ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP089

FRIB LS1 CRYOMODULE'S SOLENOID COMMISSIONING*

M. Xu†, H. Ao, B. Bird, R. Bliton, C. Compton, J. Curtin, L. Hodges, K. Holland, S. Miller, K. Saito, T. Xu and C. Zhang, Facility for Rare Isotope Beams, Michigan State University, East Lansing, USA

Abstract

The Facility for Rare Isotope Beams (FRIB) is a heavy ion accelerator that produces rare isotopes for science. To achieve the high beam quality of FRIB's linear accelerator (linac), the superconducting solenoid packages are employed for beam focusing and steering in the cryomodule. The solenoid packages will generate a maximum 8T focusing field along beam direction and 0.124 T bending field for beam steering. A total 74 solenoid packages have been produced and the first segment linac (LS1) of FRIB have completed commissioning and beam acceleration. In this paper, the cryomodule's solenoid commissioning and the performance of the LS1 linac are introduced. The lessons learned during the testing will also be presented.

INTRODUCTION

The Facility for Rare Isotope Beams will be a powerful scientific facility for making discoveries about fundamental nuclear physics and exploring applications for society by way of experiments on harvesting rare isotopes, which are produced through high speed heavy ions striking a target [1].

All kinds of species ions from proton to uranium can be accelerated to 200 MeV/u by a paperclip shaped superconducting linac, which is expected to have completed construction by 2021. The first section of linac (LS1) has successfully completed assembly, commissioning, and accelerating a few species to > 20 MeV/u at 2019 [2].

In particle accelerators, the application of superconducting solenoids can provide higher focusing gradients. As the existing cryogenic system for superconducting cavity in FRIB, integration of the solenoid with the cavity in the cryomodule is the most practical option. With development over recent years, the technology of combining the steering field with the solenoid in one package is mature. The FRIB solenoid package structure took this configuration and the coldmass of the package is shown in Fig. 1.

There are two transverse steering fields and focusing solenoid field in beam direction in one solenoid.

There are two types of cryomodule installed in LS1: three 0.041 cryomodules and eleven 0.085 cryomodules. Two types of solenoid package are used in the LS1 linac: two 250 mm solenoid packages are installed in a 0.041 cryomodule [3] and three 500 mm solenoid packages are integrated in a 0.085 cryomodule. And each of 0.29 and 0.53 cryomodules in LS2 and LS3 only include one 500 mm type solenoid package.

* Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661 and the National Science Foundation under Cooperative Agreement PHY-1102511.
† xum@frib.msu.edu

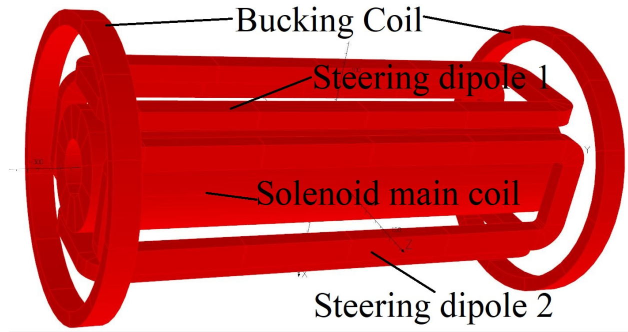

Figure 1: The solenoid structure of FRIB.

The two types of solenoid packages shared most of the same features.

SPECIFICATION

The FRIB beam optical requirements have given clear definitions on the solenoid package's basic parameters [4]. The detailed data is show in Table 1.

Table 1: Solenoid Package Parameters

	0.041 Cryomodule	**0.085, 0.29 and 0.53 Cryomodule**
Aperture	40 mm	40 mm
Solenoid integrated square Strength	13.6 T^2m	28.2 T^2m
Length	250 mm	500 mm
Maximum magnetic field	8 T	8 T
Steering magnetic field	0.12 T	0.12 T
Steering integrated field-strength	>0.03 Tm	>0.06 Tm
Solenoid Current	90 A	90 A
Steering Current	19 A	19 A

Figure 2 shows the 0.085 cryomodule layout of FRIB. solenoid packages (4.5 K) and cavities (2 K) are in separated helium cooling lines. The liquid helium to the solenoids is supplied from the bottom inlet and flows out to the top 4.5 K header, which is shown as blue pipes. The cavities are cooled from the 2 K helium header as show in green pipes. Cavities are surrounded by local magnetic shields to protect exposing the earth shield and the strong fringe field to the solenoid packages.

