U.S. Particle Accelerator School
Education in Beam Physics and Accelerator Technology

Fermilab

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Part 3 Linear Accelerator Magnets

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LCLS-II Cryomodule Magnet Package

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Argonne NATIONAL LABORATORY
CORNELL UNIVERSITY FOUNDED A.D. 1865
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Outline

- Introduction
- Magnet Package physics requirements
- Engineering Specifications
- Magnet integration
- Prototype magnet testing
- Magnets fabrication
- Production magnet tests
- Full power test in the Cryomodule
- Summary

Introduction

- *The magnet package design is based on the physics requirement documents: LCLSII-4.1-PR-0146-R0, and LCLSII-4.1-PR-0081-R0.*
- *The design is based on the Splittable Conduction Cooled magnet configuration proposed by Akira Yamamoto for ILC magnets.*
- *ILC magnet prototype was built and successfully tested in the conduction cooling mode using just 1 W cooling capacity cryocooler.*
- *The LCLS-II magnet is half the weight while requiring less than half the current as compared to the XFEL magnet.*
- *The main advantages of this magnet relatively XFEL:*
  - ✓ *Cleanroom installation not required.*
  - ✓ *No LHe vessel for the magnet and current leads.*
  - ✓ *More accurate magnet alignment in the space.*
  - ✓ *Lower superconductor magnetization effects from dipole coils.*
  - ✓ *Simple, low cost current leads.*

Magnet Package Physics Requirements

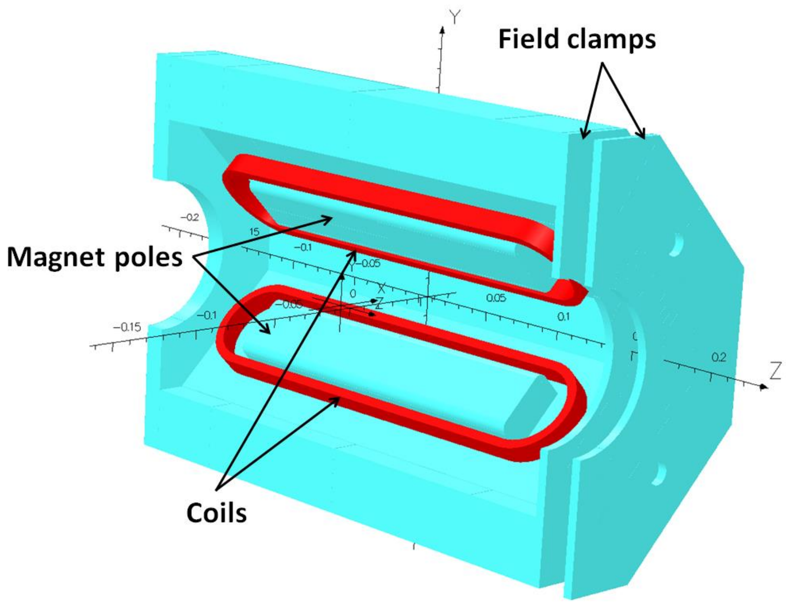
- *The Magnet Package contains a quadrupole and two built-in dipole correctors.*
- *The quadrupole integrated gradient is 0.064 T – 2.0 T. Integrated field quadrupole harmonics at 10 mm radius are: b2/b1< 0.01, b5/b1<0.01. The dipole integrated field is 0.005 T-m.*
- *The electron beam energy linearly increases along the L1B, L2B, and L3B SCRF sections of the Linac with the corresponding beam size decrease: 250, 150, 80 µm.*
- *The polarity of the quadrupole is indicated by the sign of the gradient with convention a positive gradient corresponds to a positive polarity and focuses electrons in the horizontal direction.*
- *All quadrupole magnets are unipolar, dipoles are bipolar.*
- *All 35 Cryomodules require a magnet package.*

Magnet Package Engineering Specifications

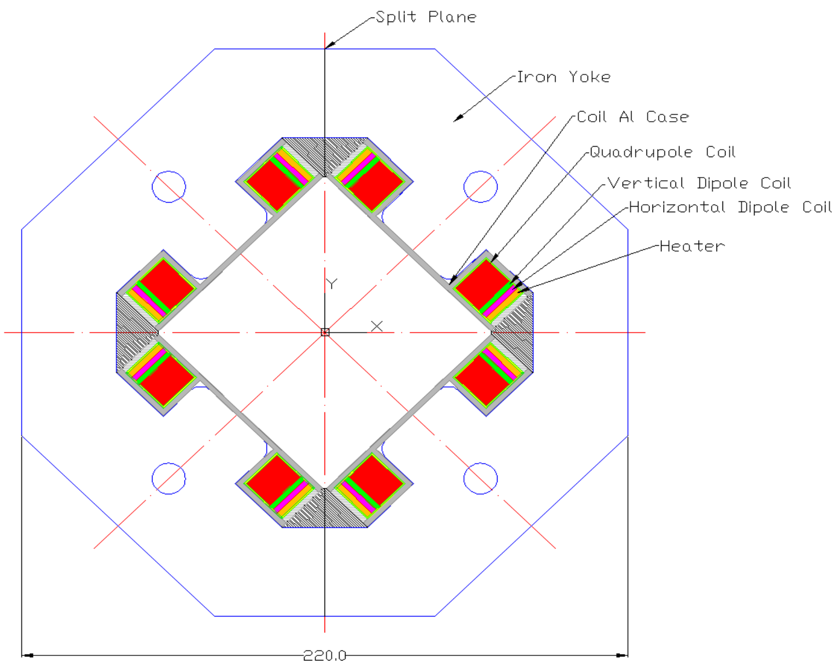
Parameter	Unit	Value
Integrated peak gradient at 10 GeV	T	2.0
Integrated minimal gradient at 0.4 GeV	T	0.064
Aperture	mm	78
Magnet effective length	mm	230
Peak gradient	T/m	8.7
Quadrupole field non-linearity at 10 mm		<0.01
Dipole trim coils integrated strength	T-m	0.005
Magnetic center offset in the cryomodule less than	mm	0.5
Liquid helium temperature	K	2.2

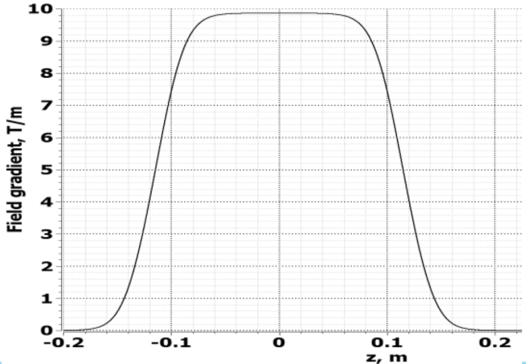
The magnet should have a splittable, and conduction cooling (cryogen free) configuration as specified in the signed and approved Cryomodule Magnet ESD LCLSII-4.5-ES-0355-R0.

Magnet Package Magnetic Design



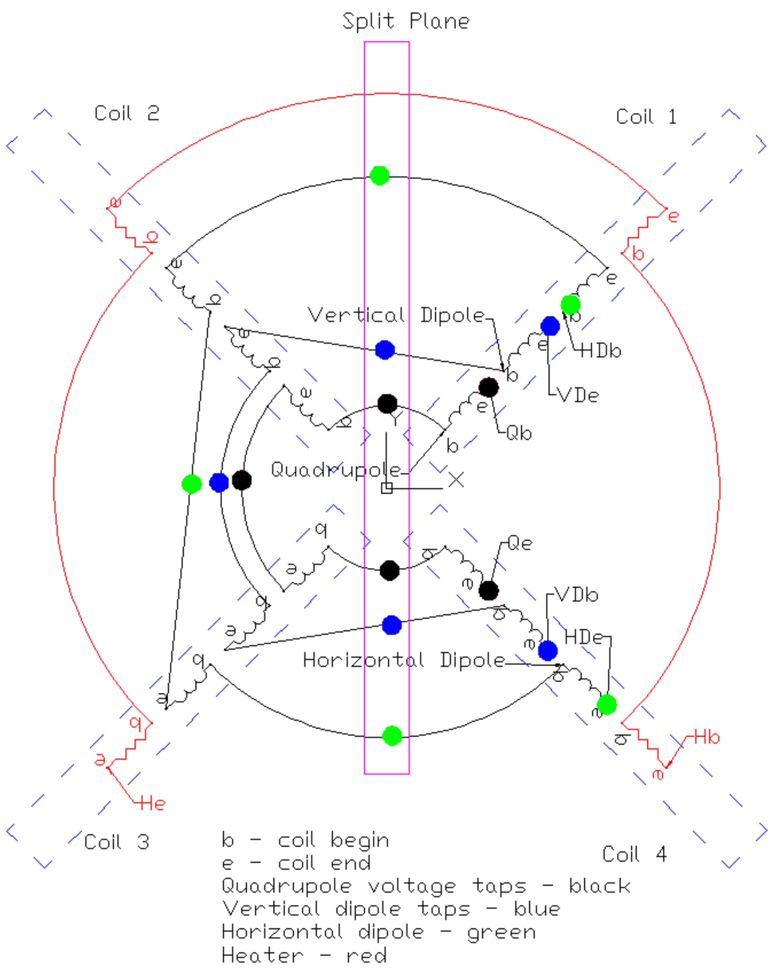
Half of the magnet





- *The magnet has 4 superconducting racetrack type coils, iron yoke with field clamps.*
- *At the magnet pole tip distance of 90 mm, and 120 mm pole length the magnetic field has large amount of end fields. So, we cannot make the magnet shorter.*

Magnet Package Schematic



- *There are 4 racetrack coil blocks in the magnet.*
- *Each block has:*
  - quadrupole coil;
  - vertical dipole coil;
  - horizontal dipole coil;
  - heater coil.
- *All coils connected in series forming quadrupole or dipole field configuration.*
- *To monitor the magnet performance, each coil end has voltage tap connected to the cryomodule instrumentation electronics.*
- *3 superconducting current lead coil pairs (6 total) go to the cryomodule top flange.*
- *Because the magnet split vertically, there are 6 external superconducting coils splices between two halves of the magnet.*

