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

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Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Part 2 Linear Accelerator Magnets

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Outline

- *Magnets for Next Linear Collider*
- *Magnets for International Linear Collider*
- *Magnets for LCLS-II*

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Next Linear Collider Magnets

Next Linear Collider Magnets

Magnet Type	Styles	Quantity
Quadrupole	38	3681
Dipole	20	1592
Corrector	3	492
Trims	13	777
Sextupole	6	402
Solenoid	4	~10
Pulsed Magnets	6	23
Others	7	48
Total	97	6967

Magnet Requirements

- *Beam based alignment for quadrupoles:*
  - *Beam centered on quad to < 1 μm.*
  - *All quadrupoles have dedicated beam position monitors(BPM's).*
- *Vibration:*
  - *Nanometer level jitter(f > 10 Hz) tolerances.*
  - *FFTB quad 'water on' vibration excessive.*
- *Strength stability($\Delta B/B_n$):*
  - *Jitter tolerance: $< 10^{-4}$ to $< 5 \times 10^{-6}$*
  - *Short term(minutes) tolerances: $< 10^{-3}$*
- *Multipoles(still defining):*
  - *Looser in Inj., ML and BD(single pass).*
  - *Tighter in DR's.*
- *NLC availability goal of 85 % for a 9 month run.*
- *Radiation dose rate(still defining):*
  - *High in DR's (50 W/m, avg.)*
  - *Lower in ML(1.4 W/m, avg.)*
- *Movers:*
  - *All quads and sextupoles on movers.*
  - *Achieve < 200 nm step size*

Beam Based Alignment

- *Beam centered on quadrupole to $< 1\ \mu m$.*
- *Use BPM feedback and mover steering to center quad on the beam. But where is the BPM with respect to the quad(mechanical offset and BPM readout error)?*
- *First step is to find the offset of each individual BPM to its quad:*
  - *Vary an individual quad's strength by 20 % in several steps.*
  - *Measure the beam kick due to quad/beam offset using downstream BPM's.*
  - *Reconstruct the orbit and determine offset of that quad to its BPM; proceed to next quad magnet.*
  - *Repeat procedure weekly, monthly as needed.*
- *Implement automated steering procedure using movers.*
- *During 20% quad strength variation, quad center must not move by more than 1 μm; the lower the better.*
- *Magnet design must minimize change in relative pole strengths during this strength variation.*

Permanent Magnets or Electromagnets

PM +	PM-
Eliminate power supplies	Difficulty in meeting BBA
Substantial reduction in cableplant	PM long term stability:
Eliminate EM power and cooling	- radiation resistance
Lower operating cost	- temperature stability
Improved availability	- long term demagnetization effects
No water flow induced vibration	
Enhanced machine protection	Limits on energy flexibility
Lower cost	

NLC PM Candidates

- *Original list of NLC PM candidates:*
  - *If injector is centralized, then transport line quads could be PM.*
  - *Bunch compressor bends and quads.*
  - *Damping ring bends and sextupoles.*
  - *Main linac quads up to 150 GeV(use EM's from 150 to 250 GeV for energy flexibility).*
  - *Main linac quads past 250 GeV(drift lattice for an initial 500 GeV CM machine).*
  - *Only soft bends, final doublet, and extraction lines in beam delivery area.*
  - *Trims, correctors, pulsed magnets, solenoids, septums, spin rotators are not candidates for PM technology.*
- *Presently assuming 50%(about 3321) of NLC magnets would be viable for PM's.*
- *Prototype results will help define limits of applying PM technology to NLC.*

PM Materials

Ferrite

Strontium or barium ferrite

Inexpensive

Radiation resistant

Low Br, .38 T

High temp coefficient,

-0.2 % / C°

Brittle

SmCo

Sm-Co 1:5, 2:17

Expensive

Small industrial base

Radiation resistant(2:17 good, 1:5 is worse)

High Br, 1.05 T

Low temp coefficient,

-0.03% / C°

Brittle

Nd-Fe-B

Cheaper than SmCo

Large industrial base

Poor radiation resistance

Highest Br, 1.2 T

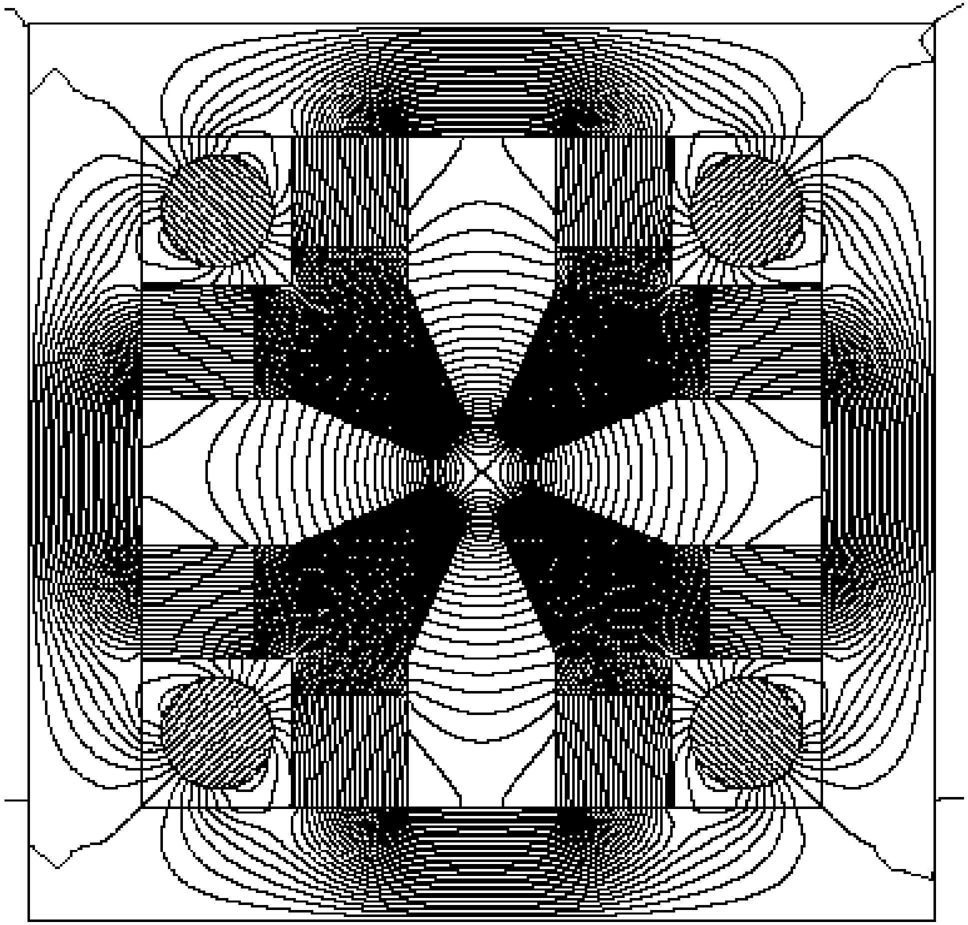
High temp coefficient,

--0.1% / C°

Plated to prevent corrosion

PM Prototype: Corner Tuner Design

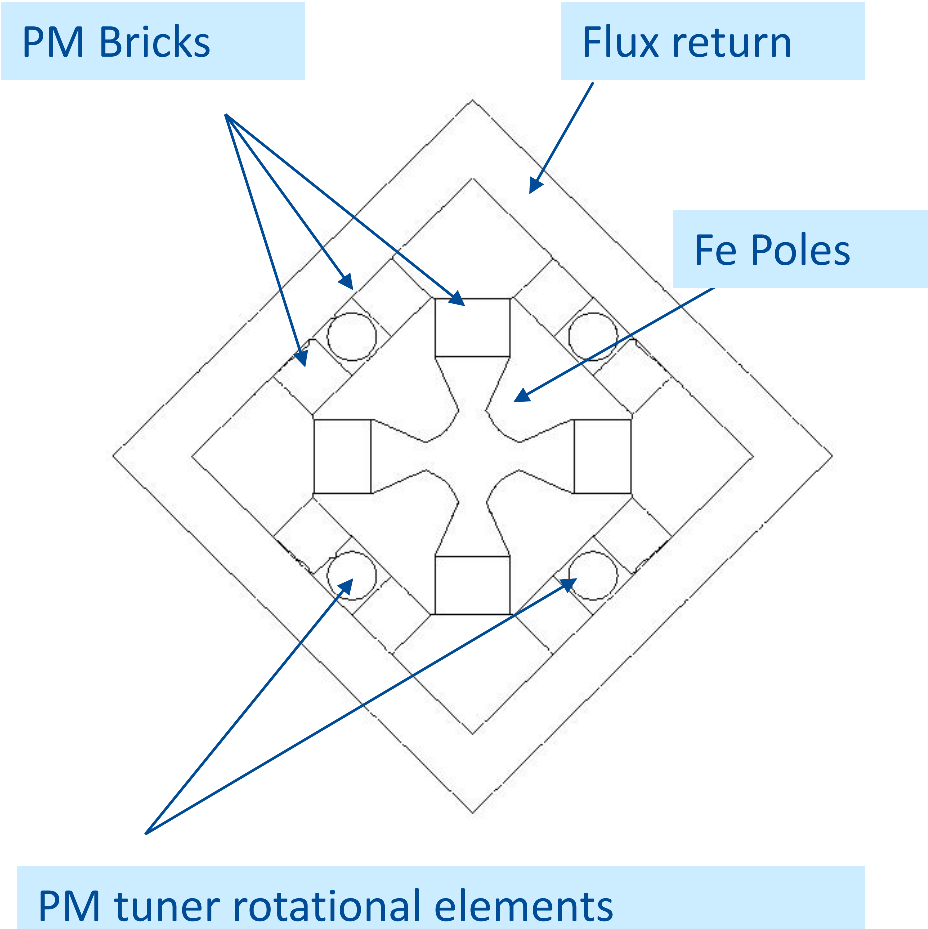
- Preliminary design:
  - Sm-Co 2:17 bricks outboard of poles.
  - Rotating Sm-Co 2:17 tuners in corners.
  - Pole supports between poles.
  - Temperature compensator(if needed); applies to all hybrid PM designs.
- Advantages:
  - Similar to recycler ring quads.
  - Large space available for pole supports.
- Disadvantages/issues:
  - PM material is not used most efficiently.
  - High demag field in some areas.
  - Non-symmetric demag fields across element, could affect center shift tolerance.



PM Quad FCS217

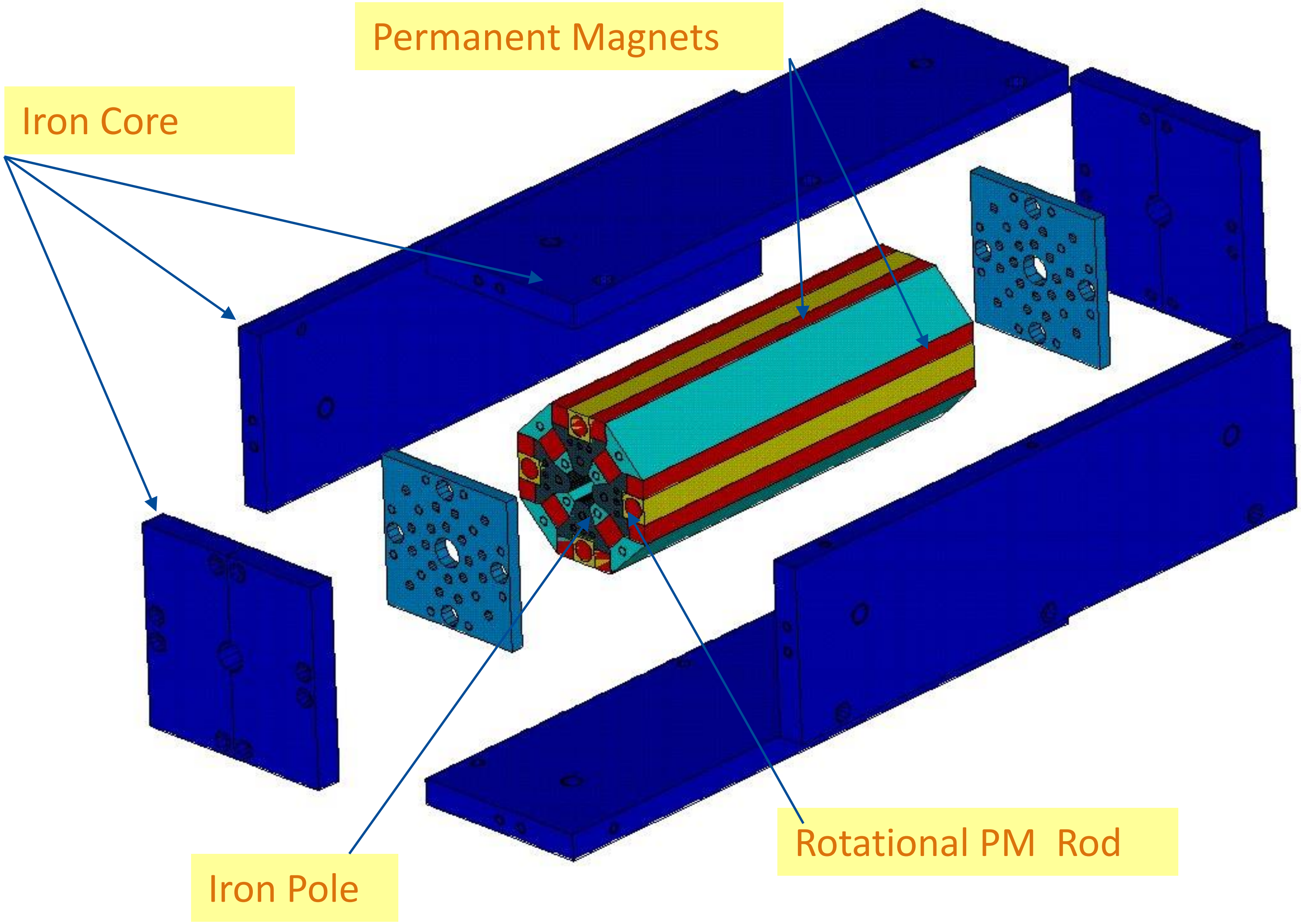
PM Prototype: Wedge Design

- *Preliminary design:*
  - *Sm-Co 2:17 bricks outboard and between poles.*
  - *Rotating tuners(Nd-Fe-B) outboard of poles.*
  - *Tuning washers outboard of lateral bricks(optional).*
  - *Flux return rotated 90° .*
- *Advantages:*
  - *PM material is used efficiently.*
  - *Symmetric demag. field across elements.*
- *Disadvantages/issues:*
  - *More complicated assembly.*
  - *Diamond flux return does not integrate well with cam-style mover.*

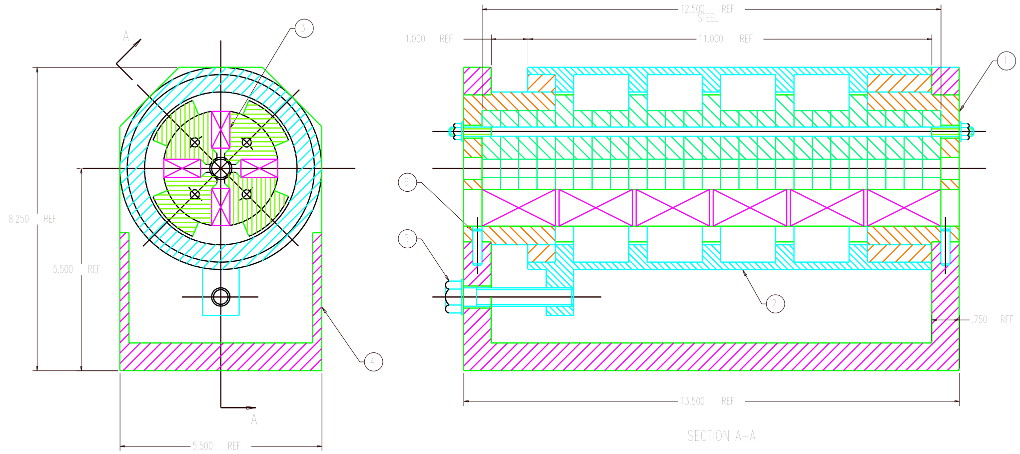


PM Quadrupole FWS217

Wedge Quadrupole Design



PM Prototype: Magnetic Shunt Design



Prototype Design:

