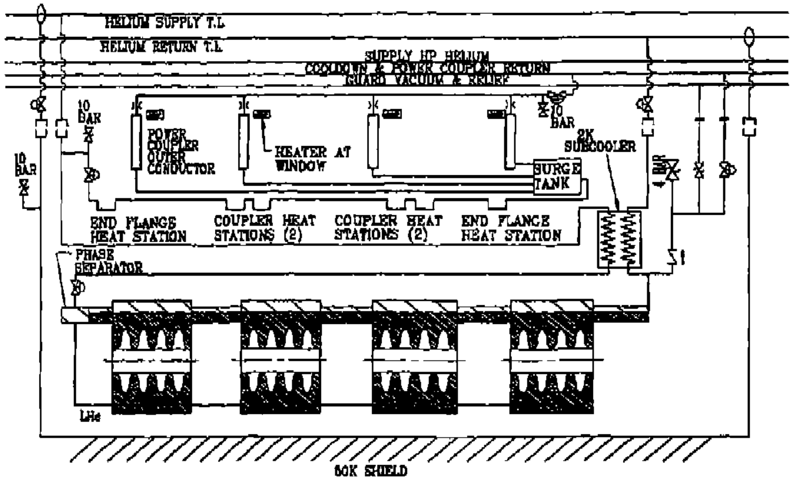

FIGURE 1. The high beta cryomodule flow schematic.

from the CHL as was done in the CEBAF machine was taken from the LHC cryogenic design. The fundamental power coupler (FPC) design [5] is scaled from an existing KEK-B design, but outer conductor requires forced-flow cooling rather than pool boiling heat transfer to minimize static and dynamic heat inputs to the cavity. The CM heat loads are absorbed by three helium streams flowing within the CM (FIG. 1). The primary circuit (3 atm, 5 K) employs a heat exchanger to pre-cool the fluid and a Joule-Thomson (J-T) valve to produce 2.1 K superfluid helium within the CM. There is a secondary circuit with J-T valve control that provides cooling to the FPC outer conductors, and a third circuit (4 atm, 35 K) that cools the radiation shield. The secondary circuit, available for use because superfluid is produced in the CM rather than at the CHL, includes heat intercepts and a surge tank to minimize the potential for flow instabilities. After exiting the CM through the side of the vacuum vessel, the exhaust is routed back to the CHL via a warm helium gas return pipe.

The design parameters for the CM were developed in conjunction with the design

TABLE 1. Cryomodule Design Parameters

	$\beta = 0.61$ (Medium)	$\beta = 0.81$ (High)
Slot Length	5.839 m	7.891 m
CM Length (bore tube)	4.239 m	6.291 m
CM Diameter	1.22 m	1.22 m
2K Heat Load Budget		
Static	25 W	28 W
Dynamic	14 W	20 W
50 K Shield Heat Load Budget	170 W	200 W
Including Transfer Line		
Maximum Helium Flow per Coupler	0.075 g/s	0.075 g/s
Control Valves per CM	5	5
Bayonets per CM	4	4
Radiation Tolerance	1 MGy	1 MGy
Pressure Rating		
2 K System – Warm	3 atm	3 atm
2 K System – Cold	5 atm	5 atm
Shield and 5 K System	20 atm	20 atm

parameters for both the cryogenic system and the SC portion of the linac and are given in TABLE 1. Specifically, the heat load budgets were developed considering operational experience with the CEBAF cryogenic system, where applicable. The heat load estimates and the budget for the CM are given in TABLE 2. This paper contains a summary of the heat loads as well as detailed descriptions of the contributions of each subsystem.

CAVITY, HELIUM VESSEL AND TUNER

The SNS helium vessel design, described in [6], supports the cavity during all phases of operation, facilitates cavity tuning and contains the cryogens with appropriate plumbing.