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP089

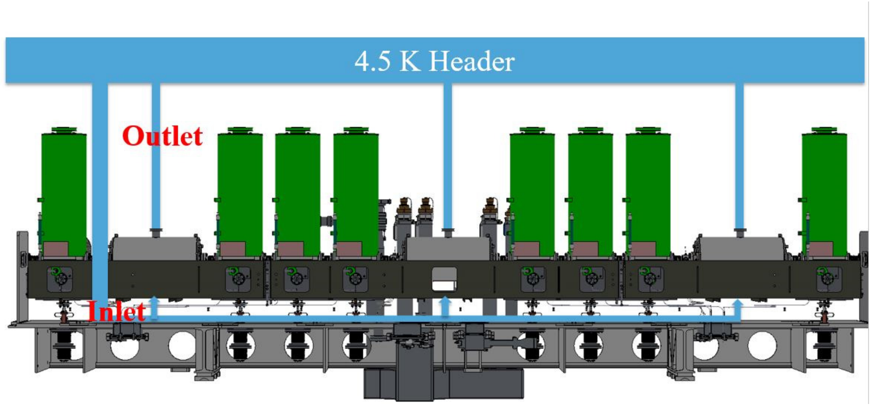

Figure 2: 0.085 Cryomodule layout of FRIB.

SYSTEM INTEGRATION

To make the solenoid package work in the tunnel, a few other systems needed integration with cryomodule, such as the current supply, cryogenic, and control system. The assembly and integration of LS1 has been conducted in two stages, the first stage included the three 0.041 cryomodules and the second stage the eleven 0.085 cryomodules.

The basic schematic related to solenoid integration is show in Fig. 3. The cooling circuit of the solenoid package is a part of the cryomodule 4.5 K system. During the cooldown, the 4.5 K liquid helium is injected from the bottom inlet of the solenoid package jacket. The helium gas is extracted from the solenoid top outlet to the 4.5 K header. When it is cooled enough, the liquid helium comes into the jacket from both the inlet of the jacket and the outlet of the 4.5 K header. The only controllable cryogenic valve is for the vapour cooling of the current leads. The helium gas comes to the top of 4.5 K header through the lead cooling channel to the outside of cryomodule return pipe.

Cooling leads by cold vapour will save a few hundred watts off of the 4.5 K cryogenic heat load through the current leads, as one vapour-cooled lead can reduce sink heat by a few watts. One solenoid package has six leads in total: solenoids two, two each dipole. The vapour cooling makes it possible to reduce a lot of sink heat for all FRIB cryomodule (several hundred watts). The solenoid and steering dipole leads are combined just in one cooling gas channel [5].

The solenoid current supply will provide 100 A maximum current and 6 V maximum voltage. The two steering dipoles current supply will provide maximum 20 A current. To achieve the maximum magnetic field, the needed current is 90 A and 19 A for solenoids and steering dipoles, respectively. Each current supply has a dump resistor for magnet protection during an open circuit.

There are a bunch of signals that need to be monitored during solenoid operation: the 4.5 K temperature sensor in the solenoid, the 4.5 K header pressure, and the liquid helium level are related to the solenoid's cryogenic environment. Current lead voltages are controlled to protect the lead from burning out. Lead can temperature control is to protect icing at the helium gas return line around the top of the can during operation. The vapour lead cooling gas valve control will deduce the lead voltage and lead can temperature. The current supply's water flow and temperature reading will be delivered to the control PLC for protection too. The cryomodule insulation vacuum and beam line vacuum are also monitored during solenoid operation.

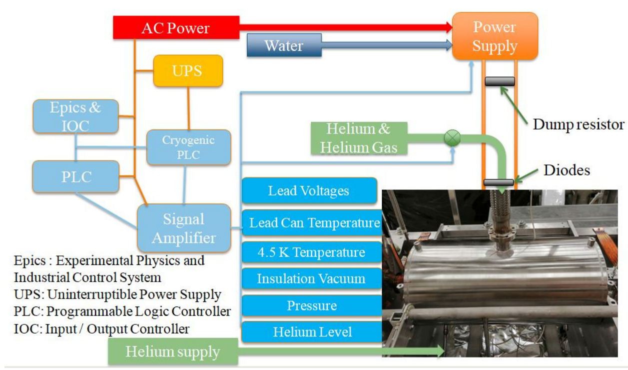

Figure 3: The solenoid's integration schematic with current supply, cryogenic and control system.

