ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLM71

THERMAL PERFORMANCE OF FRIB CRYOMODULES *

M. Xu†, W. Chang, C. Compton, A. Ganshyn, S. Kim, S. Miller, J. Popielarski, K. Saito and T. Xu,
Facility for Rare Isotope Beams, Michigan State University, East Lansing, USA

Abstract

Now SRF cavity development is advancing high-Q/high gradient by nitrogen doping, infusion, or the new low temperature bake recipe. Once cavity dynamic loss is reduced, the static heat load of the cryomodule will be of concern from the cryogenic plant capability point of view. FRIB gives us a good chance to statistically compare the cryogenic plant design and the measured results, along with a thought for future updated cryomodule design using a low/medium beta cryomodule. FRIB cryomodules have two cooling lines: 4.5 K for solenoids and 2K for cavities. The boil-off liquid helium method was used to measure the cryomodule's heat load. So far, FRIB has completed certification testing (bunker tests) on 39 of 49 cryomodules (80%). This paper reports the static heat load measurement results, which are important for future FRIB upgrades to estimate remaining cryogenic capability. The cryomodule's evolution related to heat load is introduced too.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a rare isotopes research centre under construction at Michigan State University, USA [1]. A superconducting accelerator is used to produce rare isotopes for energy conservation, as compared to a normal conducting accelerator. There are 15 Quarter-Wave Resonator (QWR) cryomodules and 31 Half-Wave Resonator (HWR) cryomodules that will be deployed in the FRIB tunnel, along with three backup cryomodules that will serve as replacements [2].

The dynamic and static heat load of the cryomodules consumes the most capability of the cryogenic plant. For validating a cryomodule's performance, the dynamic and static heat load of the cryomodules was tested during bunker testing stage. Currently, 39 of 49 cryomodules (80%) have been tested, which is enough to estimate the difference between the cryomodule's total heat load requirements and the cryogenic plant's capability.

To preserve the high clean surface necessary for the cavities, the FRIB cryomodules have two separate vacuum systems - a beam line system and an insulating system. A section view of a cryomodule is shown in Fig. 1. The cryomodule uses a three cooling line system comprising a 38 K helium gas line for thermal shield, a 4.5 K liquid helium for supporting rail and solenoid, and a 2 K liquid helium for cavity.

* 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

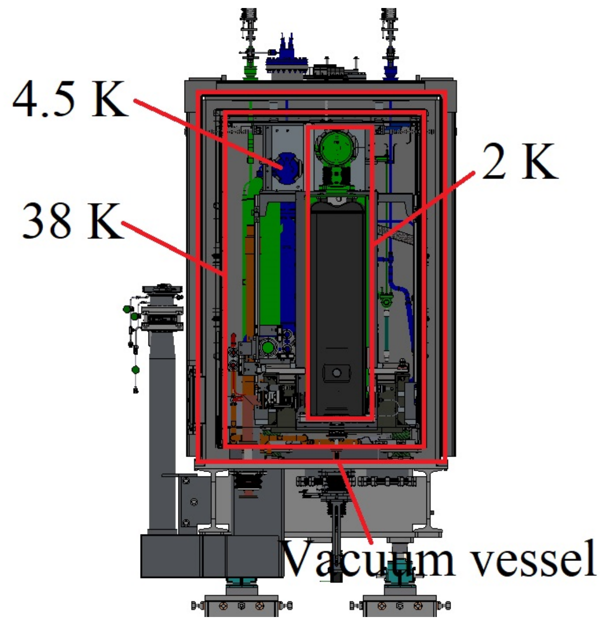

Figure 1: The section view of 0.085 cryomodule of FRIB.

Many methods are applied to reduce heat leaking to the cryogenic temperatures within the cryomodules from the outside. Multilayer insulation is used on both sides of the thermal shield to reduce radiation heat transfer. Copper straps are used for heat interception such as in beam pipe, magnet shield, tuner, and coupler. The G10 material is used for heat insulation. Cold helium gas is used to cool the coupler and solenoid current lead. Attaching the instrument wires to the thermal shield was also used for temperature interception.

