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

Fermilab

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Linear Accelerator Magnets

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June 22, 2017

Outline

- *Introduction to Magnetostatics*
- *Magnetic Field Equations*
- *Magnet Specifications*
- *Room Temperature Magnets*
- *Permanent Magnets*
- *Superconducting Magnets*
- *Magnetic Field Simulations*
- *Magnets for Next Linear Collider*
- *Magnets for International Linear Collider*
- *Magnets for LCLS-II*
- *Magnet failures*
- *Lessons learned*
- *Home Task*

Hans Christian Ørsted

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http://en.wikipedia.org/wiki/Hans_Christian_Oersted

In 1820, which Ørsted described as the happiest year of his life, Ørsted considered a lecture for his students focusing on electricity and magnetism that would involve a new electric battery. During a classroom demonstration, Ørsted saw that a compass needle deflected from magnetic north when the electric current from the battery was switched on or off. This deflection interestred Ørsted convincing him that magnetic fields might radiate from all sides of a live wire just as light and heat do. However, the initial reaction was so slight that Ørsted put off further research for three months until he began more intensive investigations. Shortly afterwards, Ørsted's findings were published, proving that an electric current produces a magnetic field as it flows through a wire.

This discovery revealed the fundamental connection between electricity and magnetism, which most scientists thought to be completely unrelated phenomena.

His findings resulted in intensive research throughout the scientific community in electrodynamics. The findings influenced French physicist André-Marie Ampère developments of a single mathematical form to represent the magnetic forces between current-carrying conductors. Ørsted's discovery also represented a major step toward a unified concept of energy.

Magnetostatics (Free Space With Currents & Conductors)

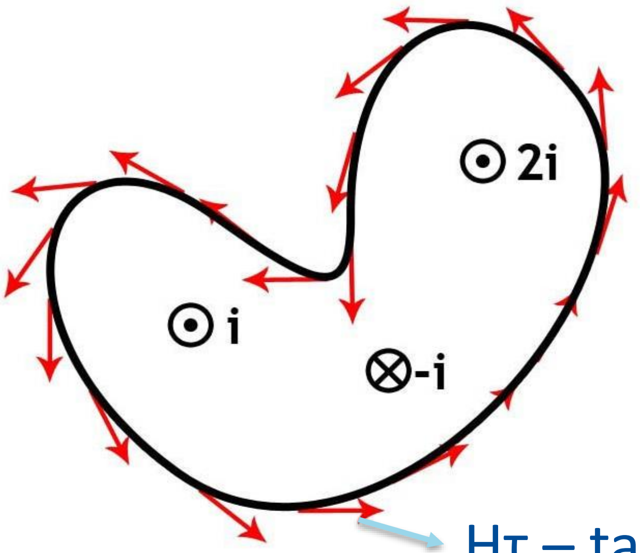
https://ocw.mit.edu/courses/electrical-engineering-and-computer-science

André-Marie Ampère,
1775-1836

portrait is in the Public Domain

Ampere's Low for Magnetostatics

$$\int_C \overline{H} \cdot d\bar{l} = \int_S \overline{J} \cdot d\overline{A} = I_{enclosed}$$

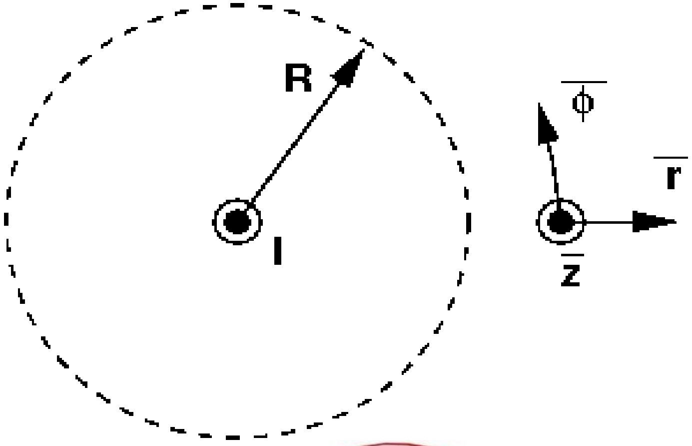


Hτ – tangential field component

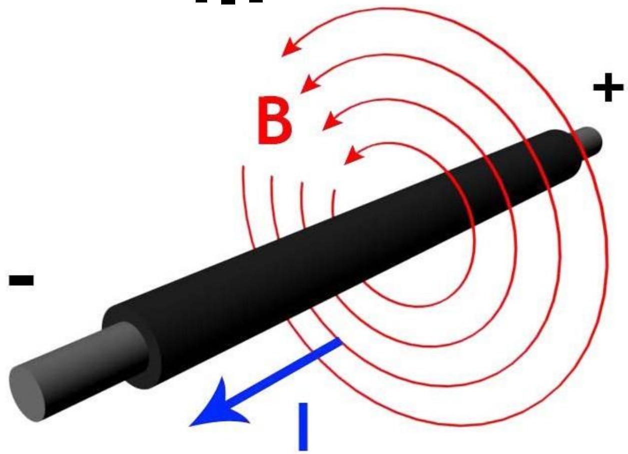
Andre-Marie Ampere, Memoir on the Mathematical Theory of Electrodynamic Phenomena, Uniquely Deduced from Experience (1826)

Magnetic Field Around a Very Long Wire Carrying Current

$$\int_C \overline{H} \cdot d\overline{l} = \int_S \overline{J} \cdot d\overline{A}$$



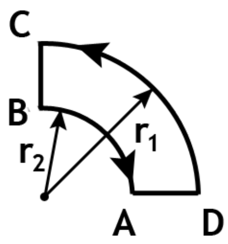
$$H_\phi 2\pi r = I \qquad \overline{H} = \frac{I}{2\pi r}\widehat{\phi}$$



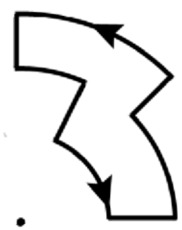
Ampere observe that:

1) the H-field is rotationally symmetric around wire
2) the H-field falls off as 1/r
3) the H-field is proportional to the current in the wire

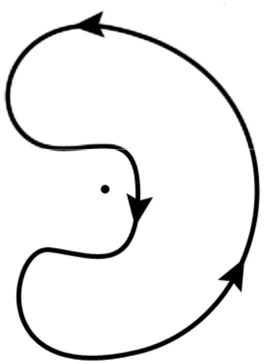
Ampere's Law Examples



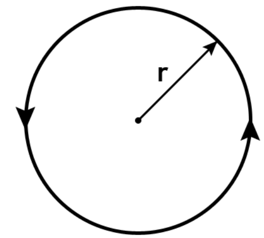
(a) Path lying in plane perpendicular to wire



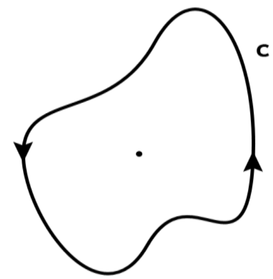
(b) Path constructed of Radial segments and arcs



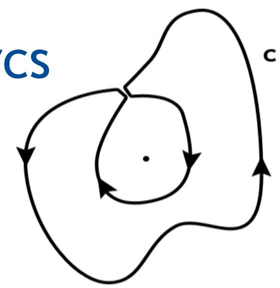
(c) Path which does not Enclose the wire



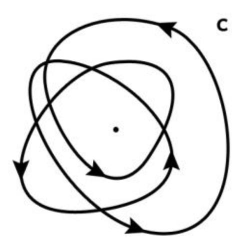
(d) Circular path enclosing wire



(d) Crooked path enclosing wire



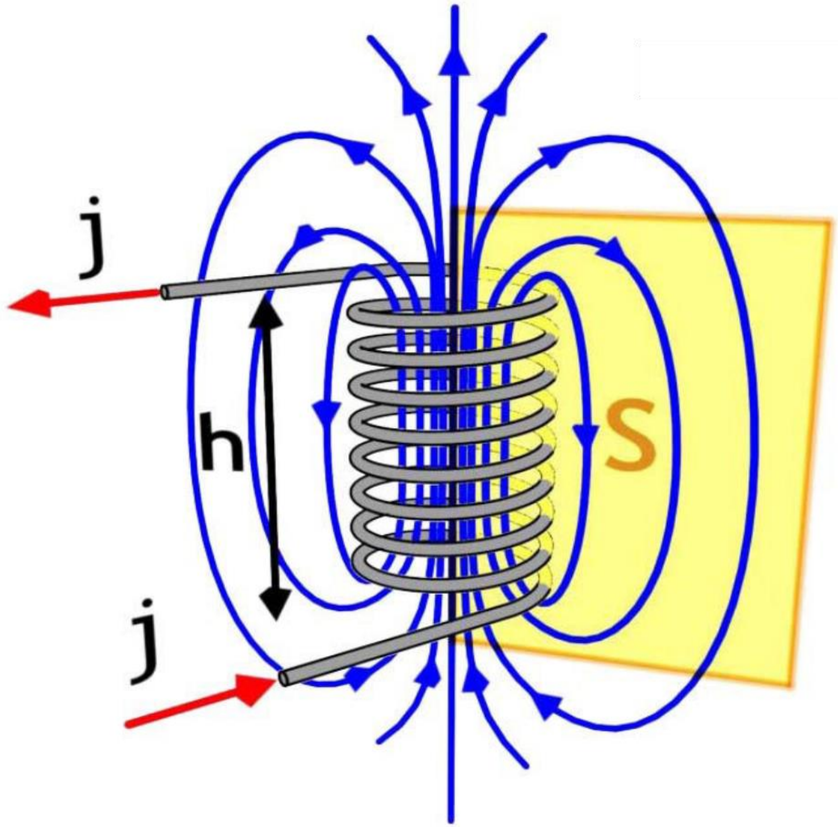
(f) Circular and crooked path NOT enclosing wire

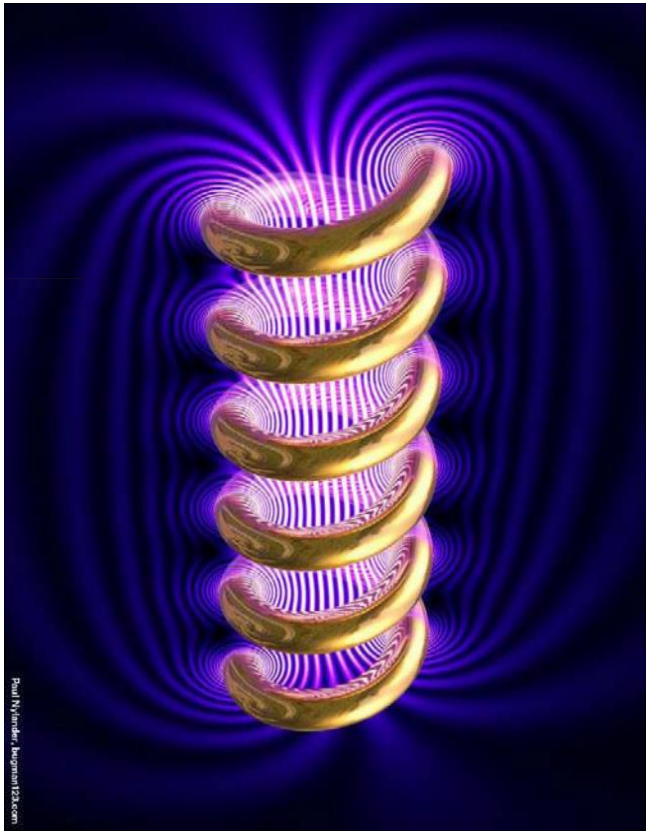


(f) Loop of N turns enclosing wire

Fields from a Solenoid

$$\int_C \overline{H} \cdot d\bar{l} = \int_S \overline{J} \cdot d\overline{A} = I_{enclosed}$$





Courtesy of Paul Nylander.

$$H_{inside} \approx \frac{N\,I}{h}$$

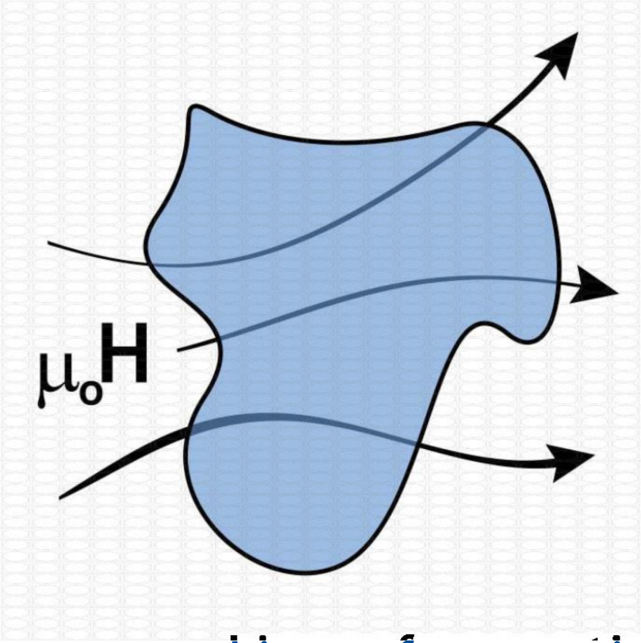
Gauss Law for Magnetic Fields

No Magnetic Monopoles

$$\nabla \cdot \mu_o \vec{H} = 0$$

$$\oiint_S \mu_o \vec{H} \cdot d\vec{S} = 0$$

$$\oiint_S \vec{B} \cdot d\vec{S} = 0$$



Magnetic flux conservation law:
No net magnetic flux enters of exits a closed surface.
What goes in must come out.

Lines of magnetic flux ($\mu_o \vec{H}$) never terminate.
Rather, they are solenoidal and close on themselves in loops.

Magnet Design Steps

1. *Magnet functional specification (physics requirement document).*
2. *Magnet engineering specification.*
3. *Conceptual magnetic and mechanical design.*
4. *Final magnetic and mechanical design.*
5. *Design verification by beam optics analysis.*
6. *Prototype fabrication.*
7. *Prototype magnetic measurements, and tests.*
8. *Correction if needed the magnet design.*
9. *Documentation for the serial production.*

Magnet Functional Specification

The functional specification usually prepared by physicists responsible for the beam optics analysis.

The specification includes:

- *Beam energy and type of particles: electrons, protons, muons…*
- *Magnet type: H-type dipole, C-type dipole, Septum, Lambertson, Quadrupole, Sextupole,Octupole,Bump, Kicker, Solenoid, etc.*
- *Beam aperture dimensions;*
- *Field, or gradient strength in the magnet center;*
- *Magnet effective length;*
- *Good field area dimensions, and the field quality;*
- *Integrated field, or gradient along the beam path;*
- *Separation between beams for Septums, Lambertsons;*
- *Beam bending angle;*
- *Fringe field limitations.*

Magnet Engineering Specification

The engineering specification usually prepared by physicists and engineers responsible for the magnet design.

In general, the specification includes:

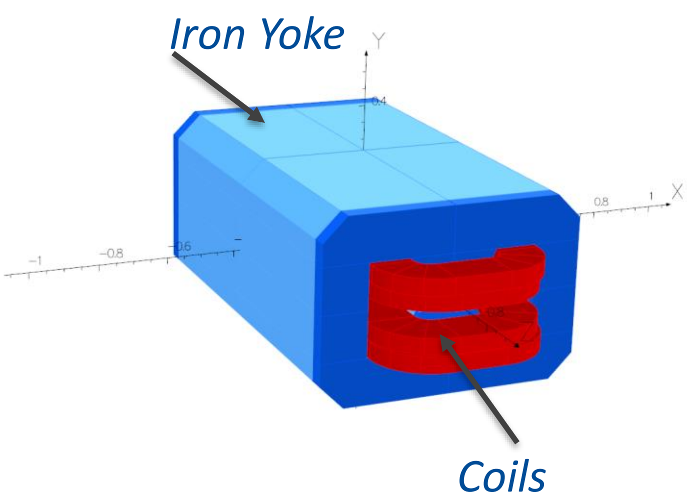
- Magnet physical aperture dimensions;
- Beam pipe dimensions;
- Magnet total length and space slot available for the magnet;
- Space and weight limitations;
- Magnet peak field, or gradient;
- Type of cooling: air, water, LHe, conduction;
- Cooling system parameters.
- Power supply parameters: peak current and voltage, AC, pulsed.
- Magnet protection and instrumentation;
- Radiation level;
- Number of magnets.

Examples of Specifications

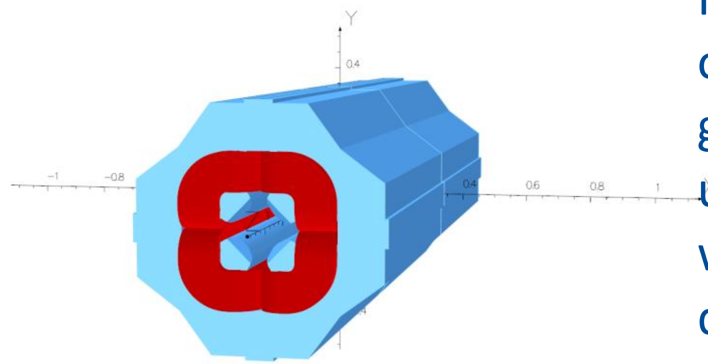
1. Physics Requirement Document. Magnets, LCLSII-2.4-PR-0081-R0 – describes functional specifications for all LCLS-II Linear Accelerator magnets (see Magnets_PRD_signed_012815.pdf).

2. Engineering Specifications Document. Cryomodule Magnet. – describes specifications for the superconducting magnets (see Cryomodule_Magnet_ESD_Signed_042015.pdf).

Conventional Iron Dominated Electromagnets



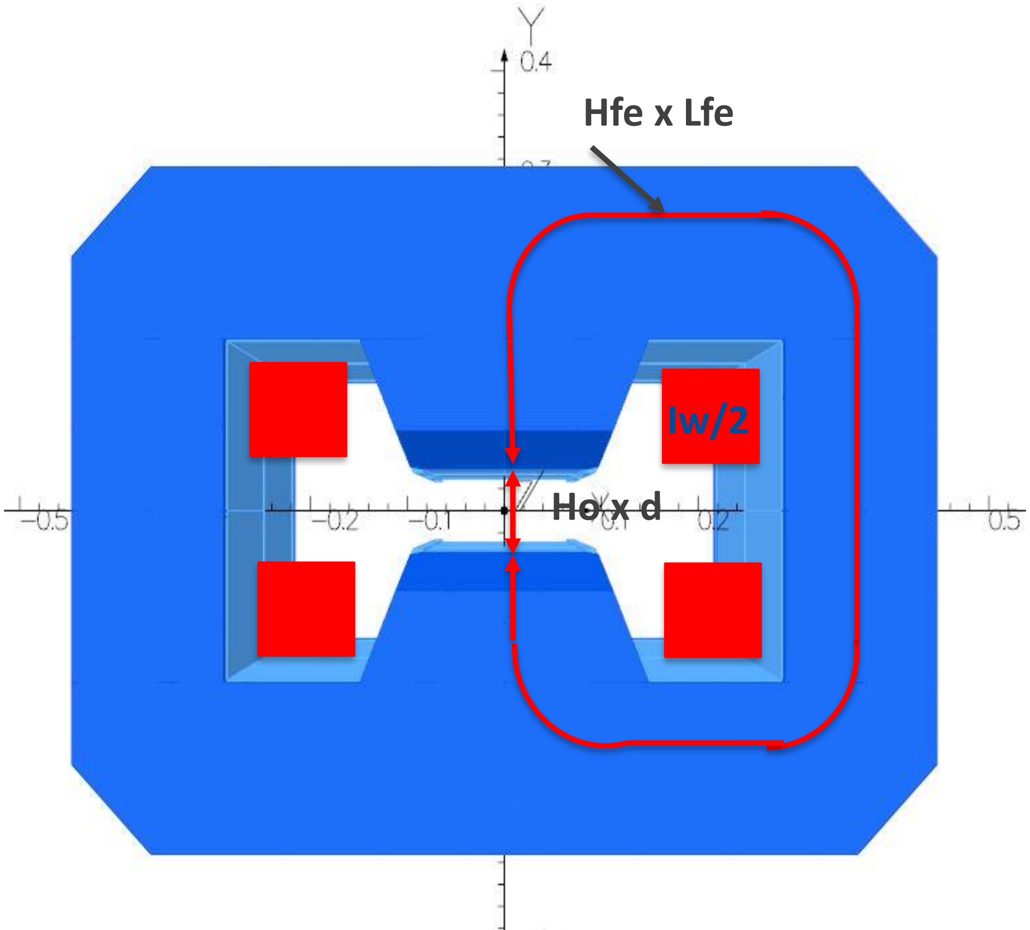
FNAL Main Injector Dipole



FNAL MI WQB quadrupole

Conventional iron dominated magnets still "a working horse" for many accelerator magnet systems having fields below 1.8 T.
They also could not be replaced by superconducting magnets for fast pulsed fields, and in very high radiation areas.
Some accelerators have hundreds, or even thousands dipole and quadrupole magnets connected in series.
In this case needed careful cost optimization to optimize capital and operational cost. This, in general, include: cost of fabrication and cost of used electricity to power magnets. For most water cooled magnets the optimal current density in copper coils around 4 A/mm^2. Iron yoke made from solid, or laminated steel.

Ampere's Law for Electromagnets



d - magnet gap, m
Hd – field strength in the gap, A/m
Hfe – Field strength in the iron yoke, A/m
Lfe – the average flux path length in the iron yoke, m
Iw – total coils ampere-turns, A
μo= 4π*e-7 H/m
Bo – flux density in the gap, T

*Ho=(Iw-Bfe*Lfe)/d (SI)*
*Bo=(μo*Iw-Bfe*Lfe)/d (SI)*

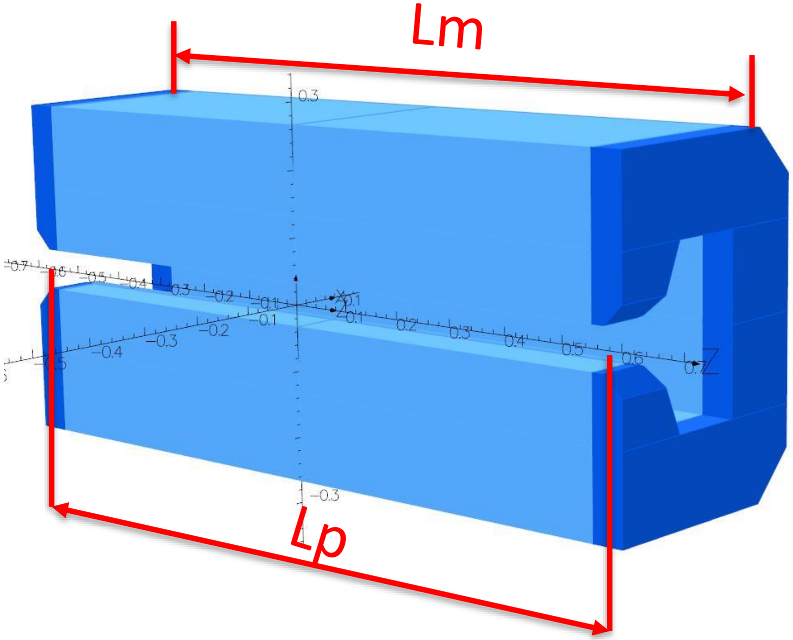
*Bo ≈ Iw/0.8*d (CGS)*
*Iw ≈ 0.8 *Bo*d (CGS)*

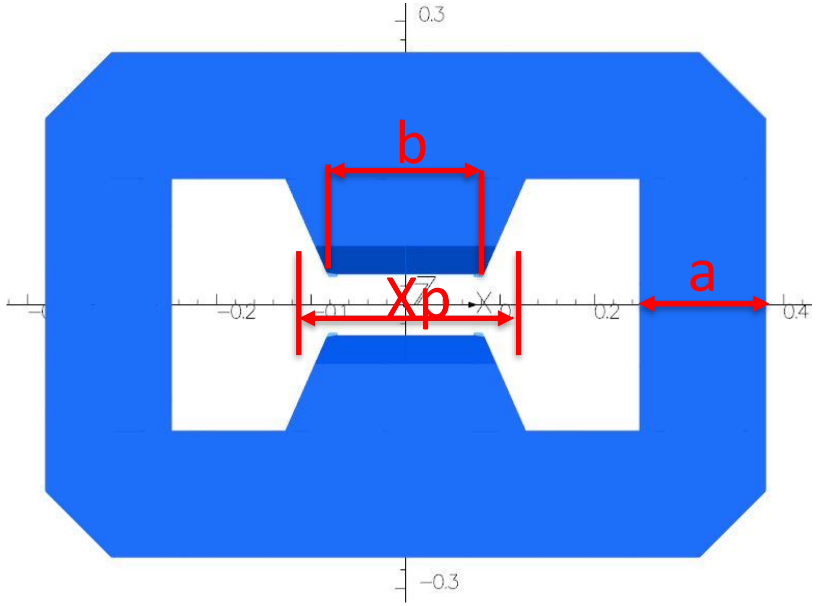
$$Ho * d + Hfe * Lfe = Iw$$

$$Bo*d/\mu o + \frac{Bfe}{\mu} * Lfe = Iw$$

Hfe = ?

Gauss Law for Electromagnets





Lp=Lp+d – pole effective length

Xp=b+d – pole effective width

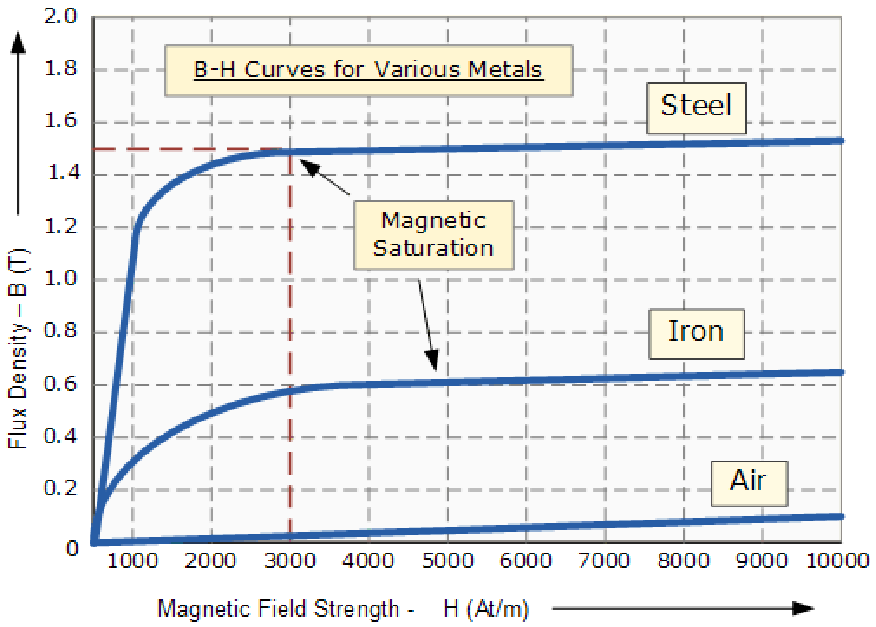
*Sp=Xp*Lp – pole effective area*

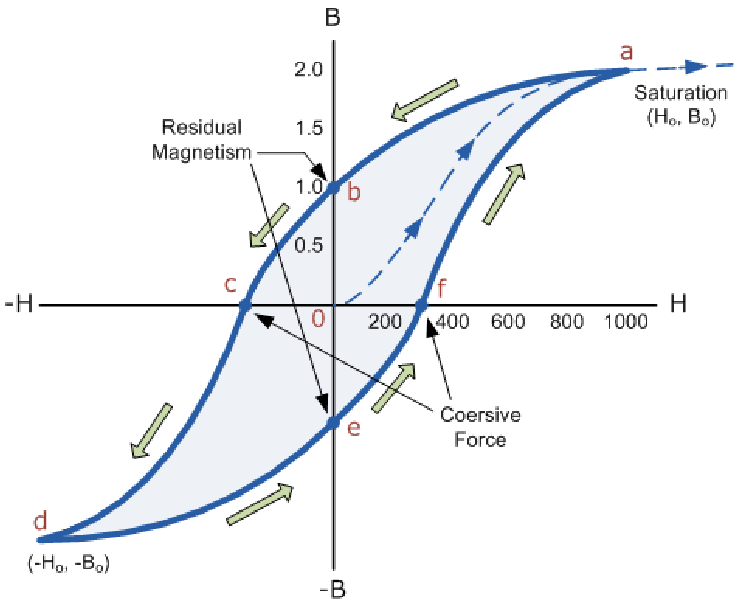
*Sy=a*Lm – yoke area*

*Φ = Bo*Xp*Lp=Bo*Sp – total flux*

Bfe= Φ/Sy

Ferromagnetic Material Properties





$B = \mu o * H + M$, or $B = \mu * H$, $\mu = B/H$

For magnet design used *B=f(H)* measured magnetic properties of rings (from thick metal), or stacks of steel strips for thin steel forming closed magnetic circuit.

