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SUPERCONDUCTING MAGNET PERFORMANCE IN LCLS-II CRYOMODULES

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Abstract

New LCLS-II Linear Superconducting Accelerator Cryomodules are under construction at Fermilab. Installed inside each SCRF Cryomodule is a superconducting magnet package to focus and steer an electron beam. The magnet package is an iron dominated configuration with conductively cooled racetrack-type quadrupole and dipole coils. For easier installation the magnet can be split in the vertical plane. Initially the magnet was tested in a liquid helium bath, and high precision magnetic field measurements were performed. The first (prototype) Cryomodule with the magnet inside was built and successfully tested at Fermilab test facility. In this paper the magnet package is discussed, the Cryomodule magnet test results and current leads conduction cooling performance are presented. So far magnets in nine Cryomodules were successfully tested at Fermilab.

INTRODUCTION

The Linac Coherent Light Source (LSLS-II) is under construction at SLAC [1]. The Main Linear Accelerator is based on SCRF Cryomodules capable to accelerate the electron beam up to 10 GeV energy. Each Cryomodule has eight SCRF cavities, and one superconducting magnet package: combined quadrupole, and two dipole correctors. The magnet design, fabrication, and prototype tests are described in [2-7]. This paper presents test results of magnet packages inside Cryomodules.

MAGNET PACKAGE

A 3D view of the superconducting magnet package installed inside the Cryomodule is shown in Fig. 1. This is an iron dominated magnet where the magnetic field is formed by four iron poles. It has a splittable in the vertical plane configuration which allows to install the magnet outside the SCRF cavity assembly clean room. The magnet is cryogen free, cooled through pure aluminium heat sinks clamped to the 2 K liquid helium supply pipe. Each magnet has three pairs of conductively cooled copper current leads. Current leads are cooled by three thermal intercepts clamped to 2 K, 5 K, and 50 K helium supply pipes. The magnet and leads conduction cooling and performance was verified during pre-prototype tests [8]. Before installation into Cryomodules all magnets passed cold tests in liquid helium which included high precision magnetic measurements by rotational coils. Field quality and coupling between the quadrupole and dipoles were also investigated.

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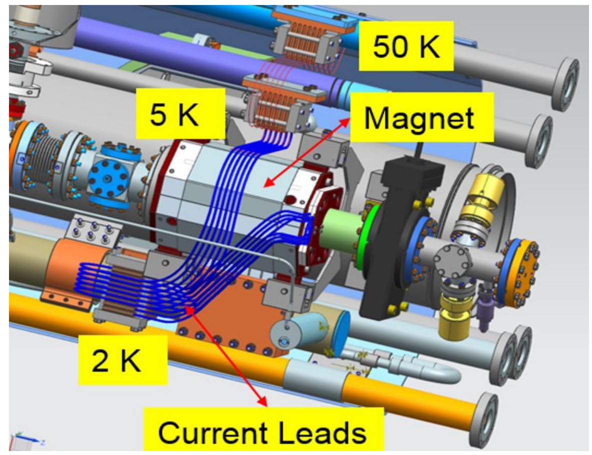

Figure 1: Superconducting magnet in the Cryomodule.

Table 1 presents main parameters of the magnet package, which consists of quadrupole, vertical and horizontal dipole correctors.

Table 1: Magnet Package Parameters

Parameter	Unit	Value
Integrated gradient at 10 GeV	T	2.0
Integrated gradient at 0.4 GeV	T	0.05
Clear bore aperture	mm	78
Effective length	mm	230
Peak quadrupole gradient	T/m	8.67
Quadrupole harmonics at 10 mm	%	<1.0
Quadrupole inductance (DC)	H	0.66
Number of coil sections		4
Number of quadrupole turns*		426
Number of dipole turns*		39
Peak current	A	20
NbTi superconductor diameter	mm	0.5
Dipole integrated strength	T-m	0.005
Max magnetic centre offset	mm	<0.5
Total length	mm	340
Magnet width	mm	322
Magnet height	mm	220
Quantity required		40

* Number turns/pole.

The magnet installed in the Cryomodule is shown in Fig. 2, and Fig. 3.

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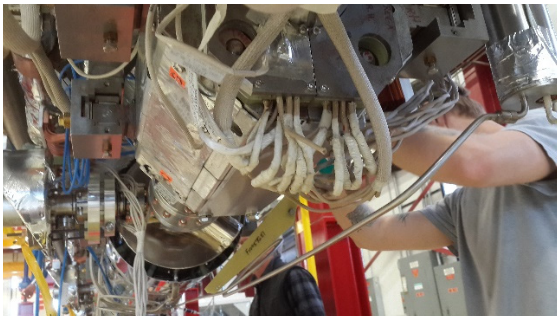

Figure 2: Magnet with leads and instrumentation wiring.

