DESIGN UPDATE OF THE SSR1 CRYOMODULE FOR PIP-II PROJECT

V. Roger [†], S. Cheban, T. H. Nicol, Y. Orlov, D. Passarelli, Fermilab, Batavia, IL 60510, USA
P. Vecchiolla[1], Sant'Anna School of Advanced Studies, Pisa, 56127, Italy
also at University of Pisa, Pisa, 56127, Italy

Abstract

This paper reports the design update of the Single Spoke Resonator 1 (SSR1) cryomodule developed in the framework of PIP-II project at Fermilab. The most recent design changes and results of calculations performed to optimize the vacuum vessel, current leads, piping system and thermal shield are described. Then the estimated heat loads of the cryomodule leading to the sizing of the cryogenic valves will be presented.

INTRODUCTION

The SSR1 325 MHz cryomodules are part of the superconducting linac architecture of PIP-II (see Fig. 1).
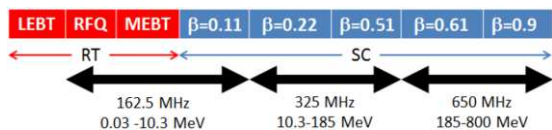

Figure 1: Layout of the PIP-II linear accelerator.

It is the first time at Fermilab that a strong-back at room temperature will be used to support all the elements of a cryomodule from the bottom. The main parts of the cryomodule are already described in a previous paper [1]. The following chapters show the main design changes including the design optimisation of the conduction cooled current leads from 300 K to 2 K which is a key design step to reduce the thermal loads.

DESCRIPTION OF THE CRYOMODULE

Two main ports are located in the middle of the cryomodule. One is dedicated to the interface with the cryogenic valves and bayonets, the other one is used for the relief line and the heat-exchanger as presented in Fig. 2.
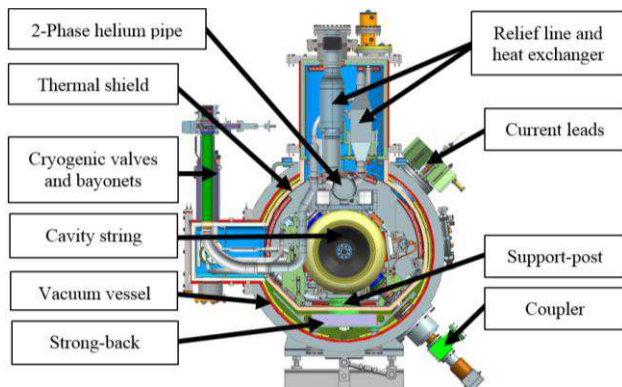

Figure 2: Cross-section of the SSR1 cryomodule.

The eight instrumentation ports are in front of the tuners (See Fig. 3). Therefore, in case of a failure it will be possible to replace the tuner motor and the piezo actuators.
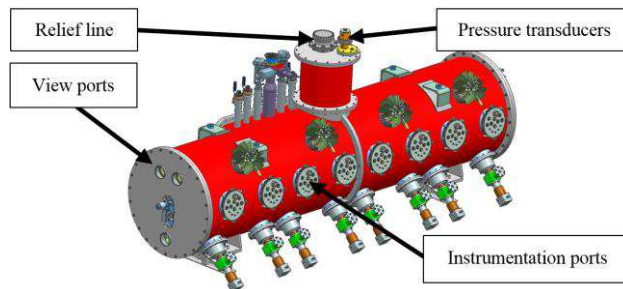

Figure 3: Vacuum vessel.

The first SSR1 cryomodule is instrumented with sensors and gauges to monitor the thermal performance of key components and to validate the design strategy and the calculations. The temperature of the strong-back will be monitored as well as the temperature of the coupler, current leads, support posts and thermal shield. This instrumentation will help also to understand better any issue occurring during the first cool down of the cryomodule.

CURRENT LEADS

Each magnet assembly is composed of one solenoid with an operating current of 70 A and 2 quadrupole correctors with an operating current of 45 A. With these magnets being cooled by liquid helium at 2 K it has been decided to use conduction cooled current leads. The current lead assembly is composed of eleven stainless-steel tubes (Fig. 4). Two are used for the solenoid leads, eight for the correctors leads and one for the voltage taps. The manufacturing process is the following: each of the copper wires are covered by a polyolefin heat shrink tube, then they are inserted in the stainless-steel tubes which were previously brazed to the copper blocks used as thermal intercepts. Finally, the tubes are formed, filled with liquid epoxy and cured in the oven.
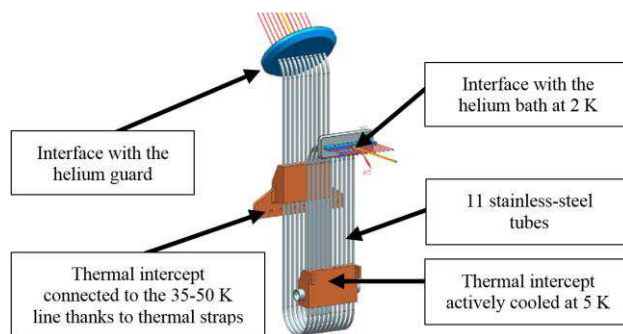

Figure 4: Current leads assembly.