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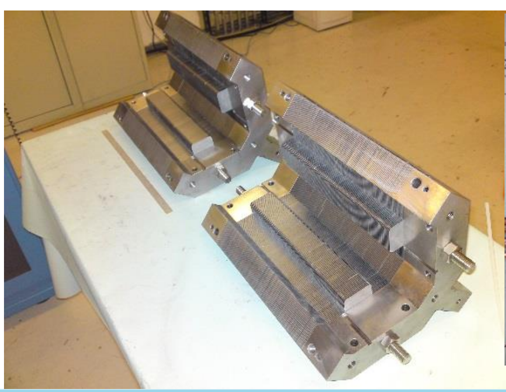
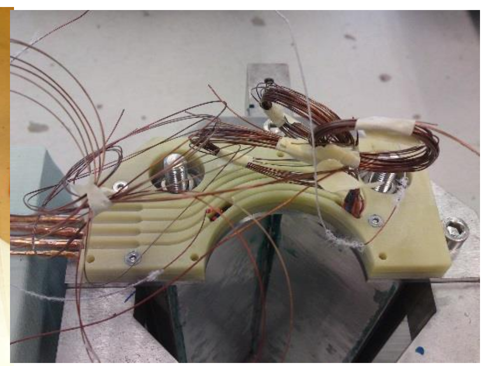
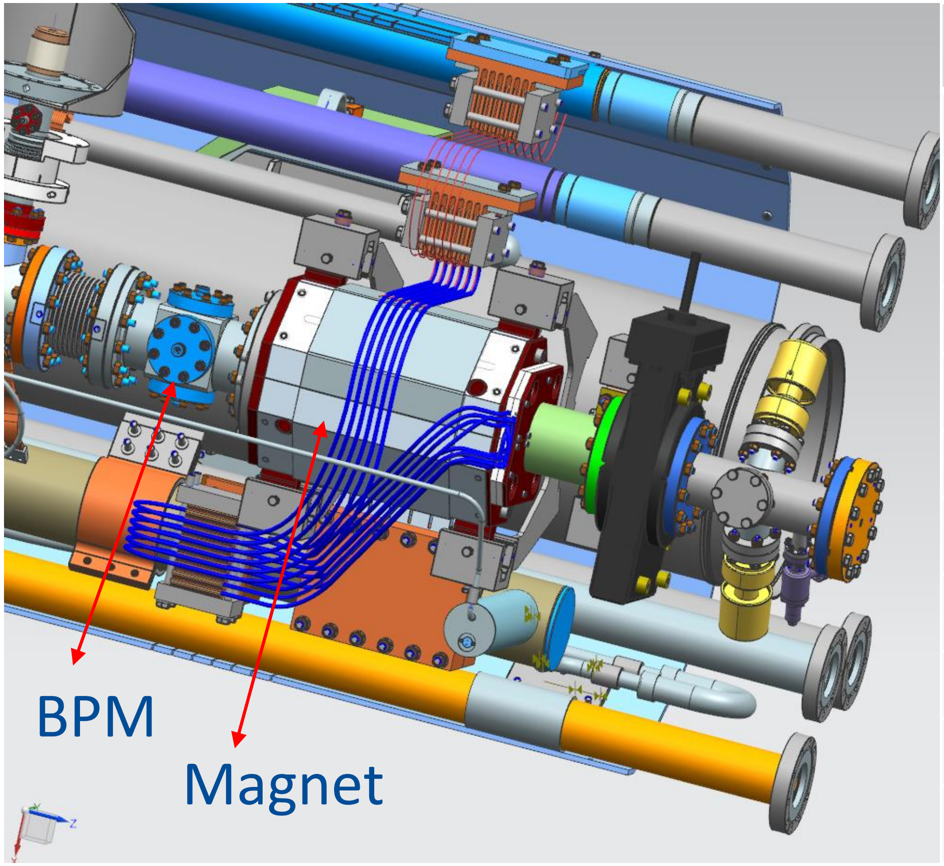
Magnet Package Pre-Prototype Fabrication





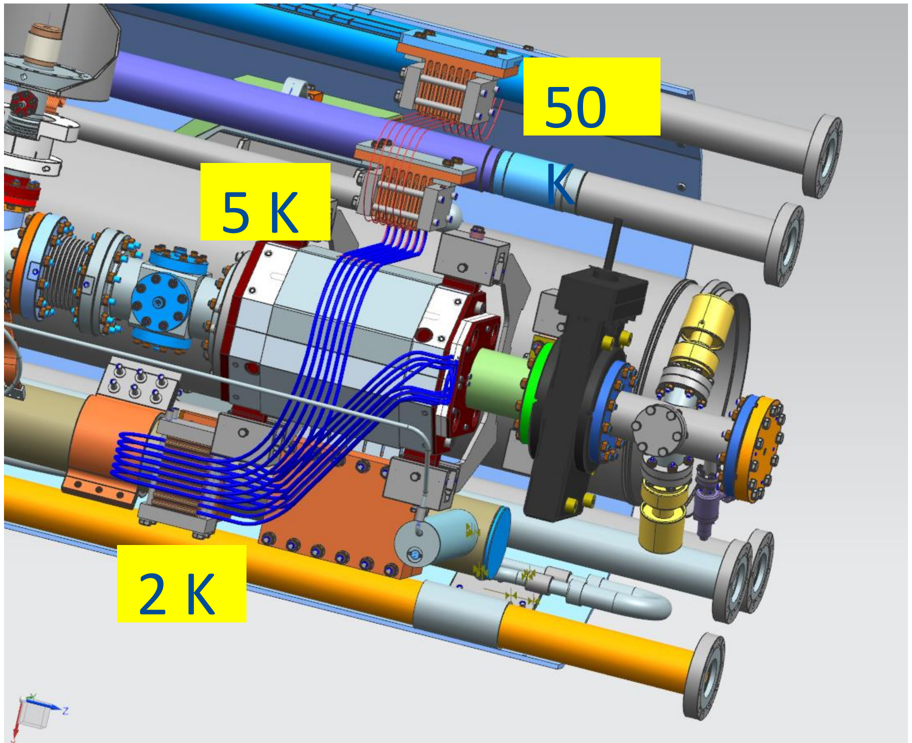
LCLS-II Magnet in the Cryomodule

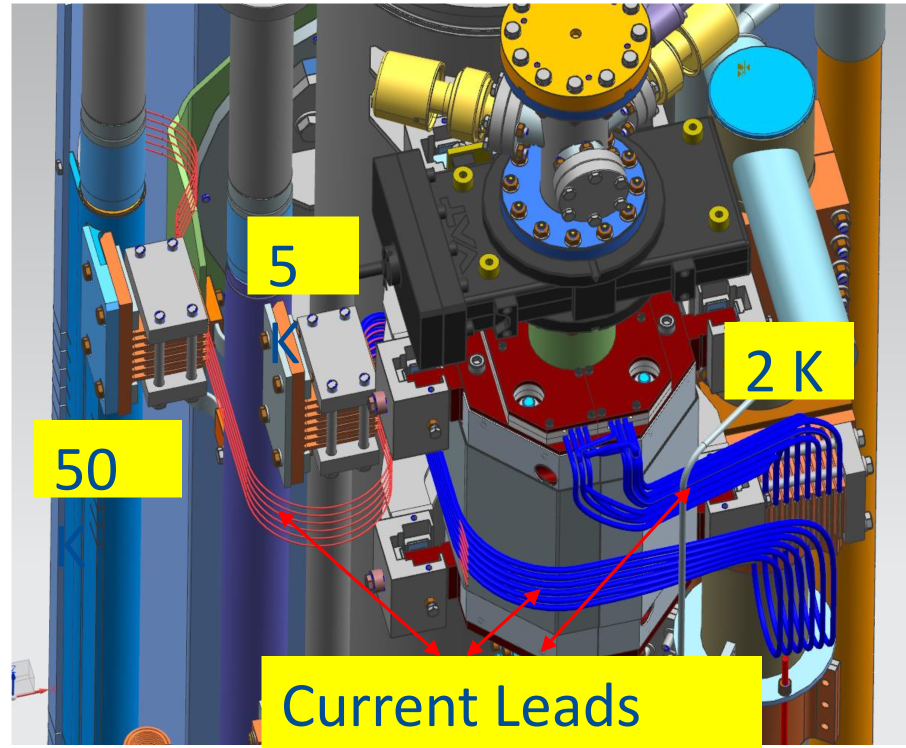


Parameter	Unit	Value
Magnet physical length	mm	340
Magnet width/height	mm	322/220
Pole tip radius	mm	45
Peak operating current	A	≤ 20
Number of quadrupole coils		4
Number of dipole coils (VD+HD)		8
Type of superconducting coils		Racetracks
NbTi superconductor diameter	mm	0.5
Quadrupole inductance at 12 Hz	H	0.58
Liquid helium temperature	K	2.2
Quantity required (with spares)		36

The magnet package will be installed at the end of the cryomodule.
Magnet conductively cooled through pure Al thermal sinks.

