CRYOMODULE COMPONENT DEVELOPMENT FOR THE APS UPGRADE SHORT PULSE X-RAY PROJECT*

J. Holzbauer†, J.D. Fuerst, A. Nassiri, Y. Shiroyanagi, B. Stillwell, G. Waldschmidt, G. Wu, Argonne National Laboratory, Argonne, IL 60439, U.S.A.
G. Cheng, J. Henry, J. Mammosser, J. Matalevich, J. Preble, R. A. Rimmer, H. Wang, K. Wilson, M. Wiseman, S. Yang, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, U.S.A.

Abstract

The short pulse x-ray (SPX) part of the Advanced Photon Source Upgrade calls for the installation of a two-cavity cryomodule in the APS ring to study cavity-beam interaction, including HOM damping, cavity timing, and synchronization. Design of this cryomodule is underway at Jefferson Lab in collaboration with the APS Upgrade team at ANL. The cryomodule design faces several challenges including tight spacing to fit in the APS ring, a complex set of cavity waveguides including HOM waveguides and dampers enclosed in the insulating vacuum space, and tight alignment tolerances due to the APS high beam-current (up to 150 mA). Given these constraints, special focus has been put on modifying existing CEBAF Upgrade-style designs, including a cavity tuner and alignment scheme, to accommodate these challenges. The thermal design has also required extensive work including coupled thermal-mechanical simulations to determine the effects of cool-down on both alignment and waveguides. This work will be presented and discussed in this paper.

INTRODUCTION

The SPX project calls for the use of an rf deflecting-mode cavity that will give the electron bunches a correlation between their longitudinal position in the bunch and their vertical momentum. Synchrotron light produced from this bunch can then be passed through a transverse slit, creating a shorter x-ray pulse at the proportional sacrifice of total flux. This scheme was first proposed by Zholents [1].

A significant amount of design work has gone into the rf cavities required for this project, details of which can be found in [2-6] This cavity application has many specific challenges including the need to heavily damp all non-operational modes to preserve beam quality for other APS users.

In an actual installation in the storage ring, two deflecting sections will be required, one to deflect and one to remove the deflection.

This allows a small portion of APS users to receive short x-ray pulses while not disrupting standard user operation elsewhere in the ring. Each of the SPX cavities has been designed to provide 0.5 MV of effective deflecting voltage with a total of 2 MV required. The full SPX installation called for two, 4-cavity cryomodules to be installed in the ring.

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†holzbauer@aps.anl.gov

DESIGN REQUIREMENT

One cryomodule with two deflecting cavities will be tested in the storage ring as part of the SPX R&D program. It will be located in Sector 5 and will produce a 1-MV peak deflection. The cryomodule will be required to support a beam current up to 150 mA, and as a result, it must incorporate features to support heavy parasitic mode damping. It will accommodate high cryogenic loads from dynamic losses, as well as from static losses due to numerous waveguide penetrations from the dampers and power couplers. Alignment tolerances are also critical to maintain LLRF tolerances. Parameters for the engineering design of the cryomodule are kept as close to the SPX parameters as possible. They are listed in Table 1.

Table 1: Selected Cryomodule Design Parameters

Parameters	Value	Unit
Total deflecting voltage	1.0	MV
Beam current	<=150	mA
Number of cryomodule	1	
Cryomodule length	1.979	m
Number of cavities	2	
Operating frequency	2815.486	MHz
Rf power	5	kW
Forward power coupler	Waveguide	
HOM coupler, waveguide	Waveguide	
LOM coupler, waveguide	On-cell	
Operating temperature	2	K
Q0 at 2.0 K and 0.5 MV	$>10^9$	
Power coupler Qext	1.00E6	
Klystron power capacity	5	kW
HOM power per cavity	< 150	W
LOM power per cavity	< 1,800	W
Intercavity coupling	< -70	dB
Cavities pressure	$< 10^{-9}$	Torr

The SPX R&D cryogenic system uses portable dewars to supply liquid helium and uses a vacuum pump to maintain 2-K operation. The vacuum pumping capacity has been measured at 64 W at 23 Torr to keep 2-K operation. The total heat load thus cannot exceed 64 W. An 80-K thermal shield will use LN2 with a heat load capacity of 400 W.