To increase the thermal exchange in the helium guard, the pressure is set to 1.8 bar and fins have been placed right after the ceramic feedthroughs (Fig. 5).
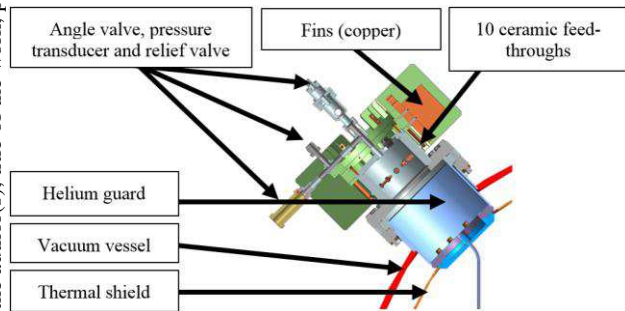

Figure 5: Cross-section of the helium guard.

Even if the value of the contact resistances between the copper, the polyolefin, the epoxy and the stainless-steel tube are not well known, simulations using the finite difference method have shown that in case of high contact resistances the heat loads will be slightly higher however there will be no risk of a hot spot. The main parameter is the RRR of the copper. If the RRR is too low, the heat generated by joule effect will be important and there will be a risk of a hot spot. If the RRR is too high, the conductivity will be higher and therefore the heat loads at 2 K will increase (Fig. 6
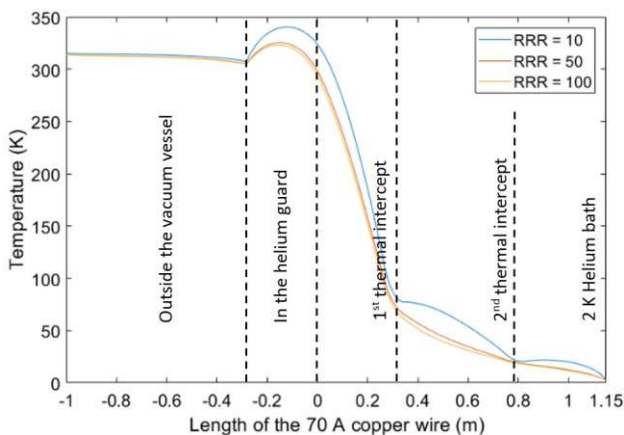

Figure 6: Temperature profile of one lead of the solenoid.

The temperature profile with a RRR of 50 or 100 is almost identical. Nevertheless, the effect on the heat loads is important (Table 1). Therefore, it has been decided to measure the RRR of the copper before manufacturing the leads. Our target is a RRR value between 50 and 75.

Table 1: Heat Loads at 2 K Due to the Current Leads

	Heat loads at 2 K (RRR = 10) [W]	Heat loads at 2 K (RRR = 50) [W]	Heat loads at 2 K (RRR = 100) [W]
Static	0.15	1.7	3.6
Static & dynamic	2.1	2.4	4.1

LESSONS LEARNED

Over the last years, Fermilab has been involved in the design and production of several cryomodules for the upgrade of the linear coherent light source (LCLS-II) at SLAC [2]. The lessons learned during this project have been an asset in designing PIP-II cryomodules and in mitigating the thermal acoustic oscillations (TAO), helium bath instability, and structural vibrations.

Calculations have been performed on the injection of helium into the two-phase helium pipe (Fig. 7) to understand the effect on the liquid level disturbance.
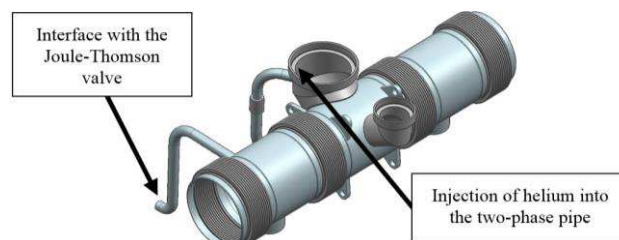

Figure 7: Design of the injection of helium into the two-phase helium pipe.

Results show a pressure difference of 0.5 Pa with the two-phase helium pipe filled at 50% (Fig. 8 and 9), compared to 1.2 Pa for LCLS-II project in its final configuration using a baffle.
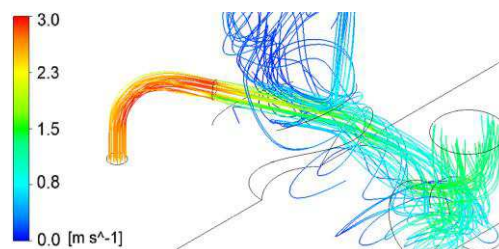

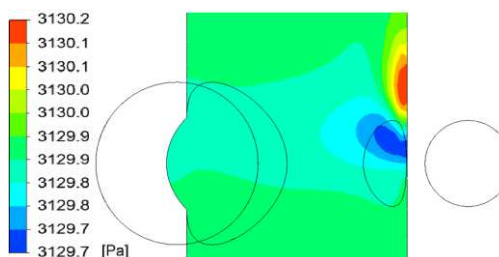Figure 8: Streamline in the two-phase helium pipe.