Soft Magnetic Materials

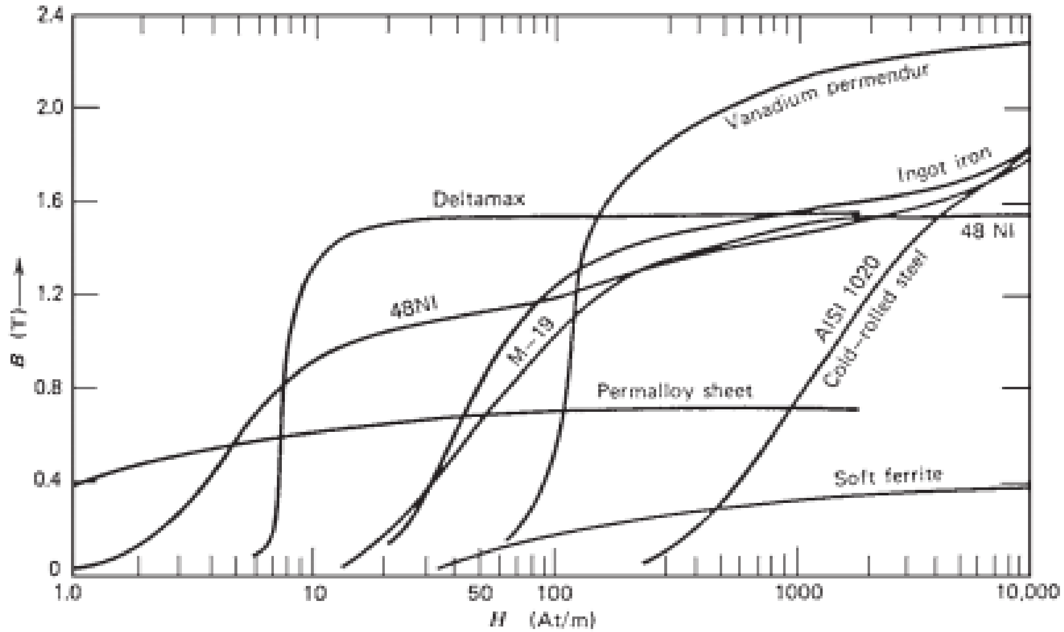


FIGURE 2.3 *B-H* curves of selected soft magnetic materials.

For accelerator magnets used low carbon steel: AISI 1006, AISI 1008, AISI 1010 with the low coercive force Hc < 2 Oe (160 A/m). Sometimes vanadium permendur is used for fields close to 2 T. Electrical type of steel used in AC magnets has up to 4% Si to reduce AC losses. It has the thickness of 0.35 mm – 0.5 mm for 50-60 Hz applications.

Ferromagnetic Material Properties

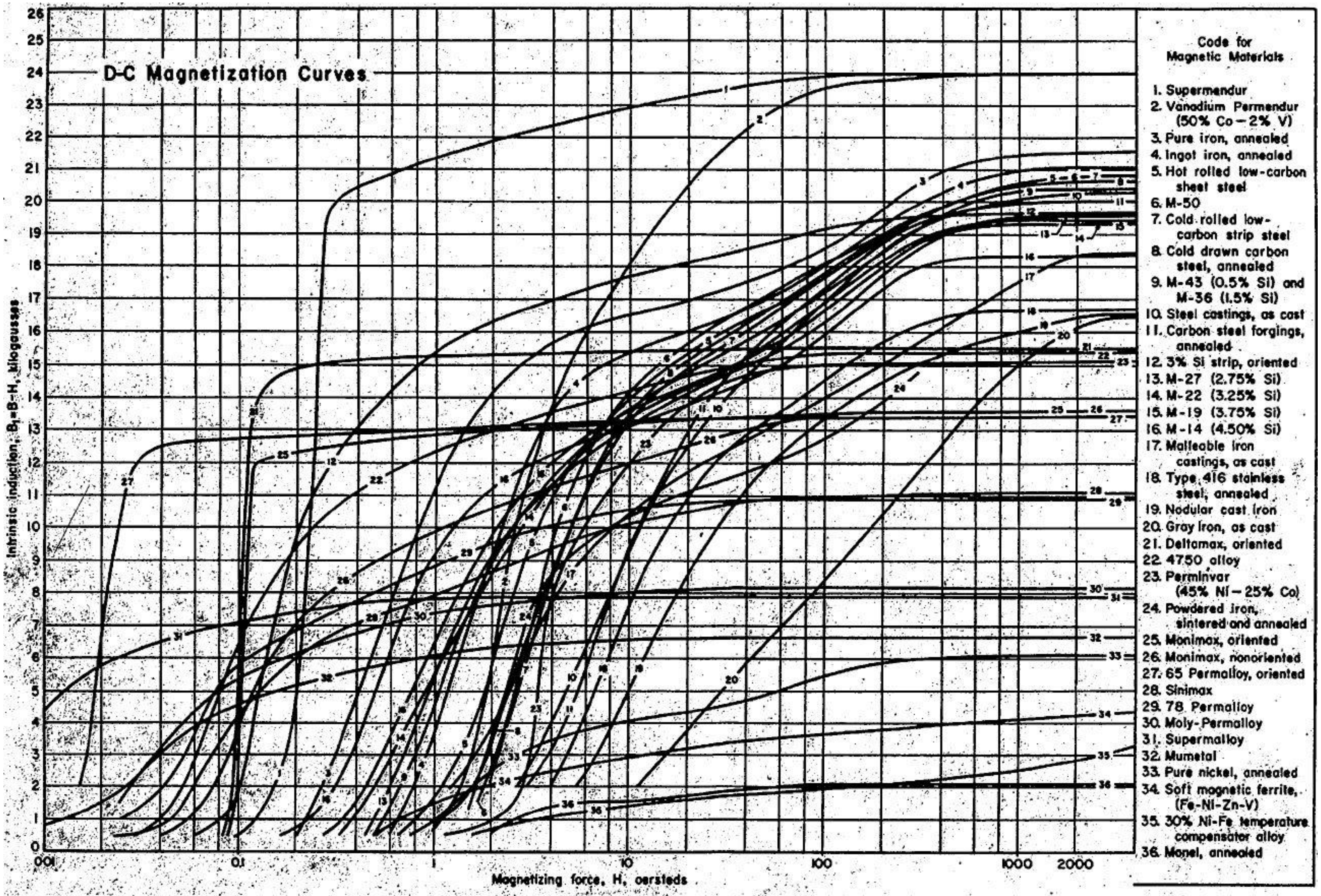


Fig. 17. Direct-current magnetization curves for various magnetic materials

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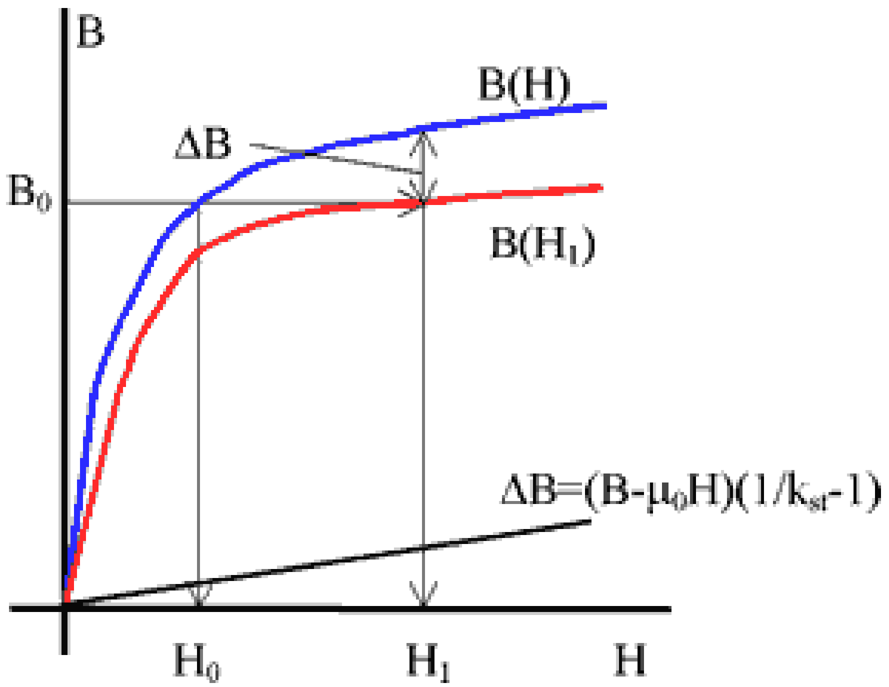
Define Hfe in the Yoke



$$Ho * d + Hfe * Lfe = Iw$$

$$Bo*d/\mu o + \frac{Bfe}{\mu} * Lfe = Iw$$

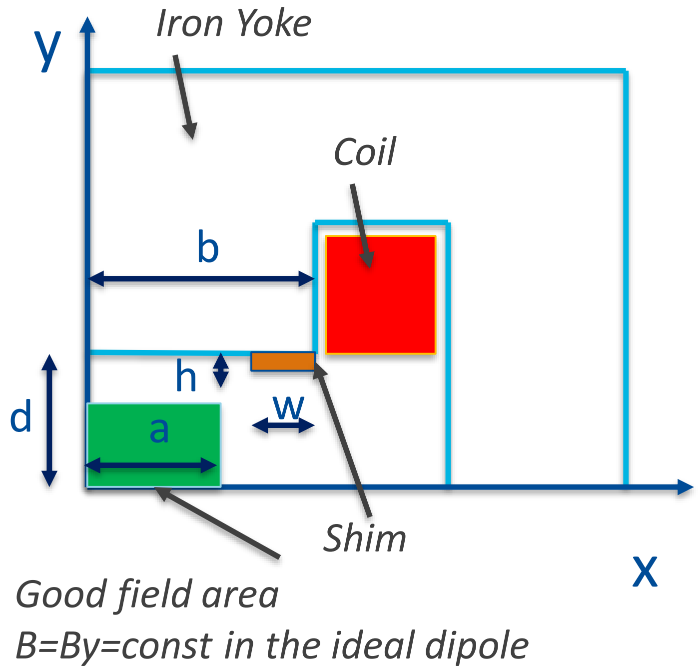
If in the yoke the flux density is Bo then using B-H curve for solid material (blue) and for laminated (red) could be defined Hfe (Ho or H1) needed to finish the magnet parameters estimation.

The Kst is laminations stacking factor.

The Kst is around 0.96-0.98.

Total ampere-turns Iw includes gap and yoke, and used for coils design.

Dipole Magnet Field Quality



Shim area: $S=0.021*d^2$

This relation is good for w/d in the range of 0.2 – 0.6.

Field in the magnet midplane:
$B=Bo(1+b1*x+b2*x^2+\ldots)$
Without shims the good field area width is:
- for 1% field homogeneity a=(b-d);
- for 0.1% field homogeneity a=(b-2d).
The good field area could be extended by adding shims:
- for 1% field homogeneity a=(b-d/2);
- for 0.1% field homogeneity a=(b-d).

For gap fields above 0.8 T used more smooth shims to reduce iron saturation effects in pole edges and shim areas.

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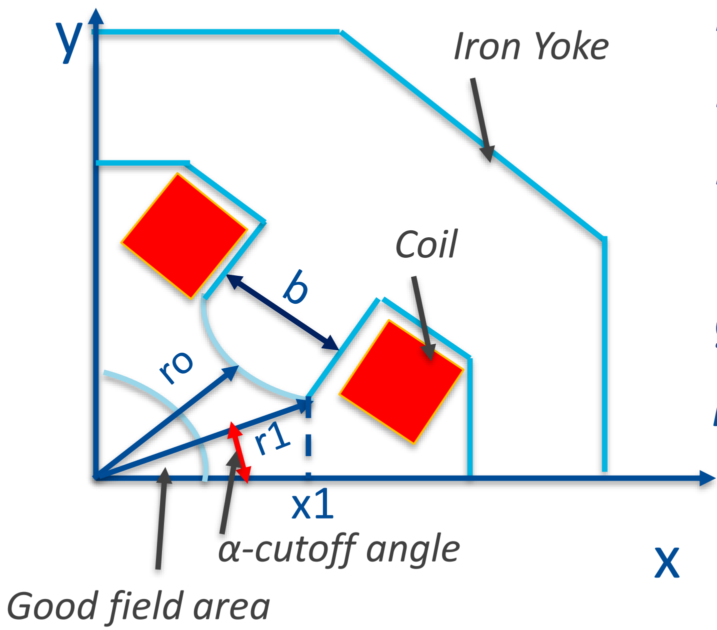
Quadrupole Magnets



At α= 18° the first undesired multipole b5 vanishes.

*r1=1.122*ro, x1=1.077*ro*

Field gradient at μ=∞ :

G=dBy/dx=b1=const

*By=G*x, G=2μo*Iw/ro²*

Field in the magnet midplane:

*B=Bo(1+b1*x+b2*x²+…)*

For the quadrupole Bo=0,

*The ideal quadrupole field : B=b1*x generated by a hyperbolic pole profile: x*y=ro²/2*

*The quadrupole half gap ampere-turns: (Hp+Ho)/2*ro=Iw, or at Ho=0;*

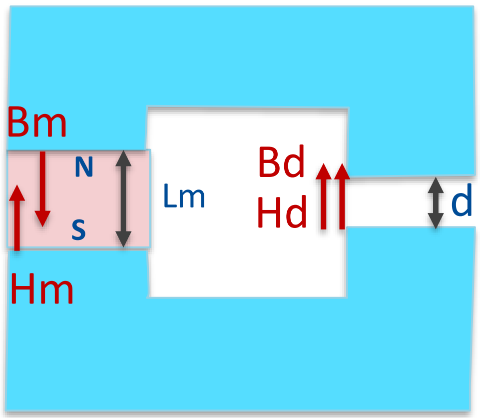
Quadrupole coil ampere-turns:

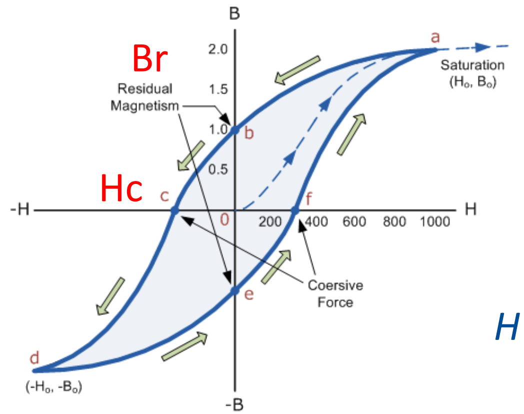
*Hp*ro/2+Hfe*Lfe=Iw,*

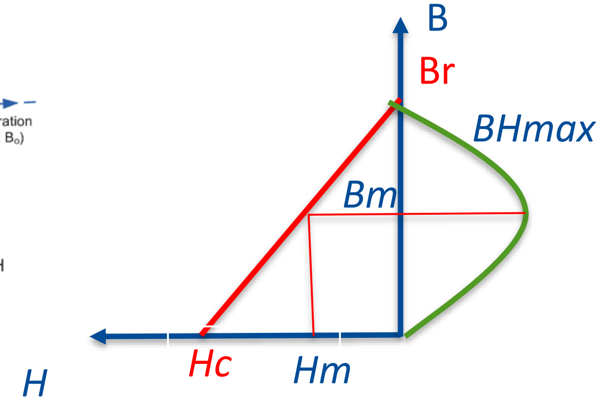
*Bp*ro/2μo+Bfe/μ*Lfe=Iw.*

Hfe, Bfe –defined as for dipoles, but because of field gradient the flux through the yoke two times lower.

Permanent Magnets







*Hm*Lm – Hd*d = 0 (Ampere's Law)*

*Am*Bm = Ad*Bd (Gauss Law)*

Where Bm, Hm permanent magnet working point on the demagnitization curve.
Bd,Hd – gap field.
Am, Ad – permanent magnet and gap areas.

*Lm=Hd*d/Hm=Bd*d/μo*Hm*

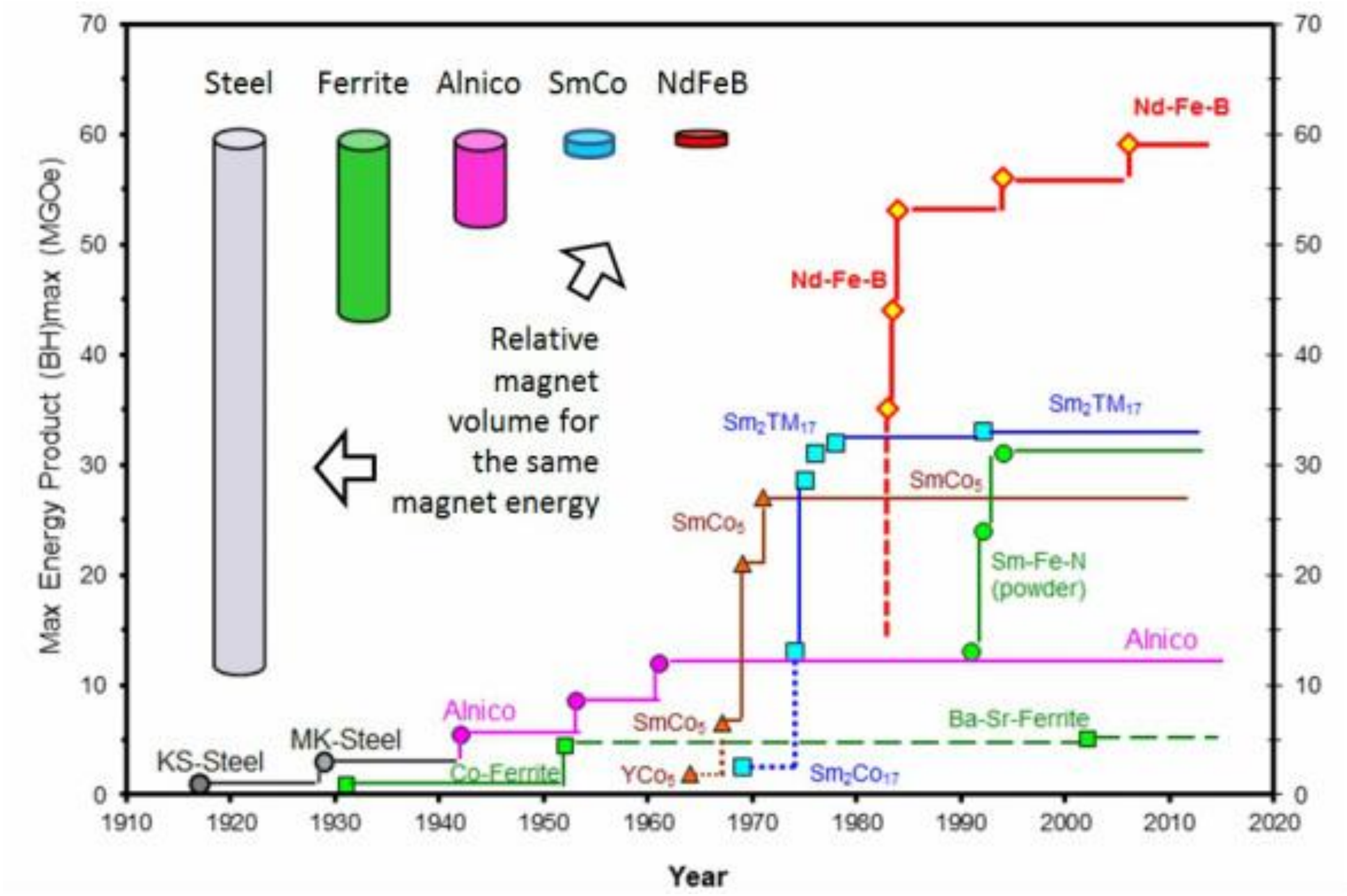
*Am=Ad*Bd/Bm*

*Vm=Lm*Am=Bd²*d*Ad/(μo*Bm*Hm) – the larger Bm*Hm the lower PM volume.*

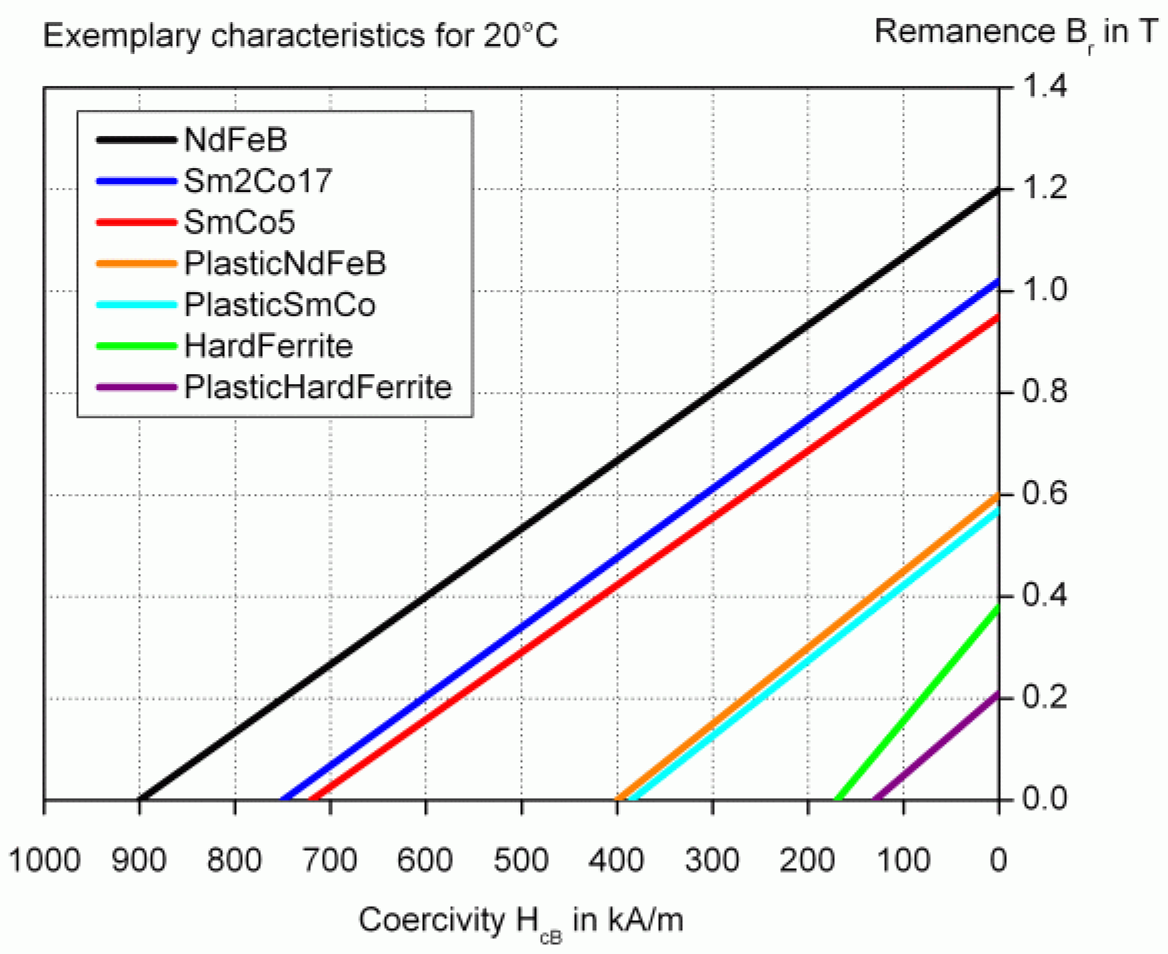
For SmCo5: Br=-μoHc, and (BmHm)max at Bm=Br/2, Hm=Hc/2

Permanent magnets are the energy source which supply the maximum energy only at BHmax.

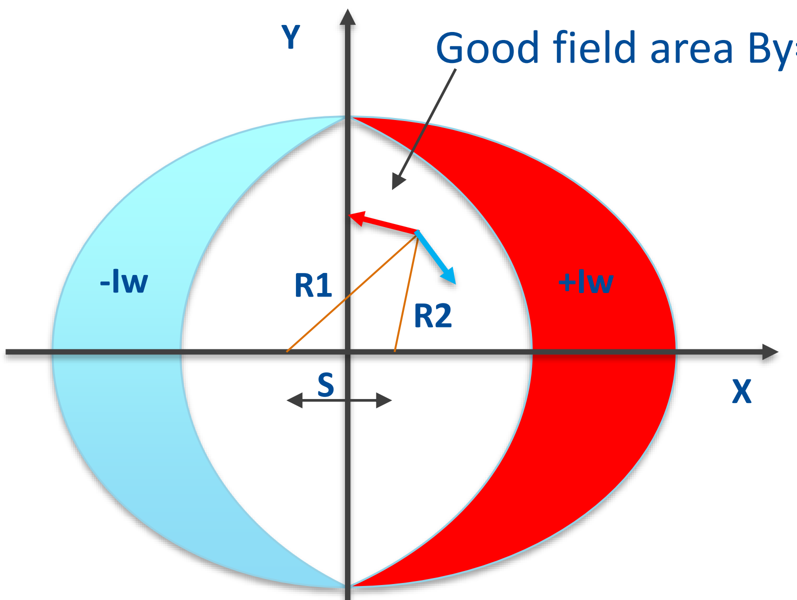
Permanent Magnets Energy Product

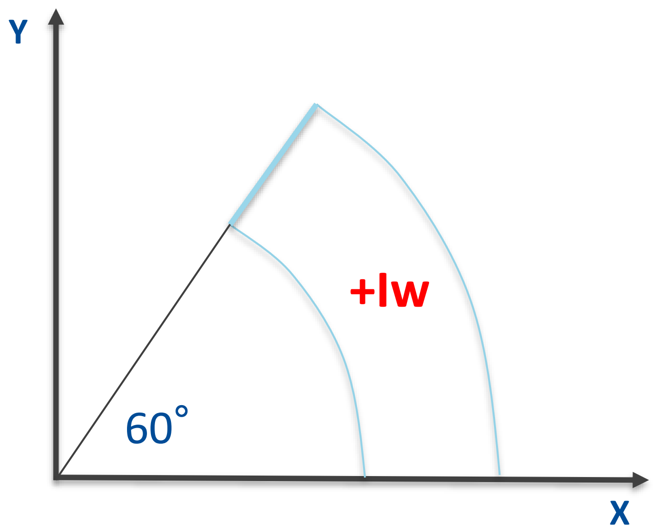


Permanent Magnets B(H)



Superconducting Magnets





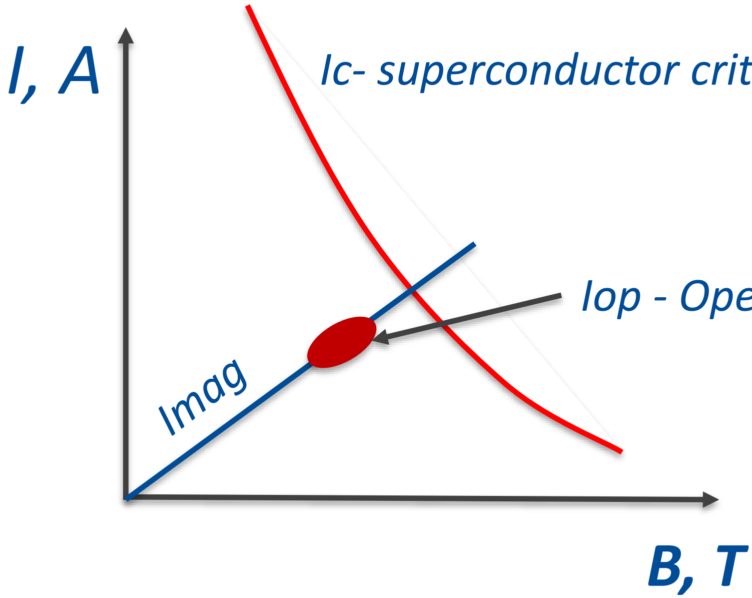
Crossing two identical round rods with opposite currents gives the homogeneous field.

By=μo*Iw/2*[-R1*cos(ϑ1)+ R2*cos(ϑ2)]=-μo*Iw*s/2

At 60° eliminated the first dipole field harmonic (sextupole).

The closer geometry approximation to the COS azimuthal current density distribution the better field homogeneity could be obtained.

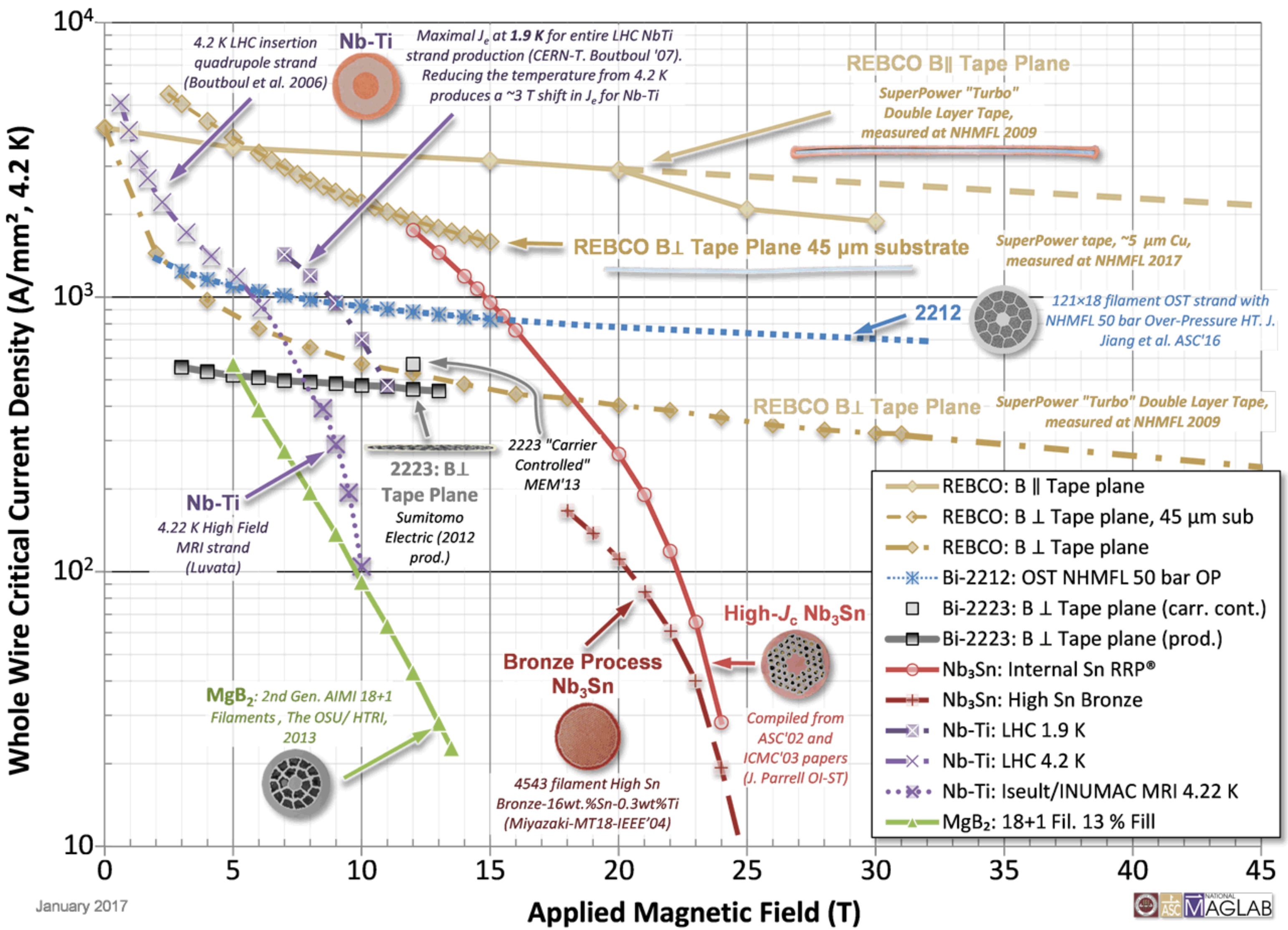
Superconducting Magnets



- ✓ *Choice of operating point (Iop) is the most critical decision in the superconducting magnet design.*
- ✓ *The closer Iop to the Ic the more risk for the magnet performance.*

- ➢ *For most accelerator magnets used NbTi superconductors: Tevatron –(4.5T, 4.2K), LHC (9 T, 2 K).*
- ➢ *Nb3Sn magnets have a good progress in recent years: LARP and HLumi LHC upgrade.*
- ➢ *HTS in an R&D phase for accelerator magnets with two main directions: low field with high temperature, and very high field with low temperature. Hybrid magnets are a main stream.*

Superconductors (P. Lee)



Superconductor References

YBCO: Tape, ∥Tape-plane, SuperPower "Turbo" Double layer (tested NHMFL 2009). Source: Aixia Xu and Jan Jaroszynski, June 2009. 20 T depression due to He bubble, dashed line estimates true performance.
YBCO: Tape, ⊥ Tape-plane, SuperPower "Turbo" Double layer (tested NHMFL 2009). Source: Aixia Xu and Jan Jaroszynski, June 2009.