The cavity-offset alignment in Table 2 refers to the offset for the whole cryomodule. A low-impedance bellows will connect the two cavities in the SPX R&D cryomodule. A similar low-impedance bellows at each side of the cavity will connect the cavity to a warm gate valve. Alignment of two cavities will be verified under warm conditions using a stretched wire technique.

Table 2: Cryomodule Alignment Requirement

Alignment	Value	Unit
X misalignment (Horizontal)	±500	µm
Y misalignment (Vertical)	±200	µm
Z misalignment (Longitudinal)	±1000	µm
Yaw misalignment	±10	mrad
Pitch misalignment	±10	mrad
Roll misalignment	±10	mrad

CYOMODULE DESIGN

The SPX R&D cryomodule requires packaging of two deflecting cavities dressed with helium vessels, their associated waveguides and dampers, cavity tuners, helium and nitrogen distribution plumbing, thermal and magnetic shielding, a space frame structure to hang the cold mass, alignment features for each cavity, and a vacuum tank that is planned to be code stamped per the ASME Boiler and Pressure Vessel Code.

String Assembly

A dressed deflecting-mode cavity [7] with attached waveguides can be seen in Figure 1.

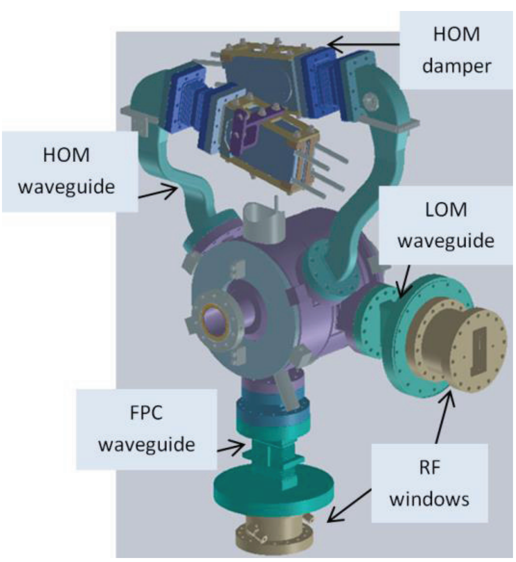

Figure 1: SPX cavity CCA3-1 prepared for vertical testing. The LOM waveguide can be seen on-cell pointing to the right and the Y-end group includes the HOM dampers (above) and forward power coupler (FPC, below).

The first design iteration of the SPX R&D cryomodule called for four gate valves on the beamline, two outside the cryomodule ("warm gate valves") and two inside the cryomodule near the cavities ("cold gate valves"). This was done to minimize the size of the clean string and to simplify installation of the clean string into the cryomodule vacuum vessel. A model of the original warm-to-cold transition, which included the cold gate valve, can be seen in Figure 2.

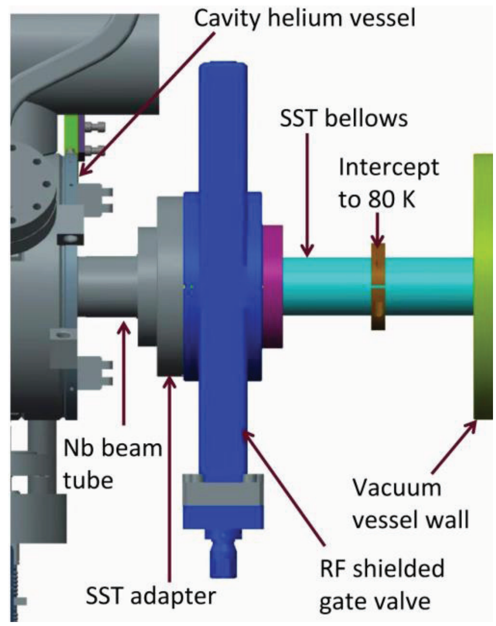

Figure 2: A model of the warm-to-cold transition for the SPX R&D cryomodule, which included a cold gate valve. The cavity on the left operates at 2 K with the rf shielded gate valve theoretically operating between 7 and 15 K, and the vacuum vessel wall (green) at 300 K.