- Bricks located between poles
- Outer ferromagnetic screen is a shunt for the magnetic flux
- Outer surface of poles and inner surface of outer screen have slots
- Magnetic resistance and magnet strength is changed on 20% during moving magnetic shunt along the quadrupole length

- Advantages:
  - shunt material properties have less variation than a PM elements
  - simple mechanics
- Disadvantages:
  - nonuniform modulating the performance of each circuit may cause a magnetic center shift
  - Strong magnetic forces

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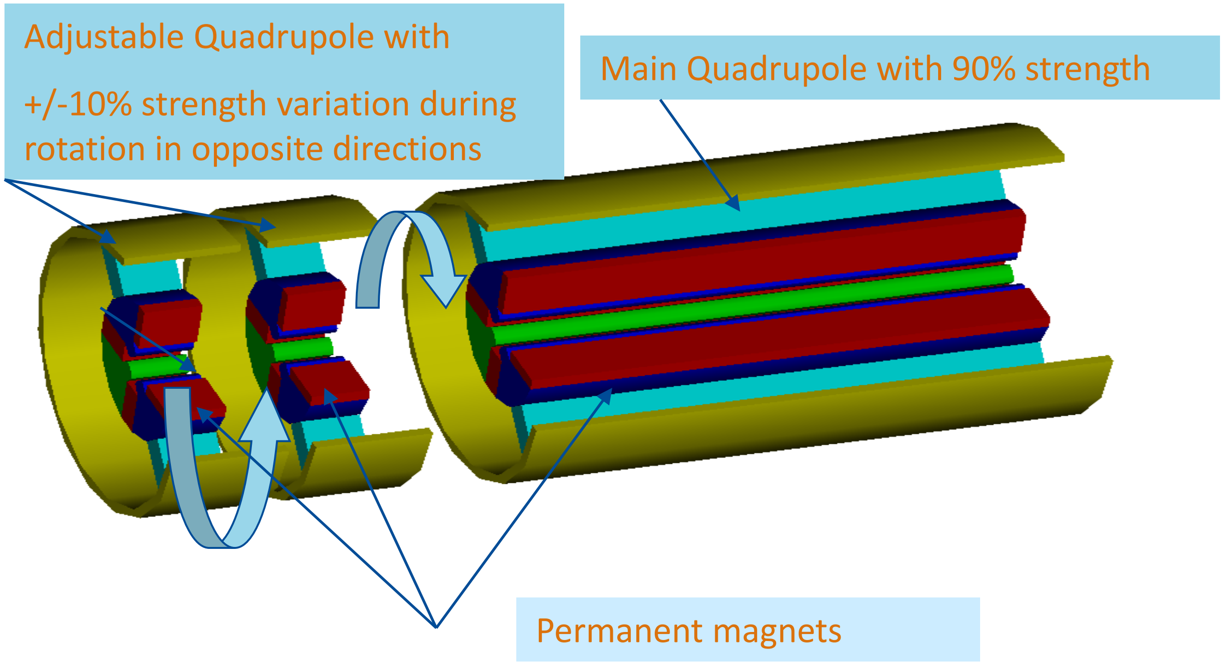
PM Prototype: Rotational Quadrupole Sections



Advantages:

The demand 1 um magnetic axis stability is transformed in 10 um at MAX strength for rotational sections. The 90% of total quadrupole strength is provided by stable main section. No magnetic forces between quadrupoles, no eddy currents, easy rotation with small power, possibility of quick quadrupole total strength change.

Disadvantages:

Longer quadrupole because of extra end screens between sections. Possible problems with BBA system when tuning only end sections.

Prototype Design:

- Quadrupole has main and adjustable sections.
- Adjustable section has 2 short quadrupoles which is possible to rotate in opposite directions to change the quad. strength in range +/-10%.
- Mechanics provides the rotation on +/-45 deg.
- All sections are screened by outer and end ferromagnetic screens.
- Magnetic axis position is corrected by magnetic shunts

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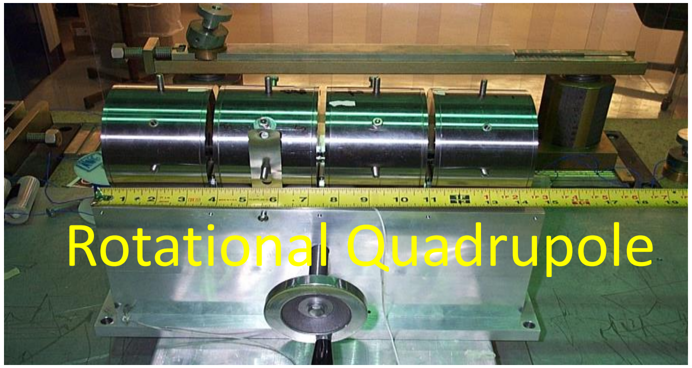
Adjustable PM Quadrupoles for NLC



FNAL R&D

Item	Value
Aperture	12.7 mm
Quantity Length	288 324 mm 399 432mm 576 965mm
Pole tip field	0.62 Tesla for 324mm 0.80 Tesla for other
Adjustment	+0 to –20%
Temperature stability	0.5% at 25 ± 1 °C
Sextupole	$b_3/b_2 < 0.02$ at r=5mm
Field accuracy	±0.5% at any field
Center location	To Fiducial ± 0.1mm
Center stability	± 0.001 mm over range of adjustment

Measurement Results

	Max Grad Tesla	Min Grad Tesla	Center Shift Microns
Corner	17.5	14.1	100.0
Wedge	23.7	18.4	20.0
Sliding Shunt	25.9	21.8	15.0
Rotating	36.3	30.3	4.5

Summary

- *Permanent magnets used in various accelerators because eliminate the cost of electricity and fabrication.*
- *The main drawback is the fixed field strength was overcome by developing adjustable magnets.*
- *It was shown that magnets could provide microns stability of magnetic center in quadrupoles which is very difficult to achieve for any magnet type.*
- *Because permanent magnets has a very high magnetic concentration in small volumes they could produce larger fields or gradients in small apertures than electromagnets.*

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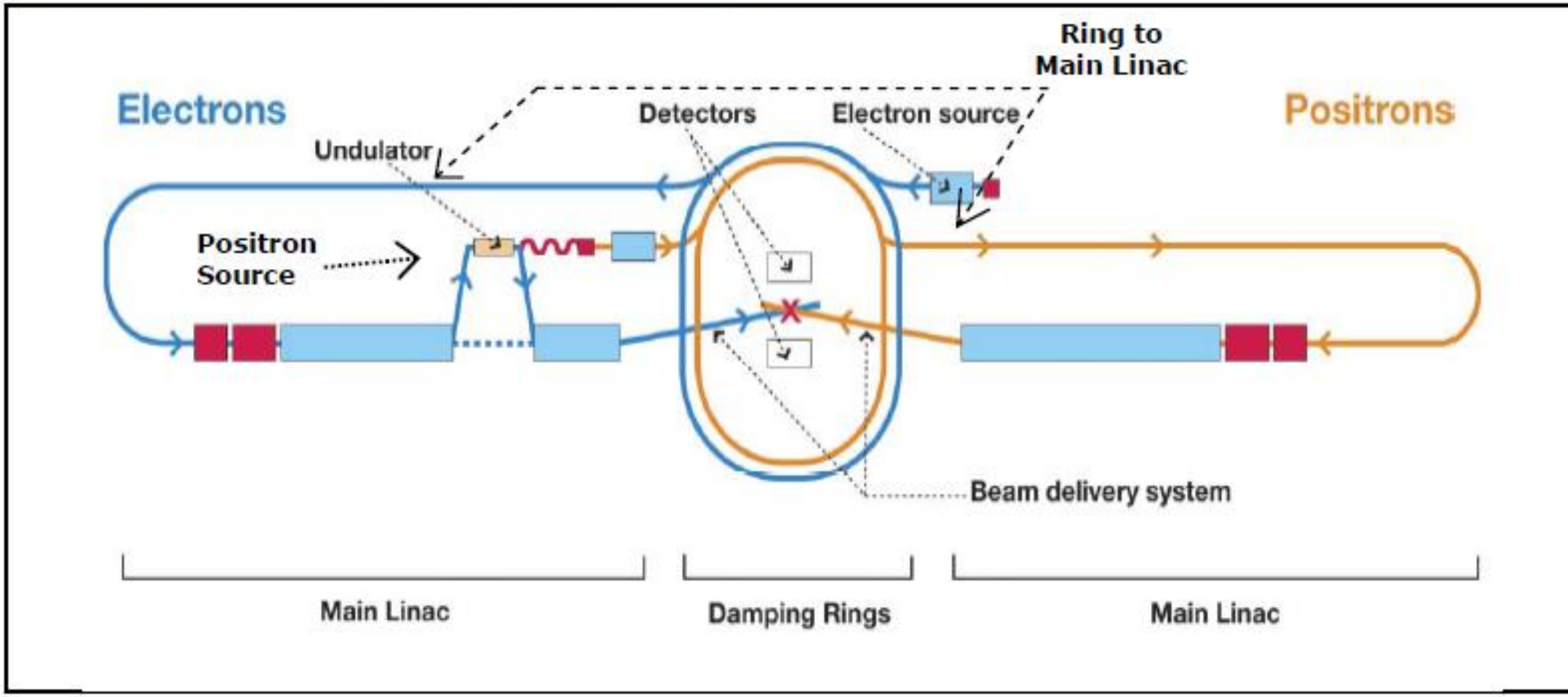
International Linear Collider Magnets

Outline

- ILC magnets
- ILC full scale splittable quadrupole at KEK
- KEK test results and status at FNAL
- Quadrupole Doublet for FNAL ASTA #CM3
- New splittable quadrupole for KEK Cryomodule 1
- Integrated magnet system concept
- Stabilization coils
- ILC magnet program results

ILC Layout



Schematic view of ILC major components.

ILC Layout

Table 1: ILC RDR Magnet Summary Table (250GeV X 250GeV – 14 December 2006)

Magnet Type	Grand Totals		Sources		Damping Rings		2 RTML Qty	2 Linacs Qty	2 BeamDel Qty
	Styles	Quantity	e-	e+	e-	e+			
Dipole	22	1356	25	157	134	134	716	0	190
Normal Cond Quad	37	4182	93	871	823	823	1368	0	204
Sextupole	7	1050	0	32	504	504	0	0	10
Normal Cond Solenoid	3	50	12	38	0	0	0	0	0
Normal Cond Corrector	9	4047	0	871	540	540	2032	0	64
Pulsed/Kickers/Septa	11	227	0	19	46	46	52	0	64
NC Octupole/Muon Spoilers	3	8	0	0	0	0	0	0	8
Room Temp. Magnets	*92*	*10920*	*130*	*1988*	*2047*	*2047*	*4168*	*0*	*540*
Supercond Quad	16	715	16	51	0	0	56	560	32
Supercond Sextupole	4	12	0	0	0	0	0	0	12
Supercond Octupole	3	14	0	0	0	0	0	0	14
Supercond Corrector	14	1374	32	102	0	0	84	1120	36
Supercond Solenoid	4	16	2	2	0	0	8	0	4
Supercond Wiggler	1	160	0	0	80	80	0	0	0
Supercond Undulator	1	42	0	42	0	0	0	0	0
Superconducting Magnets	*43*	*2333*	*50*	*197*	*80*	*80*	*148*	*1680*	*98*
Overall Totals	135	13253	180	2185	2127	2127	4316	1680	638

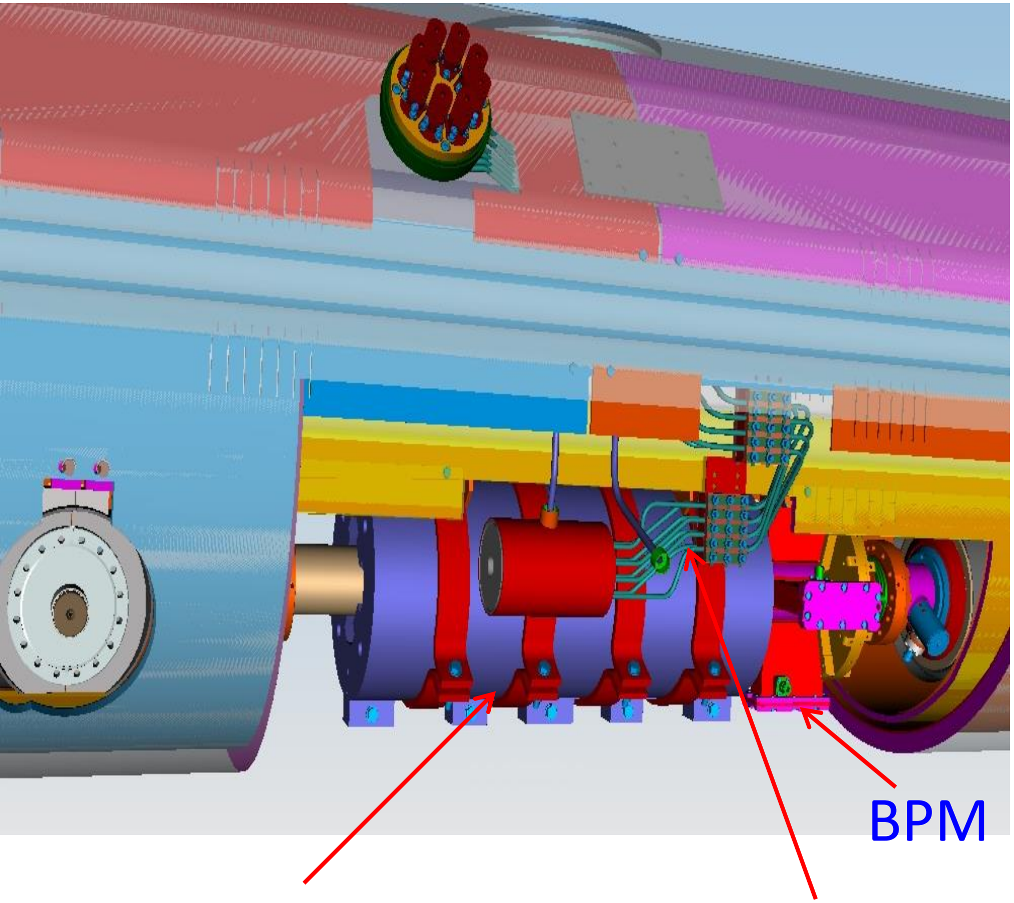
Total 135 magnet styles, and quantity 13253.

