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Half-Wave Cryomodule for the Project X Injector Experiment (PXIE) Functional Requirements Specification

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Revision History

Revision	Date	Section No.	Revision Description
0	10/3/2011	All	Initial Draft

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INTRODUCTION AND SCOPE

The goals of the Project X Injector Experiment (PXIE) are validation of the Project X concept, elimination of technical risks mainly related to the Project X front end, and demonstration of its reliable operation. For the superconducting part of the project the number of trips per cavity should not exceed 1 in every 500 hours.

The superconducting part of PXIE will consist of two cryomodules, the half-wave (HW) and SSR1. If successful the plan is to use these cryomodules in the Project X low energy linac with only minor modifications, if any. The HW cryomodule will have 9 half-wave resonators operating at 162.5 MHz. The SSR1 cryomodule will have 8 spoke resonators operating at 325 MHz. Transverse beam focusing in each cryomodule will be done by solenoidal lenses making axially symmetric beam focusing. The superconducting cavities in both cryomodules will operate at 2 K. The cryomodules operate in CW regime with a beam current of 1 mA. The RMS normalized bunch emittance does not exceed 0.25 mm mrad for each of 3 planes.

This specification addresses the design of the HW cryomodule. It includes cryogenic systems and instrumentation, cavity and lens positioning and alignment, current leads, magnetic shielding, cold-to-warm beam tube transitions, and interfaces to interconnecting equipment and adjacent modules. The layout of the PXIE beamline is shown in figure 1.

Note: *Throughout this specification, 2 K refers to the sub-atmospheric, cavity side helium circuit, 5 K refers to the JT-valve side of the helium supply and low temperature thermal intercept circuit, and 70 K refers to the intermediate thermal shield and thermal intercept circuit, regardless of their actual operating temperatures.*

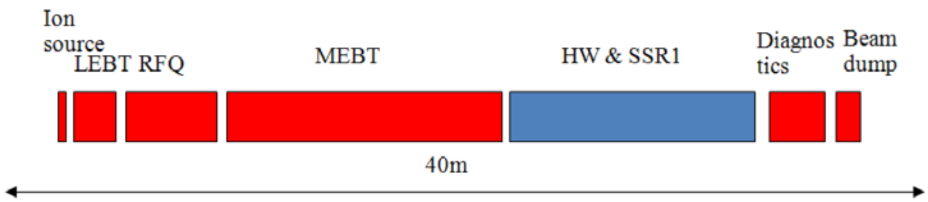

Figure 1: Layout of the PXIE beamline

HW CRYOMODULE DESIGN

The HW cryomodule will contain 9 HW cavities, 6 focusing solenoids, 6 dipole correctors for each of 2 transverse planes, and 6 four-electrodes beam position monitors in a single standalone string similar to that shown in ~~figure~~ Figure 2.

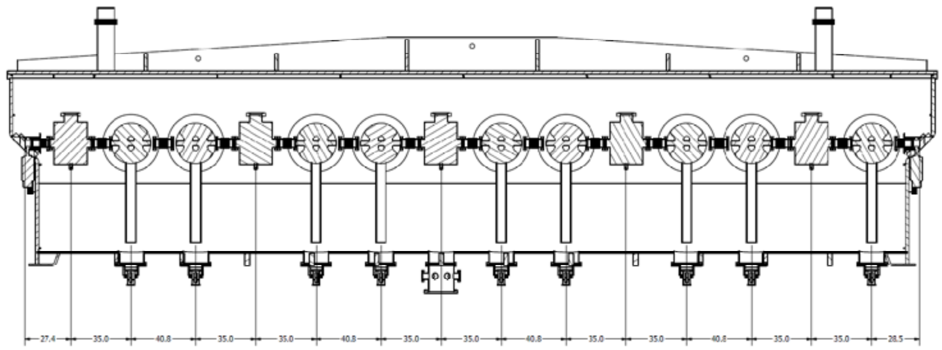

Figure 2: HW cryomodule assembly

Comment [v1]: we need picture update from ANL. VL

The intent if that the cryomodule is a standalone unit with all external connections to the cryogenic, RF, and instrumentation systems made at the cryomodule itself. The only connection to interconnecting beamline devices is the beam pipe itself. The cavity string is pre-assembled in the clean room and is terminated by beam valves at both ends. It is desirable that some maintenance operations, e.g. tuner motor replacement, be possible without removing the cryomodule from its installed position.