TABLE 2. Calculated heat loads (Watts) for the medium and high β cryomodules

Estimate Summary		MBCM			HBCM	
	Qty	2.1 K	50 K	Qty	2.1 K	50 K
Static - (See Itemized List)	1	9.7	131	1	11.5	161
U-Tube Allotment	1	10.0	24	1	10.0	30
Dynamic (See Itemized List)	1	8.3		1	17.1	
Total Heat Load per CM		28.0	155		38.6	191
Budget per CM		39.0	170		48.0	200
Dynamic Contributions	**Qty**	**2.1 K**	**50 K**	**Qty**	**2.1 K**	**50 K**
Cavity	3	6.0		4	14.0	
Power Coupler	3	0.6		4	0.8	
Bellows	2	0.2		3	0.3	
HOM (2 per Cavity)	3	1.5		4	2	
Total Dynamic		8.3			17.1	
Static Contributions	**Qty**	**2.1 K**	**50 K**	**Qty**	**2.1 K**	**50 K**
Radiation - HV & Bellows	3	1.1	41.7	4	1.8	65.3
Power Coupler (Radiation)	3	2.1		4	2.8	
Tuner	3	0.75		4	1	
He Vessel Supports	3	0.2	18	4	0.3	24
Warm Beam Tube Conduction	2	0.1	2	2	0.1	2.5
Warm Beam Tube Radiation	2	0.9	0.9	2	0.9	0.9
Cables (3 per Cavity)	1	0.5	1.8	1	0.5	1.8
Supply Bayonets	2	1.0	12	2	1.0	12
Radiation	1	0.04	9.0	1	0.04	9.0
PC J-T Valve	1	0.25	2	1	0.25	2
Subcooler J-T Valve	1	0.25	2	1	0.25	2
Shield Relief	2	0.0	4	2	0.0	4
5K Transfer Line	1	0.1		1	0.1	
50 K Transfer Line	1		3	1		3
Return Bayonets	2	1.5	6	2	1.5	6
Radiation	1	0.1	11.2	1	0.1	11.2
Cooldown/PC Return	1	0.25	10	1	0.25	10
Shield Relief	1	0.3	2	1	0.3	2
Cooldown Valve	1	0.25	2	1	0.25	2
5K Transfer Line	1	0.0		1	0.0	
50 K Transfer Line	1		3	1		3
Total Static		9.7	131		11.5	161

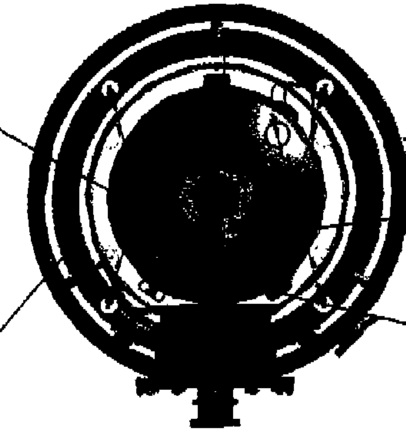

FIGURE 2. Nitronic-50™ support rods attach the helium vessel assembly to the space frame.

Each titanium helium vessel, ⌀ 0.61m, contains a single niobium cavity whose six cells are immersed in ~150 liters of He-II during normal operation. The ends of the cavities protrude through the helium vessel heads into the insulating vacuum to allow beamline assembly as well as attachment of FPCs, Higher Order Mode (HOM) filters and field probes. These end groups are subject to radiation heat transfer from the 50 K shield and the FPC, solid heat conduction from instrumentation leads and the FPC as well as power generated within the HOMs. Extraction of HOM signals to room temperature is planned, requiring ⌀ 3.6 mm semi-rigid coaxial cable running from the cavity to the vacuum tank exterior. Based on finite element analysis, the heat loads incident on the HOMs must not exceed 0.25 W in order to maintain the HOMs well below the niobium critical temperature. Additionally, instrument wiring for temperature diodes, liquid level sensors, and heaters are routed from the helium vessel to the vacuum tank exterior. The helium vessel heads possess attachment points for Nitronic-50™ stainless steel support rods and the cavity tuner. The calculated heat load intercepted by the cavity and helium vessel assembly is given in TABLE 2.

The dynamic heat load for each cavity design has been calculated for E_{peak} = 27.5 MV/m. It is desirable to increase the accelerating gradient such that E_{peak} = 35 MV/m, thereby reducing the number of HBCMs required to reach a given linac output energy. The dynamic heat load increases at least quadratically with increasing peak gradients or higher if operated in the field emission region. These increased losses would be handled by some portion of the available margin in the primary circuit of the refrigeration system.