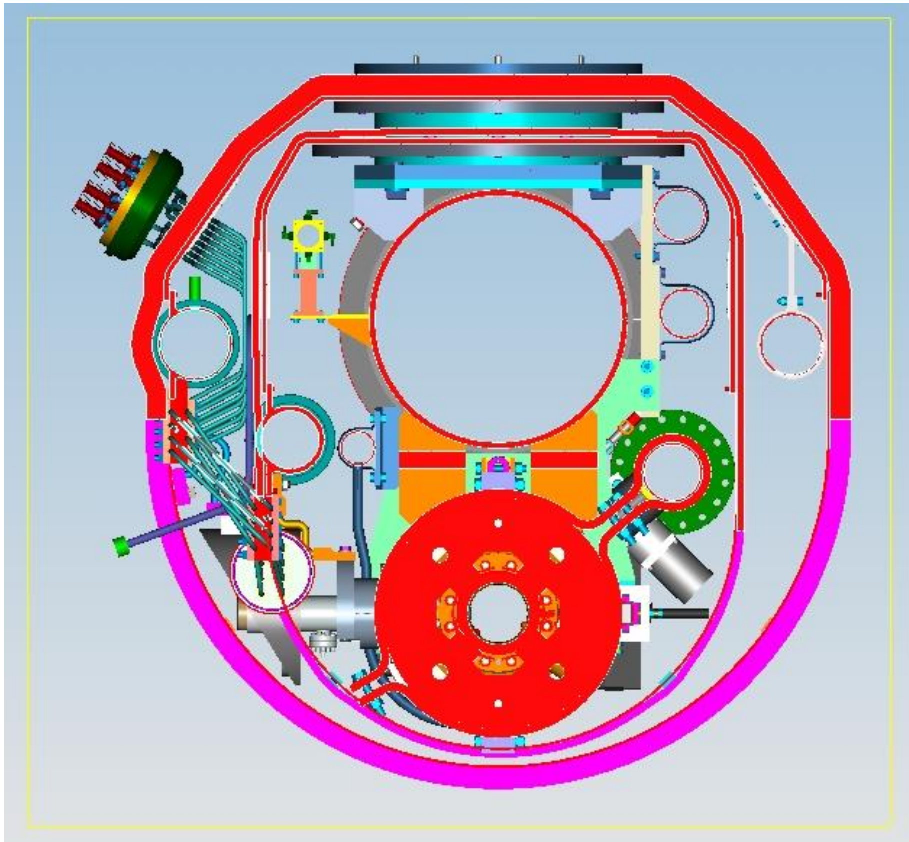
ILC Quadrupole Specification & Superconductor

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

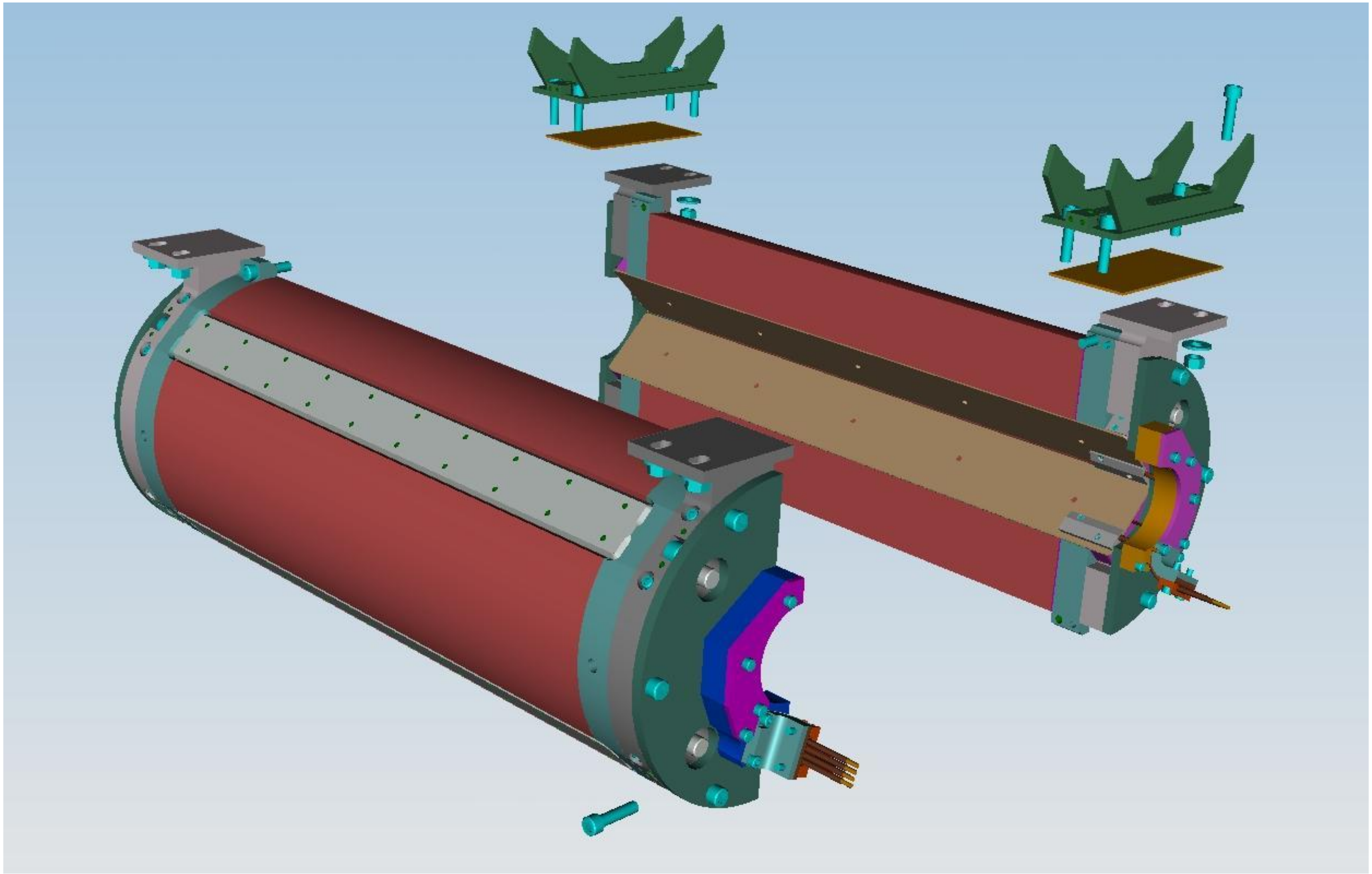
NbTi wire diameter, mm	0.5
Number of filaments	7242
Filament diameter, um	3.7
Copper : Superconductor	1.5
Insulated wire diameter, mm	0.54
Insulation	Formvar
Twist pitch, mm	25
RRR of copper matrix	100
Critical current Ic @ 4.2K, at 5T	204 A