Initial design assumed that there would be no additional heat generated in these gate valves. They were planned to be actuated beyond general assembly via a special tool, once during cryomodule assembly, when the warm gate valves had been attached and the intervening space had been pumped to ultra-high vacuum. Because the cold gate valves were intended to operate at cryogenic temperatures, they were not planned with automatic actuation functionality and were inaccessible once the module was closed unless the insulating vacuum space is back-filled and open.

It was discovered that similar gate valves used elsewhere in the APS ring operate at temperatures well above ambient, indicating significant beam-induced heating. While these valves have an elliptical aperture instead of the circular aperture planned for the SPX R&D cryomodule, the cross-sectional area is similar, so the heating terms should be similar. It should also be noted that the beam chambers surrounding the operational gate valves were different from what is expected in the SPX R&D cryomodule, so the wakefield heating terms are likely quite different. Measurements were made on one of these operational gate valves in the storage ring, monitoring temperatures of the valve body and flanges. These showed a significant heating term near the beam aperture, with smaller effects further away from the beam. The maximal temperature rise seen was 80°C, indicating a significant amount of heating.

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A heating term this significant could not be explained by the differences in situation such as aperture and surrounding wakefield terms. It is likely that a large portion of the heating came from nearby shielded bellows for that particular gate valve. From previous studies we know that the bellows liners only reach 50 to 60 degrees C under the same current and fill pattern [8]. Because the temperature at the gate valve is measured to be 80 degrees, significant RF heating of the gate valve itself appears very likely. There is a concern that the cold gate valves in the SPX R&D cryomodule would likely cause a similarly significant, potentially serious increase in the 2-K heat load. Several potential mitigation strategies were studied as conservative measures, including a 5-K thermal intercept between cavity and valve, moving the valve closer to the 80-K intercept, and moving the 80-K intercept between the cavity and the valve. After careful consideration, it was decided that the best solution was complete removal of the cold gate valves and relocation of the warm gate valve to the cryomodule interior.

Removal of the cold gate valves removed the potential heating term and meant that two less gate valves were required for the cryomodule. The additional complexity of the clean room cavity string and the required tooling for assembly was the major downside of the valve removal. A picture of the current clean string assembly design can be seen in Figure 3.

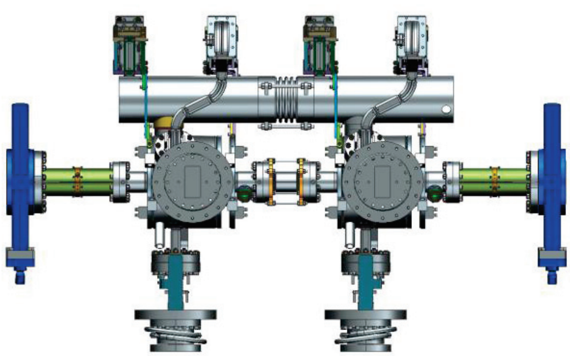

Figure 3: A model of the SPX R&D cryomodule clean room cavity string with warm-to-cold transitions called out in green and the warm gate valves called out in blue. Note that the helium header is included because it must be assembled in the clean room with the HOM waveguides.

Tuner

The dressed SPX cavity will be fitted with a scissor-jack tuner as shown in Figure 4. Slow tuning will be realized by a stepping motor. Fast tuning will be accomplished through a piezo-electric actuator, which is optional. Both the stepping motor and piezo actuator will be located outside of the cryostat. Tuners will be set to "tension" during initial installation. A tuning range of ±200 kHz, with a fine adjustment range of ±25 kHz and a tuning resolution of 40Hz are required. Tuner parameters are listed in Table 3.

The optional fast tuner mostly serves the functions of machine protection instead of microphonics compensation commonly practiced in other SRF accelerators. The benefit of such fast tuning may allow quick detuning of SPX cavities to maintain stored beam operation while decoupling the cavity from the beam. For SPX cavities with loaded Q around 1×10^6, the frequency detuning needs to be 12 kHz to sufficiently drop the cavity stored energy driven by the beam to 5% of an on-resonance nominal stored energy. A 13-kHz tuning range should provide sufficient margin for quick cavity detuning. The resolution of such fast tuning is not critical. The response time should be less than 1 ms, which is close to the decay time of SPX cavities [9].

