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PROGRESS IN FRIB CRYOMODULE BUNKER TESTS*

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Abstract

The Facility for Rare Isotope Beams (FRIB) is under construction at Michigan State University (MSU). The FRIB superconducting driver linac will accelerate ion beams to 200 MeV per nucleon. The driver linac requires 104 quarter-wave resonators (QWRs, β = 0.041 and 0.085) and 220 half-wave resonators (HWRs, β = 0.29 and 0.54). The jacketed resonators are Dewar tested at MSU before installation into cryomodules. All cryomodules for β = 0.041, 0.085, 0.29 and 5 cryomodules for β = 0.53 have been certified; 33 out of 49 cryomodules are certified via bunker test. All cavities tested at or above specified operating gradient. The bunker certification also completed 58 out of 74 solenoid packages. All the magnets energized at FRIB goal. In this paper, we report the bunker test result.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) driver linac is designed to accelerate ion beams to 200 MeV/u with 46 cryomodules. As seen in Table1 [1], there are six different types of FRIB superconducting cryomodules (SCM): SCM041 containing four β = 0.041 quarter-wave resonators (QWRs) and two solenoids, SCM085 containing eight β = 0.085 QWRs and three solenoids, SCM29 containing six β = 0.29 half-wave resonators (HWRs) and one solenoid, SCM53 containing eight β = 0.53 HWRs and one solenoid, SCM085-matching containing four β = 0.085 QWRs and SCM53-matching containing four β = 0.53 HWRs. The FRIB linac needs 49 cryomodules in total, including 3 spare cryomodules.

Table 1: FRIB Cryomodules Needed

β	Type	Component Counts (baseline + spares)		
		Cryomodules	*Cavities*	*Solenoids*
Quarter Wave Cryomodule				
0.041	accelerating	3 + 1	12 + 4	6 + 2
0.085	accelerating	11 + 1	88 + 8	33 + 3
	matching	1 + 1	4 + 4	-
Half Wave Cryomodule				
0.29	accelerating	12	72	12
0.53	accelerating	18	144	18
	matching	1	4	-
TOTALS		46 + 3	324 + 16	69 + 5

All cryomodules are installed with certified cavities. These jacketed FRIB cavities are etched, rinsed and Dewar test certified, then installed onto a coldmass in the cleanroom with RF couplers, tuners and solenoid packages together [2-7]. The coldmass is assembled into a cryomodule [8], then it will be put into a bunker for cryomodule performance certification.

Two test bunkers are to support FRIB cryomodule cold tests as shown in Figure 1. The ReA6 bunker is located in the NSCL (National Superconducting Cyclotron Laboratory) east high bay sharing the ReA3 re-accelerator cryogenic system. The ReA6 bunker can support all type cryomodules test, but has no closed circuit for 2 K operation. An SRF bunker is located in the SRF high bay building sharing the FRIB Vertical test cryogenic system [9]. The SRF bunker have a 2 K operation closed circuit, so 2 K long term cavity phase locking can be tested in this bunker. However, the SRF bunker only supports tests for SCM29, SCM53 and SCM53-matching cryomodules.

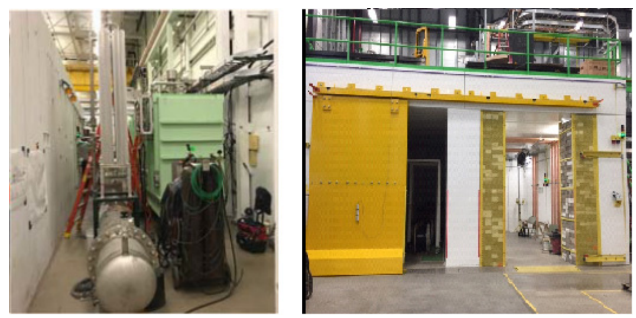

Figure 1: ReA6 Bunker (left) and SRF Bunker (right).

Until April 2019, all cryomodules for SCM041, SCM085 and SCM085-matching are tested and certified in ReA6 bunker; all SCM29 and five SCM53 cryomodules are tested and certified in two bunkers parallels. After bunker test certified, cryomodules are transported and installed into the FRIB linac tunnel.

CRYOMODULE BUNKER TEST

FRIB Cryomodule Test Goal

The FRIB cryomodules use 4 different types of superconducting cavities and 2 different length of solenoid packages. Specification parameters for cavities in cryomodule are shown in Table 2. Specification parameters for solenoid packages are shown in Table 3 [7].