YBCO: Tape, ⊥ Tape-plane, SuperPower 45 μm substrate with 5 μm Cu layer, sample courtesy of D. van der Laan (ACT), tested at NHMFL 2017 (D. Abraimov with A. Francis - Ic measurements, and N. Gibson - (IA)).

Bi-2223: B ⊥ Tape-plane "DI" BSCCO "Carrier Controlled" Sumitomo Electric Industries (MEM'13 presented by Kazuhiko Hayashi).
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Nb-47Ti 4.22 K for 11.75 T Iseult/INUMAC MRI: Kanithi H, Blasiak D, Lajewski J, Berriaud C, Vedrine P and Gilgrass G 2014 Production Results of 11.75 Tesla Iseult/INUMAC MRI Conductor at Luvata IEEE Transactions on Applied Superconductivity 24 1–4 http://dx.doi.org/10.1109/TASC.2013.2281417

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doi: 10.1109/TASC.2004.830344
MgB_2: 18 Filament - The OSU/HTRI C 2 mol% AIMI ("Advanced Internal Mg Infiltration") 33.8 Filament to strand ratio, 39.1% MgB_2 in filament. G. Z. Li, M. D. Sumption, J. B. Zwayer, M. A. Susner, M. A. Rindfleisch, C. J. Thong, M. J. Tomsic, and E. W. Collings, "Effects of carbon concentration and filament number on advanced internal Mg infiltration-processed MgB 2 strands," Superconductor Science and Technology, vol. 26, no. 9, p. 095007, Sep. 2013. http://dx.doi.org/10.1088/0953-2048/25/11/115023

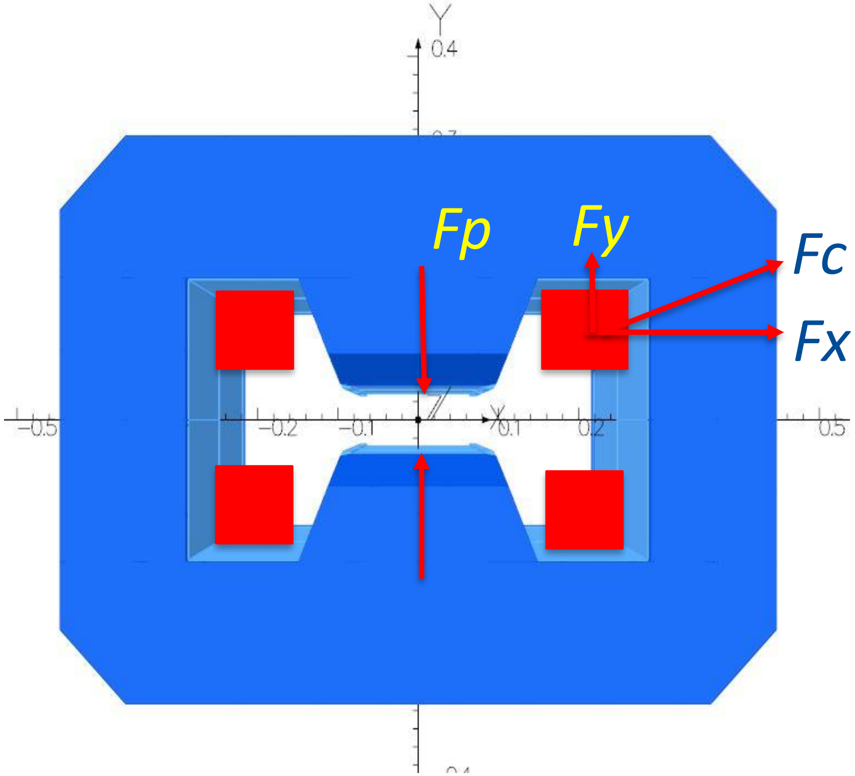
Links to ASC, MT and ICMC Proceedings can be found on the conferences page.

Superconducting Magnet Quenches and Protection

- ✓ Superconducting magnets quenched if there is generated enough heat to transfer the superconductor locally or globally in the normal condition.
- ✓ Quenches happened because of “flux jumps”, mechanical motion, epoxy cracking, not enough cooling, etc.
- ✓ Most magnets have quench detection and protection systems.
- ✓ Quench detected by monitoring the resistive voltage rise on the coil(s).
- ✓ Quench protection system initiate the stored energy extraction on dump resistor. Also used heaters to transfer the whole winding in the normal condition.

MRI Explosion:
https://www.youtube.com/watch?v=1R7KsfosV-o

Magnet Stored Energy and Lorentz Forces



Magnet stored energy:

$$W = \int_V \mathbf{B}*\mathbf{H}/2 *dV = \int_V \mathbf{B}^2/2\mu o*dV$$

*More than 90% of magnet stored energy concentrated in the magnet air gap because **H** in the iron yoke is very small.*

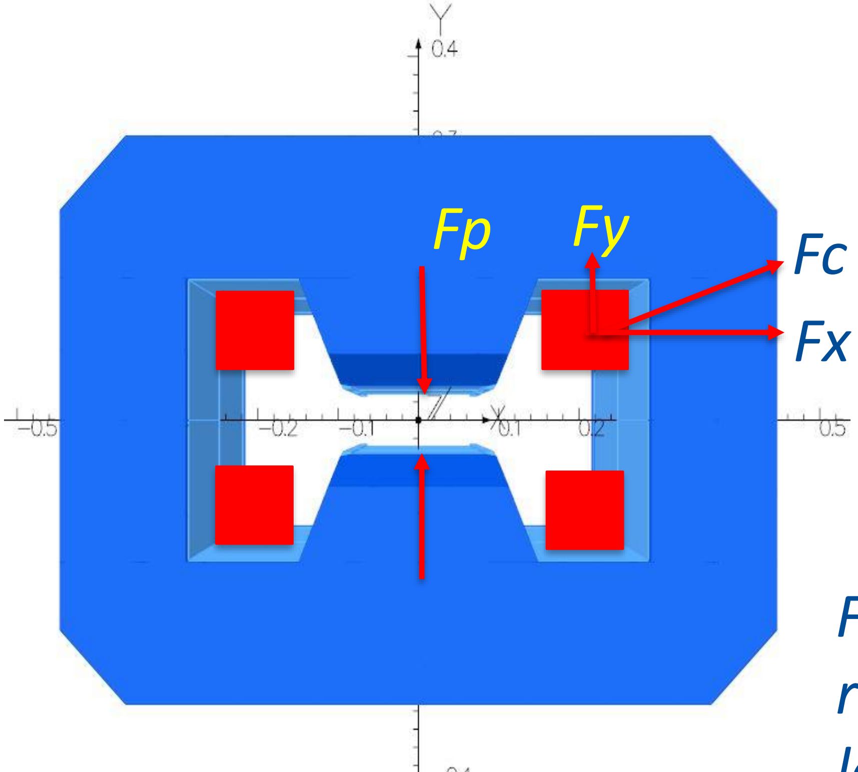
Force between poles Fp:

Fy= -dW/dg = - W/g,
g- magnet gap

Lorentz forces on the coil Fc:
*Fx= By*Iw*Lc*
*Fy= Bx*Iw*Lc*

More accurate forces calculated by volumetric integration.

Magnet Resistance and Inductance



Magnet coil resistance at 20 C:

$R = (1+\alpha*dT)*\rho*Lc/q$

For Cu: $\alpha = 0.004$ [1/C°]

Lc – conductor length;

q – conductor cross-section;

α – temperature coefficient.

For superconducting magnets resistance defined by current leads and external cables.

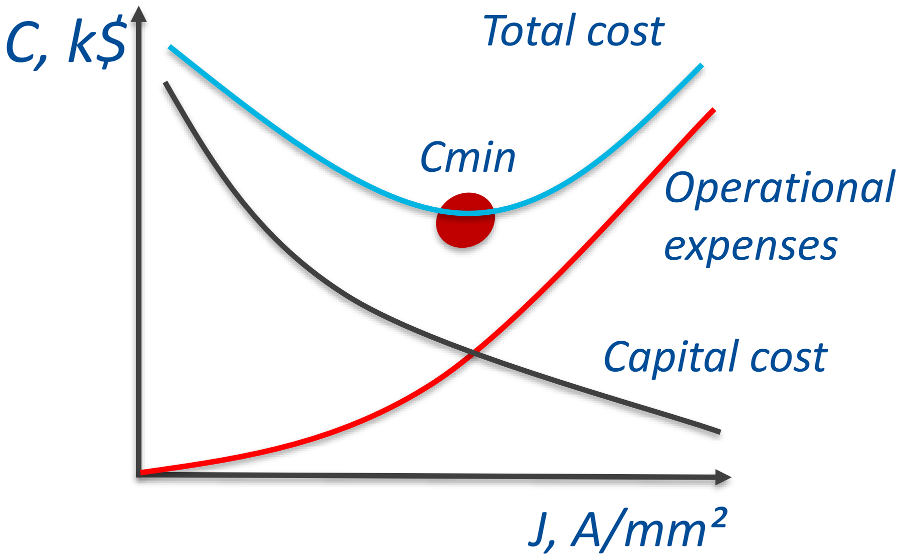
Magnet inductance:

$L = \psi/I = \omega\Phi/I$, or

$L = 2*W/I^2$

Magnet R, and L needed for the power supply design, and quench protection in the case of superconducting magnet.

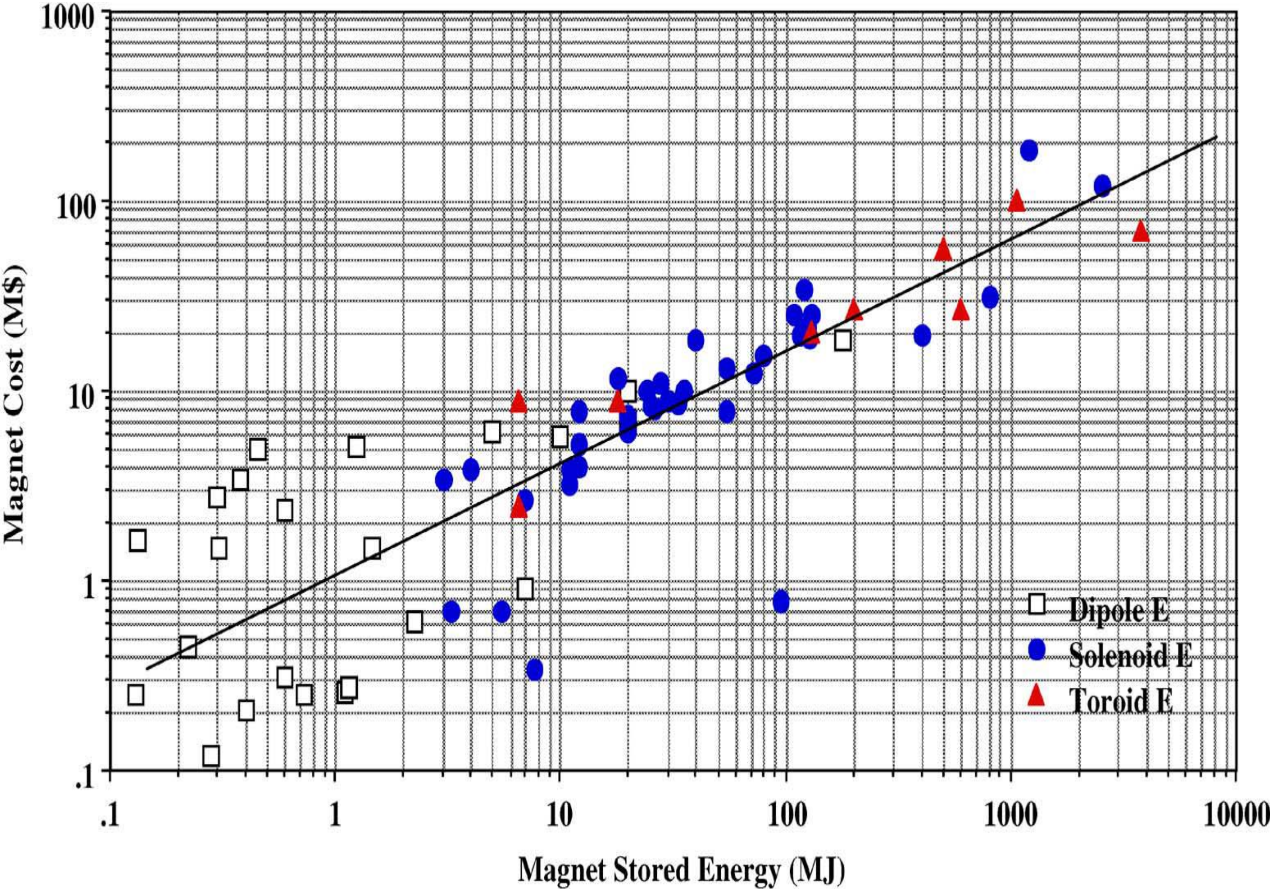
Magnet Cost



- ✓ *Cost of magnets:*
- *Small – 10k$- 50k$;*
- *Medium – 50k$ - 100k$;*
- *Large - > 100 k$.*
- *Cost of prototype is at least 3 times more than at a serial production.*

- ✓ *Capital cost includes cost of conductors, materials, tooling, and fabrication.*
- ✓ *Operational expenses include cost of electricity, water or LHe cooling for 10 years of operation at 5000-7000 hours/year.*
- ✓ *Optimal current density for air cooled magnets is 1.5 A/mm^2 - 2.0 A/mm^2.*
- ✓ *Optimal current density for water cooled magnets is 4.0 A/mm^2.*
- ✓ *For superconducting magnets the operational peak current density should be below critical, at least 20%, measured for the short sample.*

Magnet Stored energy vs. Cost



The Cost of Superconducting Magnets as a Function of Stored Energy and Design Magnetic Induction Times the Field Volume

Michael A. Green and Bruce P. Strauss

$$C(M\$) = 0.92\,[E(MJ)]^{0.60}$$

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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 $< 1\ \mu m$.*
  - *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*
No water flow induced vibration	*effects*
Enhanced machine protection	*Limits on energy flexibility*
Lower cost	

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NLC PM Candidates

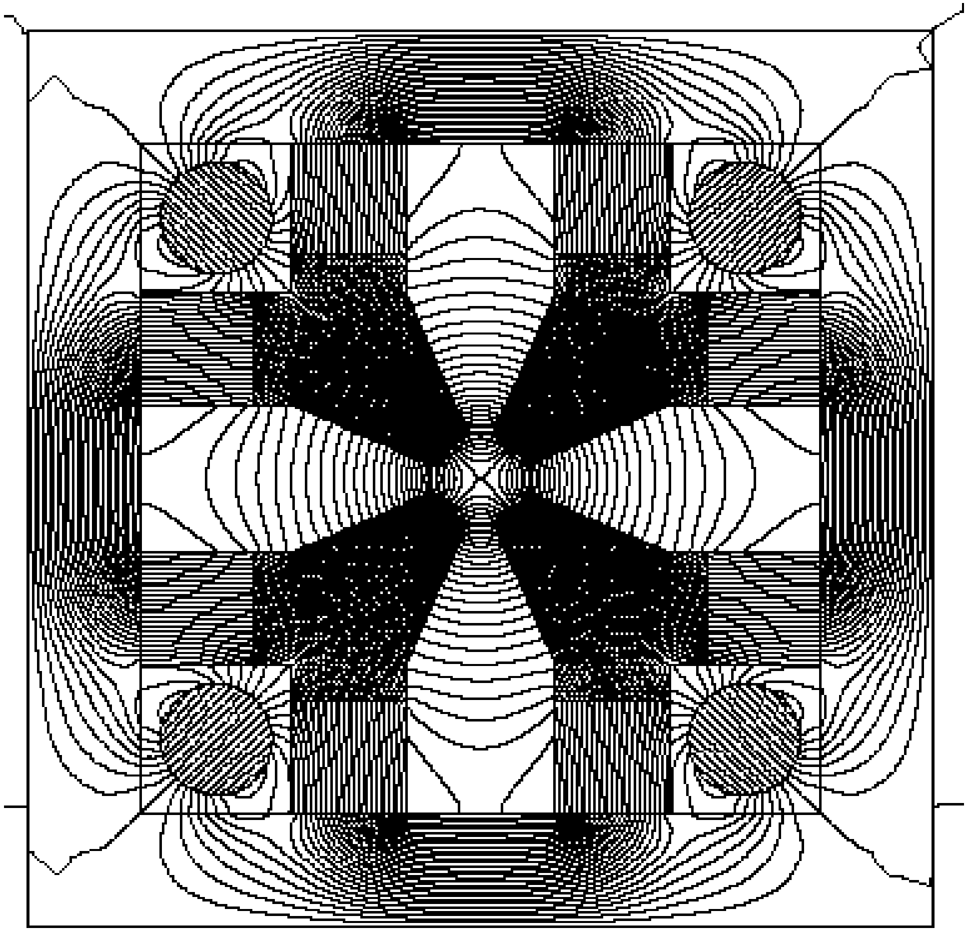
- Original list of NLC PM candidates:
  - If injector is centralized, then transport line quads could be PM.
  - Bunch compressor bends and quads.
  - Damping ring bends and sextupoles.
  - Main linac quads up to 150 GeV(use EM's from 150 to 250 GeV for energy flexibility).
  - Main linac quads past 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	SmCo	Nd-Fe-B
Strontium or barium ferrite Inexpensive Radiation resistant Low Br, .38 T High temp coefficient, -0.2 % / C° Brittle	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	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

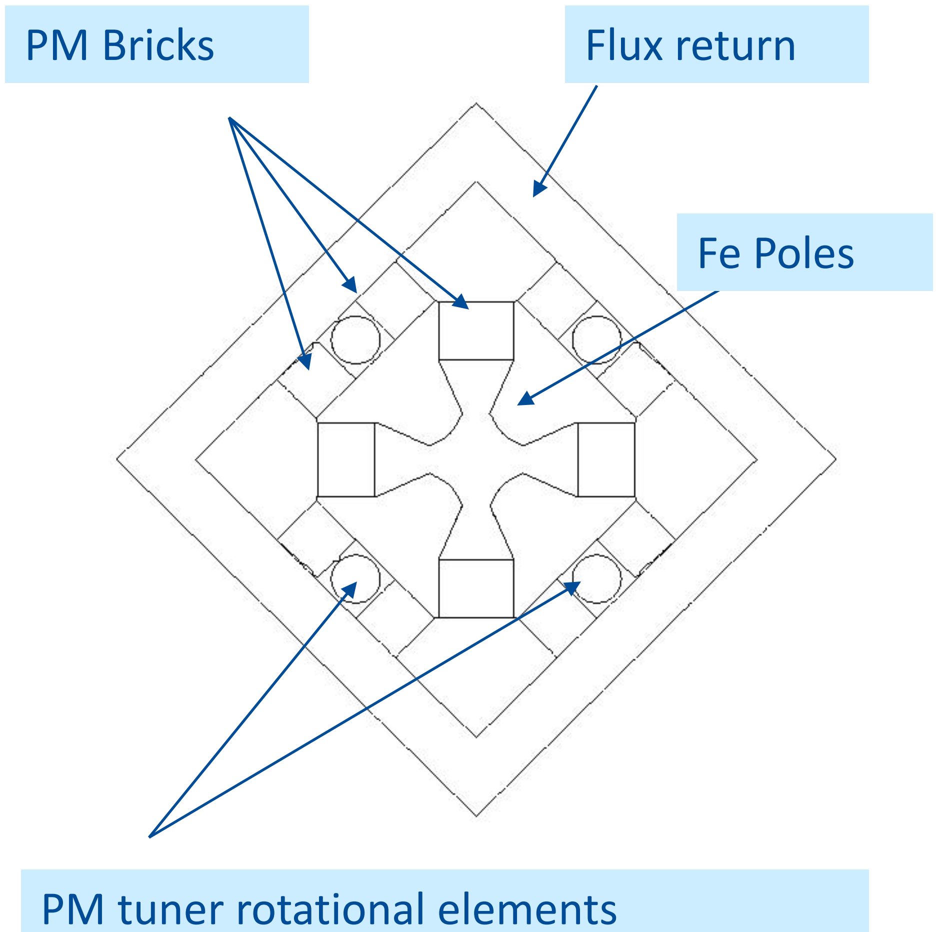
- Preliminary design:
  - Sm-Co 2:17 bricks outboard of poles.
  - Rotating Sm-Co 2:17 tuners in corners.
  - Pole supports between poles.
  - Temperature compensator(if needed); applies to all hybrid PM designs.
- Advantages:
  - Similar to recycler ring quads.
  - Large space available for pole supports.
- 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

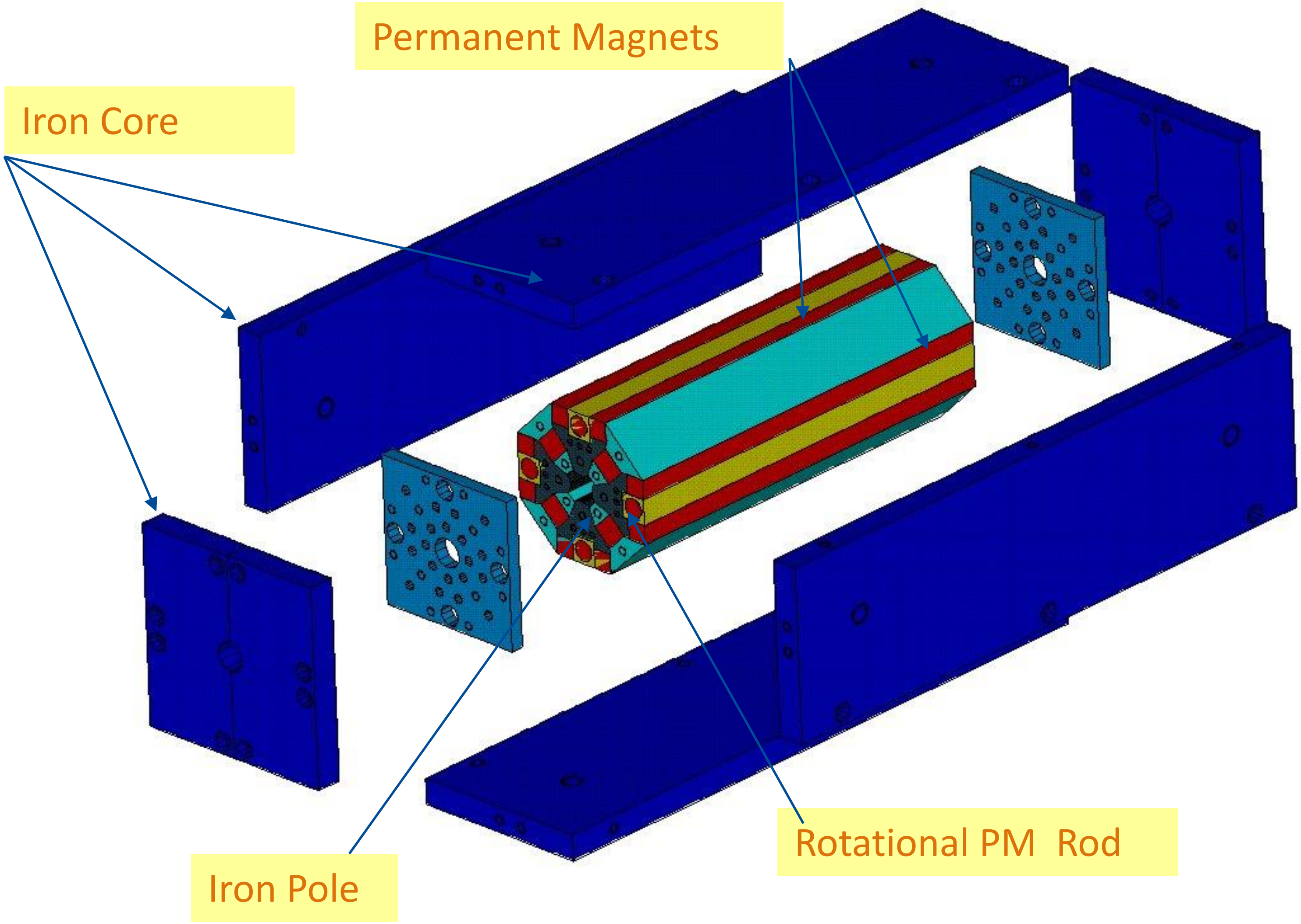
PM Prototype: Wedge Design

- 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.

