650 MHZ CRYOMODULES FOR PROJECT X AT FERMILAB – REQUIREMENTS AND CONCEPTS*

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Abstract

Cryomodules containing 650 MHz superconducting niobium RF cavities and associated components (input couplers, tuners, instrumentation, etc.) will be developed for Project X, a high intensity proton accelerator facility based on an H- linear accelerator at Fermilab. This paper describes the requirements of the 650 MHz cryomodules and the implications of those requirements for the cryomodule design. Cryomodule string segmentation, integration with the cryogenic system, features for maintainability and access, piping and emergency venting considerations, pressure vessel issues, and thermal and mechanical design concepts will be described.

INTRODUCTION

Project X will be a multi-MW proton accelerator facility based on an H- linear accelerator using superconducting RF technology [1]. The Project X 3 GeV CW linac will employ 650 MHz cavities [2] to accelerate 1mA of average beam current of H- in the energy range 160 – 3000 MeV. We describe the requirements of the 650 MHz beta = 0.9 cryomodules (see Figure 1) and implications of those requirements for the design concepts.

The baseline design concept includes cryomodules closed at each end, individual insulating vacuums, with warm beam pipe and magnets in between cryomodules such that individual cryomodules can be warmed up and removed while adjacent cryomodules are cold. The cryostat must:

- Provide the required insulating and beam vacuum
- Minimize cavity vibration and coupling of external sources to cavities
- Provide good cavity alignment (<0.5 mm)
- Allow removal of up to 250 W of heat at 2 K per cryomodule
- Protect the helium and vacuum spaces including the RF cavity from exceeding allowable pressures
- Intercept significant heat loads at intermediate temperatures above 2 K to the extent possible in full CW operation
- Provide high reliability in all aspects of the cryomodule (vacuum, alignment stability, mechanics, instrumentation) including after thermal cycles
- Provide excellent magnetic shielding for high Q0
- Minimize cost (construction and operational)

The focus in this report will be on some of the unique features which result from the continuous wave (CW) operation and resulting heat loads of as much as 30 W per RF cavity.

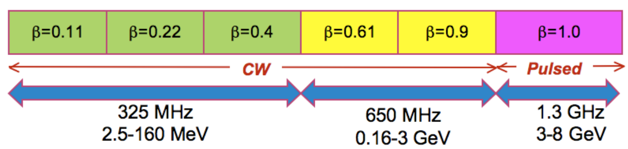

Figure 1: Project X incorporates six types of cryomodules, shown in this map. This paper describes the requirements for 650 MHz, beta = 0.9 cryomodules.

CRYOMODULE MECHANICAL COMPONENTS

The cryomodule consists of various subassemblies and components which are integrated into one vacuum jacketed vessel. These include:

- Eight (8) dressed RF cavities [1,2]
- Eight RF power input couplers
- One intermediate temperature thermal shield
- Cryogenic piping, connections to supply and return lines, and valves
  - 2 K liquid level control valve
  - Cool-down/warm-up valve
  - 5 K thermal intercept flow control valve
- A heat exchanger will be incorporated into the cryomodule design which precools helium from approximately 4.5 K to 2.2 K upstream of the cryomodule liquid level control valve.
- Pipe and cavity support structure
- Vacuum vessel, external supports with features for positioning the cryomodule, and alignment fiducials on the vacuum shell with reference to cavity positions
- Instrumentation
- Beam tube connections at the cryomodule ends with beam vacuum isolation valves.

The lattice developed for Project X assumes eight RF cavities per 650 MHz high energy (HE650) cryomodule. Cryomodule linac lattice dimensions and spacing [3] are shown in Figure 2.