The fundamental goal for bunker certification testing of cavities and solenoid packages is to meet specification parameters. In addition, tuning range of tuner and coupler temperature are measured and tested. During cavity test, the multipacting barriers and field emission conditioning are also important, and cavity operation stability which

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include tuner performance, amplitude and phase locking by LLRF control are also tested.

Table 2: FRIB Cavity Parameters in Cryomodule

Cavity Type	QWR041	QWR085	HWR290	HWR530
f (MHz)	80.5	80.5	322	322
Ea (MV/m)	5.1	5.6	7.7	7.4
BW (Hz)	43	41.5	57	33.3
QL	1.9E+06	1.9E+06	5.6E+06	9.7E+06
2K Dynamic heat load (W)	1.32	3.85	3.55	7.9
Qo_cryomodule	1.2E+09	1.8E+09	5.5E+09	7.6E+09

Table 3: FRIB Solenoid Packages Parameters

Packages	Maximum field on axis	Ramping rate	Current
25 cm solenoid	≥8 T	≥ 0.3 A/s	≤ 91 A
25 cm dipoles	≥0.06 Tm	≥ 0.5 A/s	≤ 20 A
50 cm solenoid	≥8 T	≥ 0.3 A/s	≤ 91 A
50 cm dipoles	≥0.03 Tm	≥ 0.5 A/s	≤ 20 A

For all the above purposes to be met, the bunker test is divided into six parts: bandwidth and tuning range test, self-excited loop (SEL) high power test, locking test, 2K dynamic heat load measurement, solenoid packages test and static heat load measurement.

Bandwidth and Tuning Range Test

After cryomodule cool-down to 4K, the bandwidth (BW) and frequency tuning range of cavities will be tested first.

There are two way to measure the BW. Before transmission line connected to coupler, the vector network analyser (VNA) can be used for the BW measurement. Meanwhile, the S11, S21 parameters can be measured too, so Q_L, Q_{ext2} and cables calibration for the cavity should be calculated. After transmission line connected, the decay time way could be selected. The cavity will be excited to low field (we usually excited the cavity to 2 MV/m) at the central frequency, then turn off the RF to measure -6 dB power (that is -3 dB voltage) correspond time, so the BW can be calculated. The decay time way can be choice to verify the VNA way.

The tuning range test is to certify the performance of the tuner. The FRIB cavities use two type of tuners, the stepper motor tuner for QWRs and the pneumatic tuner for HWRs.

For stepper motor tuner, the frequency range can be measured by the motor moving through up and down mechanical limiter. For pneumatic tuner, the tuner bellow will be pressurised helium gas up to 45 PSI (bunker test maximum pressure) and released the pressure to 16 PSI (bunker test minimum pressure), so the frequency range should be get between minimum and maximum. Once the frequency range be measured at 4 K, correspond 2 K frequency range could be estimated by cavity pump-down sensitivity (cool-down from 4 K to 2 K) which based on vertical test result [3]. We will know if the frequency range can cover the operation frequency of the cavity or not and also how much the tuning margin it have.

SEL High Power Test

Cavity operation gradient Ea meet the specification is the core of the cryomodule performance. To verify the cavity performance in the cryomodule, we excited cavity up to 10% ~ 20% higher than specification gradient by (SEL) mode. The SEL mode is good for frequency tracking, so we can focus on cavity conditioning and Ea measurement. To increase cavity Ea, the forward power will be increased with small step to avoid producing too much X-rays during high barrier multipacting. Some cavities have field emission (FE), we use CW power or Pulse power to condition it. If the FE still strong at high field and cavity Ea already meet the specification, we will stop to increase RF power to avoid cavity de-conditioning. Figure2 is shown a typical SEL high power test Ea vs. X-ray plot. For this cryomodule SCM211 (S29 CM211 as shown in Figure 2), high barrier multipacting range from 2.2 ~ 4.5 MV/m, we keep X-ray level < 200 mR/hr during high barrier multipacting conditioning; cavity5 have FE at high field, since the gradient already reached 8.0 MV/m (3.8% higher than specification) and X-ray was 2.0 mR/hr, we stopped at here, other cavities were excited up to 9.0 mR/hr (16.8% higher than specification) without FE.

