Compact Superconducting Magnets for Linear Accelerators

V. Kashikhin, N. Andreev, J. DiMarco, N. Kimura, M. Tartaglia, Y. Orlov, A. Yamamoto

Workshop on Special Compact and Low Consumption Magnet Design, CERN November 26–28, 2014.

Outline

- ILC full scale splittable quadrupole design
- ILC Quadrupole fabrication
- ILC Quadrupole tests at FNAL and KEK
- Quadrupole Doublet for FNAL ASTA #CM3
- Design and fabrication splittable quadrupole for KEK-STF
- Novel approach to LC integrated magnet system
- Quadrupole magnetic center stabilization
- Summary

US-Japan Collaboration

- Fermilab and KEK in 2008 had an agreement to collaborate in the area of ILC superconducting magnets design and tests.
- Akira Yamamoto proposed to investigate the possibility of using splittable conduction cooled quadrupole for ILC.
- The main goal is to perform the magnet final assembly out of clean room around a beam pipe. This also drives the magnet design to the conduction cooling.
- There were designed, fabricated, and tested two magnets:

1. Full scale ILC quadrupole with the peak integrated gradient 36 T;
2. Short quadrupole for KEK-STF Cryomodule 1 with the peak integrated gradient 3 T.

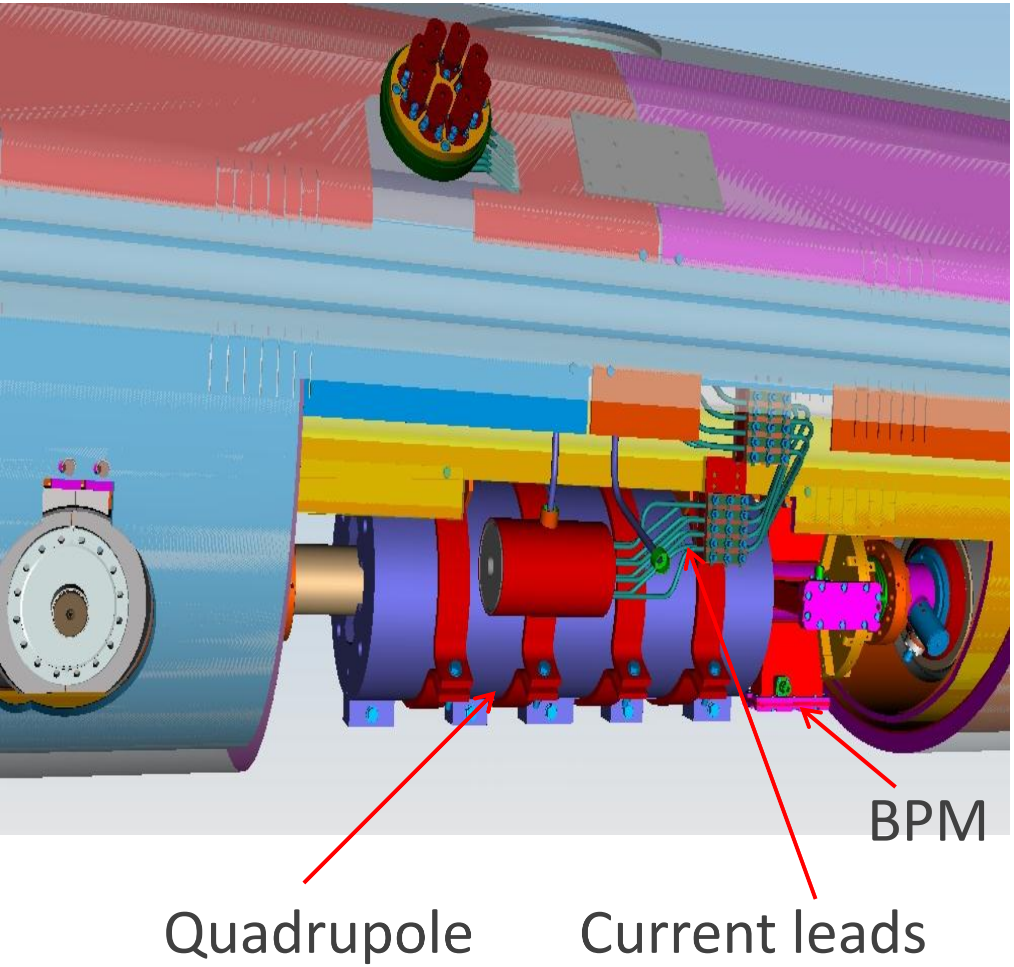
Program Main Goals

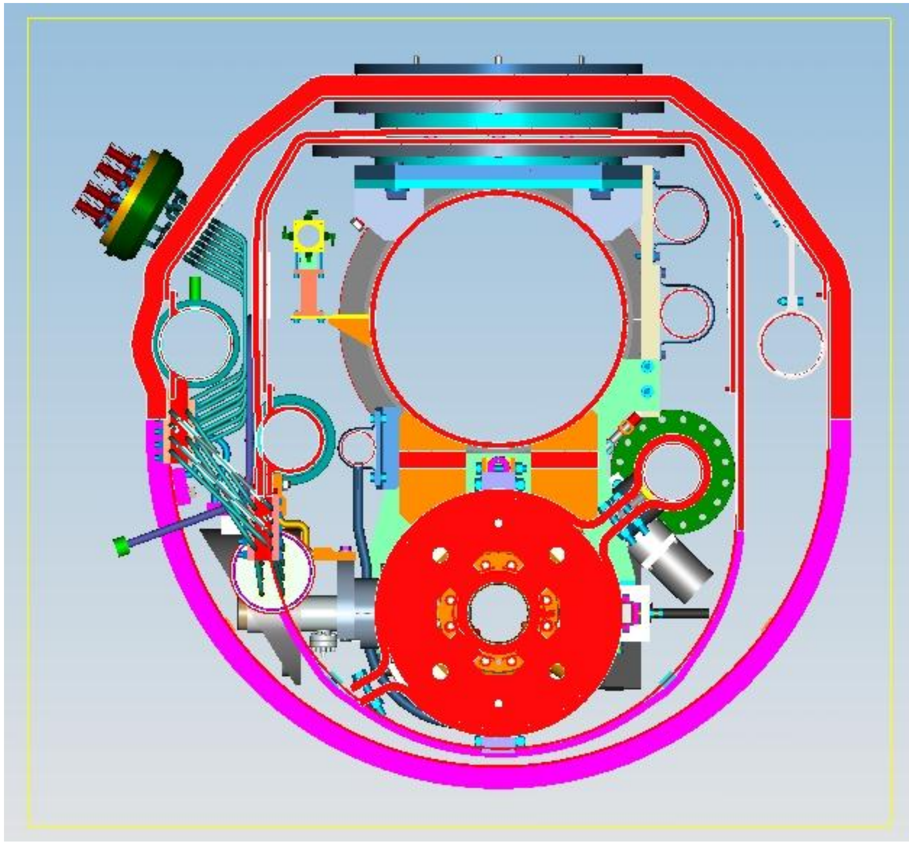
- ***Split Quad # 1:***
  - Full length ILC prototype, quad only
    - 4K bath tested; modified, many tests completed in conduction cooling mode
    - Preliminary result: meets ILC requirements
- ***Split Quad #2:***
  - ~half ILC quad length, quad+2 dipoles
    - Just installed in 1st KEK ILC Cryomodule (2014 beam tests)
    - Lead, instrumentation wire final details to be completed
- ***Split Quad #3:***
  - Identical to #2, constructed
    - To replace #1 in KEK/Toshiba/FNAL conduction-cooled test stand (a new procedure, some modifications required)
    - 2014 performance tests

ILC/XFEL/ASTA/LCLS-II Quadrupole Specifications

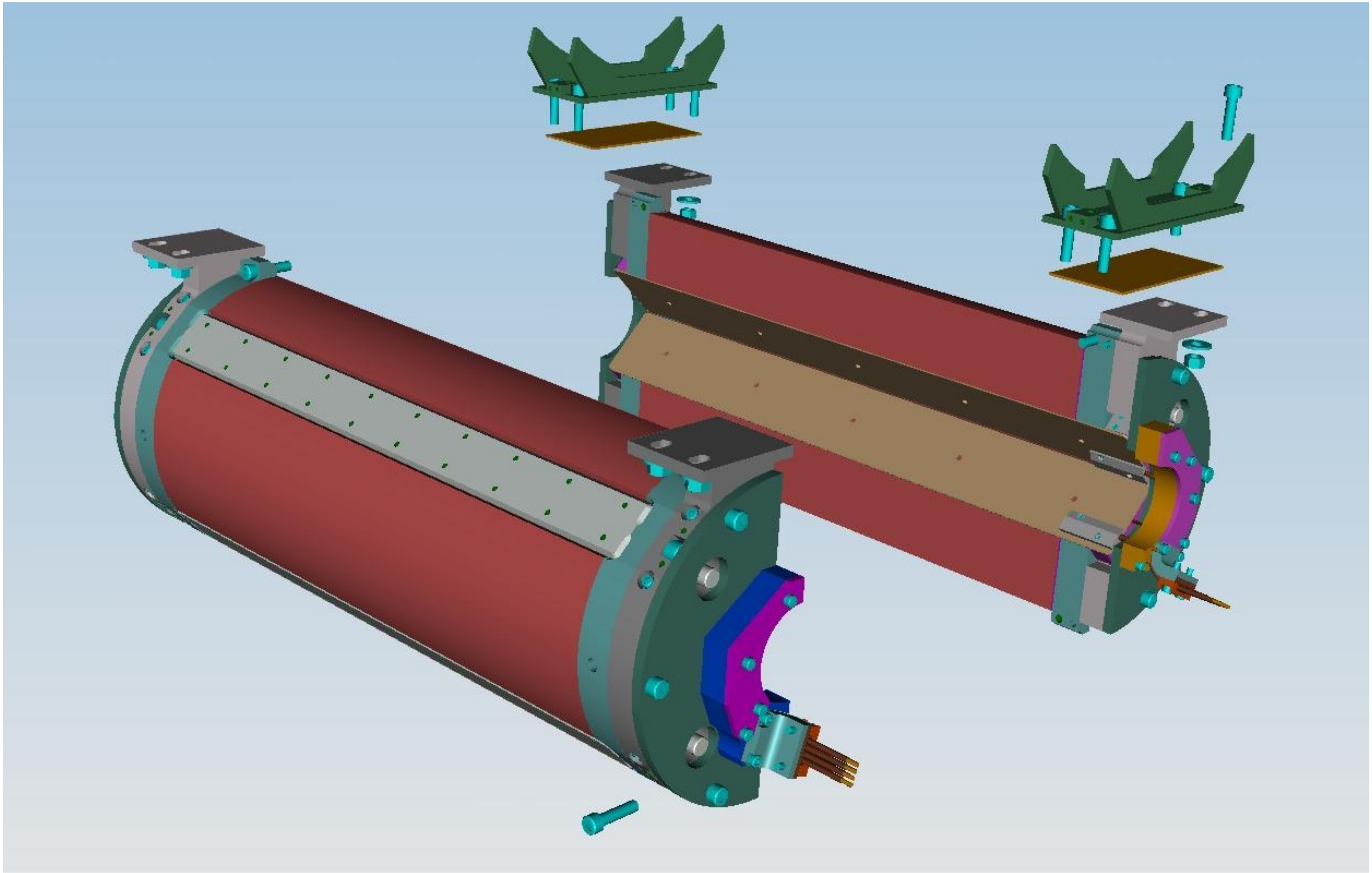
Parameter	ILC	XFEL	ASTA	LCLS-II
Integrated gradient, T	36	5.2	3.0	2.0
Aperture, mm	78	78	78	78
Magnet effective length, mm	660	195	2x190	230
Peak gradient, T/m	54	26.7	19.2	8.7
Peak current, A	100	50	50	50
Superconductor diameter quad/dipole, mm	0.5	0.55/0.7	0.5	0.5
Superconductor filament size quad/dipole, um	3.7	6.0/3.5	3.7	3.7
Dipole corrector integrated strength, T-m	0.075	0.009	2x0.005	0.005
Max magnetic center offset in cryomodule, mm	0.3	0.5	0.5	0.5
Total length, mm	800	300	650	350
Quantity required	560	103	-	36