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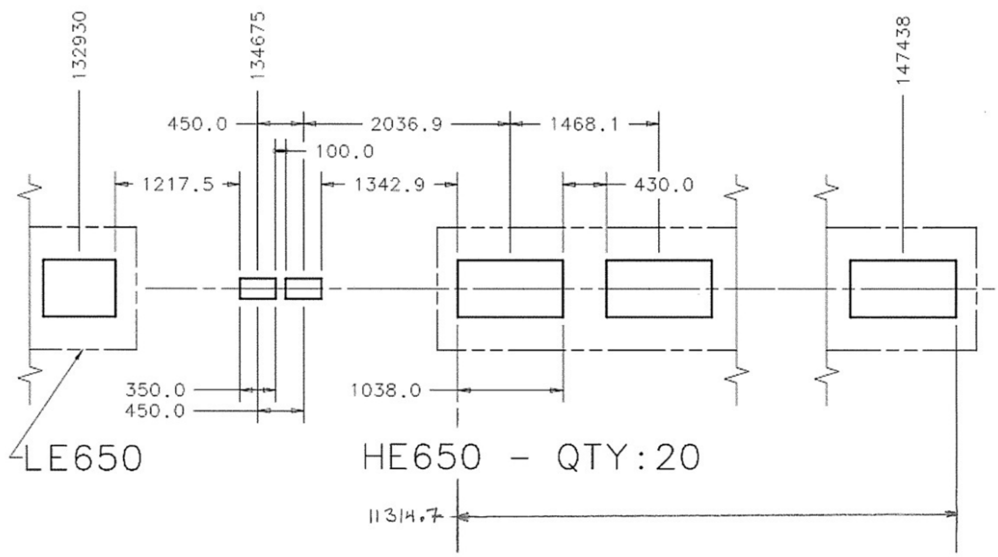

Figure 2: 650 MHz beta = 0.9 cryomodule lattice spacing. Dimensions, in mm, are effective RF and magnetic field lengths, which is approximately end iris to end iris distance for cavities. HE650 refers to the beta = 0.9 cryomodules, of which there will be 20. LE650 refers to the beta = 0.61 cryomodules. Large rectangles represent RF cavities, small rectangles represent magnets. One HE650 cryomodule will be 11.3 meters long from the start of the first RF cavity to the end of the last.

CRYOMODULE THERMAL AND FLOW REQUIREMENTS

Temperature Levels

There will be three temperature levels of helium cooling in the cryomodules. For the RF cavities, 1.8 K to 2.1 K are possible operating temperatures under consideration. This level is referred to as "2 K" in this document.

A next temperature level will be in the range 4.4 K to 8.0 K. A 4.4 K subcooled liquid or 2-phase system may be incorporated, or a supercritical pressure stream in the range 5.0 to 8.0 K. This level is referred to as "5 K" in this document.

The highest temperature level will be helium in the range 30 K to 80 K, the precise range yet to be determined. This level is referred to as "70 K" in this document.

Thermal Radiation Shields

There will be one level of radiative thermal shield at the nominally 70 K level. There will be no liquid nitrogen in the Project X tunnel. However, for test purposes in various test cryostats and facilities, the "70 K" thermal shield may be cooled with liquid nitrogen at approximately 80 K.

Due to the relatively low amount of thermal radiation from 70 K to 2 K relative to the large 2 K dynamic heat loads, a thermal radiation shield at the 5 K level is not required. Thermal intercepts at the 5 K level will be available for the support structure, input couplers, warm-to-cold beam tube transitions, and higher order mode (HOM) absorbers, if any.

The thermal shield should be designed such that introduction of cold (process temperature) helium into the thermal shield piping when the thermal shield is warm, resulting in a very fast cool-down, does not damage the thermal shield or other parts of the cryomodule. (The issues are warping and associated forces, thermal stresses, etc.)

Heat Loads

Heat loads will depend on the detailed cryomodule design. However, for initial design purposes estimated heat loads (Table 1) at each temperature level are being used. These are the best estimate of heat load; no multiplier for uncertainty was yet applied to those numbers. Heat sources include not only RF dynamic loads but input couplers, the RF cavity and piping support structure, cryomodule end effects such as end shine into the cold beam tube, and thermal radiation. Magnets and current leads are not included in the 650 MHz high-beta cryomodule heat load estimates since magnets are envisioned as being warm, between cryomodules.

Figure 3 illustrates our conceptual flow scheme for satisfying these cooling requirements. The rationale for the stand-alone configuration of the cryomodule are discussed further in the section on piping and segmentation.

