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UPGRADES TO CRYOGENIC CAPABILITIES FOR CRYOMODULE TESTING AT JLAB

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Abstract

The cryogenic facilities for cryomodule testing at Jefferson Lab (JLab) have been modified and to enable testing of Linear Coherent Light Source-II (LCLS-II) cryomodules. Temporary changes in u-tube connections at the Cryogenic Test Facility (CTF) has enabled rates of cavity cooling that are a factor of 10 higher than previously achieved. Cryogenic connections at JLab's Low Energy Recirculator Facility (LERF) have been repurposed to enable two LCLS-II cryomodules to be tested in series. This testing shares the helium space with the Central Helium Liquefier (CHL) that is also used by the Continuous Electron Beam Accelerator Facility (CEBAF). Cryomodule testing can occur while beam operation is ongoing at CEBAF. Improvements to these facilities have allowed the testing of the JLab's highest ever performing cryomodules.

INTRODUCTION

A total of 35 LCLS-II cryomodules are being assembled at JLab and the Fermi National Accelerator Laboratory (FNAL), to be installed at the Stanford Linear Accelerator Center (SLAC). The final part of the fabrication sequence is acceptance testing at the operating temperature of 2K. At JLab, the CMs are primarily tested at the Cryomodule Test Facility (CMTF). Due to schedule constraints, cryomodule testing was also started at the LERF at JLab.

Initial testing at the CMTF found the Q values to be far lower than that achieved during individual cavity testing in the Vertical Test Area (VTA), and lower than that specified at SLAC. The low Q values were attributed to trapped magnetic flux in the cavities, to which they are very sensitive. Testing at FNAL determined a direct correlation between the Q value and speed at which the cavities are cooled through the transition temperature of niobium (9.25K) [1]. Efforts were started at JLab to improve the cooldown speed of the cryomodules in the CMTF.

BACKGROUND

CMTF

The CMTF was commissioned in 1988 for testing the original CEBAF C20 cryomodules [2]. Since then, the facility has tested the reworked C50 and upgrade C100 cryomodules, as well as SNS high-β and medium-β cryomodules. Most recently, it has been refitted for testing LCLS-II cryomodules.

The cryogens are supplied by the CTF which is located in the same building. CTF has a refrigeration capacity of 650 W for the 4.5K primary supply (using the newly installed Cold Box 3) and 1kW for the 40K shield supply [3]. In addition to the CMTF, CTF also supplies cryogens to the VTA, which has eight dewars for testing individual cavities, and the Upgrade Injector Test Facility (UITF). A lack of cryogenic capacity usually means that no two of the facilities can function together unimpeded.

LERF

The LERF was formerly known as the JLab Free Electron Laser (FEL). It consisted of three cryomodules and an injector cryomodule, with its cryogenic supply coming from CEBAF's CHL. The production bottleneck at the CMTF and the increased cryogenic capacity of the CHL lead to the LERF being used for cryomodule acceptance testing.

One of the cryomodules was removed from the LERF and the cryogenic connections were used to supply two LCLS-II cryomodules in series. These cryomodules could then be tested using the same helium space as the CEBAF South Linac. In addition, the LCLS-II cryomodule testing would be done in a layout akin to the first segment of the SLAC tunnel [4].

CRYOMODULE TESTING REQUIREMENTS

The testing requirements for LCLS-II cryomodules are outlined in the SLAC acceptance criteria document [5]. The major components include:

- Cavities are tested individually to determine their maximum usable gradient. This may be limited by factors such as quenching or field emission.
- Heat loads on the 2K, 5K and 50K lines are measured. Eight cavities running at 16 MV/m each should have a dynamic heat load of 80W.
- Qs are measured after a cavity temperature bump to 40K and fast cooldown (FCD)
- Multi-cavity runs; the acceptance criteria calls for all eight cavities to be run, but the current CMTF cryogenic capacity only allows four to be run at the design gradient at one time.