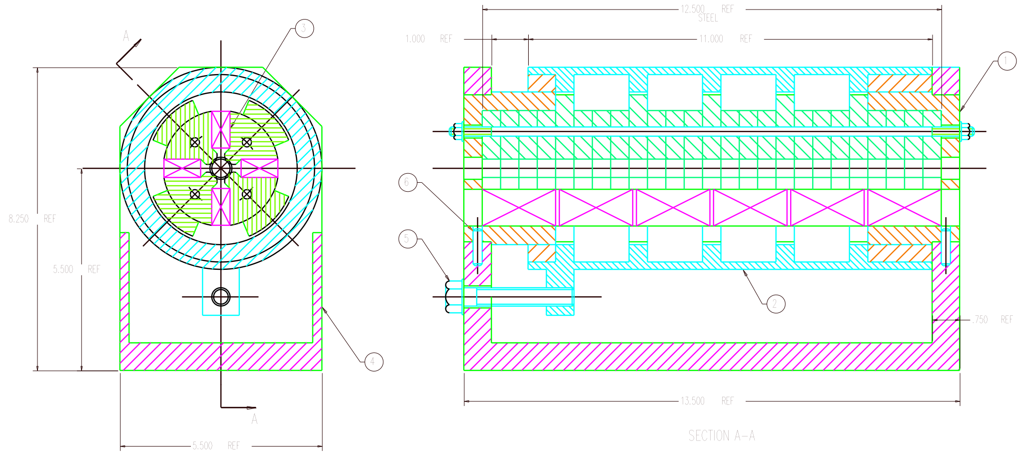


PM Quadrupole FWS217

Wedge Quadrupole Design



PM Prototype: Magnetic Shunt Design

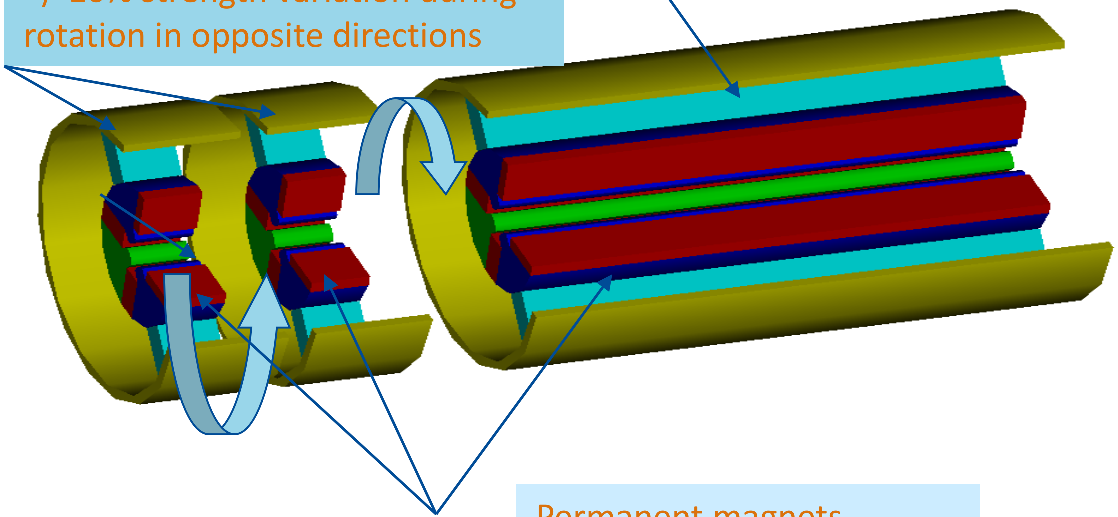


Prototype Design:

- 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

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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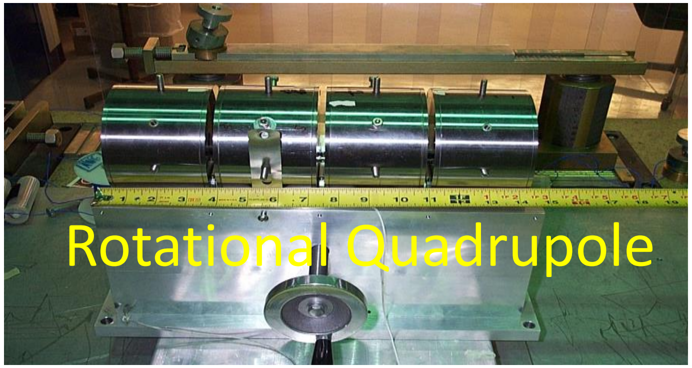
Adjustable PM Quadrupoles for NLC



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 overcomed 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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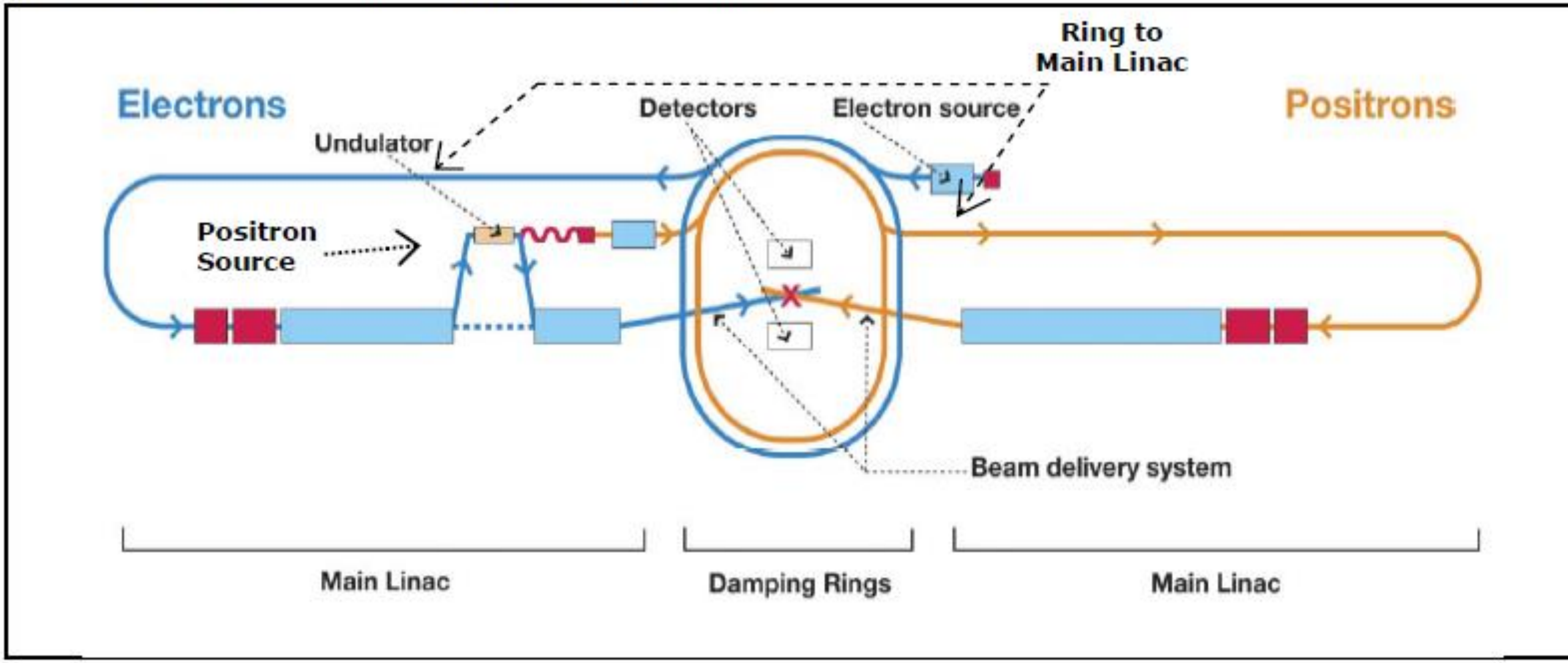
International Linear Collider Magnets

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 Styles	Grand Totals Quantity	Sources e-	Sources e+	Damping Rings e-	Damping Rings e+	2 RTML Qty	2 Linacs Qty	2 BeamDel Qty
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

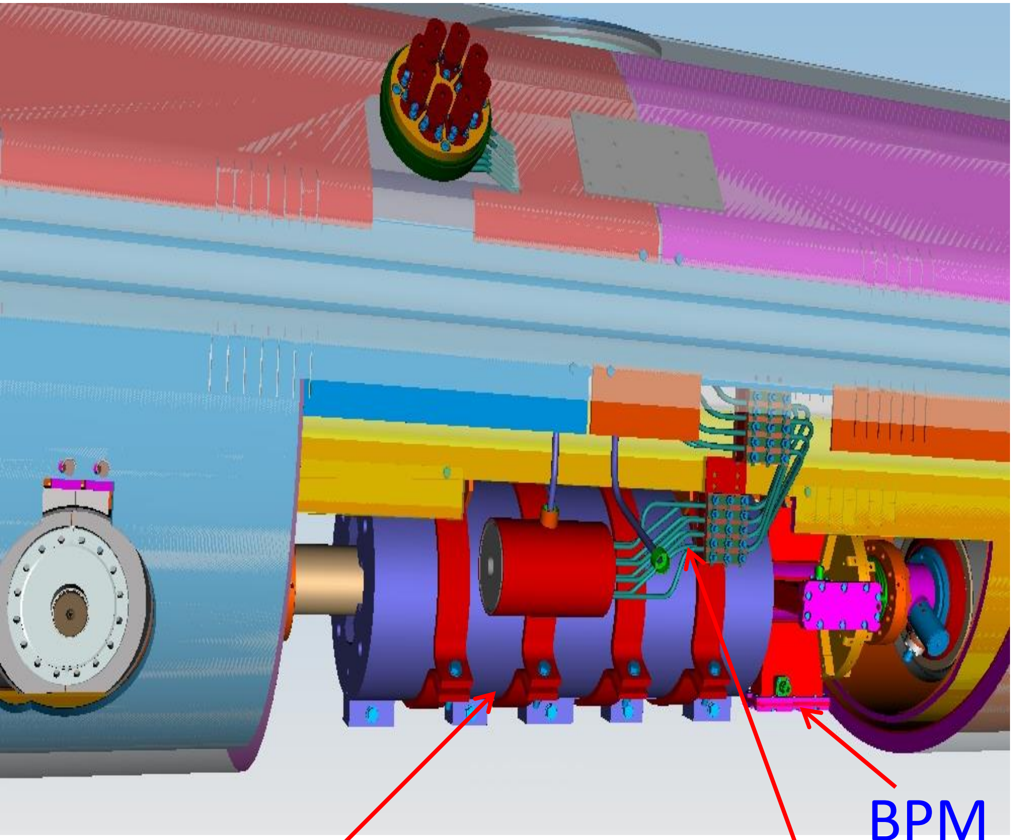
Total 135 magnet styles, and quantity 13253.

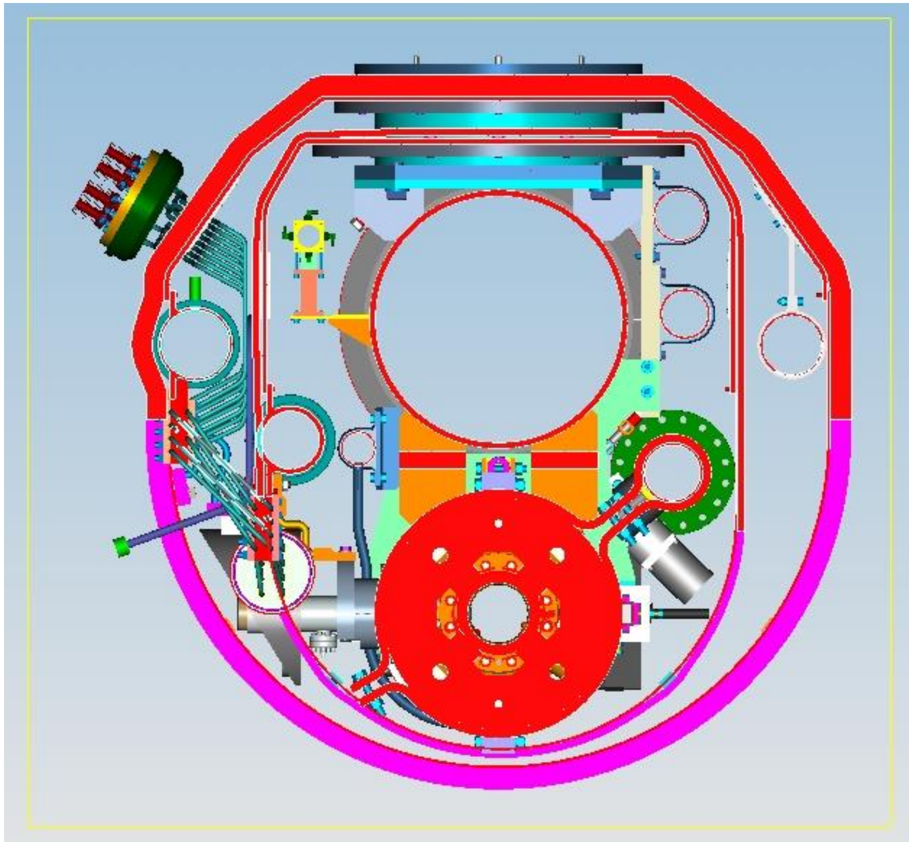
ILC Quadrupole Specification & Superconductor

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

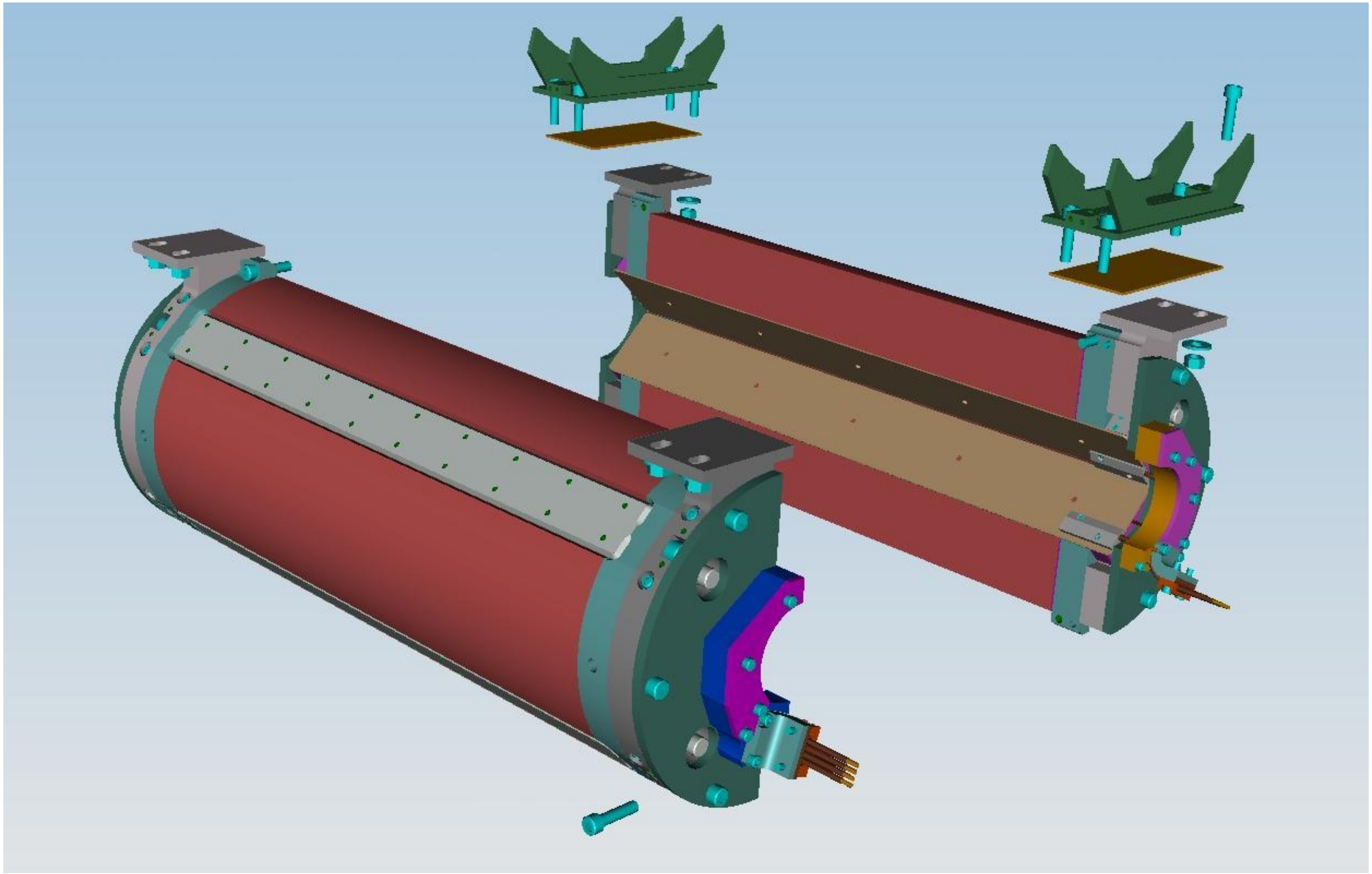
NbTi wire diameter, mm	0.5
Number of filaments	7242
Filament diameter, um	3.7
Copper : Superconductor	1.5
Insulated wire diameter, mm	0.54
Insulation	Formvar
Twist pitch, mm	25
RRR of copper matrix	100
Critical current Ic @ 4.2K, at 5T	204 A