ILC Splittable Quadrupole in Cryomodule

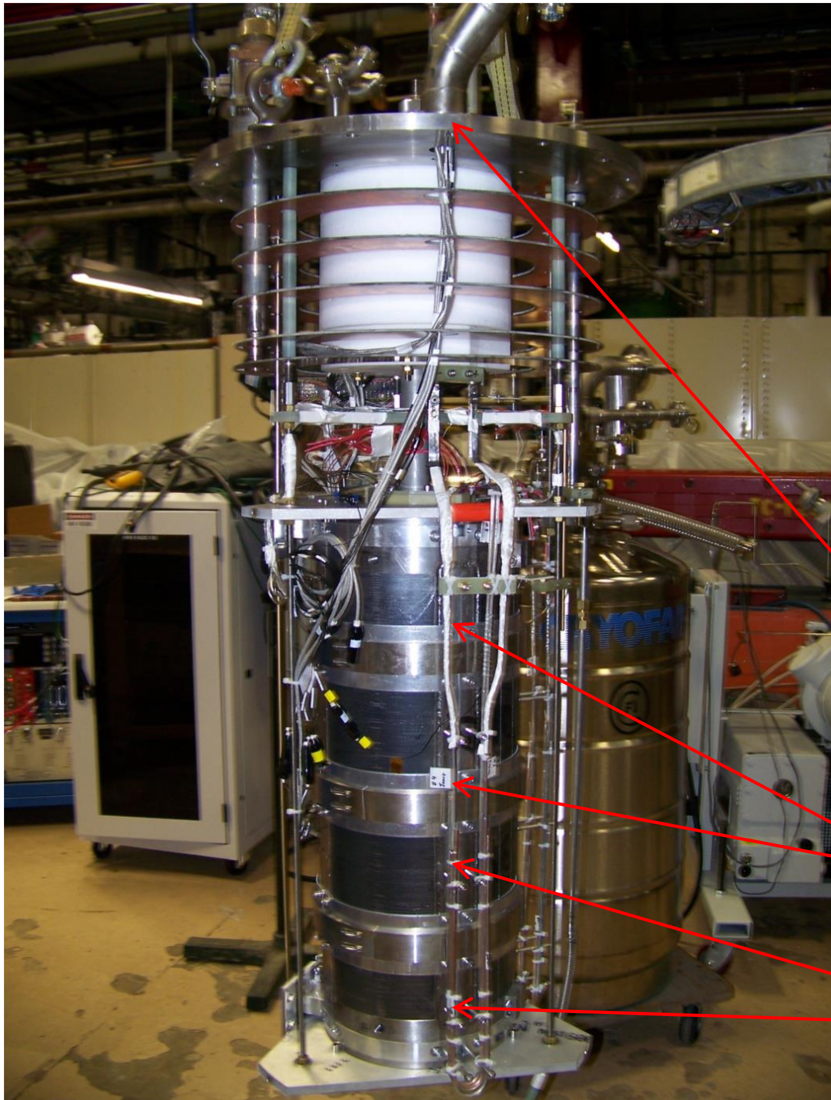


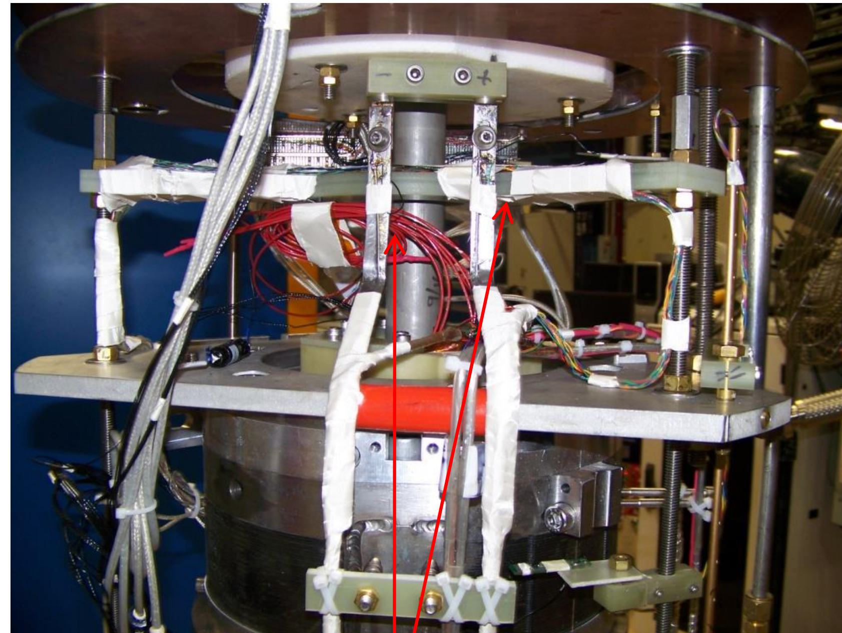


ILC Two Halves of the Quadrupole



ILC Quadrupole with Top Head Assembly





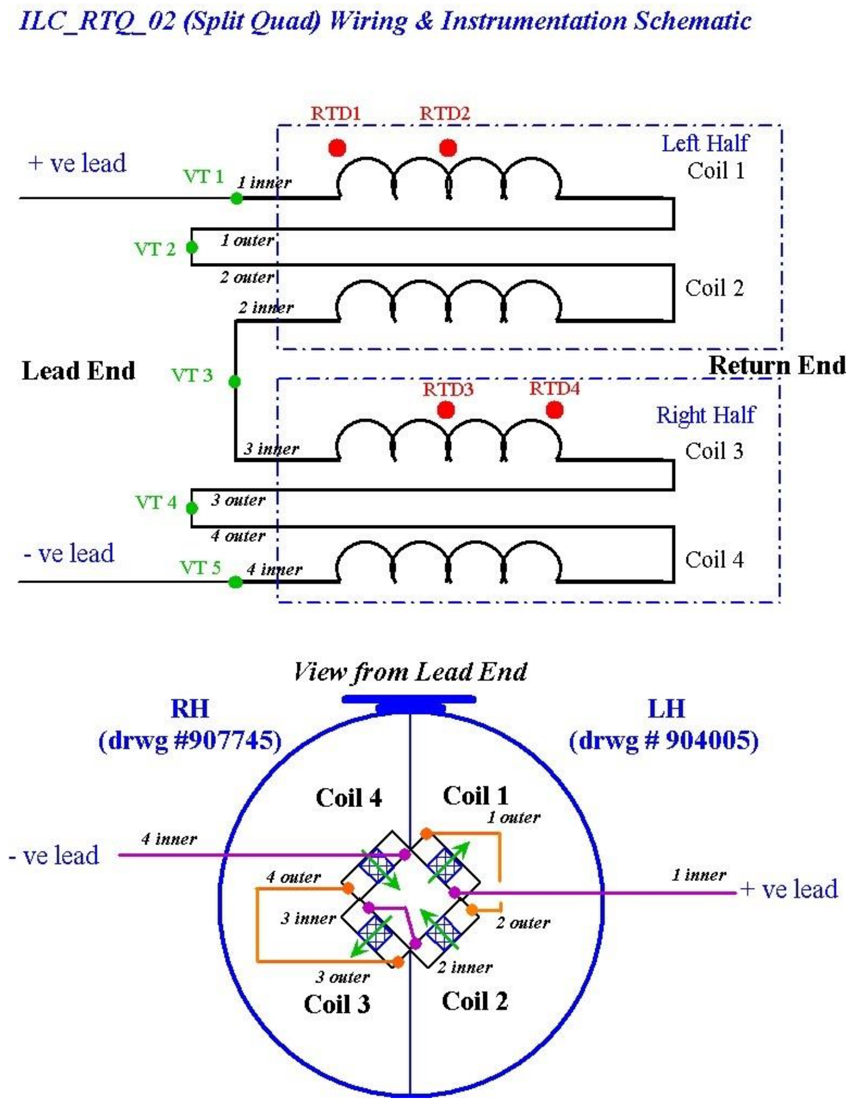
Current leads

Top head

Quadrupole yoke

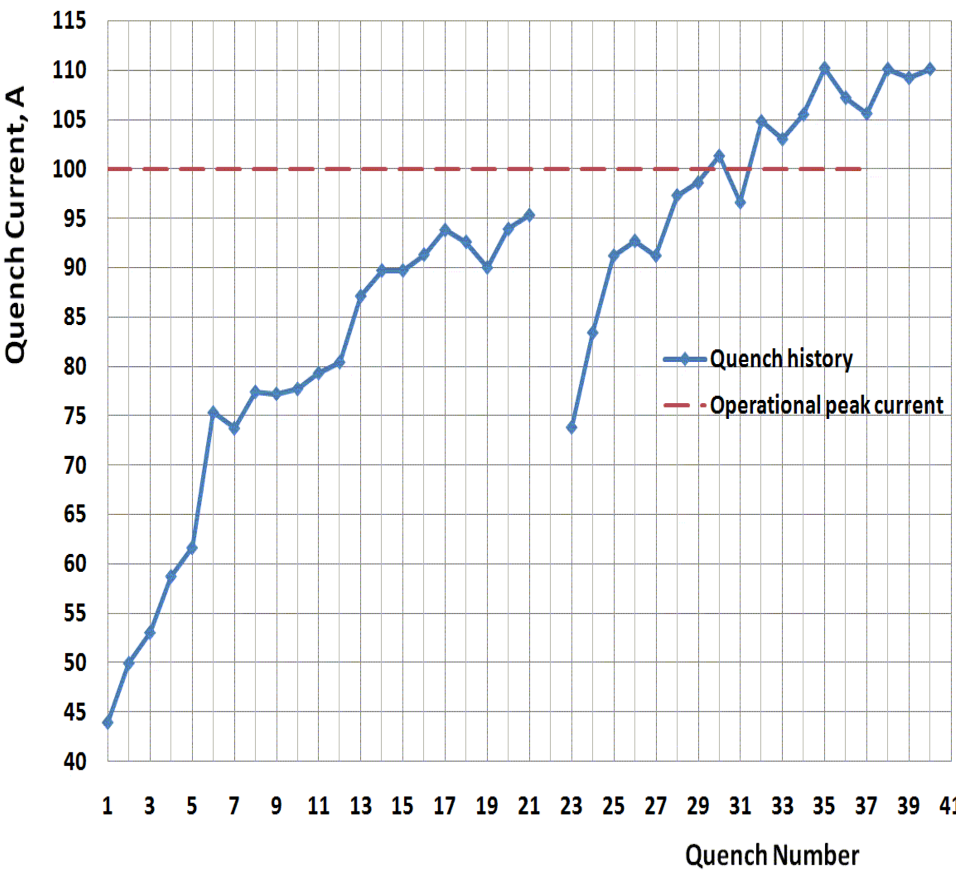
Two quadrupole halves clamping rings

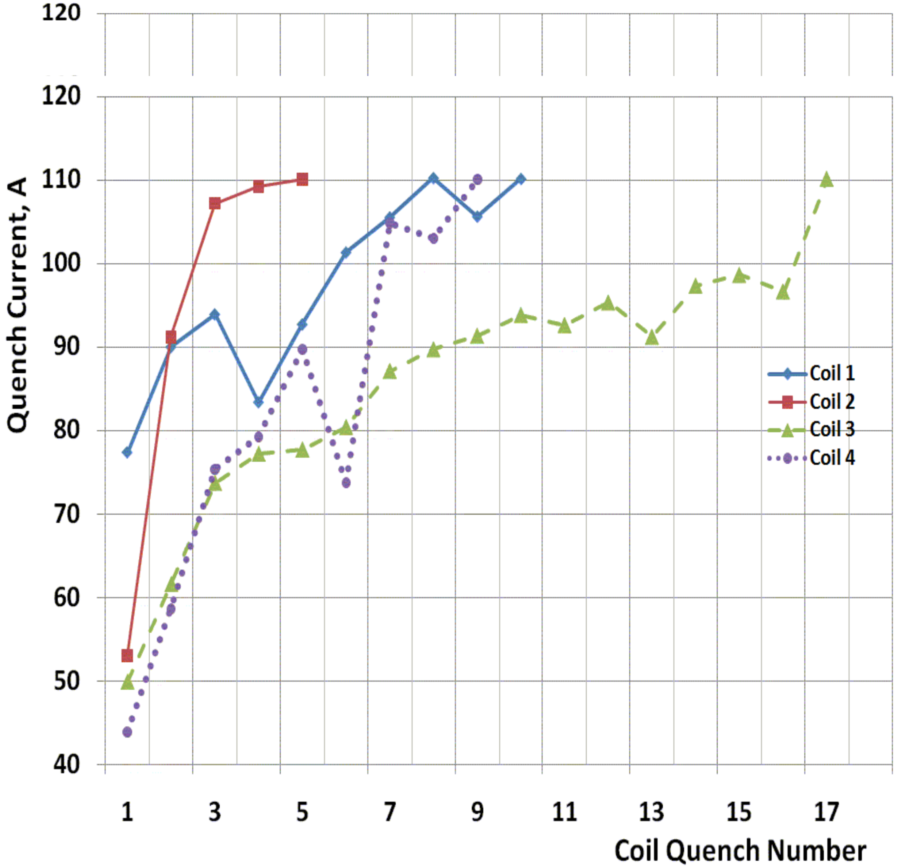
ILC Quadrupole Electrical Scheme



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 Quadrupole Quench History



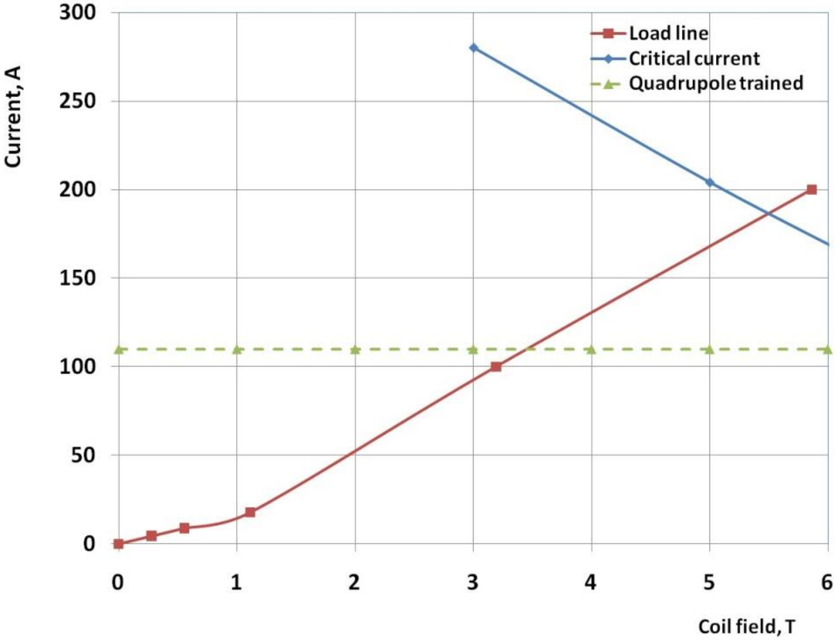


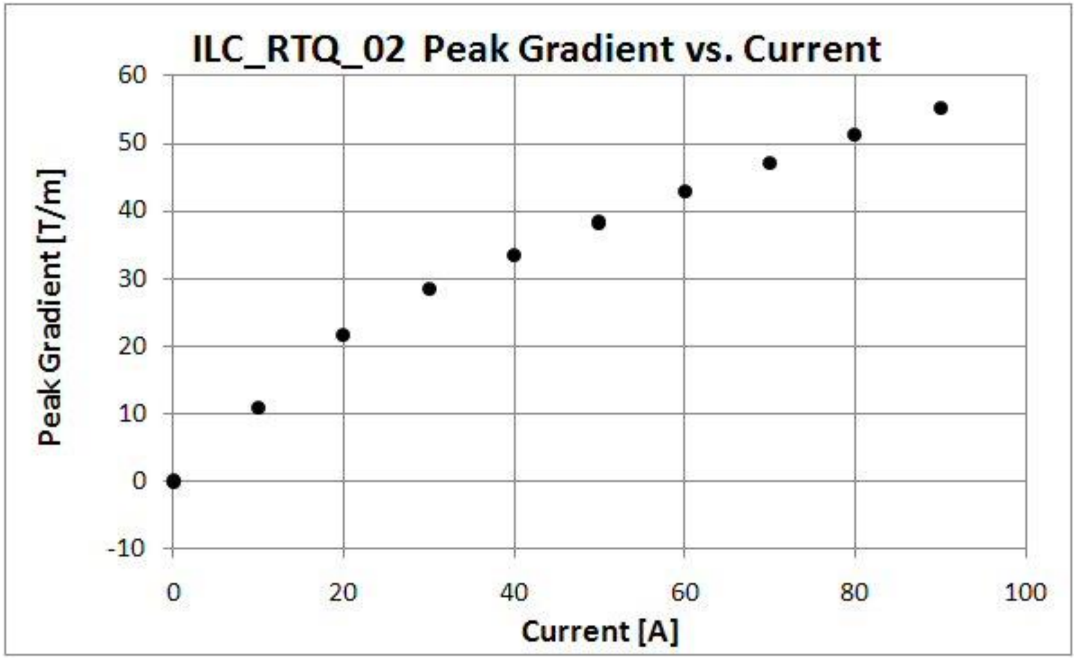
Quench history for two thermal cycles

Quench history for each coil

Peak operating current 100 A. Magnet trained up to 110 A – limit for the Stand 3 peak safe pressure during uncontrollable quench.

ILC Quadrupole Critical Current & Load Line

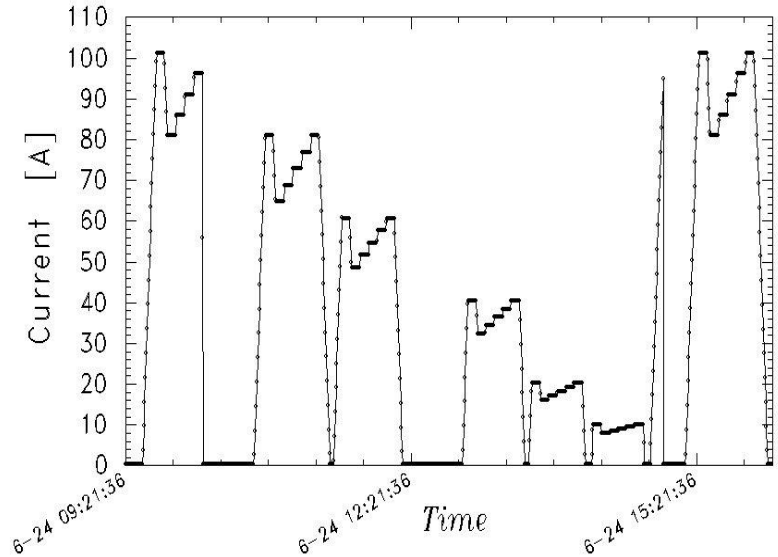


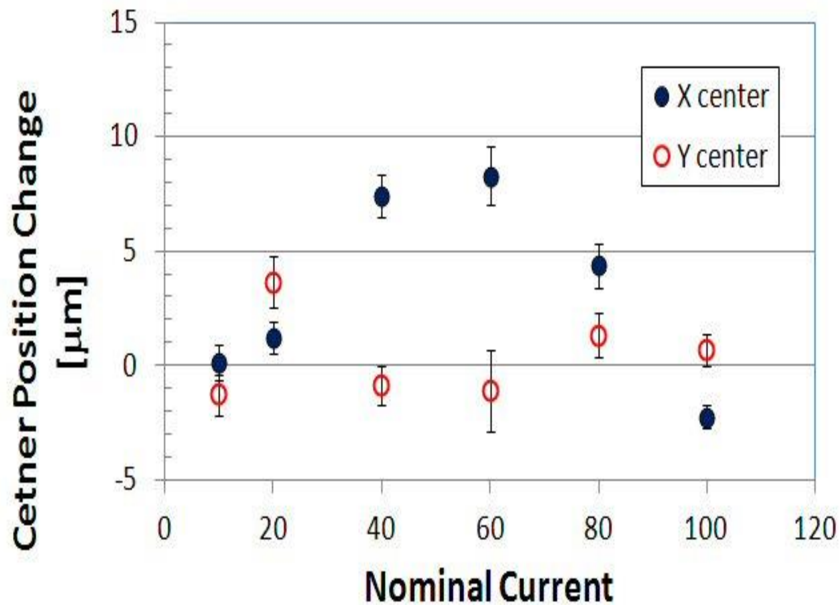


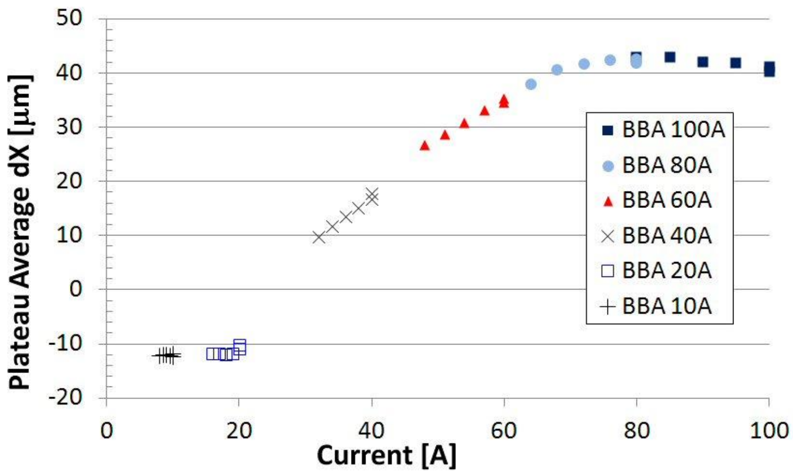
Peak operating current 100 A. Magnet trained up to 110 A (green line).
Critical current (short sample limit) for this magnet is 185 A at the coil field 5.4 T.

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.

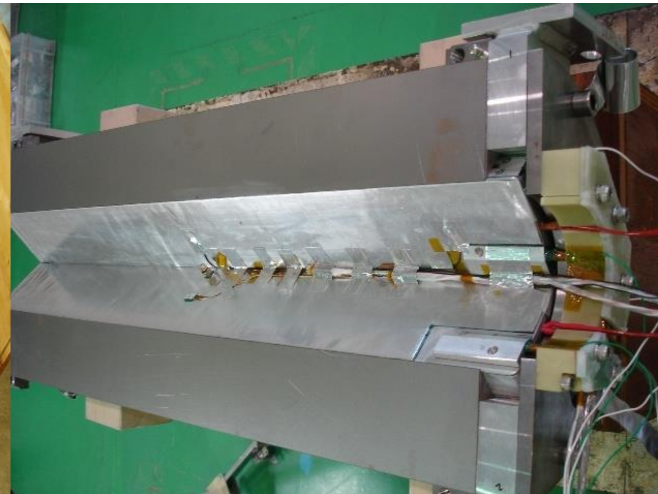
Quadrupole Measurement Results

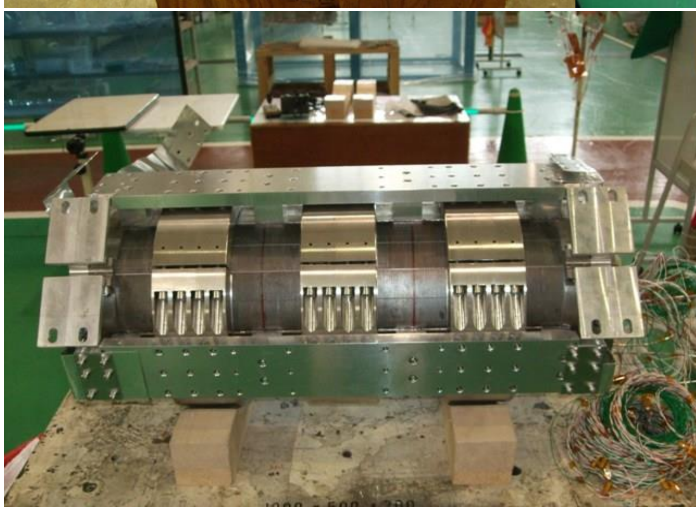
- During magnetic center position measurements was observed the time dependent effect. At -20% current change from the investigated maximum value, the magnetic center shift was less than 6 um.

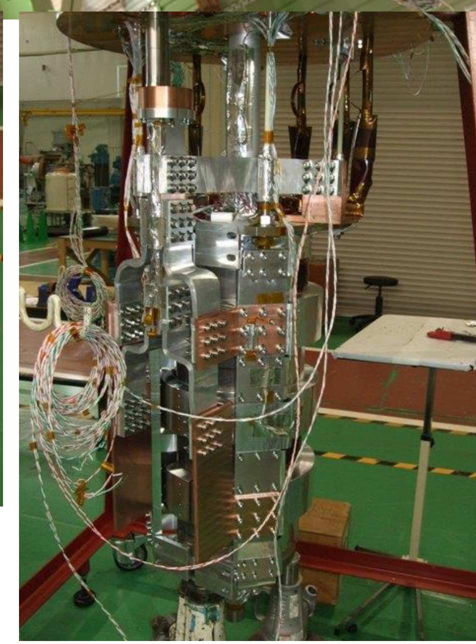
- Nevertheless, the first obtained results are very promising and close to the specified value 5 um.

- The main center shift was observed for dx in the X-direction, and about zero for Y. This might be the effect of gap fluctuations between two halves of the magnet, or the measurement fixture displacement between measurement runs.