CMTF DESIGN

The CEBAF cryomodules for which the CMTF was designed have two independent helium circuits: the primary 2K circuit and the 40K shield circuit. LCLS-II cryomodules have an additional 5K shield circuit which cools the Fundamental Power Couplers (FPC) and quad-magnet. To make the most efficient use of the limited cryogenic helium supply, a 4K-2K heat exchanger was used in series with the primary supply circuit (Fig. 1).

The heat exchanger in question is derived from an experimental unit, which had been developed for the Facility for Rare Isotope Beams (FRIB).

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The helium is supplied from the Junction Box which is located in the CMTF cave. The 5K, 3 atm supply from the Junction Box first passes through the 5K circuit and then into the high-pressure side of the heat exchanger (where it is cooled to ~4.5K) and into the 2K supply line. The return from the 2K supply line goes through the low-pressure side of the heat exchanger and pre-cools the incoming 5K gas. The 2K liquid is made by the Joule-Thomson effect at the cryomodule JT valve.

The heat exchanger originally had a line built in place to bypass the low-pressure side to aid in cooldown and warm-up. It was found that the line's capacity was not high enough for the flow to fully bypass the heat exchanger.

As the 5K and 2K lines are in series, there was not an easy way to run one independent of the other. A bypass line (the vaporizer) was installed to allow flow through the 5K circuit while the valves to the 2K circuit were closed e.g. during Q measurements. As an added benefit, the vaporizer line could increase the flow through the main supply transfer line to stop the latter from warming up.

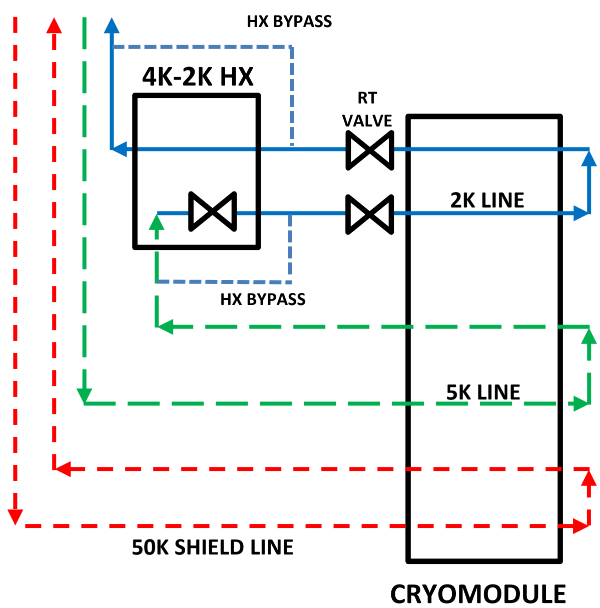

Figure 1: Cryogenic lines in the CMTF.

LERF DESIGN

The LERF had cryogenic connections for three cryomodules and one quarter-cryomodule. The central cryomodule was removed and replaced by a cryogenic transfer line, with bayonet stubs that connected to the existing cyro lines via u-tubes. The transfer line is attached to the Cryo Can which contains the valves and piping to supply the LCLS-II cryomodules.

The higher refrigerator capacity of the CHL means that a heat exchanger is not required in the LERF. Like the CMTF, the cryo connections in the LERF are designed for cryomodules with two lines i.e. the primary 2K line and the shield line. Here, the piping in the cryo can splits the 4K, 3.0 atm supply into the primary supply and the 5K shield circuits (Fig. 2). The 2K supply is fed back into the primary return, while the 5K circuit is mixed with the shield return line. Valves in the cryo can allow each circuit to run independently. A Coriolis flow meter is installed on each of the lines.

Being tied into the CHL also means that testing in the LERF is dependent on the operations of CEBAF. The LCLS-II cryomodules were only scheduled to cool down and warm-up with the rest of the cryomodules in the CEBAF South Linac. To allow for extra flexibility, a separate Cooldown Line and valve were installed in the cryo can which allows the primary circuit flow to be directed straight to the CHL recovery header. A 300K helium gas line is also installed to allow for temperature bumps and fast warm-up.