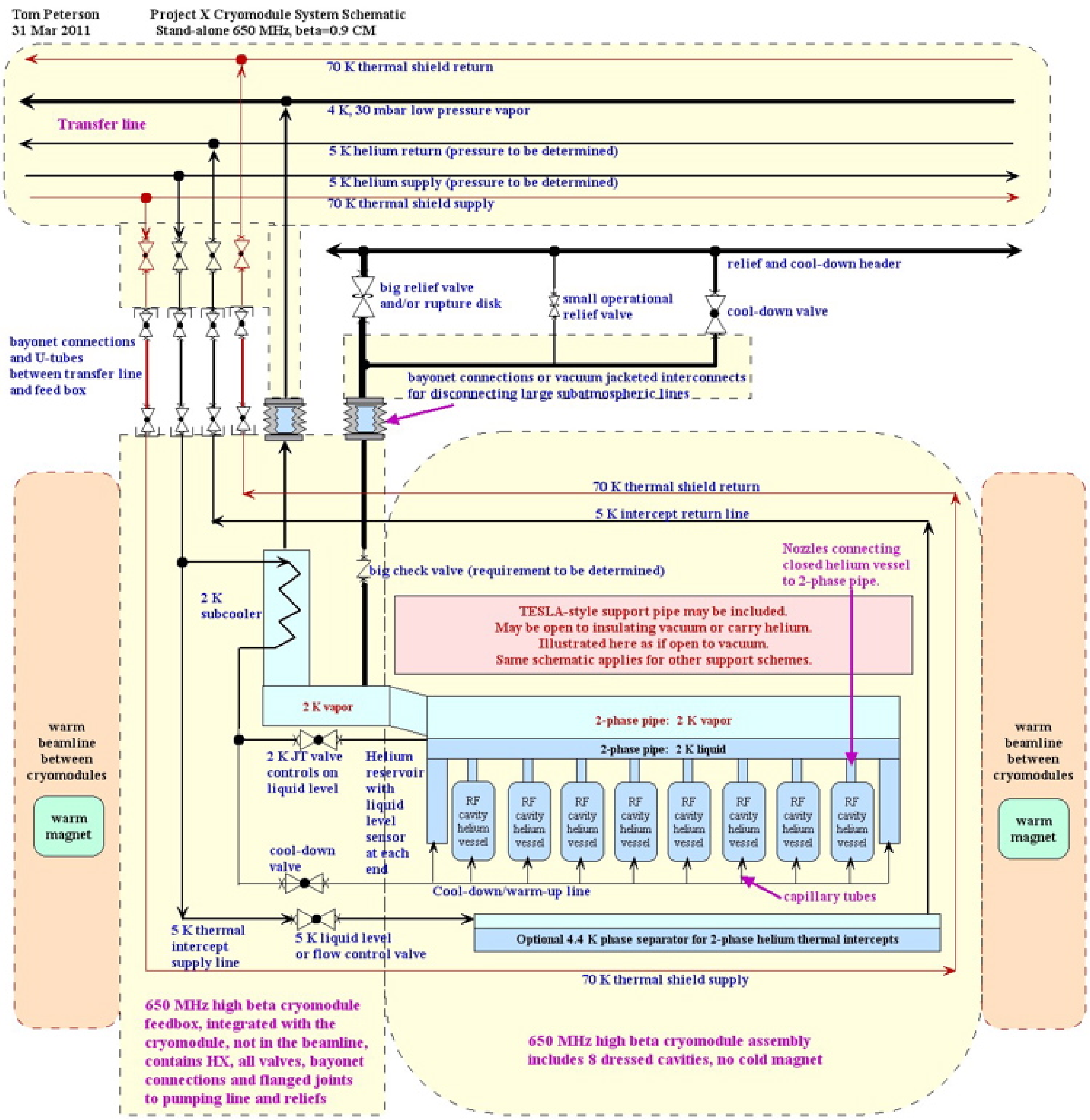

Figure 3: 650 MHz beta = 0.9 cryomodule schematic

Table 1: Estimated heat loads

650 MHz beta = 0.9 cryomodule heat	Most heat (no multiplier) (W)
2 K, per cavity	26
2 K, per cryomodule	208
5 K, per cryomodule	34
70 K, per cryomodule	436

MAXIMUM ALLOWABLE WORKING PRESSURES

Due to the very ductile condition of the niobium RF cavities, the maximum allowable working pressure (MAWP) at the 2 K level must be kept rather low. (See Table 2.) We can take advantage of the increased strength of niobium at low temperature to allow a higher cold MAWP. Nevertheless, the low MAWP sets constraints on the pipe sizes and lengths of cavity strings which are discussed further below.