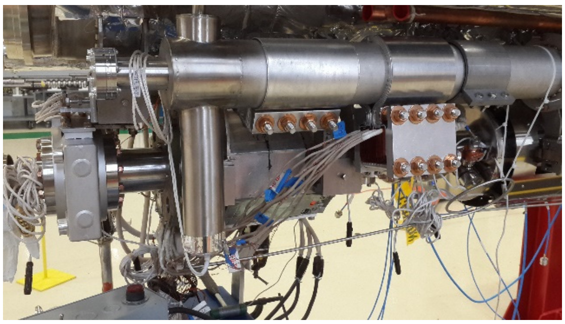

Figure 3: Magnet side view with heat sinks installed.

The magnet package is instrumented with a number of thermal sensors and voltage taps. Magnet coils were powered by three KEPCO power supplies having the peak current 20 A, and the voltage 5 V. The voltage across each magnet is sensed using voltage taps to protect the superconducting coils. A switch is triggered by any voltage rise above 0.5 V threshold, which disconnects the corresponding power supply, and discharges the magnet through an external dump resistor. There are also four coil heaters which could be used to heat coils above a critical temperature to clear the superconductor persistent currents. Temperature sensors are used to monitor the magnet and current leads temperatures while cooling down, and in operation.

MAGNET TESTS

The magnet package tests in the Cryomodule included:

- Verification that all signal cables and leads were connected to the correct instruments and sources.
- Monitoring magnet and leads while cooling down.
- Magnet acceptance test, one hour at the peak 20 A current in all coils prior to further operations.
- Full power SCRF and 20 A magnet test for 24 hours.

Magnet test results are presented in Table 2, and Fig. 4 – Fig. 6. Table 2 summarizes tests of eight Fermilab-built Cryomodules, and one (J1.3-04) from JLAB. The first Cryomodule (F1.3-01) was used as a prototype, and the magnet had more temperature sensors to obtain the full information about the magnet performance in a conduction cooling mode. During initial tests the long cables between the magnet and three KEPCO power supplies (PS) limited magnet currents to 15 A, due to the 5 V PS limit. These cables were replaced with larger cables whose voltage drop was around 2.7 V. However, during the full power operation of all three magnets at the 20 A peak current, a slow temperature rise and corresponding voltage growth was observed on the 5K to 50K current leads section (See Fig. 4).

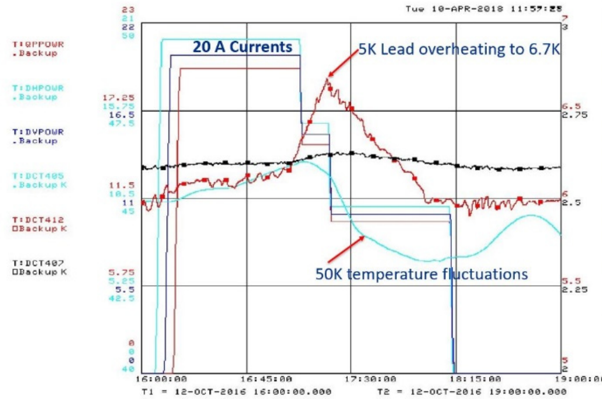

Figure 4: Current leads temperature rise at 20 A in all coils.

At that time the cryogenic system was very unstable having large temperature fluctuations on 5K and 50K current leads temperature intercepts clamped around these pipes. After the first Cryomodule test the cryogenic system was upgraded, and since that time there were no issues with the current leads instabilities. It also should be noted, that the magnet never quenched if coil temperature was below 4.5K. The magnet coils, and the magnet iron core are thermally attached to the 2K pipeline, and there is a substantial temperature margin for the operation. Pre-prototype magnet conduction cooling tests showed that the superconducting coils transition to normal condition at 8.5K.

The magnet cool down is rather slow, lagging the profile of other Cryomodule temperatures (See Fig. 5).

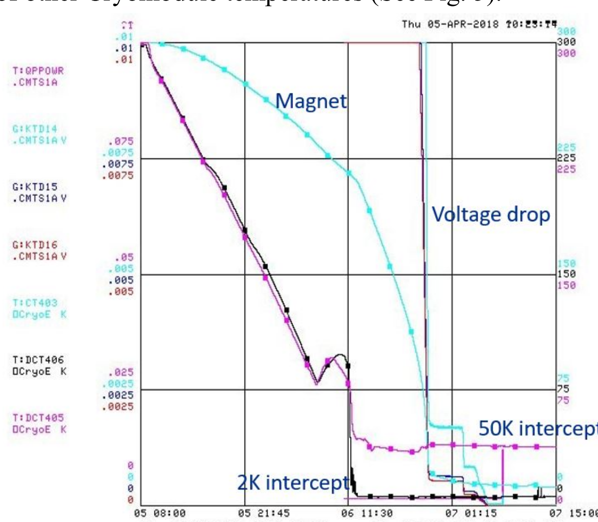

Figure 5: The magnet cooling down to the superconducting state.