Each of the cryomodules in the LERF may be tested together or one at a time. The cryomodule furthest from the cryo can may also be uninstalled and replaced, keeping the main piping connections intact. Alternatively, the LERF may have only a single cryomodule installed and tested at one time.

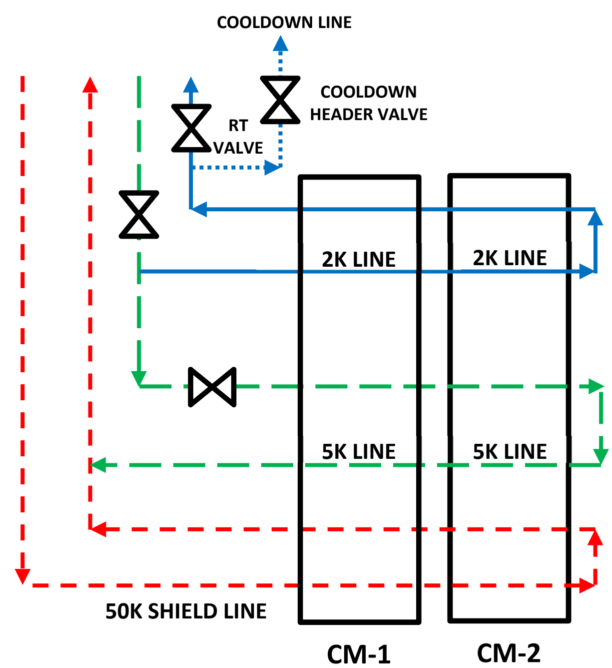

Figure 2: Cryogenic lines in the LERF.

TESTING OPERATIONS

Cryomodules are tested at JLab at 2.07K which is the operating temperature of CEBAF. The cryomodules are initially cooled and filled with liquid at 4K. The Kinney pumps in the CTF, or the sub-atmospheric cold box in the CHL, then lowers the pressure to 21 torr and produce superfluid helium at 2K. The results from cryomodule testing are corrected to 2.0K for LCLS-II cryomodules.

Cryomodules can be tested in the LERF during beam operation at CEBAF. As they share the same helium space, pressure and flow fluctuations in the LCLS-II cryomodules

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can cause cavity trips in CEBAF (especially in C100 cryomodules) or worse, trip the CHL itself. To date, the most strenuous activity on the CHL was the process of pumping the helium space down from 1.0 atm to 21 torr while the remainder of the South Linac was at 2K.

Q measurements in the CMTF rely on completely isolating the cryomodule helium space; this is achieved by closing supply and return valves (RT Valve). Heat output of the cavities are determined by comparing the pressure rise from a known heat input to that of cavity operation. The process has been the standard for all CEBAF and SNS cryomodules.

Standard Q measurements are not ideal in the LERF as the pressure fluctuations involved may disrupt the physics program. As the cryogenic supply from the CHL is far more stable than the CTF, the same concept of testing could be carried out in a steady-state method. Instead of closing valves, the supply valve is set to a value so as to maintain a constant liquid level. The heat generated by the cavities can then be determined using the rate of change in liquid level as an indicator.

UPGRADES FOR FASTER COOLDOWN

The first five cryomodules fabricated at JLab suffered from Q values well below the specification of 2.7e10. Trapped magnetic flux in the cavities were thought to be the cause. A method for expelling the trapped flux was rapid cooling through the niobium transition temperature (9.25K). At FNAL experiments were conducted with increasing the helium flow rates (30 g/s – 80 g/s) to obtain higher Qs [1]; a positive correlation was found between the flow rate (and hence cooling rate) and the cavity Q.

The CMTF has no reliable way to measure the helium flow rate through the cryomodule. The estimated liquefier mode capacity of CTF at the time was only ~5 g/s. The rate of cooling (K/min) would instead be used as a means of comparing cooldowns.