First Concept of ILC Splittable Quadrupole

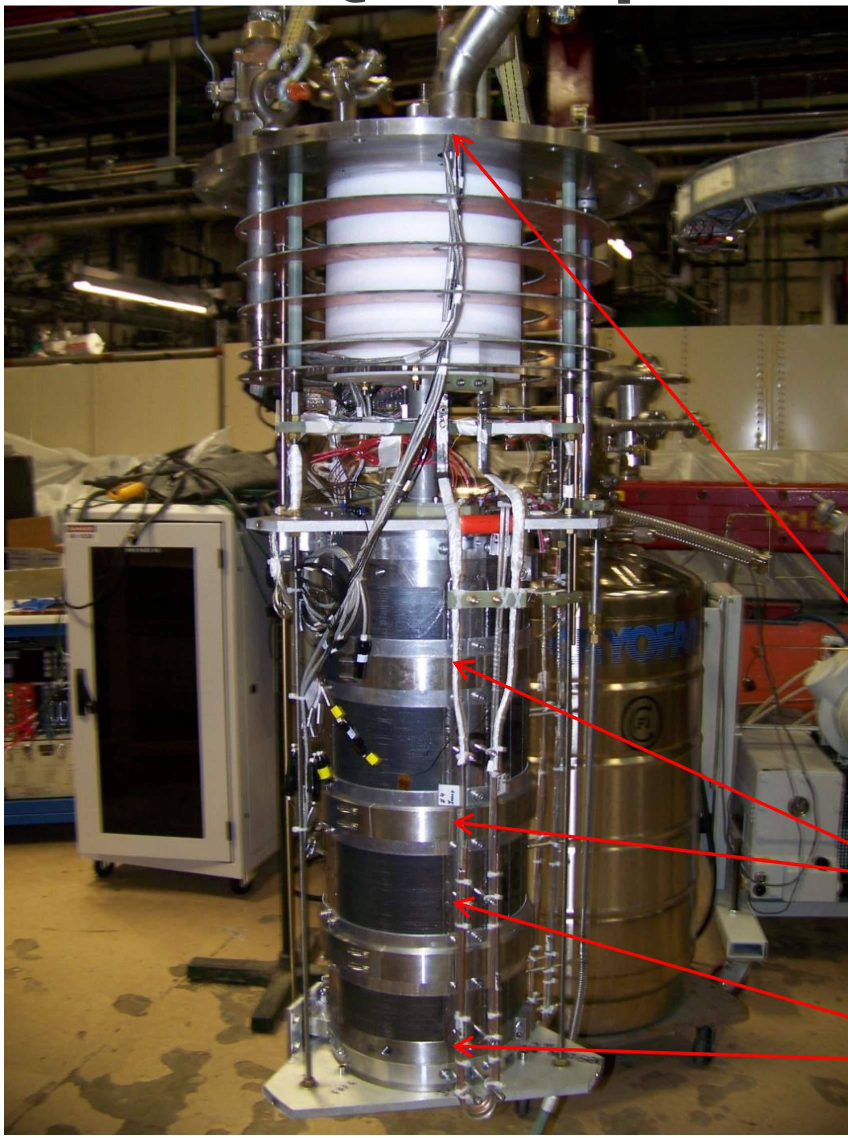


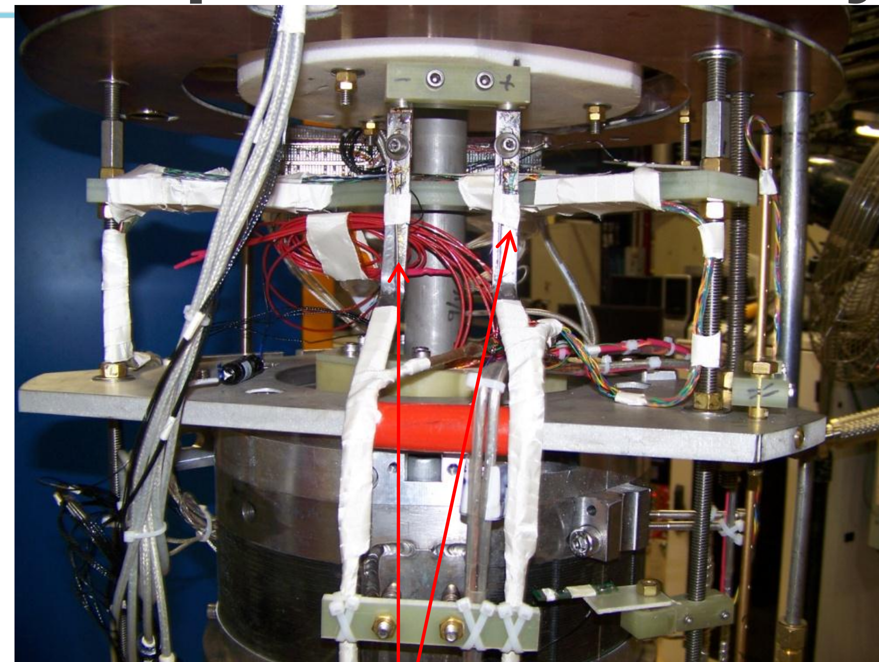


ILC Two Halves of the Quadrupole



ILC Quadrupole with Top Head Assembly





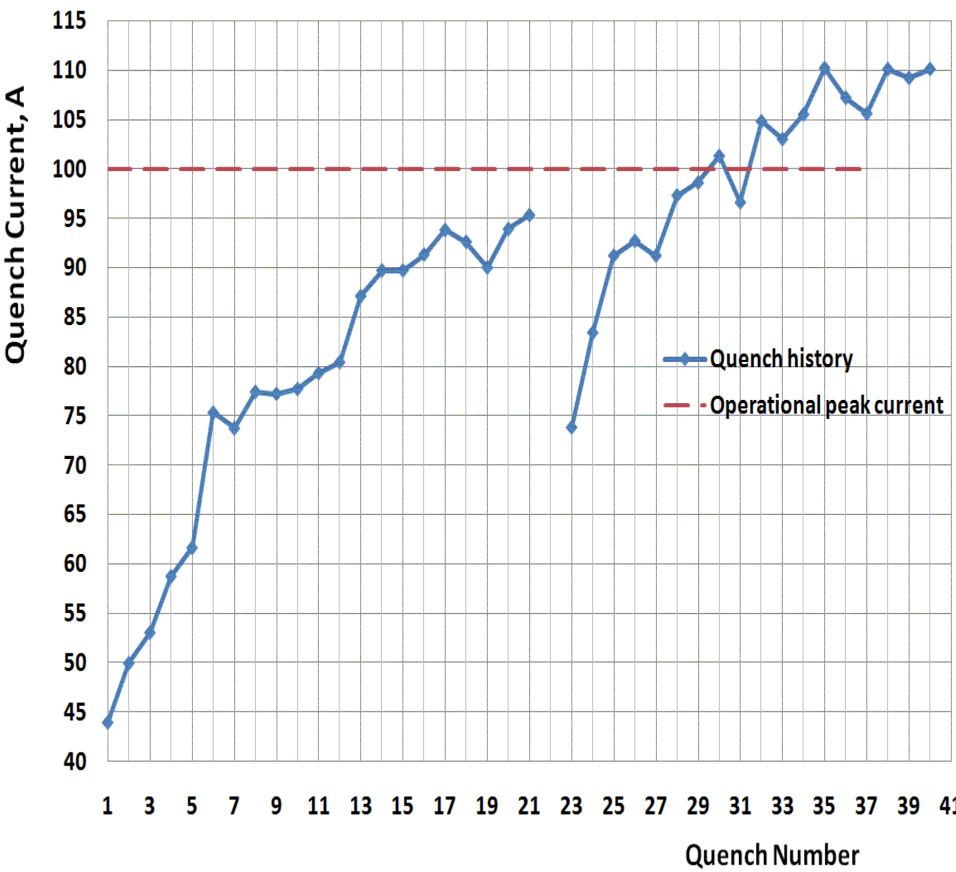
Current leads

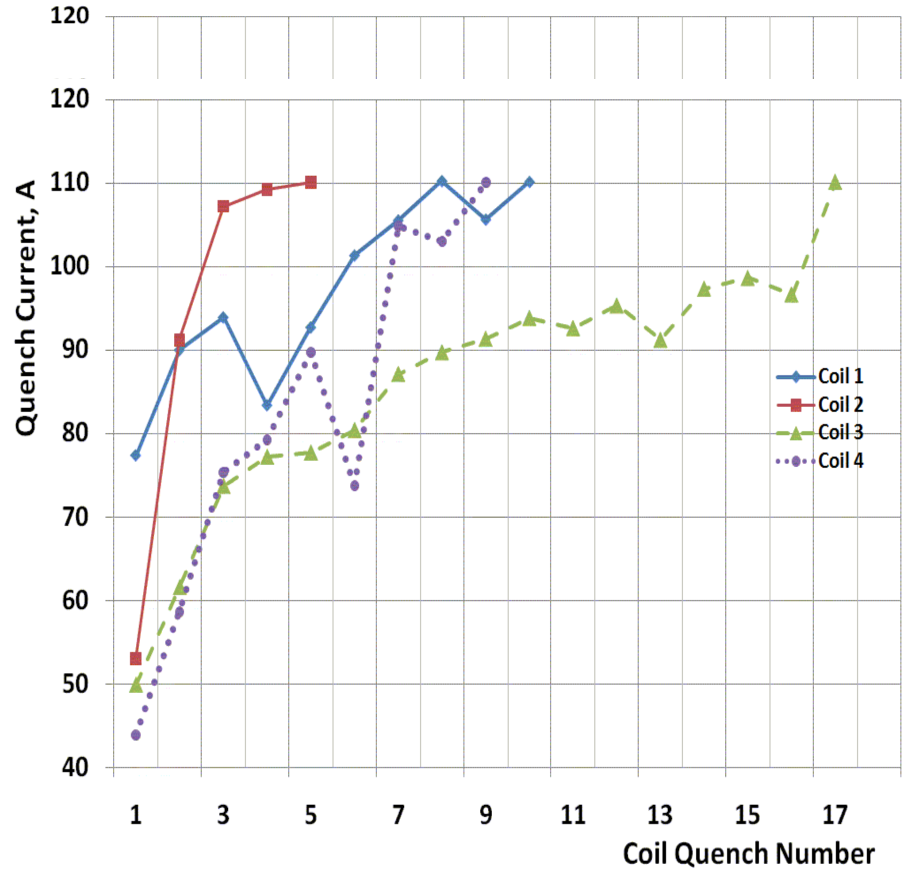
Top head

Quadrupole yoke

Two quadrupole halves clamping rings

ILC Split Quadrupole Quench History



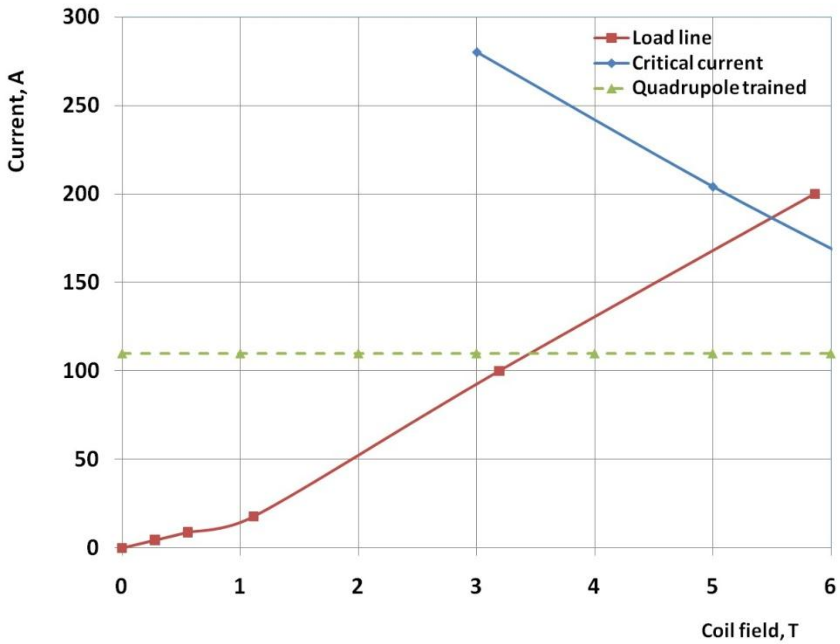


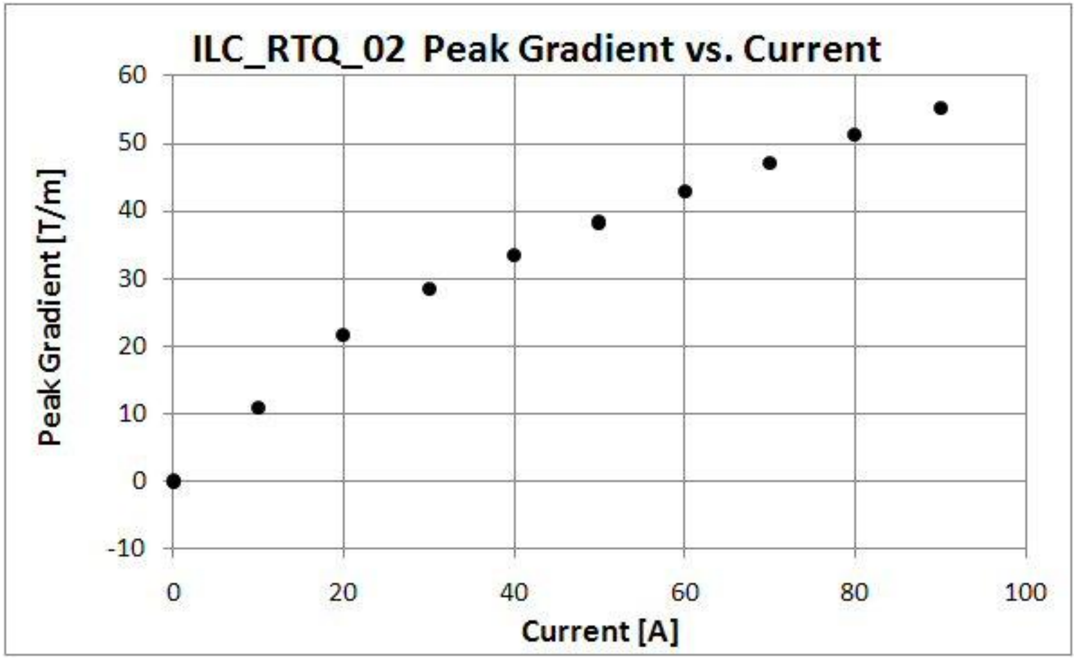
Quench history for two thermal cycles

Quench history for each coil

Peak operating current is 100 A. Magnet trained at FNAL in a bath cooled mode up to 110 A – limit for the Stand 3 peak safe pressure during uncontrollable quench.