VACUUM VESSEL AND SPACE FRAME

The vacuum vessel and space frame, described in [7], serve to locate the cavities accurately within the CM via the Nitronic-50™ support rods, provide the structural links to the external supports and remain at room temperature (300 K) during normal operation (FIG. 2). The vacuum vessel, ⌀ 0.99 m, contains the insulating vacuum and provides pressure containment in the unlikely event of cryogenic piping failure. The insulating vacuum is cryo-pumped during accelerator operation to less than 1.3 x 10^{-9} atm, an adequate vacuum level to minimize residual gas conduction. If a cryogenic piping failure occurs, two spring-loaded parallel plate pressure reliefs, identical to those used in the CEBAF CM, open at 1.2 atm on the vacuum vessel. In addition, there are many flanged

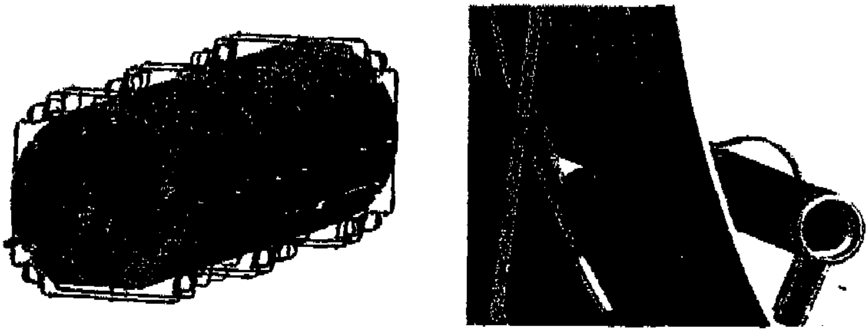

FIGURE 3. MBCM Thermal shield assembly (left) and piping strain-relief (right).

penetrations in the vacuum vessel: ports in the bottom of the vacuum vessel through which the FPC provides RF power to the cavities, instrumentation ports containing electrical feed-throughs for diodes, cavity heaters, tuner power and limit switches, field probes, and connections for the warm helium coupler exhaust.

THERMAL RADIATION SHIELD

As in CEBAF, a copper shield 2.37 mm thick, operating between 35 and 50 K is used to intercept thermal radiation (FIG. 3). The shield is cooled by supercritical helium gas (4 atm, 35 K) through a single pipe, 22.2 mm outer diameter by 1 mm thick wall. Thermal analysis of both single- and three-pass shield cooling showed ~2% increase in the total static heat load to 2 K with a single-pass cooling scheme. Cost ultimately dictated the choice of single pass vs. three-pass piping.

The shield is divided into segments that cover the helium vessel assemblies and bridges that cover both the cavity-cavity and cavity-end-can interconnect regions. The bridge sections allow access to the cavity string for assembly, alignment, instrumentation wire routing and tuner maintenance. There are three segments in a MBCM and four segments in a HBCM. A hydro-formed stainless steel bellows, soldered with EasyFlo-45™, connects the copper piping between segments. In addition to the bellows, a series of tabs 76 mm long x 76 mm wide, where the pipe is soldered with BCuP to the shield, provides strain relief from differential thermal contraction of the piping and shield during cool down and operation.

The horizontal and vertical helium vessel Nitronic-50™ support rods are heat-stationed to the shield segments by copper straps, 1 mm x 25 mm x 125 mm long. All wiring and cabling routed to 2 K is heat stationed at 50 K on the nearest shield segment as well. Due to the long length (>600 mm), small cross-sectional area (20 mm^2) and difficulty during assembly, the two axial support rods are not heat stationed. The additional heat load to 2 K is negligible (< 1 mW/support).

Each bridge is fixed at only one end to an adjoining segment with PEM fasteners and allowed to slide over the other neighboring segment. Each segment-bridge assembly weighing ~45 kg is supported by eight G10 straps, 38 mm x 4.8 mm x 508 mm long, terminated with stainless steel pipe clamps affixed to the space frame support tubes. The four horizontally oriented supports react lateral shipping and handling loads, the four vertically oriented supports react both gravity and transportation loads and all eight react any axial loads.

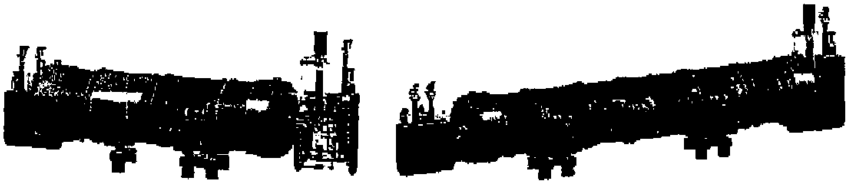

FIGURE 4. Cut-away of MBCM assembly (left) and HBCM assembly (right).

MULTILAYER INSULATION (MLI)

The insulation system design is identical in principle to that employed in the original CEBAF CM and is expected to achieve the same thermal performance. The insulation scheme reduces the radiative heat load to the cold surfaces, provides ample mass and heat capacity to mitigate thermal transients and is comprised of materials suitable for use in a high radiation environment.