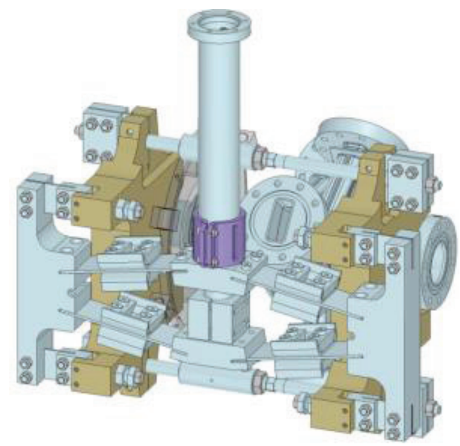

Figure 4: SPX scissor-jack tuner.

Table 3: Tuner Parameters

Parameters	Numbers	Unit
Tuning Sensitivity	9000	KHz/mm
Stiffness	170,000	lbs/in
Deflection for 200KHz shift	22	µm
Force of 200KHz shift	149	lbs
Stepper Motor Resolution	800	Steps/rev
Harmonic Drive Ratio	100	
Ball Screw Pitch	2	mm/rev
Full Step Frequency shift	31.6	Hz
¼ Step Frequency Shift	7.9	Hz
Piezo Range in Drive Axis	60	µm
Piezo Range in Cavity Axis	75.8	KHz
Piezo Resolution Drive Axis	0.13	nm
Piezo Resolution Cavity Axis	0.16	Hz

A set of limit switches is employed. Hardware-based upper-limit and lower-limit switches and another software limit switch are implemented into the tuner control software. A tuner-neutral position will be established before the rf is turned on.

Changes in the cavity frequency will be monitored during cavity cool-down and also during helium system pump-down. While not critical during the assembly, the data helps to finely adjust the initial tuner location for the right tuning range during beam operation. It is also required to assure that the tuner will not unduly tune the cavity to the plastic deformation condition.

Dampers

The LOM and HOM SPX dampers were designed as high-power waveguide loads to absorb rf power produced primarily by beam-generated wakefields from a 150-mA beam current in the APS storage ring. Analysis of the HOM damper design is described in [10].

The intent of the damper design was to produce directly connected cavity-vacuum LOM and HOM damper loads with a maximum power handling capability of 2 kW (LOM dampers @ 150-mA beam current). A four-wedge damper design was eventually selected based on efforts to offset the effects of high volumetric rf power densities in the lossy ceramic material and to reduce the potential for particulation of the damping material. The HOM dampers will be installed in the warm section inside the cryomodule. Water channels built into the damper's copper housing will provide the cooling of the dampers.

The LOM waveguide assembly was eventually designed with a broadband rf window due to the predominantly narrowband nature of the beam-induced rf spectrum. As a result, a commercially available high-power, out-of-vacuum LOM damper was procured from Mega Industries. The HOM waveguide assembly, on the other hand, was necessarily broadband in order to maintain the beam stability requirements outlined in the Physics Requirement Document, and, as a consequence, was an in-vacuum load. The power handling requirements evolved to a 150-mA beam current where the power output through each of the waveguide ports is shown in Figure 5.

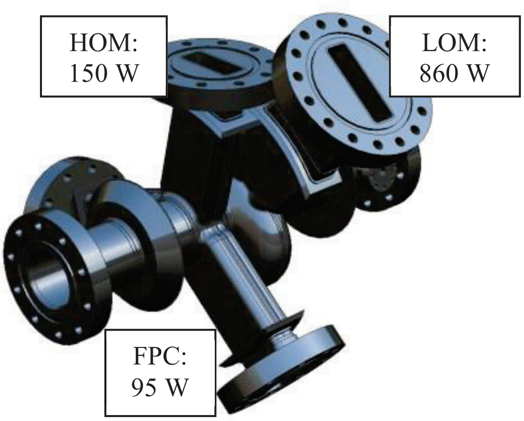

Figure 5: Beam-induced rf power output through each waveguide port.