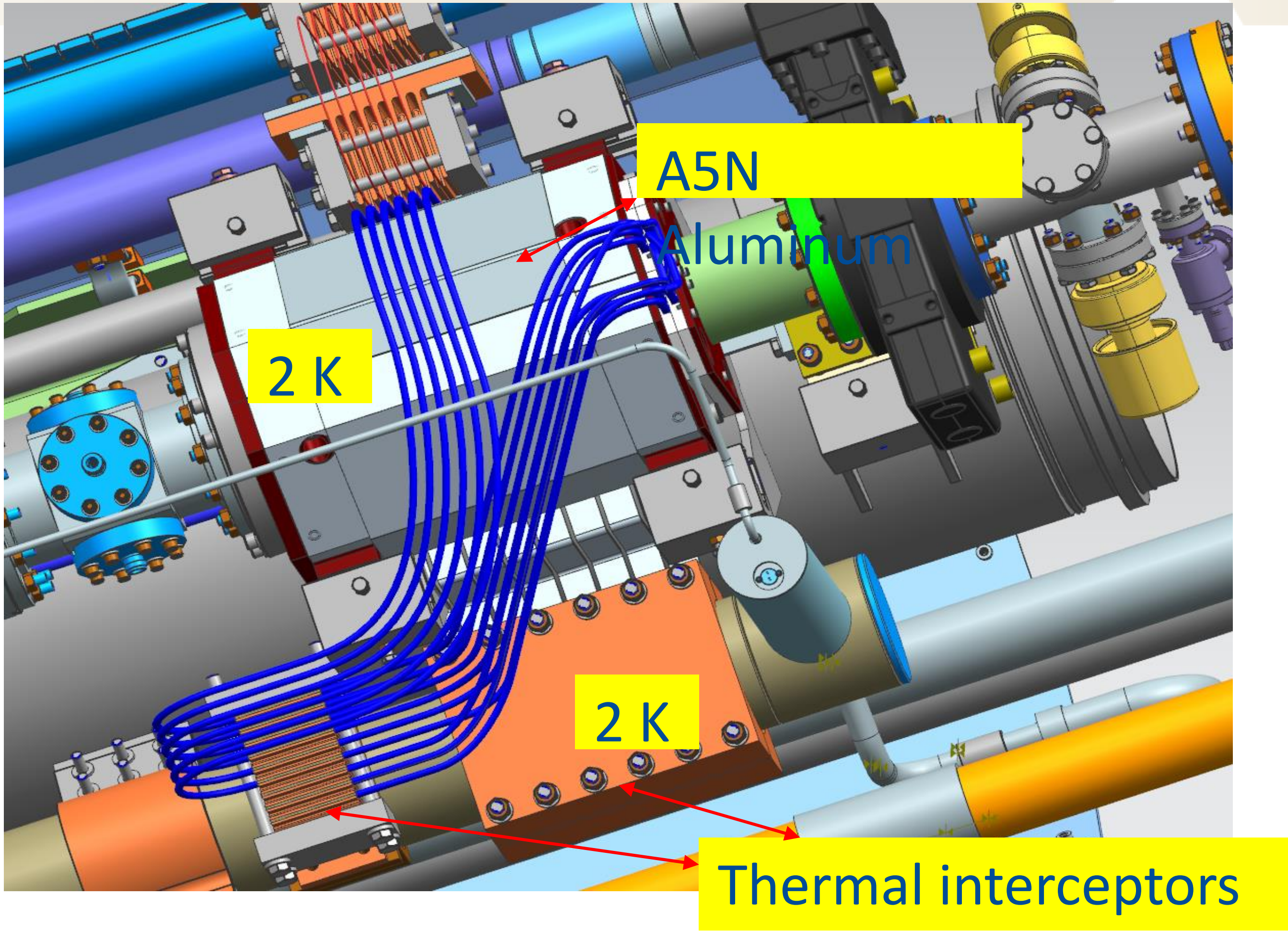
Magnet Package Current Leads





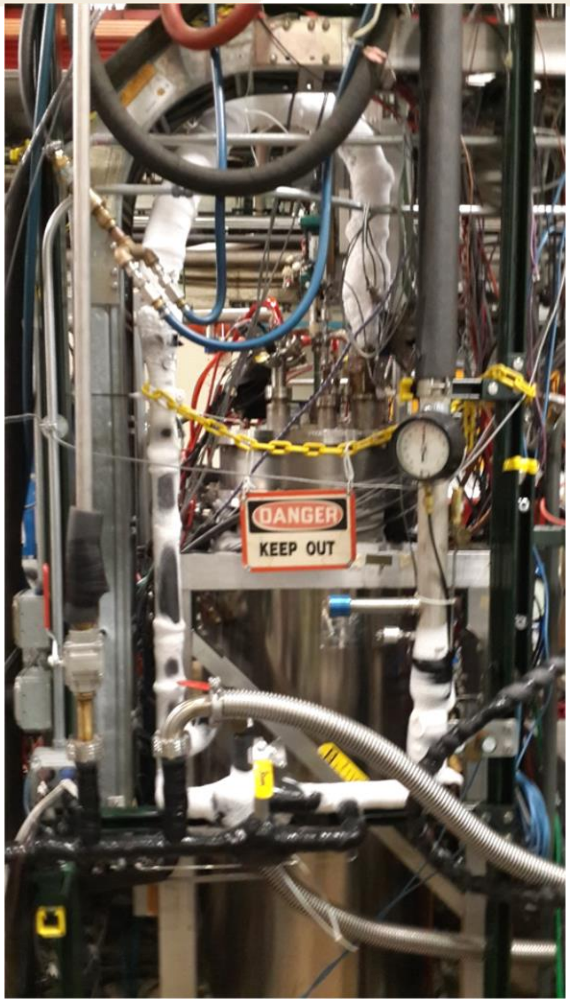
Six conduction cooled current leads made from the copper.
They have thermal interceptors at 2 K, 5 K, and 50 K thermally attached to the corresponding cooling pipes.

Magnet Coils and Yoke Cooling



Pure A5N aluminum foils glued and mechanically clamped to the magnet yoke outer surface, superconducting coils, and all thermal interceptors.

Magnet Prototype Test at Stand 3



Magnet cooled down to 4.5 K and tested in the bath cooling mode at Stand 3.

Joe DiMarco made all magnetic measurements by rotational probe.

Prototypes Electrical and Quench Tests

The tests for both magnets followed the same basic run plan:

1) Warm magnetic polarity and electrical checks.

2) Liquid helium cool down and cold electrical checks.

3) Detailed integral magnetic field quality measurements using a rotating coil probe, starting at low current and increasing the current to study iron and superconductor magnetization effects up to 10A.

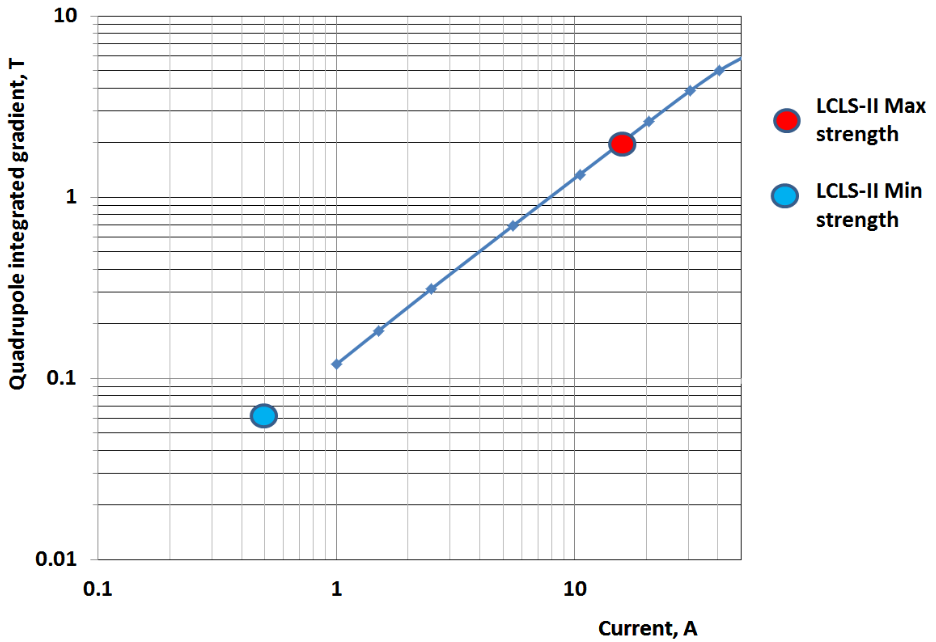
4) Quench performance of all three windings to 30 A (50% above the maximum operating current).

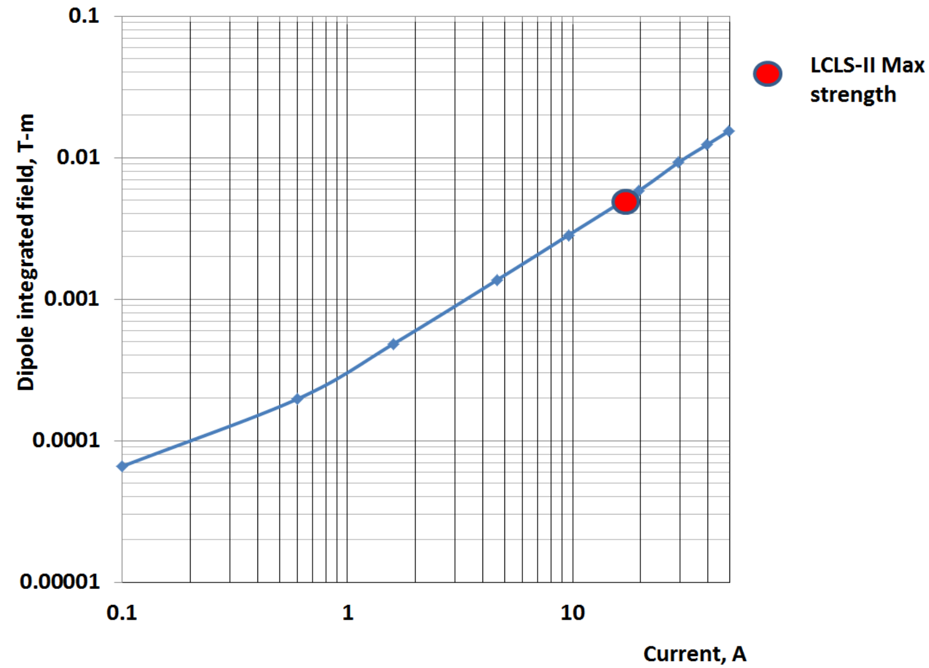
5) Additional magnetic measurements up to 30 A.

6) Warm magnetic axis alignment.

The first magnet prototype SPQA01 was cold tested in October 2015, SPQA02 in December 2015.

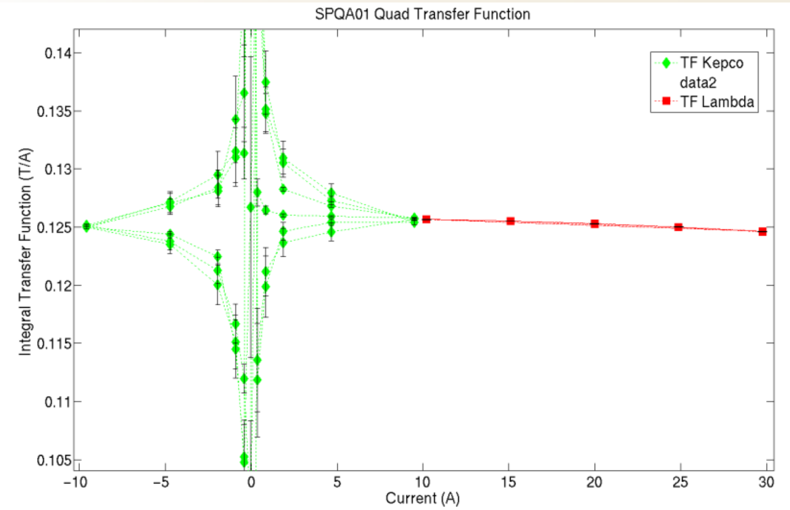
Quadrupole and Dipole Magnets Strength

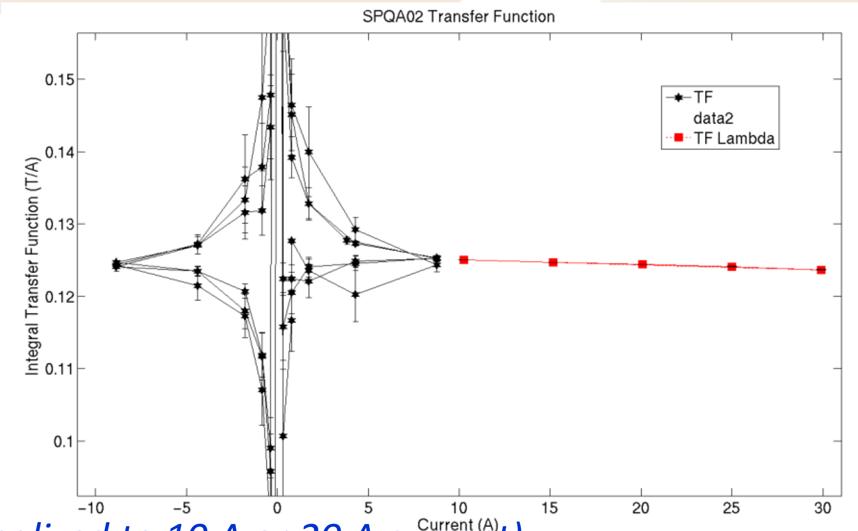




- *Only one quench was observed at 48.5 A during quadrupole magnet ramping up to 50 A during bath cooling test.*
- *2.0 T LCLS-II peak integrated gradient was reached at 15 A.*
- *No quench was observed during vertical and horizontal dipoles ramping up to 50 A during bath cooling test.*
- *Dipole 0.005 T-m peak integrated field was reached at 17 A.*