ILC Splittable Quadrupole in Cryomodule

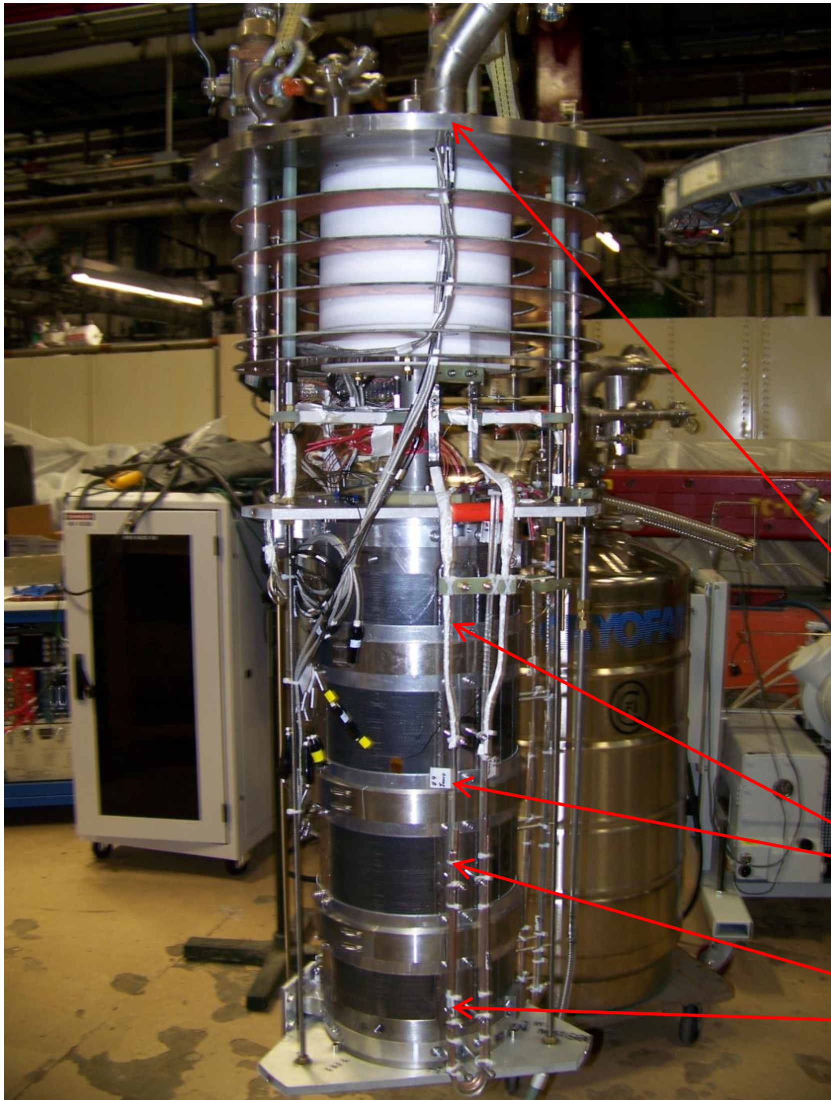


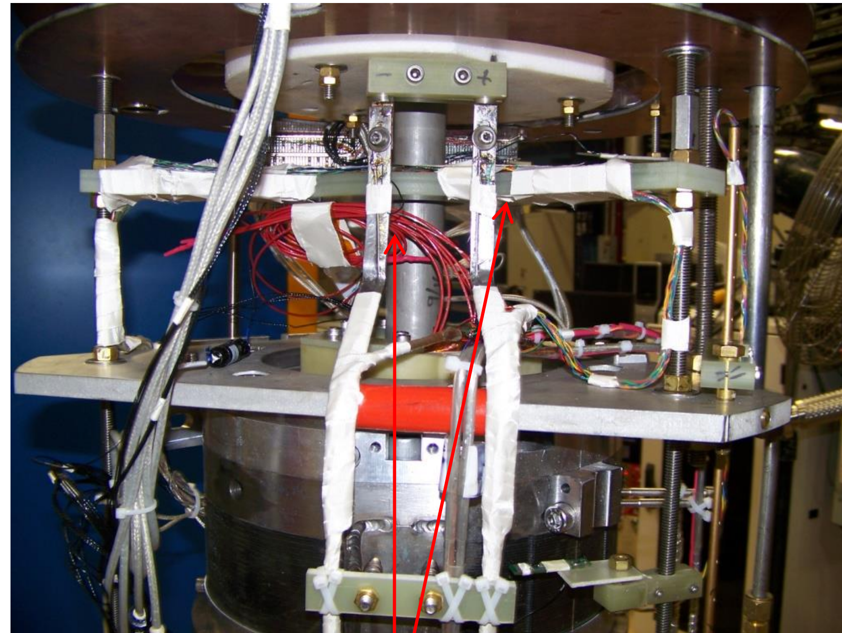


ILC Two Halves of the Quadrupole



ILC Quadrupole with Top Head Assembly





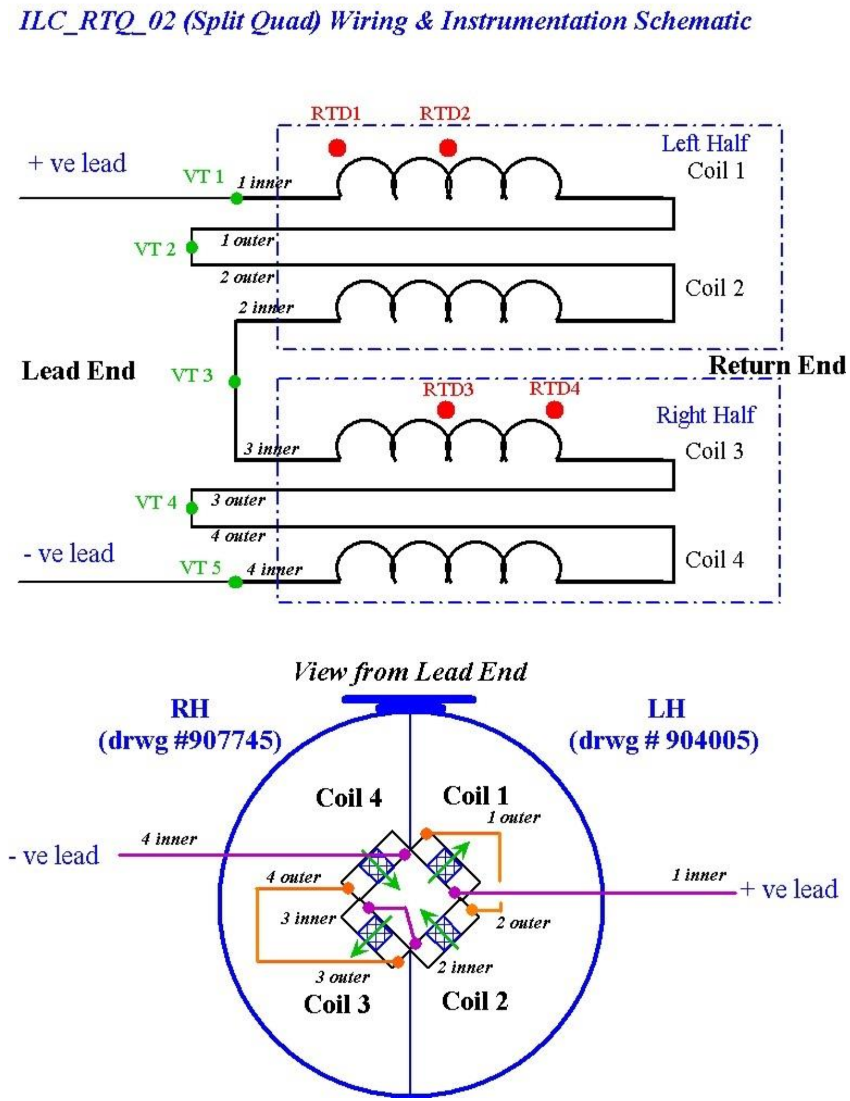
Current leads

Top head

Quadrupole yoke

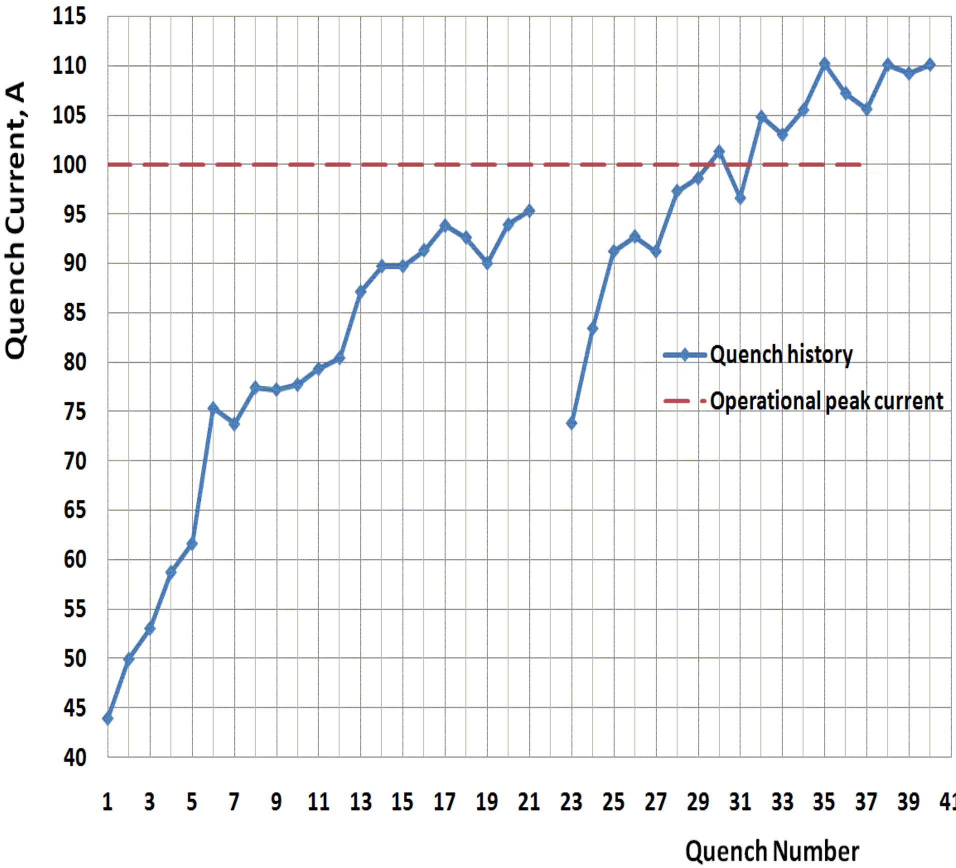
Two quadrupole halves clamping rings

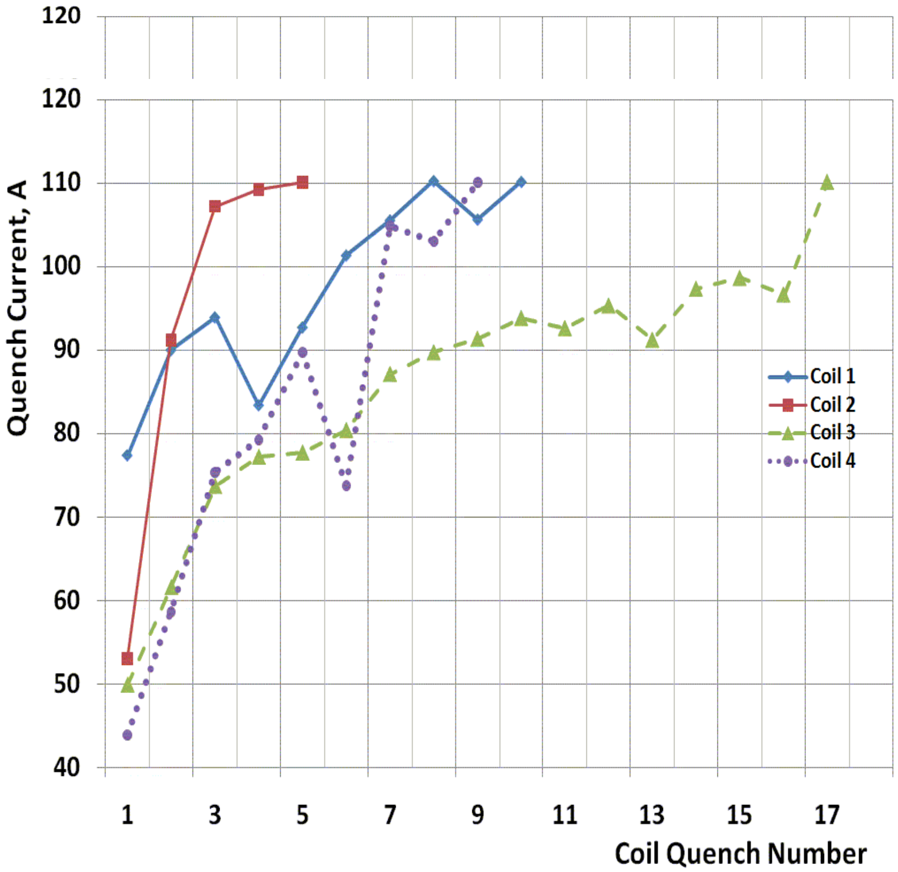
ILC Quadrupole Electrical Scheme



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



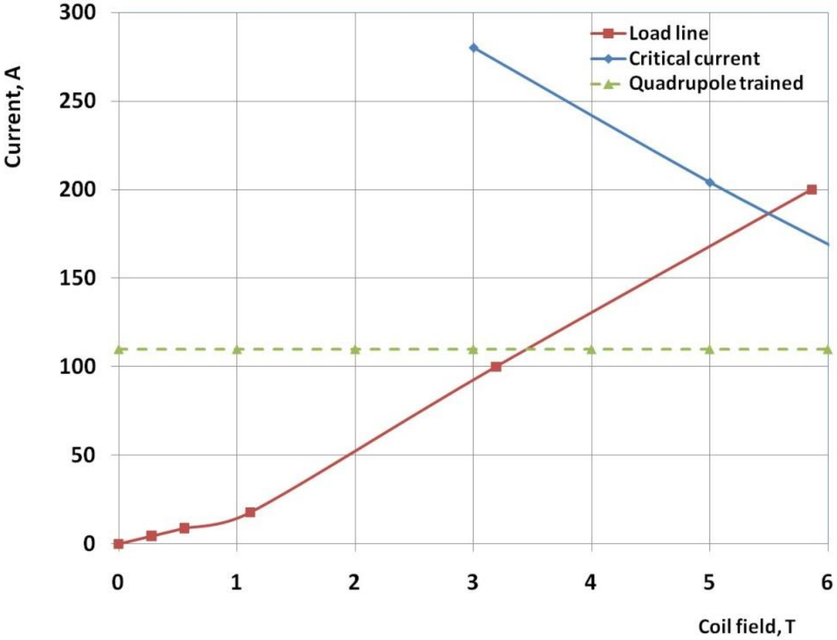


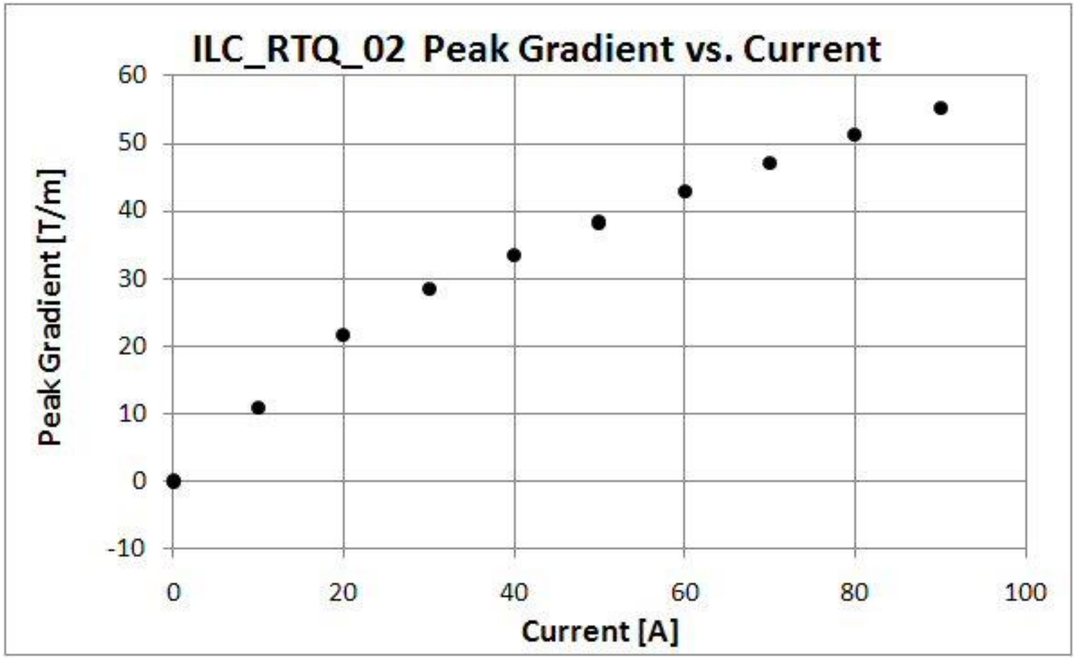
Quench history for two thermal cycles

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

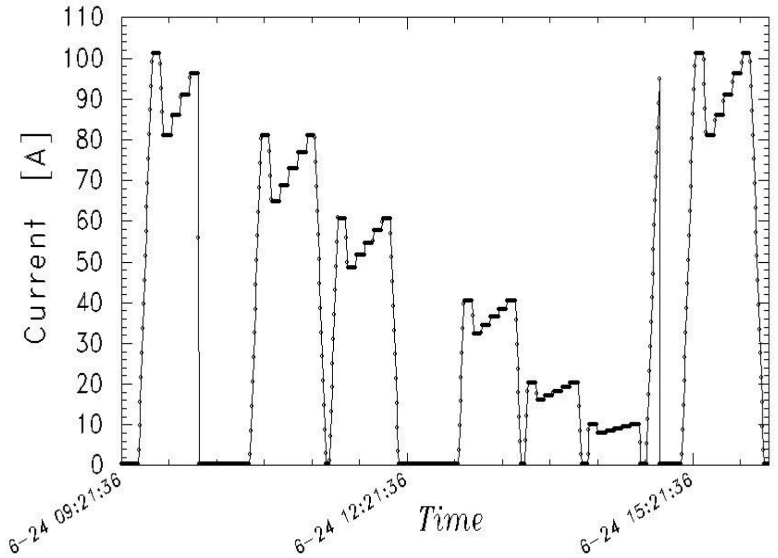


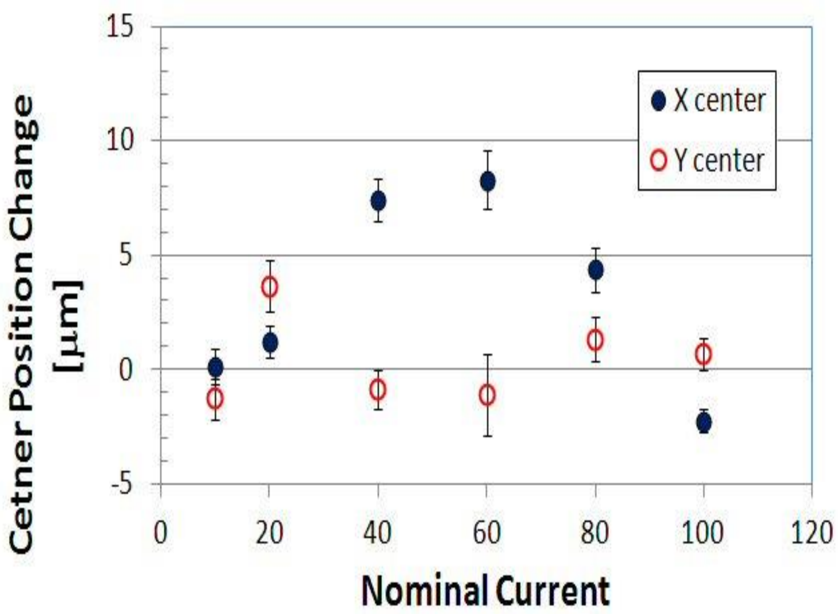


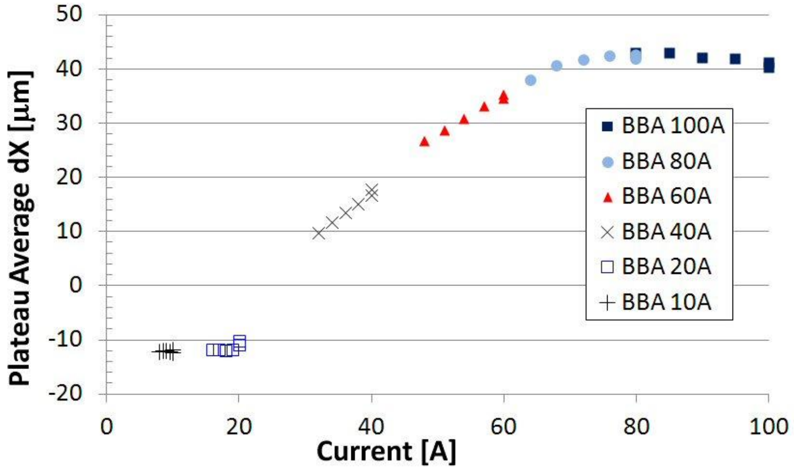
Peak operating current 100 A. Magnet trained up to 110 A (green line).
Critical current (short sample limit) for this magnet is 185 A at the coil field 5.4 T.

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.

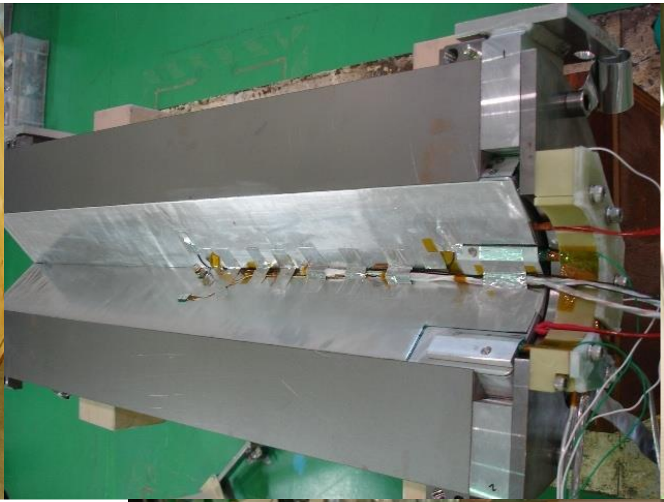
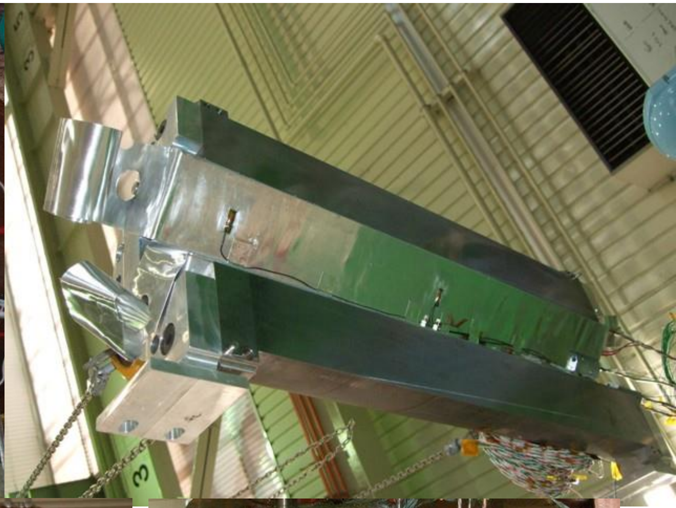
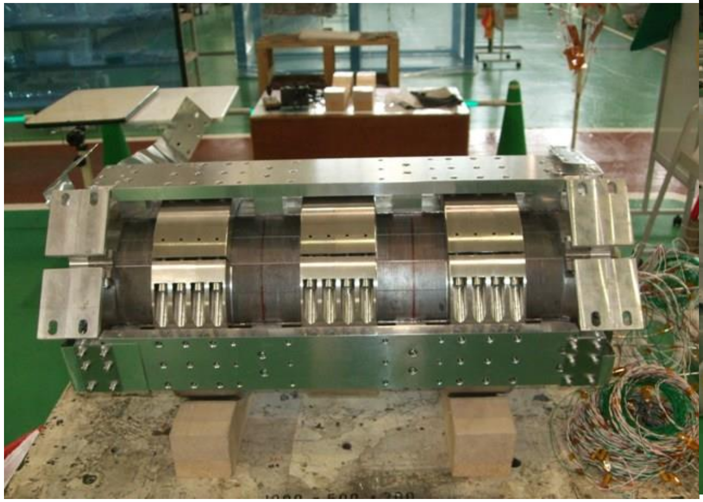
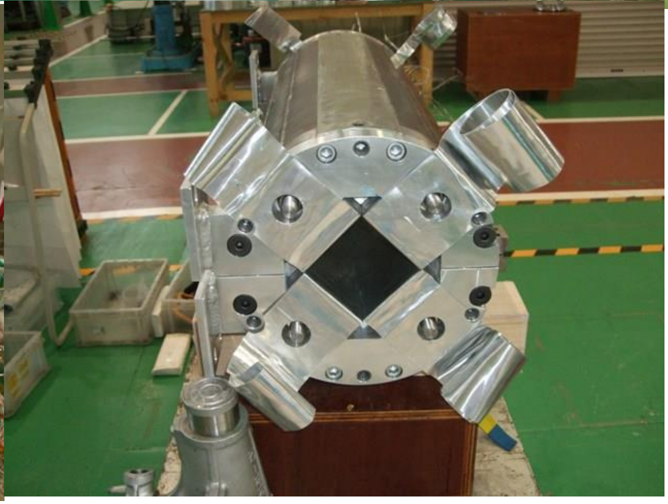
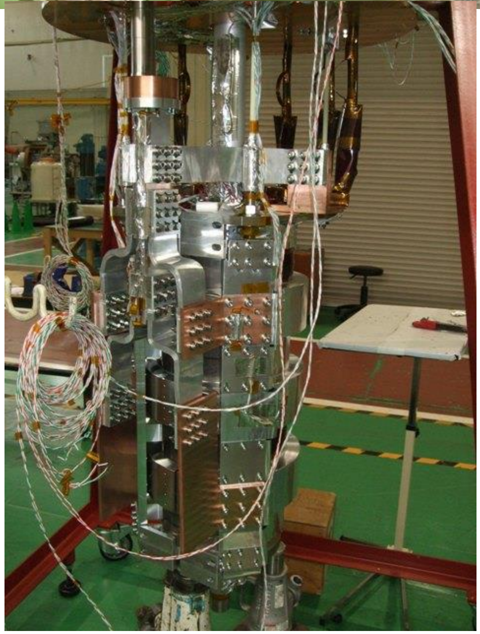
Quadrupole Measurement Results

- 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**

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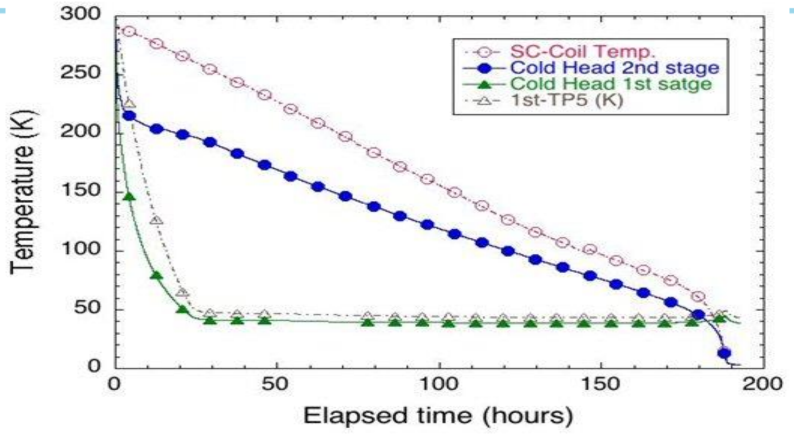
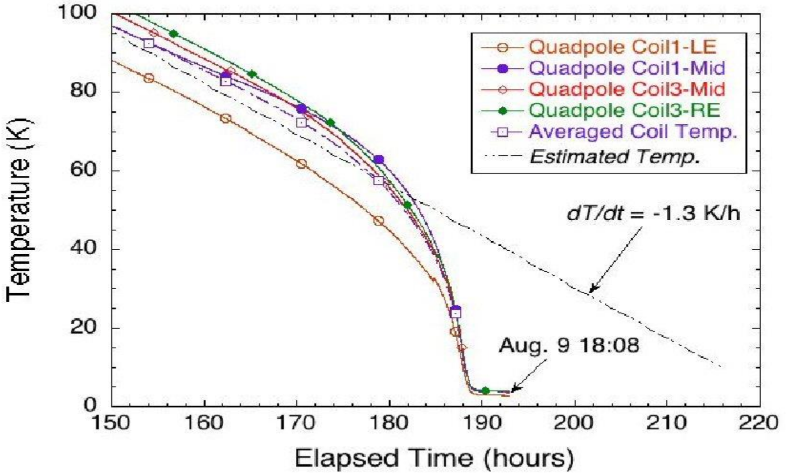
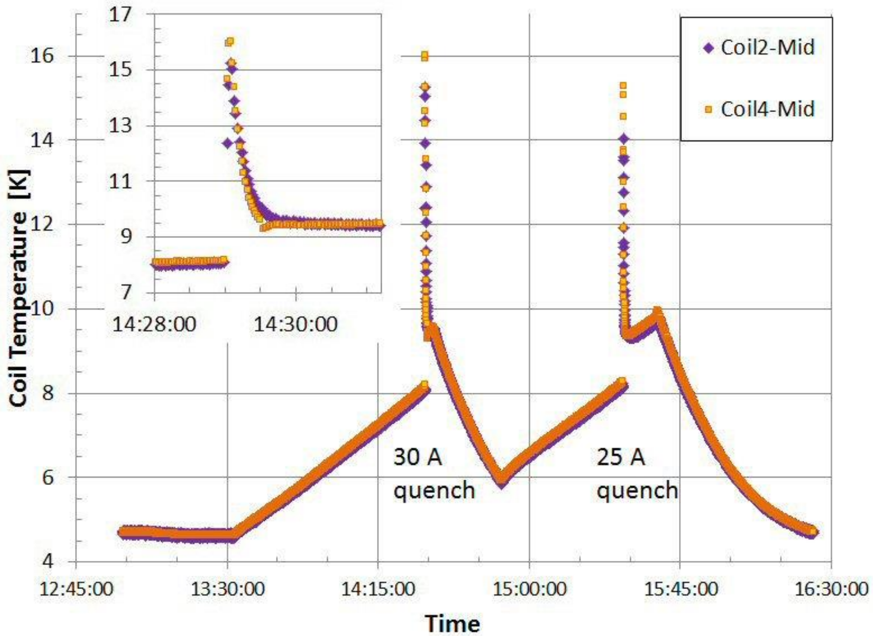
Quadrupole Test at KEK [1]



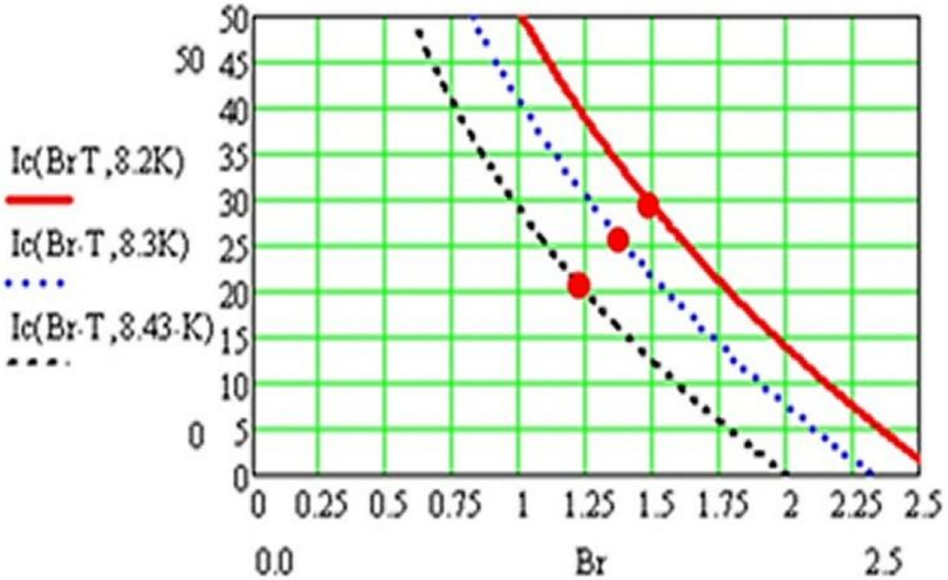


The KEK Test Stand was assembled and the magnet cooled down (8 days) to 4.5 K under supervision of Akira Yamamoto and Hitoshi Kimura

Conduction Cooling Tests at KEK [2]



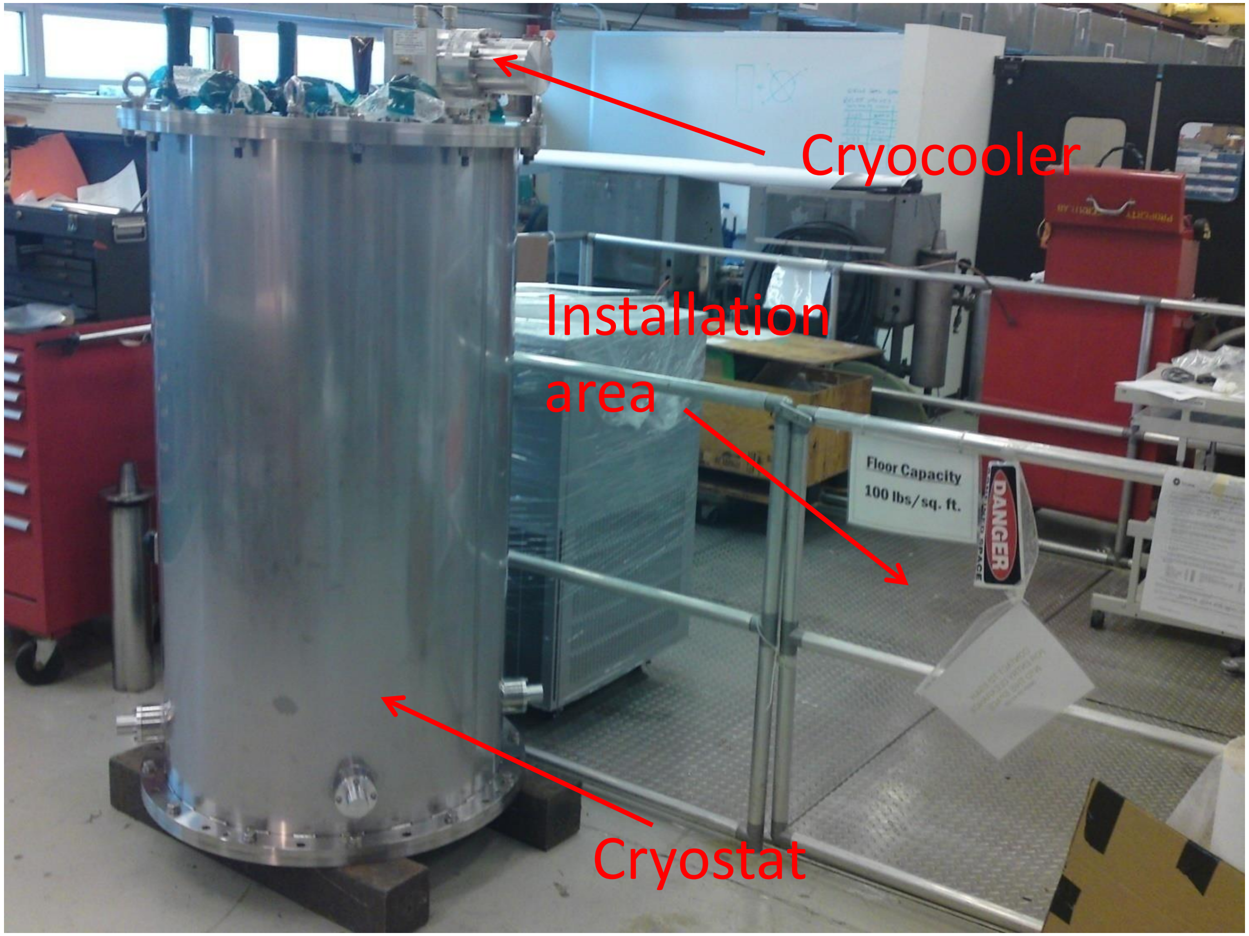
Coil temperature rise due to background heat load when compressor was turned off with magnet powered at fixed currents.



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



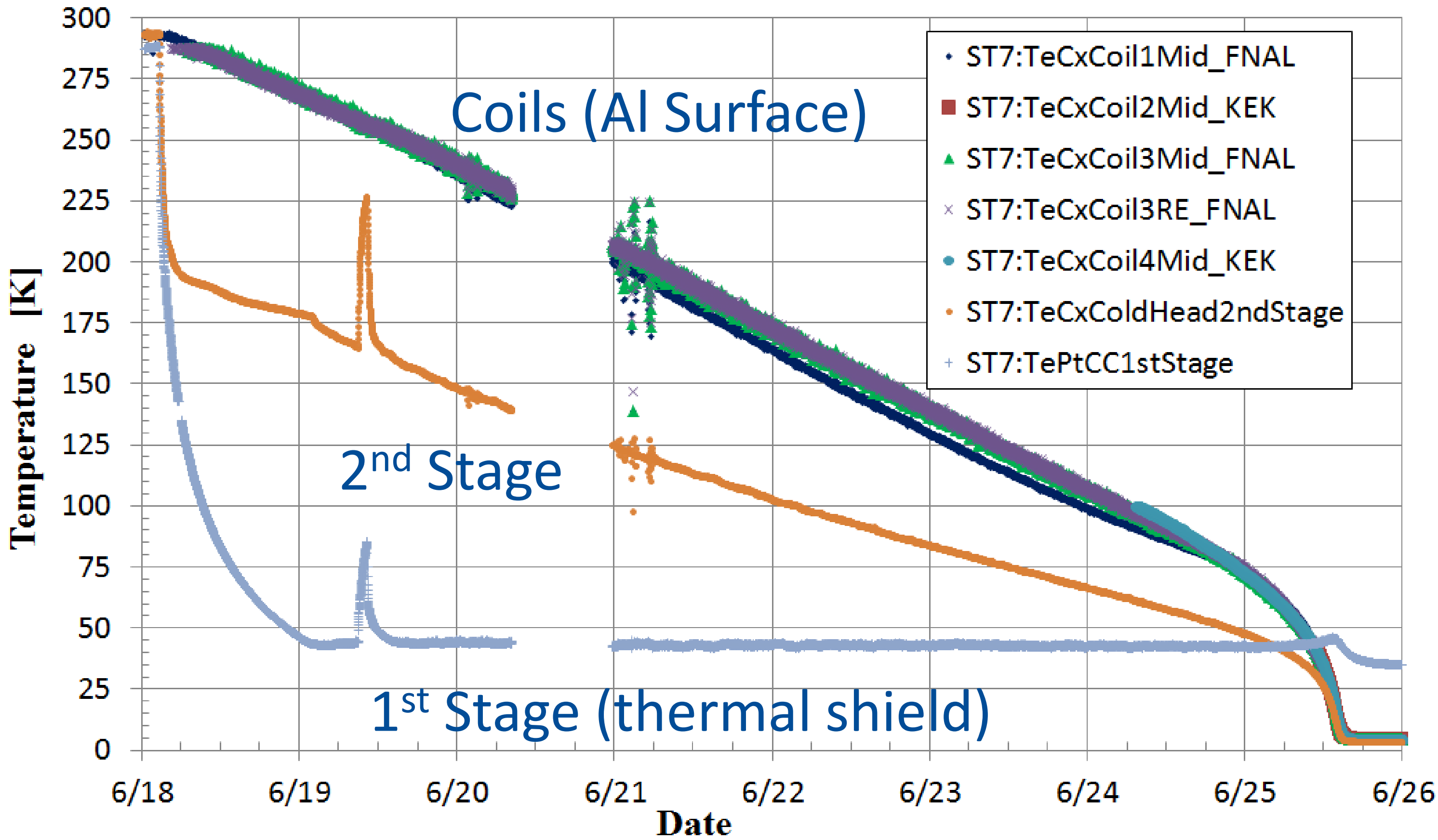
The KEK cryostat with cryocooler and ILC magnet inside was shipped at FNAL and will be allocated in this area pit.

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.

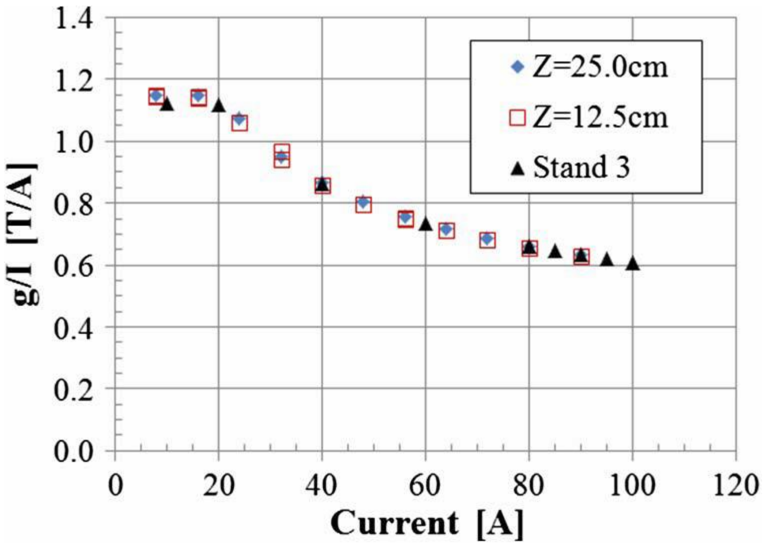
The ILC quadrupole will be tested up to the max (110 A) current combined with a high presicion magnetic measurements

First Cool Down at FNAL

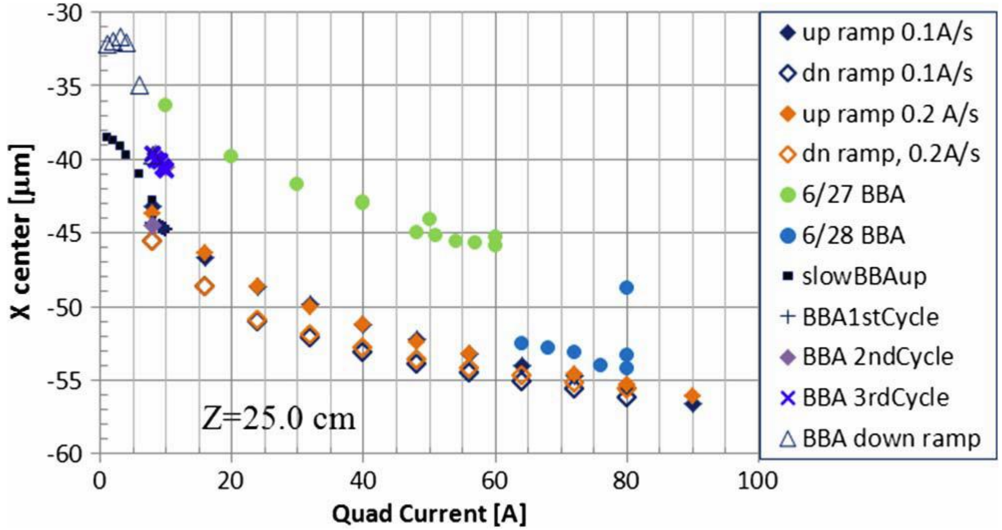


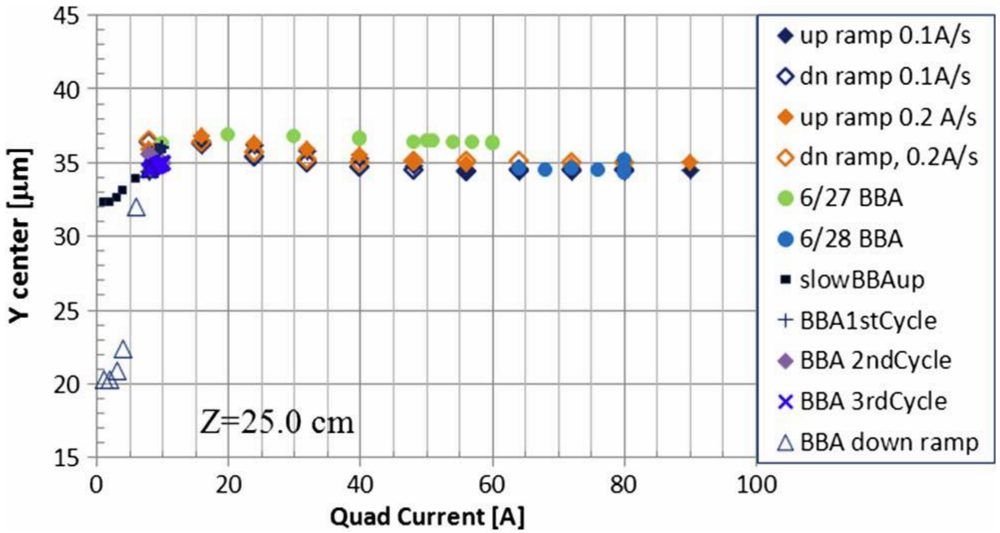
First Cool Down to 4K: 8 days, the same as at KEK.

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.