ILC Quadrupole Critical Current & Load Line

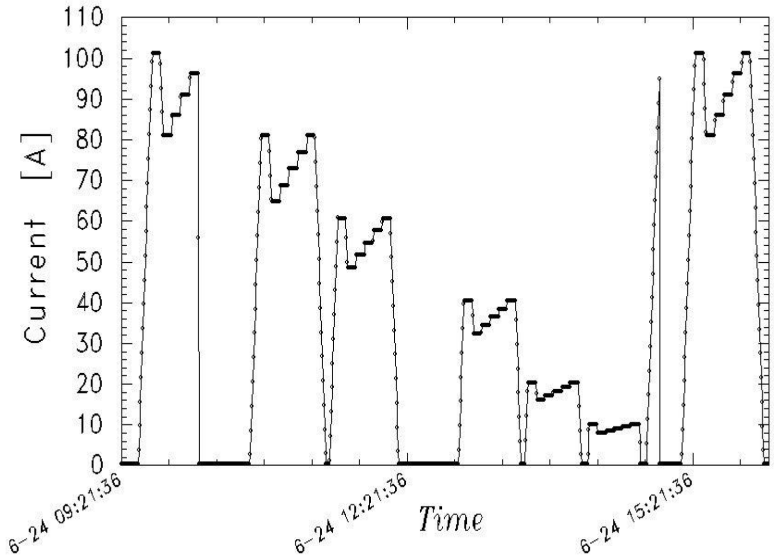


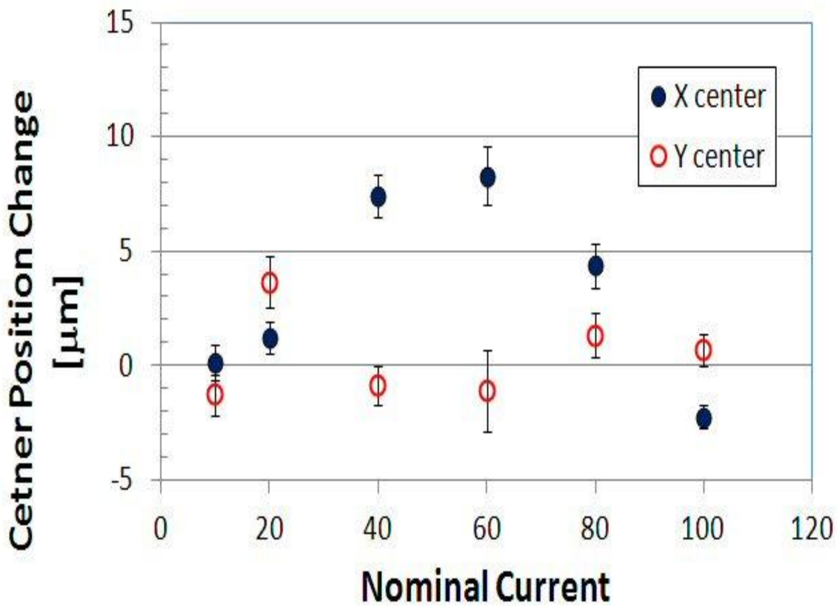


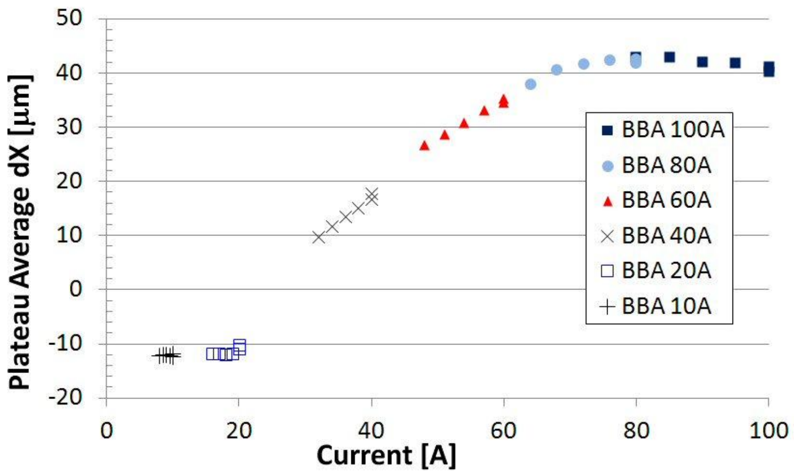
Peak operating current 100 A.
Magnet trained up to 110 A (green line).
Critical current (short sample limit) for this magnet is 185 A at the coil field 5.4 T.

At 90 A current the quadrupole reached the specified peak gradient 54 T/m.

Center Stability Measurement Results







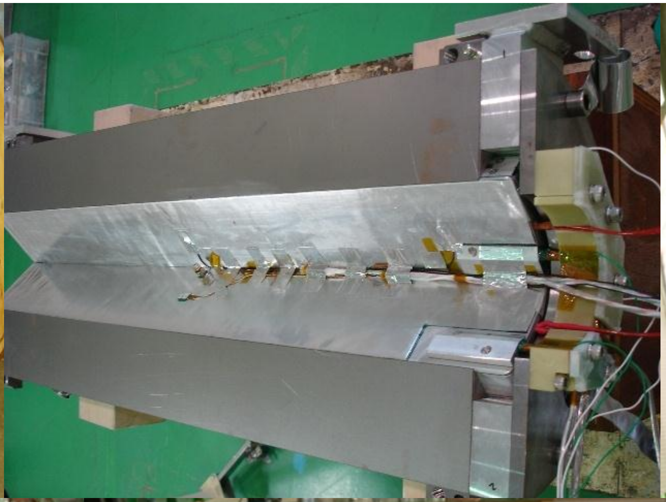
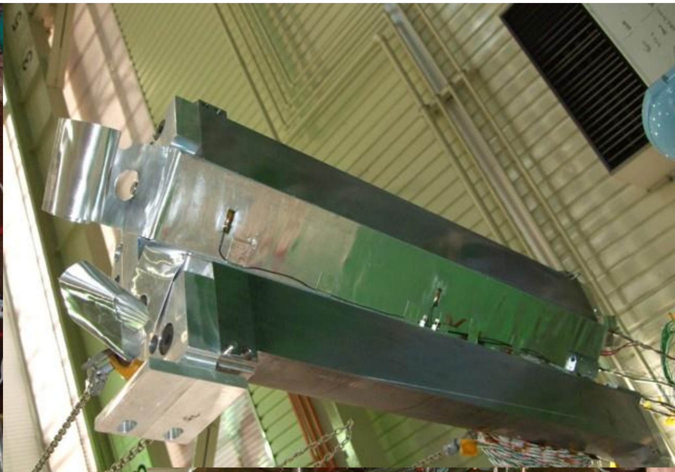
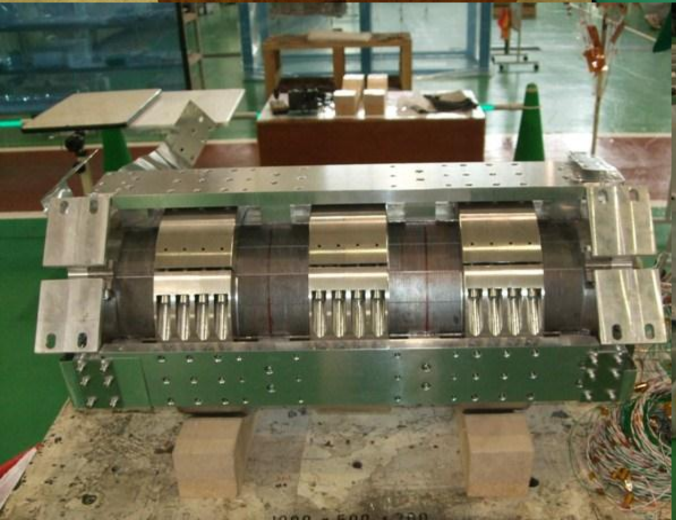
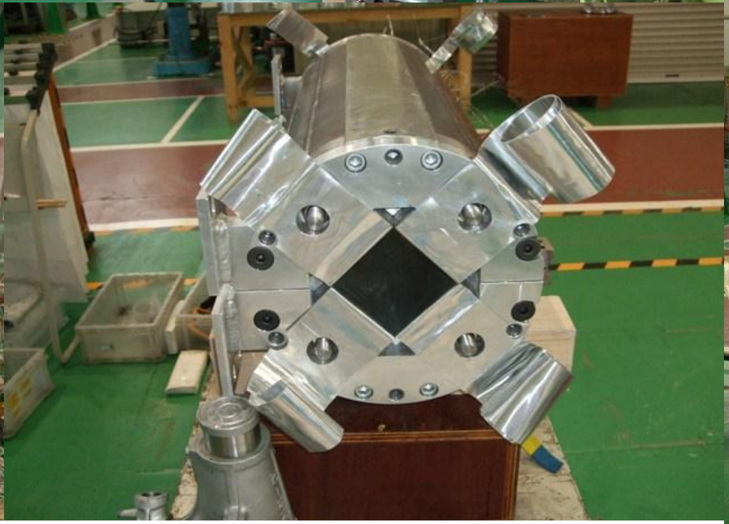
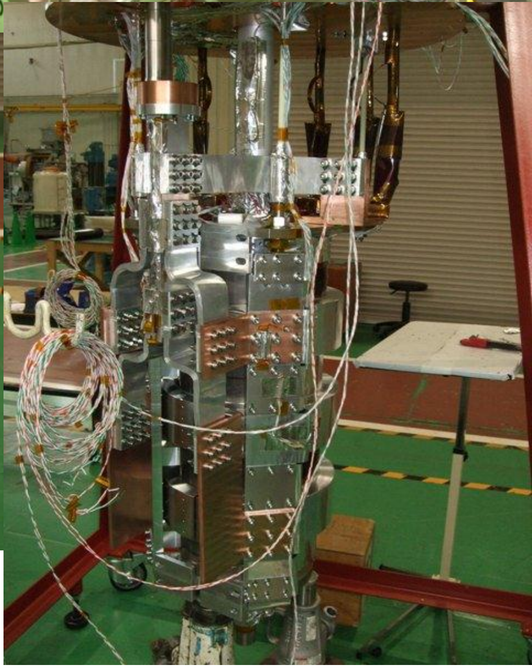
Measured Quadrupole magnetic center stability for BBA -20% of dx=8-10 µm (goal=5), dy<5 µm.

Small partial gaps <0.3 mm between two halves of the yoke in the split plane.

Collaboration FNAL-KEK-Toshiba

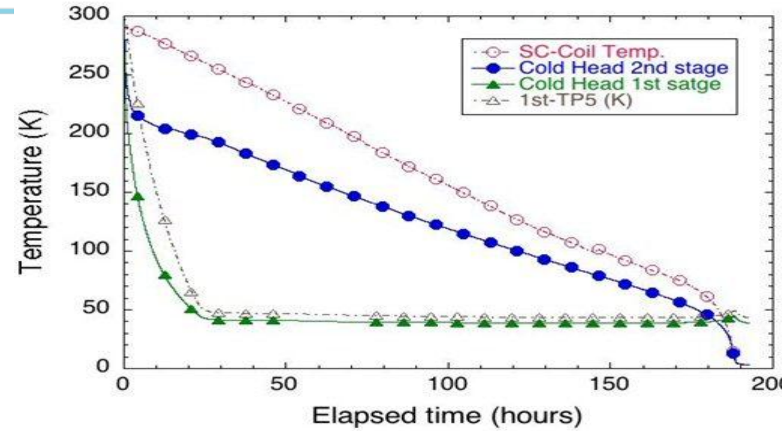
- Ship magnet to KEK (Dec. 2011).
- New Conduction-cooled cryostat design & fabrication (1.5 W cryo-cooled vacuum vessel; HTS leads; warm bore).
- Machine yoke faces flat, add 0.5 mm iron shim)
- Glue 5N purity Al cooling strips to coil faces for the conduction cooling.
- Assemble into cryostat (June 2012).
- Thermal, Quench Tests at KEK, to 30 A, (Sep. 2012).
- Ship the cryostat with the magnet to FNAL and test it with high precision magnetic measurements.

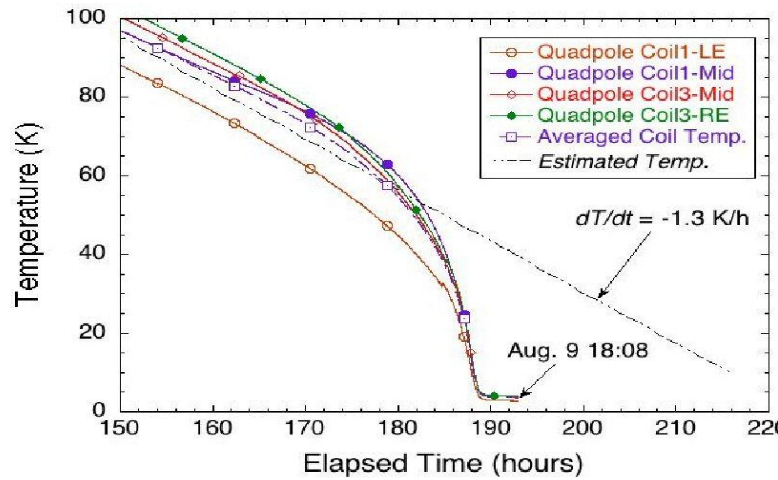
KEK-TOSHIBA Quadrupole Upgrade

1. Machined and shimmed split surfaces
2. Glued Al cooling foils
3. Added conduction cooling elements

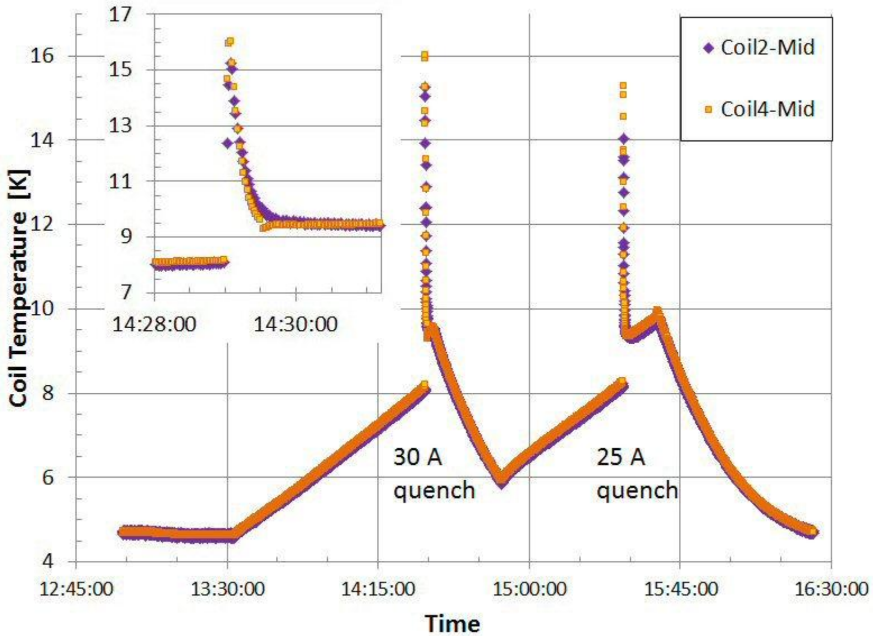
Conduction Cooling Test at KEK [1]



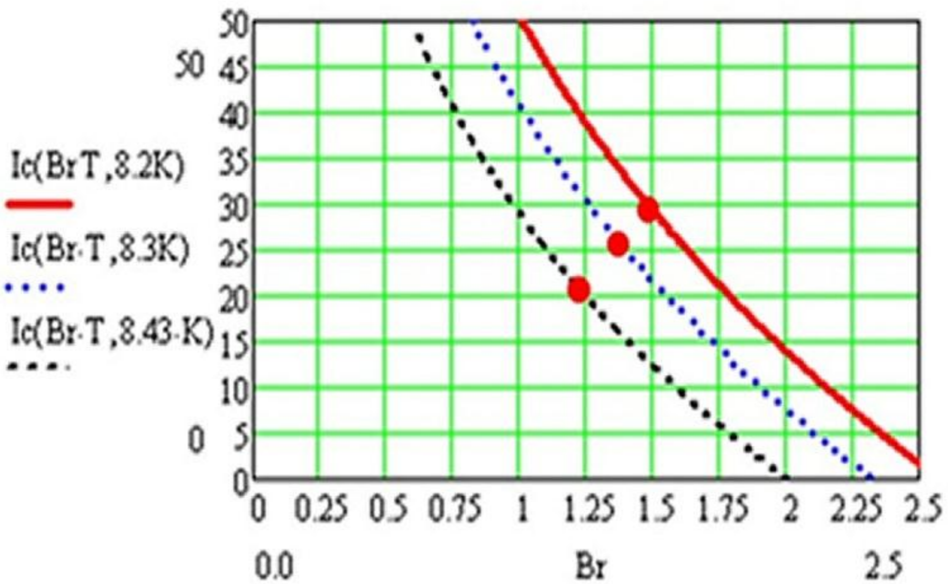


The KEK Test Stand was assembled and the magnet cooled down (8 days) to 4.5 K under supervision of Akira Yamamoto and Hitoshi Kimura

Conduction Cooling Tests at KEK [2]



Coil temperature rise due to background heat load when compressor was turned off with magnet powered at fixed currents.