MEASUREMENT OF STATIC HEAT LOAD

The cryomodules were designed to operate at 2 K for bulk niobium cavities and 4.5 K for the superconducting solenoids initially. The method of boiling off liquid helium was applied to both the cooling systems for measuring the static heat load of the cryomodule. Helium's phase changing energy is a certain number if keeping a stable pressure in saturated temperature, which is known as the heat of vaporization. From the liquid helium consumption we can deduce how much heat leaks to the low temperature system. The helium volume was indicated by the helium level sensors. The relation between helium level and helium volume was calculated from the cryomodule Solidworks 3D model. During the measurement, pressure change was avoided, as this will cause the results to swing.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLM71

2k Header Heat Load Testing

There are two testing bunkers for cryomodules, and only the SRF high bay bunker has helium gas recycle during pump down to 2 K. So, for saving helium and reducing the pump down time, the 2 K header's static heat load testing was performed in a 4.5 K temperature. Otherwise, the heat transfer from 4.5 K to 2 K is tiny in the cryomodule too.

In the beginning, the 2 K head level was refilled to one number between 85% ~ 90%. FRIB's cryomodule 2K header structure enables this level to provide enough helium for performing heat load measurement and also maintain a certain safety margin. Then the 2 K header supply JT valve was turned off.

There are two return line systems for FRIB's cryomodule: a cold return line that will go back to the compress system, which is used for normal operation, and a warm return line that will go back to the gas storage system, which is used for cooling down. For static heat load testing, the warm return line is used as the pressure (1.05 atm) is lower than the cold return system (1.2 atm), which is closer to helium liquid/vapour pressure. The thermal shield supply and 4.5 K supply will keep normal operation as before. A typical measurement using this procedure is shown in Fig. 2, (in this example, 0.53 cryomodule SCM 504).

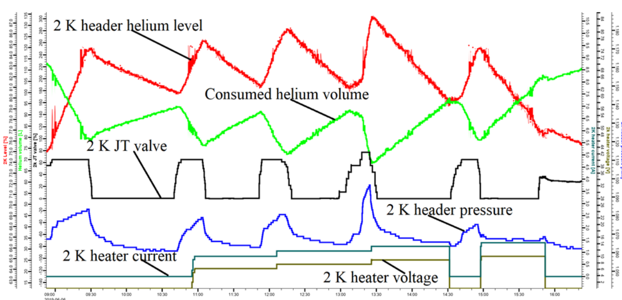

Figure 2: The 2 K header static heat load measurement of SCM 504.

The red line is the 2 K header helium level. Each time it will be decreased to 80% by boiling off, and the boiling off ratio will be used to calculate the static heat load. To reach a stable condition, a longer duration (typically a half hour) was used during the measurement. The header pressure is 1.105 bar. The helium vaporize energy ratio 0.698 J/L was used. For example, without turning on the 2 K heater power, the helium boil off ratio is 12.996 L/hour for SCM 504, the static heat load is 9.07 W.

In practical terms, the 2k header heater was used to calibrate the testing data. The 2 K heater is located inside the 2 K header, which is direct contact with liquid helium. It was designed to compensate for the 2 K system heat load change during operation. This heat swing makes it difficult to control the cavity. The heater's current and voltage can be obtained from the power supply, so the heater's power can be easy calculated. For cryomodule SCM 504, different heater power was turned on four times during heat load testing. The details of this testing are shown in Fig. 3.

The 2 K heater was turned on at a power of 5.2 W, 8 W, 11 W, and 14 W. The total heat load (heater power plus static heat load) can be calculated according the helium consumed. The trending line is shown as a consistent result with no heater power.