Quadrupole Field Transfer Function

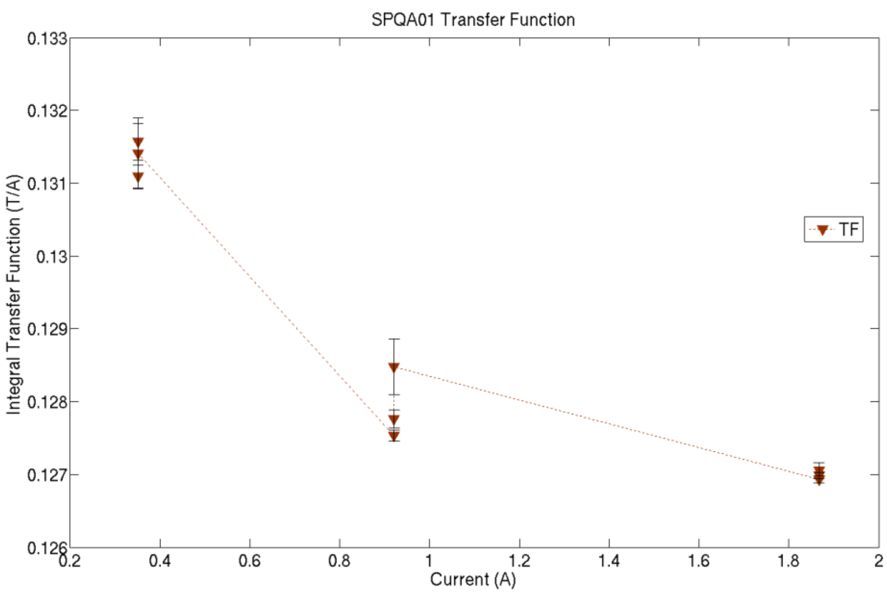


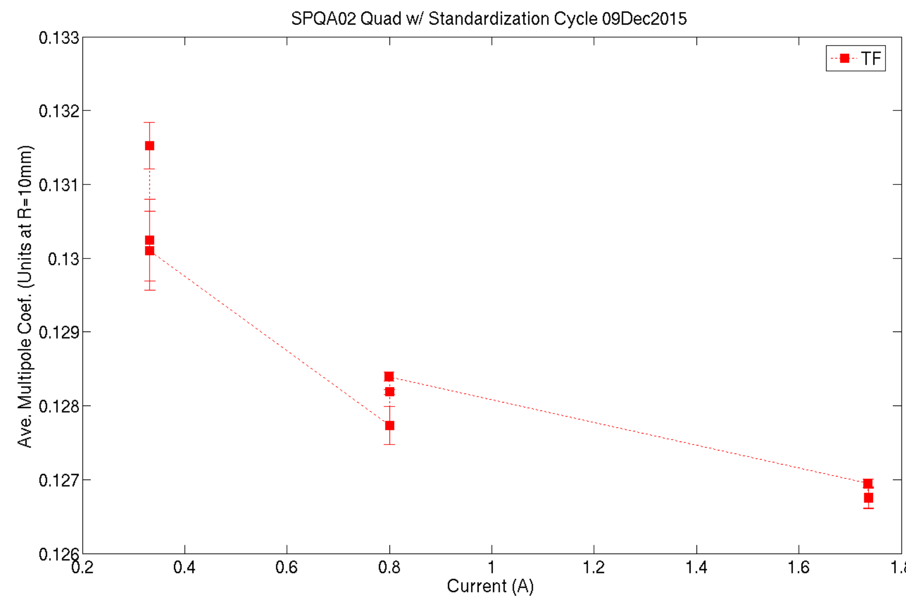


Transfer function= Magnet strength/Current (normalized to 10 A or 20 A current)

The magnet package magnetic measurements were performed by rotational coils at FNAL Stand 3. The rotational coil system utilizes a PC Board design and provides a measurement accuracy of ~1 unit (10^{-4}). The probe rotates in an anti-cryostat (warm bore tube) placed within the magnet aperture as the assembly is suspended in the LHe vessel. The probe radius is limited by the ~30mm inner diameter of the warm bore. Field strength of the quadrupole was measured over 3 cycles at different currents. For the low field bi-polar measurements, a bipolar 10A Kepco power supply was used. For current from 10A to 30A, a unipolar Lambda power supply was used. The measurements match the 0.125 T/A design value well. The hysteresis width at 1A shows that the change in the transfer function (TF) at lower current is about± 5%.

Quadrupole Field Reproducibility and Quality

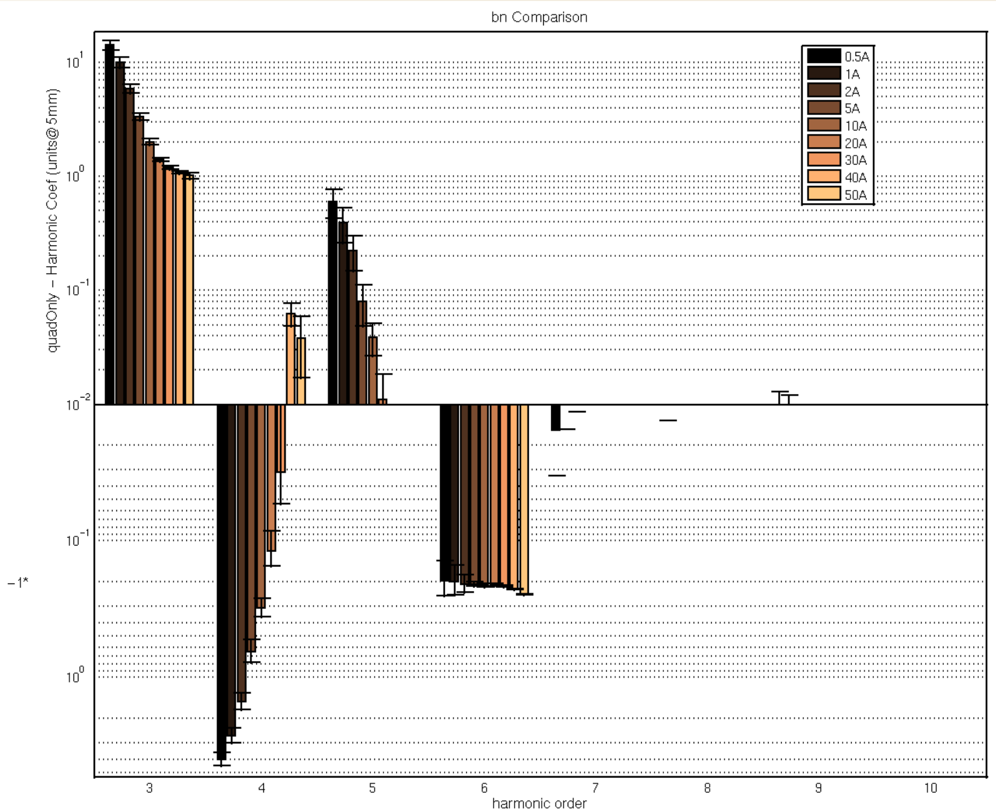




Figures show the repeatability of quadrupole TF during standardization cycles which approach the nominal current by damped current swings about the set value (e.g. the 1A position would be approached by ramping the power supply through 0, 1.6, 0.4, 1.4, 0.6, 1.2, 0.8, 1A). The reproducibility here is better than about ±0.5%, though measurement uncertainties may be largely contributing to this.

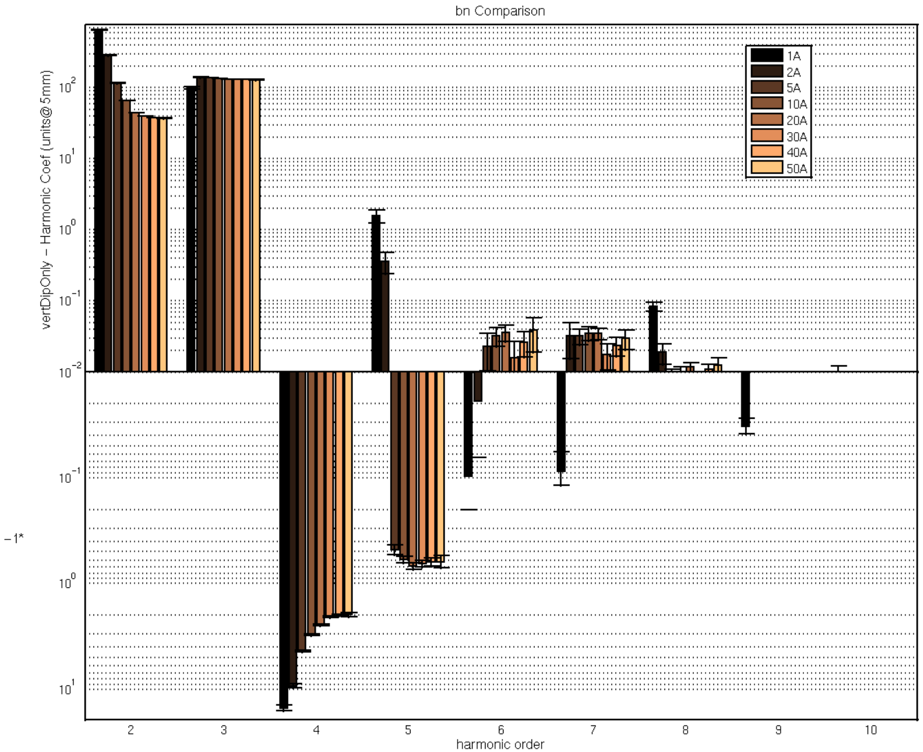
The largest field harmonics are below 0.1%, except at the lowest current measured of 0.4A, where they are still less than 0.5% for SPQA01 and 0.25% for SPQA02, including any persistent current or magnetization contributions (see LCLSII-4.5-EN-0612).

Quadrupole Field Harmonics



At 1.0 A : b3=30, b4=-4.0, b5=0.8, b6=-0.2 units (10^-4), R=5 mm
At 50 A : b3=1.0, b4=0.04, b5=0.01, b6=-0.02 units (10^-4). R=5 mm
The spec is 100 units.