TECHNICAL REQUIREMENTS

General		
	Physical aperture, mm	~~30~~40
	Cavity to cavity spacing, adjacent cavities, mm	408
	Cavity to solenoid spacing, mm	350
	Solenoid to solenoid spacing, mm	1108
	Overall length, m	5.7
	Maximum allowed heat load to 70 K, W	250
	Maximum allowed heat load to 4.5 K, W	80
	Maximum allowed heat load to 2 K, W	15
	Maximum number of lifetime thermal cycles	20
	Intermediate thermal shield temperature, K	45-80
	Thermal intercept temperatures, K	5 and 45-80
	Pressure stability at 2 K, mbar	<0.1
Cavities		
	Number	9
	Frequency, MHz	162.5
	β	0.11
	Operating temperature, K	2
	Operating mode	CW
	Gradient, nos. 1 and 2, MV/cavity	1

Comment [v2]: Does not look as a large number, VL

Comment [v3]: Should it be "Cryoplant pressure stability "

	Gradient, nos. 3 through 9, MV/cavity	1.8
	Alignment requirement, mm RMS	<±1
	Alignment requirement, mrad RMS	<±10
Solenoids		
	Number	6
	Operating temperature, K	4.5
	Current at maximum strength, A	50
	∫B^2dL, T^2m	3.5
	Max. a~~A~~lignment ~~requirement~~error (center position), mm RMS	±0.5
	Max a~~A~~lignment ~~requirement~~error (angle)~~,~~ mrad ~~RMS~~	±0.~~5~~2
	Maximum fringe field at ~~TBD cm~~the cavity walls, mT	~~TBD~~2
	The polarity of the solenoids will alternate with each solenoid in the string.	
Correctors		
	Number, total	6
	Number, per solenoid package	~~1~~2
	Current, A	50
	Strength, T-m	0.005
	Corrector orientation will alternate with each solenoid package. The first will be vertical.	
BPMs		
	Number	6
	Number of plates	4
	Absolute a~~A~~ccuracy of the measurements, mm	±0.5

Table 1: Technical requirements

HEAT LOAD DISTRIBUTION

Details of the heat load distribution are shown in Table 2.

SSR1 8 cavities, 4 solenoids	Each unit			Mult	Total		
	80 K	4.5 K	2 K		70 K	4.5 K	2 K
Input coupler static	2.37	0.66	0.01	8	18.96	5.28	0.08
Input coupler dynamic	0.00	0.00	0.25	8	0.00	0.00	2.00
Cavity dynamic load	0.00	0.00	0.80	8	0.00	0.00	6.40
Support post	2.76	0.36	0.05	12	33.12	4.32	0.60
Conduction lead assembly	36.80	13.20	1.24	5	184.00	66.00	6.20
MLI (total 70 K + 2 K)	30.54	0.00	1.42	1	30.54	0.00	1.42
Cold to warm transition	0.72	0.08	0.01	2	1.44	0.16	0.02
Total					**268.1**	**75.8**	**16.7**

Comment [v4]: Looks OK but … (VL)

Comment [v5]: Has to be agreed between the following people: Champion, Yakovlev, Ostroumov, Ristori and Lebedev (VL)

Comment [v6]: Looks too large current for this strength

Comment [v7]: Discuss a necessity of 2 correctors inside each solenoid

Comment [v8]: Below numbers need to be updated for HW cryomodule

Table 2: Details of heat load distribution

PRESSURE SYSTEM REQUIREMENTS

Details of the pressure system requirements are shown in Table 2.