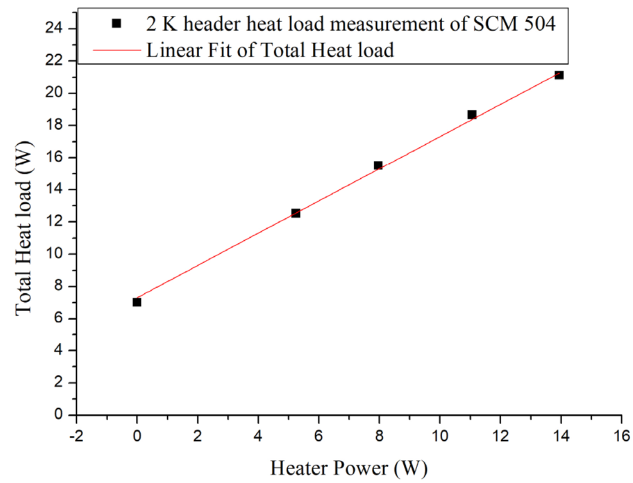

Figure 3: The cryomodule SCM 504 static heat load testing with 2 K heater calibrations.

4.5 k Header Heat Load Testing

The 4.5 K header's static heat load measurement uses the same boil off of liquid helium method as the 2 K header. During the testing, the 38 K thermal shield supply and 2 K header supply are kept on as part of normal operation. Only the 4.5 K header supply's JT valve was closed and the liquid helium was boiled off with time. The helium gas is returned to the warm return line. The testing details are shown in Fig. 4.

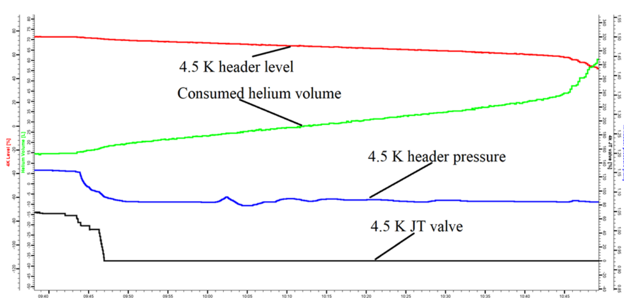

Figure 4: The 4.5 K header's heat load testing of cryomodule SCM 504.

The 4.5 K header pressure is 1.13 bar, the helium vaporize energy ratio is 0.69J/L. The helium consumed is 25.522 L/hour. So the 4.5 K header static heat load is 17.61 W for SCM 504.

TOTAL HEAT LOAD SUMMARY

Since 2015, when the first cryomodule started integration assembly, FRIB has completed 44 of 49 cryomodule assemblies (90%). Thirty nine cryomodule have completed the certification test. Most of the cryomodule static heat loads have been tested. The summary of 2 K header static heat load is shown in follow Fig. 5.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

ISBN: 978-3-95450-223-3 ISSN: 2673-7000 doi:10.18429/JACoW-NAPAC2019-WEPLM71

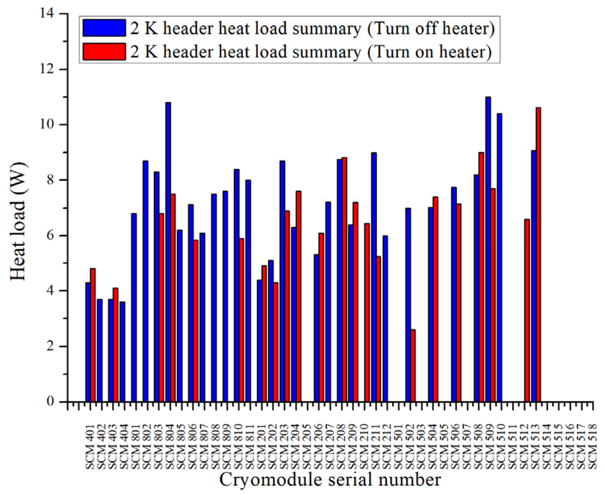

Figure 5: The 2 K header static heat load summary of FRIB cryomodule.