The production LCLS-II cavities have Cernox temperature sensors on the Cavity 1 and Cavity 5 helium vessels (top and bottom). These sensors were not reliable on early cryomodules, and could not be used to define the cooling rate. Other temperature sensors are located on the cavity end groups, on the heat sinks attached to the HOM damper cans; these were a more-reliable method of determining the cooling rate. As they are not in contact with liquid helium, the HOM diodes go through the transition temperatures later than the cavity cells.

Magnetic fluxgates are installed on cavities 1, 2, 5, 7 and 8. As they are located outside the helium vessels, they do not provide an exact measure of the cavity magnetic field. However, they are effected by the trapped flux expulsion when the cavities go through the transition temperature, and can be used as a guide to determine the time at which this occurs.

The majority of the fluxgate fluctuations can be seen while the end group temperatures are cooling from 20K – 15K; it is assumed that the cavity cells are going through the transition temperature at this stage. The cooling rates reported in this paper refer to that of the end groups between 20K and 15K. Though this is not the actual transition-cooling rate, it may be as a comparison between different cryomodules.

The CMTF in its original configuration was able to cool through transition at 1.0 – 1.5 K/min. The main impediments to the faster cooldown were thought to be:

- Limited supply capacity in CTF;
- Pressure drop through CTF heat exchangers and main dewar;
- Pressure drop and choked flow through the CMTF heat exchanger.

CTF Cold Box 3

In Spring, 2017 a planned upgrade of the CTF saw the installation of the new higher-capacity cold box 3 (CB3). CB3 raised the liquefaction capacity of CTF from 5 g/s to 9.5 g/s [3]. Due to the other reasons stated above, the new cold box was not enough by itself to increase the cooldown rates for the LCLS-II cryomodules; it did however allow more simultaneous testing at the CMTF and VTA.

CTF U-Tube Configuration Change

A temporary change in the u-tube configuration at CTF was proposed to bypass the pressure drops associated with certain systems. In this layout, the helium flow would come to the CMTF directly from CB3, bypassing the 10,000 liter dewar at the 2K sub-cooler in the Valve Box. This raised the supply temperature to 6.5 – 7.0 K, and the inlet pressure was increased from 3.2 atm to 6.0 atm. The return path would bypass the recovery system and feed back to the cold box cold injection and to the main compressors (Fig 3.). In this way, it was estimated that 30 – 40 g/s of flow could be achieved.

The routing was done via long, flexible u-tubes which were installed between the relevant components. The change would be carried out while the cryomodule temperature bump was in progress. The u-tubes were reverted after the cooldown to enable pumping down to 2K.

Heat Exchanger Modification

The 4K-2K heat exchanger in the CMTF originally contained a bypass line and valve that allowed the flow to bypass the low-pressure side of the heat exchanger. This valve setup could only open the bypass, and not stop flow through the coils of the heat exchanger, which limited the effectiveness of the former.

Two new valves and another bypass line were added to the high-pressure side of the heat exchanger. One of the valves controlled the flow through the bypass line, while the other stopped all flow through the coils on the high-pressure side. With the two bypass valves open and the other valve closed, the incoming flow could avoid the pressure drop and choking associated with the heat exchanger coils, thus enabling higher flow.

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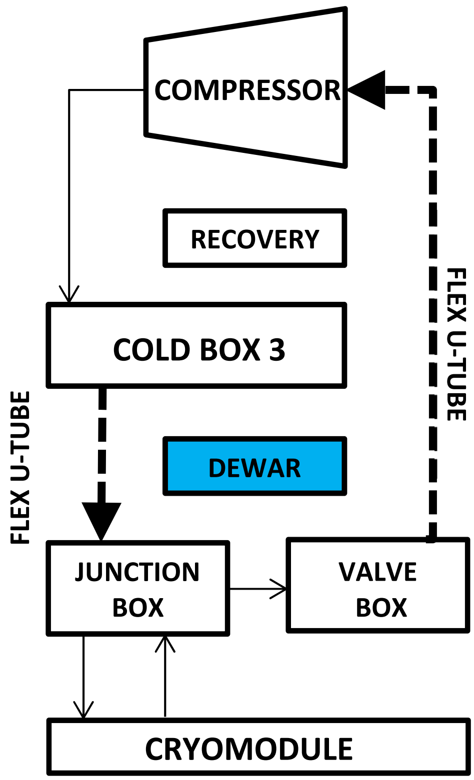

Figure 3: CTF reconfigured for FCD.