Performed Tests

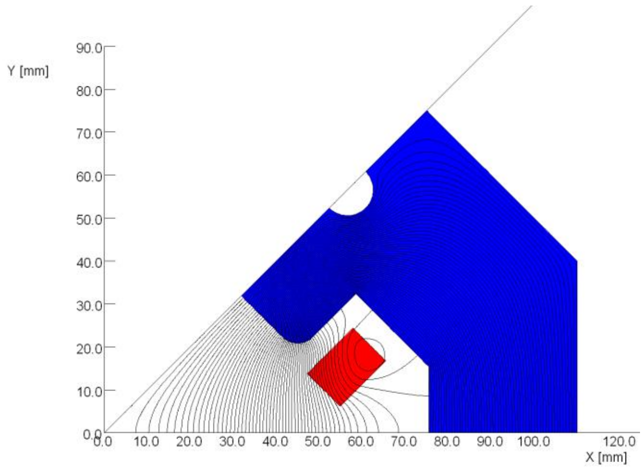
1. **The ILC magnet was tested at the new FNAL Test Stand in IB1.**
2. **Main test results:**
   - **Tested the magnet in the conduction cooling mode;**
   - **Investigated the performance up to the 110 A;**
   - **Repeated the high precision magnetic measurements.**

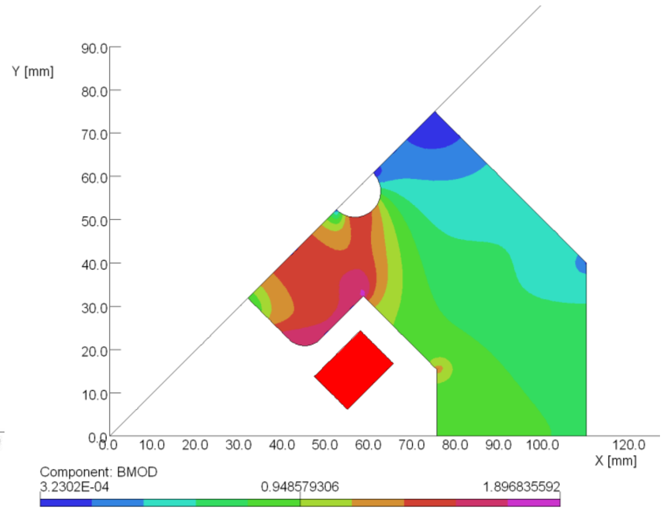
- The most critical design and fabrication issue for ILC quadrupoles is the 5 micron level of magnetic center stability which only could be verified by very high precision magnetic measurements.

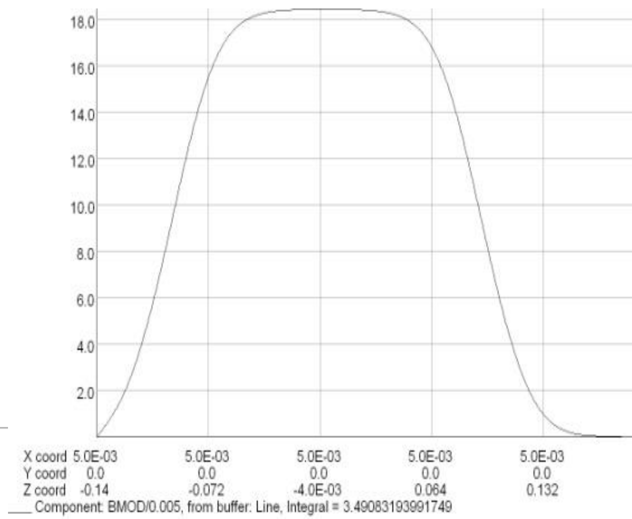
Magnet Package for KEK #CM 1

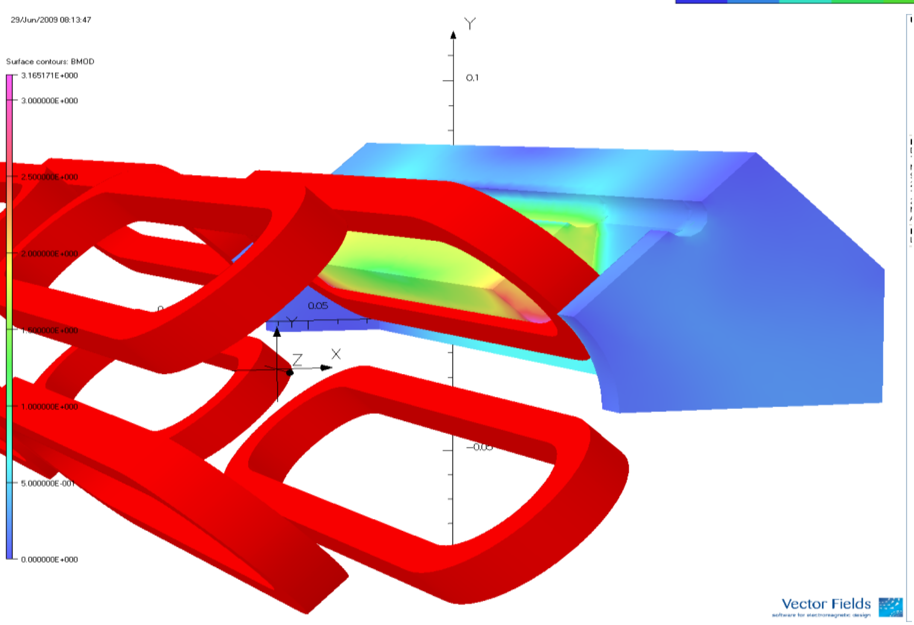
1. The first KEK Cryomodule will be assembled and tested in January 2014.
2. Akira Yamamoto proposed that FNAL built the quadrupole magnet for this Cryomodule.
3. Because the slot space is short it was decided to use one Quadrupole from the ASTA Splittable Quadrupole Doublet.
4. Such approach will save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

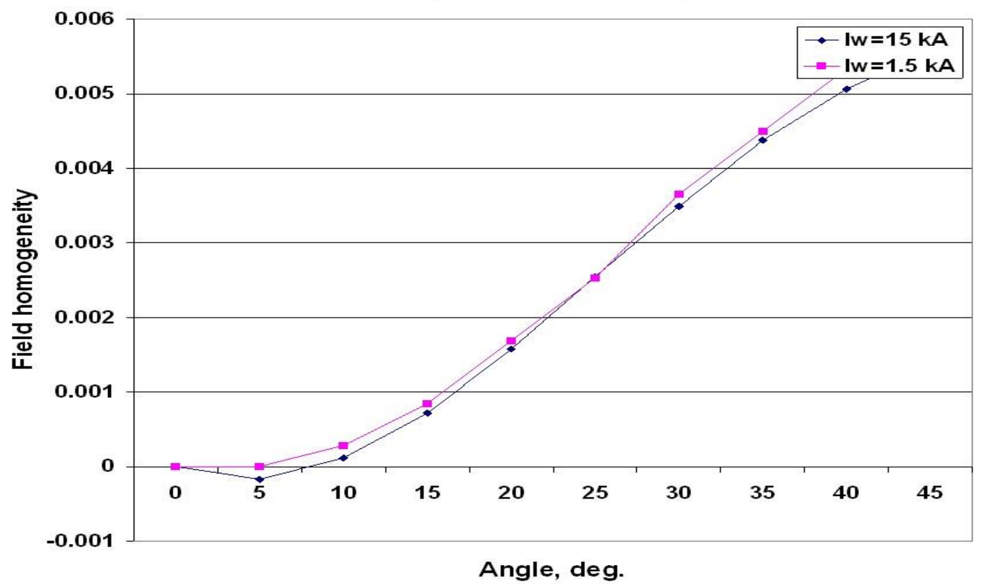
ASTA Quadrupole Doublet Magnetic Design





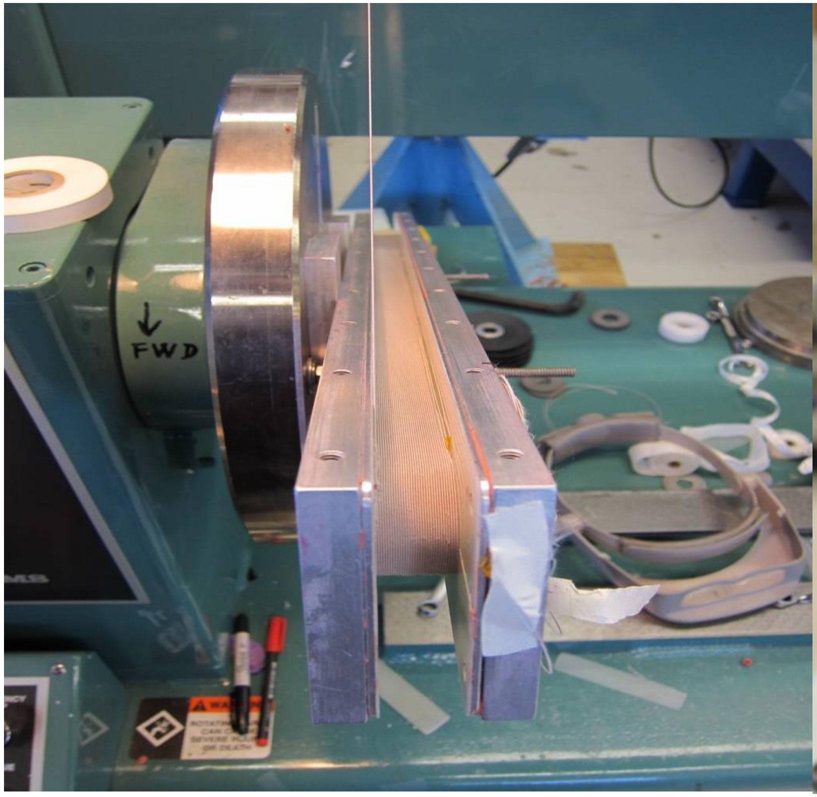


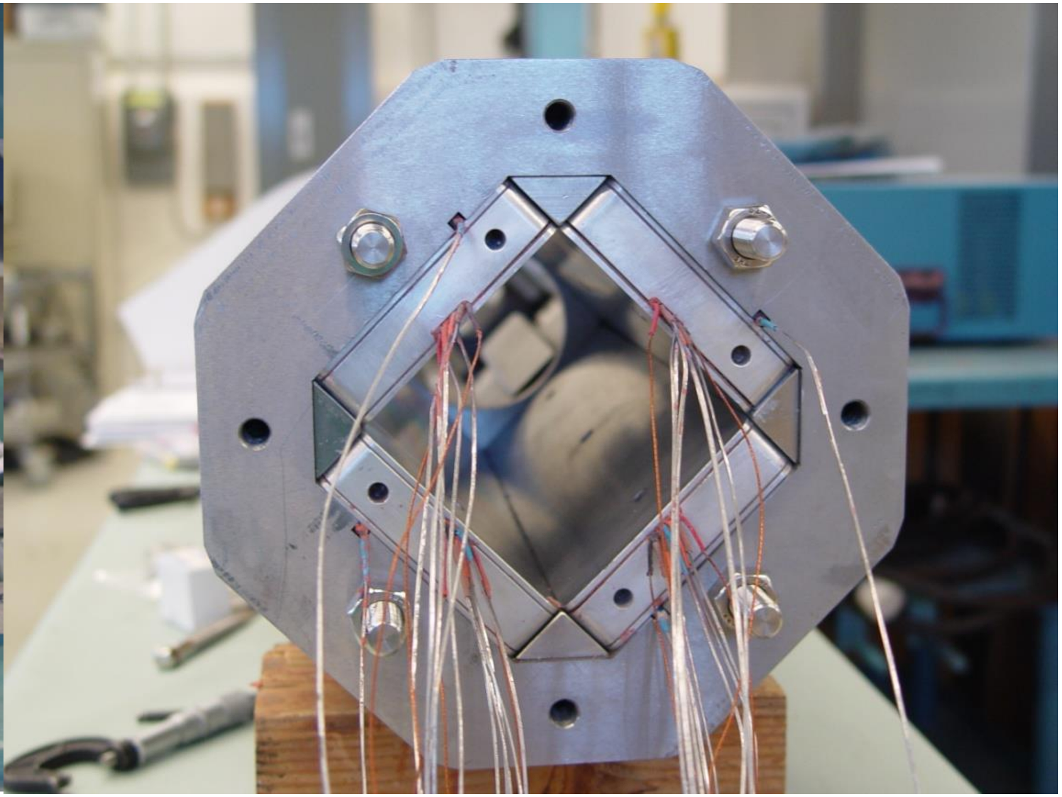




Integrated field homogeneity at 10 mm radius 0.6%, at 5 mm 0.18% (Spec. 0.5% at 5 mm).

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.

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FNAL ASTA Quadrupole Doublet for #CM3

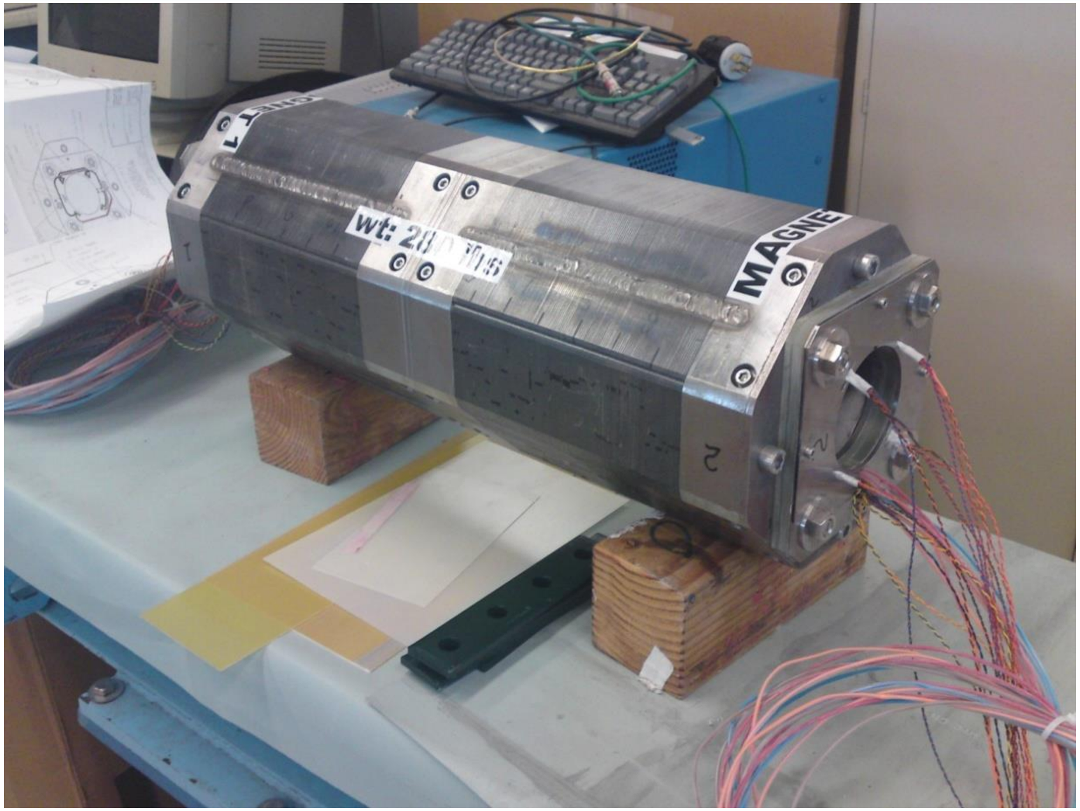
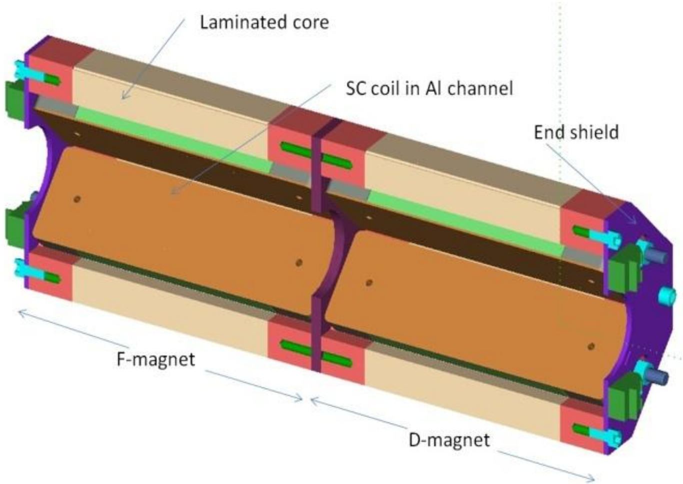


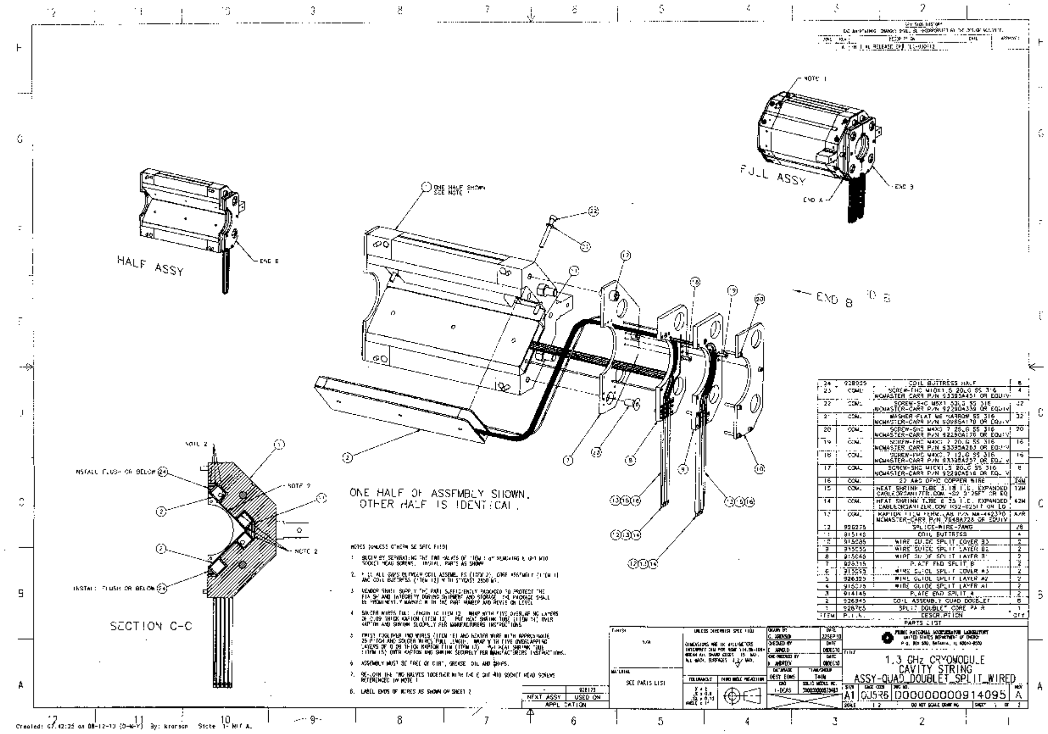
Table 1. Quadrupole Doublet Parameters

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 and are waiting for the test at IB1 Stand 3. They will operate in the bath cooling mode.

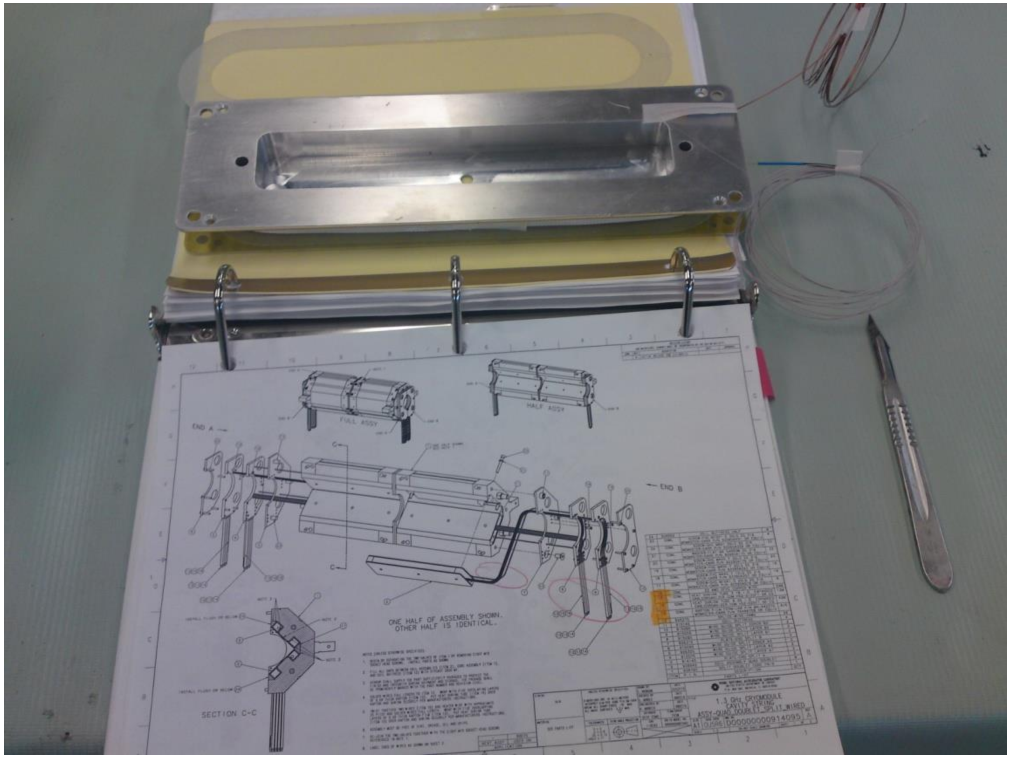
New Magnet for KEK #CM1





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.

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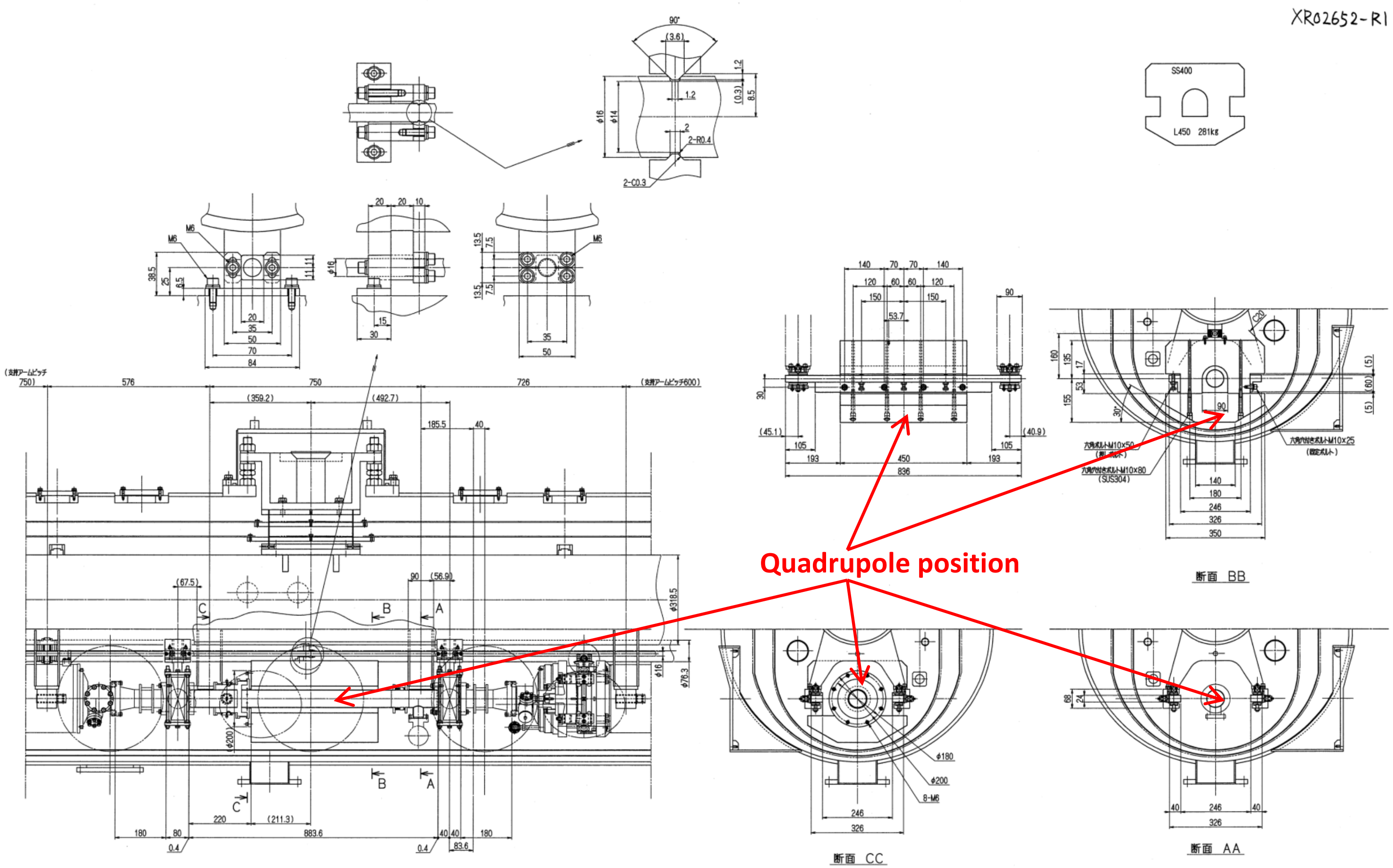
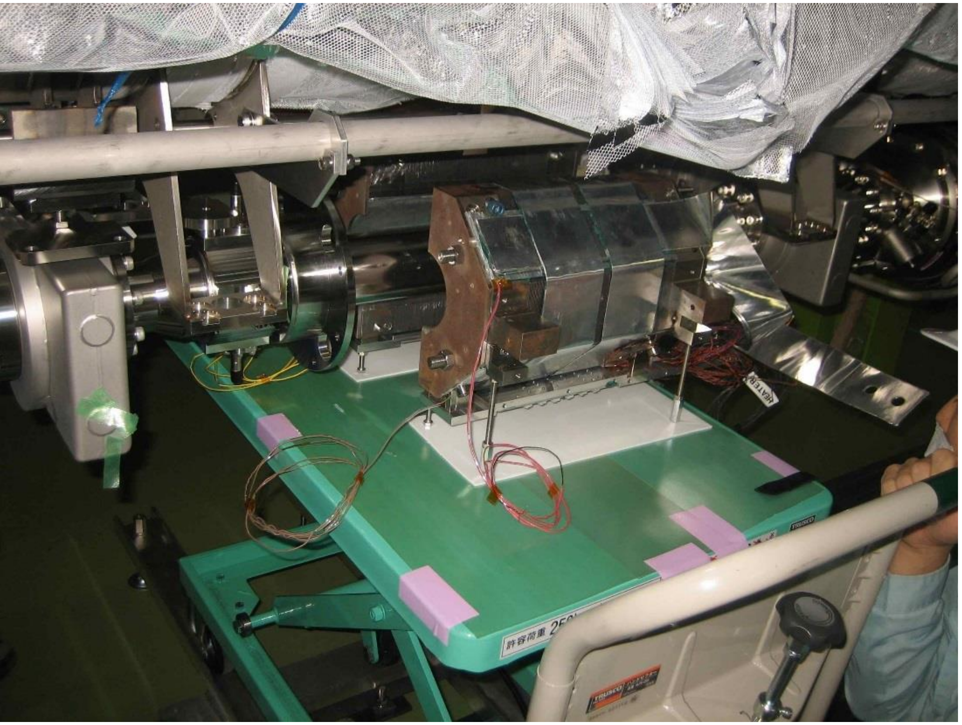
Quadrupole Integration with KEK #CM1

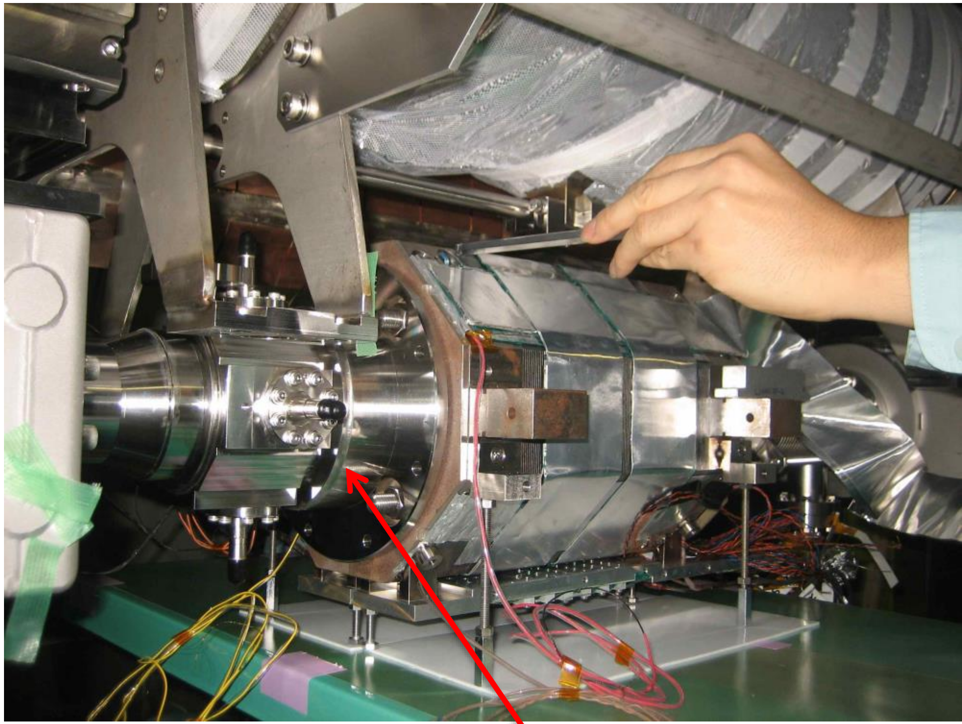


Magnet length should be less than 450mm,
Beam pipe aperture can be negotiable.
Current BPM design use 84mm outer diameter of chamber.
However BPM need to redesign its chamber outer diameter, not cavity part.