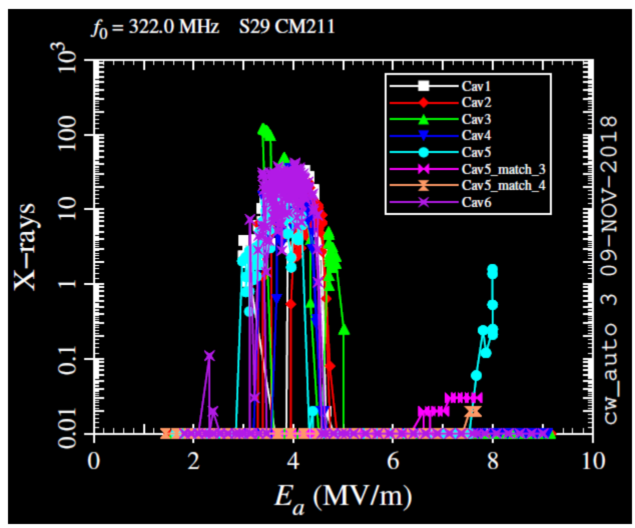

Figure 2: SEL High Power Test Ea vs. X-ray (SCM211).

At maximum power which is we got the final cavity gradient, the coupler temperature status also be verified. The temperature high limit interlock had been set before test, so the PLC will trip the RF system when the coupler temperature reach the limit.

Locking Test

The cryomodule operation stability is the second core of the cryomodule performance. We check cryomodule instability which could came from microphonics or tuner operation before the cryomodule install into the tunnel.

For type SCM041, SCM085, SCM085-matching and SCM029 cryomodule, we did amplitude and phase locking

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test at 4 K and cavity was operated at specification gradient. For type SCM530 cryomodule, the S53 HWR cavity heat load is much larger than other types cavity at specification gradient at 4 K, estimated heat load is more than 120 W (correspond Q0 < 1.02E9 @ 7.4 MV/m) , this heat load will make bath liquid very boiling and also make cryogenic system very unstable, cavity cannot lock at this status. So we lock S53 HWR cavity at 5.6 MV/m (estimated heat load is 70 W) at 4 K or pump-down to 2 K to do locking test. We only have the SRF bunker to support 2 K locking test as mentioned above.

All cavities in the cryomodule are proceed locking test at specification gradient more than 1 hour. If no trip happens, the cavity will be certified by locking test with cavity voltage amplitude < ±1% and phase ±1° condition.

2K Dynamic Heat Load Measurement

The cavity 2 K dynamic heat load is based on helium bath pressure measurements. When helium supply and return line's valve of the cryomodule be closed, the 2 K header helium bath as shown in Figure 3 is an adiabatic system (green part). The cavity heat or heat from heater dumping to the helium bath will convert to the internal energy change which can make the bath pressure change. The bath pressure change will be measured with 3 conditions: 1) cavity RF of and heater off, 2) cavity RF on at operation gradient but heater off, 3) cavity RF off but heater turn on at a fixed value. We can get different pressure increase slope from these different conditions. And the condition 2) the cavity RF on heat off is the 2 K dynamic heat load, which can be calibrated by condition 1) "no heat load zero watts" and condition 3) "explicit heat load from heater fixed watts".

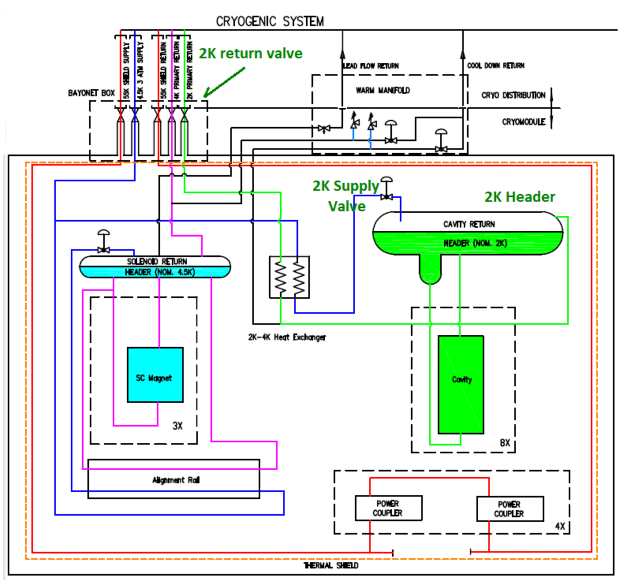

Figure 3: Simplified diagram of the cryogenic system for the cryomodule [10].