LERF

The fast cooldown in the LERF is not limited by a lack of flow. The piping system was designed with LCLS-II cryomodules and their cooldown requirements in mind. However, the flow through the cryomodules is limited by the effects of sudden increase in flow through the 2K subcooler at CHL. The flow into the cryomodules must be dialed back if the pressure at the main compressors exceeds 1.8 atm, as there is a danger of tripping the CHL.

The temperature bump at the LERF first uses the cavity helium vessel heaters to bring the cryomodule to atmospheric pressure, and then gas at 300K to warm the cavities to 40K. All return flow is directed to the recovery header.

FAST COOLDOWN RESULTS

The CMTF upgrades mentioned in the previous section were carried out in phases over the course of several months. A number of cryomodules were tested using the different combinations of the upgraded system (Table 1).

Table 2 shows the average cavity cooling rates and the average Qs from the tested cryomodules. The temperatures for the cooling rates are taken from the HOM can diodes on the tuner side of each cavity. Figure 4 shows the cavity 1 cooling profiles of some later cryomodules.

While both J1.3-05 and J1.3-12 were installed in the LERF, the former only underwent an FCD while testing in the CMTF. The setup allowed for the temperature bump and FCD to be carried out on one cryomodule while the other idled at 4K. The cooldown rate for J1.3-12 was restricted by the rising compressor pressure in the CHL caused by the increased flow.

Table 1: CMTF Modifications for Each CM Tested

Cryomodule	Modifications
J1.3-04	None
J1.3-05	CB3, CTF U-Tubes
J1.3-07	CB3, CTF U-Tubes
J1.3-08	CB3, CTF U-Tubes, Heat-X
J1.3-10	CB3, CTF U-Tubes, Heat-X
J1.3-12	LERF
J1.2-13	CB3, CTF U-Tubes, Heat-X
J1.3-14	CB3, CTF U-Tubes, Heat-X
J1.3-15	CB3, CTF U-Tubes, Heat-X

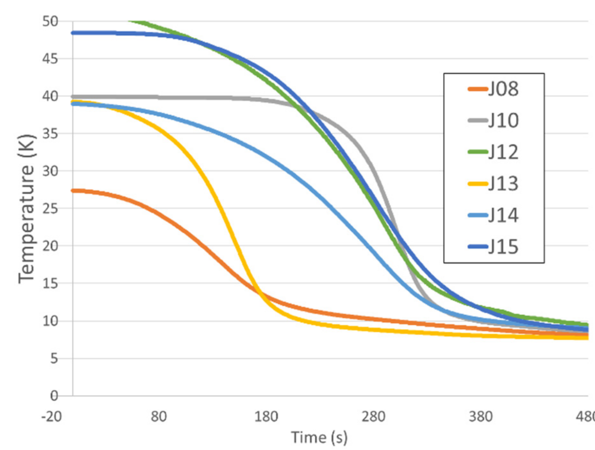

Figure 4: Cavity 1 cooling rates during FCD.

Table 2: Cavity Cooling Rates and Average Q Values

Cryomodule	Cooling Rate (K/min)	Q0
J1.3-04	1.5	2.0e10
J1.3-05	2.5	2.1e10
J1.3-07	1.6	2.0e10
J1.3-08	7.3	2.8e10
J1.3-10	21.4	3.1e10
J1.3-12	15.1	2.9e10
J1.2-13	18.7	2.7e10
J1.3-14	10.5	2.6e10
J1.3-15	12.0	2.3e10

The Q values quoted here are after an FCD procedure, in which the cavity temperatures are warmed up to 40K and then cooled rapidly. In the CMTF, the FCD also involves raising the inlet pressure to 6.0 atm.