Dipole Field Harmonics

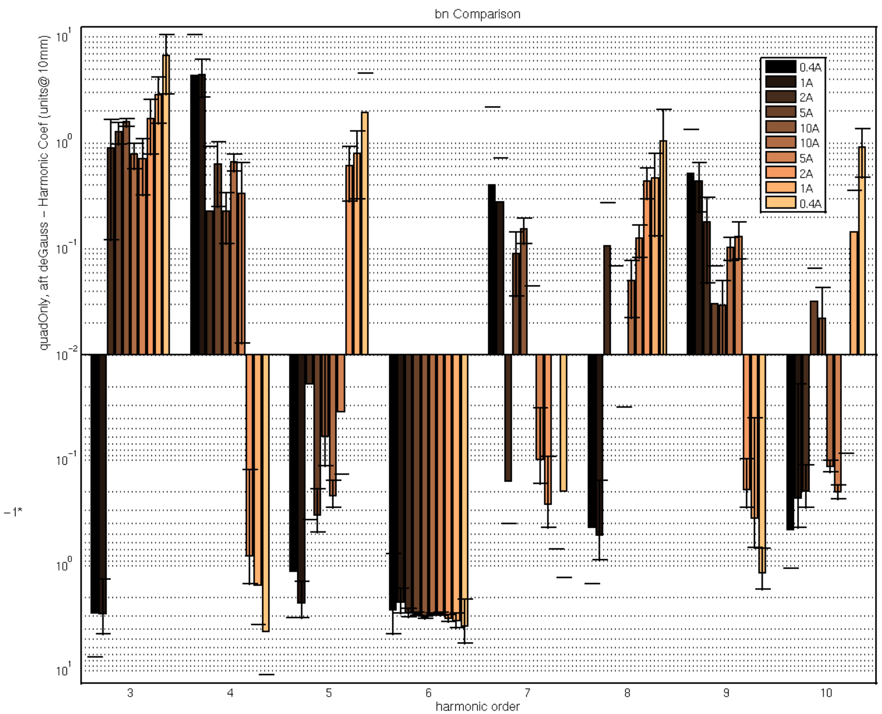


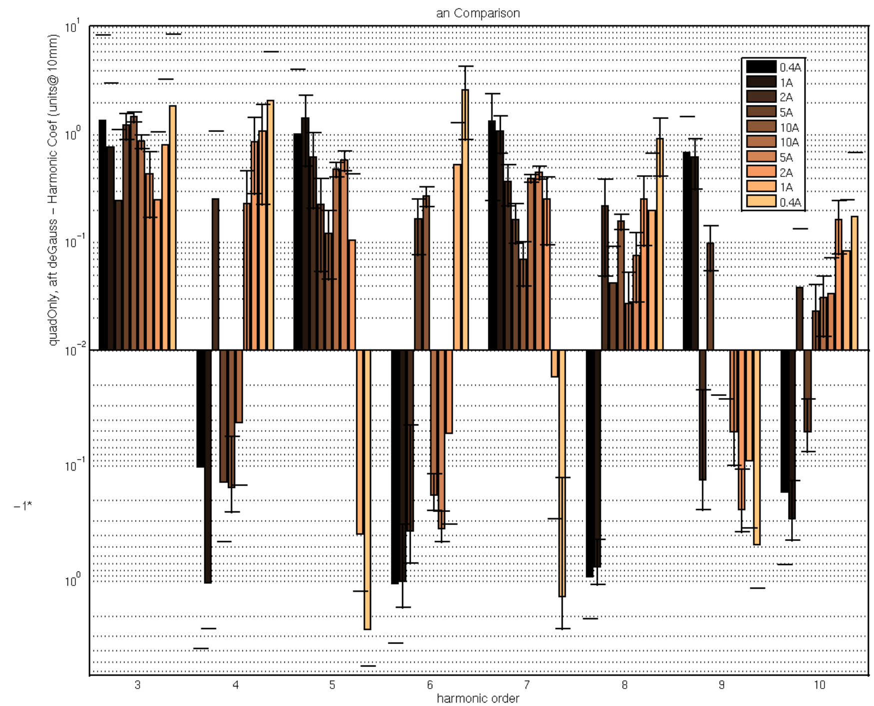
At 0.5 A : b2=600, b3=100, b4=-15,   b5= 2   units (10^-4), R=5 mm

At 1.5 A : b2=300, b3=120, b4=-10,   b5= 0.07

At 50 A : b2=40,   b3=100, b4=-2,   b5=-0.06

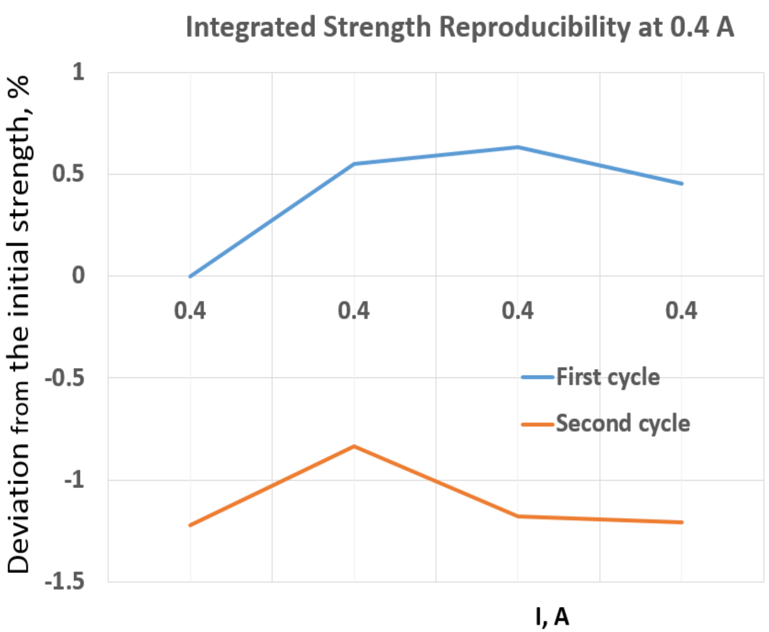
Quadrupole Geometric Harmonics

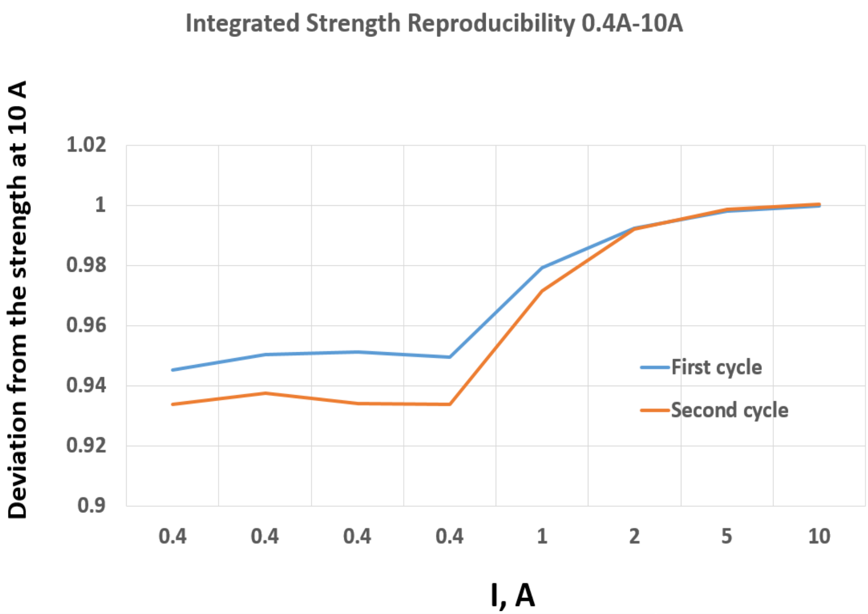




- *Geometric harmonics were determined by averaging after measurements with ramping current up from -10 A to +10 A.*
- *In this case excluded: external fields, iron and superconductor hysteresis.*
- *After the cold test magnet was tested at the room temperature at very low current 0.4 A.*
- *All harmonics are less than 10 units at 10 mm radius and meet specifications.*

Quadrupole Field Reproducibility



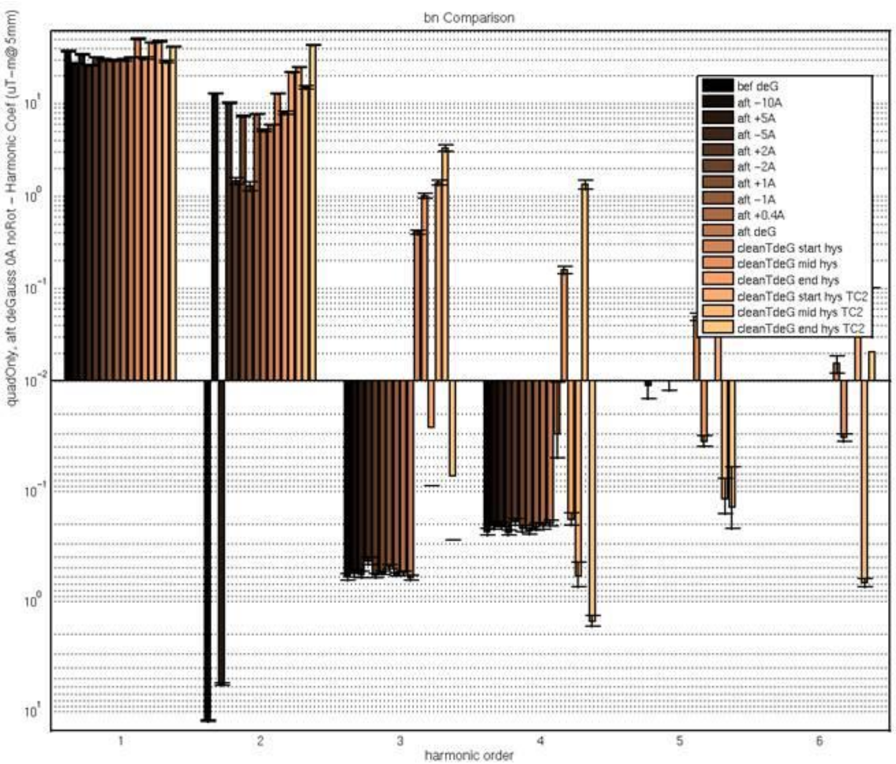


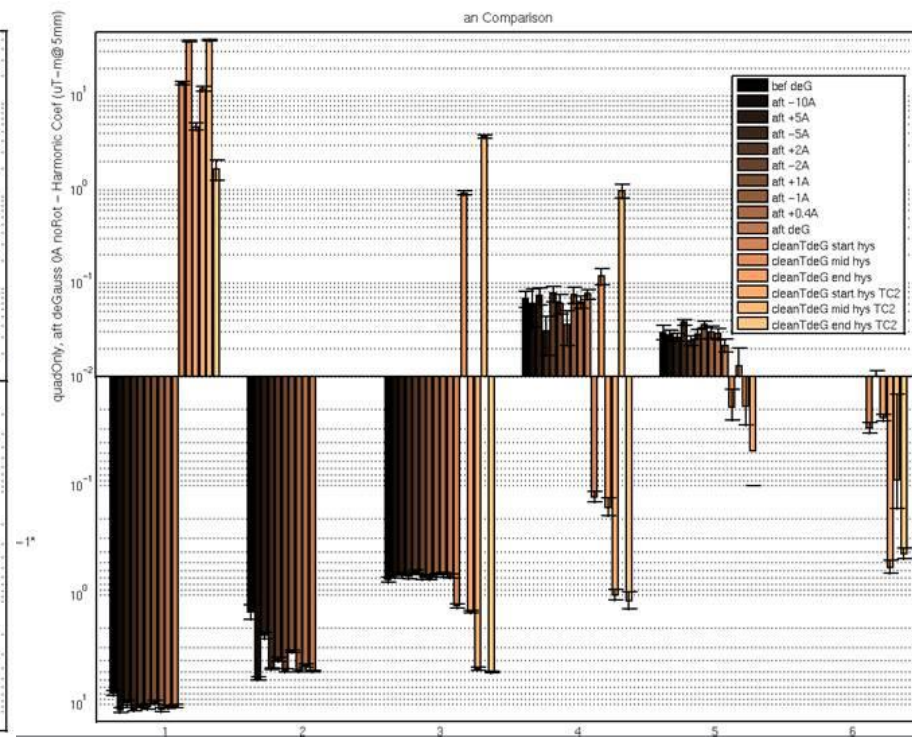
1) Certainly above 2 A current, the repeatability looks very good: better than 0.1%

2) For 0.4 A the difference in means is about 1.5% (+/- 0.3%),
but there may be a very significant systematic error in comparing these because
It was set the current by hand - it could have easily been 0.005A (1%)

The goal for the reproducibility is 1 % and could be reached by using standardizing cycles. It was verified during prototype tests.