KEK-TOSHIBA Quadrupole Upgrade

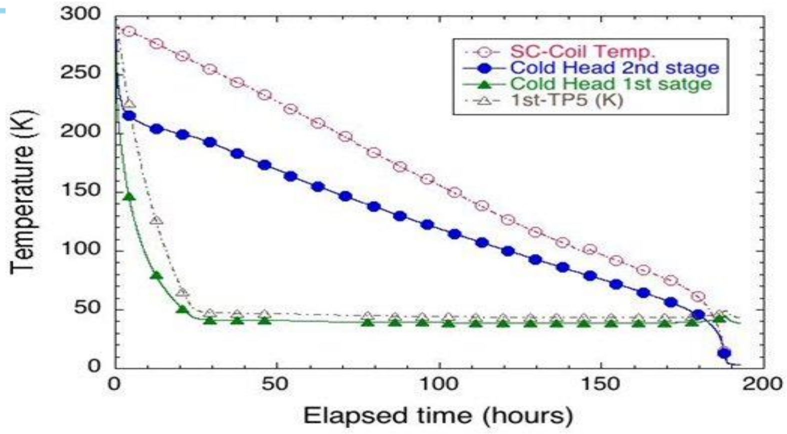



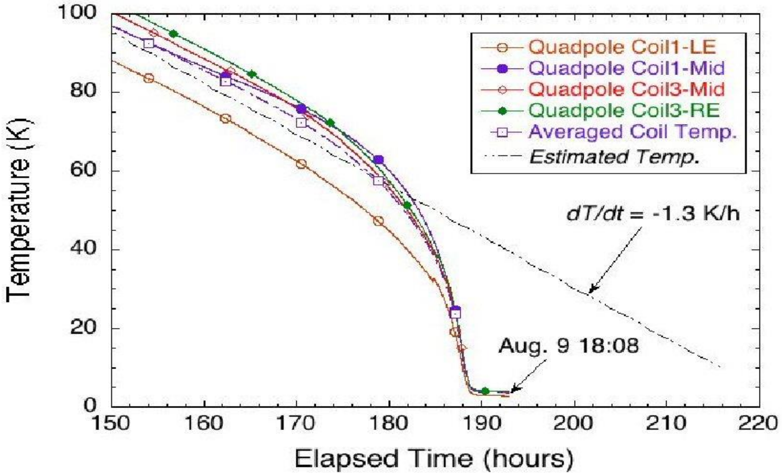




1. **Machined and shimmed split surfaces**
2. **Glued Al cooling foils**
3. **Added conduction cooling elements**

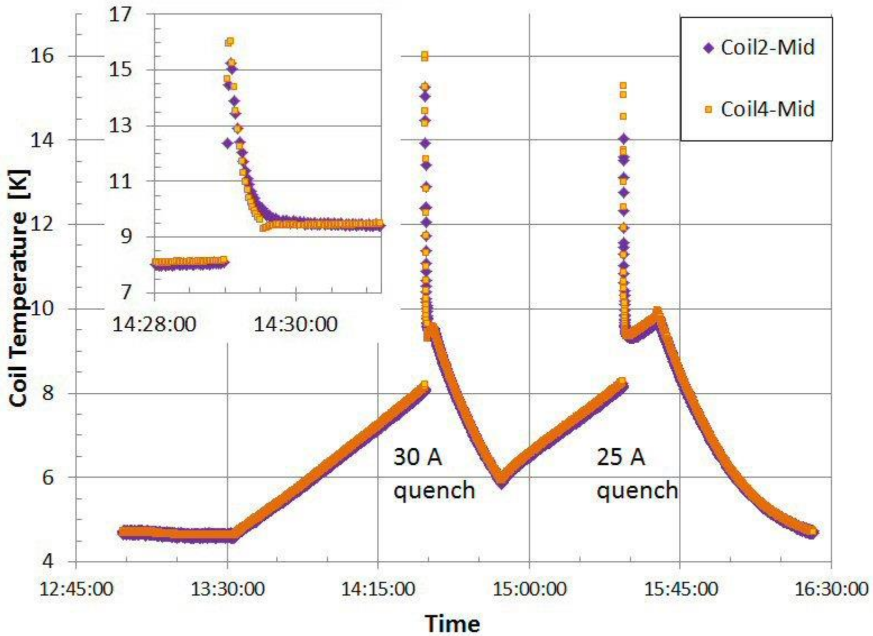
Quadrupole Test at KEK [1]

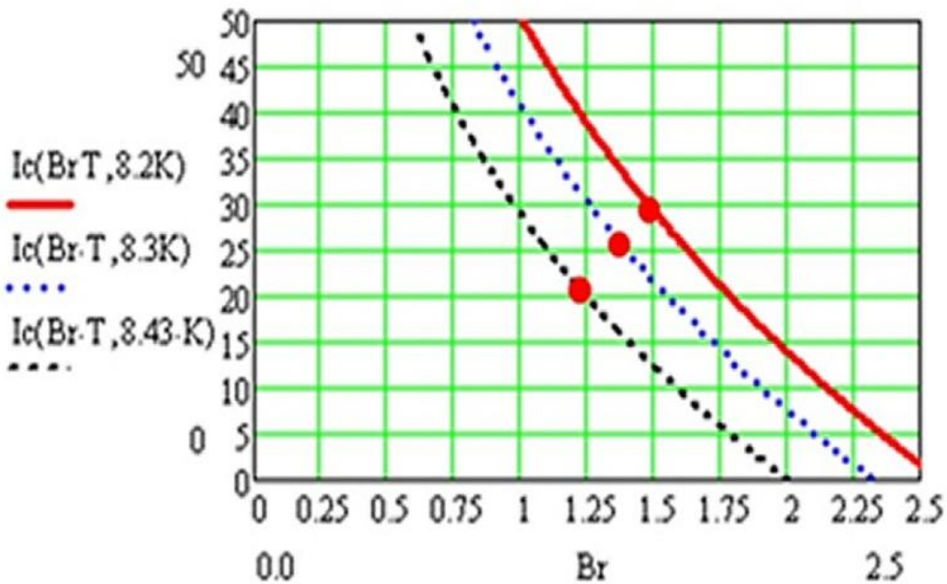




The KEK Test Stand was assembled and the magnet cooled down (8 days) to 4.5 K under supervision of Akira Yamamoto and Hitoshi Kimura

Conduction Cooling Tests at KEK [2]



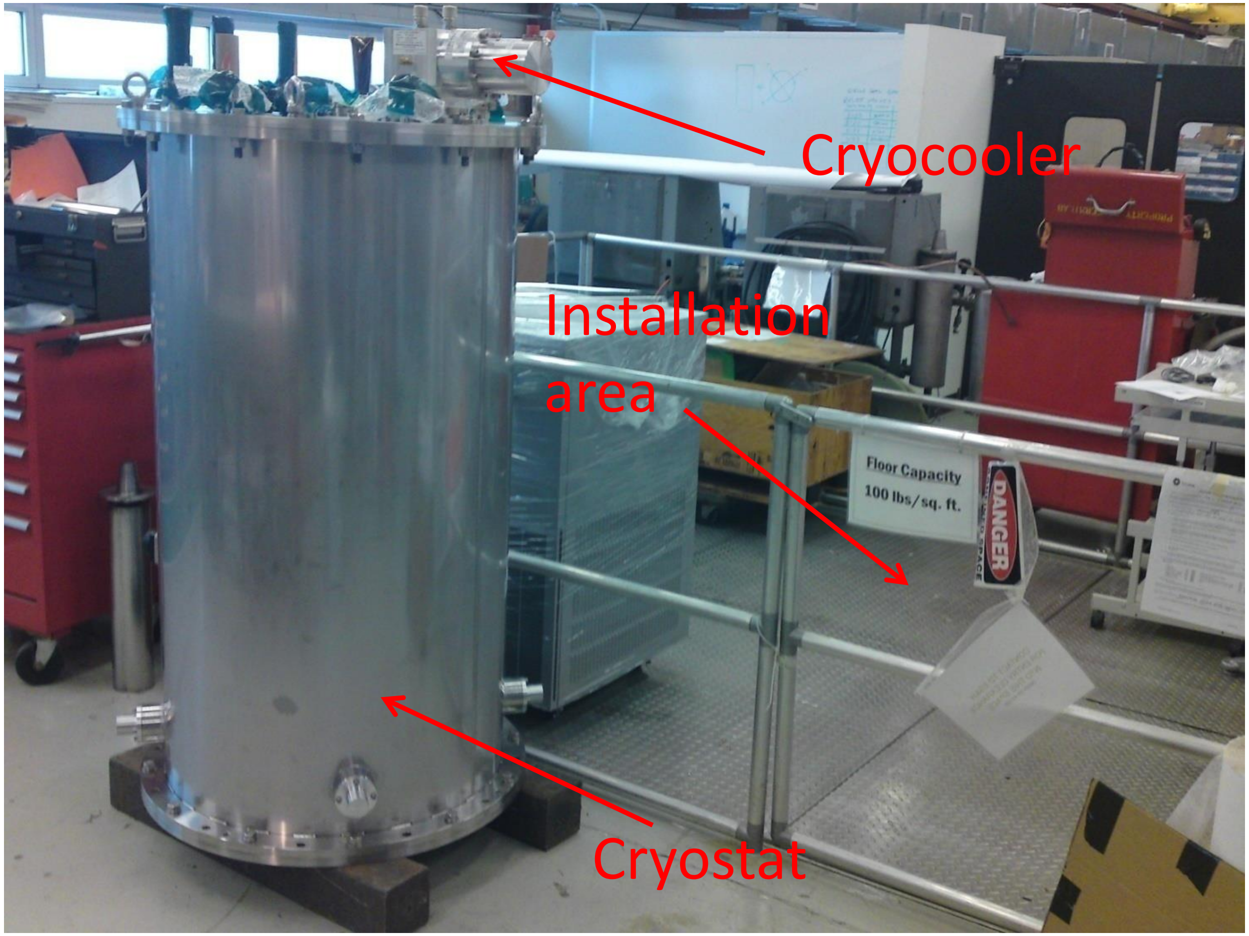


Coil temperature rise due to background heat load when compressor was turned off with magnet powered at fixed currents.

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 in IB1



The ILC quadrupole will be tested up to the max (110 A) current combined with a high presicion magnetic measurements

The KEK cryostat with cryocooler and ILC magnet inside was shipped at FNAL and will be allocated in this area pit.

The magnet will be 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 ends for magnetic measurements.

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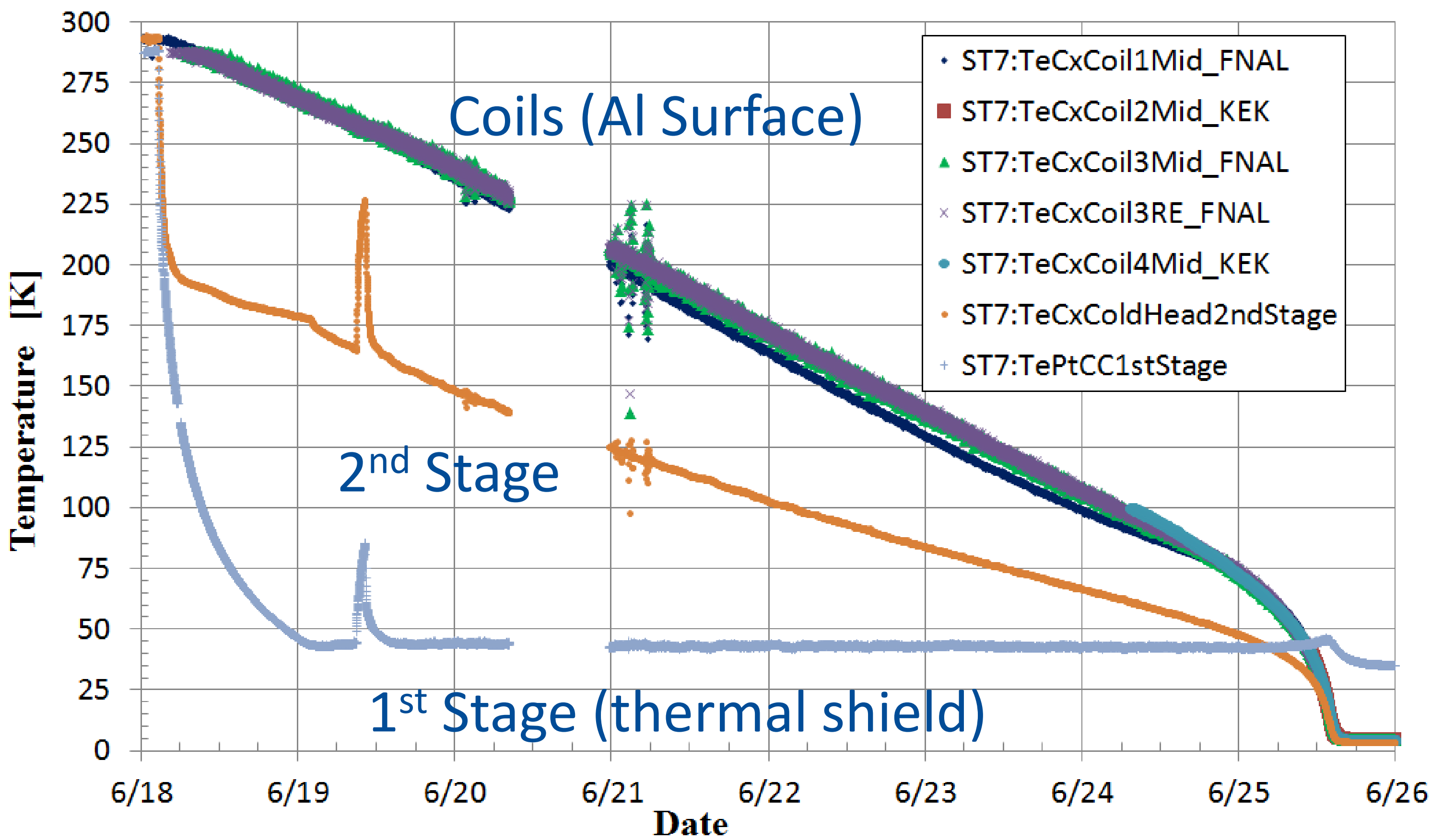
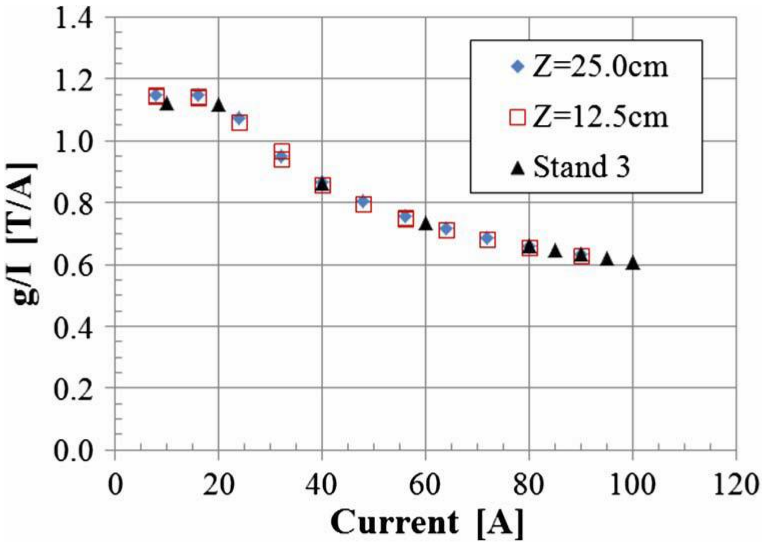
First Cool Down at FNAL