While a correlation between the cooldown rate and the average Q0 value is apparent (Fig. 5), it is not the only factor in the Q determination. Other factors depressing the Q values include:

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- cavity field emission;
- source and heat treatment of the cavity material; some combinations expel flux better than others;
- the function of components used for measurements e.g. leaking valves or malfunctioning heaters.

In general, it was accepted that the improvements to the cryogenic systems allowed LCLS-II cryomodules to test to their rated Q specification.

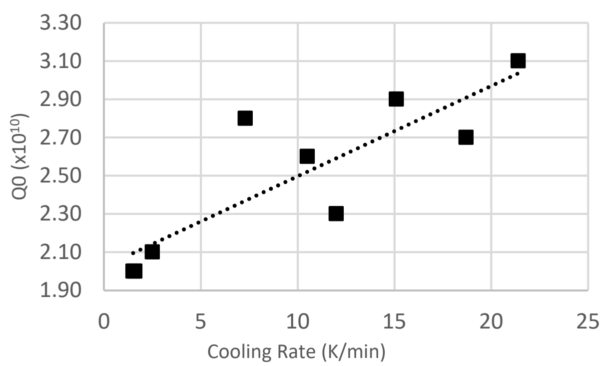

Figure 5: Comparison of average Q and cooling rate.

MULTI-CAVITY RUNS

The cryomodule acceptance criteria calls for all eight cavities to be run simultaneously at their design gradient of 16 MV/m for a minimum of eight hours. At this gradient, each LCLS-II cavity (after flux expulsion) is estimated to produce 10W of heat. The Kinney pumps in CTF were not able to support such a high dynamic heat load, and so multi-cavity testing at the CMTF is currently limited to four cavities at a time.

An attempt was made to run all 16 cavities in J1.3-05 and J1.3-12 simultaneously in the LERF. The final cavity gradients are shown in Table 3. A total voltage of 230 MV was achieved. The cavities in J1.3-05 had not been put through a fast cooldown, and so generated more heat than normal; several cavities had to be run at a lower gradient in order to keep the helium pressure at an acceptable level; cavity 6 on J1.3-05 could not be run due to issues with the RF system. The test was carried out during beam operation in CEBAF and did not cause any disturbances to the physics program.

FUTURE WORK

Nine cryomodules are still to be tested as part of the LCLS-II project, and possibly another ten as part of the High Energy (HE) Upgrade. These will be tested by a combination of the CMTF and LERF. Future development work includes:

- Achieving eight-cavity operation in the CMTF. Changes to the operation of the Kinney pumps may allow for a temporary increase in capacity
- The LERF will continue to be used by SLAC as a testbed for Low-Level RF (LLRF) control systems which will eventually be installed at SLAC
- Simultaneous operation of two cryomodules will be used to investigate the interactions between adjacent cryomodules in the SLAC tunnel.

Table 3: Gradients During the 16 Cavity Run on J1.3-05 and J1.3-12 in the LERF

Cavity	J1.3-05 (MV/m)	J1.3-12 (MV/m)
1	13.59	16.13
2	16.02	16.04
3	16.01	15.94
4	16.01	16.01
5	15.43	16.01
6	-	15.99
7	12.51	16.14
8	12.52	16.00

SUMMARY

Cryomodule testing of LCLS-II at JLab is primarily carried out at the dedicated CMTF. The LERF has been refitted with new cryogenic connections to allow cryomodule testing and is able to test two connected LCLS-II cryomodules simultaneously. Initial limitations in the CMTF did not allow cryomodules to be cooled at a rapid enough rate to expel magnetic flux and reach specified cavity Qs. Adjustments to the equipment at CMTF and temporary piping changes in the CTF have allowed faster cooldowns which lead to higher Qs. This has been replicated in the LERF, which has also been proven to function as a test facility while CEBAF is running beam.

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