Table 2: Maximum allowable working pressures (MAWP) (differential pressure)

Region	Warm MAWP (bar)	Cold MAWP (bar)
2 K, low pressure space	2.0	4.0
2 K, positive pressure piping (separated by valves from low P space)	20	20
5 K piping	20	20
70 K piping	20	20

PIPE SIZING AND SEGMENTATION

The combination of large steady-state heat loads and stringent venting requirements at the 2 K level combine to dictate rather large diameter 2 K pipes and short distances between relief valves. For heat transport from the RF cavity to a 2-phase pipe with a nearly closed helium vessel as illustrated in Figure 3, 1 W/sq.cm. is a conservative rule for maximum heat flux through helium II through the vertical pipe [4, 5]. The critical heat flux for a non-vertical pipe connection from the helium vessel to the 2-phase pipe may be considerably less than 1 W/sq.cm. Configurations other than vertical require analysis to verify that the anticipated heat flux is less than the critical heat flux.

The two phase pipe size and/or helium vessel vapor space must accommodate a 5 meters/sec vapor "speed limit" over liquid [6]. The consequence for required pipe diameter versus number of cavities operating in series is shown in Figure 4. No downward dips or features of the 2 K vapor piping which could trap liquid as a separate bath from the main 2 K bath are permitted, due to the liquid helium control difficulties which would result.

During loss of vacuum venting, pressure in the helium vessel of the dressed cavity must be less than the cold maximum allowable working pressure (MAWP) of the helium vessel and dressed cavity. A heat flux as high as 4 W/sq.cm. of cavity surface area could result from sudden loss of beam vacuum to air, with a resulting helium flow rate of many kilograms per second to be removed at low pressure. The venting path includes the nozzle from the helium vessel, the 2-phase pipe, may include the gas return pipe, and also includes any external vent lines. (See Figure 3.)

Pipes have to be sized for the worst case among steady-state, peak flow rates, upset, cool-down, warm-up, and venting and conditions. Total 2 K vapor volume required for pressure stability and control may also be a factor influencing pipe sizes.

Due to the desirability of short cryogenic pipe lengths, short 2 K liquid distances for managing control, and frequent vent line spacing, the baseline cryomodule design selected is a closed, stand-alone cryomodule with connections to an external, parallel transfer line (Figure 3). Each cryomodule includes at least two closed vacuum spaces: cavity/beam vacuum and cryomodule insulating vacuum. Vacuum isolation breaks separate cryomodule insulating vacuum from the transfer line vacuum.

The baseline cryomodule structure includes short enough warm to cold transitions such that cavity to cavity spacing from one cryomodule to the next is acceptable with allowance for warm magnet(s), instrumentation between cryomodules, and access for their installation. Warm-to-cold transition heat loads must be relatively small, in particular, less than 2 W each to the 2 K level.

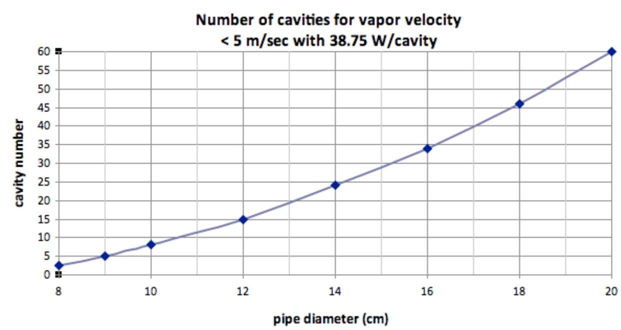

Figure 4: Number of 650 MHz cavities in series, using 1.5 x the estimated heat load shown in Table 1, which results in a vapor flow rate of 5 m/sec versus pipe size.