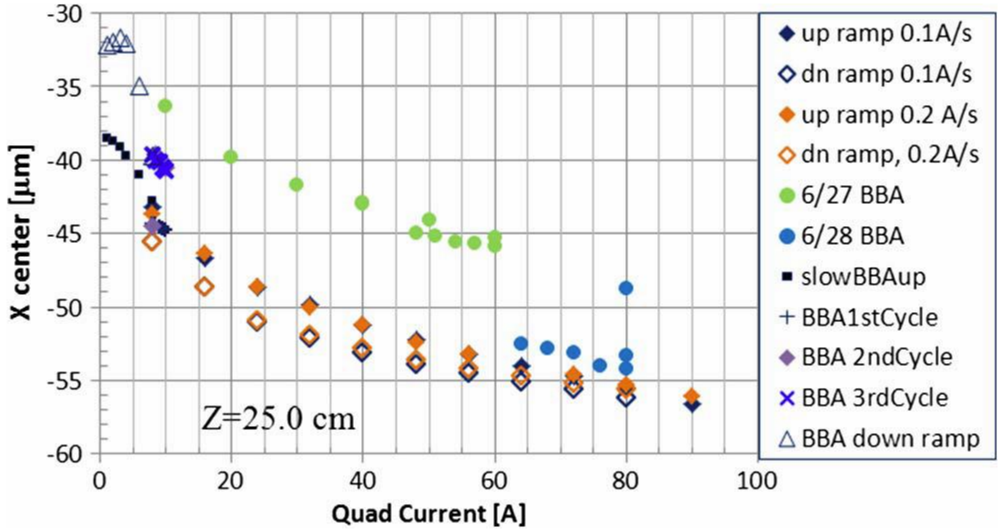


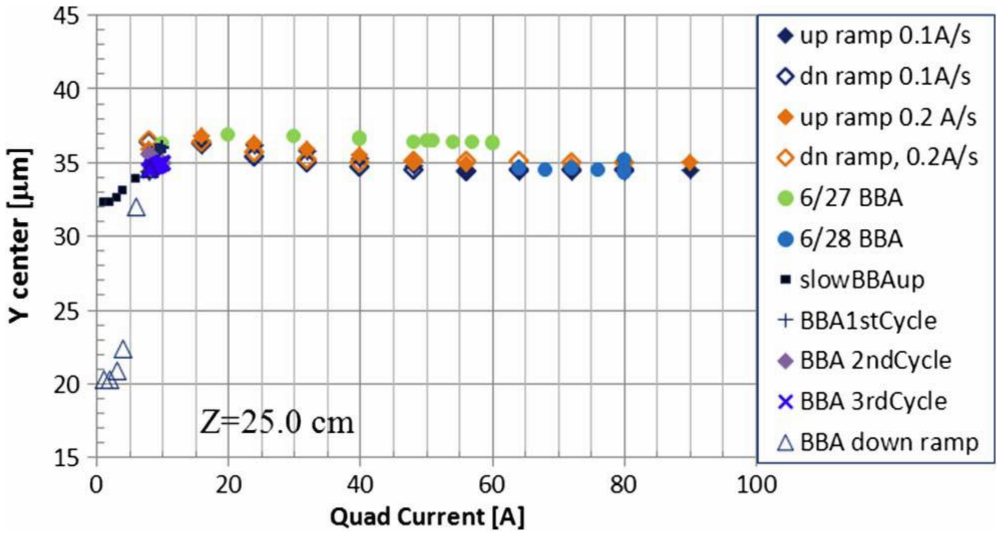
First Cool Down to 4K: 8 days, the same as at KEK.

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.

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Performed Tests

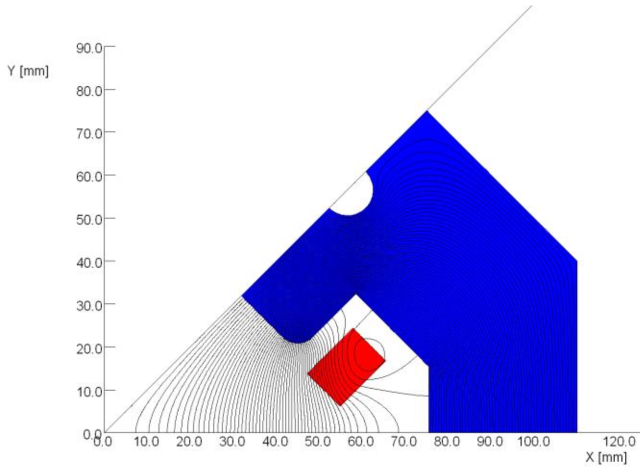
1. **The ILC magnet was tested at the new FNAL Test Stand in IB1.**
2. **Main test results:**
   - **Tested the magnet in the conduction cooling mode;**
   - **Investigated the performance up to the 110 A;**
   - **Repeated the high precision magnetic measurements.**

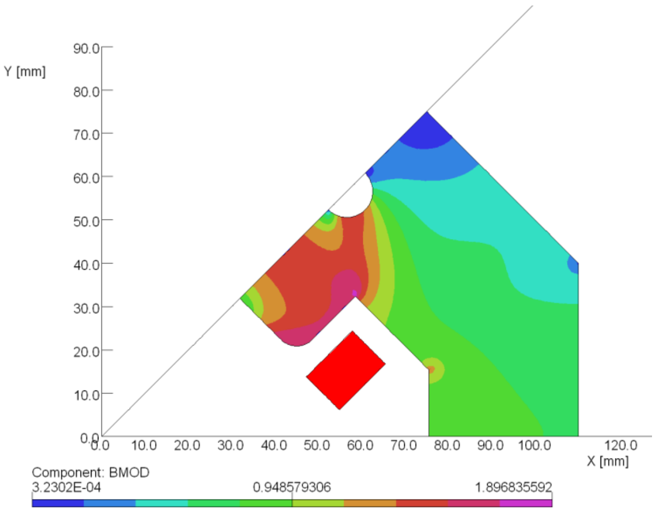
- The most critical design and fabrication issue for ILC quadrupoles is the 5 microns level of magnetic center stability which only could be verified by very high precision magnetic measurements.

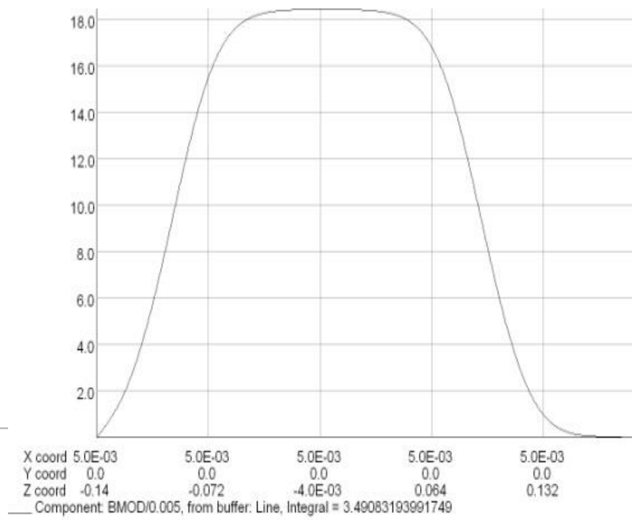
Magnet Package for KEK #CM 1

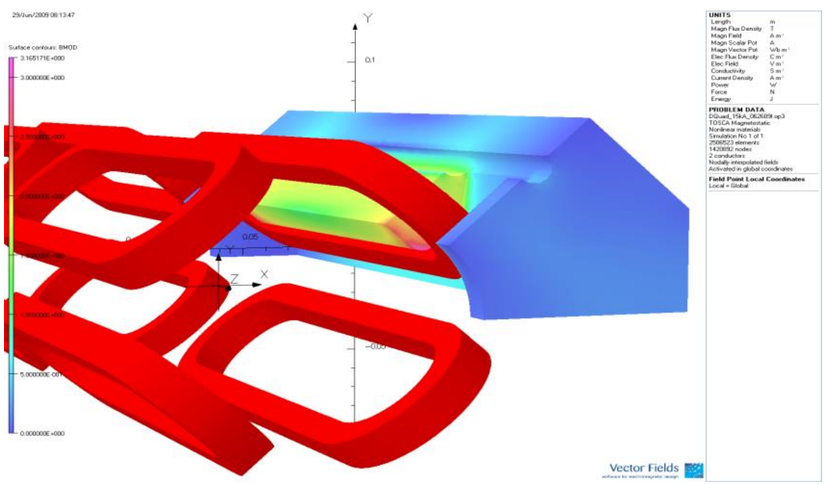
1. The first KEK Cryomodule was assembled and tested in January 2014.
2. Akira Yamamoto proposed that FNAL built the quadrupole magnet for this Cryomodule.
3. Because the slot space is short it was decided to use one Quadrupole from the ASTA Splittable Quadrupole Doublet.
4. Such approach will save time and funds of US-Japan collaboration.
5. Two magnets were built and tested in September 2013.

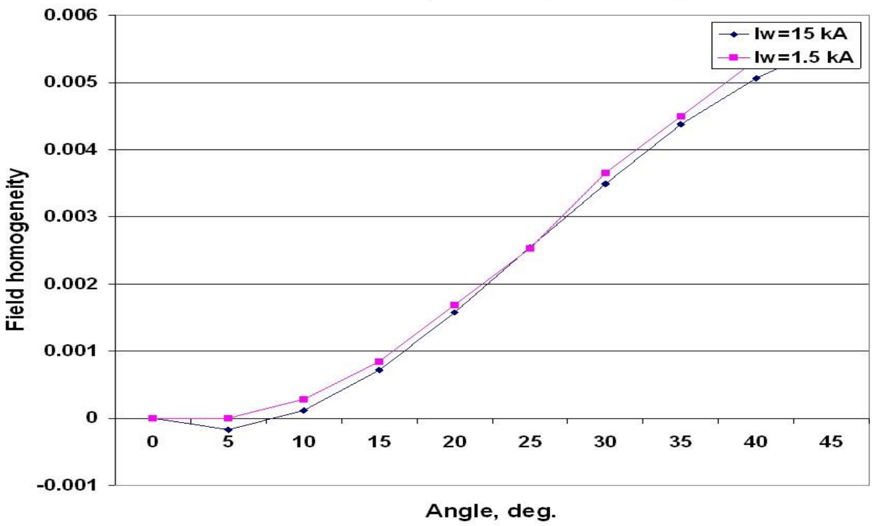
ASTA Quadrupole Doublet Magnetic Design





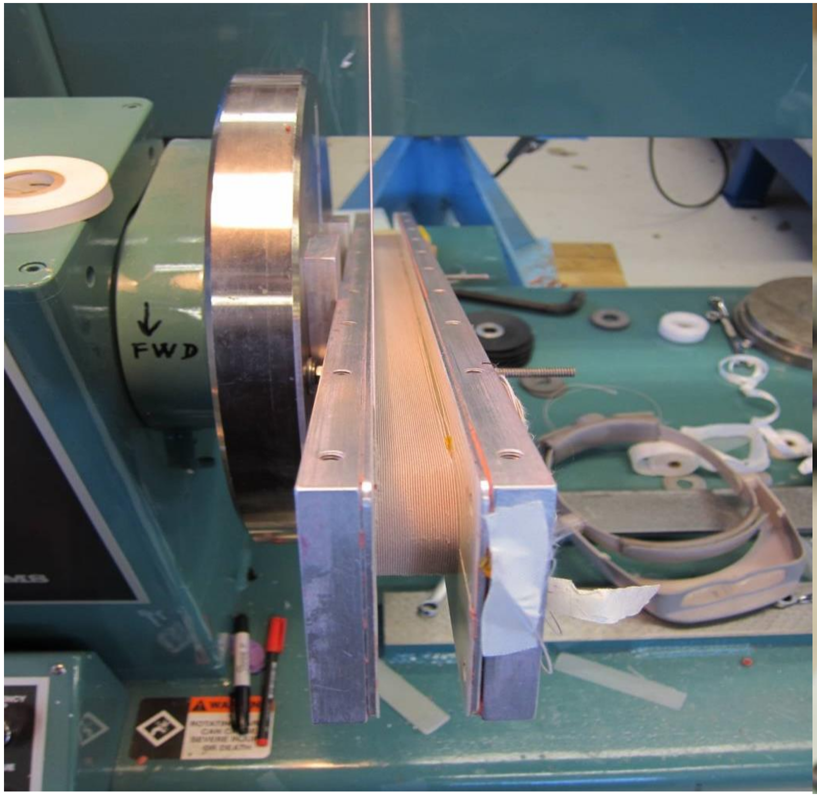


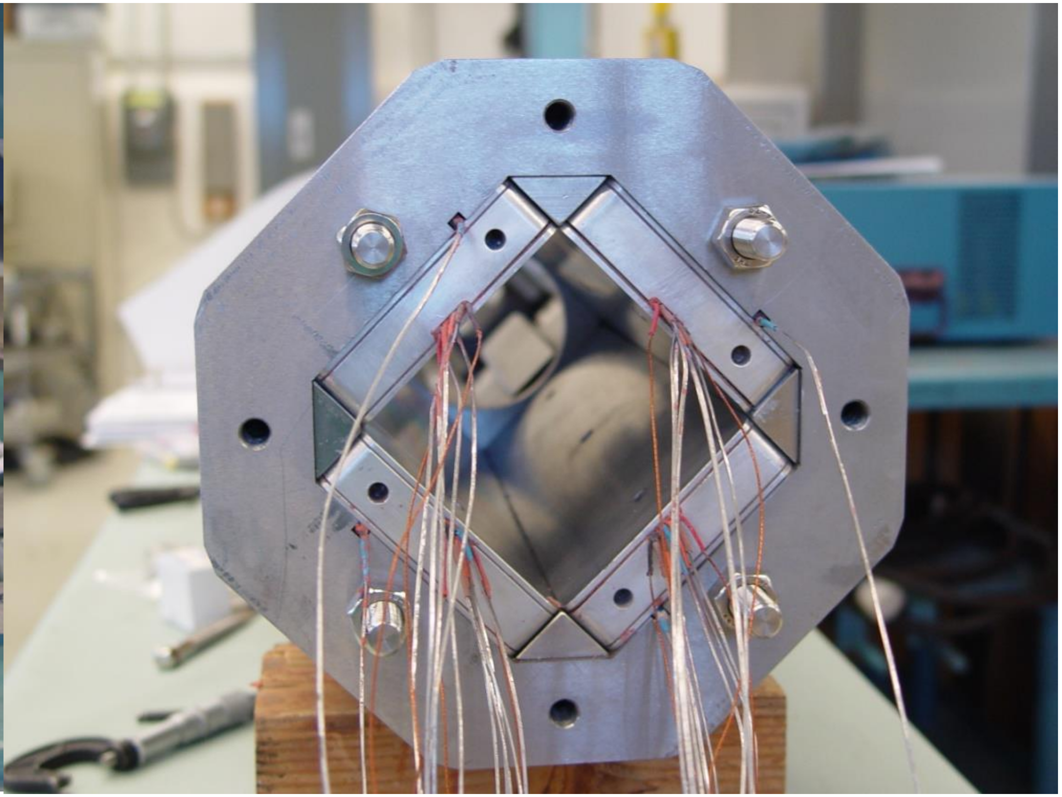




Integrated field homogeneity at 10 mm radius 0.6%, at 5 mm 0.18% (Spec. 0.5% at 5 mm).

ASTA Quadrupole Doublet Fabrication





Two Quadrupole Doublets for FNAL #CM3 were fabricated in 2011-2012.
Each racetrack coil has two additional sections connected in series to form the vertical and horizontal dipole correction fields. A heater, wound on the outer surface of coils, can be powered from an external power source when a quench is detected.