The superconductor critical current as a function of coil peak field. Dots represent the quench currents (20 A, 25 A, 30 A) at elevated coil temperatures (8.43 K, 8.3 K, 8.2 K).

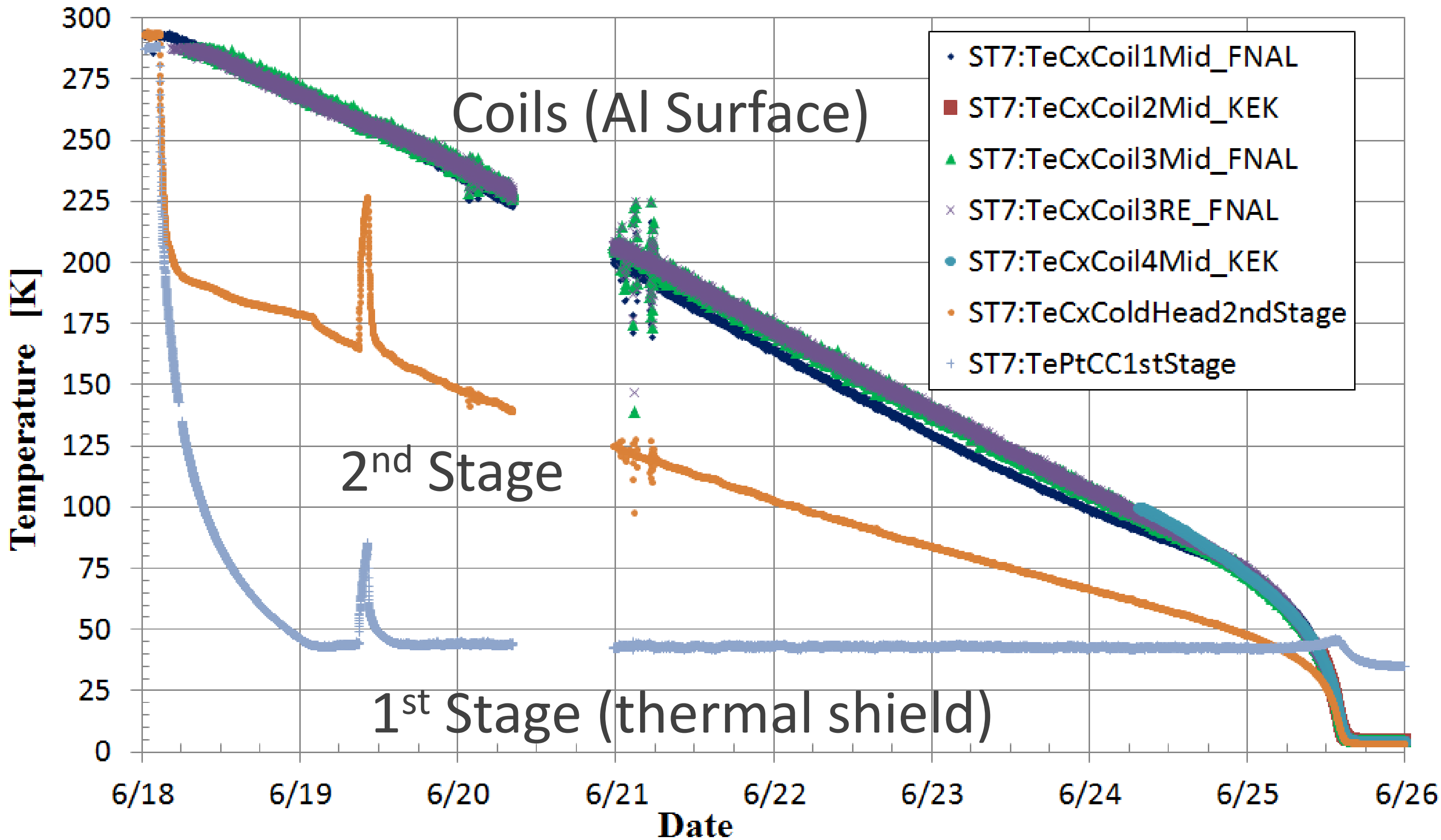
The magnet cooled by conduction with only a single cryocooler (1.5 W), and has a large temperature margin (at 30 A current, and 1.5 T, 8.2 K - 4.2 K = 4 K). This is a very promising result because in the cryomodule the quadrupole will be cooled to 2 K by a LHe supply pipe.

New Test Stand at FNAL

The KEK cryostat with cryocooler and ILC magnet inside was shipped to FNAL and became a main part of new Stand 7.
The magnet is cooled by Cryocooler (1.5 W on the cold head), and tested in a conduction cooling mode.
Cryostat has a vertical room temperature bore open at both ends for magnetic measurements.

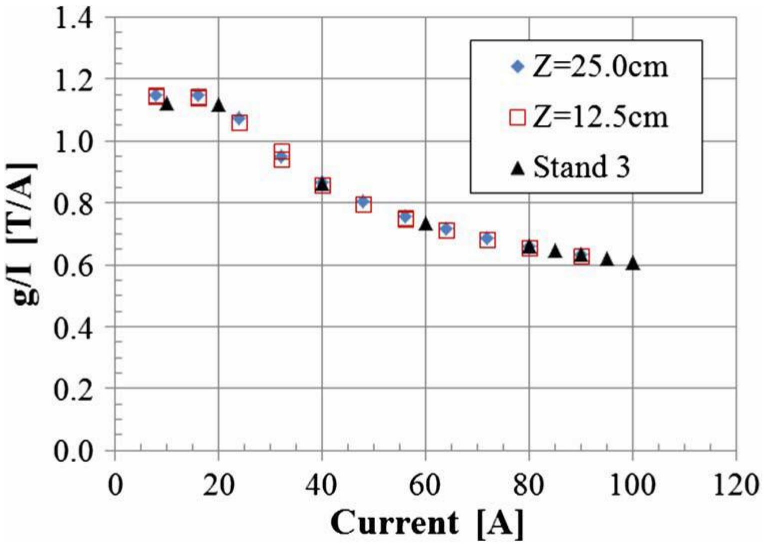
The ILC quadrupole was tested up to the max (110 A) current combined with a high precision magnetic measurements.

First Cool Down at FNAL

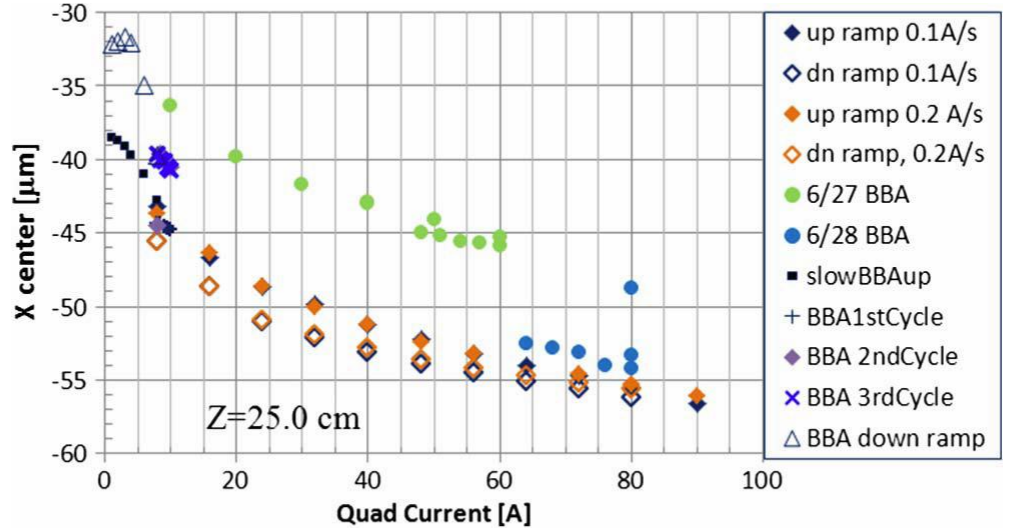


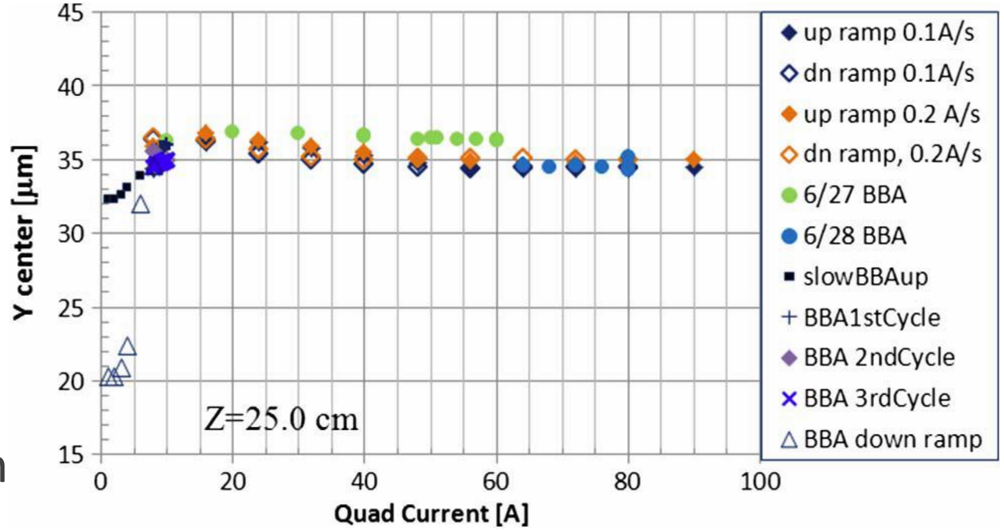
First Cool Down to 4K: 8 days, the same as at KEK.

Magnetic Measurements at FNAL



Normalized gradient vs. current.



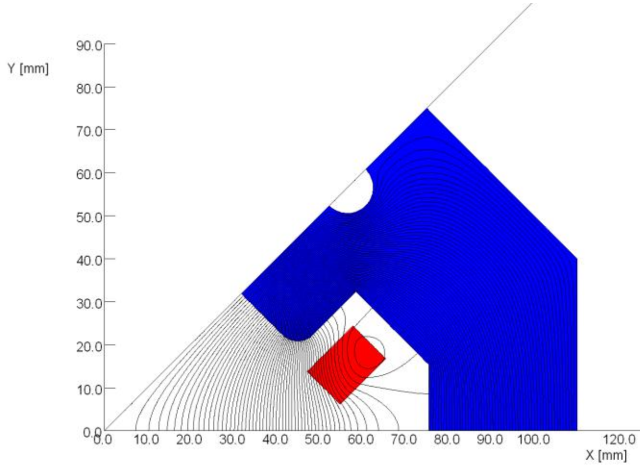


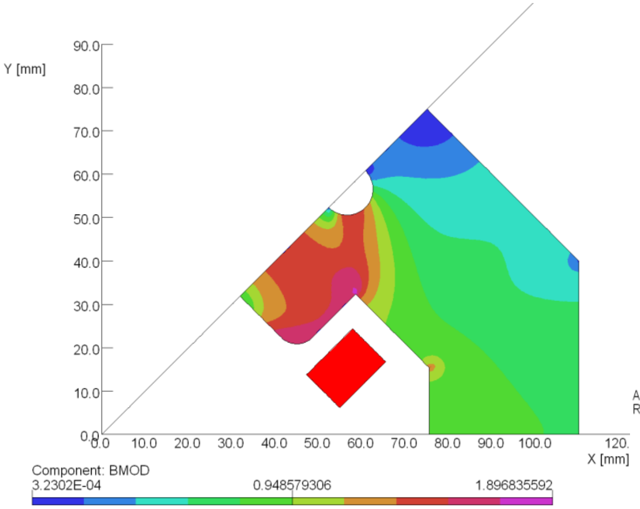
The measured field quality is better than specified 0.05% at 5 mm radius. The magnetic center shift for BBA is less than 5 um. But some unexpected shifts were observed probably caused by mechanical shift of rotational system bushings or the coil probe.