Solenoid Packages Test

Solenoid packages certification test is proceed after RF cavity test done. The procedure of solenoid packages test as shown in Figure 4. Magnets can be energized individually first (Individual Energizing), the polarity of each magnet can be check too. Then the solenoid and dipoles are energized and operation together (Mutual Test). After that, the closest pair of SRF cavities will be excited up to specification gradient with energized magnets operate simultaneously (Integration Operation). The solenoid usually be energized ≤ ± 91A, dipoles are energized ≤ ± 19A. The solenoid packages should be verified if no trip by magnet quench, cavity RF trip, temperature limit or vacuum limit during this certification test.

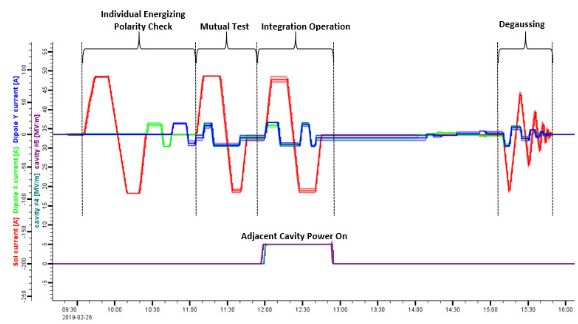

Figure 4: Typical solenoid package test procedure.

Static Heat Load Measurement

The static heat load measurement contain 2K header (which shown in Figure 3 green part, cavities' header) heat load and 4K header (which shown in Figure 3 left part, solenoid packages' header) heat load. The method of boiling off liquid helium is used for the static heat load measurement. Which means the heat load can be calculated from liquid helium consumption. The 2K header and 4K header static heat load is tested separately. For 2K header heat load measurement, sometimes the 2K heater could be turn on for calibration purpose.

BUNKER TEST RESULT

Until April 2019, the FRIB cryomodule bunker certification progress is shown in Table 4. For FRIB linac operation purpose, all SCM041, SCM085, SCM085-matching and SCM29 cryomodules were certified, 27.8% SCM53 cryomodules were certified. About 69.6% in totals were done, if including spare cryomodules 67.3% were done.

Table 4: FRIB Cryomodule Bunker Certification Progress (until April 2019)

FRIB Cryomodule Type	Certified|Operation Need	Completed (include spare)
SCM041	3+1|3+1	100% (100%)
SCM085	11+0|11+1	100% (91.7%)
SCM085-matching	1+0 | 1+1	100% (50%)
SCM29	12|12	100% (100%)
SCM53	5|18	27.8%
SCM53-matching	0|1	0%
Totals	32+1|46+3	69.6% (67.3%)

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Figure 5 shows cavity BW measurement result and compare with specifications for FRIB cryomodules. Average BWs for FRIB 4 type cavities are 39.0 Hz for SCM041, 36.7 Hz for SCM085, 67.9 Hz for SCM29 and 28.7 Hz for SCM53. Although results have offset with specification numbers, they are still acceptable for operation. In Figure 5, we can find some cavities' BW are far from specification and average. That because some cavities have microphonics issue, those cavity couplers were adjusted coupling to get broader BW to fix the issue.

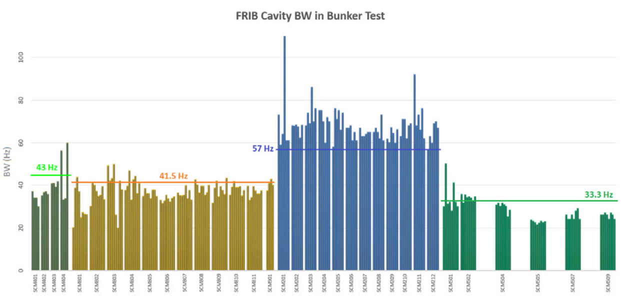

Figure 5: Cavity BW Measurement Result (until April 2019).

Stepper motors tuning range measurement result is shown in Figure 6. Some cavities in type SCM041 cryomodule tuning range cannot cover the operation frequency (80.5 MHz), we did some rework procedure for these out of range tuner to fix tuning range after bunker test. And some SCM085s cavity maximum frequency are too close to the operation frequency. These cavities have tuner operation issue during commissioning in tunnel [11]. We replaced original step motor to bigger one to increase tuning range to solve this issue.