FNAL ASTA Quadrupole Doublet for #CM3

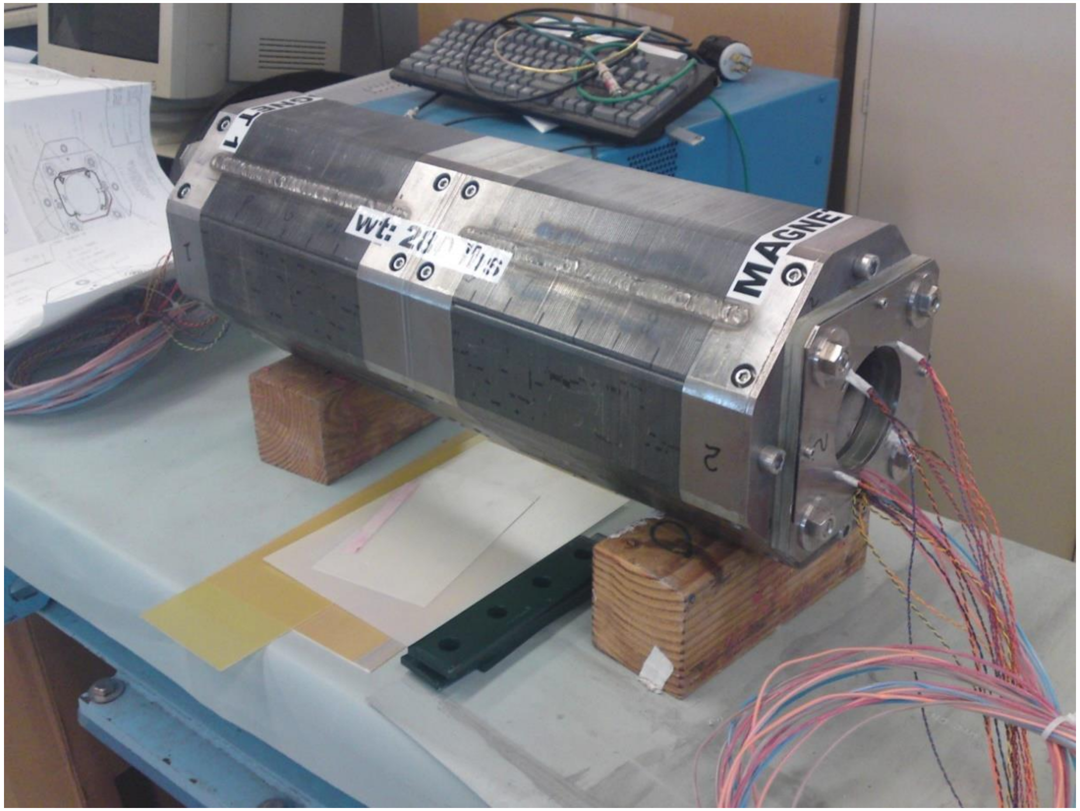
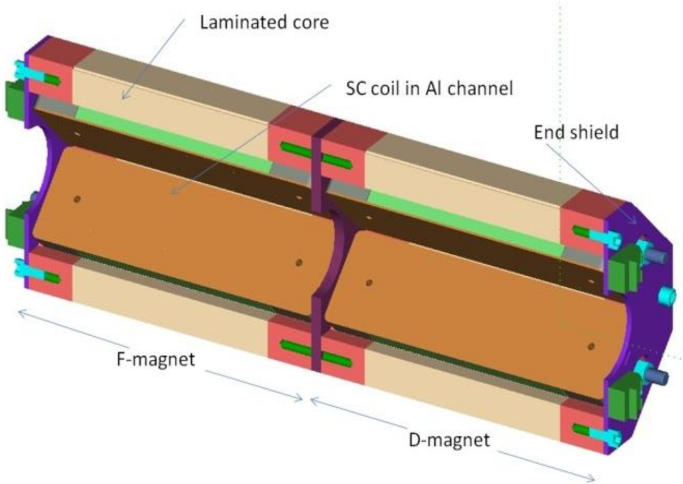


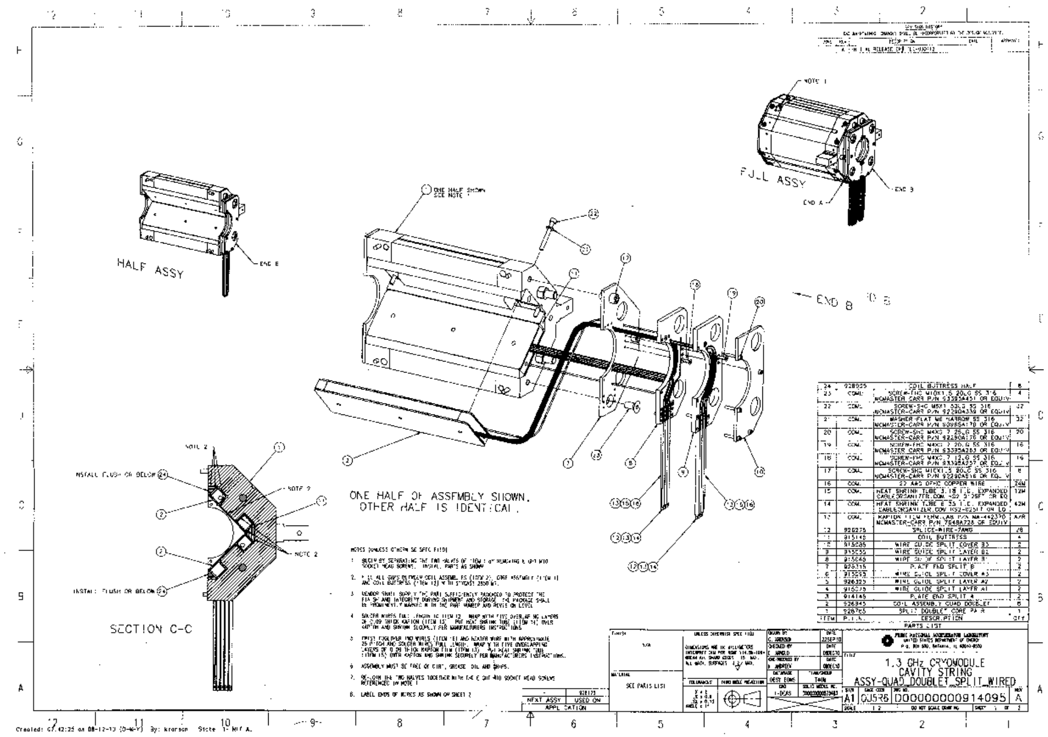
Table 1. Quadrupole Doublet Parameters

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.

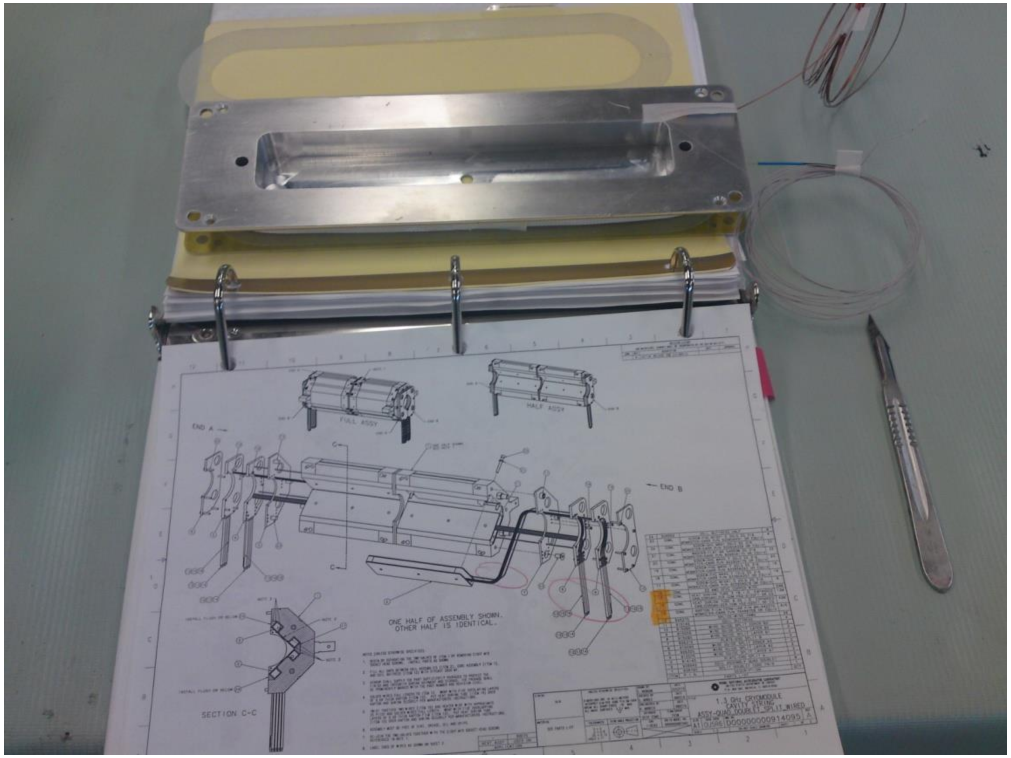
New Magnet for KEK #CM1





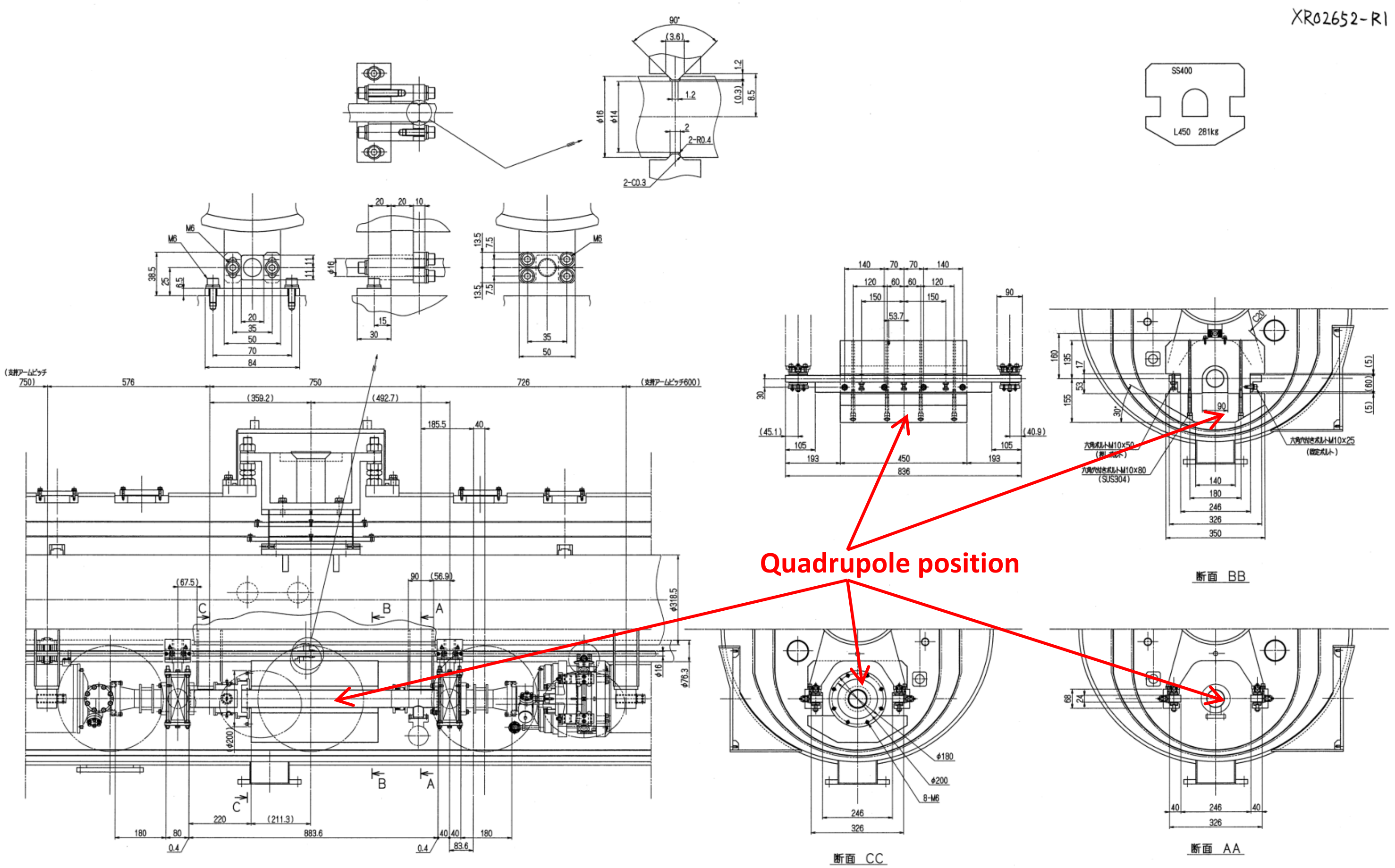
Because of a very tight schedule and space it was decided to use the Splittable Quadrupole Doublet design for ASTA and manufacture only one part of the Doublet. The quadrupole will be also combined with dipole correctors as in the Doublet.

Quadrupole Coil Winding for KEK



March 2013. Two new quadrupole coils are wound for KEK magnet by Tom Wokas.

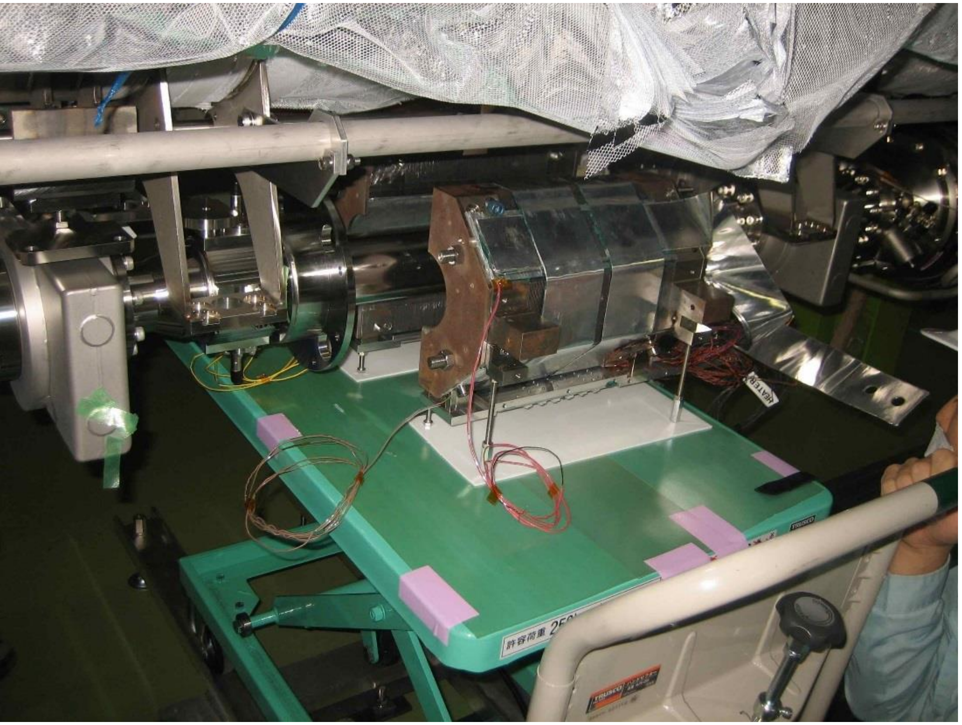
Quadrupole Integration with KEK #CM1

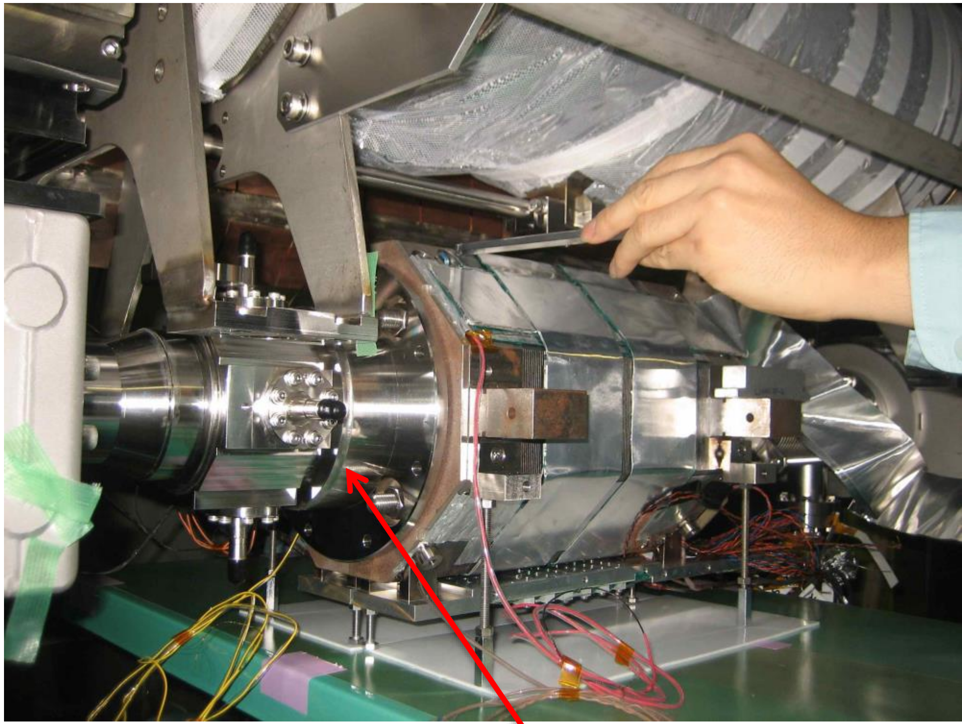


Magnet length should be less than 450mm,
Beam pipe aperture can be negotiable.
Current BPM design use 84mm outer diameter of chamber.
However BPM need to redesign its chamber outer diameter, not cavity part.