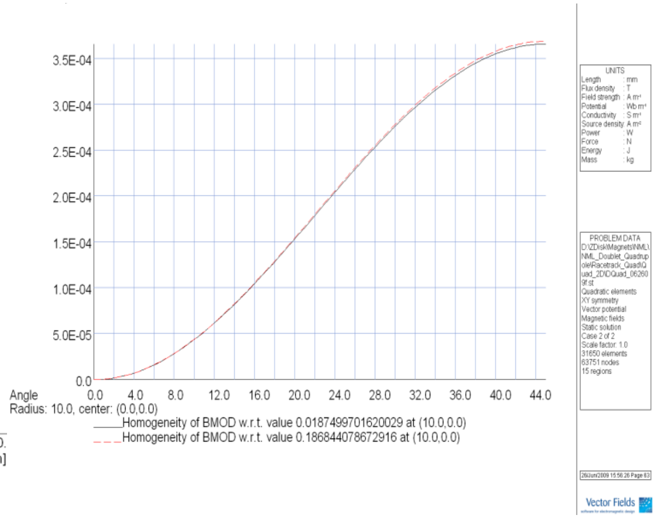
Magnet Package for KEK #CM 1

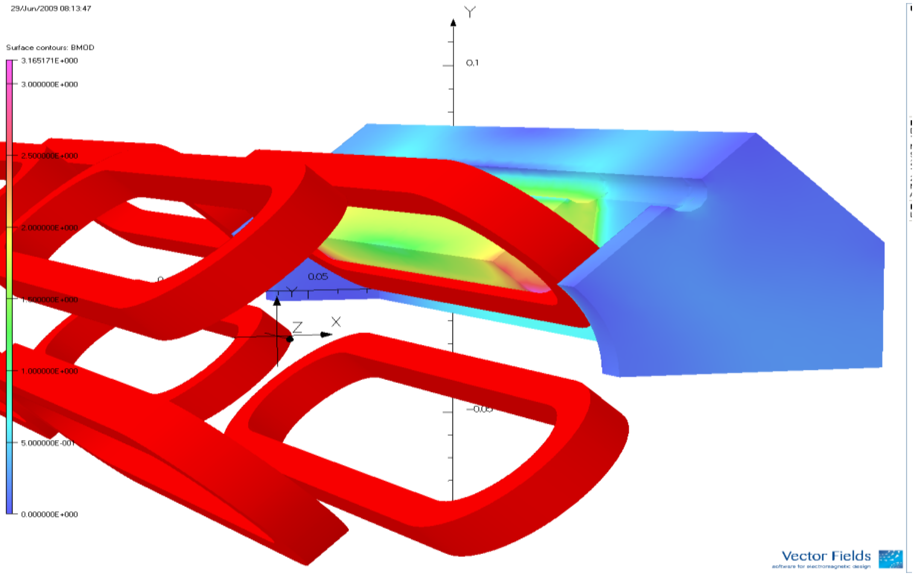
1. The first KEK-STF Cryomodule will be assembled and tested with the beam in 2014.
2. Akira Yamamoto proposed that FNAL built the splittable quadrupole for this Cryomodule.
3. Because the slot space is short it was decided to use one Quadrupole designed for ASTA Splittable Quadrupole Doublet.
4. Such approach saved time and funds of US-Japan collaboration.
5. Two magnets were built. One of them shipped to KEK, upgraded by Toshiba and installed in KEK-STF cryomodule.

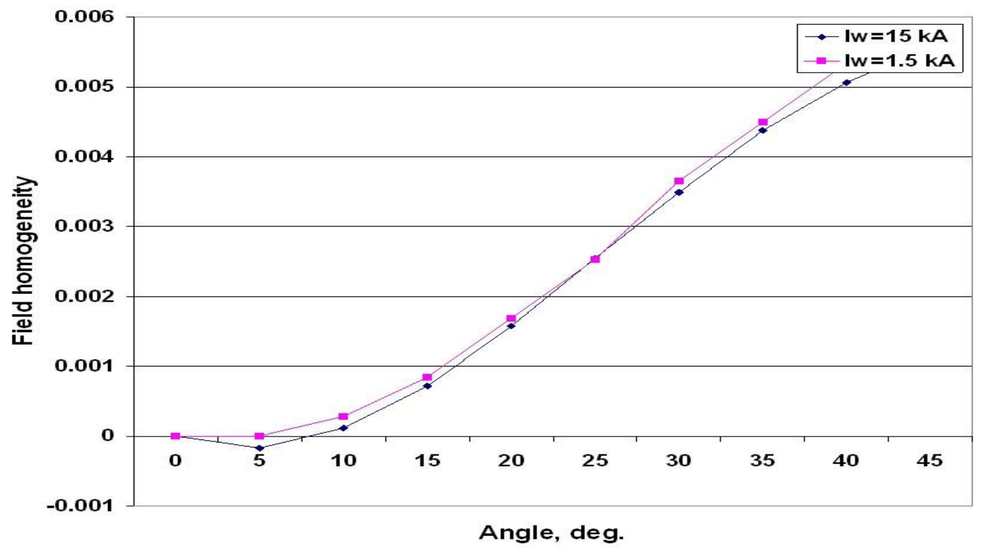
FNAL ASTA Quadrupole Doublet Magnetic Design





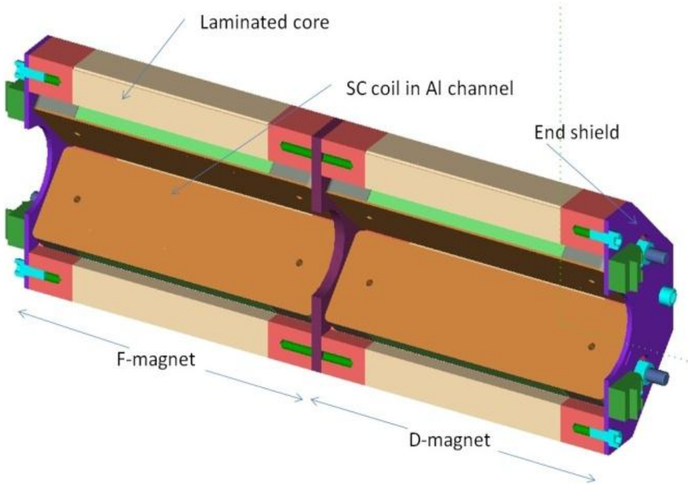


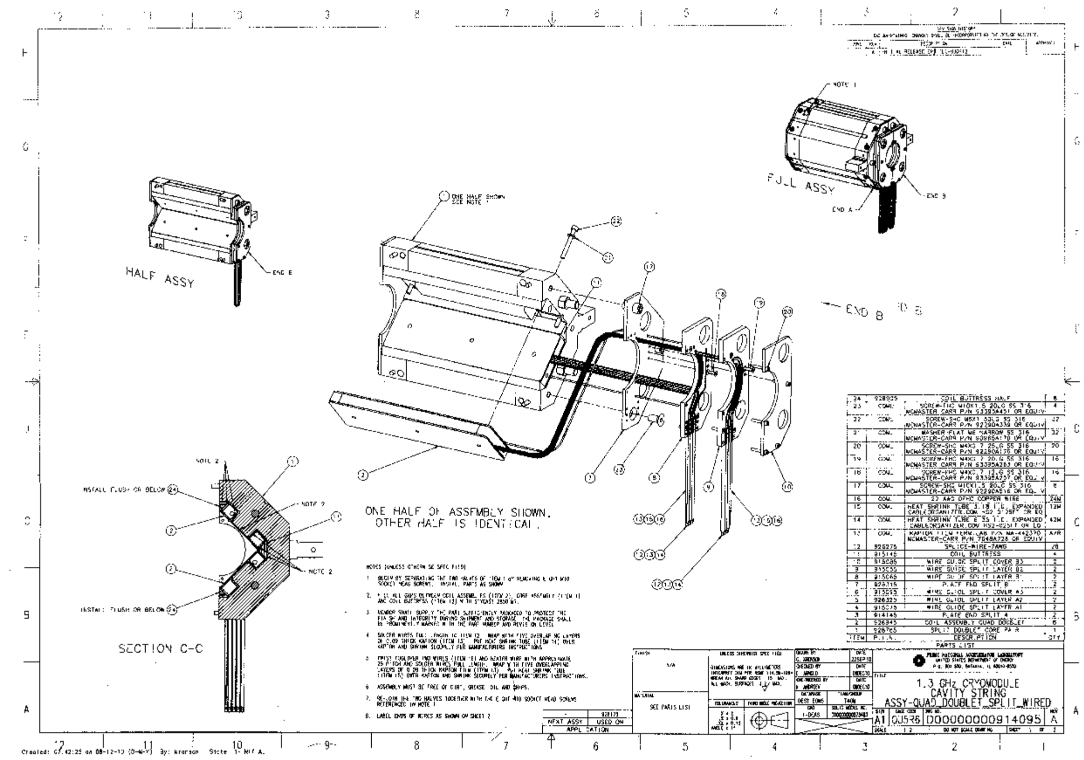




Integrated field homogeneity at 10 mm radius 0.6%, at 5 mm 0.18% (Spec. 0.5% at 5 mm).

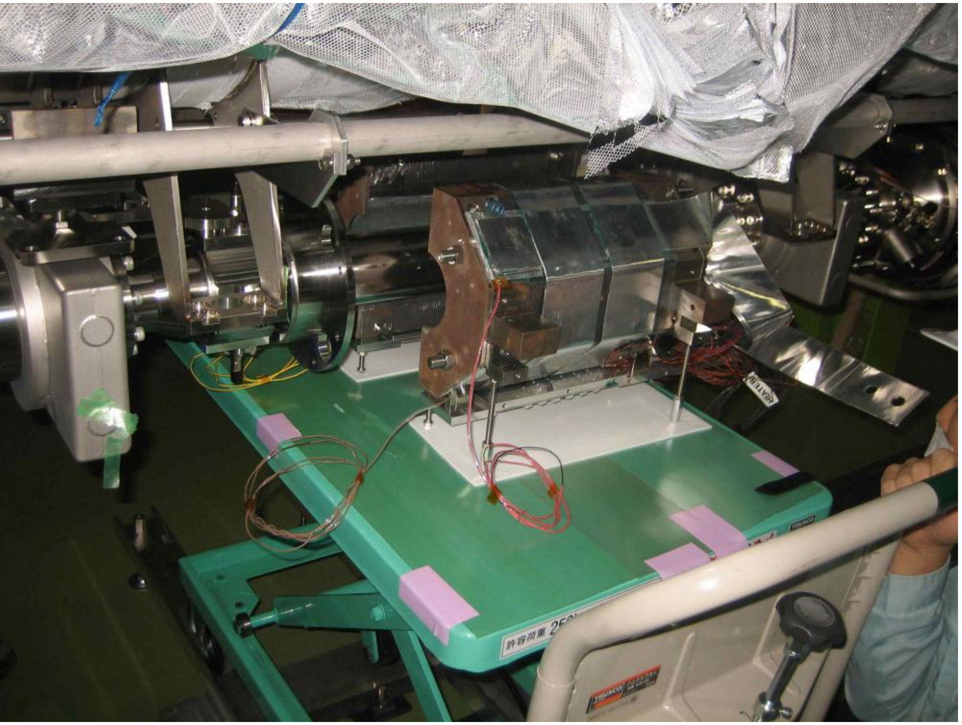
New Magnet for KEK-STF #CM1

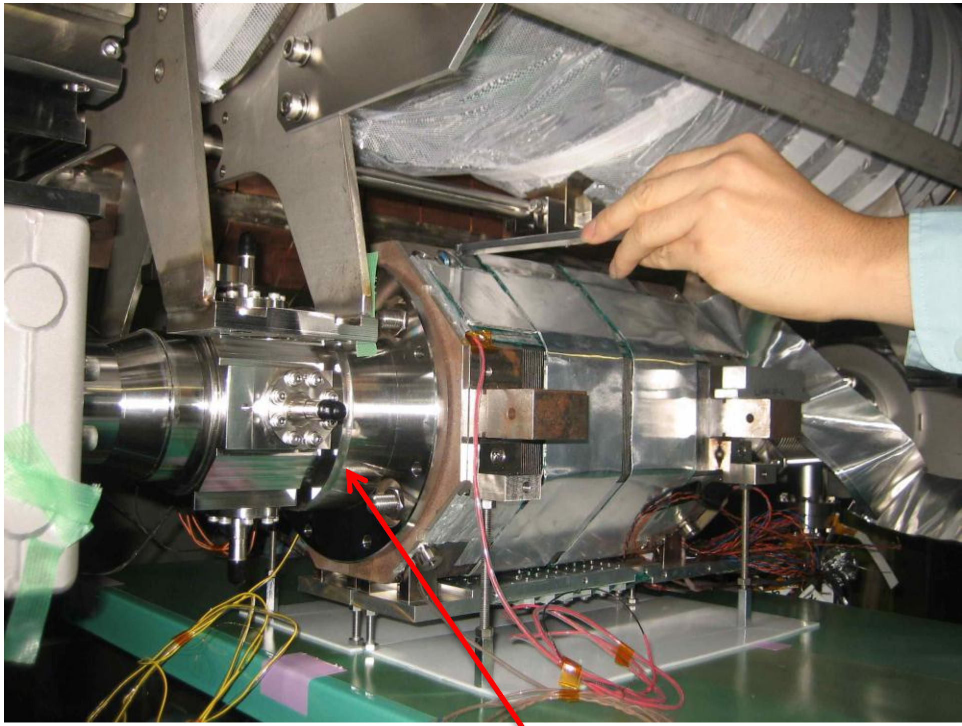




Because of a very tight schedule and space it was decided to use the Splittable Quadrupole Doublet design for ASTA (3 T integrated gradient), and manufacture only one part of the Doublet. The quadrupole is also combined with dipole correctors as in the Doublet.