Hexoloy alpha-sintered, iso-pressed silicon carbide (SiC) [10] from St. Gobain was selected as the damping material in the HOM damper due to its rf, mechanical, and vacuum properties. It is a lossy ceramic material with an average loss tangent of approximately 0.1 and relative permittivity of approximately 11.5 across the SPX frequency band.

Windows

Double FPC and LOM windows are planned for the SPX. The FPC window extends downward from the cryomodule, while the LOM window extends into the aisle of the storage ring.

The LOM and FPC waveguides were designed with a guard vacuum section to protect cavity vacuum integrity.

Initial design considerations for the SPX windows are described in [11]. Six WR284 windows (FPC) and six WR340 windows (LOM) were procured for the SPX R&D cryomodule. The pillbox windows are similar to existing WR284 windows installed in the APS linac, which were manufactured by CML engineering. All FPC windows consist of a compact design with custom-sized round flanges to minimize space requirements in the cryomodule, see Figure 6. Three of the LOM windows also use a similar compact design. The three remaining LOM windows use a standard rectangular Merdinian® flange to reduce encroachment of the aisle in the APS storage ring tunnel when installed on the cryomodule.

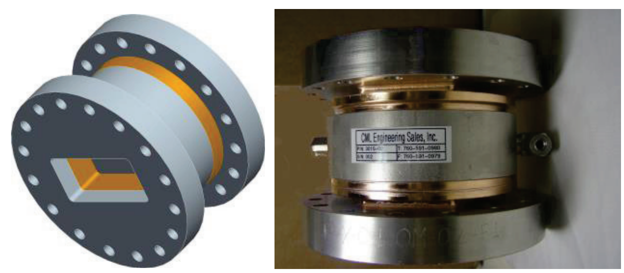

Figure 6: Compact FPC window design.

Power Coupler

The rf power is transmitted from the source to the interface of the cryostat through a WR284 waveguide. The vertical arm of the cavity's Y-end group serves as the main power coupler, which has a step transition from cavity waveguide size to WR284 size. The step position was adjusted to have effective coupler external Q at 1×10^6. A 90-degree E-miter turns the waveguide upwards to the cryostat waveguide assembly. The E-miter has a monitor port with light-of-sight to the ceramic window to allow temperature monitoring via an IR detector. The waveguide is pressurized with dry nitrogen. The pillbox rf window, made of pure Al_2O_3 ceramic, is designed to transmit more than 10 kW of rf power. The waveguide sub-assembly is equipped with a view port to allow light to go through to an arc detector.

A 4-stub tuner is inserted into the transmission line, and its position relative to the cavity is determined later for optimized tuning range. The stub tuner can be adjusted to measure the tuning range of Qext.

A semi-rigid waveguide bellows will connect a waveguide feedthrough and the fundamental waveguide coupler. The waveguide feedthrough, waveguide bellows, and fundamental waveguide coupler are made of stainless steel with a thin copper plating on the inner surfaces. The feedthrough waveguide flanges are standard WR284 Merdinian® flanges. All other waveguide flanges, including cavity round flanges, use indium seals.

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Magnetic Shielding

It is well known that a DC residual magnetic flux inside the cavity can be trapped in the niobium material when it cools below transition temperature. For 2.815 GHz, each additional milli-gauss (mG) of trapped magnetic field increases the cavity residual resistance by 0.5 nΩ. Vertical tests of the deflecting cavity where residual magnetic field is known to be negligible showed its surface resistance was dominated by a residual resistance of 120 nΩ. Any additional increase of residual resistance will decrease the operating Q_0 to be below 1×10^9. To ensure the surface resistance is low when the cavities are in the cryomodule, the residual DC magnetic field needs to be maintained at less than 20 mG. For the SPX cryomodule, the cavity string magnetic shield will be realized using two layers. The first layer of the magnetic shield encloses the cavity string outside of the helium vessels. Due to the large number of port openings associated with waveguides of the SPX deflecting cavities, a second layer of magnetic shielding will be inserted inside of each helium vessel to provide a direct encapsulation of the niobium cavities. Engineering analysis is being pursued to verify that this is a practical shielding solution.