Residual Integrated Quadrupole Field at Zero Current





At zero current in the quadrupole all remnant field absolute harmonics are less than 50 uT-m at 5 mm reference radius or 2.2 Gauss for 0.23 m magnet effective length.

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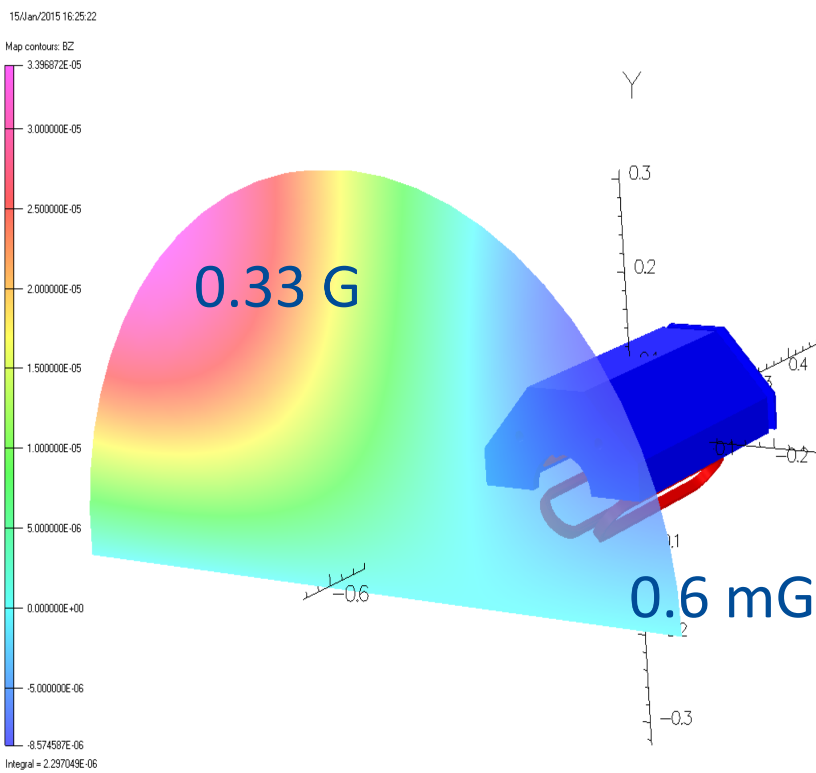
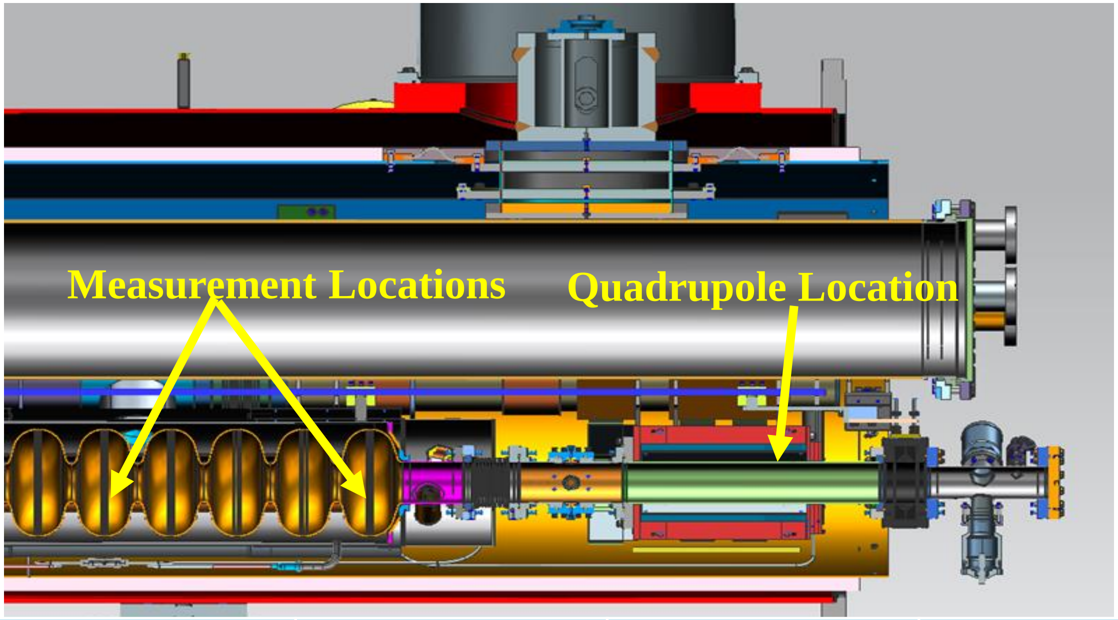
Magnet Fringe Field at Peak Strength

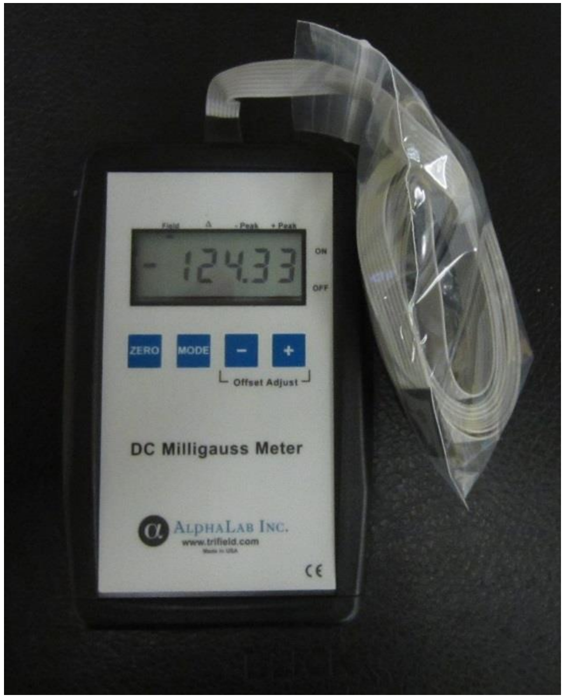


- *This fringe field Bz=0.33 Gauss at 0.4 m will be during Linac operation and the peak magnet strength.*
- *SCRF cavities are very sensitive to external fields during cooling down. During cavity cool down, all magnet currents will be zero.*
- *The only residual magnetic fields will be due to the iron yoke. The yoke will be degaussed before magnet installation and in the cryostat.*
- ***It was measured less than 0.5 mGauss the magnet fringe field at zero current inside the SCRF ferromagnetic shield !***

- *The peak field from the quadrupole of 2 T strength, dipole of 0.005 T-m at the distance 0.4 m (SCRF shield area) is 0.33 Gauss.*
- *The fringe field from the pair of current leads with 10 mm between them at +/- 50 A is 2 mGauss. There is no specs for the magnet fringe field.*

Magnetic Field inside the Cryoperm 10 Shield





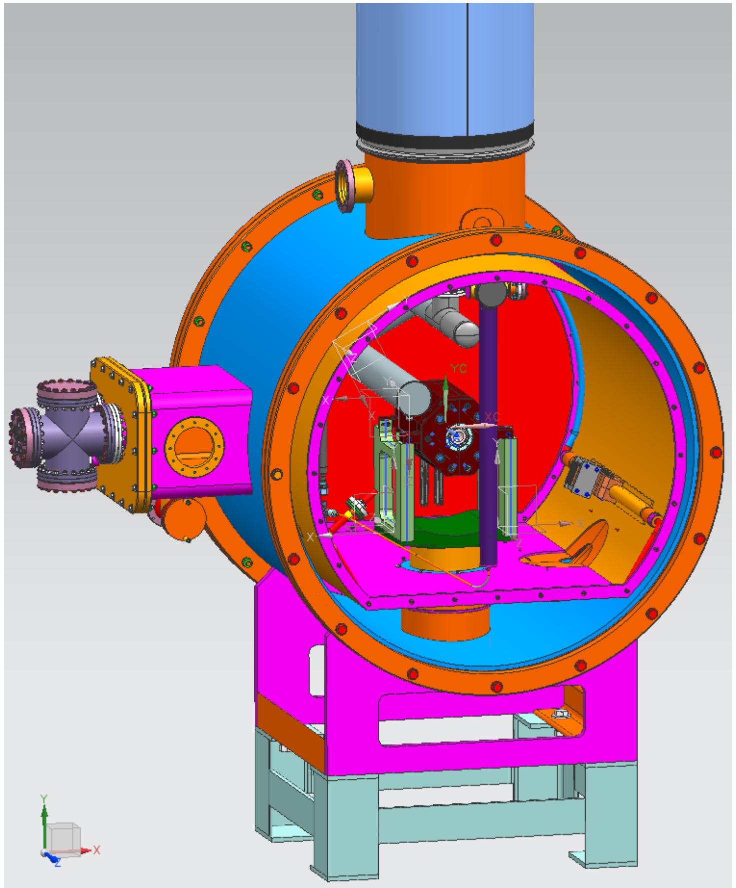
	Cell 1 (- Quad) [milliGauss]	Cell 1 (+Quad) [milliGauss]	Difference [milliGauss]
B_x	+7.7	+7.8	-0.1
B_y	+0.8	+0.3	+0.5
B_z	-2.2	-2.4	+0.2
	Cell 5 (- Quad) [milliGauss]	Cell 5 (+Quad) [milliGauss]	Difference [milliGauss]
B_x	0.0	-0.1	+0.1
B_y	-0.1	-0.1	0.0
B_z	-1.4	-1.5	+0.1