Quadrupole Assembly around Beam Pipe

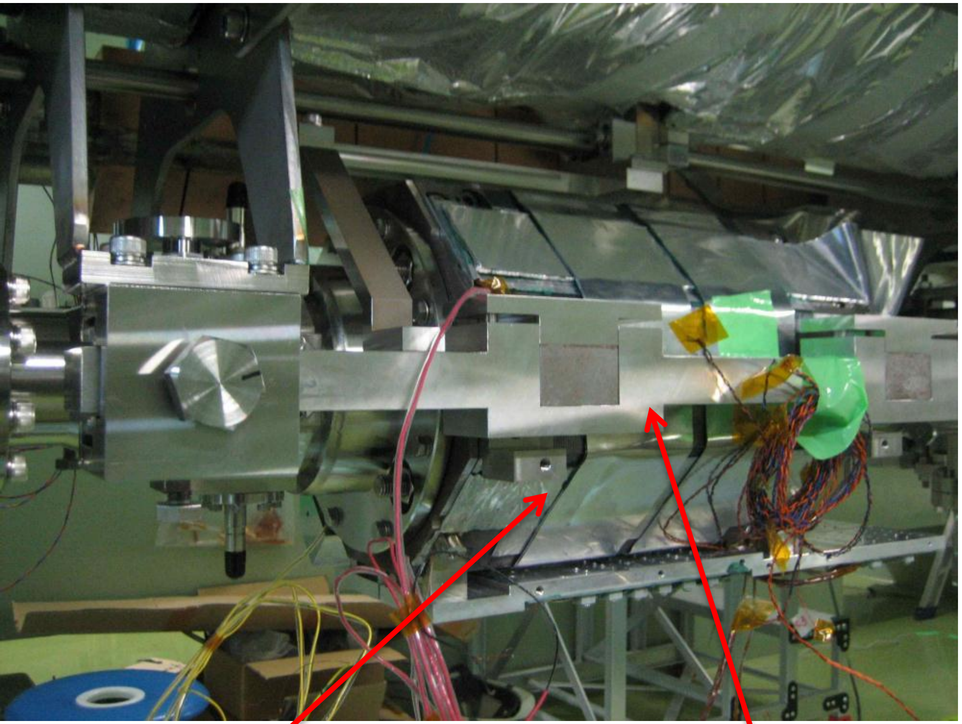


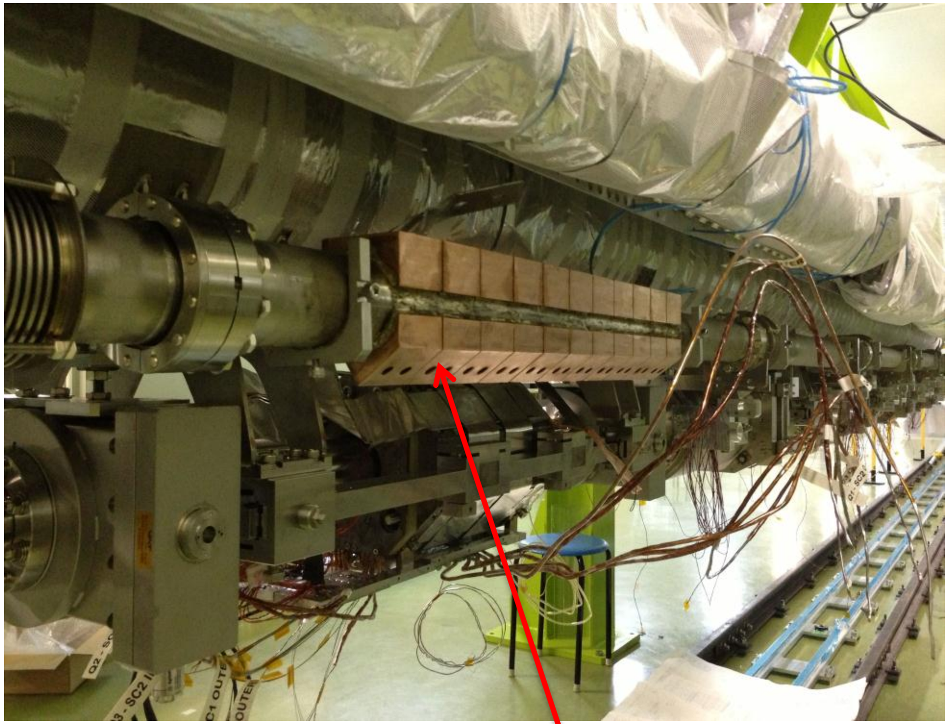


BPM

1. Lifting up the magnet to right position.
2. Aligning the iron yoke halves, and couple them.
3. Attaching the BPM.

Quadrupole Final Assembly

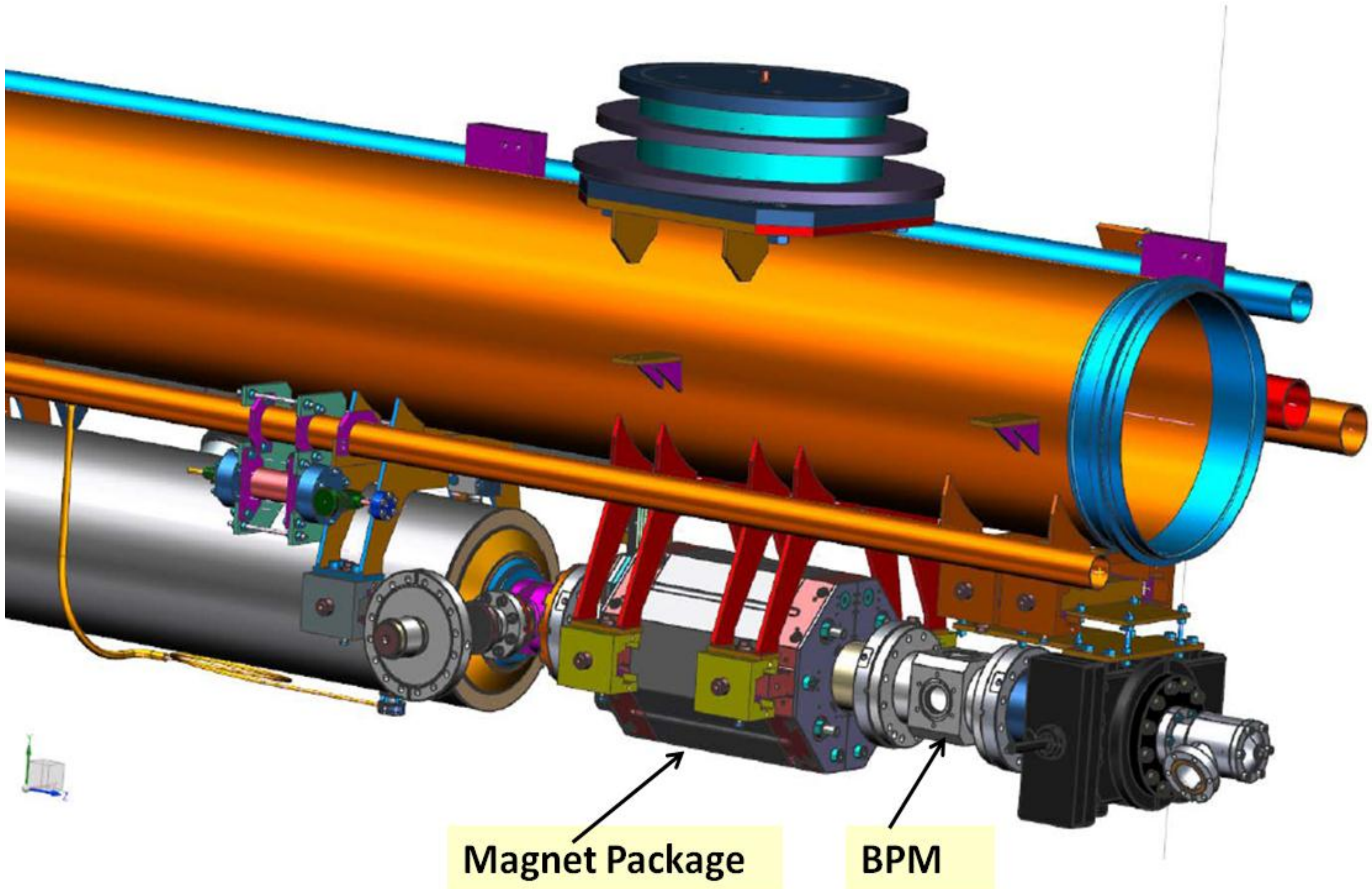




Magnet at supporting bars.

2K He pipe, brazed Cu blocks for leads and coils conduction cooling.

SLAC LCLS-II Magnet Concept

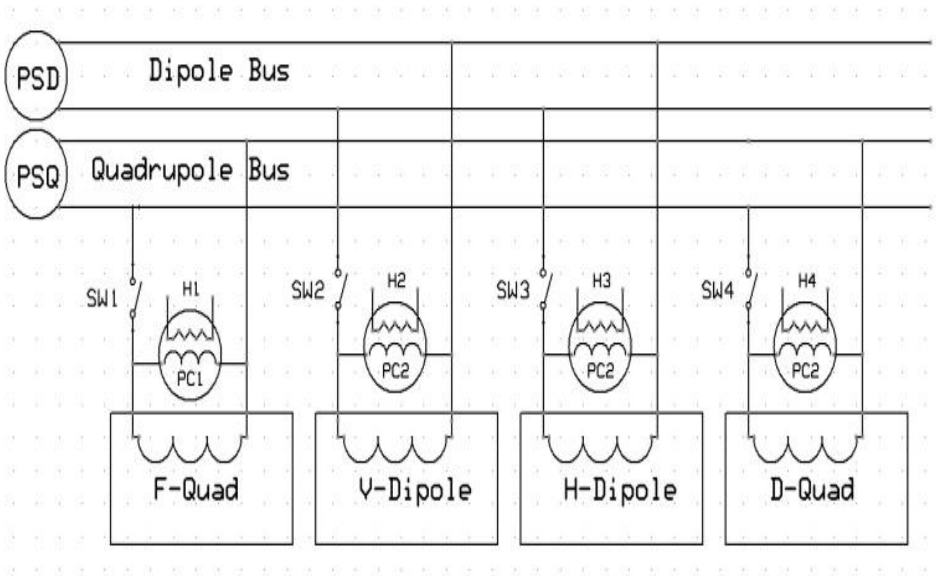


It is supposed to use splittable conduction cooled magnet for LCLS-II.

Integrated Magnet System Concept

- In most Linear Accelerators beam transport superconducting magnets powered by separate power supplies. Each magnet has at least a pair of current leads, power supply, long cables to connect them, quench detection and protection systems. Such large number of elements substantially increases the system cost and reduce the magnet system reliability
- Another approach is to use the possibility of superconducting magnets to work in the persistent current mode. MRI Solenoids routinely use this technique. The main magnet system parameters should have:
  - large magnet inductances;
  - very low splice resistances;
  - high performance persistent current switches;
  - long low inductive superconducting busses;
  - efficient control system.

Integrated Magnet System Scheme



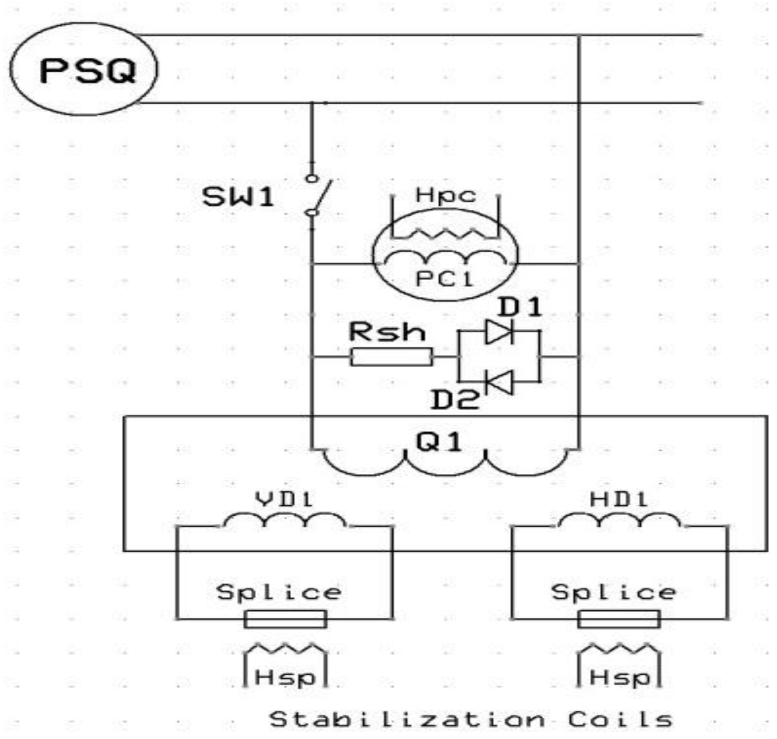
The magnet system cell schematic. SWn- superconducting switch, PCn- persistant current switch, Hn – PCn heaters, PSD and PSQ dipole and quadrupole power supplies.

To explore the proposed approach all magnets should be combined in magnet groups having the same electrical current supply bus. It is more convenient to have two or three busses to power quadrupoles and dipoles separately.

The magnet has 5 splices which could be made with a very low resistance < 10 nΩ. If the magnet will operate in the persistent current mode, the current decay time constant will be in the range of 12 years for the 3.9 H winding inductance and 10 nΩ total external circuit resistance. The magnet current will decay with the rate 0.02 %/day.

Fermilab

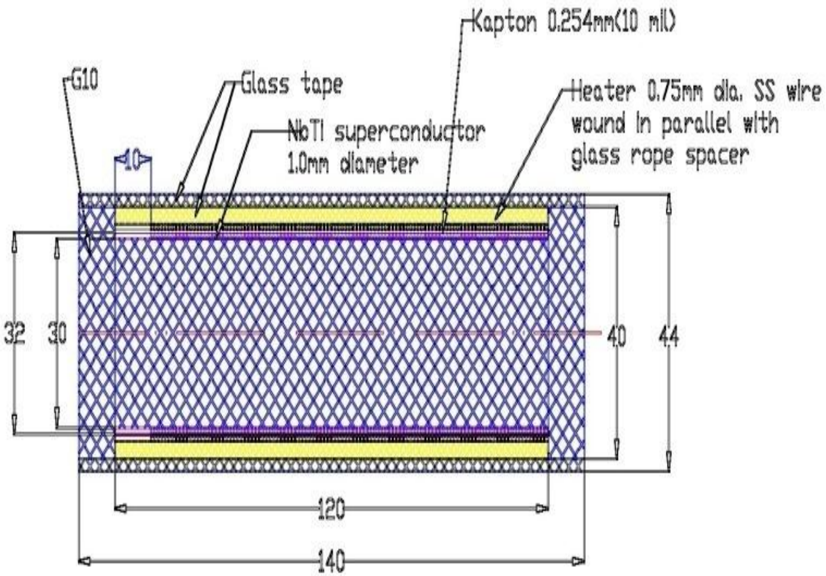
Single Cell Quadrupole Magnet Scheme



Quadrupole package schematic. Q1 – quadrupole winding, Dn – cold diodes, Rsh – protection shunt resistor, VD1 – vertical dipole, HD1 – horizontal dipole.

The most complicated problem with the quadrupole magnets for Linear Colliders is the magnetic center stabilization.
It is proposed to use superconducting stabilization coils. Because the quadrupole magnetic center shift is defined by the dipole field component, stabilization coils should have dipole configuration. During the magnet operation these coils should be short circuited. In this case, any dipole field component change will be eliminated by the current induced in this coil. The stabilization coil inductance should be relatively large and the splice resistance very low to obtain a reasonably long decay of the induced current. The induced currents will be low because in the ideal geometry there is no coupling between quadrupole and dipole windings. Only a misalignment between quadrupole and dipole fields will cause the dipole current.