Thermal Design

The helium distribution system in the module was designed to accept cryogenic flow through flanged field joints instead of the more standard bayonet connections. This decision was made due to space constraints in the APS ring. The internal helium cryogenic plumbing includes a 2-K heat exchanger, helium return pipe, and "5 K" cooling bus using the low-pressure exhaust of the heat exchanger to reduce the static heat load, all of which can be seen in Figure 7. All connections between 300 K and 2 K also include a thermal intercept connected to the 80-K copper shield that is cooled by liquid nitrogen.

In Figure 7, the 2-K heat exchanger can be seen on the left. The helium return pipe can be seen above the cavities but below the HOM waveguides. This position required it to be installed during clean room assembly because it is trapped by the HOM waveguides and beamline gate valves. The helium intake and return line and the 5-K cooling bus are shown in yellow, and the JT valve piping is shown in orange.

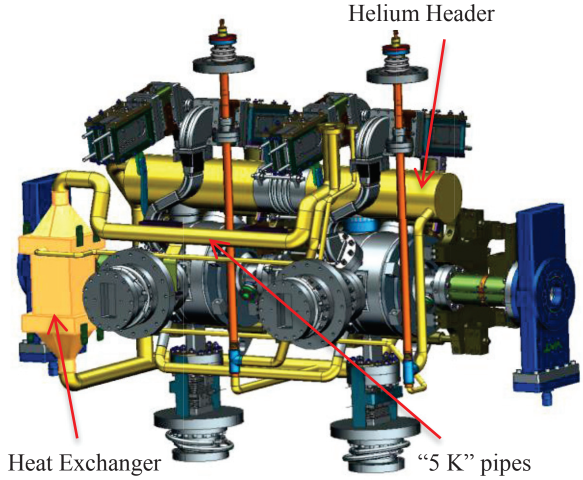

Figure 7: The SPX R&D cryomodule including clean room string assembly and cryogenic distribution system (called out in yellow).

With so many connections between 2 K and room temperature, each component's thermal design became quite important. All components in the waveguides including bellows, tapers, copper plating thicknesses, and thermal intercepts were simulated and optimized for adequate rf transmission and minimal static and dynamic heat load. An extensive analysis of these waveguides can be found in [10].

Sink Temperature:		**2.00 K**				**5-8 K Thermal Bus**				**80 K LN2 Shield**			
Item	**QTY**	**Static**	**Dynamic**	**Per Item Total**	**Module Total**	**Static**	**Dynamic**	**Per Item Total**	**Module Total**	**Static**	**Dynamic**	**Per Item Total**	**Module Total**
Cavity	4	0	7/14	7/14	28/56	0	0	0	0	0	0	0	0
HOM	8	0.07	0.40	0.47	3.76	0.41	1.09	1.50	12.0	0.58	0.42	1.00	8.00
LOM	4	0.03	0.04	0.07	0.28	1.47	0.08	1.55	6.20	4.80	0.09	4.89	19.6
FPC	4	0.13	0.05	0.18	0.72	1.50	0.19	1.69	6.76	3.88	0.37	4.25	17.0
Beam tube bellows (static)	2	0.10	-	0.10	0.20								
Beam tube bellows (dynamic)	5	-	0.30	0.30	1.5								
Cold gate valves	0	-	-	-	-								
Cryomodule static load estimate					<15				<20				<180
TOTAL					**49/77**				**45**				**225**
TOTAL (2 Cavities)					**33/47**				**32**				**202**

Figure 8: Heat load table for the SPX R&D cryomodule. Specific thermal sources are called out on the left and broken out by thermal sink temperature. The table has not yet reached the final design stage.

Figure 8 shows the anticipated cryomodule heat loads broken down by heat source and sink temperature. While the largest contributions are the static heat load (~15 Watts) and the dynamic heat load (between 7 and 14 Watts per cavity depending on cavity performance) the cavity waveguides all contribute to both the static and dynamic heat load.