System	Warm MAWP (bar)	Cold MAWP (bar)
2 K, low pressure	2.5	4.0
2 K, positive pressure piping	20.0	20.0
5 K piping	20.0	20.0
70 K piping	20.0	20.0
Insulating vacuum	1 atm external, vacuum inside	na
Cavity vacuum	2.5 bar external, vacuum inside	4.0 bar external, vacuum inside
Beam pipe outside cavities, includes beam position monitors and warm to cold transitions	1 atm external, vacuum inside	1 atm external, vacuum inside

Table 2: Details of pressure system requirements

INTERFACES

The cryomodule assembly has interfaces to the following.

- Bayonet connections for helium supply and return.
- Cryogenic valve control systems.
- Pumping and pressure relief line connections.
- Vacuum vessel support structures.
- Beam tube connections at the cryomodule ends to adjacent beamline components as defined by the defining optics layout.
- RF cables to the input couplers.
- Instrumentation connectors on the vacuum shell.
- Power supply cables for the solenoid connections.
- Alignment fiducials on the vacuum shell with reference to cavity positions.

MAJOR COMPONENTS

VACUUM VESSEL

The vacuum vessel serves to house all the cryomodule components in their as-installed positions, to provide a secure anchor to the tunnel floor, to insulate all cryogenic components in order to minimize heat load to 70 K, 5 K, and 2 K, as well as maintain the insulating vacuum. It is approximately XX m long, XX wide, and XX m high and

Comment [v9]: Need numbers from P. Ostroumov manufactured from 300-series stainless steel. The vacuum vessel will be closed at each end of the HW cryomodule assembly by an end closure through which will extend the beam tube connection to the next beamline device.

MAGNETIC SHIELD

If needed a magnetic shield to shield the cavities from the earth's magnetic field can be incorporated into the design and located just inside the vacuum vessel inner wall. Preliminary tests show that a 1.5 mm-thick mu-metal shield at room temperature reduces provides effective and adequate shielding. It is likely that a separate magnetic shield will be installed around each individual magnetic element to further reduce the potential for trapped fields in the superconducting cavity structures.

MULTI-LAYER INSULATION

- Insulation for the 70 K thermal shield shall be fabricated as two blankets, each consisting of 30 reflective layers separated by spacer material.
- Insulation at the 5 K and 2 K levels shall consist of 10 reflective layers separated by spacer material.
- Insulation blankets shall be fabricated according to Fermilab specification 5520-ES-390121.
- Fermilab drawing no. MD-460996 may be used as a reference for installation of multi-layer insulation around individual pipes and tubes.

THERMAL SHIELD

- There shall be one level of thermal radiation shield at the nominally 70 K level.
- A thermal radiation shield at the 5 K level is not required.
- Thermal intercepts at both the 70 K and 5 K levels shall be available for the support structure, input couplers, conduction cooled current leads, and warm-to-cold beam tube transitions.
- The thermal shield shall employ "weld slits" along the length to minimize the potential for thermal distortions during cooldown.
- The thermal shield shall include baffles or equivalent devices to allow the free flow of helium to the outer vacuum vessel in the event of an internal vessel failure.
- The thermal shield will be manufactured from 6000-series aluminum.

STRUCTURAL SUPPORT SYSTEM

The structural support system inside the cryomodule to support all the internal components will consist of a central strongback installed between the vacuum vessel and thermal shield operating nominally at room temperature and a series of composite support posts. Each cavity and solenoid will be supported by a single post located at the center of each device. In this way, there will be no axial displacement of any device as the result of cooldown. There will still be a change in the vertical position due to thermal contraction of the device (cavity or solenoid) and the support post.

DRESSED CAVITIES

The cryomodule will contain dressed HW cavities subject to the “Technical Requirements” specified elsewhere in this document.

FOCUSING SOLENOIDS

The cryomodule will contain focusing solenoids subject to the “Technical Requirements” specified elsewhere in this document.

STEERING CORRECTORS

The cryomodule will contain steering correctors subject to the “Technical Requirements” specified elsewhere in this document.

RF INPUT COUPLER

Each cavity will have an RF input coupler with the following features and operating parameters.

- 50-ohm coaxial design.
- TBD kW CW.
- Copper inner conductor.
- Stainless outer conductor (no copper plating).
- Two ceramic windows, one at 300 K, one at 70 K. Separate vacuum for the space between windows.
- Thermal intercepts at 70 K and 5 K.
- Adjustment from outside of approximately ±2 mm axial positioning of the center conductor, under vacuum, but not cold.