This delay in the cooling is caused by rather large conductively cooled magnet mass. It takes ~ 48 hours to reach superconducting condition in all coils.

The magnet coils heater study showed that 1 W power loss on heater triggered the quench detection system (QD) after ~ 4 minutes at only 1 A coil current. The larger are magnet currents the faster is the response of QD.

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Table 2: Cryomodule Magnet Package Tests

CM#N	Data	Time start	Time end	I, A	2K	5K	50K	Comments
F1.3-01	9/20/2016	16:00	17:25	12.5	5	5.75	55	Power supplies trips at 5 V.
F1.3-01	9/21/2016	15:00	15:40	11.5	5.5	6.5	57	Stable at 11.5 A current.
F1.3-01	9/22/2016	16:00	16:50	11.5	5.9	5.75	55	Stable at 11.5 A current.
F1.3-01	10/5/2016	9:00	9:35	20	5.5	5.75	49	Unstable cryosystem.
F1.3-01	10/6/2016	11:00	11:54	20	4.9	5.6	47	Leads voltages rise.
F1.3-01	10/12/2016	16:00	18:14	20	4.8	6	47	Leads voltages rise.
F1.3-01	10/18/2016	14:24		20	4.8	5.75	52	Lead voltages rise.
F1.3-01	10/28/2016	10:09	10:13	1	4.8	5.75	52	Heater study: 1 W triggered QD after 4 min.
F1.3-01	10/31/2016	11:13	12:07	20	4.8	5.75	52	Ramps: 0.1, 0.2, 0.3, 0.4 A/s.
F1.3-01	11/1/2016	8:10	8:43	20	5.5	5.8	52.5	Study degaussing cycles.
F1.3-02	5/3/2017	9:34	9:50	20	3.27	4.95	39.6	*Stable=cryosystem upgrade.*
F1.3-02	5/9/2017	9:35	10:36	18	3.23	5.39	39.52	Temperature rise.
F1.3-02		10:46	13:00	18	3.22	5.51	35.28	Stable adding 50K cooling.
F1.3-02		13:00	14:00	20	3.23	5.55	34.87	Stable at full current.
F1.3-03	6/20/2017	9:41	10:41	20	4.51	5.65	36.39	Stable at full current.
F1.3-04	6/20/2017	10:03	15:00	20	3.63	5.75	40.56	Stable at full current.
J1.3-04	9/27/2017	13:00	15:20	20	3.23	5.3	39.9	JLAB Cryomodule test at FNAL. Stable temperatures.
F1.3-05	12/8/2017	9:15	10:20	20	5.93	5	46.24	Cryosystem set up was at 50K, and reduced to 45K.
F1.3-06	11/1/2017	14:55	17:09	20	4.66	5.63	42.39	Stable at full current.
F1.3-07	1/10/2018	13:26	14:52	20	4.4	5.52	38.3	Stable at full current.
F1.3-09	3/5/2018	8:00		0.01	300	300	300	Start cooling down.
F1.3-09	3/7/2018	7:06		0.01	13	6	38	Coils superconducting.
F1.3-09	3/13/2018	9:04	10:05	20	4.47	5.94	31.57	Stable at full current.

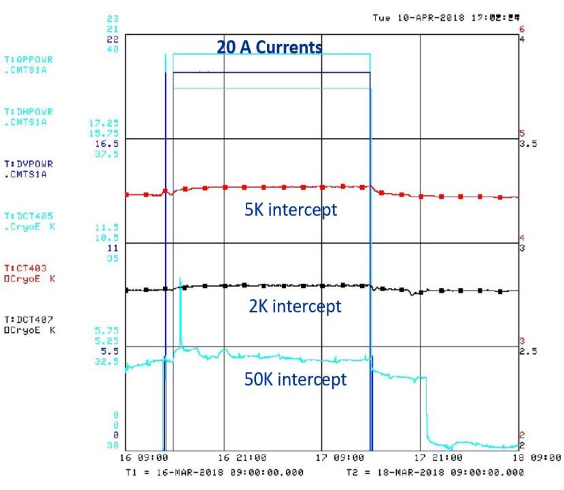

Figure 6: Full power 24 hours test.

CONCLUSION

Eight FNAL magnets were fabricated and installed in Cryomodules; these and one JLAB Cryomodule were tested at FNAL Test Facility. The intensive first magnet tests helped to resolve some cooling issues. All magnets showed a good stable performance at the peak currents for 24 hours of Cryomodule full power operation.

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