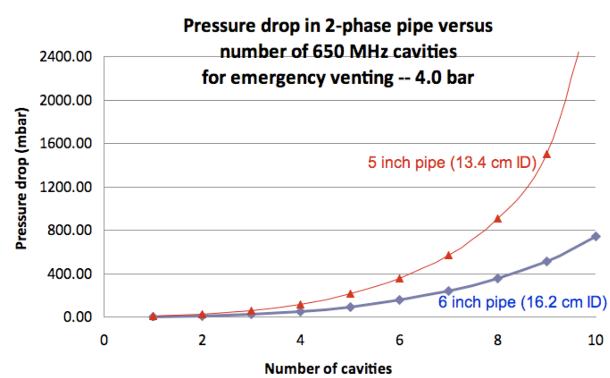

Figure 5: Loss of cavity vacuum to air -- venting pressure drop in 2-phase pipe

Figure 5 shows pressure drop through the 2-phase pipe with 650 MHz RF cavities venting due to loss of cavity vacuum. One can see that for 8 cavities in series, a 5-inch pipe is becoming marginally small. Given the uncertainties in these analyses and the need for a pressure drop in other parts of the system including vent piping, we would select 6-inch (16.15 cm) pipe.

Comparing Figures 4 and 5, we can see that the loss of cavity vacuum to air forces a larger pipe size than the steady-state vapour speed limit of 5 m/sec does.

STRUCTURAL STIFFNESS AND ALIGNMENT

Cavity alignment requirements relative to external reference are summarized in Table 3. Cavity positions relative to fiducials on the vacuum vessel are set during assembly with no requirement for later internal adjustment of cavity position within the cryomodule after assembly. Alignment must be maintained (return to position within 0.5 mm RMS tolerance) with thermal and pressure cycling. The cryomodule will be designed for a minimum of 20 thermal cycles. Final alignment is of the vacuum vessel assembly by means of the external fiducials which were referenced to the cavity string.

Table 3: Positional tolerances within the cryomodule

	Subassembly	**Tolerances**	**Total envelopes**
Cryo-module assembly	Cavity and He vessel assembly	+/- 0.1 mm	Positioning of the cavity with respect to external reference +/-0.5 mm
	Supporting system assembly	+/- 0.2 mm	
	Vacuum vessel construction	+/- 0.2 mm	
	Action		
Transport, testing, and operation	Transport and handling (+/- 0.5 g in any direction)	+/- 0.1 mm	Reproducibility, stability of the cavity position with respect to external reference +/-0.5 mm
	Vacuum pumping, cool down, RF tests, warm-up, thermal cycles	+/- 0.2 mm	

HEATER FOR 2 K FLOW AND PRESSURE CONTROL

The presence of a steady-state pressure drop results in a pressure change at the cryomodule with a change in flow rate (e.g., due to heat load change or liquid level control valve position change), even with constant cold compressor inlet pressure (perfect cryoplant pressure regulation). Heaters distributed within the cryomodules will be required to compensate for heat load changes so as to control subsequent flow and pressure changes.

ACCESSIBILITY AND MAINTENANCE

A concern based on experience with cryomodules in various laboratories is the occasional need to access the mechanical slow tuner or tuner motor. For this reason, the tuner motor location in the 650 MHz Project X cryomodules is required to be accessible without disassembly of the cryomodule. The present baseline concept includes ports on the vacuum vessel providing access to each tuner motor.

The baseline cryomodule design as a closed, stand-alone cryomodule with connections to an external, parallel transfer line allows individual cryomodule warm-up and also space for warm magnets and warm beam instrumentation between cryomodules.

CONCLUSIONS

The relatively large heat loads of over 200 W per cryomodule due to CW operation and low maximum allowable working pressure of the RF cavity helium vessels due to the use of soft niobium combine to produce stringent thermal and mechanical constraints on the cryomodule design. The concept for Project X is to move away from long cryomodule strings like the TESLA or ILC concept and utilize stand-alone cryomodules. These provide naturally short cryogenic string lengths for liquid helium control and allow for frequent connections to relief venting lines. The conceptual design follows these conclusions regarding the implications of the requirements for these 650 MHz cryomodules.

REFERENCES

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