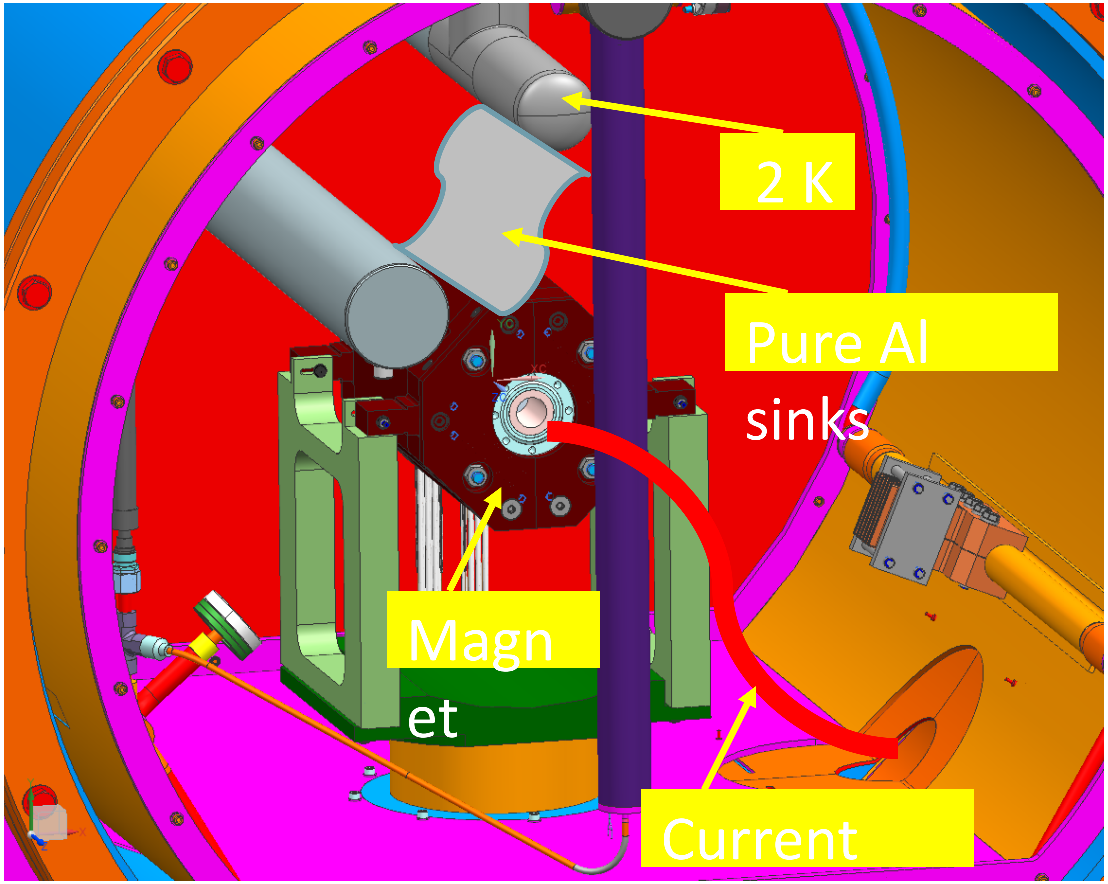
Accuracy +/- 0.5 mG

***Conclusion**: There is an insignificant effect on the field at the cavity from remnant field in the quadrupole.*

Curtis Crawford

Conduction Cooling Test at STC cryostat





The main goal of this test is to confirm the efficiency of magnet conduction cooling at 2 K having the same configuration as in the Cryomodule.

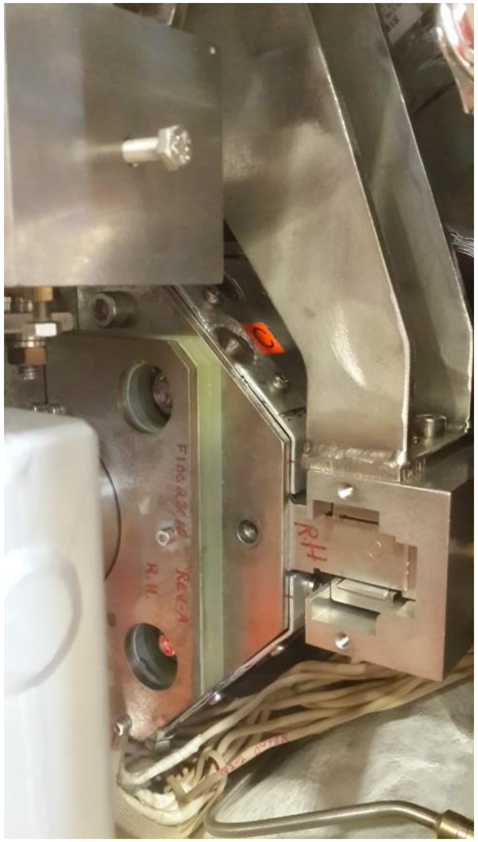
Test Results

- *At a 50 A current, field distortion was measured to be 0.01 % for the quadrupole, and 0.3 % for the dipole.*
- *At a 1 A current, field distortions were measured to be 0.3 % for quadrupole, and 3 % for the dipole.*
- *The field measurement at 180 K and 0.1 A current confirmed field distortions related to the external field effects.*
- *The measured geometric harmonics are less than 10 units.*
- *The degaussing was limited by bipolar KEPCO power supply to +/- 10 A. It did not show the degaussing effect. Room temperature and conduction cooling tests will be continued.*
- *The needed magnet good field area is less than 1 mm with the beam size < 0.25 mm, and 0.5 mm magnet installation tolerance.*

Magnet Installation in Cryomodule (1)

Magnet delivered in MP9.

Post for clamping magnet around a beam pipe in MP9.



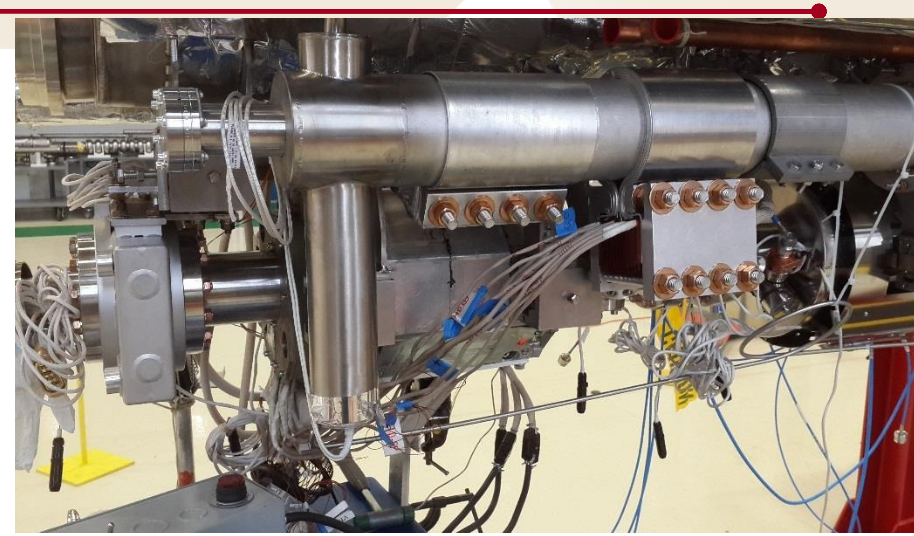
Magnet on adjustable bearings.

Sub-assembly in central Bld.

Thermal sink clamps.

Magnet Installation in Cryomodule (2)

Magnet leads and instrumentation wiring.

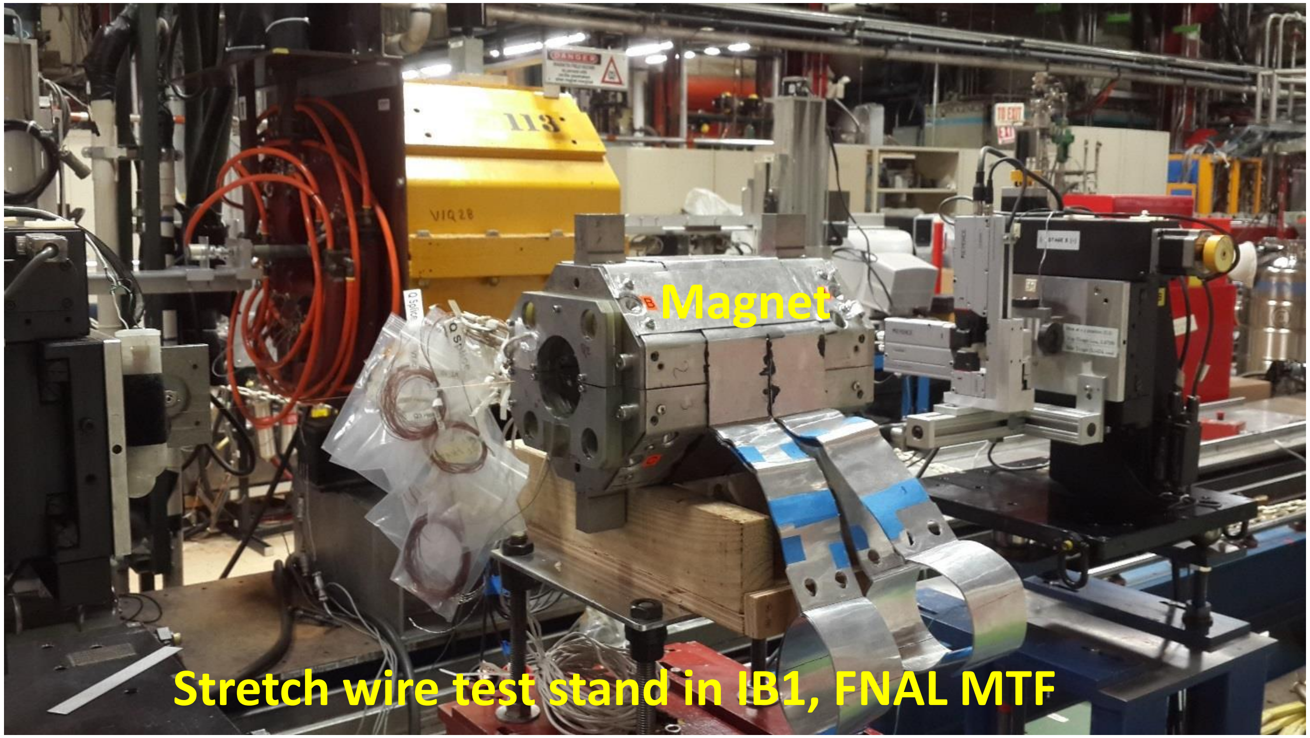


Magnet heat sinks clamps installed.

Superinsulation applied.

External power leads flags.