Figure 9: Pressure in the two-phase helium pipe.

The experience from LCLS-II will also be useful during the assembly of the cryomodule to define the torque, the use of Loctite and indium to lock the fasteners and assure a good contact of the thermal straps. With more than 100 thermal straps used inside the cryomodule, this assembly process will be a key step to minimise heat loads at 2 K and assure the proper operation of the coupler.

Moreover, LCLS-II and SSR1 cryomodules share the same design for the cryogenic valves. The helium inlet is located below the valve, the outlet on the side and wiper rings are used to mitigate the TAO.

CRYOGENIC DESIGN

The coldmass is composed of one thermal shield actively cooled at 35-50 K. The 5 K line is used as a thermal intercept for the support posts, couplers, current leads, tuners and also to cool down the cavity string from 300 K to 5 K. Then, by using a heat-exchanger, a Joule-Thomson valve and by pumping the helium gas in the two-phase helium pipe the temperature reaches 2 K. The Fig. 10 describes the main cryogenic lines in the cryomodule.
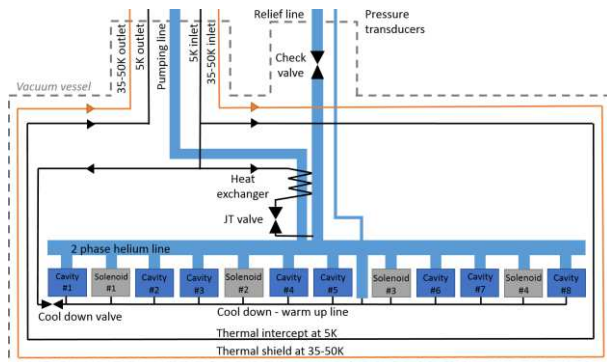

Figure 10: Schematic of the cryogenic lines.

The heat loads have been estimated in static and dynamic (Table 2). At 2 K, a mass flow rate from 0.9 to 2.2 g/s is expected.

Table 2: Heat Loads of SSR1 Cryomodule

	35-50 K stage [W]	5 K stage [W]	2 K stage [W]
Static	131.4	35.9	24.1
Static & dynamic	185.8	45.1	52.0

Cryogenic Valves

At 4.5 K, the nominal flow of the heat exchanger (7 g/s) matches the mass flow through the Joule-Thomson valve when the valve is around 75% open (Fig. 11). At 2 K, the valve po-sition should be set around 40 - 55% to match the operating mass flow rate. Therefore, it will be possible to regulate the mass flow during the operation at 2 K.
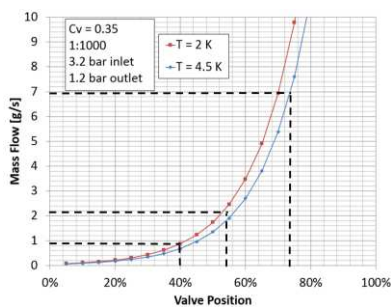

Figure 11: Mass flow through the Joule-Thomson valve.

Thermal Shield

The thermal shield is composed of three extruded pipes connected to the aluminum 1100-H14 shells with finger welds (Fig. 12) as on the Tesla Test Facility cryomodule [3].
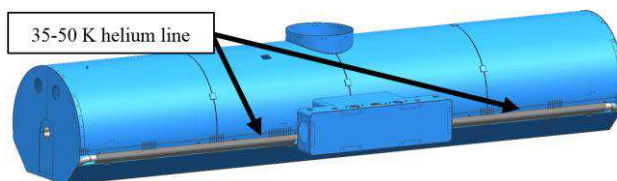

Figure 12: Main part of the SSR1 thermal shield.

In steady state, a maximum thermal gradient of 9 K is expected. The hottest spot will be located at the interface with the current leads on the extruded pipe and the coolest spot will be located at the inlet of the line (Fig. 13).
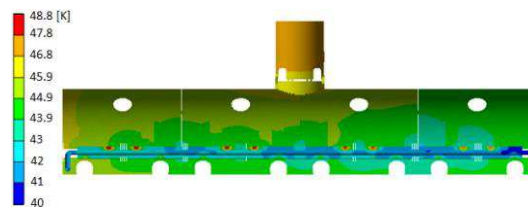

Figure 13: Temperature profile of the thermal shield.

Transient thermal analyses were performed to simulate the cool down process at 5 K/hour and 10 K/hour and to evaluate the stress (Table 3).

Table 3: Results of Transient Thermal Analyses

Cool down rate [K/hour]	Maximum gradient across the shield [K]	Average stress at weld location [MPa]
5	40	45
10	75	77

To avoid stress above the allowable value for welded aluminum 6061-T6 of 55MPa defined according to ASME code B31.3 the maximum thermal gradient must be kept below 50 K across thermal shield during the cool down.

CONCLUSION

The design of the SSR1 cryomodule has been completed and the procurement process has just begun. In the coming months further details, such as the specification of the torque, the alignment strategy and the magnetic shield design will be finalized.

ACKNOWLEDGMENT

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