Persistent Current Switch

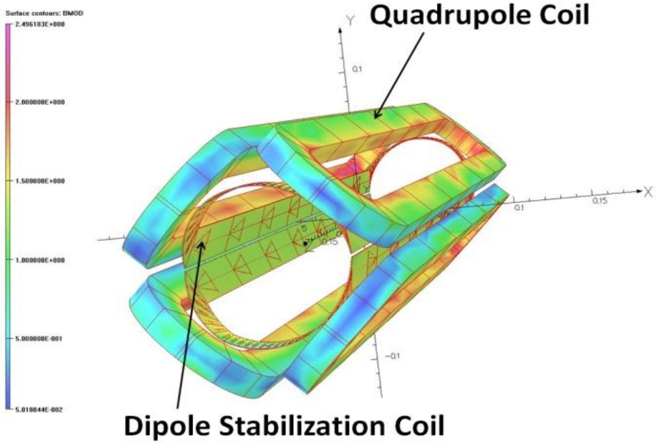


The magnet system cell schematic. SWn- superconducting switch, PCn- persistant current switch, Hn – PCn heaters, PSD and PSQ dipole and quadrupole power supplies.

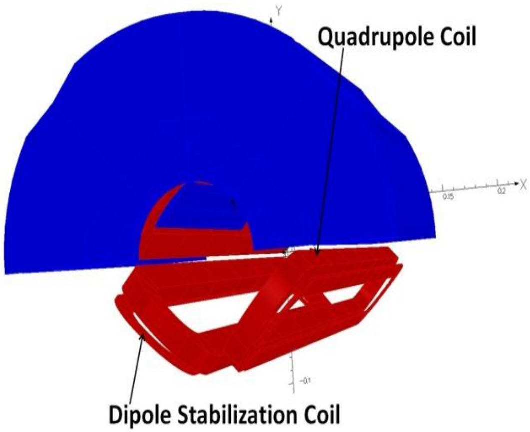
Parameter	Unit	Value
Peak operating current	A	150
SC coil resistance at 20 °C	Ω	7.8
Heater resistance	Ω	23.5
NbTi wire diameter	mm	1.0
Superconductor stabilization material		CuNi
Stainless steel heater wire diameter	mm	0.75
Heater current	A	0.5
Switch performance at 100 A SC current, and (0.5 A, 3 s) heater current and time: - Transition from the superconducting to the normal condition - Transition from the normal to the superconducting condition	s s	1.8 4.3
Switch open resistance (at 0.5 A, 3s) heater current and time	Ω	3.2

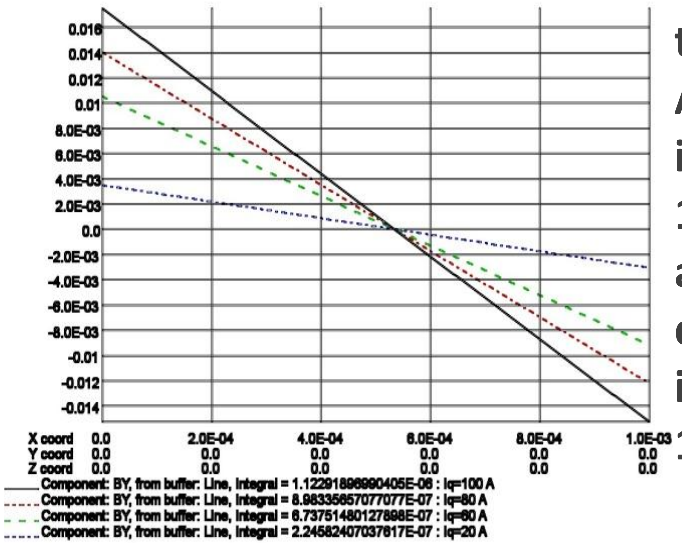
D. Turrioni from FNAL successfully tested 2 switches. No quenches were observed up to 150 A current

Stabilization Coil Simulation

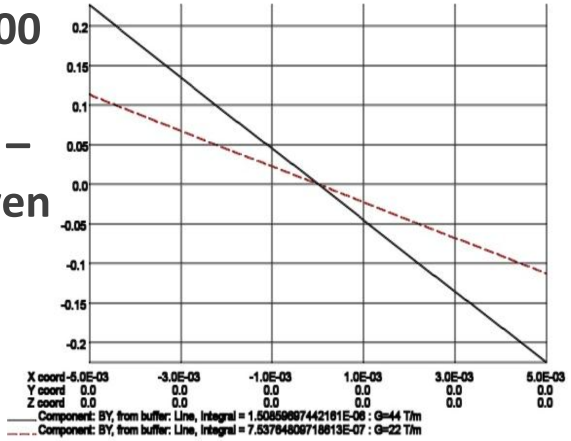


Figures show that the quadrupole magnetic center is very stable at quadrupole currents 20 ÷100 A. The dipole winding consists of two shell type coils having 74 turns each. In this coils at 1 mm dipole center shift relatively the quadrupole winding at 100 A in the quadrupole was induced stabilization current – 16.7 A. In the real magnet even at 0.3 mm quadrupole and dipole coils misalignment induced current will be only 1.7 A.





Dipole shell coils



Dipole racetrack coils

Possible Cost Savings and Improvements

The implementation of the proposed technique for Linear Accelerators may substantially reduce the magnet system cost. In this case, a large number of the following components will be eliminated (there are 560 magnet packages for ILC):

- **Power supplies (3 PS/cryomodule) . Instead of 1680 PS will be 168 (3 PS/ 10 cryomodules);**
- **Current leads (6 leads/cryomodule). Instead of 3360 leads will be 336;**
- **Quench detection system;**
- **External quench protection system with heater firing units.**

The magnet system performance might be improved:

- **High magnetic center stability provided by stabilization dipole coils;**
- **Zero noise from power supplies during operation;**
- **Zero fringing magnetic fields from leads, and buses;**
- **High reliability passive quench protection system without external detection and protection systems.**
- **Low heat load from current leads and instrumentation wires.**

Besides, in this case, the magnet specification may be more relaxed to the magnet design, and a fabrication technology.

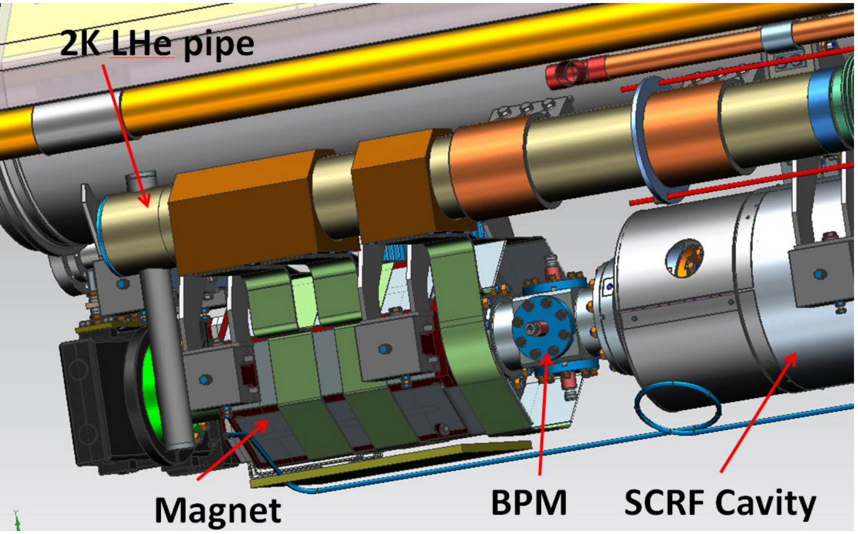
ILC Magnet Results

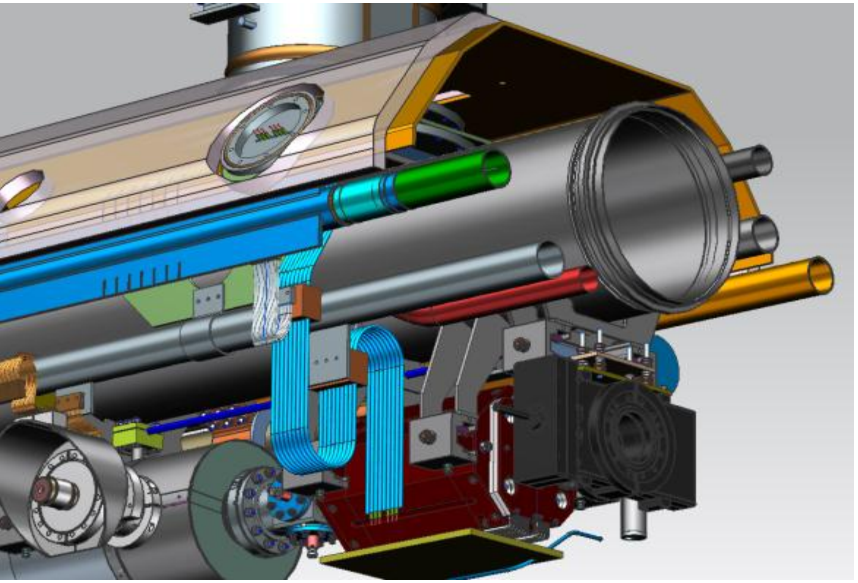
1. The splittable conduction cooled quadrupole magnet technology was proved for using in Superconducting Linear Accelerators.
2. The ILC Splittable Quadrupole was successfully tested in the conduction cooling mode at KEK and FNAL, and met specified parameters: peak gradient, field quality, magnetic center stability.
3. The magnetic center stability was investigated with the high precision rotational probe, and met the specification 5 um.
4. Designed and fabricated two Splittable Quadrupoles for the KEK-STF #CM1.
5. Started the Quadrupole integration with KEK-STF #CM1.
6. The splittable conduction cooling magnet technology proposed for the SLAC LCLS- II magnets.
7. Proposed the promising way of integrated magnet system.
8. Proposed the quadrupole magnetic center stabilization.

ILC Quadrupole after Successful Tests

May 9, 2014

LCLS-II Splittable Quadrupole Prototypes

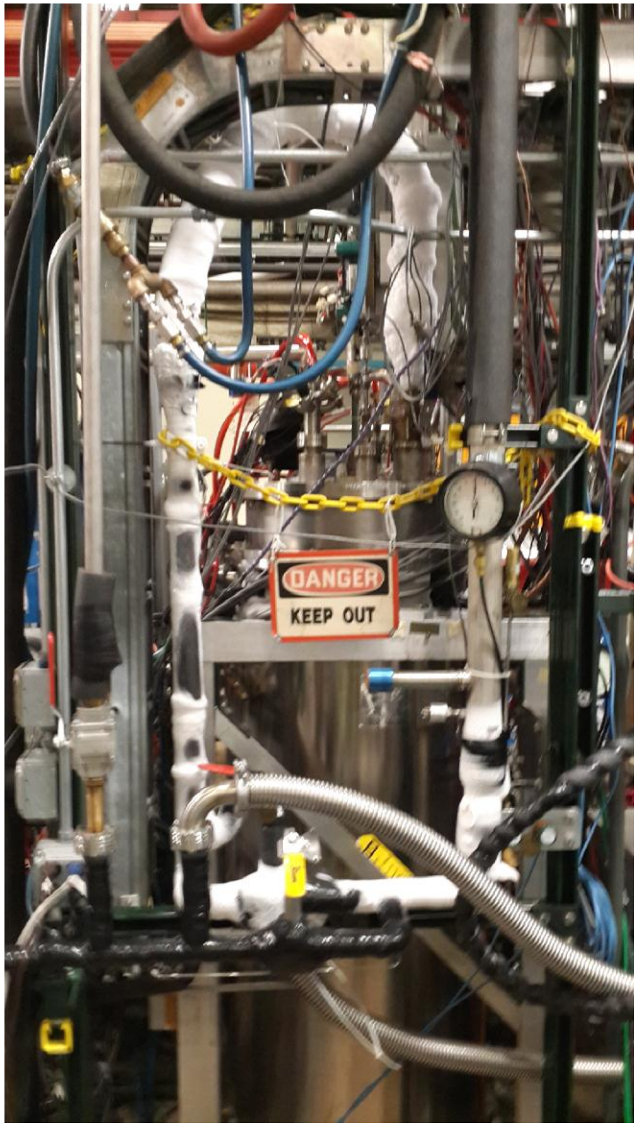




Parameter	Unit	Value
Magnet physical length	mm	340
Magnet width/height	mm	322/220
Pole tip radius	mm	45
Peak operating current	A	≤ 50
Number of quadrupole coils		4
Number of dipole coils		8
Type of superconducting coils		Racetracks
NbTi superconductor diameter	mm	0.5
Quadrupole inductance	mH	82
Liquid helium temperature	K	2.2
Quantity required (with spares)		38

The magnet package for 2 prototypes will have combined quadrupole and dipole coils.

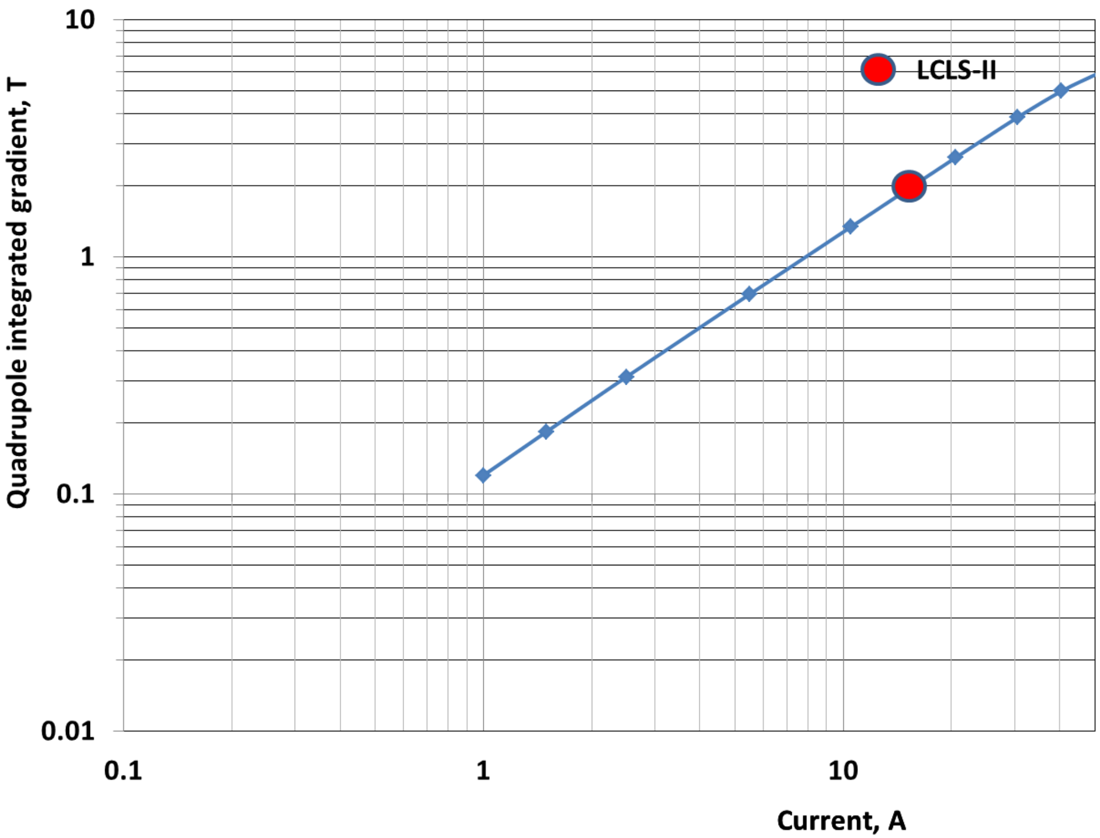
Magnet Prototype Test at Stand 3



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

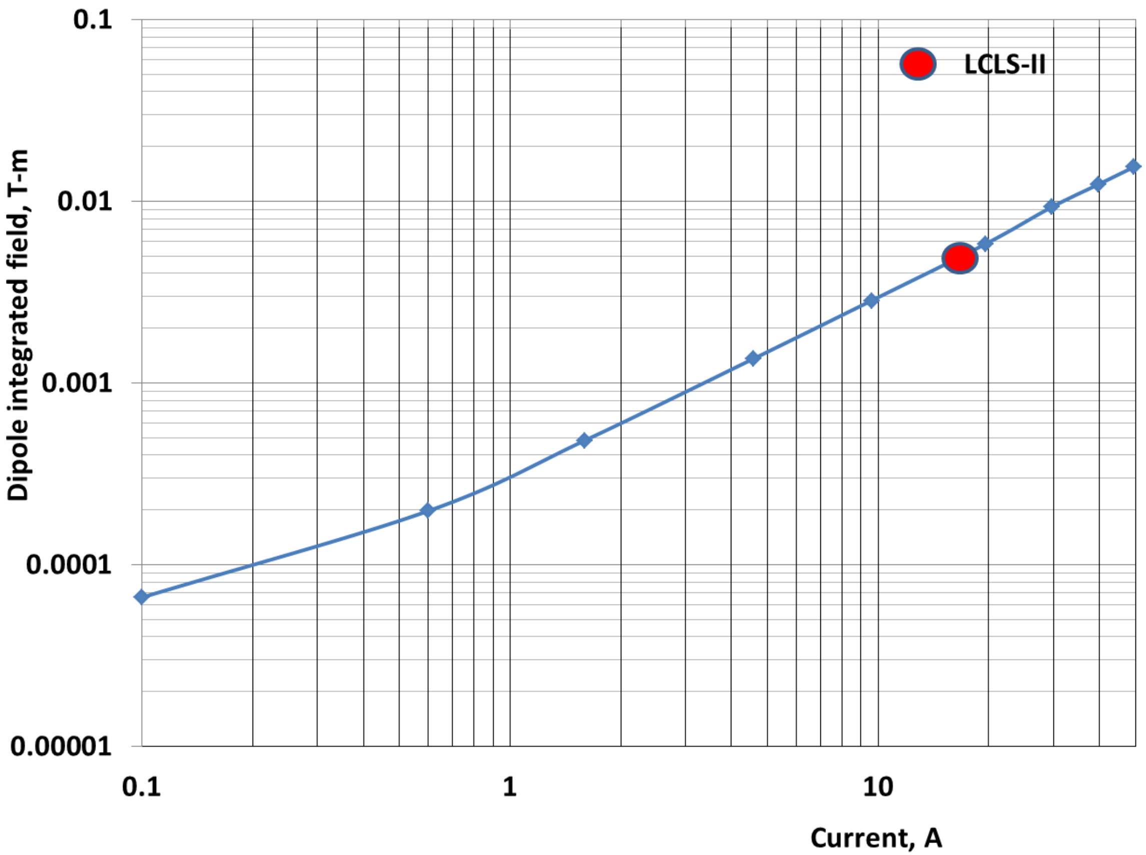
Joe DiMarco made all magnetic measurements by rotational probe.

Quadrupole Magnet Training



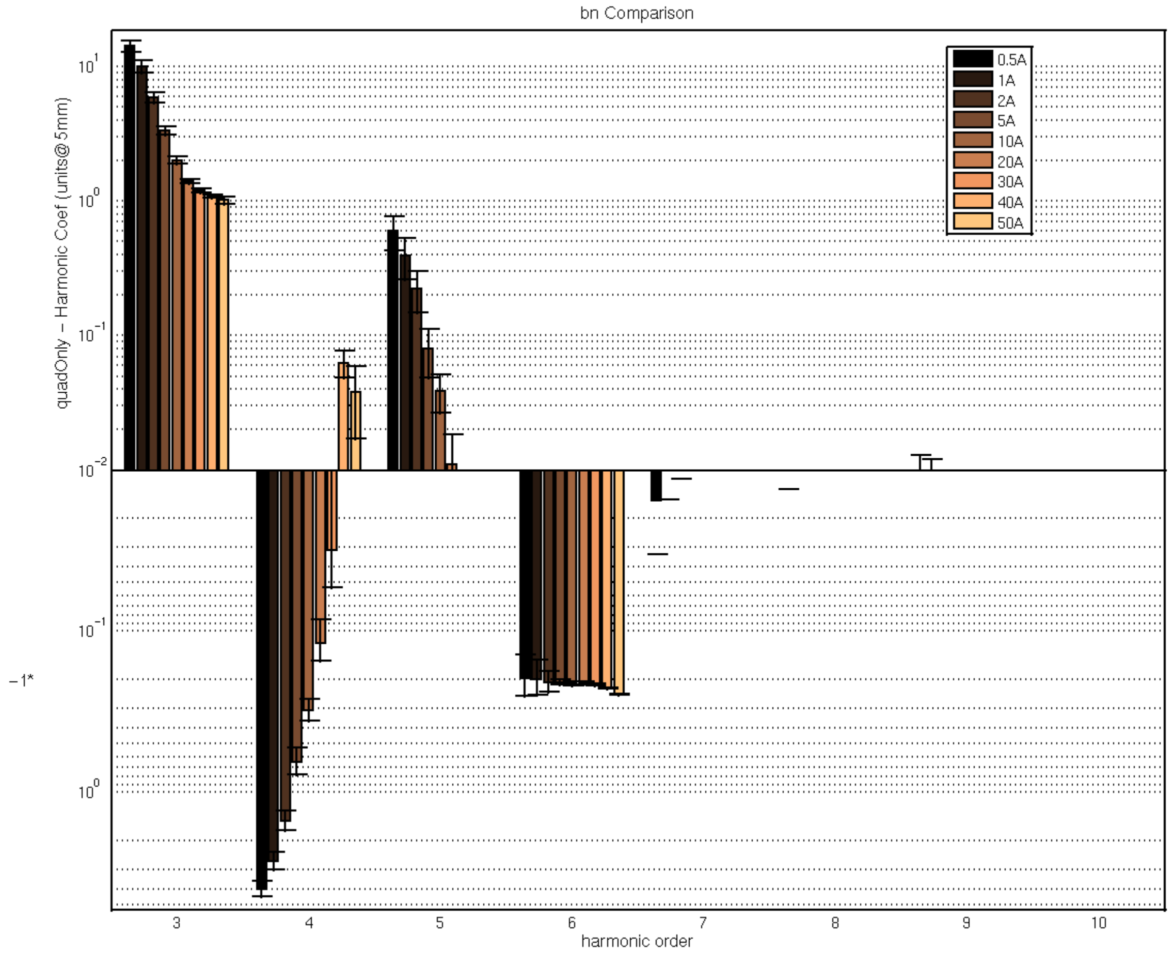
Only one quench was observed at 48.5 A during quadrupole magnet ramping up to 50 A. 2 T integrated gradient reached at 15 A.

Dipole Magnets Training



No one quench was observed during vertical and horizontal dipoles ramping up to 50 A. Dipole 0.005 T-m integrated field was reached at 17 A.

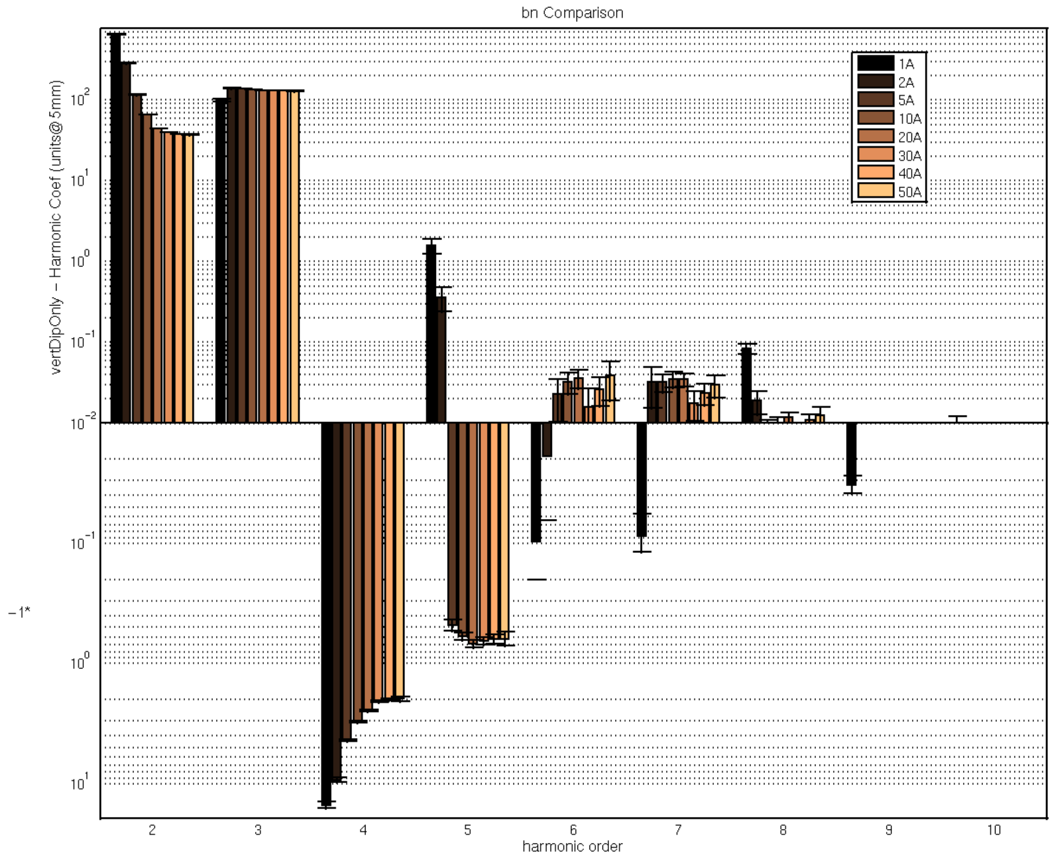
Quadrupole Field Harmonics



At 1.0 A : b3=30, b4=-4.0, b5=0.8, b6=-0.2 units (10^-4)

At 50 A : b3=1.0, b4=0.04, b5=0.01, b6=-0.02 units (10^-4)

Dipole Field Harmonics



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

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

Test Results

- Magnet showed a very good performance for larger current 50 A: 0.01 % for the quadrupole, and 0.3 % for the dipole.
- As expected at a very low current (1 A) increased field distortions: 0.3 % for quadrupole, and 3 % for the dipole.
- The field measurement at 180 K and 0.1 A current confirmed that field distortions possibly related to the iron residual magnetization effects.
- The degaussing was limited by bipolar KEPCO power supply to +/- 10 A. It did not show the degaussing effect.
- Tests will be continued.

Summary

- The latest approach to superconducting magnets for SCRF Linear Accelerators based on the splittable, and the conduction cooled configurations. It is more convenient for installation and operation as a cryogen free unit.
- For any type of SC magnet were observed rather large residual magnetization effects at minimal operating currents. Moving SC coils far from the aperture reduce the superconductor magnetization effects.
- The ILC magnet prototype showed acceptable magnetic center stability which is the most critical specification.
- The residual iron core magnetization could be reduced by degaussing.

References

[1] "International Linear Collider Reference Design Report," http://www.linearcollider.org/cms/?pid=1000025.

[2] V.S. Kashikhin *et al.*, "Design and Manufacturing Main Linac Superconducting Quadrupole for ILC at FERMILAB," *IEEE Transactions on Applied Superconductivity*, vol. 18, No. 2, June 2008, pp. 155-158.

[3] V.S. Kashikhin, *et al.*, "Test results of a superconducting quadrupole model designed for linear accelerator applications," *IEEE Transactions on Applied Superconductivity*, vol. 19, Issue 3, Part 2, June 2009, pp. 1176-1182.

[4] V.S. Kashikhin, *et al.*, "Superconducting Magnets for SCRF Cryomodules at Front End of Linear Accelerators," Proceedings of IPAC'10, Kyoto, Japan, 2010, pp. 379-381.

[5] G.V. Velev *et al.*, "A Fast Continuous Magnetic Field Measurement System Based on Digital Signal Processors," IEEE Trans. of Applied Superconductivity, Vol. 16, No. 2, June 2006, pp. 1374-1377.

[6] V.S. Kashikhin, *et al.*, "Superconducting Splittable Quadrupole Magnet for Linear accelerators," *IEEE Transactions on Applied Superconductivity*, vol. 22, Issue 3, Part 2, 2012, Article#: 4002904.

[7] N. Andreev, *et al.*, "Conduction Cooling Test of a Splittable Quadrupole for ILC Cryomodules," *IEEE Transactions on Applied Superconductivity*, vol. 23, Issue 3, Part 2, 2013, Article#: 3500305.

[8] N. Kimura, et al, "Cryogenic Performance of a Conduction Cooling Splittable Quadrupole Magnet for ILC Cryomodules," submitted to the 2013 CEC/ICMC conference.

[9] R. Carcagno, *et al.*, "Magnetic and Thermal Performance of a Conduction-Cooled Splittable Quadrupole," *IEEE Transactions on Applied Superconductivity*, vol. 24, Issue 3, 2014, Article#: 4001604.