Quadrupole Magnetic Center Position

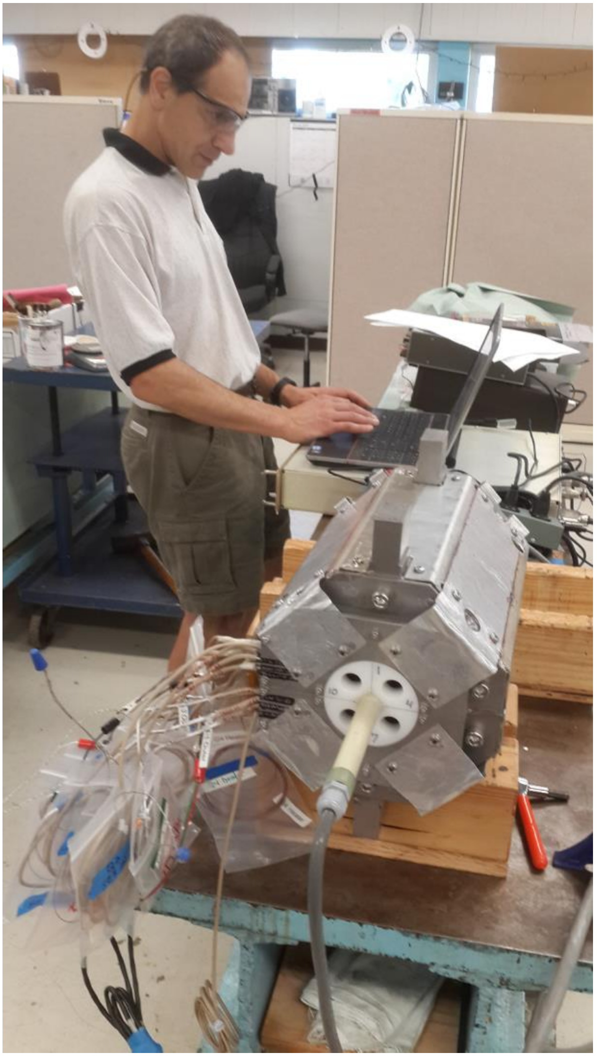


- *Each magnet was tested at room temperature by a stretch wire technique.*
- *The quadrupole magnetic center position was transferred on 8 reference points at magnet ends.*

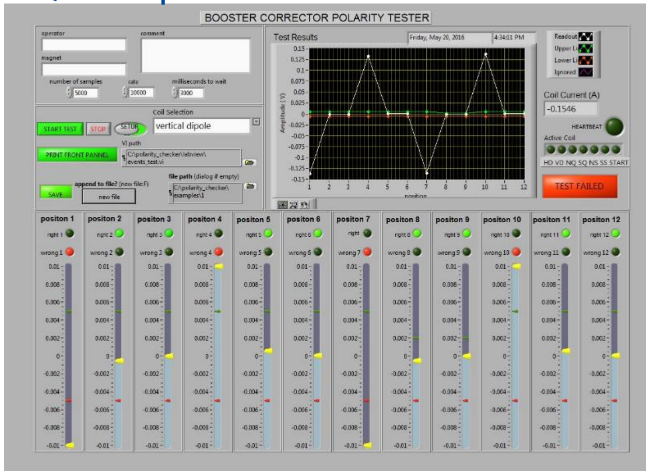
Technical status

- Technical challenges:
-     - Complicated coils wiring for 3 magnets in one.
-     - Magnet and current leads conduction cooling.
-     - Remnant magnetic fields and hysteresis effects at low currents.
- How they were addressed:
  - Designed and commissioned computer controlled magnetic field polarity checker.
  - Conduction cooling was extensively simulated, and verified by STC magnet test (FAC October 2015 and LCLSII-EN-0577-R0).
  - Designed degaussing and standardization procedures which will be verified at #3 and #4 magnets cold tests integrated with SLAC power supply.

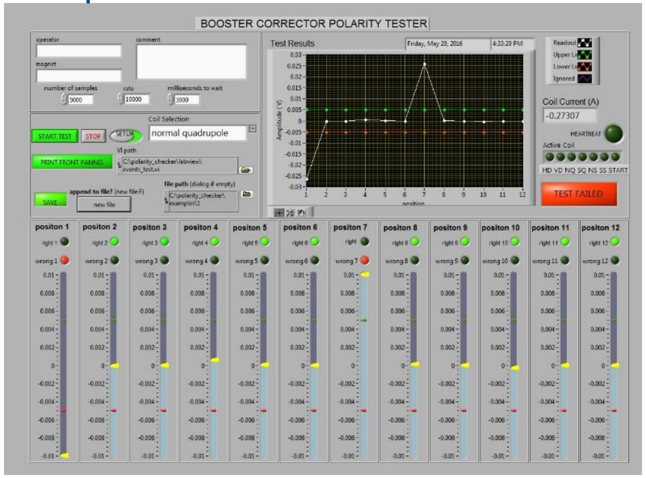
Magnetic Field Polarity Checker



Quadrupole Field

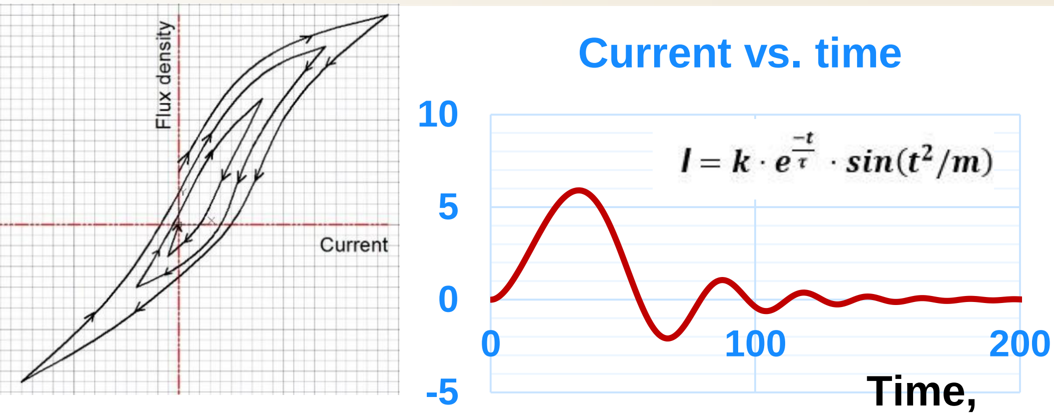


Dipole Field

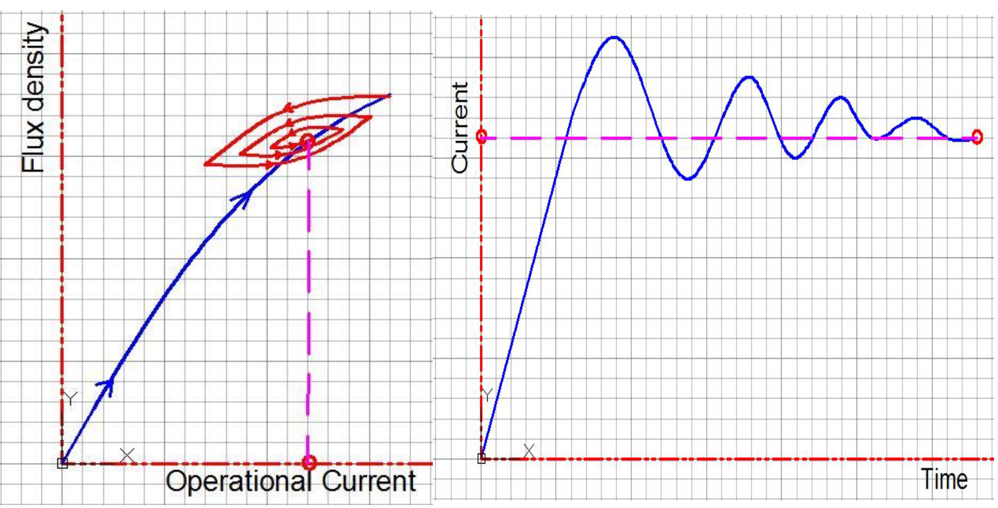


- *Magnet have 24 coil leads.*
- *Leads must be spliced correctly to form a quadrupole, and dipole configurations.*
- *The polarity check is a critical step for the verification.*
- *This check is included in the acceptance of magnet delivered from industry.*

Magnet Degaussing and Standardization



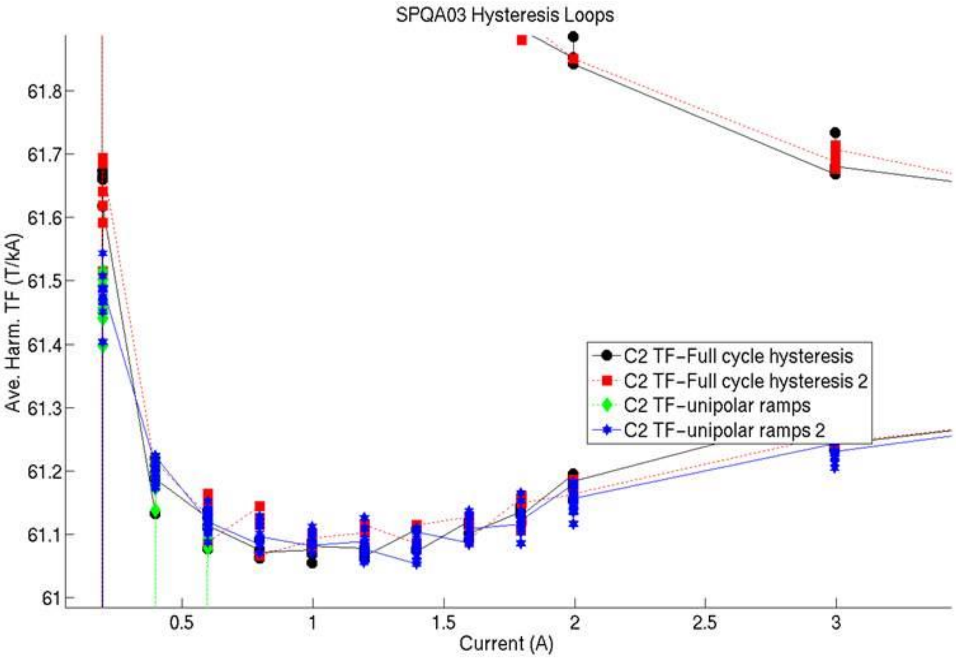
Degaussing cycling



Standardization cycling

- *One of the most critical magnet specifications is to provide quadrupole, and dipole corrector field reproducibility +/-1%.*
- *Most of uncertainty in the magnet strength is caused by the iron core hysteresis effects. To reduce these effects will be used degaussing and standardization procedures. Bipolar cycling will be used for magnets degaussing.*
- *During operation the quadrupole magnet will not change the polarity, and unipolar full or partial cycling will be used for the quadrupole standardization procedure (see LCLSII-4.5-PP-0731-R0)*

Magnet #3 Cold Test Results



Control panel Degaussing

- *The quadrupole integrated strength transfer function is 0.123 T/A.*
- *The specification for the magnet strength reproducibility is +/- 1%.*
- *After the degaussing for full or unipolar current changes the transfer function reproducibility is 0.1/61.1*100= 0.16%, or +/-0.1% for currents 0.4 A-2 A.*
- *For currents above 2 A the reproducibility is even better.*
- *Measurements made by rotational coil system integrated with SLAC PS and QD.*

Summary

- *Magnet design is complete.*
- *Magnets serial production transferred to industry.*
- *Fabricated two magnet prototypes.*
- *First magnet installed in the FNAL cryomodule prototype.*
- *Fabricated magnet #3 and started fabrication #4.*
- *Prepared the test plan for magnets #3 and #4 including integration with SLAC PS and PS control system.*
- *Started the cold test of #3 integrated with SLAC PS. The performance of PS and QD systems is verified. Magnet reached the peak operating current 20 A without quenches.*
- *Verified degaussing cycling of integrated Magnet-PS. Magnetic measurements by rotational coils are in progress.*

First LCLS-II Cryomodule Successfully Tested !

Now all cryomodules fabricate, tested and most of them installed in the LCLS-II tunnel.
DOE approved the High Energy upgrade to increase the beam energy by adding more cryomodules.