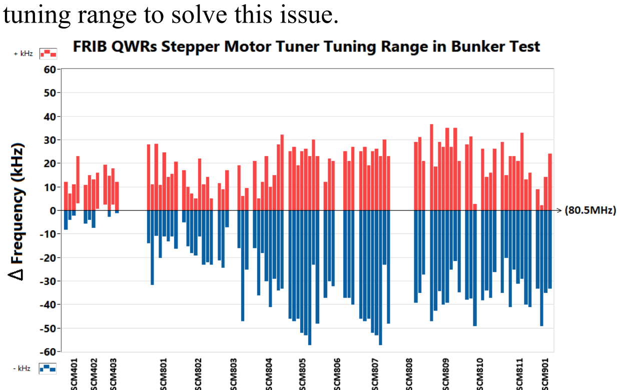

Figure 6: FRIB QWRs Stepper Motor Tuner Tuning Range in bunker test, Operation Frequency 80.5 MHz, Frequency Range Unit: kHz (until April 2019).

For pneumatic tuner, we measure tuning range at 4K, then calculated helium pressure requirement at 2K. Required pressure for each cavity is seen in Figure 7. A few pneumatic tuners require more than 45 PSI over the bunker supply pressure up limit. In the FRIB tunnel, the helium supply line can support up to 60 PSI pressure, so all these cavities still can be operated at specification frequency 322.0 MHz in the tunnel. In bunkers or the FRIB tunnel, the helium line pressure down limit is based on the cryogenic helium return pipe pressure, it is a litter bite higher than one atmosphere (about 16 PSI). All these cryomodules pneumatic requirement pressure are higher than helium supply down limit (until April 2019).

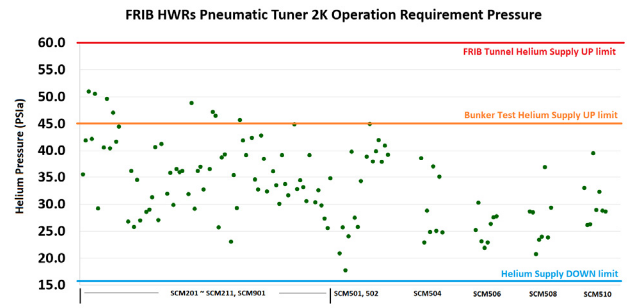

Figure 7: FRIB HWRs Pneumatic Tuner Requirement Pressure for Specification Frequency at 2K (until April 2019).

Figure 8 shows operation gradient Ea of each cavity in bunk test. All cavities Ea (blue bar) meet the specification gradient (green line), some cavities have FE, and FE onset level (red spot) is shown in this Figure. FE X-rays at specification operation gradient and maximum gradient is seen in Figure 9. The pink bar is X-ray level at cavity specification Ea, the blue bar is at maximum Ea measured X-rays. A few cavity have high FE at high gradient, rest FE cavities have moderate X-ray level.

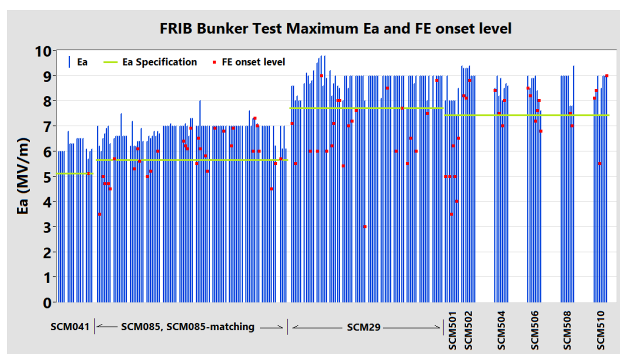

Figure 8: FRIB Cryomodule Bunker Test (until April 2019), Maximum Ea and FE onset level.

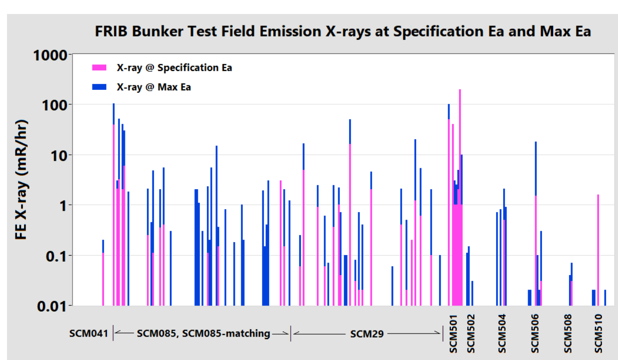

Figure 9: FRIB Cryomodule Bunker Test (until April 2019), Field Emission cavity X-rays at Specification Ea and Max Ea.