CURRENT LEADS

Current leads for the main solenoid windings and all corrector windings will be conduction cooled or vapor cooled and configured such that all the leads for one magnet package are contained in one assembly. Each lead assembly with consist of a heat exchanger at 300 K to minimize the potential for frosting at the room temperature end and intercepts at 70 K and 5 K.

BEAM TUBE AND COLD-TO-WARM TRANSITIONS

All transitions between cold and warm beam tube sections shall consist of a warm-to-cold transition with thermal intercepts at 70 K and 5 K which limit the conduction heat load to 2 K to less than 2 W.

Beam tube extensions beyond the cavities, and attachments to the beam tube such as vacuum valves, BPMs, beam absorbers, etc. are to be "particle free" and cleaned for UHV like the cavities themselves. Beam tube interfaces inside and outside the cryomodule may require special attention the RF characteristics of the connections and connection components.

The beam tube at each end of the cryomodule will be terminated by a warm gate valve installed on the cavity string in the clean room. The valve will be a VAT model 1032-UE41.

CRYOGENIC VALVES AND TRANSFER LINE CONNECTIONS

All cryogenic valves and bayonet connections to the transfer line will be located at a central vacuum vessel location. In addition to the cryogenic valves and bayonets, there will be provisions for pumping the insulating vacuum and the insulating vacuum relief valve.

- Valves appropriate for low temperature helium cryogenic service shall be used.
- Valves shall be thermally intercepted at 70 K.
- Valves shall have bellows stem seals.
- Valves shall be sized and have control characteristics based on the anticipated operating flow rates with allowance for worst-case conditions such as cool-down, warm-up, or recovery from some other upset condition.
- Fermilab standard bayonet designs shall be used for the positive pressure connections to the cryogenic distribution system.
- Jefferson Lab or SNS sub-atmospheric bayonet design shall be used for any sub-atmospheric connections to the cryogenic distribution system.

HEAT EXCHANGER

- A heat exchanger shall be incorporated into the cryomodule design which pre-cools helium from approximately 5 K to 2 K upstream of the cryomodule liquid level control valve (JT-valve).
- The heat exchanger may be tube-in-shell or plate-fin style.
- The elevation of the bottom of the heat exchanger shall be at least 5 cm higher than the highest top of the 2 K liquid level in the system.

- Shell side pressure drop shall be no more than 2 mbar at worst-case steady-state design flow.
- Tube side pressure drop shall be no more than 100 mbar at worst-case steady-state design flow.

INSTRUMENTATION

Cavity and cryomodule instrumentation will include, but not be limited to the following. Internal wiring shall be of a material and size that minimizes heat load to the internal systems.

- Beam position monitors.
- Cavity field probes.
- Coupler e-probes.
- Diode x-ray detectors.
- Cavity tuner control and diagnostics.
- Input coupler temperature sensors.
- Thermal shield temperature sensors.
- Cavity helium vessel temperature sensors (externally mounted).
- Cavity helium vessel heater (externally mounted).
- Helium system pressure taps.
- Helium level probes in the 2 K phase separator.
- Helium temperature sensors in the 2 K phase separator.
- Cavity vacuum monitors.
- Insulating vacuum monitors.
- Input coupler vacuum monitors.

PIPING AND BELLOWS

The piping internal to the cryomodule will have sizes, nominal operating temperatures and design pressures as defined in Table 3.

Pipe description	Size (in)	Temperature (K)	Pressure (bar)
Cooldown/warm-up	2	5 K	20
LHe supply	1	5 K	20
2 K low pressure	5	2 K	2.5
2 K high pressure	1	5 K	20
5 K intercept	1	5 K	20
70 K shield supply and return	1	70 K	20

Table 3: Cryomodule piping design parameters and operating conditions

Figure 3 shows the flow schematic for the cryomodule. The supply and return flows for the 70 K and 5 K shield and thermal intercepts are fed through conventional bayonet connections located at a common point on the vacuum vessel discussed above and shown in Figure 4. The pumping and relief lines exit through a common port at the top of the vacuum vessel. The heat exchanger (HX), JT-valve, and cooldown/warm-up (CD) valve are all located inside the cryomodule.