H. Hayano

Quadrupole Assembly around Beam Pipe

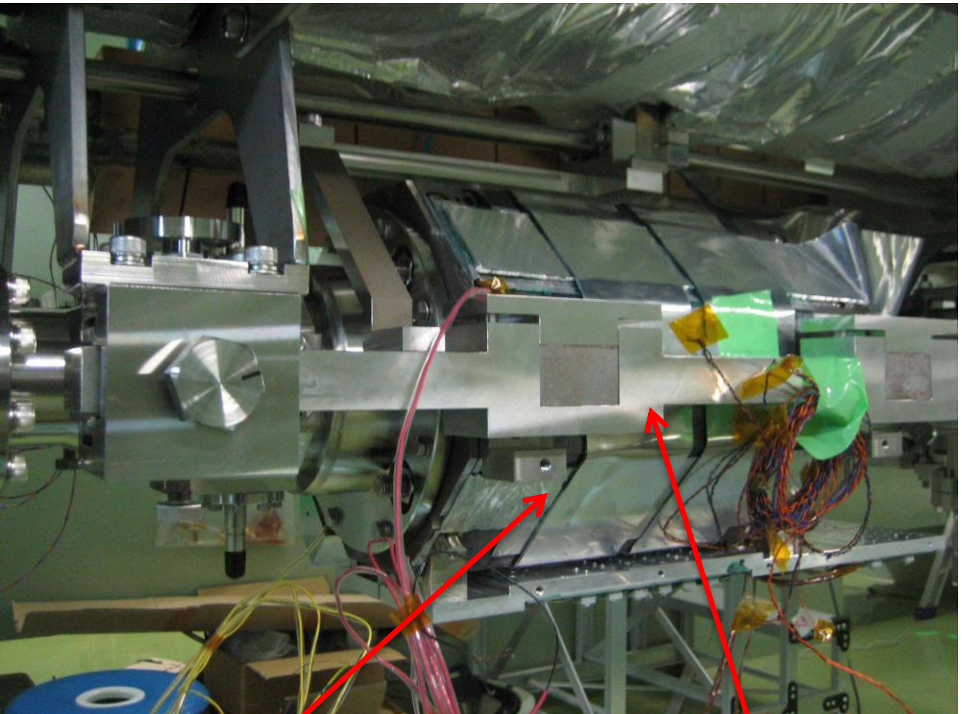


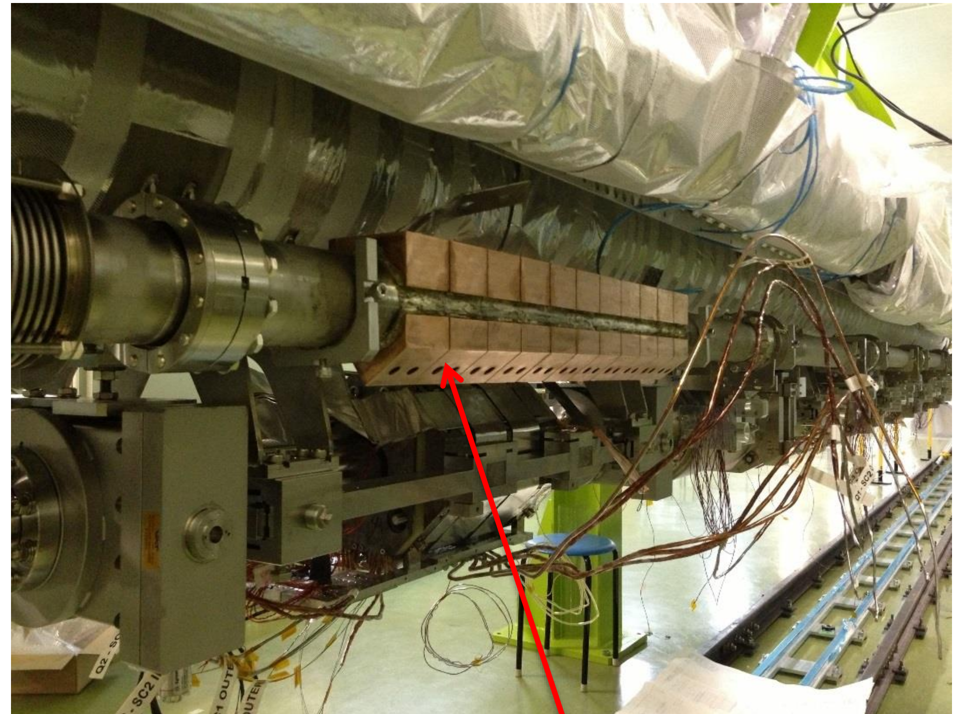


BPM

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

Quadrupole Final Assembly





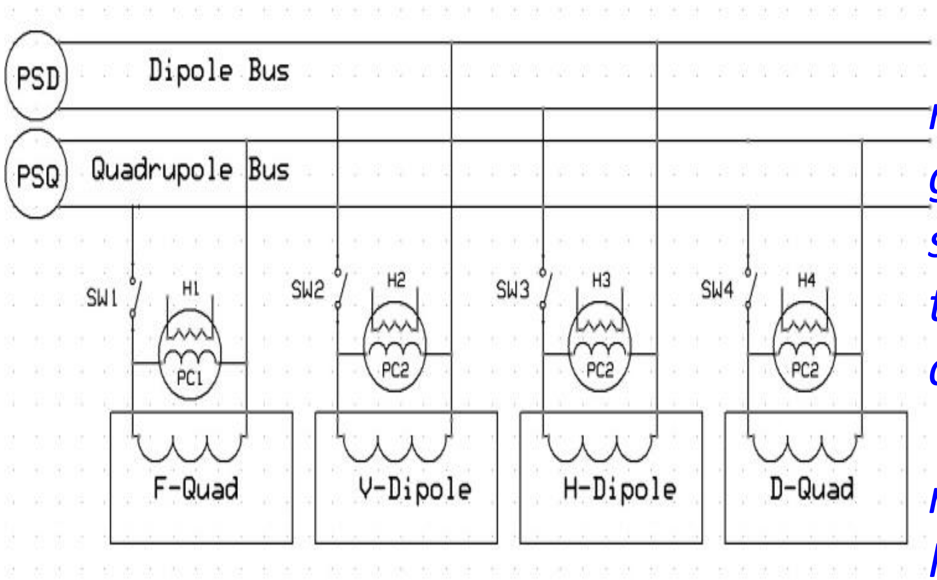
Magnet at supporting bars.

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

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

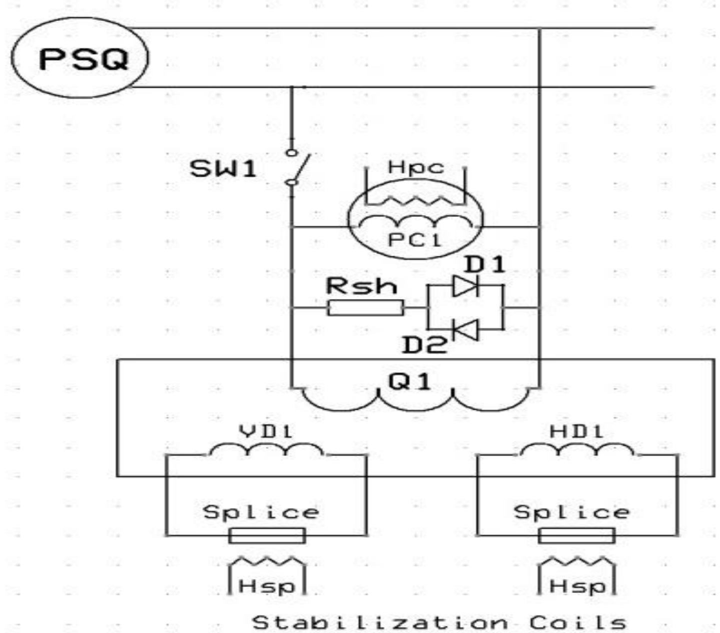


The magnet system cell schematic. SWn- switch, PCn-persistant current switch, Hn – PCn heaters, PSD and PSQ dipole and quadrupole power supplies.

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 of 0.02 %/day.

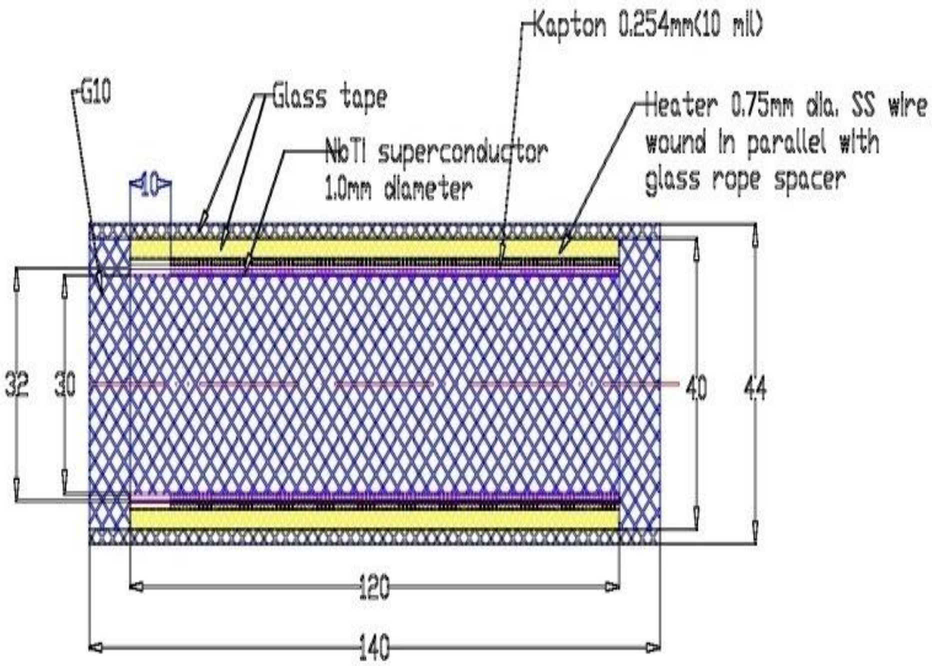
Single Cell Quadrupole Magnet Scheme



Quadrupole package schematic. Q1 – quadrupole winding, Dn – cold diodes, Rsh – protection shunt resistor, VD1 – vertical dipole, HD1 – horizontal dipole. SW1- switch, PC1-persistant current switch, Hn – PCn heaters, PSD and PSQ dipole and quadrupole power supplies.

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.

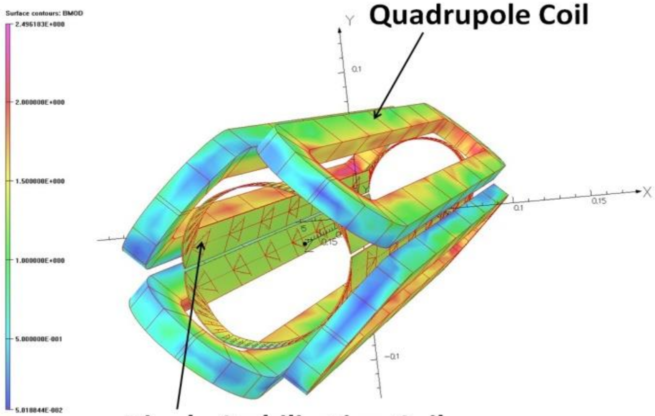
Persistent Current Switch

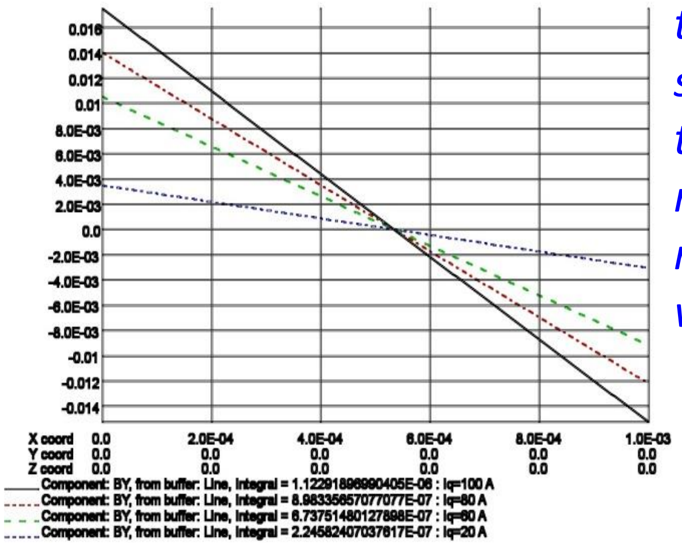


Parameter	Unit	Value
Peak operating current	A	150
SC coil resistance at 20 °C	Ω	7.8
Heater resistance	Ω	23.5
NbTi wire diameter	mm	1.0
Superconductor stabilization material		CuNi
Stainless steel heater wire diameter	mm	0.75
Heater current	A	0.5
Switch performance at 100 A SC current, and (0.5 A, 3 s)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

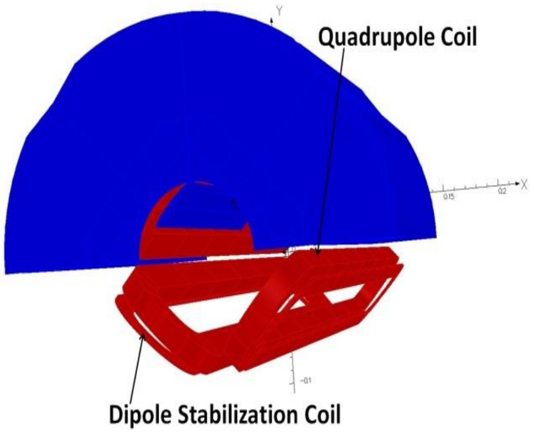
Stabilization Coil Simulation

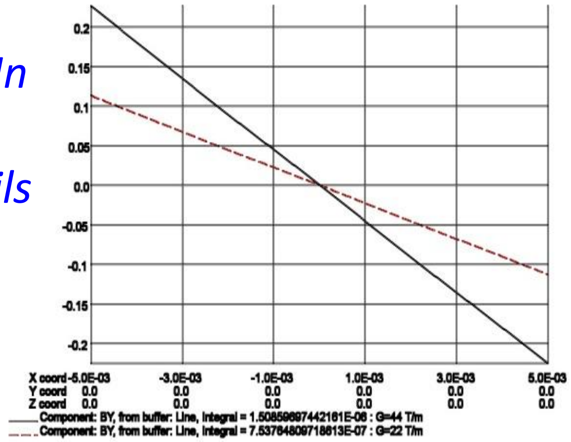




Dipole shell coils

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 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 Quadrupole after Successful Tests

May 9, 2014

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. *The Quadrupole was tested at 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.*