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About cavity locking test, every cavity was amplitude and phase locked by LLRF controller [12] at least one hour at specification Ea or 1~10% higher than specification Ea in bunkers. All tested cavities voltage amplitude and phase stability can satisfy FRIB linac operation requirement (amplitude < ±1% and phase ±1º).

For 2K dynamic heat load measurement, we usually operated two cavities at specification gradient to measure heat load. The dynamic heat load statistic result of all certified cryomodules is shown in Figure 10. SCM402, SCM403, SCM803, SCM807 and SCM901 2K dynamic heat load were estimated numbers (hollow bar in figure), they all meet the specifications; SCM810 dynamic heat load measurement was skipped; others are all good to satisfy the FRIB cryomodule dynamic heat load requirement.

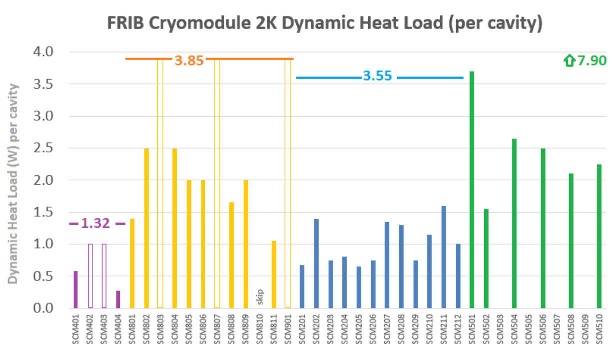

Figure 10: FRIB Cryomodule 2K Dynamic Heat Load Measurement Results, Unit: Watts per Cavity (until April 2019).

Solenoid packages test certification statistics is seen in Table 5, all magnets were certified by testing procedures with no issue.

Table 5: FRIB Cryomodule Solenoid Packages Certification (until April 2019)

CM Type	Number of CM finished	Solenoid package length (cm)	Number of solenoid package per cryomodule	Completion status
SCM041	4	25	2	No quench; specification passed.
SCM085	11	50	3	No quench; specification passed.
SCM29	12	50	1	No quench; specification passed.
SCM53	5	50	1	No quench; specification passed.

Static heat load measurement result is shown in Figure 11 (2K header heat load) and Figure 12 (4K header heat load).

SUMMARY

Until April 2019, 69.6% (67.3% include spare) FRIB cryomodules were certified by bunker test. All certified cryomodules are satisfied with FRIB specifications. All type QWRs cryomodules were already installed into the FRIB tunnel for beam commissioning [13], and other certified cryomodules are ready for tunnel installation.

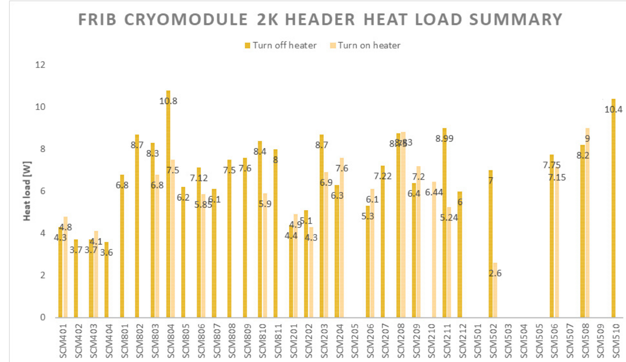

Figure 11: FRIB Cryomodule 2K Header Static Heat Load measurement result (until April 2019).

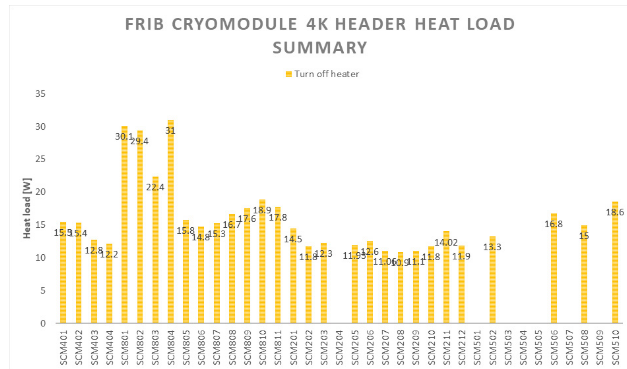

Figure 12: FRIB Cryomodule 4K Header Static Heat Load measurement result (until April 2019).

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