COMMISSIONING

The commissioning of the LS1 solenoids has been conducted one by one in each cryomodule. The necessary checking, testing and optimization has been proceeding during this stage. The detailed procedures are as follow:

1. Walking through the cryomodule and visually checking.
2. Control panel parameter setting up and checking.
3. Small current checking, monitoring ramp current ration and interlock setting.
4. Ramp up to high current for thermal imaging checking at the cable connection located on the top of the cryomodule.
5. Ramp up to current for magnetic field polarity checking.
6. Lead flow control parameters optimization.
7. Solenoid stabilization testing for long operation.

Magnet polarity is important for beam comissioning. A gauss probe is used to measure the fringe field outside the

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP089

cryomodule for each solenoid/dipole during ramp-up current. The fringe field pattern of the solenoid and steering dipoles are different and they are carefully checked for confirming the polarity. During the testing, a few mixed up cable connection were noticed and corrected.

The solenoid lead is cooled by the helium gas vapour from 4.5 K header. The gas flow is controlled by two parallel valves, a manual one connected to the gas cooling line and an automatic one on the bypass line. Lead voltages and lead can temperature are the indicator parameters to control the automatic valve. The model is: lead voltages go up, turn down the valve (increases the gas flow in the gas cooling line); lead can temperature goes up, turn up the valve (decrease the gas flow in the gas cooling line). The automatic valve control is balanced by these two factors. During testing, a few parameters are adjusted to make the valve much more fit to the temperature and voltage's changing. The typical example of adjusting the lead flow valve control is shown in Fig. 4 for the CB10 cryomodule.

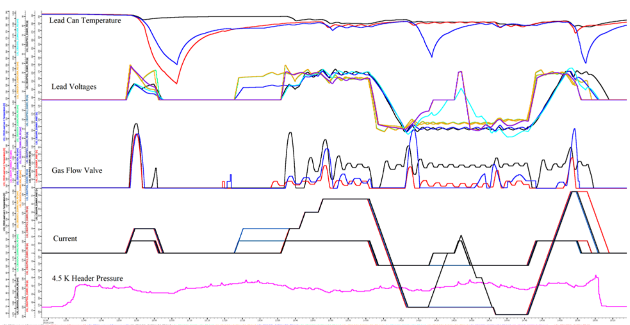

Figure 4: The CB10 solenoid's commission details.

The pressure difference between 4.5 K header and warm return pipes causes the cold helium gas flow through the current lead. The 4.5 K header pressure of CB10 shows that it has been pressurized about 0.1 bar during the testing. Under normal pressure, it doesn't cool the leads enough for full current operation. The valve spring force needs to be adjusted after pressurized. As we can see from the Fig. 4, the lead can temperature dropped to near 240 K because the spring force of the valve can't support valve turn off.

To simplify all cryomodule controls, all LS1 cryomodule's 4.5 K pressure has been increased 0.1 bar from the cryogenic system.

One of the CB11 solenoid current supplies was shut down during change the setting current due to an internal unstable current supply. The details are shown in Fig. 5.

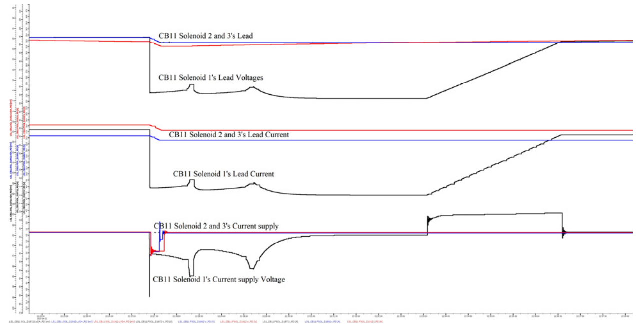

Figure 5: The CB11 solenoid's commission details.

As shown, the current supply turns off and on in a short time. When it's off, the protecting diode becomes open. Current in the solenoid goes through the diode and the magnet stored energy is consumed in the helium. The current reading from current supply shows a sharp drop from 42 A. The helium level drops about 1%, which corresponds to the vaporizing helium of 5 L. It's roughly equal to most stored energy of solenoid (13 KJ) that has been consumed in the liquid helium.