The addition of the 5-K cooling bus with heat stations on all of the cavity waveguides significantly reduced the expected heat load to 2 K. This is especially true in the case of the HOM waveguides because there is expected to be a significant amount of operational mode power that evanesces into the waveguide, contributing most of the HOM waveguide dynamic heat load. At two HOM waveguides per cavity, this sums to an expected 6 Watts of 5-K heat load from the HOM waveguides alone.

Because of the complexity of the cryomodule internal rf systems, the design of the 80-K shield became quite complex. The thermal shield had to be assembled with penetrations for eight waveguides (four per cavity) in addition to the standard instrumentation, cavity tuner, and cryogenics plumbing. Further complicating matters was the need to assemble the shield around the HOM waveguides, which include an 80-K intercept but must have room outside of the 80-K shield for the cryomodule-internal HOM dampers. A cross section of the cryomodule design in Figure 9 calls out the thermal shield in pink.

Alignment

The cryomodule alignment requires the cavity electrical center to be within ±200 µm vertical compared to the beam axis, which is referenced to the beamline flanges. Horizontal and longitudinal misalignment is much relaxed at ±500 µm and ±1,000 µm. As this tolerance is the upper and lower boundaries, the measurement of the electric center movement needs to be ±50 µm to be able to discern the directions in which the electrical center moves. To be able to adjust the cavity back to within the ±200 µm limit, the measurement accuracy needs to be very close to the movement accuracy. It is prudent to set the measurement accuracy to within ±5 µm. And the measurement of the vertical movement is most important for the beam operation. The measurement of the horizontal movement and longitudinal movement will be beneficial and is considered optional.

Similar to the implementation in an ILC cryomodule [12], an individual laser displacement sensor will be installed on the side of the cryomodule's cavity location through the optical view port. The laser shines on a small area on the surface of the helium vessel. A measured shrinkage of the cavity helium vessel will be included in the final measurement of the displacement.

Extra care must be taken during assembly of cavity pairs. Cavities will be subjected to a rigorous process of fiducialization and measurement.

During cavity fabrication, tooling ball receptacles will be machined onto the cavity, typically on the beam pipe flanges. Stretched-wire measurements will then be used to locate the cavity electrical centers and to monitor excessive cavity center deviation between cavity processing steps, which includes helium vessel dressing and rf tuning. Coordinate measurement machine (CMM) measurements will pre-determine potential flange misplacement. Once the cavity's electric centers are located relative to the tooling balls, cavities can go to their final qualification, and cavity pairs can be assembled. At this stage, the cavity tooling balls serve to locate the cavity electrical centers, which can then be transferred to alignment "rabbit ears" on the space frame and out to the cryostat vacuum shell. These rabbit ears can then be used to align a cryomodule to the beamline during tunnel installation.

