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DESIGN AND MANUFACTURING CHALLENGES OF THE SSR1 CURRENT LEADS FOR PIP-II*

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Abstract

The SSR1 cryomodule contains eight 325 MHz superconducting single spoke cavities and four solenoid based focusing lenses operating at 2 K. The focusing lens for SSR1 cryomodule, is a superconducting magnet surrounded by a helium box which will be filled with liquid helium. The magnet assembly is composed of one solenoid with operating current 70 A and 2 quadrupoles correctors with operating current 45 A. The conduction cooled current leads will be used to power magnets. The details of current leads design, fabrication and room temperature qualification will be presented. Main emphasis will be put on the design and production process challenges and possible solutions to fulfill operation requirements under the low temperature conditions.

INTRODUCTION

Proton Improvement Plan-II (PIP-II) is Fermilab's plan for providing powerful, high-intensity proton beams to the laboratory's experiments. Fermilab is planning a program of research and development aimed at testing of critical components. The first single spoke resonators cryomodule SSR1 is a prototype cryomodule containing eight cavities and four focusing lenses [1]. The focusing lens assembly is composed of one solenoid with an operating current 70 A and 2 quadrupole correctors with an operating current 45 A. The focusing lens being cooled by liquid helium at 2 K and powered by conduction cooled current leads. The current leads assembly consist of two 70 A solenoid leads, eight 45 A quadrupole leads and voltage taps sub-assembly. The focusing lens quench protection system uses cold diodes shunting the windings. The current leads are the key components that make a connection between room-temperature electrical conductors and focusing lens superconductor wires at cryogenic temperature. The conduction-cooled leads where chosen due to their relative simplicity compare to other options. The conduction-cooled leads using common materials, have no superconducting/normal state transition, and have no boil-off vapor circuit. The special attention was paid to conductor materials and geometry choice, the design of intermediate heat sinks, feasibility of final integration in tight space environment of the cryomodule on different stages of assembling process.

CURRENT LEADS DESIGN

The SSR1 cryomodule current leads assembly consists of 10 stainless tubes with copper conductors inside (Fig. 1). The instrumentation wires combined in one subassembly and located in the middle stainless-steel tube. The two thermal intercepts (5 K, 35-50 K) placed along the length of the leads can alleviate the heat management problem [2]. The particular choice of thermal intercepts depends on the specifics of the cryostat. The thermal intercepts 2 is actively cooled by 5 K line flow and its copper block directly brazed to cooling pipe. The thermal intercepts 1 copper block is connected to 35-50 K thermal shield pipe through a set of copper straps. A set of copper fins will be installed outside of cryostat at room temperature, this will help to keep temperature at the top above due point to avoid condensation and freezing during cool down process. Also it will help to decrease temperature during operation mode if the temperature of power cable will be higher than 300 K .

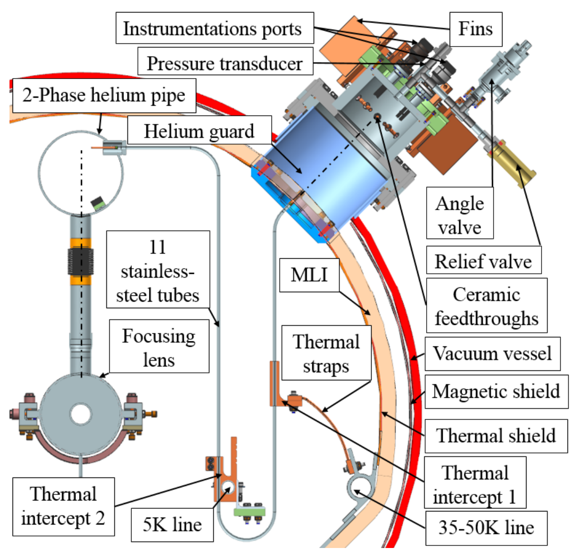

Figure 1: Current Leads.

HEAT LOADS

The current leads represents one of the major sources of heat leak into the magnets, thus into the 2K Helium bath. The heat conduction through current leads assembly and the heat generation due to the Joule heating in the leads themselves are the two primary modes of this leak. The design of current leads aims to minimize the total cooling power. Making the cross-section of the lead smaller to reduce conduction will increase its resistance and therefore the Joule power. Making the cross-section larger to decrease the resistance and the Joule power will increase conduction. The design procedure requires calculation to evaluate such operational characteristic as the heat leak as a function of the geometry of the conductor. The simulations using the finite difference

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method was performed to evaluated heat loads. The material of conductor was set to copper. The main variable parameter is the RRR of the copper. If the RRR is too low, the heat generated by Joule heating will dominate and therefore will be a risk of leads run away due to high temperature zone. If the RRR is too high, the conductivity will be higher, and the heat loads at 2 K will increase. The RRR of first copper conductor butch was measured at 102 for 70A leads and 140 for 45A leads. The RRR of production copper conductor butch was measured at 120 for 70A leads and 180 for 45A leads. The simulation was performed using latter values to evaluate heat loads using copper from production butch (see Table 1) [3].

Table 1: Heat Loads at 2 K

	70A RRR=120	45A RRR=180	Total
Static	1.05 W	0.46 W	5.8 W
Static & dynamic	1.2 W	0.55 W	6.8 W

CURRENT LEADS PROTOTYPING

Prior to the manufacturing of the full prototype current leads assembly, a comprehensive research phase was performed on small samples in order to validate the best technique and material to fill the gap between the copper conductor and the stainless steel jacket. The filling material must guarantee the electrical insulation and leak tightness throughout the entire lead under sever thermal conditions. Each sample was cold shocked and hipoted to validate used technique. Figure 2 shows few samples used during testing: 1 - sample filled with epoxy CTD101K, 2 - sample filled Stycast 2850FT with 23LV catalist, 3 - signal wires sample, 4 - real length samples for 70A and 45A copper wires, 5 - brazed copper intercept, 6 - welded cold flange, 7 - warm flange filled with epoxy, 8 - tube filled with epoxy and welded afterwards. The Stycast 2850FT with 23LV catalist samples proved to be vacuum tight and successfully pass hipot test after 10 cold shock cycles (submerged to liquid nitrogen - warmed up with heat gun up to about 170 °F).

The in-vacuum cryogenic service wire was chosen for instrumentation (Fig. 2 item 3). Cryogenic service wire is a kapton insulated in-vacuum wire designed for high and ultrahigh vacuum environments to 1×10^{-10} Torr, suited for cryogenic service down to 1 K, it is also bakeable to 525 K. Special sealing technique were used. The 5 mm kapton was removed from wire and wires were separated and installed G10 spacer to allow epoxy fully penetrate in between.The bending technique for full size current lead tubes were developed and tested for both size of copper wires (Fig. 2 item 4). The geometrical parameters proved to be within tolerances per drawings. The lead samples were successfully tested. The brazing procedure at thermal intercepts (Fig. 2 item 5) and welding procedure at cold flange (Fig. 2 item 6) were tested to avoid damage of insulation and copper wire inside

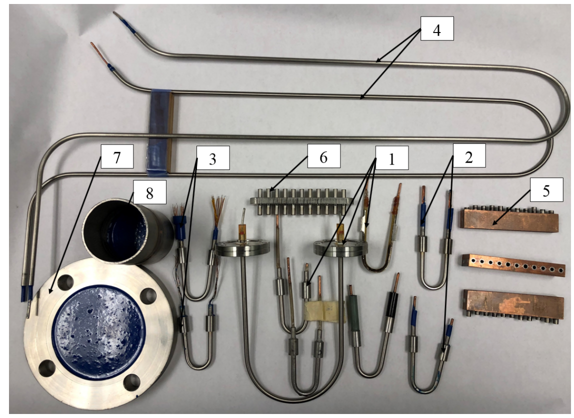

Figure 2: Current Leads Prototyping.

of stainless steel tube. The epoxy performance in proximity of weld was tested. The distance of 50 mm between epoxy and weld proved to be safe (Fig. 2 item 8).

CURRENT LEADS PROTOTYPE MANUFACTURING

The first current leads assembly prototype was manufactured and tested at Fermilab (See Fig. 3).

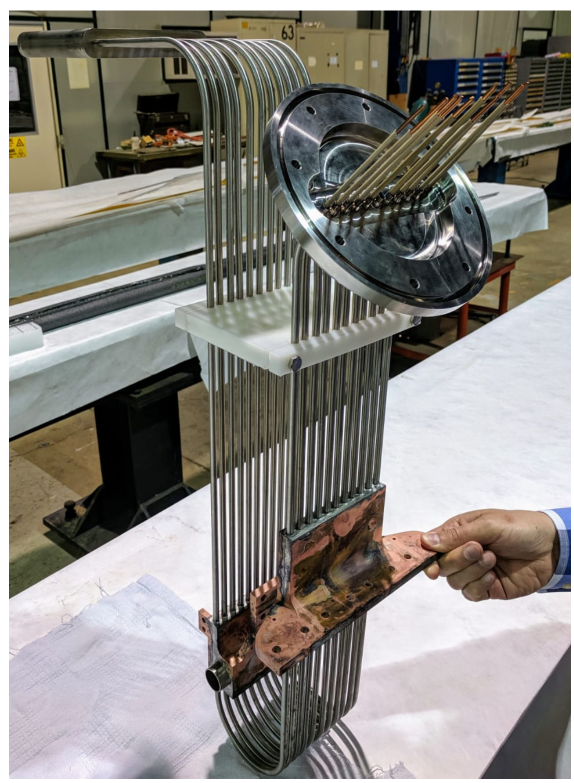

Figure 3: Current Leads Prototype.

The following manufacturing process was used. Each stainless-steel tube was etched from inside, washed off with distilled water, cleaned with alcohol and purged with nitrogen. The copper wires were cleaned with alcohol, covered with fiber glass braided sleeving isolation and loaded inside

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of the stainless-steel tubes. The middle stainless-steel tube was left empty for instrumentation wires. The tubes were individually bended. The special aluminum gauge was used to verify that all tubes were bend identically and per drawings. The warm and cold stainless flanges were welded to stainless steel tubes. The copper thermal intercepts 5 K and 35 K-50 K were brazed to stainless steel tubes. The tin-silver brazing rod with maximum brazing temperature 450 °F was used. The fiber glass maximum continuous operating temperature is 1200 °F. The instrumentation wires were installed. The hi-pot test was performed. The leak check and pressure test were performed to qualify the welds. The maximum allowable working pressure of the current leads assembly and focusing lens helium box is equal to 59.5 psig. The current lead assembly was purged with dry nitrogen to remove moisture and vacuumized afterwards.

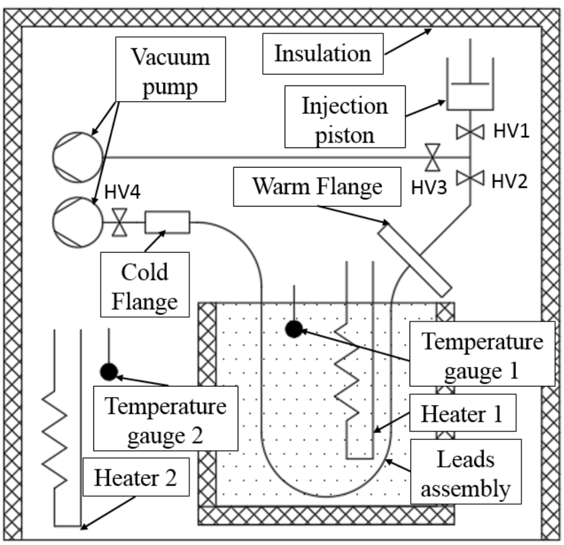

Figure 4: Current Leads Epoxy Filling Scheme.

The STYCAST 2850FT was used to encapsulate copper conductor. The CAT 23LV was used as a catalyst. The manufacturer listed product benefits: thermally conductive, electrically insulative, low CTE, low viscosity, long pot life, excellent thermal shock and impact resistance, excellent low temperature properties. The design aims to maximize thermal performance (low heat load at 2 K), make leads assembly electrically insulative and leak tight. Making the epoxy layer thinner to reduce thermal resistance at intercept zones will increase complexity during filling and chances of high voltage brake at tube bending regions during quench. Making the epoxy layer thicker to facilitate the manufacturing process will make assembly envelope bigger, increase thermal resistance and chances to occur epoxy crack during cool down-warm up process. To keep epoxy layer thickness at 0.6 mm suction and injection was used during filling process. The transparent tube was used to calibrate required amount of injection force. The overall length 1.5m requires to keep epoxy viscosity low. In order to achieve it the epoxy was preheated to 140 °F before filling process and the lead assembly was submerged into hot water at 140 °F during filling process (Fig. 4, Fig. 5). The filling manifold was vacuumized individually for each stainless steel tube and fill out with epoxy one by one. The 150 °F curing for 4 hours was used in order to achieve full penetration epoxy inside the fiberglass sleeve.

Figure 5: Current Leads Epoxy Filling Fixture.

CONCLUSION

The SSR1 prototype current lead assembly was manufactured and tested at Fermilab. Procedures to successfully prepare additional four units for SSR1 cryomodule are understood and the plan is to prepare all four units and integrate them into the cold mass assembly by end of CY 2019.

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