The serial number of SCM 4xx and SCM 8xx represents the beta 0.041 and 0.085 QWR cryomodules, and SCM 2xx and SCM 5xx represents 0.29 and 0.53 HWR cryomodules respectively. Only the 0.53 cryomodule is still undergoing bunker testing. Most of cryomodules' 2 K headers show an average 7 W static heat load. The 0.041 cryomodule shows about a 4 W static heat load, as their structure is a little smaller than the other type of cryomodule. There are a few cryomodules not measured the static heat load due to some unexpected reasons, such as schedule conflicts, cryogenic supply issues, or cryomodule issues.

The 4.5 K header static heat load is summarised in Fig. 6.

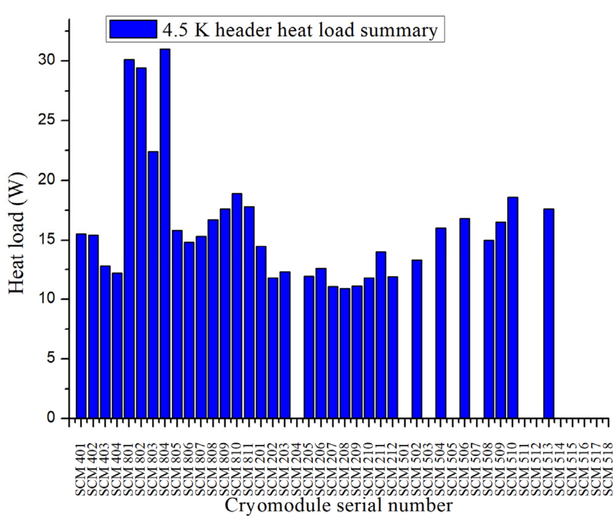

Figure 6: The 4.5 K header static heat load summary of FRIB cryomodule.

Normally it averages about 15 W. The first few 0.085 cryomodules show a high number because the measurement configuration is not consistent with the operation. FRIB's cryomodules have a superconducting solenoid for focusing the beam. The lead of the solenoid is designed with helium gas vapour cooling for reducing the heat load. During the first cryomodule testing, the closed vapour cooling line made the heat load show a few watts higher and the shorter test time induced a few watts higher too, as the system was not reaching a stable condition. During the testing of cryomodule SCM 805, the 4.5 K heater, which is located outside of the solenoid, was used to calibrate the testing result. It confirms the 4.5 K header static heat load is about 15 W.

DISCUSSION AND CONCLUSION

In the beginning, the estimate of the total cryogenic requirement was made by the principal source: 2 K heat load is 2.85 KW, 4.5 K heat load is 2.1 KW, and 38 K heat load is 13.1 KW. The cryogenic plant was designed based on these heat load requirements: the maximum 2 K mass flow is 180g/s, which means it is equal to 3.6 KW 2 K capabilities, 4.5 K and 38 K is 4.5 KW and 20 KW respectively.

The total dynamic and static heat load of FRIB cryomodules can be expected to be 1.2 KW in 2 K from the existing measurement data, which was estimated to be 2.35 KW in the requirement document. The gap between the measurement and the requirement is mainly due to the cavity surface processing development reducing the cavity's dynamic heat load. Even considering the proposed upgrade of FRIB cryomodules, which needs an additional 1 KW 2 K capacity, the cryogenic capacity of FRIB is adequate for use.

The total 4.5 K heat load of the cryomodules is estimated to be about 808 W from the existing measurement data, which does not exceed the required 1.2 KW.

The QWR cryomodule with a frequency of 80.5 MHz shows a potential to stably operate at 4.5 K for both cavity and solenoid, which was planned to work at 2 K for the cavity and 4.5 K for the solenoid [3]. The option of changing operation temperature for the QWR cryomodule will give more flexibility for cryogenic capability.

ACKNOWLEDGEMENTS

We would like to thank the FRIB control department's support of the cryomodule static heat load testing.

REFERENCES

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

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

[3] 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.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI