Split Quadrupole Magnets for ILC/KEK-STF

Vladimir Kashikhin for Fermilab-KEK Collaboration

TTC Meeting at DESY

March 24-27, 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
- 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 Lhe bath tested; modified, many tests completed in conduction cooling mode
    - 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

Responsibilities

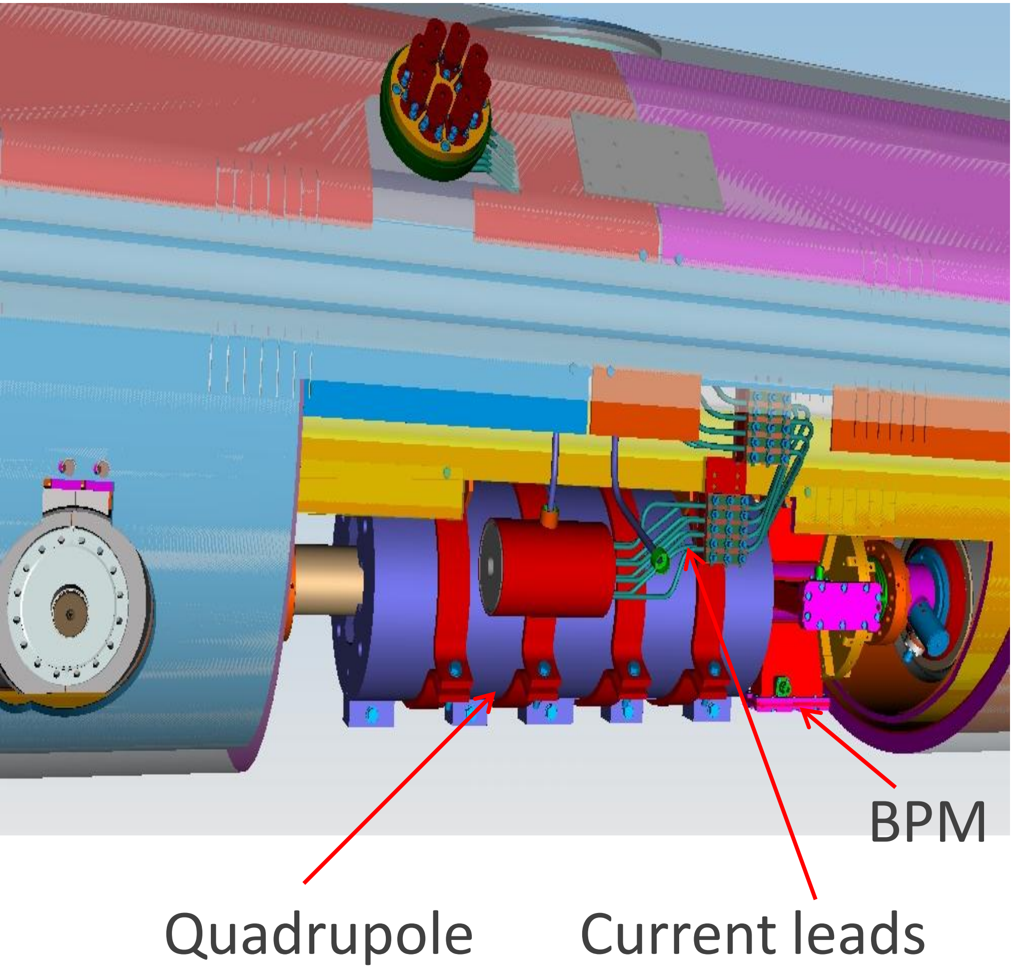
- H. Hayano, V. Kashikhin, A. Yamamoto – KEK Magnet Specification
- R. Stanek, C. Ginsburg – FNAL-KEK coordination
- N. Andreev, V. Kashikhin – Quadrupole design, fabrication
- H . Hayano, Y. Orlov, N. Andreev – Magnet-Cryomodule integration
- D. Orrys, M. Tartaglia – Instrumentation integration with KEK
- N. Kimura – Toshiba Cryostat and cooling in KEK Cryomodule
- M. Takahashi, T. Tosaka (Toshiba) – Quadrupole upgrade and final assembly at Toshiba site.
- O. Kiemschies – Quadrupole yoke assembly in FNAL/IB2
- T. Wokas – Coil fabrication, quadrupole assembly in FNAL/IB2
- N. Kimura, C. Hess – Quadrupole mounting to the top head, splices
- F. Lewis – electrical wiring, tests, and electronics
- D. Orrys – test preparation, DAQ, quench detection and protection
- M. Tartaglia – test leader, magnet training and Hall measurements
- J. DiMarco – rotational probe magnetic measurements

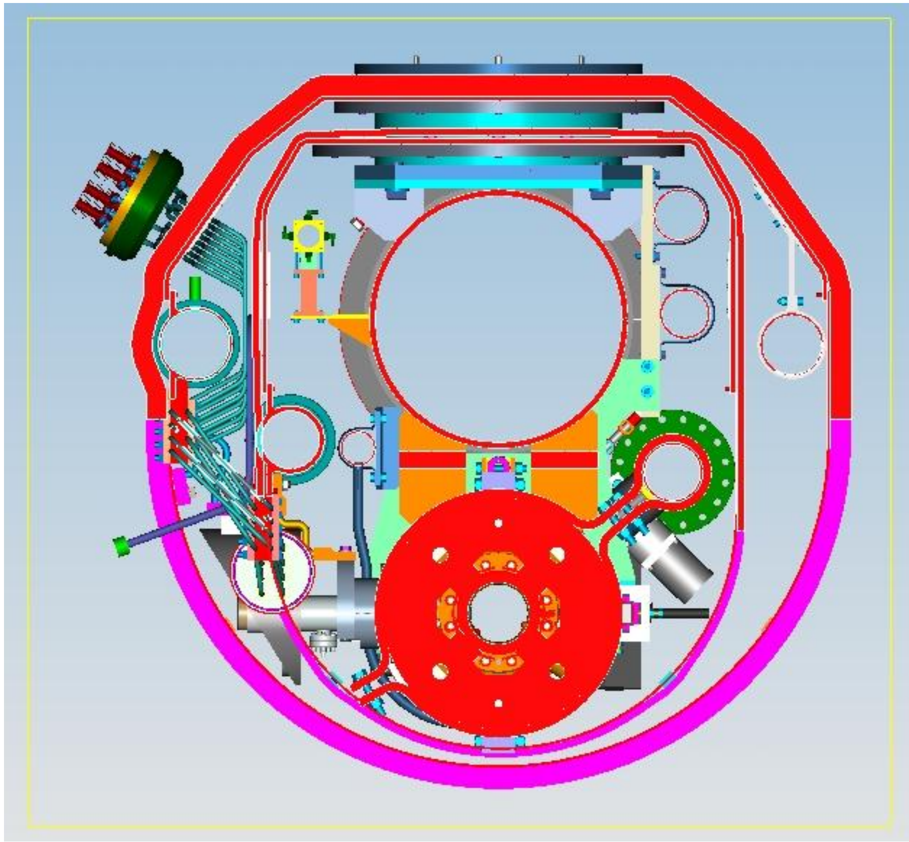
ILC Quadrupole Specification & Superconductor

Integrated gradient, T	36
Aperture, mm	78
Effective length, mm	666
Peak gradient, T/m	54
Peak current, A	100
Field non-linearity at 5 mm radius, %	0.05
Quadrupole strength adjustment for BBA, %	-20
Magnetic center stability at BBA, um	5
Liquid Helium temperature, K	2
Quantity required	560

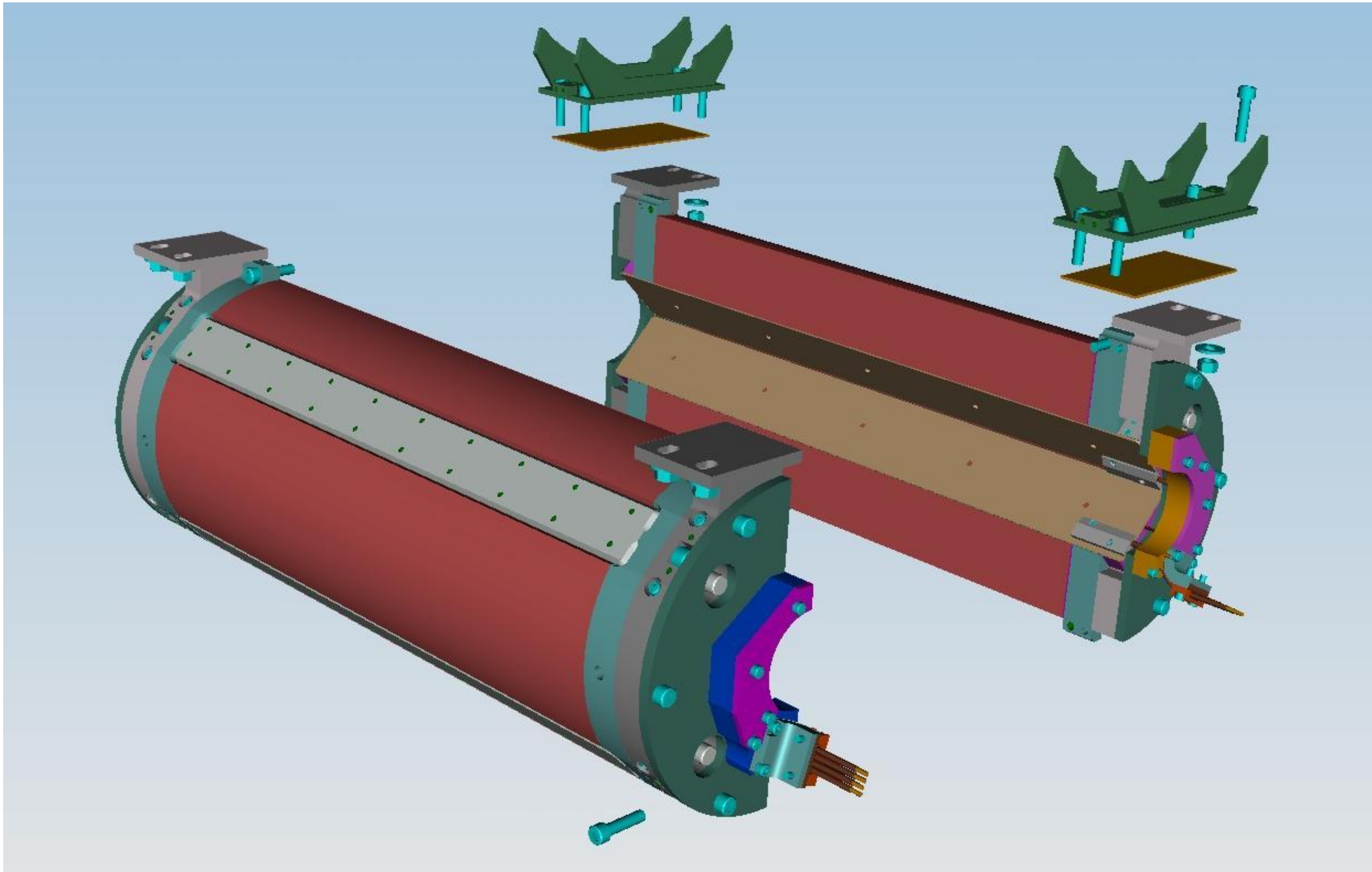
NbTi wire diameter, mm	0.5
Number of filaments	7242
Filament diameter, um	3.7
Copper : Superconductor	1.5
Insulated wire diameter, mm	0.54
Insulation	Formvar
Twist pitch, mm	25
RRR of copper matrix	100
Critical current Ic @ 4.2K, at 5T	204 A

First Concept of ILC Splittable Quadrupole

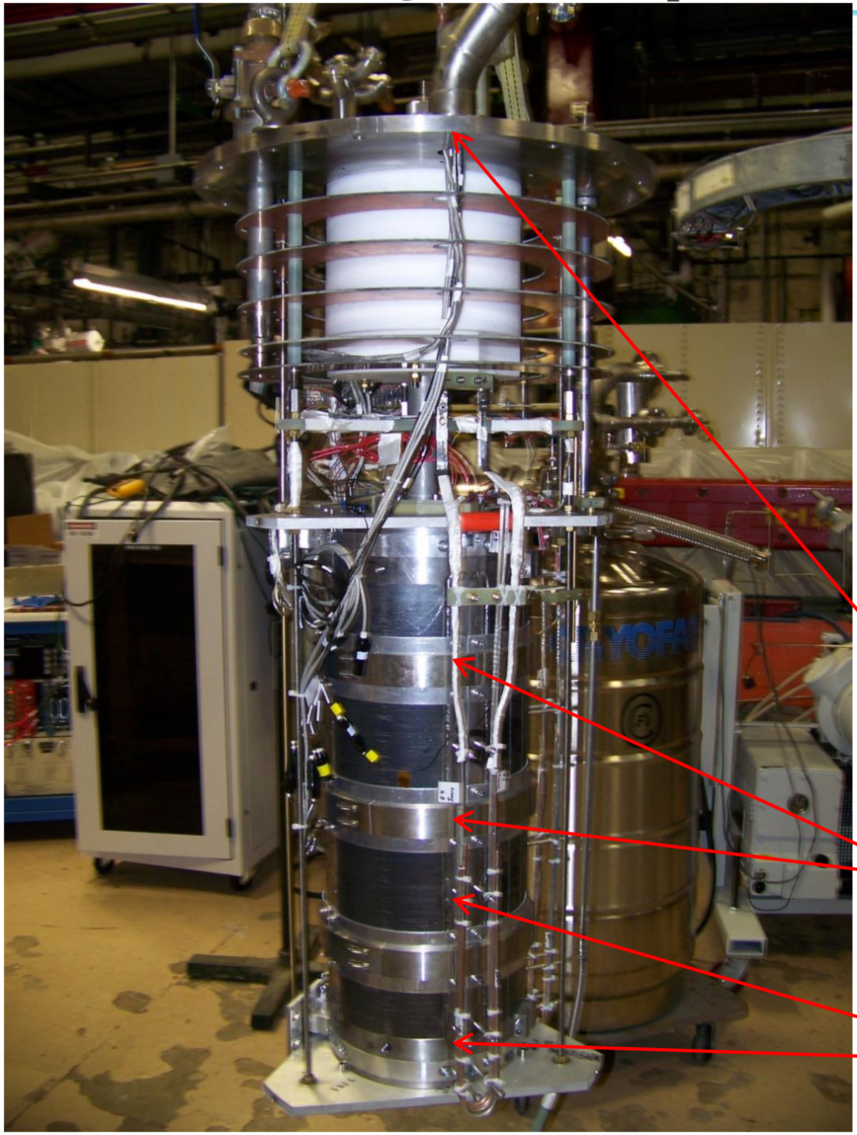




ILC Two Halves of the Quadrupole



ILC Quadrupole with Top Head Assembly



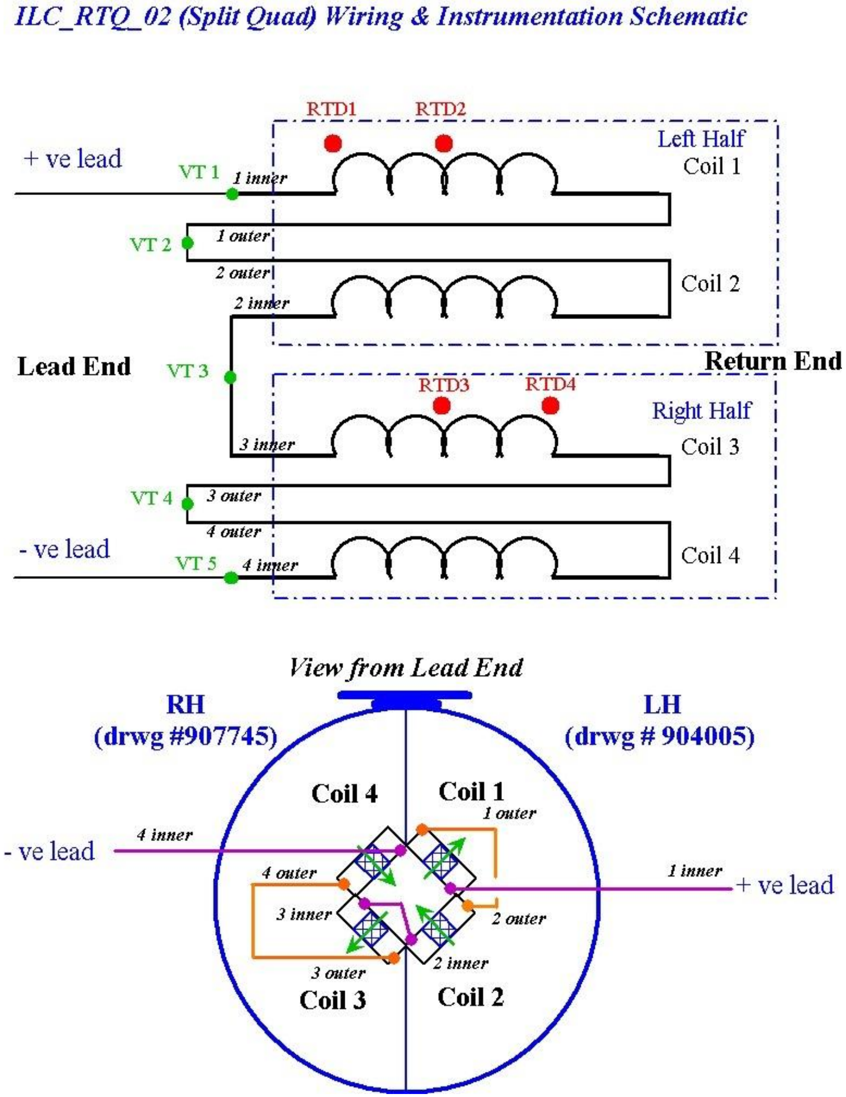
Current leads

Top head

Quadrupole yoke

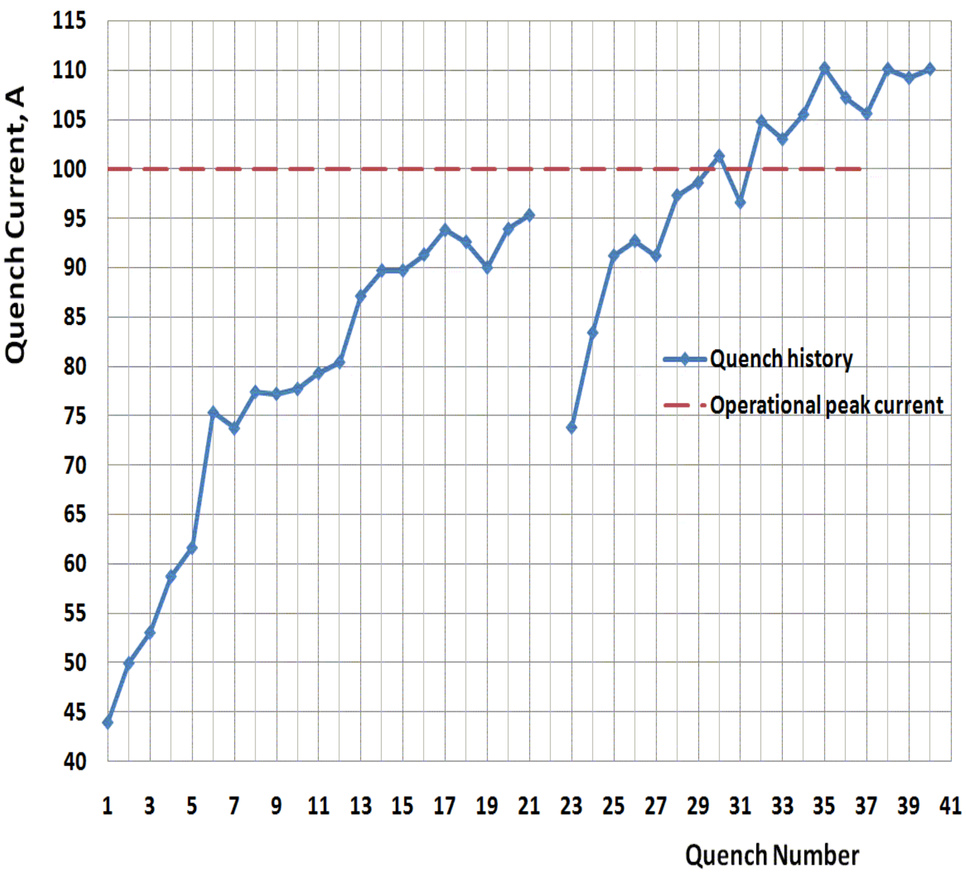
Two quadrupole halves clamping rings

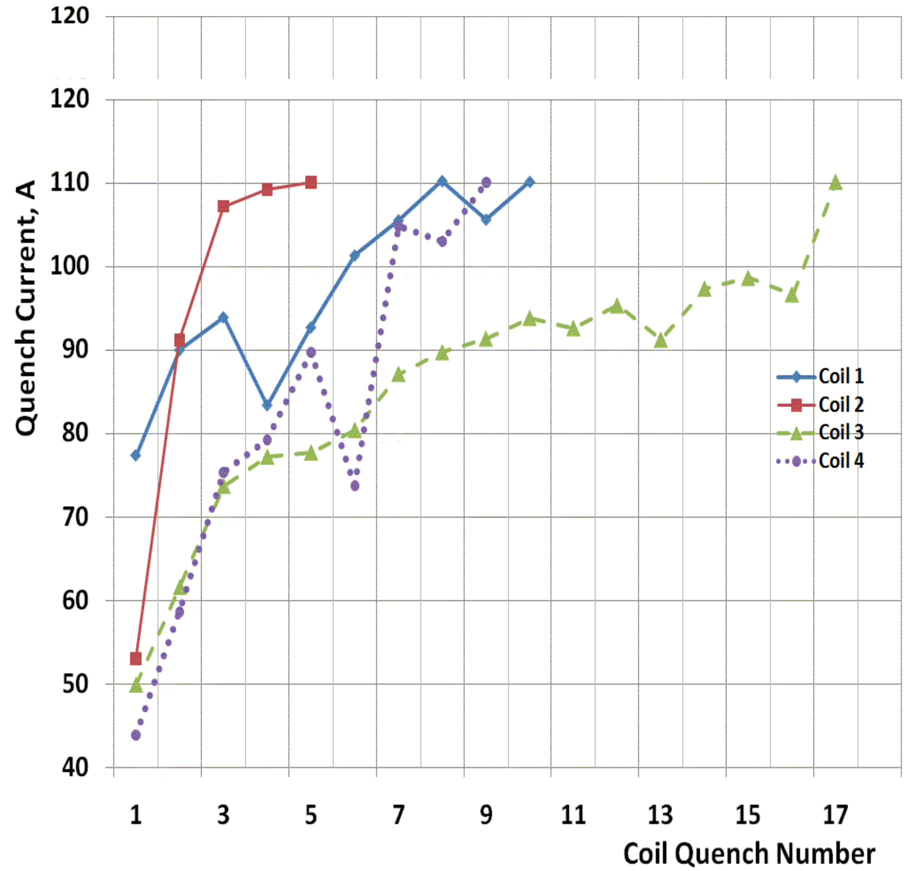
ILC Quadrupole Electrical Scheme



All coils connected in series.
4 RTD's to monitor the temperature.
5 voltage taps to detect the quench.
4 coil heaters connected in series and fired when the quench event is detected.
Quadrupole is protected with 9 Ohm dump resistor.
The peak voltage is < 1kV.

ILC Split Quadrupole Quench History



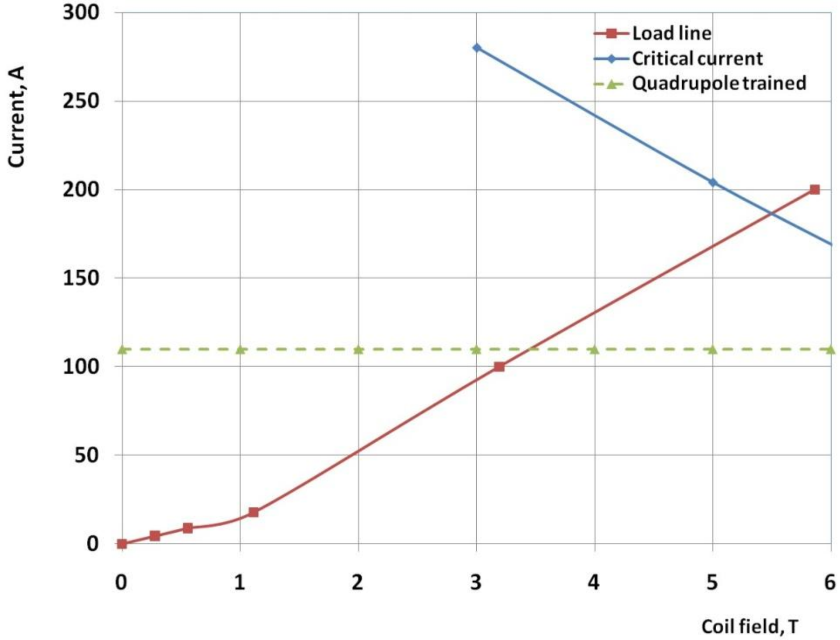


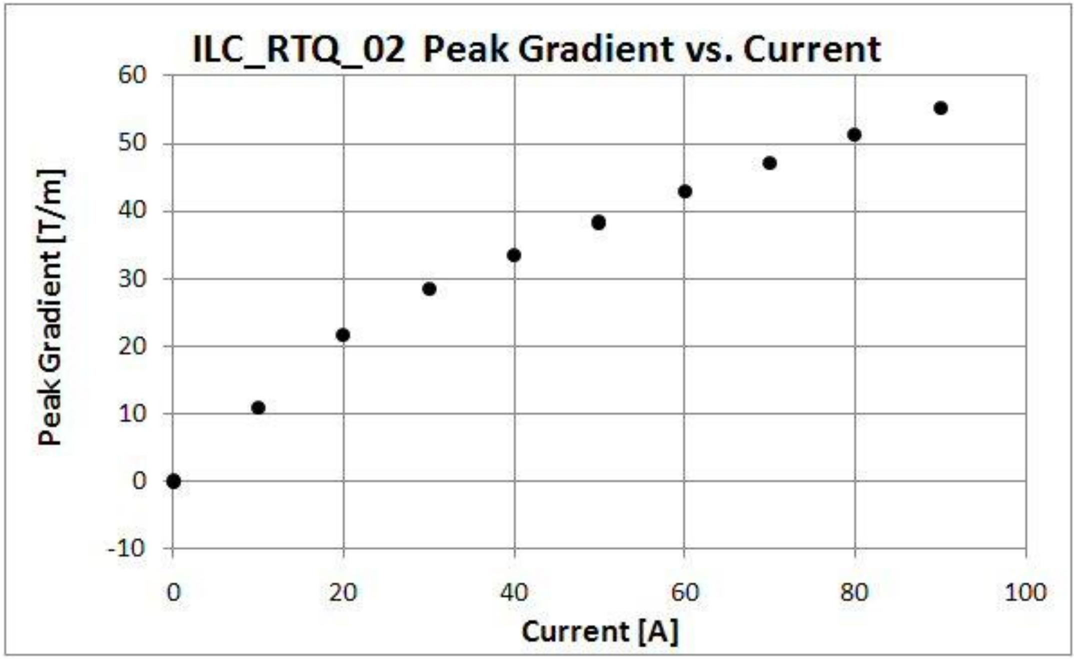
Quench history for two thermal cycles

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

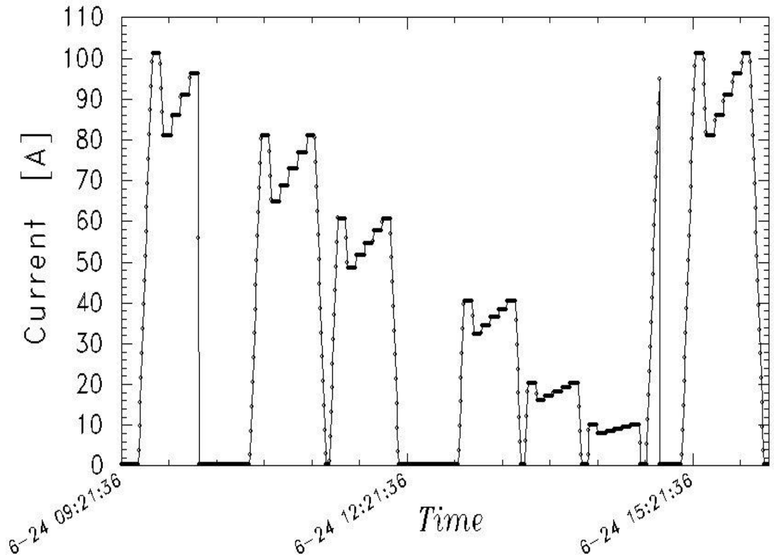


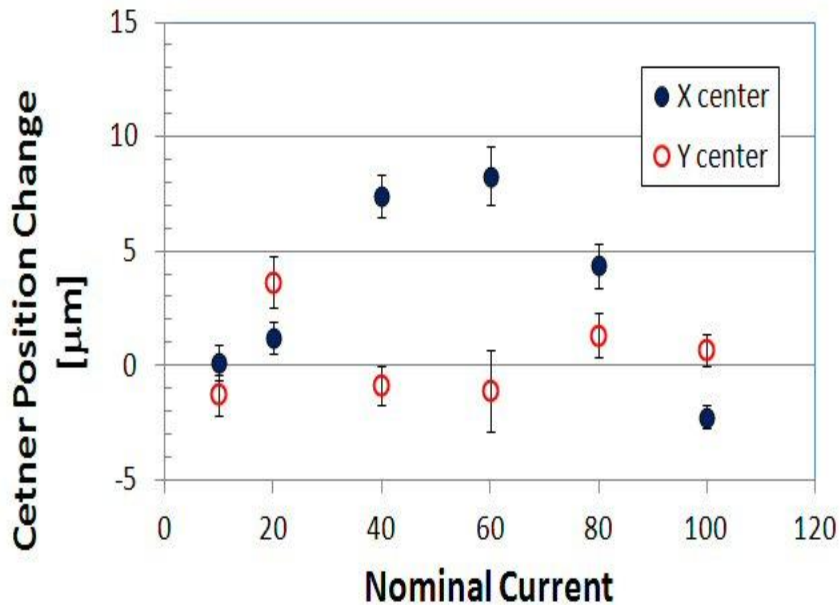


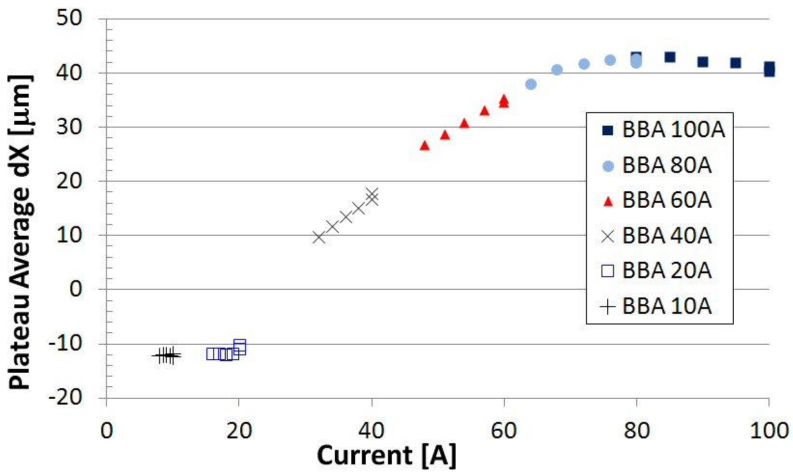
Peak operating current 100 A.
Magnet trained up to 110 A (green line).
Critical current (short sample limit) for this magnet is 185 A at the coil field 5.4 T.

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

Center Stability Measurement Results







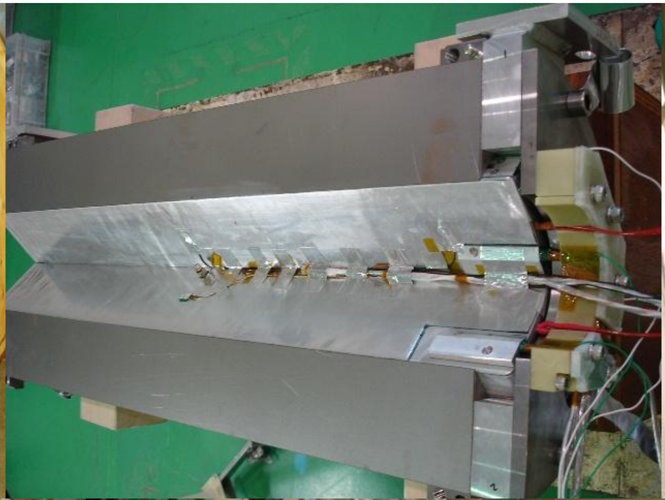
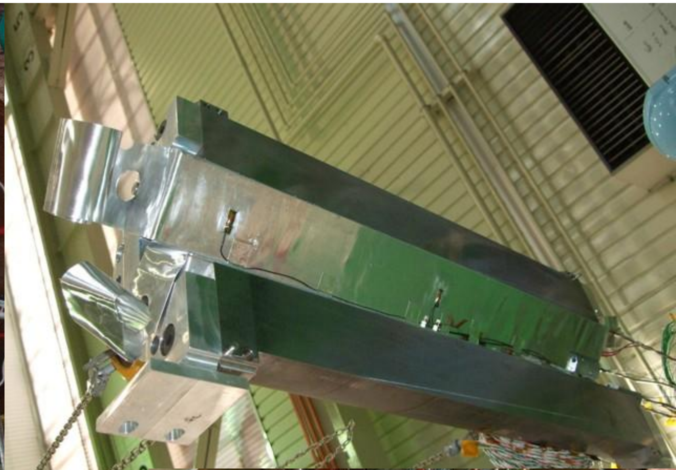
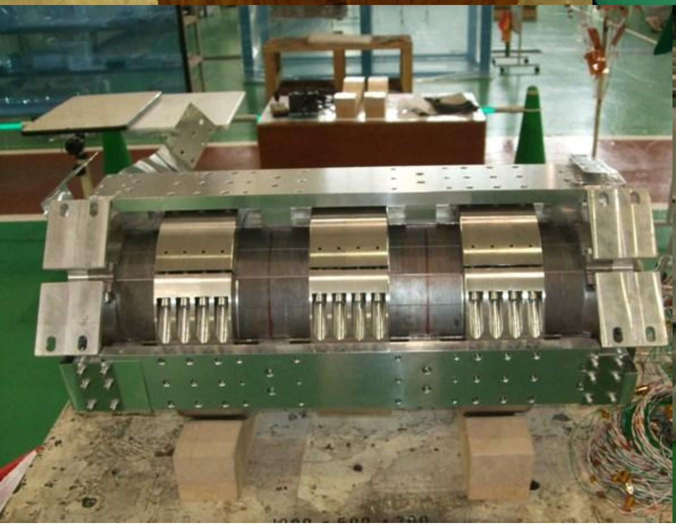
Measured Quadrupole magnetic center stability for BBA -20% of dx=8-10 µm (goal=5), dy<5 µm.

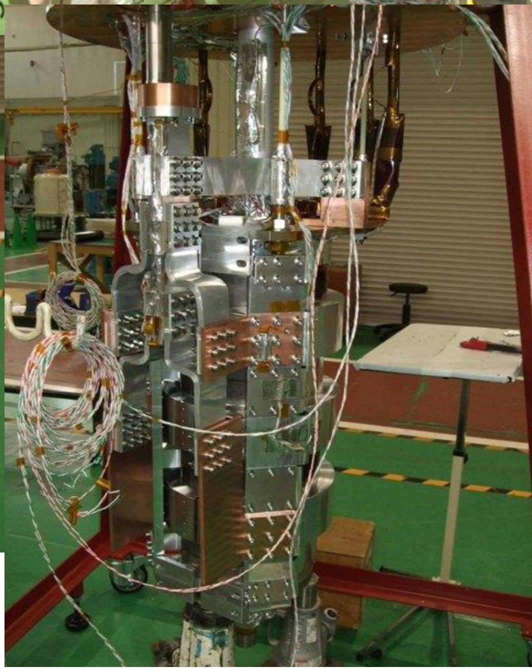
Small partial gaps <0.3 mm between two halves of the yoke in the split plane.

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.

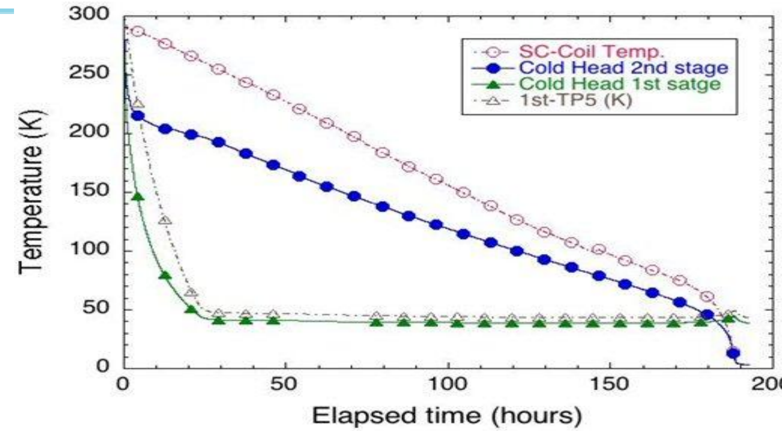
KEK-TOSHIBA Quadrupole Upgrade

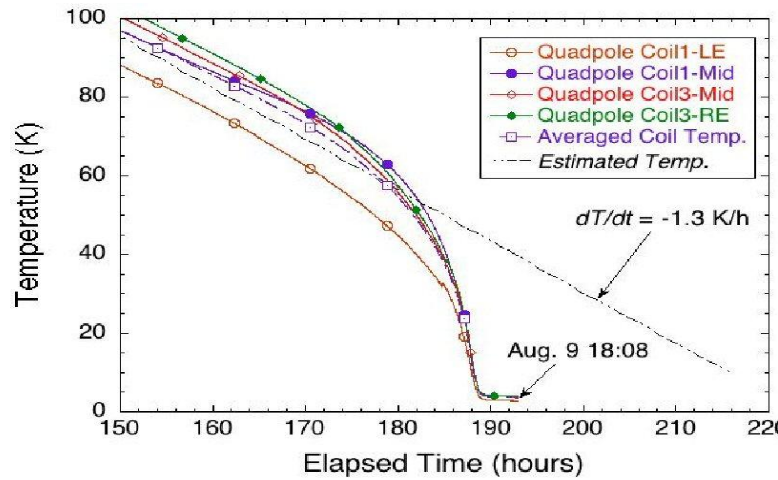







1. **Machined and shimmed split surfaces**
2. **Glued Al cooling foils**
3. **Added conduction cooling elements**

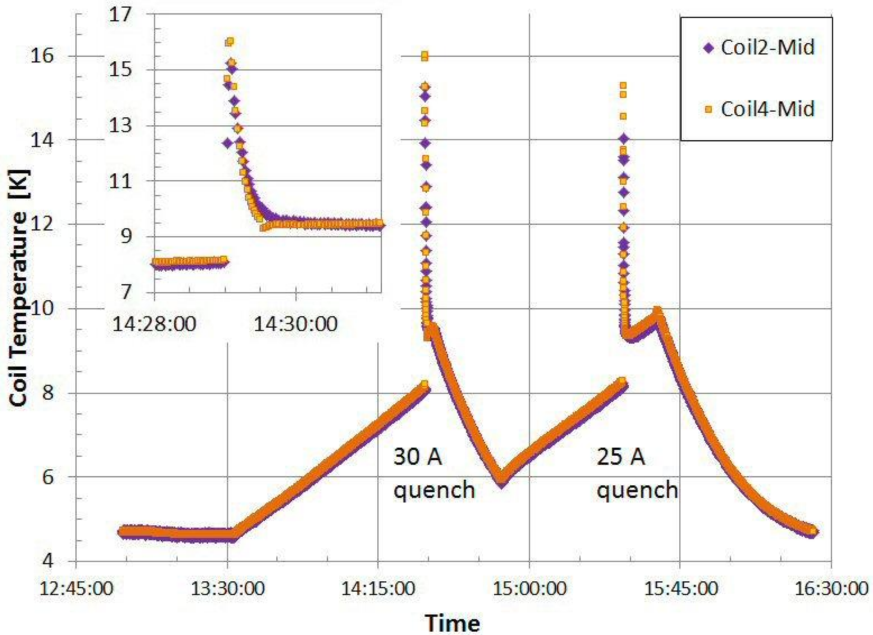
Conduction Cooling Test at KEK [1]



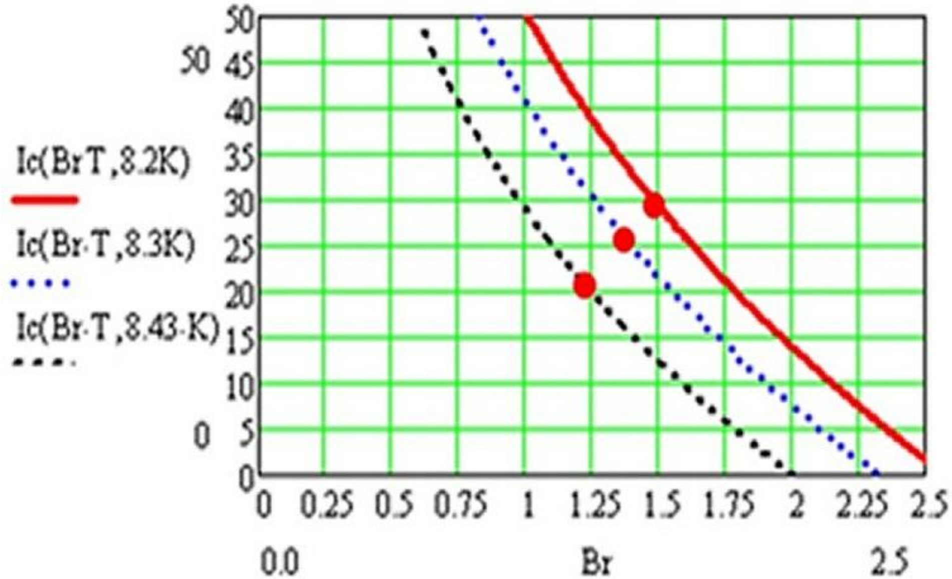


The KEK Test Stand was assembled and the magnet cooled down (8 days) to 4.5 K under supervision of Akira Yamamoto and Hitoshi Kimura

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).

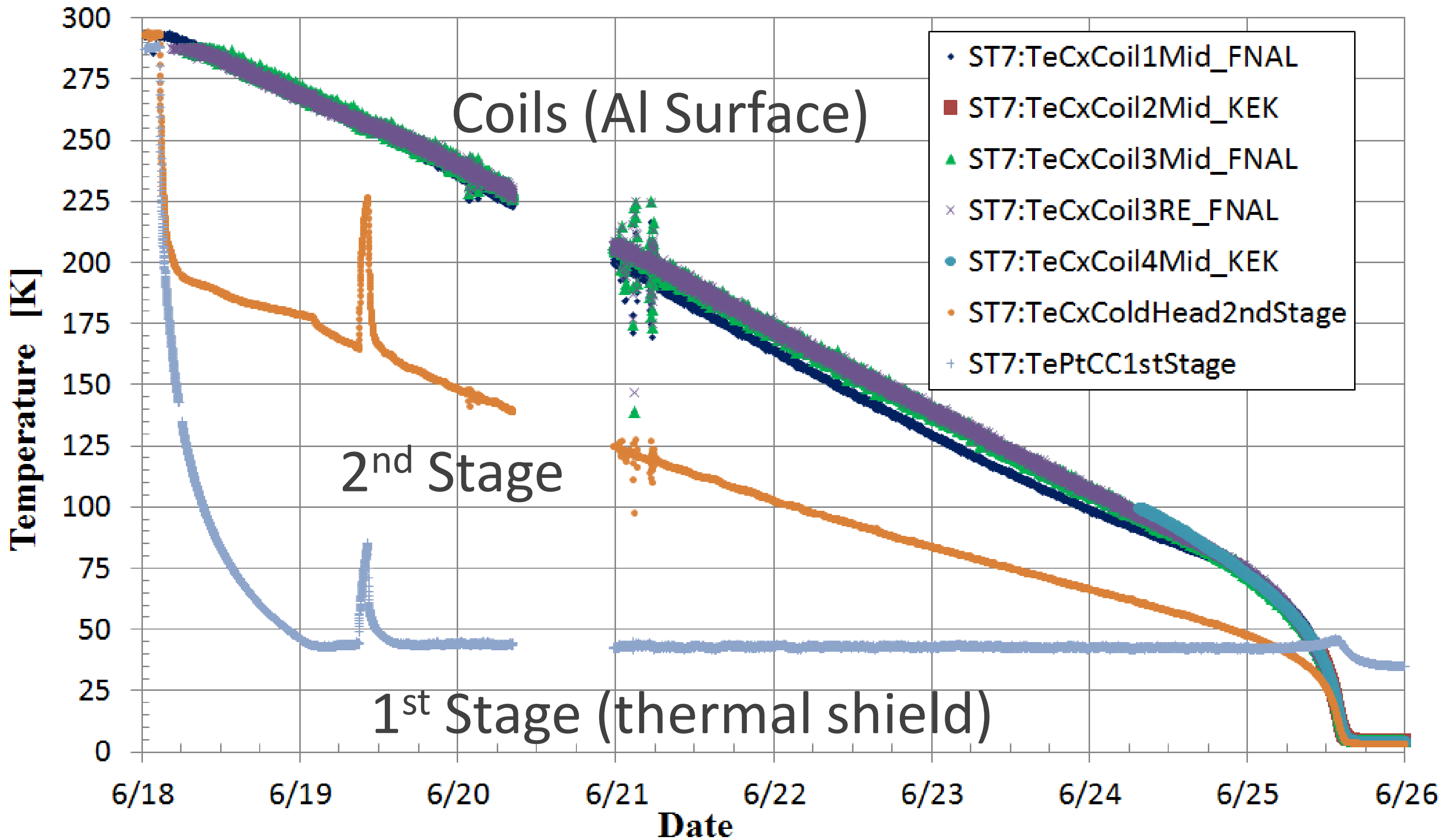
The magnet cooled by conduction with only a single cryocooler (1.5 W), and has a large temperature margin (at 30 A current, and 1.5 T, 8.2 K - 4.2 K = 4 K). This is a very promising result because in the cryomodule the quadrupole will be cooled to 2 K by a LHe supply pipe.

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.

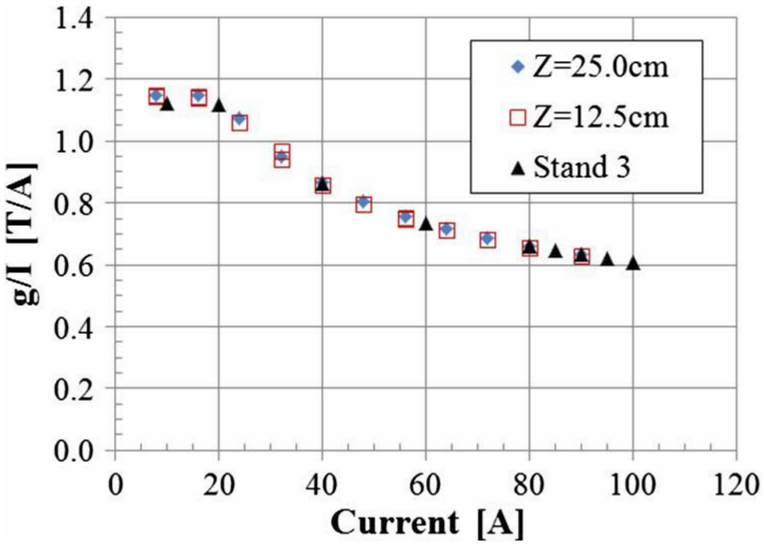
The ILC quadrupole was tested up to the max (110 A) current combined with a high precision magnetic measurements.

First Cool Down at FNAL

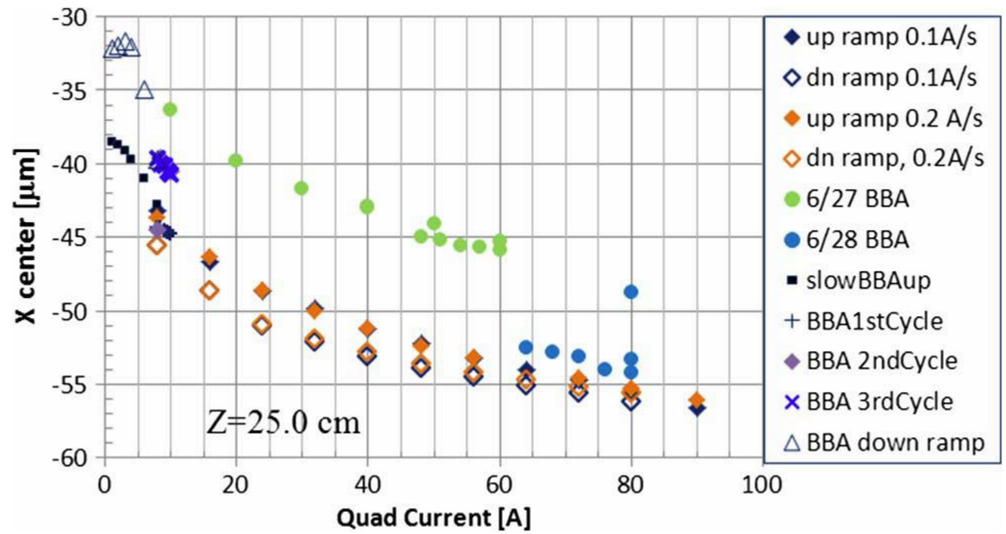


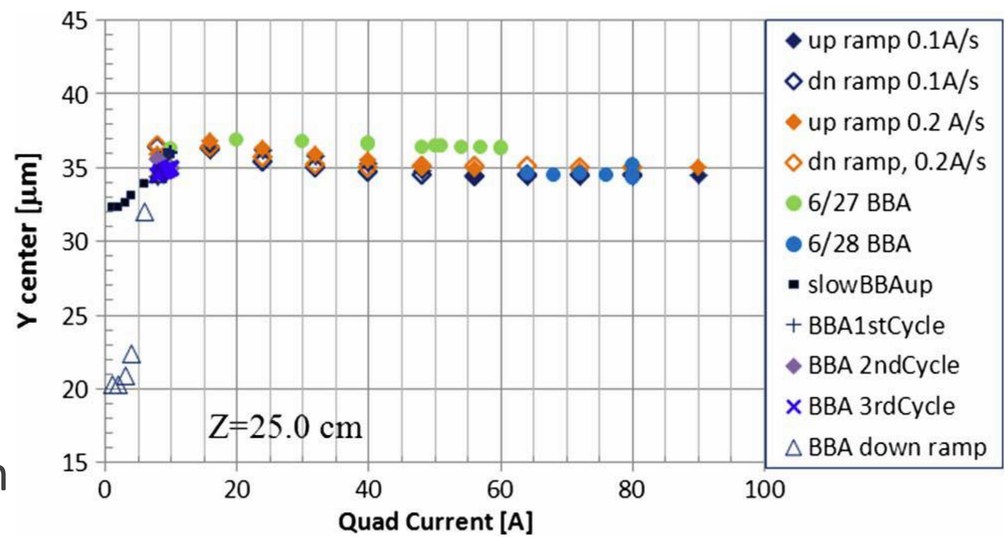
First Cool Down to 4K: 8 days, the same as at KEK.

Magnetic Measurements at FNAL



Normalized gradient vs. current.



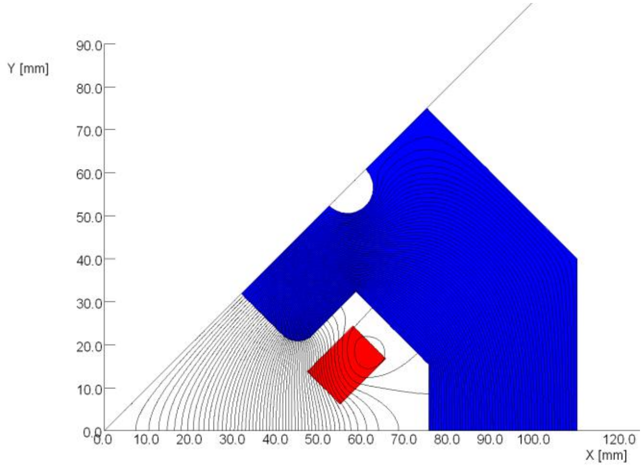


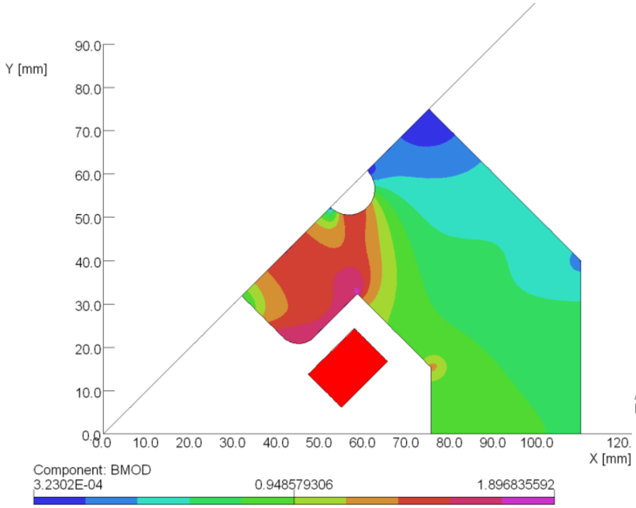
The measured field quality is better than specified 0.05% at 5 mm radius. The magnetic center shift for BBA is less than 5 um. But some unexpected shifts were observed probably caused by mechanical shift of rotational system bushings or the coil probe.

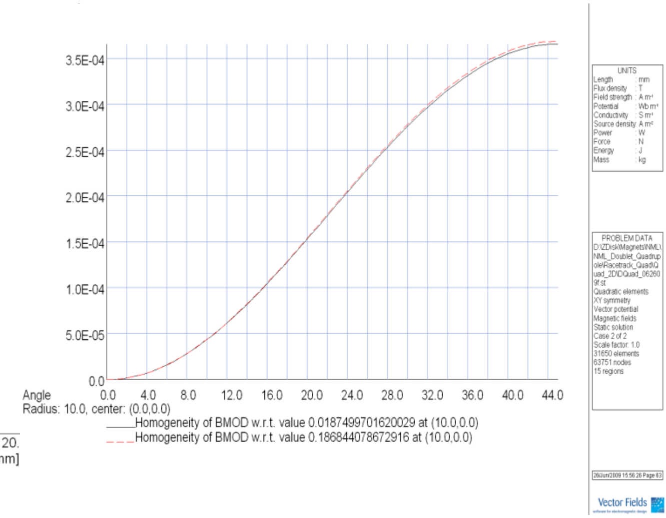
Magnet Package for KEK #CM 1

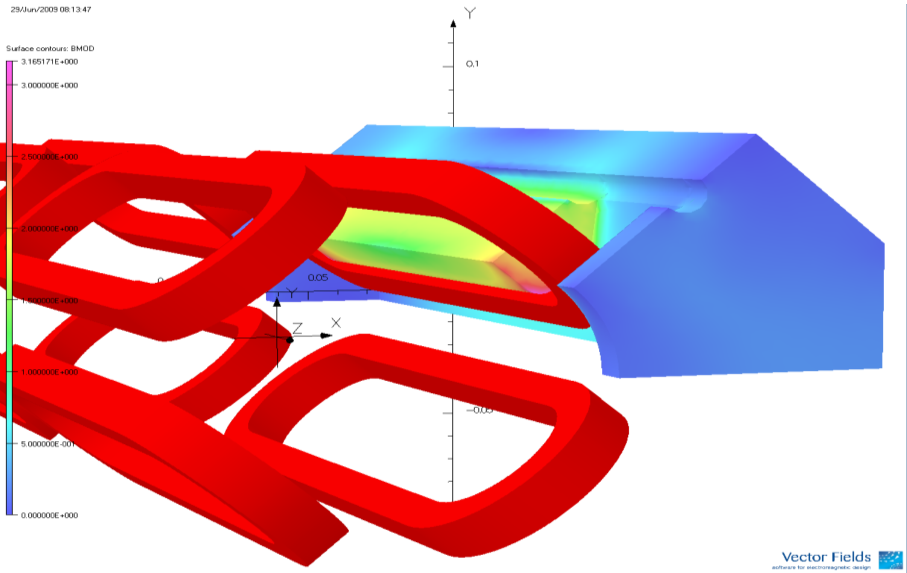
1. The first KEK-STF Cryomodule will be assembled and tested with the beam in 2014.
2. Akira Yamamoto proposed that FNAL built the splittable quadrupole for this Cryomodule.
3. Because the slot space is short it was decided to use one Quadrupole designed for ASTA Splittable Quadrupole Doublet.
4. Such 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.

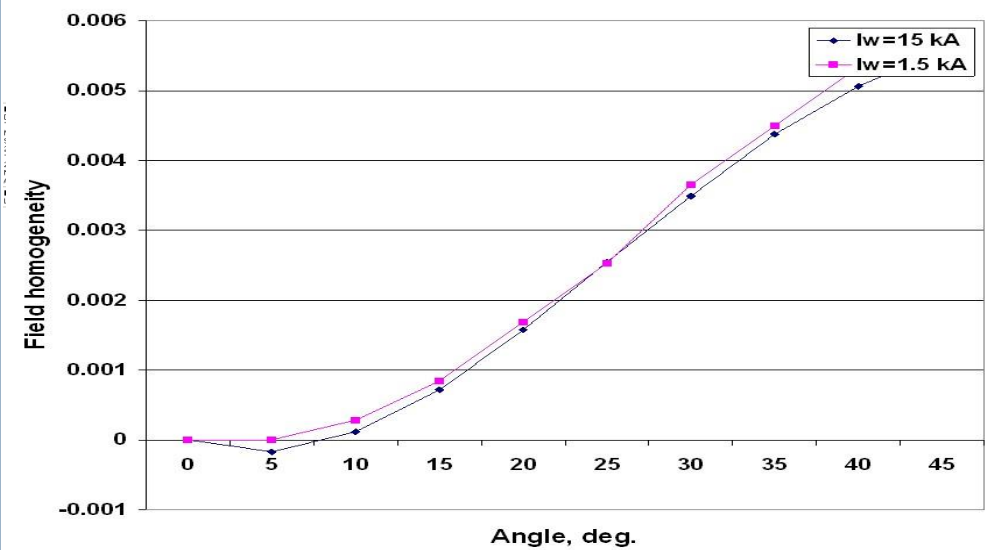
FNAL ASTA Quadrupole Doublet Magnetic Design





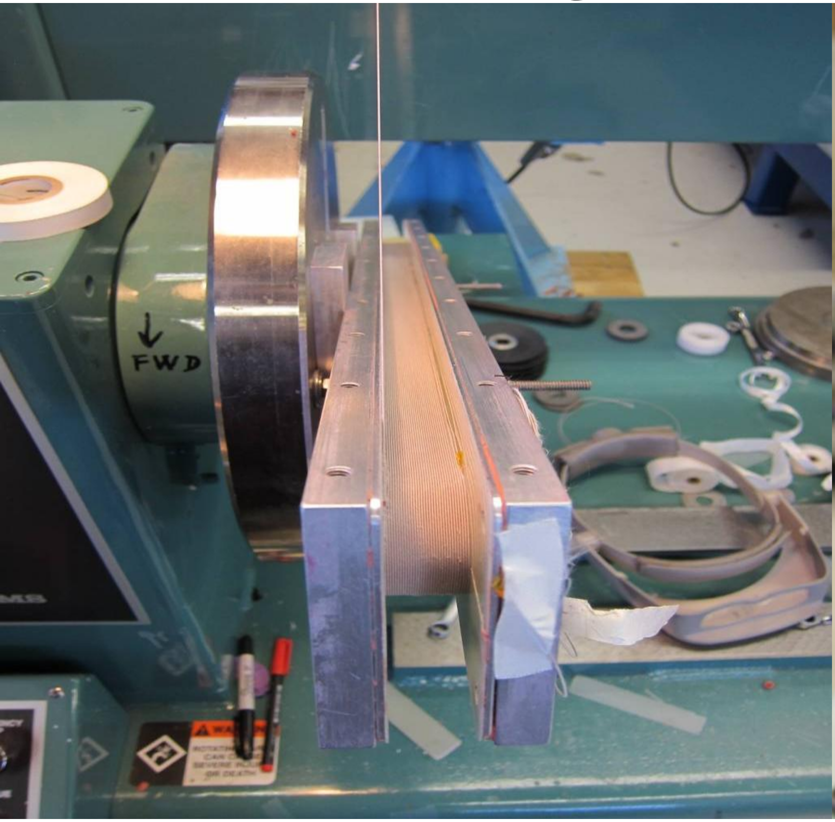


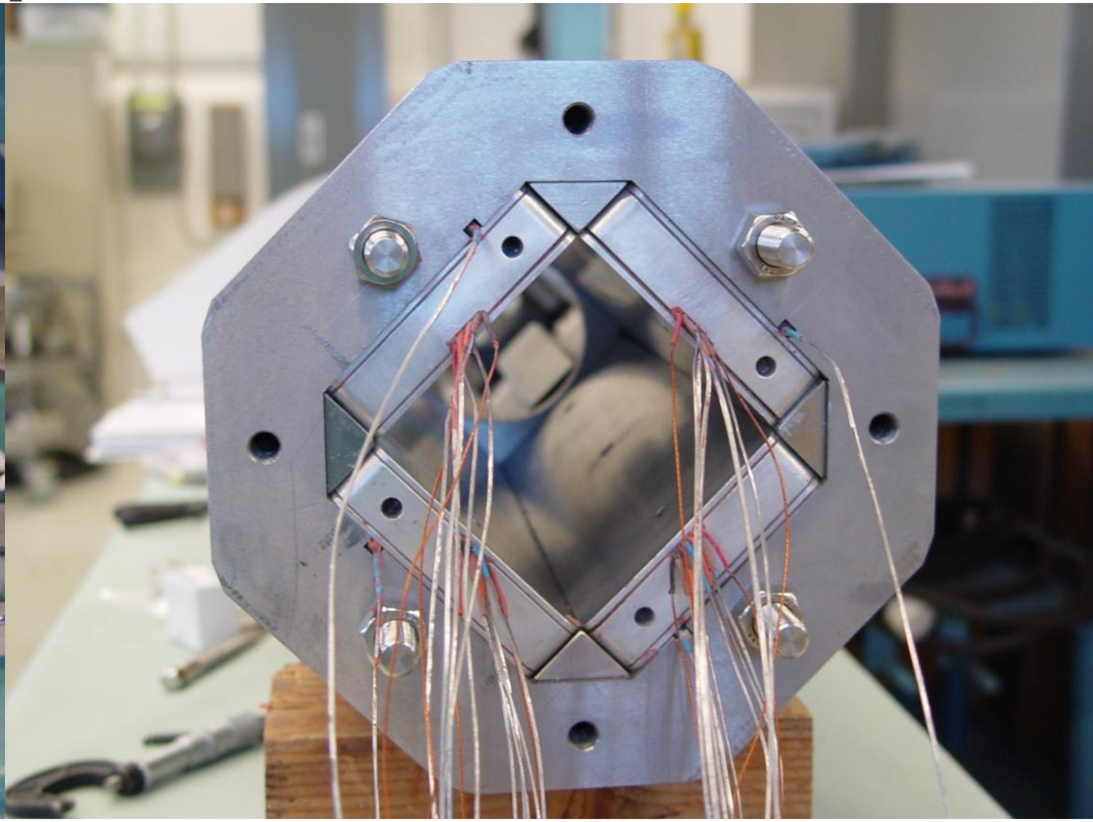




Integrated field homogeneity at 10 mm radius 0.6%, at 5 mm 0.18% (Spec. 0.5% at 5 mm).

ASTA Quadrupole Doublet Fabrication





Two Quadrupole Doublets for FNAL #CM3 were fabricated in 2011-2012. These quadrupoles mounted inside LHe vessels.

Fermilab

FNAL ASTA Quadrupole Doublet for #CM3

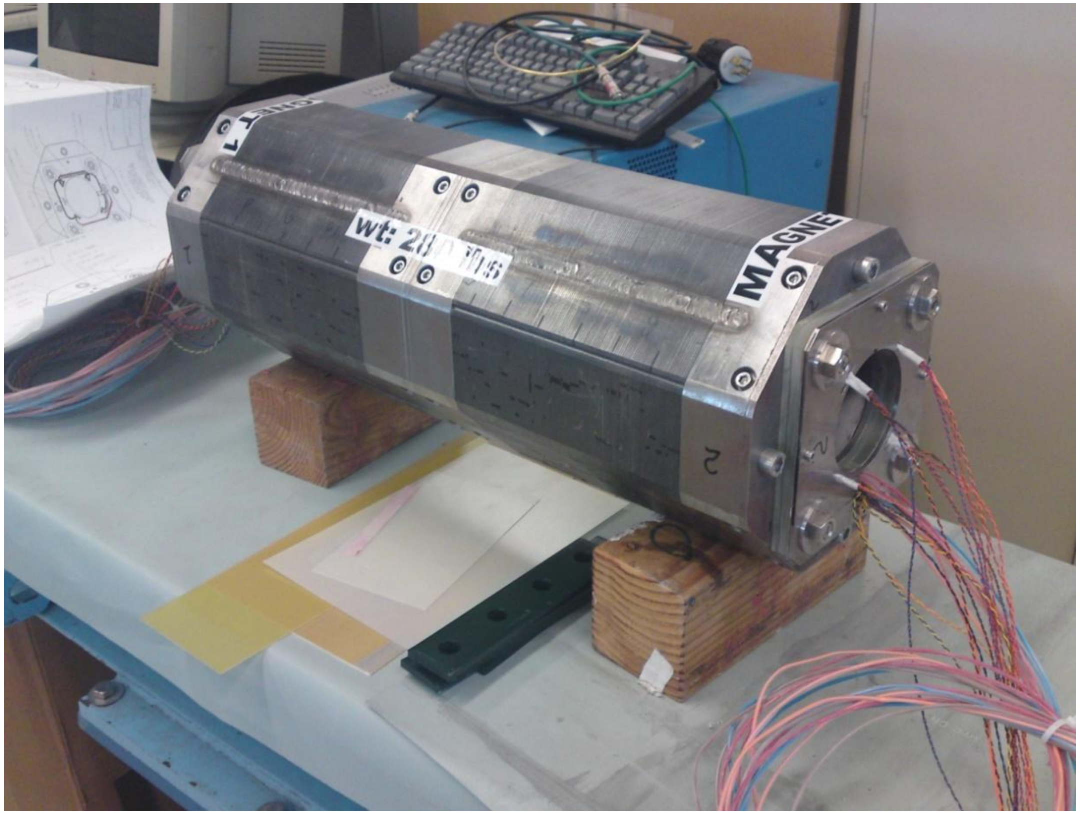
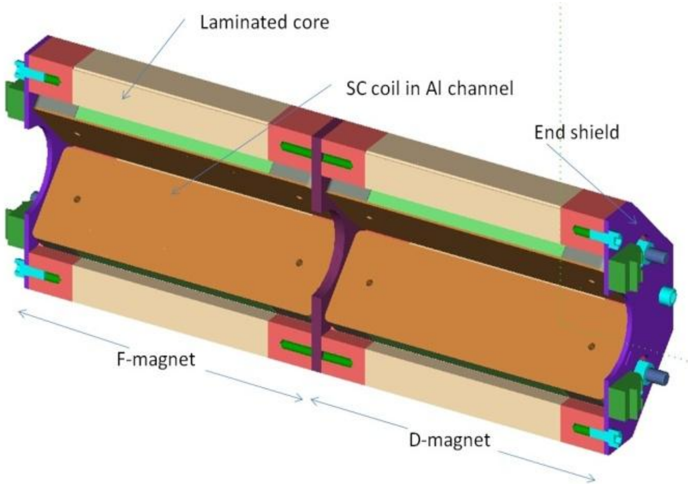


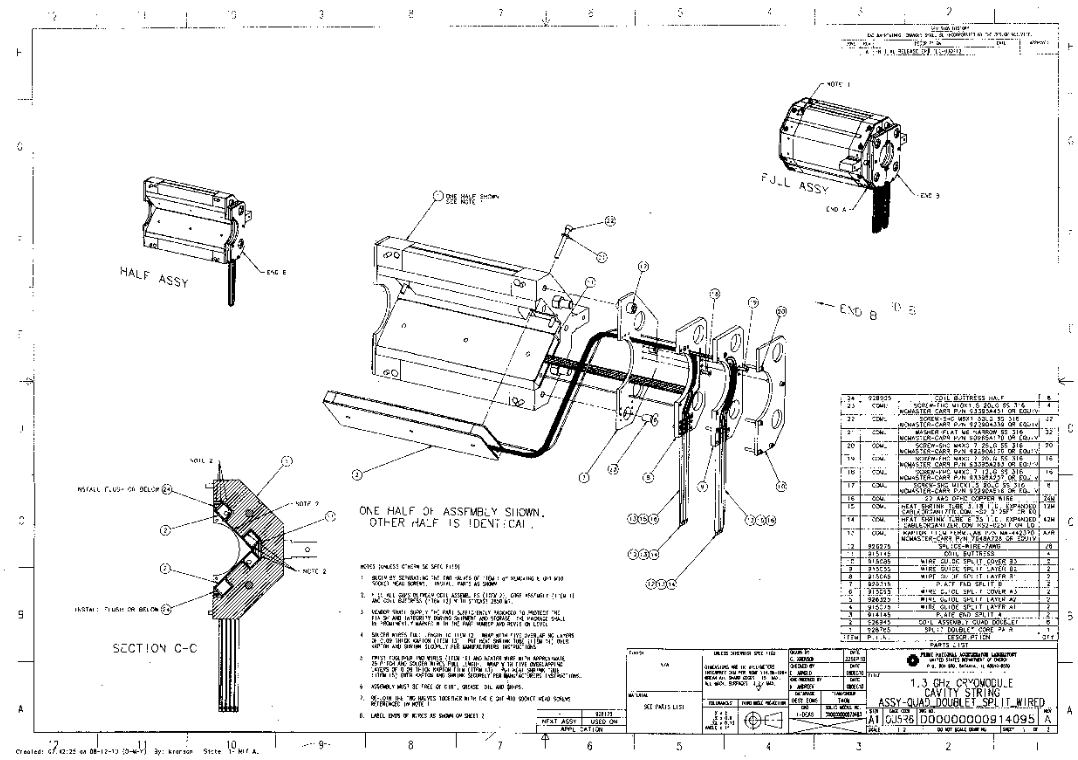
Table 1. Quadrupole Doublet Parameters

Parameter	Unit	Value
Beam pipe OD	mm	78
Integrated strength	T	3.0
Distance between quadrupole centers	m	0.3
Integrated dipole corrector strength	T-m	0.01
Quadrupole field quality at 5 mm radius	%	< 0.5
Dipole field homogeneity at 5 mm radius	%	< 5
Peak coil ampere-turns	kA	15
Operating temperature	K	2

Two unsplittable Quadrupole Doublets were built for ASTA #CM3.
They will operate in the bath cooling mode.

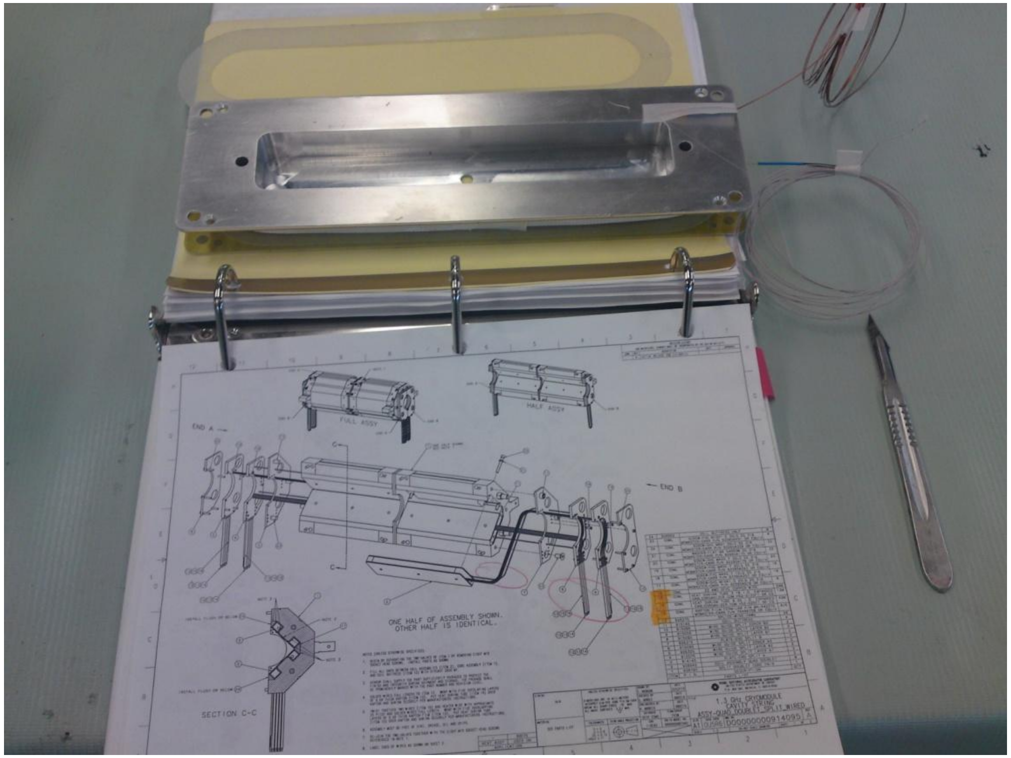
New Magnet for KEK-STF #CM1





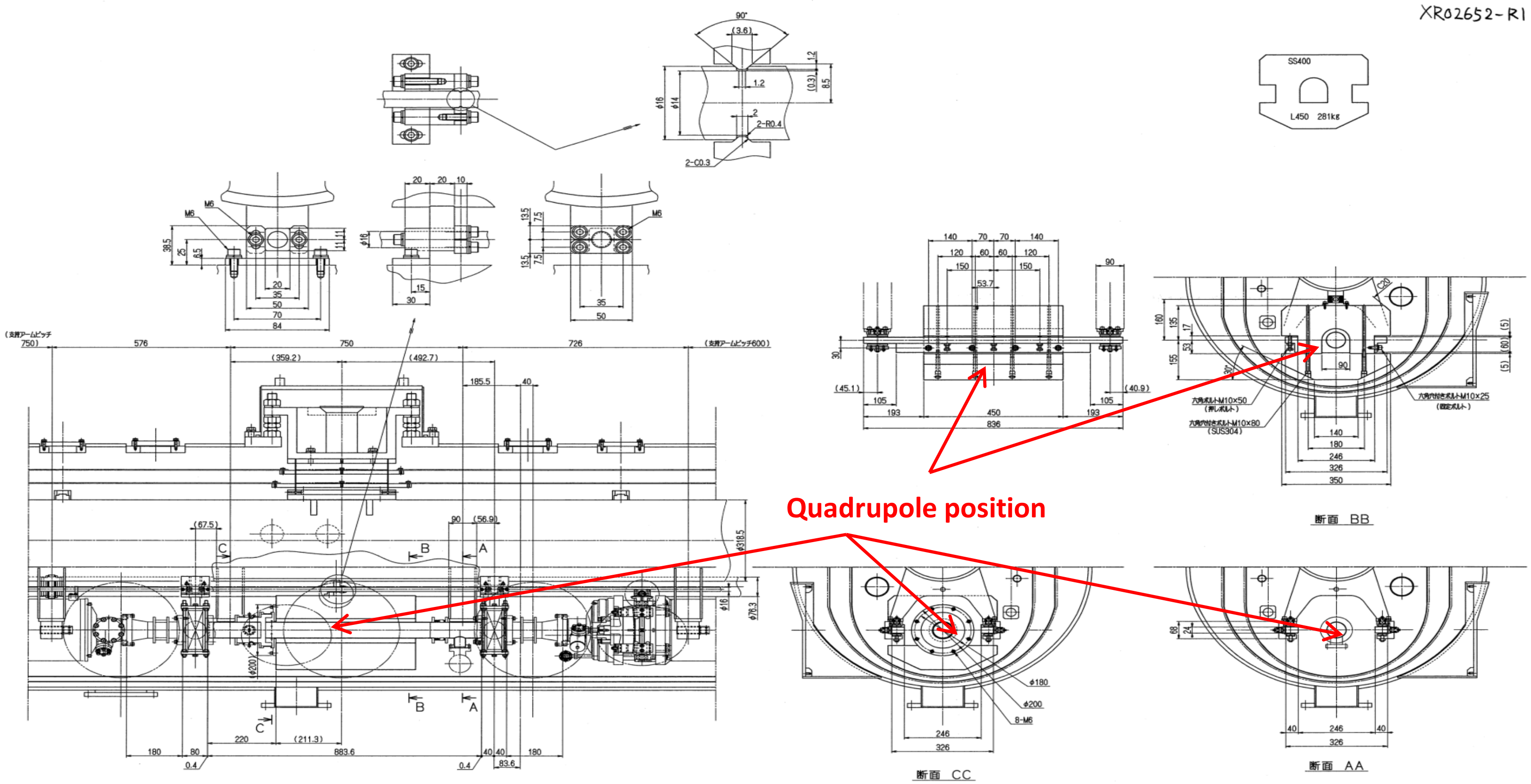
Because of a very tight schedule and space it was decided to use the Splittable Quadrupole Doublet design for ASTA and manufacture only one part of the Doublet. The quadrupole is also combined with dipole correctors as in the Doublet.

Quadrupole Coil Winding for KEK



Eight new quadrupole coils were wound, epoxy vacuum impregnated, and assembled with two magnets by Tom Wokas.

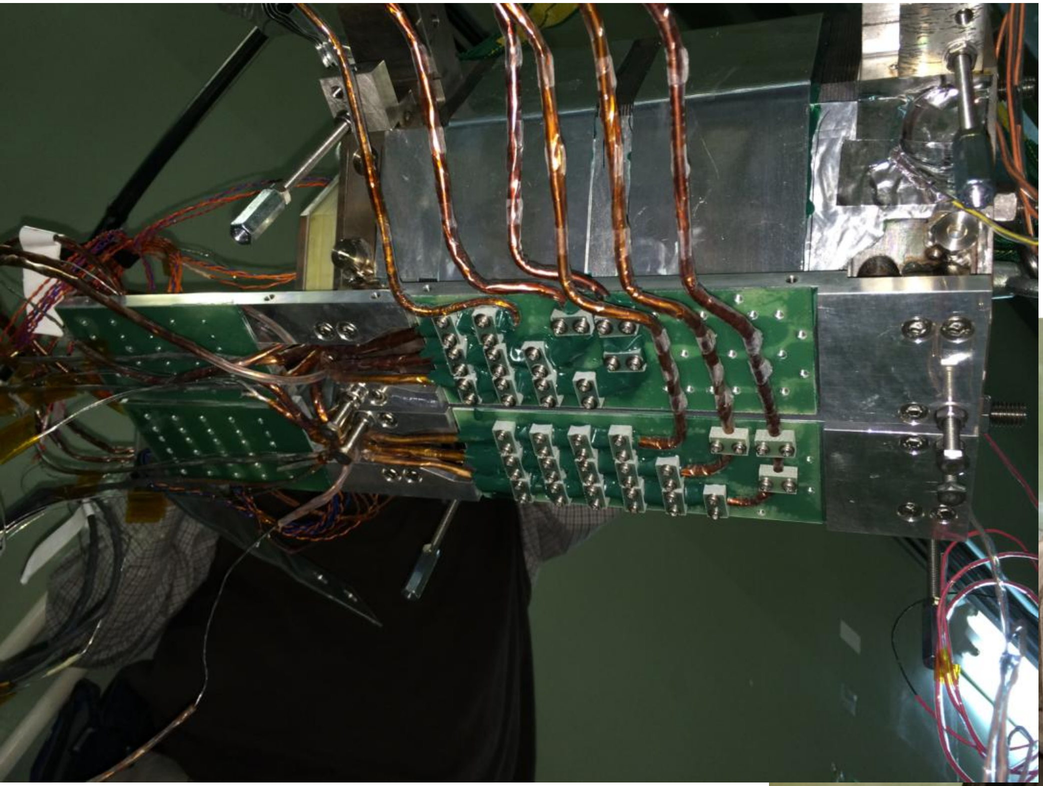
Quadrupole Integration with KEK #CM1



Magnet length should be less than 450mm,
Beam pipe aperture can be negotiable.
Current BPM design use 84mm outer diameter of chamber.
However BPM need to redesign its chamber outer diameter, not cavity part.

H. Hayano

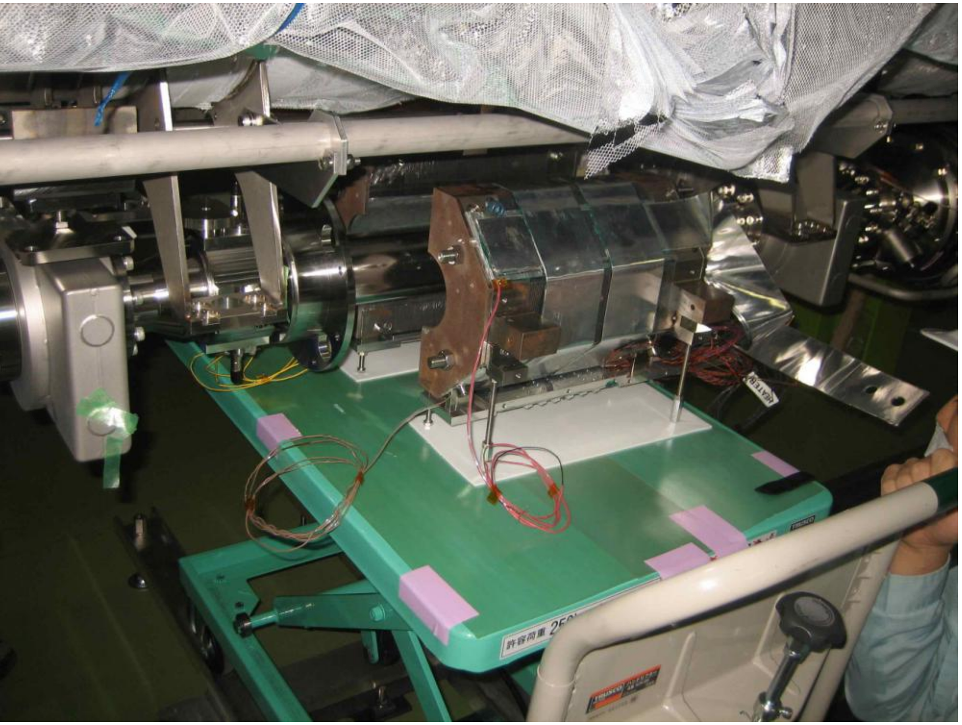
Quadrupole Final Inspection at KEK

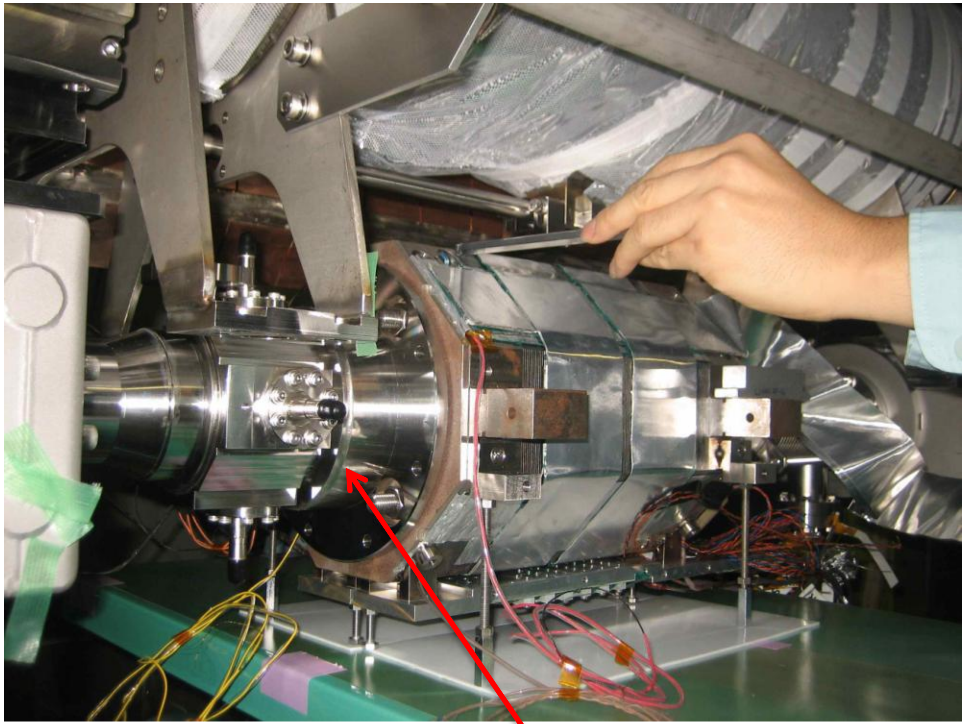


Leads and splices routing below the magnet circuits supporting plate.

Checking field polarities with Hall probe

Quadrupole Assembly around Beam Pipe

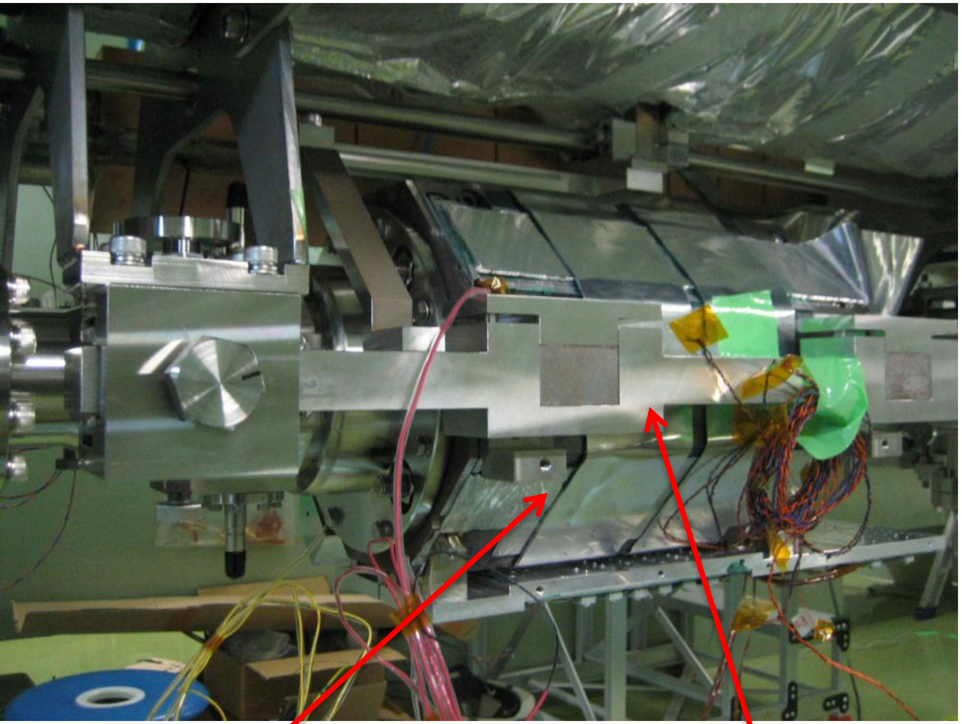


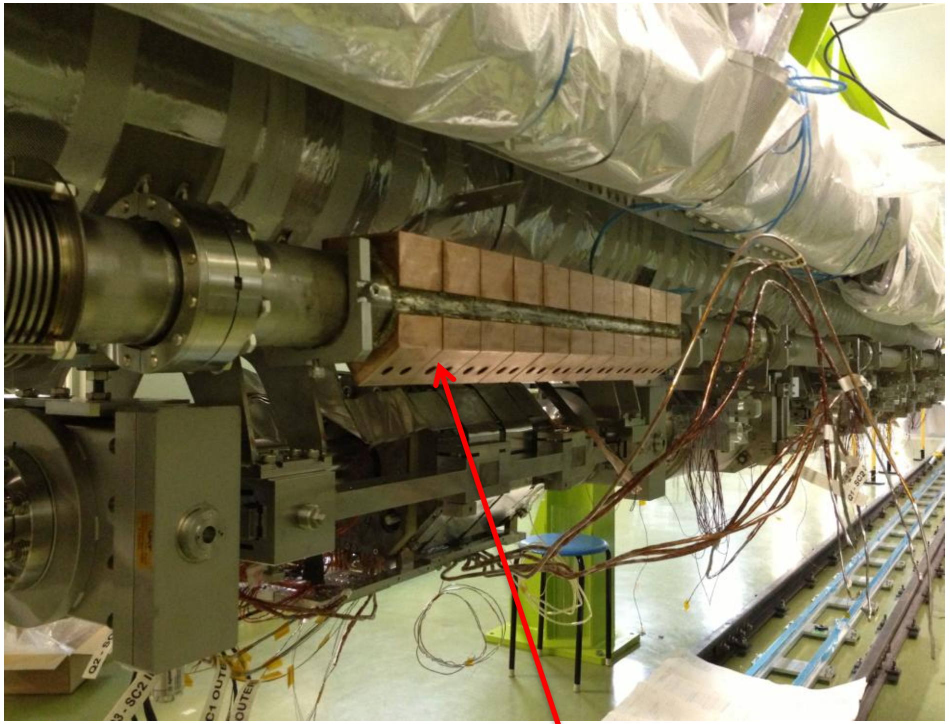


BPM

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

Quadrupole Final Assembly

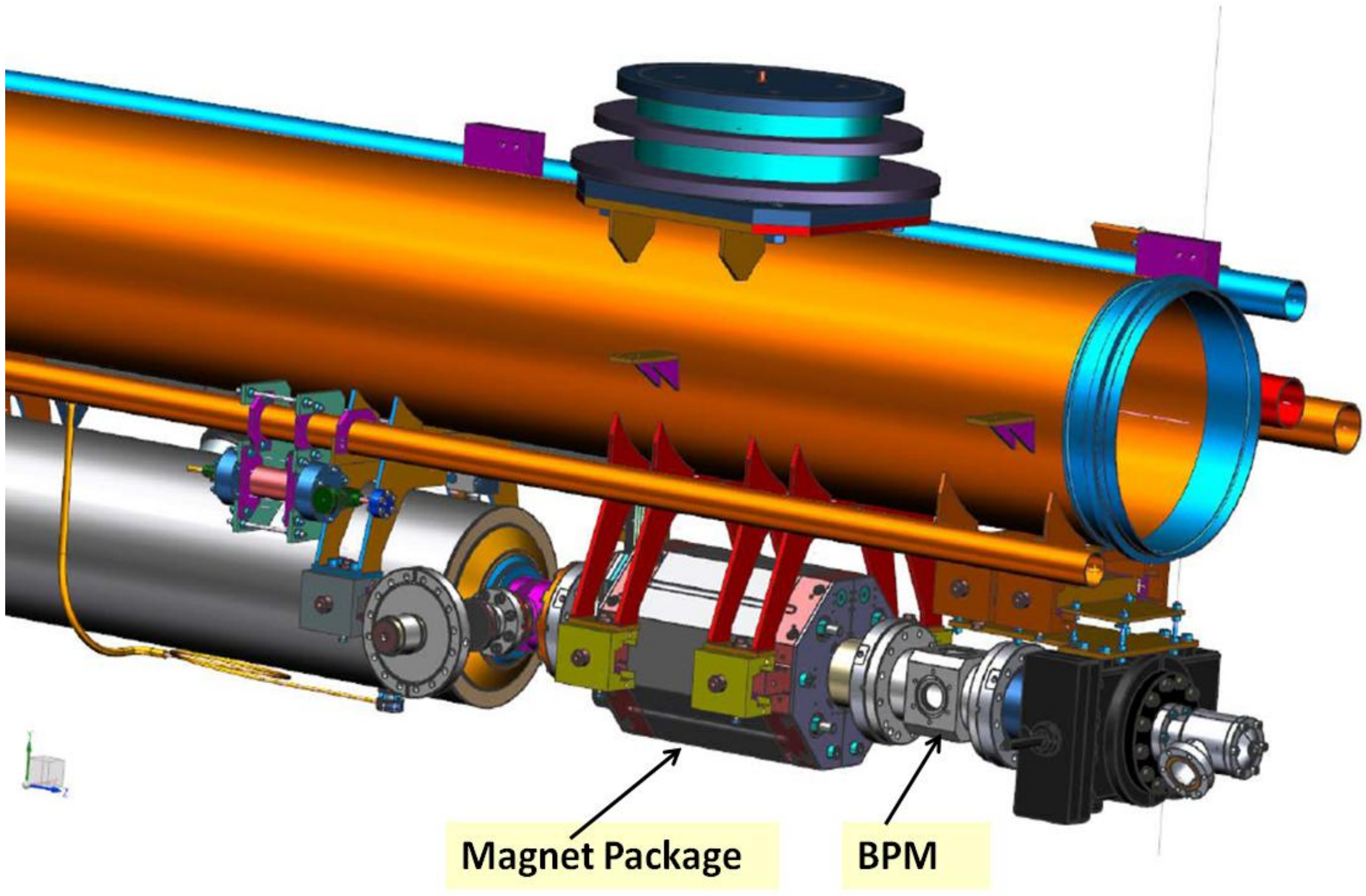




Magnet at supporting bars.

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.

Summary

1. **The splittable conduction cooled quadrupole magnet technology was proved for using in Superconducting Linear Accelerators.**
2. **The ILC Splittable Quadrupole was succesfully 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.**

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.