Blankets are constructed of alternating layers of double-aluminized Mylar™ (DAM), 25 μm thick, and Reemay™ #2250, a spun-bonded polyester 75 μm thick. The maximum emissivity allowed by emissometer measurement is 0.035 at room temperature. The surfaces of the helium vessel are covered with two 12-layer blankets, the beamline components and piping are spiral-wrapped with 15 layers at a 50% overlap, and the 50 K surfaces are covered with four 15-layer blankets. The joints and seams, staggered both axially and around the circumference by 25 to 50 mm, are closed with 25.4 mm wide aluminized Mylar™ tape.

Effective thermal conductance through the blanket layers is calculated considering three mechanisms: radiative heat transfer – governed by emissivity (ε) and geometry, solid conduction – governed by effective thermal conductivity (k_{eff}) and geometry, and residual gas conduction – governed by average local pressure. A Fortran program, TRANSAM, written originally for transfer line design was used to estimate the expected heat flux to the 50 K and 2 K surfaces. Using a worst-case scenario with average pressure of 10^{-4} torr, ε = 0.2 and k_{eff} = 1.5 mW/cm·K, the heat flux to the 50 K thermal shield was calculated conservatively as 2.5 W/m^2. Using the same average pressure, ε = 0.06 (lowered since emissivity typically decreases with decreasing temperature) and k_{eff} = 1.5 mW/cm·K, the heat flux to the 2 K surfaces was calculated as 94 mW/m^2. While these values are conservative, proper assembly and installation of the blankets is required for ideal performance. Taped joints, insufficient overlap and compaction of blanket layers can reduce the effectiveness of the MLI thereby increasing significantly the incident heat load. Combining the realities of assembly with the fact that nine of twenty-two measured CEBAF CMs, as reported in [3], exceeded the 50 K static heat load design criteria, it was decided to increase the estimated radiation heat load to 200% of the calculated values.

END CANS, HEAT EXCHANGER AND CRYOGENIC PIPING

The end cans route helium to and from the CM, provide controls for the primary and secondary circuits, provide beamline vacuum connections and contain pressure relief valves used in the event of loss of vacuum (FIG. 4). The end cans use bayonet connections that are identical to those used in the CEBAF CM [8]. In addition to the primary and shield supply bayonet connections, two J-T valves similar to those used in CEBAF are installed in the supply end can: the primary J-T has a C_v = 0.3 and the secondary J-T has a C_v = 0.05. The return end can contains a sub-atmospheric primary return bayonet, the shield return

TABLE 3. Heat Exchanger Design Parameters

	High Pressure Side	Low Pressure Side
Core Length	600 mm	-
Core Cross Section	100 mm x 100 mm	-
Maximum Allowable Helium Leak Rate	1×10^{-9} mbar-liter/sec external 1×10^{-4} mbar-liter/sec cross-passage	-
Pipe Size	26.7 mm OD x 2.1 mm wall (¾" IPS Schedule 10)	60.3 mm OD x 2.8 mm wall (2" IPS Schedule 10)
Maximum Flow Rate	6.0 g/s	6.0 g/s
Fluid Inlet Pressure	2.95 atm	0.040 atm
Maximum Pressure Drop	0.020 atm	0.001 atm
Inlet Temperature	5.0 K	2.1 K
Outlet Temperature	2.2 K	3.96 K
Capacity	60 W	-
NTU (Integrated)	4.37	-
Effectiveness	0.97	-
UA (Integrated) & UA Margin	93.2 W/K & 20%	-

bayonet, a Circle Seal™ pressure relief valve plumbed in parallel with a parallel plate relief valve, a cool-down valve with a $C_v = 3.0$ and a helium-helium heat exchanger (HX).

The counter flow HX (Fig. 5) is a plate-fin type core constructed of aluminum with a pressure rating of 12 atm. Stainless-to-aluminum joints transition from the aluminum body to the stainless steel process piping. The design parameters are given in Table 3. Silicon diodes are installed in the assembly to measure HX terminal temperatures in order to assess the HX effectiveness.

The stainless piping within the CM is strain-relieved from the end can connections with flexible metal hose. All of the shield circuit, the fill-lines between helium vessels and the primary circuit plumbing through the HX high-pressure side are 26.7 mm OD x 2.1 mm wall. The primary return piping through the HX and in the relief stack is 60.3 mm OD x 2.7 mm wall, sized for a catastrophic loss of beamline vacuum. The helium vessel return headers are 88.9 mm OD x 3.0 mm wall, and along with the helium vessel provide 10% ullage. The secondary circuit consists of 6.35 mm outer diameter x 1.3 mm wall stainless steel tubing, sized to reduce helium inventory in that circuit, and a 1 liter surge tank which functions to damp potential flow oscillations that may arise during operation.