H. Hayano

Quadrupole Assembly around Beam Pipe

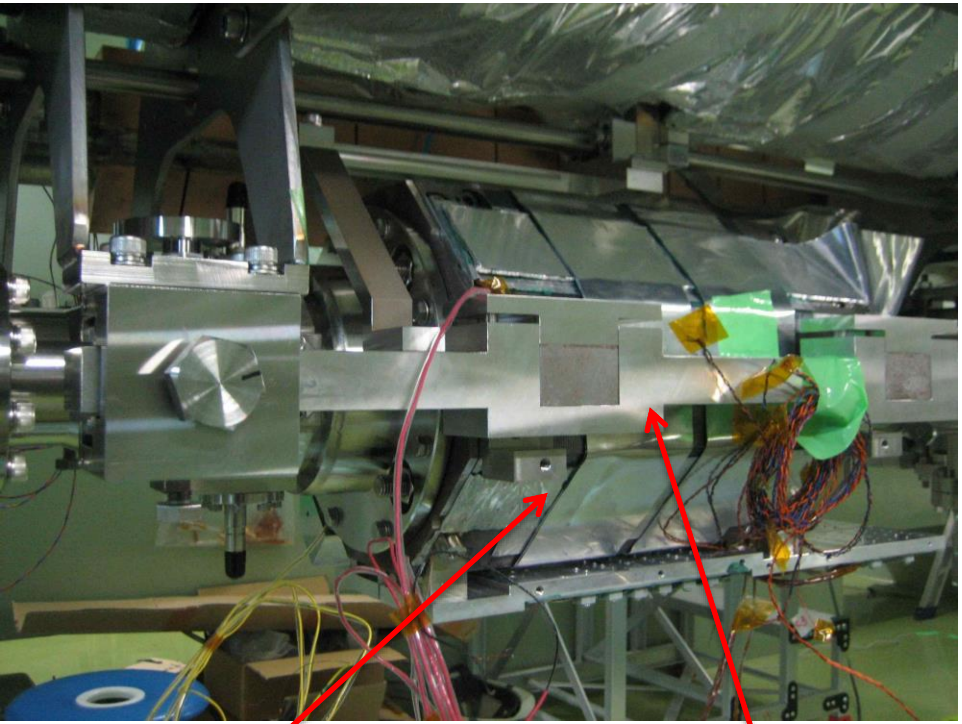


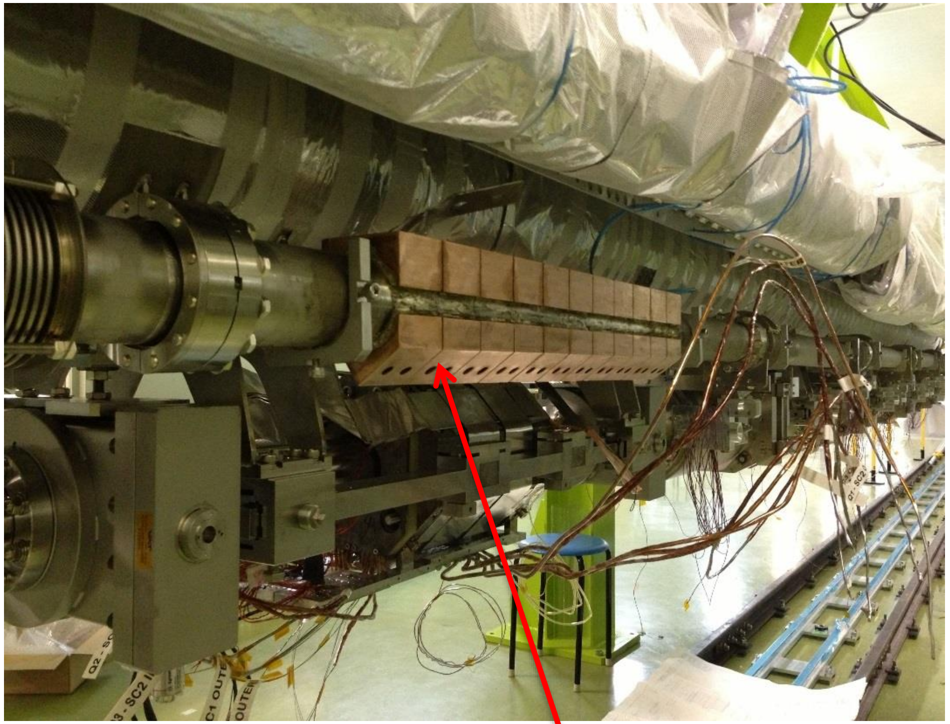


BPM

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.*

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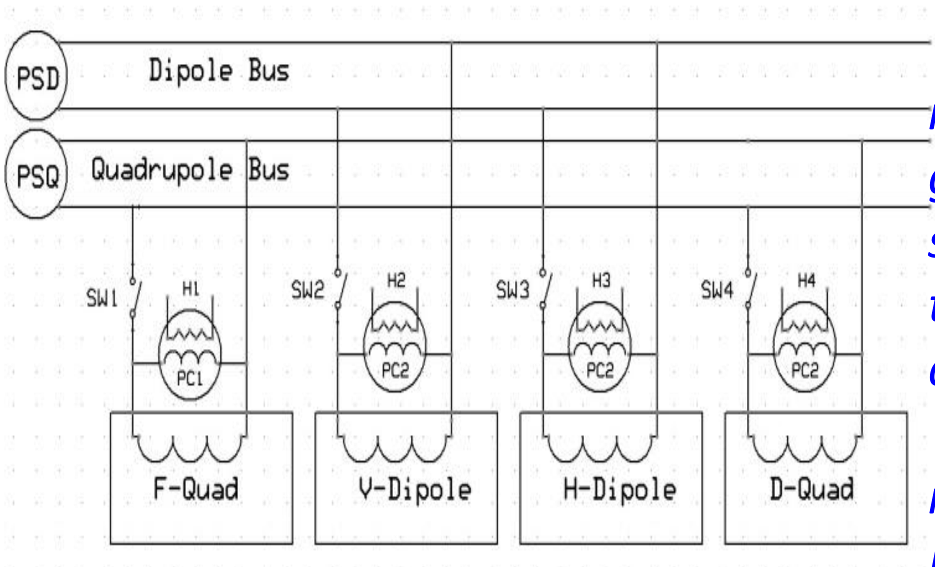
Integrated Magnet System Scheme



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.

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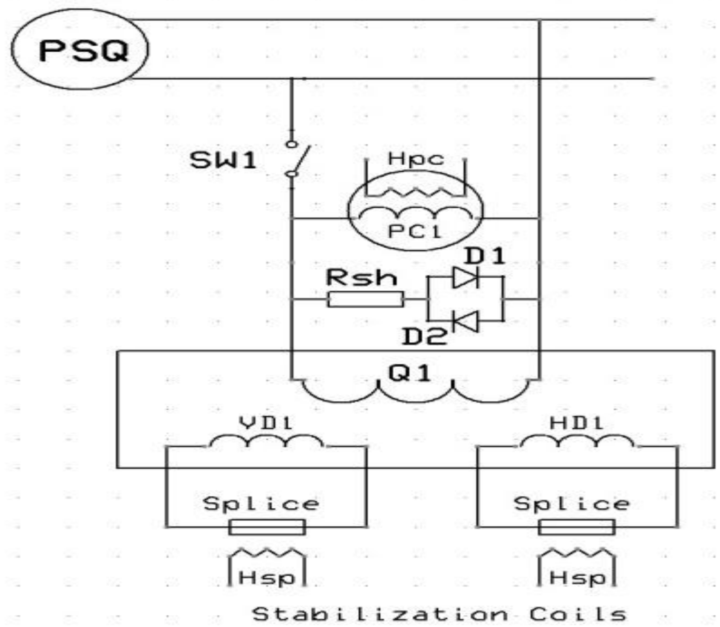
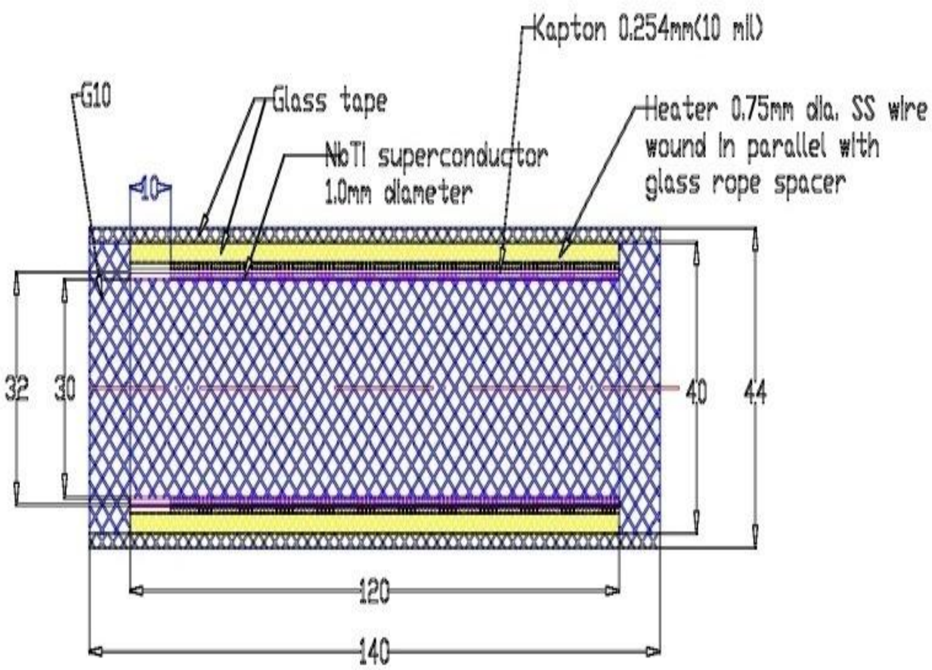
Single Cell Quadrupole Magnet Scheme



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.

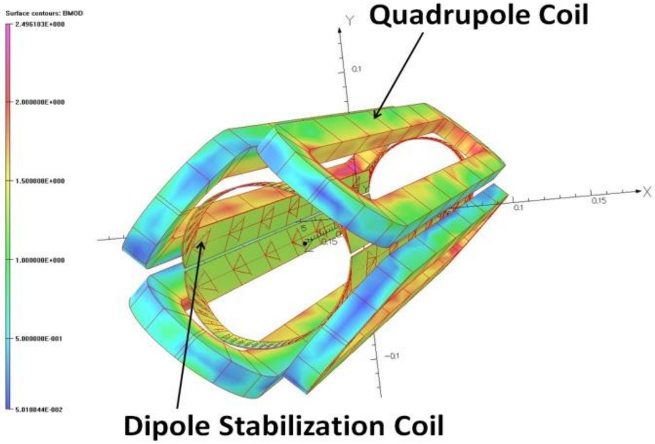
Persistent Current Switch



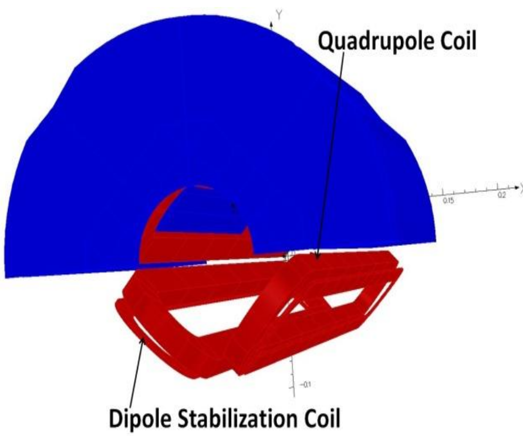
Parameter	Unit	Value
Peak operating current	A	150
SC coil resistance at 20 °C	Ω	7.8
Heater resistance	Ω	23.5
NbTi wire diameter	mm	1.0
Superconductor stabilization material		CuNi
Stainless steel heater wire diameter	mm	0.75
Heater current	A	0.5
Switch performance at 100 A SC current, and (0.5 A, 3 s) 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

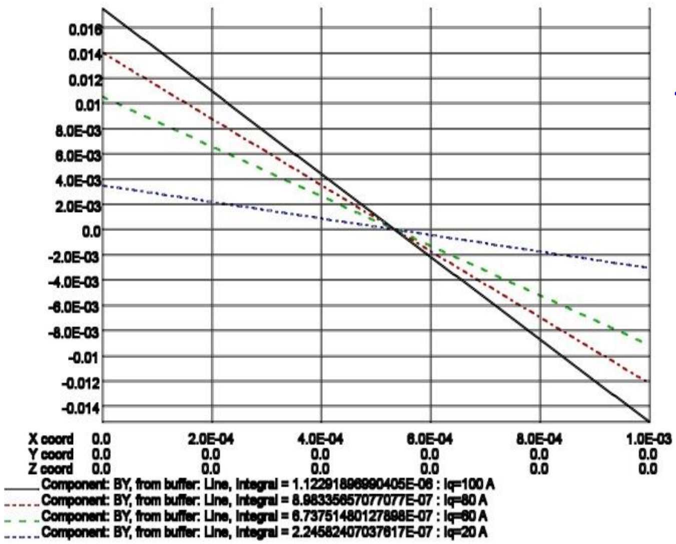
D. Turrioni from FNAL successfully tested 2 switches. No quenches were observed up to 150 A current

Stabilization Coil Simulation

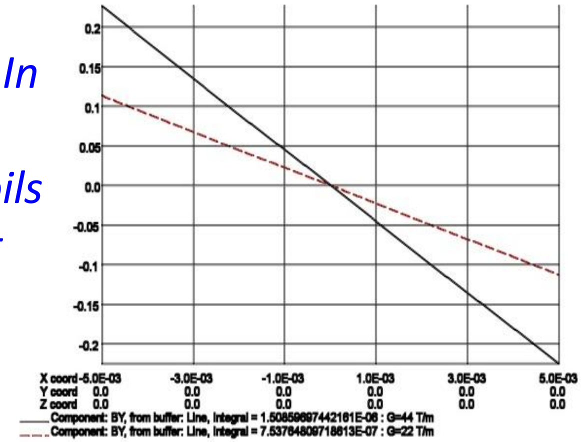


Figures show that the quadrupole magnetic center is very stable at quadrupole currents 20 ÷100 A. The dipole winding consists of two shell type coils having 74 turns each. In this coils at 1 mm dipole center shift relatively the quadrupole winding at 100 A in the quadrupole was induced stabilization 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 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.*

LCLS-II

LCLS-II Cryomodule Magnet Package

SLAC NATIONAL ACCELERATOR LABORATORY

BERKELEY LAB Lawrence Berkeley National Laboratory

Argonne NATIONAL LABORATORY

CORNELL UNIVERSITY FOUNDED A.D. 1865

Fermilab

Jefferson Lab

U.S. DEPARTMENT OF ENERGY Office of Science

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

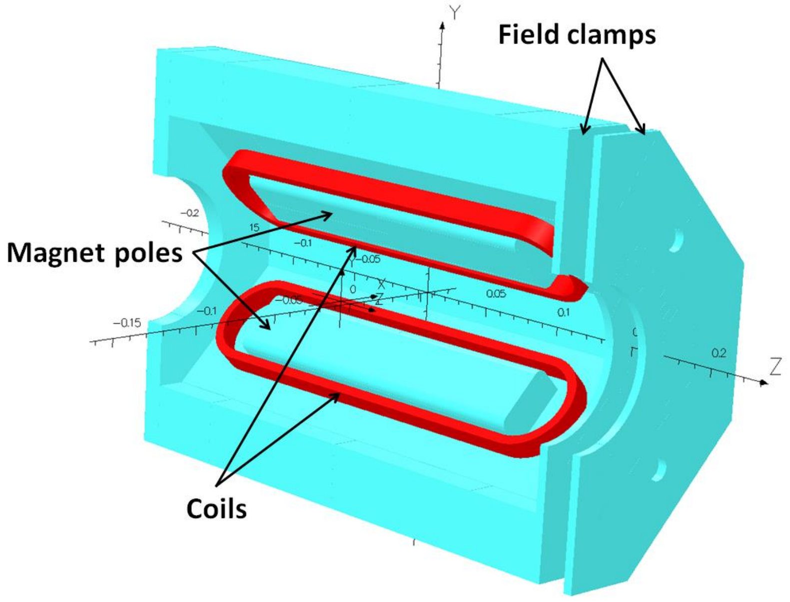
- The Magnet Package contains a quadrupole and two built-in dipole correctors.
- The quadrupole integrated gradient is 0.064 T – 2.0 T. Integrated field quadrupole harmonics at 10 mm radius are: $b2/b1 < 0.01$, $b5/b1 < 0.01$. The dipole integrated field is 0.005 T-m.
- The electron beam energy linearly 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 where by 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

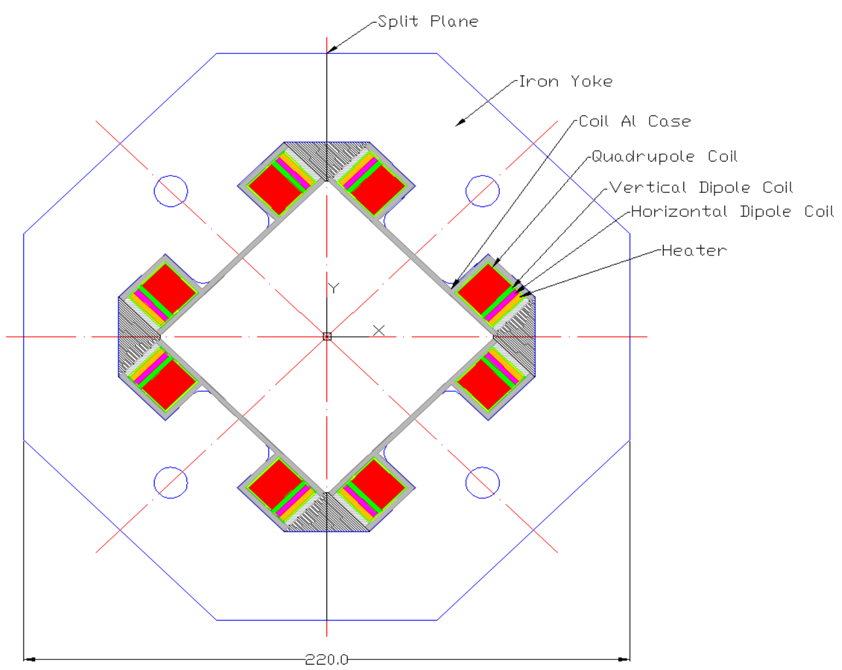
Parameter	Unit	Value
Integrated peak gradient at 10 GeV	T	2.0
Integrated minimal gradient at 0.4 GeV	T	0.064
Aperture	mm	78
Magnet effective length	mm	230
Peak gradient	T/m	8.7
Quadrupole field non-linearity at 10 mm		<0.01
Dipole trim coils integrated strength	T-m	0.005
Magnetic center offset in the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

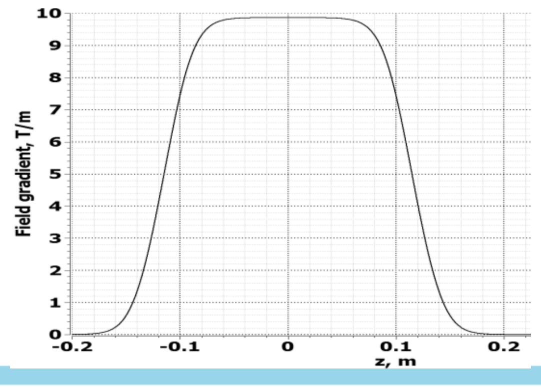
The magnet should have a splittable, and conduction cooling (cryogen free) configuration as specified in the signed and approved Cryomodule Magnet ESD LCLSII-4.5-ES-0355-R0.

Magnet Package Magnetic Design



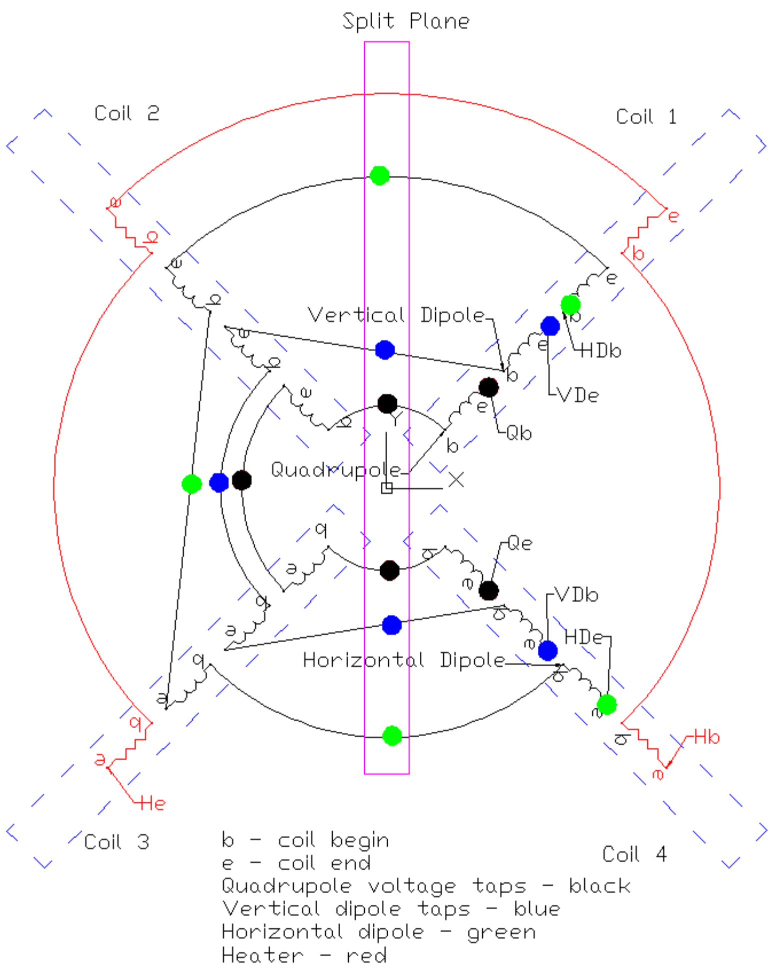
Half of the magnet





- *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 superconducting coil splices between two halves of the magnet mounted on the Al magnet bottom plate.*

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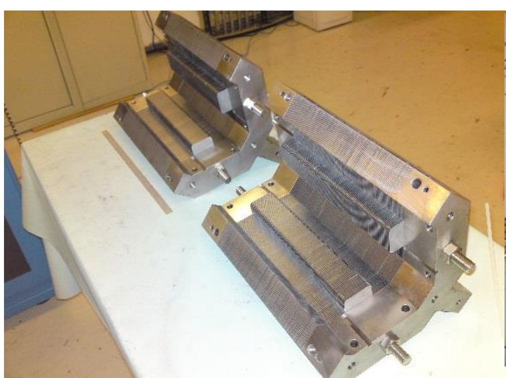
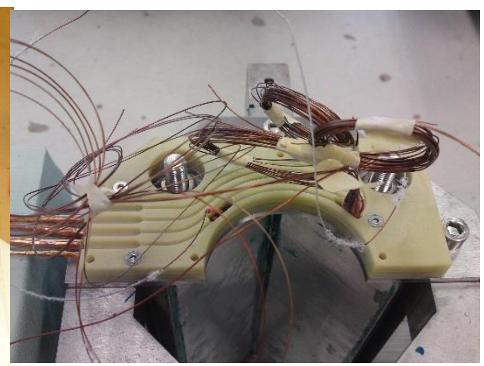
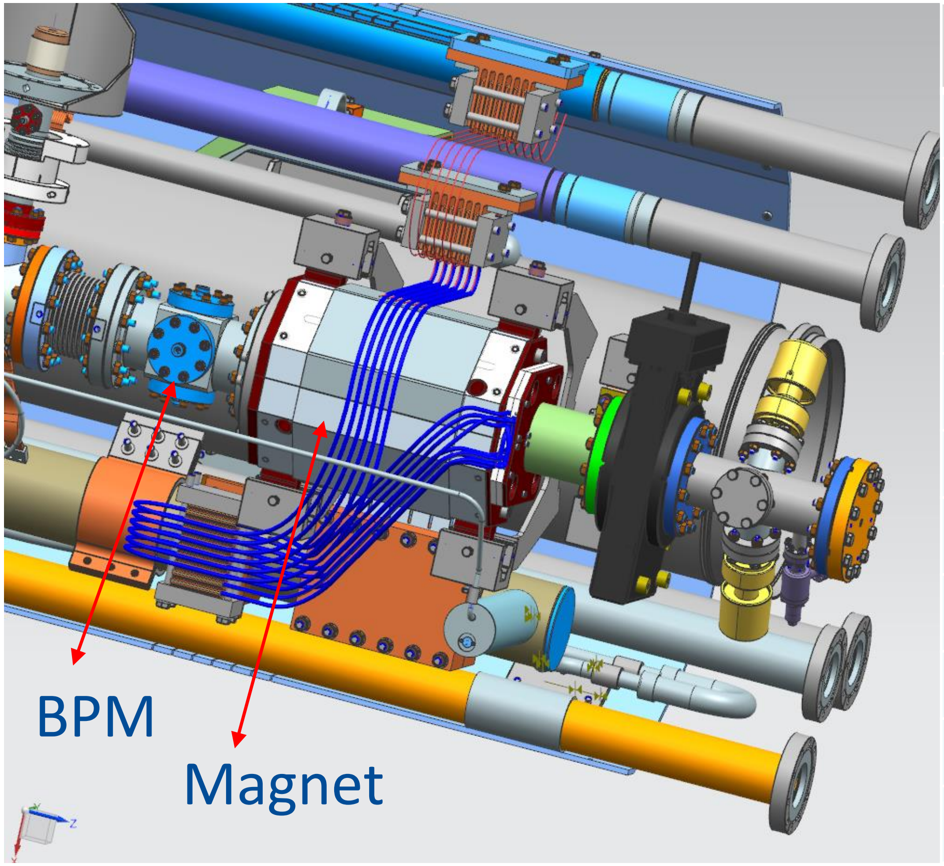
Magnet Package Pre-Prototype Fabrication





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.

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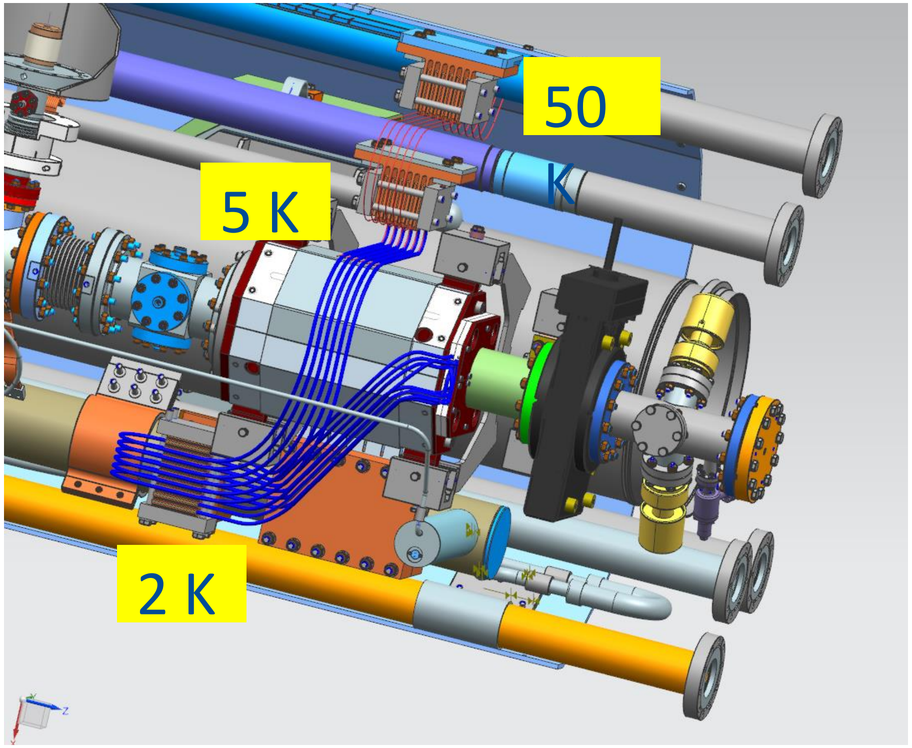
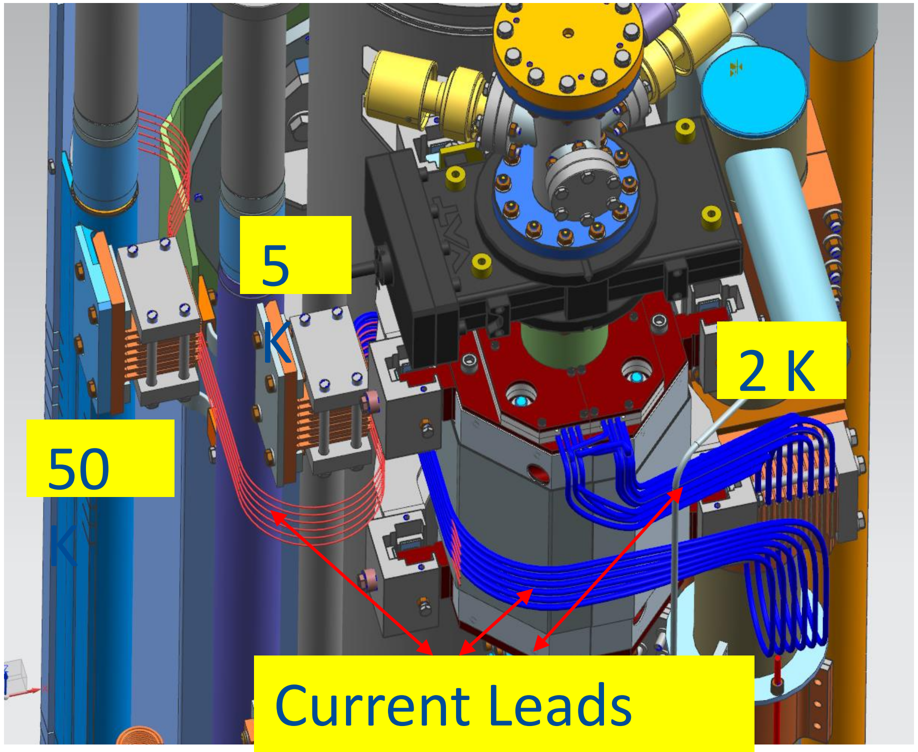
Magnet Package Current Leads





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.