In the beginning, the dump resistor located in the current supply was used to discharge the stored energy. Considering the vapour cooling lead has a weak point for the open circuit, adding a circuit loop, even without the lead, is necessary. So a pair of diodes in opposite directions was added to the solenoid in parallel within the helium vessel. This design change will protect the solenoid even in the worst case, but most stored energy will be consumed in the liquid helium. The 4.5 K helium volume is enough to handle the small amount of stored energy. This current supply was replaced at the end of testing.

During the commissioning testing, a few of the interlock parameters were optimized. The cooling water pressure jumping of the current supply caused a few of the cryomodules to shut down operation. A delay time was added to avoid such false alarms shut downs.

The cryomodule position alignment actually exceeded expectations, most of the steering dipoles needed no ramp up to the design value (design maximum current 19 A, actually less than 5 A). To prevent error, all steering dipole current is limited to 5 A, from the point of the protecting cavity by steering beam.

PERFORMANCE DURING BEAM COMMISSON

The first section of the FRIB driver linac LS1 has been commissioned and beam has been accelerated to > 20 MeV/u, which meets the requirement. All the LS1 solenoids have been ramped up during the beam commissioning to supply sufficient focusing and steering magnetic field. The solenoid only uses 72% (65A) of the full current capability to focus the beam. The steering dipoles only use 15% of the full current. The typical current (CB01) is shown in Fig. 6 during beam commissioning. No quench events happened due to the solenoid. One failed power supply and one helium level monitor have been quickly replaced. The solenoid vapour cooling lead shows very stable

ISBN: 978-3-95450-211-0 doi:10.18429/JACoW-SRF2019-TUP089

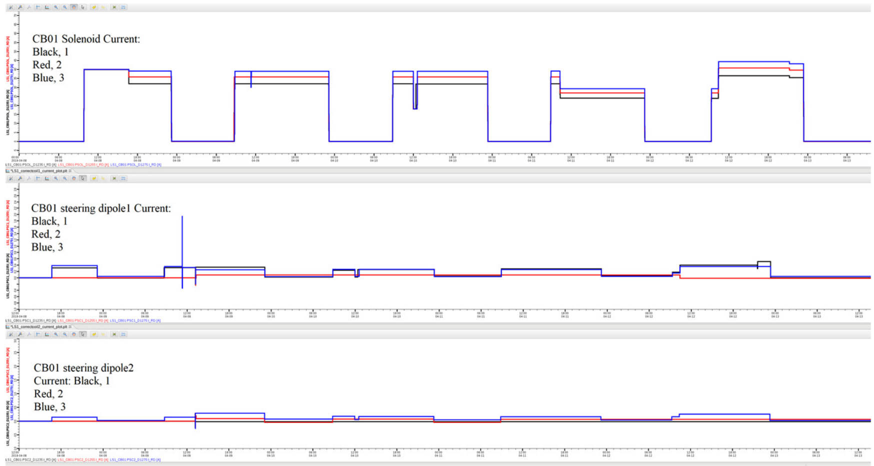

Figure 6: CB01's solenoid ramped current during beam commissioning.

automatic control, there is no need of operator adjustment at all.

CONCLUSION

All the LS1 solenoid packages have completed the necessary commissioning and configuration. During the beam commission for LS1, all solenoid packages showed stable and repeatable control. This testing shows that the solenoid packages are ready for supporting future nuclear experiments. The lessons learned and procedure experiences are valuable for future LS2 and LS3 commissioning.

ACKNOWLEDGEMENTS

We would like to thank the FRIB cryogenic department's support of the LS1 solenoid commissioning.

REFERENCES

[1] Thomas Glasmacher et al., "Facility for Rare Isotope Beams Update for Nuclear Physics News", *Nuclear Physics News*, Vol. 27, No. 2, 2017.

[2] J. Wei *et al.*, "The FRIB SC-Linac - Installation and Phased Commissioning", presented at the 19th Int. Conf. RF Superconductivity (SRF'19), Dresden, Germany, Jun.-Jul. 2019, paper MOFAA3.

[3] Y. Yamazaki et al., "FRIB Driver Linac Beam Optical Element Requirements", FRIB, East Lansing, MI, USA, Rep. FRIB-T31201-SP-000019-R003, March 2014.

[4] T. Xu *et al.*, "FRIB Cryomodule Design and Production", in *Proc. 28th Linear Accelerator Conf. (LINAC'16)*, East Lansing, MI, USA, Sep. 2016, pp. 673-678. doi:10.18429/JACoW-LINAC2016-WE2A02

[5] M. Xu et al., "Development of vapour cooling Current leads for FRIB cryomodule", submitted for publication