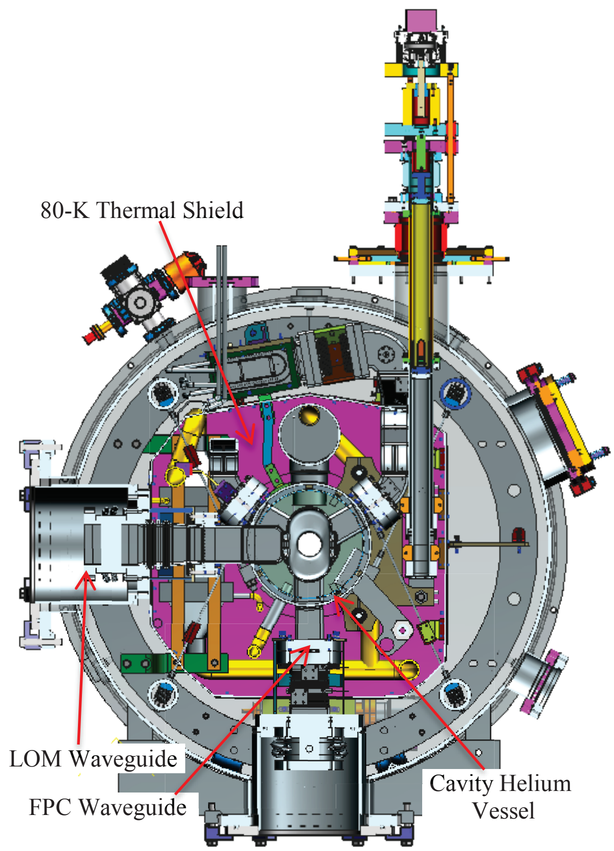

Figure 9: A section-view of the SPX R&D cryomodule design. Cavity in helium vessel can be seen in the center with FPC waveguide pointing down, LOM waveguide pointing to the left, and the 80 K thermal shield envelope called out in pink.

Beamline Bellows

The SPX cryomodule requires a flexible bellows at three temperature zones. Two deflecting cavities are joined by one flexible bellows operated around 4 K. It is cooled by thermal conduction. Its cooling can be enhanced by extra thermal anchoring in the middle of the bellows. There are two other bellows assemblies with one at each end. These are the warm-to-cold transition bellows from 2 K to 300 K. Each WCT assembly has two bellows. In this assembly one bellows is from 2 K to

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80 K and one transitions from 80 K to 300 K. These bellows are in close proximity to the cavities, and they are required to have minimal particulate generation during bellows flexing. A bellows at the end of the cryomodule will be completely at room temperature. Since its location is far away, its particulate-free requirement can be relaxed; hence, a shielded bellows can be used.

The heat generation from wake fields deposited in these bellows has to be minimized in order to avoid excessive load on the cryogenic system. For an SPX cryomodule, the heating of the bellows itself would be less than 0.5 W. It is preferable for the inter-cavity bellows to have high thermal conductivity to allow thermal strapping to be effective in removing heat from the bellows. For the transitional bellows, a lower thermal conductivity is preferred to reduce the static heat flow from high-temperature components to cryogenic components. This suggests a copper-coated stainless steel inter-cavity bellows and a stainless-steel-based transitional bellows.

Alignment parameters require that the bellows be flexible enough to allow transverse skew motion of 0.5 mm. Thermal contraction requires the bellows to allow a longitudinal motion of 1.0 mm. The SPX cryomodule plans are to employ the same physics design for both inter-cavity bellows and thermal transition bellows [13].

Instrumentation and Controls

In addition to the major subsystems, there was an extensive interlock and instrumentation system designed to support standard operation, interlocks, and meet the research and development goals of this demonstration cryomodule. In addition to the standard cryogenic temperature sensors and heaters for stable operation, a complex thermal design such as this required the design of an extensive set of instrumentation to monitor static and dynamic heating of the cryomodule internal waveguides and dampers.

Notably complex was the instrumentation of the HOM waveguides and dampers. The waveguide and dampers span temperatures from 2 K at the cavity to 300 K at the dampers. Heating of the dampers and performance of the thermal intercepts must be quantified, and the water lines used to cool the dampers have to be carefully monitored and interlocked to prevent freezing damage to the lines and dampers.

Pressure Safety

The MAWP for the vacuum vessel (VV) is 2.5 atm. An ASME-certified burst disc attached to the VV will relieve at 2.6 atm. To offer additional protection, a secondary relief (parallel plate) will relieve the VV at 1.2 atm. To be conservative, the internal pressure used for design of the VV is 3.0 atm.

The waveguides need to withstand an external differential pressure of 1.0 atm. Designing to an external differential pressure of 1.2 atm (or greater) would provide protection against a condition that pressurizes the VV until the parallel plate relief is lifted.

An internal pressurization will be protected by a burst disc on the beamline (outside of cryostat), which relieves at 1.9 atm (absolute). In the event of a beamline pressurization failure, an internal differential pressure in the waveguides of 1.9 atm could occur.

CONCLUSION

The design of the SPX R&D cryomodule is nearly completed. A horizontal test of a dressed cavity demonstrated the cavity, helium vessel, and tuner design exceeds design specifications. Current cryomodule design has several complicating features that required creative design solutions to satisfy all cryogenic, rf, and mechanical requirements in the space envelope available in the APS ring.

ACKNOWLEDGMENT

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