FUNDAMENTAL POWER COUPLER

Due to operating frequency and space constraints, a coaxial coupler with inner and outer conductors was selected instead of a waveguide coupler to provide fundamental RF power to the cavities. Besides delivering RF power, the coupler must not adversely affect

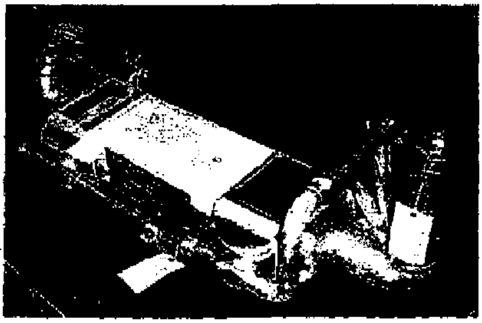

FIGURE 5. Helium-helium heat exchanger.

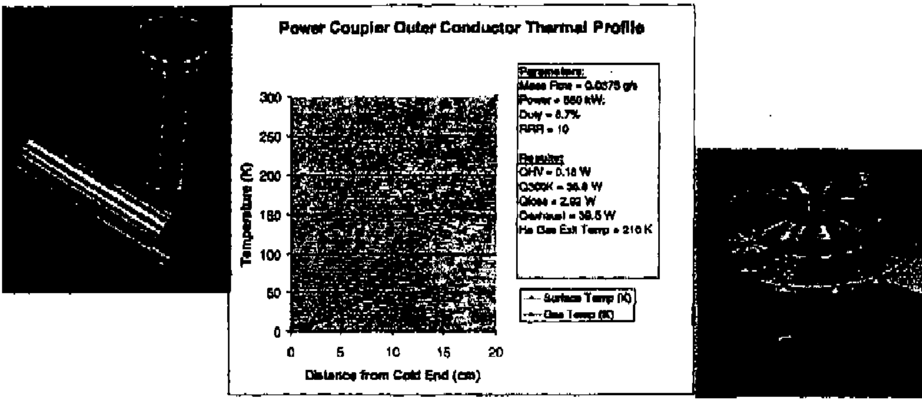

FIGURE 6. He gas cooling passages (right) and FPC outer conductor assembly (left). The helium gas flow rate of 0.038 g/s produces an exhaust temperature of 210 K (center).

the electromagnetic performance of the cavity or the thermal performance of the cryomodule. Cavity cleanliness procedures require the coupler to be inserted into the cavity at the six o'clock position.

To handle static and dynamic heat loads in the coupler and cavity, the outer conductor is cooled by a nominal stream of 3 atm, 5 K supercritical helium flowing at 0.038 g/s per coupler and the inner conductor is conduction cooled by a 1 liter per minute water flow. The ceramic RF window is maintained at 300 K during operation by a heater-thermocouple control loop.

The outer conductor is a machined and welded stainless steel assembly with flanged connections to the cavity and the warm window. The internal vacuum surface is copper-plated with a nominal thickness of 15 μm and an estimated RRR = 10 to reduce resistive wall losses induced by the RF surface currents. A single helical, square-grooved flow passage, 2.3 mm wide x 1.6 mm deep (FIG. 6), with a pitch of 2.6 turns/cm is machined into a thick-walled stainless steel tube, 75.75 mm internal diameter. A thin-walled (1.6 mm) stainless steel tube is then shrunk-fit over the outer diameter of the flow passages and welded leak tight onto the ends nearest the flanges. Due to the small hydraulic diameter of 2.16 mm, flow velocities and Reynolds number are kept high to mitigate potential deleterious effects of buoyancy, re-circulation and poor heat transfer in the helium stream.

Conduction heat load estimates (TABLE 2) were calculated for the outer conductor using an Excel model that included combined conduction and convection heat transfer as well as temperature-dependent thermal properties for stainless, copper and supercritical helium gas (FIG. 6). A separate estimate of the static radiation heat load emitted from the FPC to the beam pipe was calculated. The values were used as input to a finite element model of the cavity ends to verify that they remain below the niobium critical temperature.

In an effort to determine if thermo-acoustic oscillations or flow instabilities exist in the secondary circuit, a test rig has been designed and built. Experiments to evaluate the flow circuit are planned for this summer.

CONCLUSION

The estimated heat loads and calculated thermal performance of the SNS medium and high β cryomodules do not exceed the specified budget and are consistent with the refrigeration system design capacity.

ACKNOWLEDGEMENTS

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