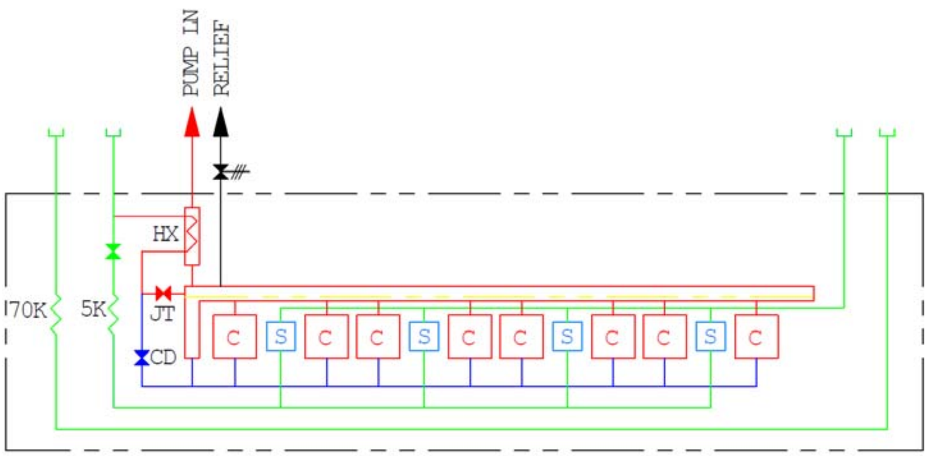

Figure 3: SSR1 cryomodule flow schematic (4 K magnets)

Interconnect piping required to connect to adjacent components shall be positioned within a tolerance range of ±5 mm with respect to the nominal position.

All bellows shall be designed for a total extension/compression of 40 mm and a minimum cycle life of 1000 cycles.

TECHNICAL REFERENCE

For purposes of calculating pressure relief requirements, conduction and radiation heat loads, etc., the following may be used for reference.

- Worst-case heat flux to liquid helium temperature metal surfaces with loss of vacuum to air shall be assumed to be 4.0 W/cm^2.
- Worst-case heat flux to liquid helium temperature surfaces covered by at least 5 layers of multi-layer insulation (MLI) shall be assumed to be 0.6 W/cm^2.
- Thermal radiation to the 2 K or 5 K level under a 70 K thermal shield is approximately 0.1 W/m^2.
- Thermal radiation to the 70 K thermal shield from room temperature vacuum vessel is approximately 1 W/m^2.

ENGINEERING AND SAFETY STANDARDS

All vacuum vessels, pressure vessels, and piping systems will be designed, documented, and tested in accordance with the appropriate Fermilab ES&H Manual (FESHM) chapters. This includes the superconducting cavities and their associated helium vessels which must be designed, manufactured, and tested in accordance with FESHM chapter 5031.6, Dressed Niobium SRF Cavity Pressure Safety. Bellows shall be designed using the requirements of the Expansion Joint Manufacturers Association (EJMA).

TEST REQUIREMENTS

The cryomodule will be tested before installation in the linac. Tests will check the following.

- Leak tests and pressure tests for quality assurance and FESHM compliance.
- Temperature profiles.
- Approximate heat loads.
- RF cavity performance.
- Tuner performance.

QUALITY ASSURANCE

A complete cryomodule traveler is to be developed documenting all stages of materials inspection, cryomodule component fabrication, piping and weld inspection, cryomodule assembly, and test.

REFERENCES

1. B. Webber, "325 MHz Spoke Cavity Prototype Cryomodule Functional Requirements Specification", http://projectx-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=794.
2. T. Nicol, "325 MHz SSR0 Cryomodule Functional Requirements Specification", http://projectx-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=880.
3. T. Peterson, "650 MHz Cryomodule Requirements Document", http://projectx-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=885.
4. V. Lebedev, "Major Requirements to PXIE Optics and Design", http://projectx-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=930.