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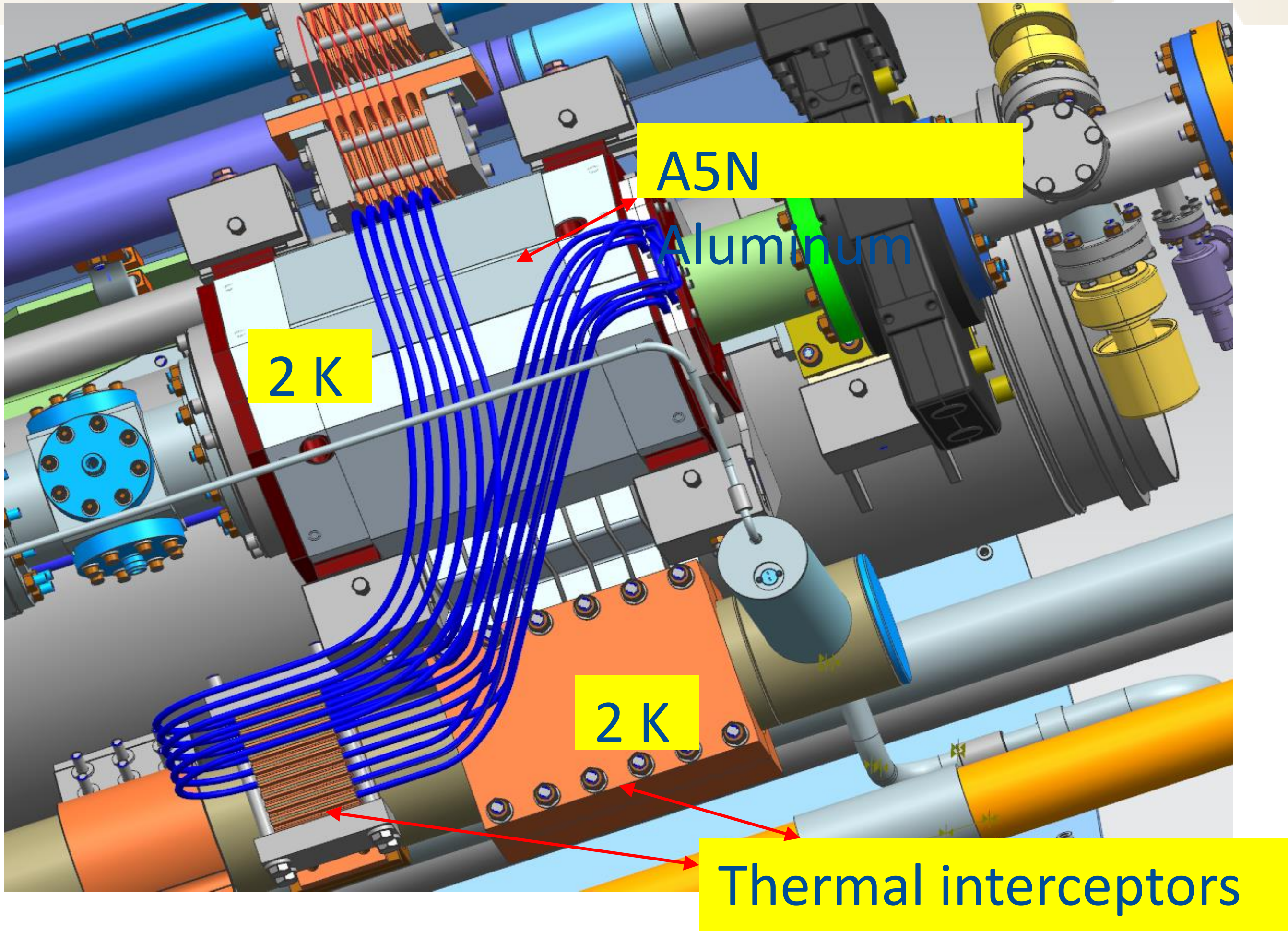
Magnet Coils and Yoke Cooling



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

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.

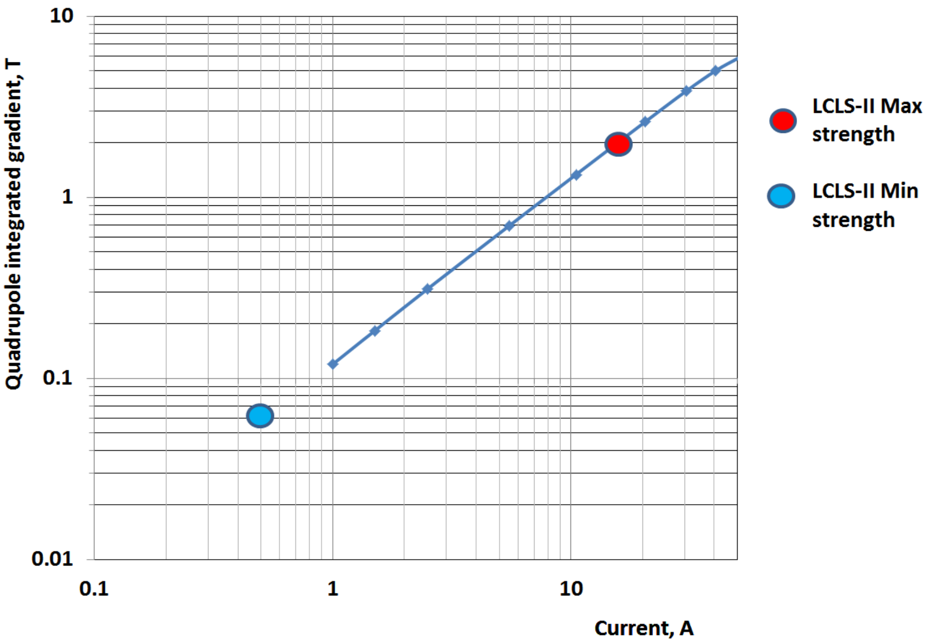
3) Detailed integral magnetic field quality measurements using a rotating coil probe, starting at low current and increasing the current to study iron and superconductor magnetization effects up to 10 A.

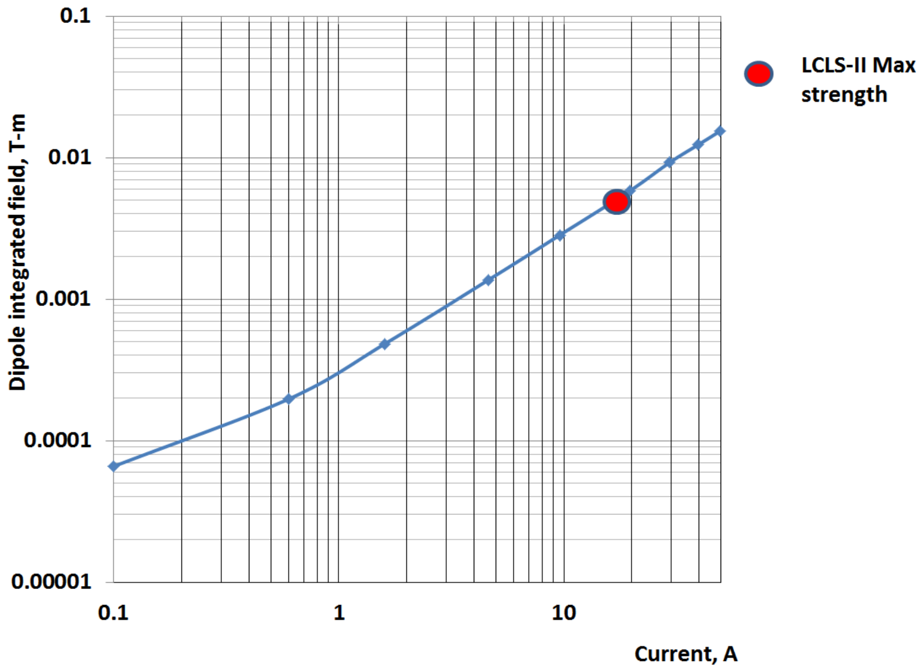
4) Quench performance of all three windings to 30 A (50% above the maximum operating current).

5) Additional magnetic measurements up to 30 A.

6) Warm magnetic axis alignment and fiducialization.

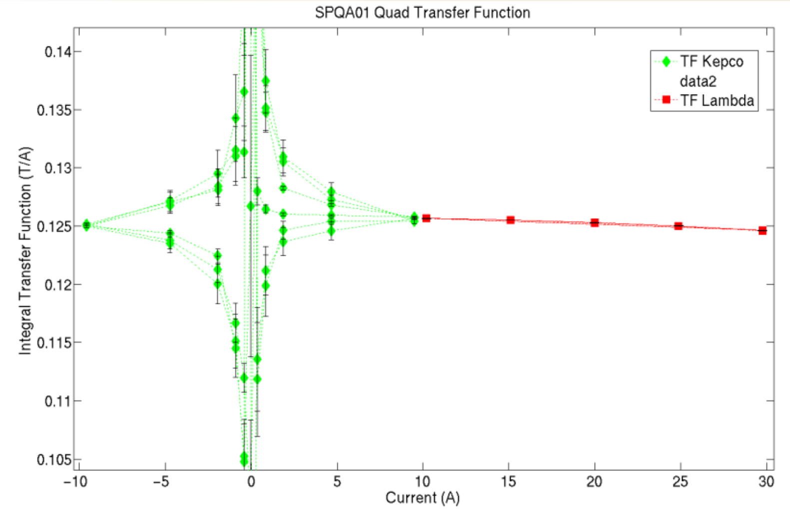
Quadrupole and Dipole Magnets Strength

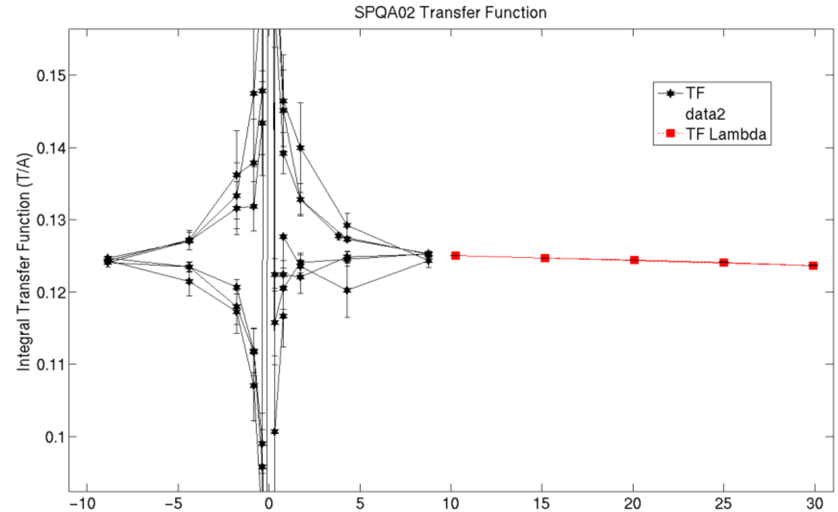




- *Only one quench was observed at 48.5 A during quadrupole magnet ramping up to 50 A during bath cooling test.*
- *2.0 T LCLS-II peak integrated gradient was reached at 15 A.*
- *No quench was observed during vertical and horizontal dipoles ramping up to 50 A during bath cooling test.*
- *Dipole 0.005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

Quadrupole Field Transfer Function

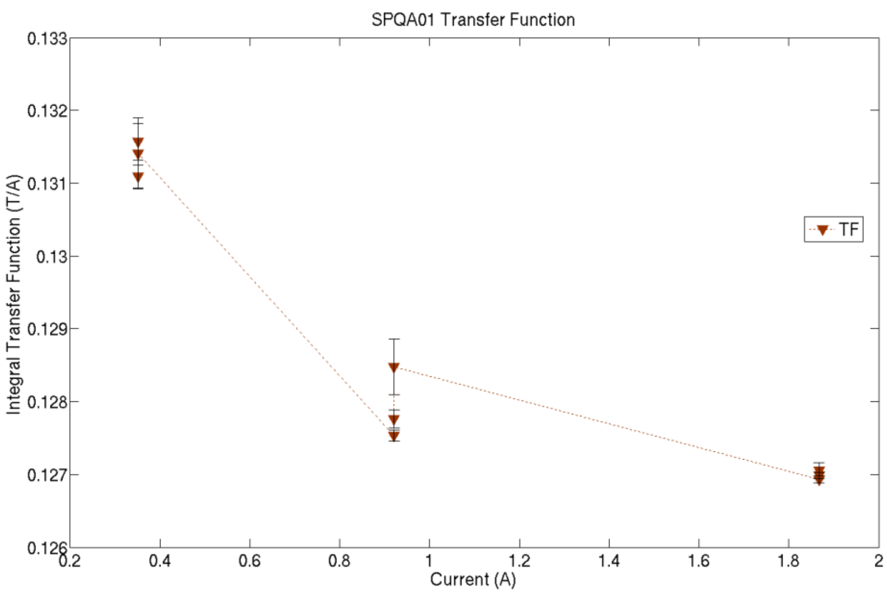


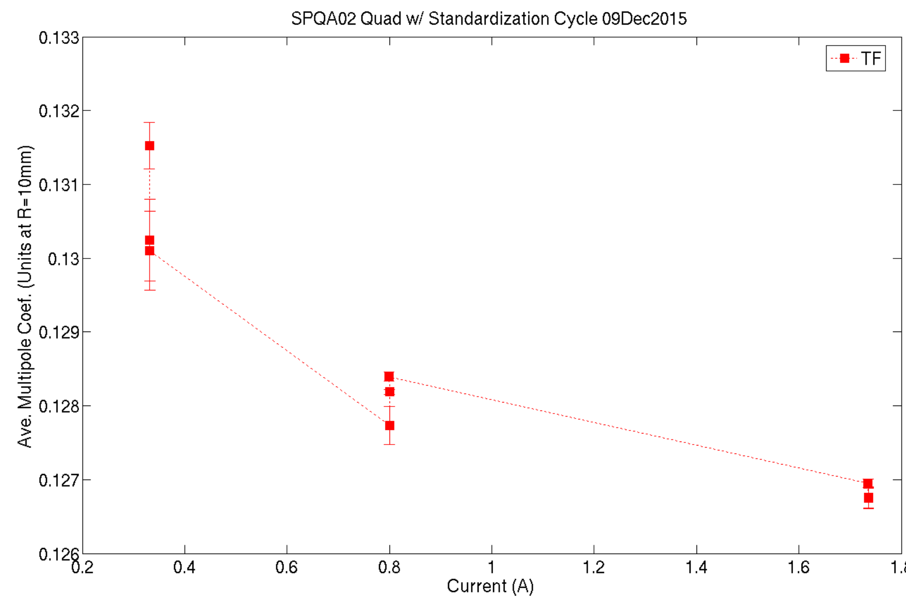


Transfer function= Magnet strength/Current (normalized to 10 A or 20 A current)

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

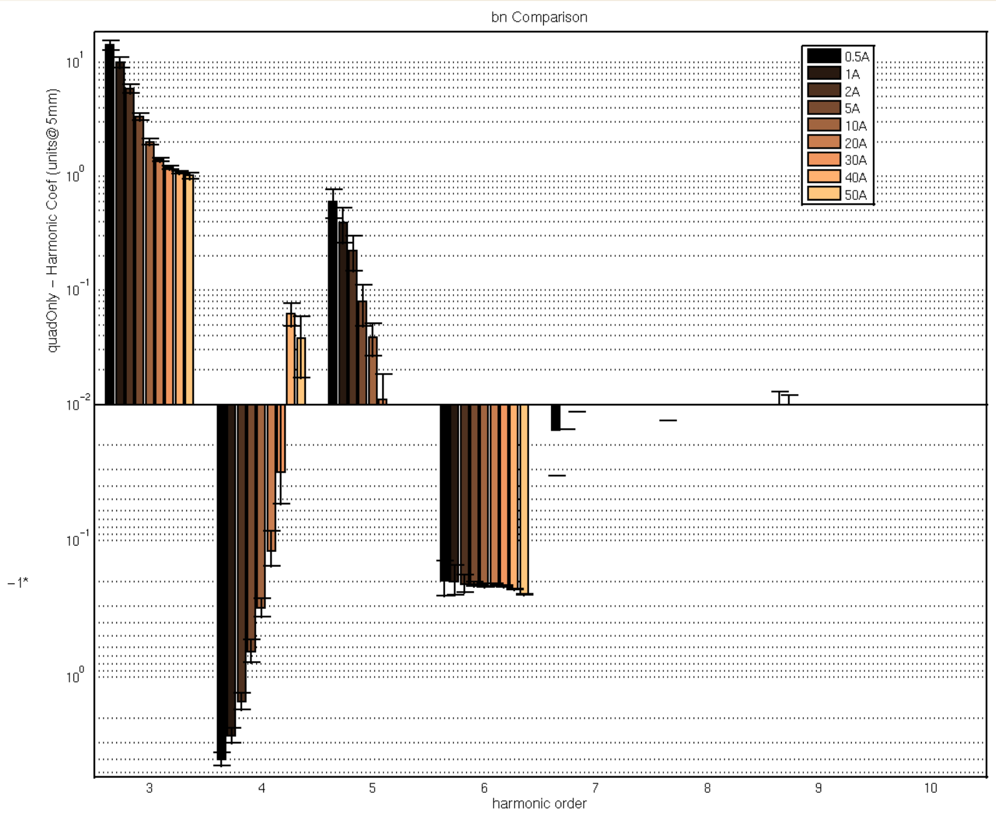




Figures show the repeatability of quadrupole TF during standardization cycles which approach the nominal current by damped current swings about the set value (e.g. the 1A position would be approached by ramping the power supply through 0, 1.6, 0.4, 1.4, 0.6, 1.2, 0.8, 1A). The reproducibility here is 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.

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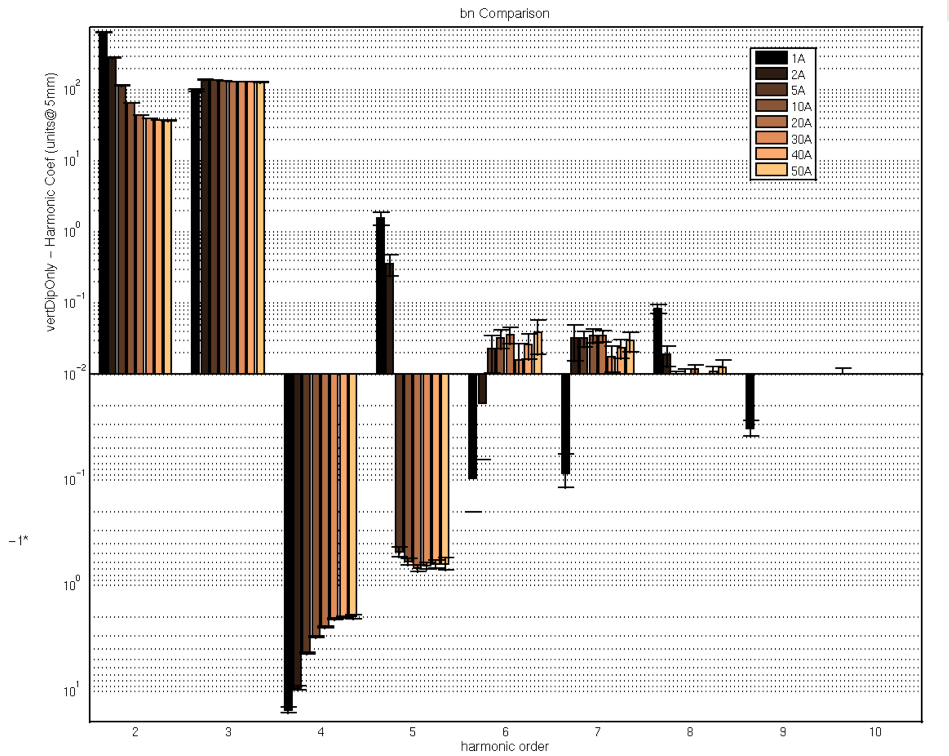
Dipole Field Harmonics

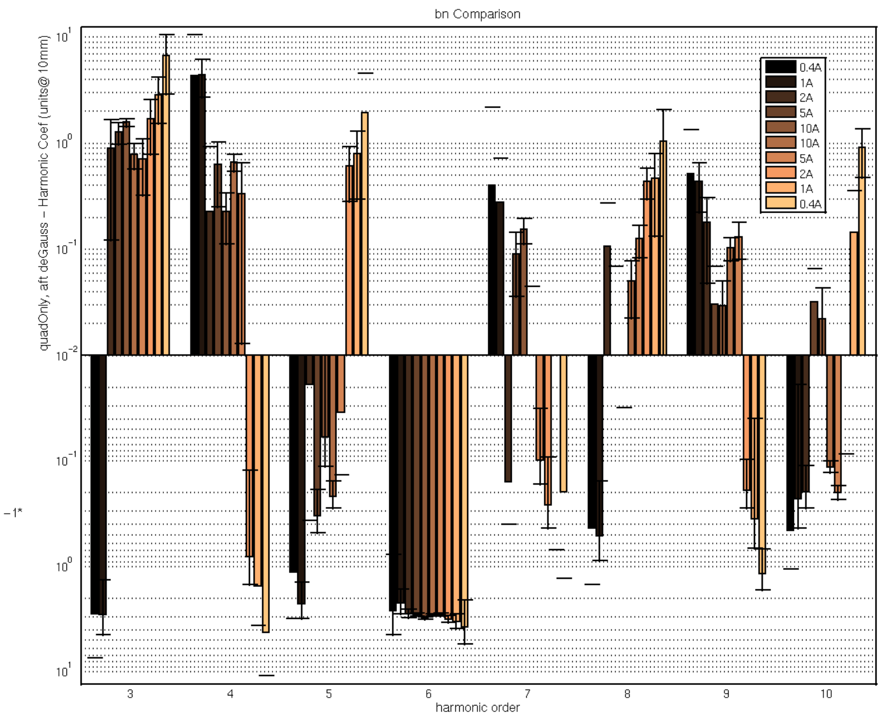


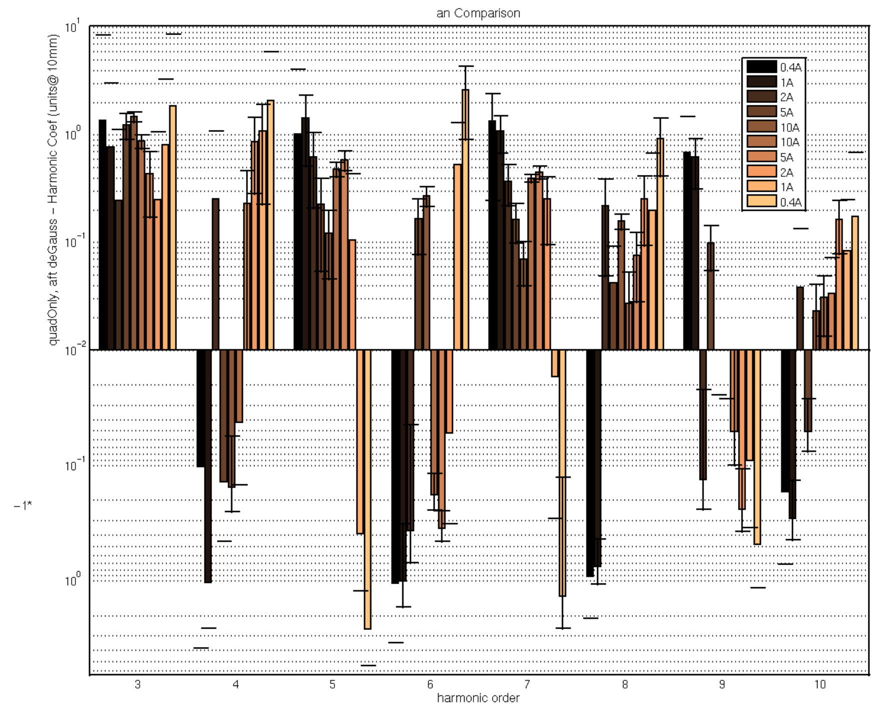
At 0.5 A : b2=600, b3=100, b4=-15, b5= 2 units (10^-4), R=5 mm

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

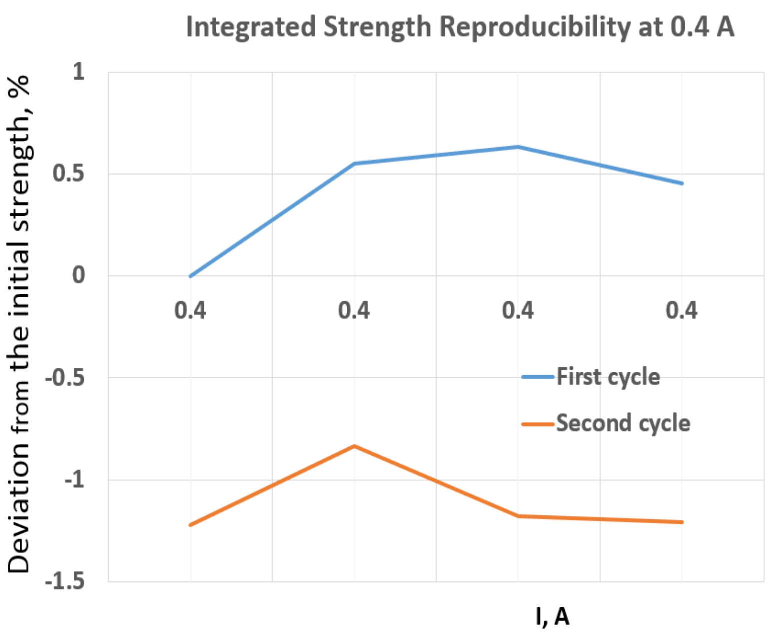
Quadrupole Geometric Harmonics

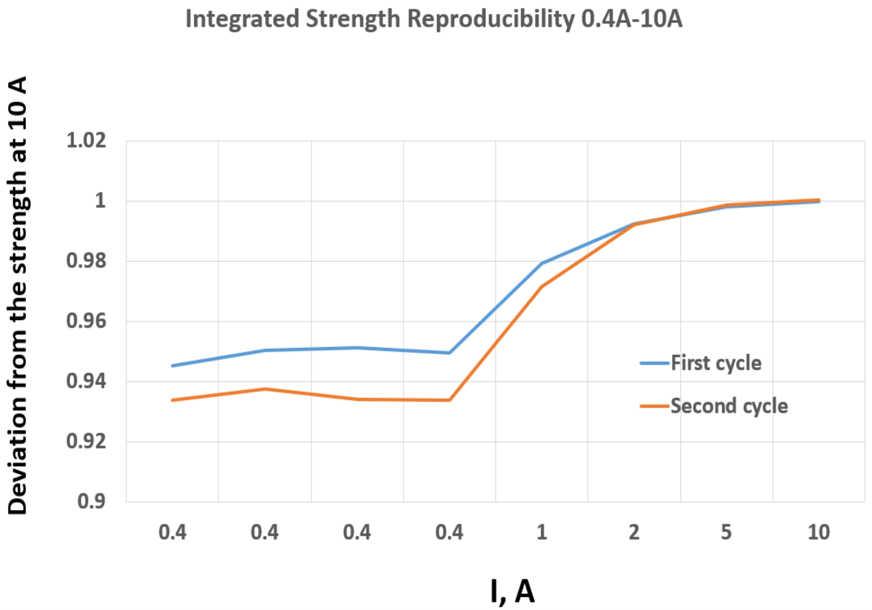




- *Geometric harmonics were determined by averaging after measurements with ramping current up from -10 A to +10 A.*
- *In this case excluded: external fields, iron and superconductor hysteresis.*
- *After the cold test magnet was tested at the room temperature at very low current 0.4 A.*
- *All harmonics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

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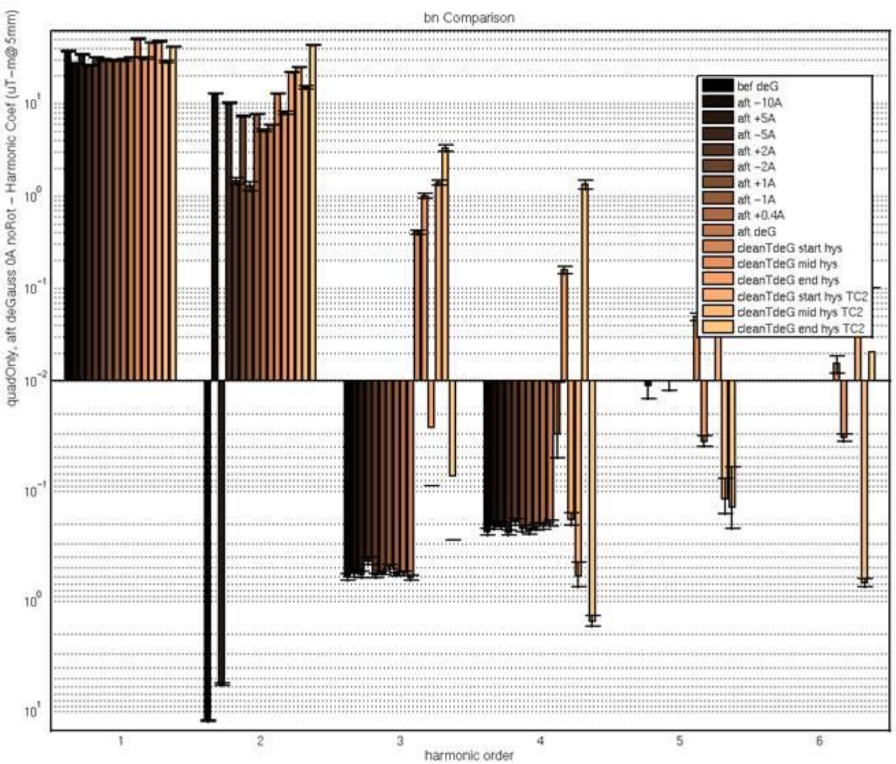
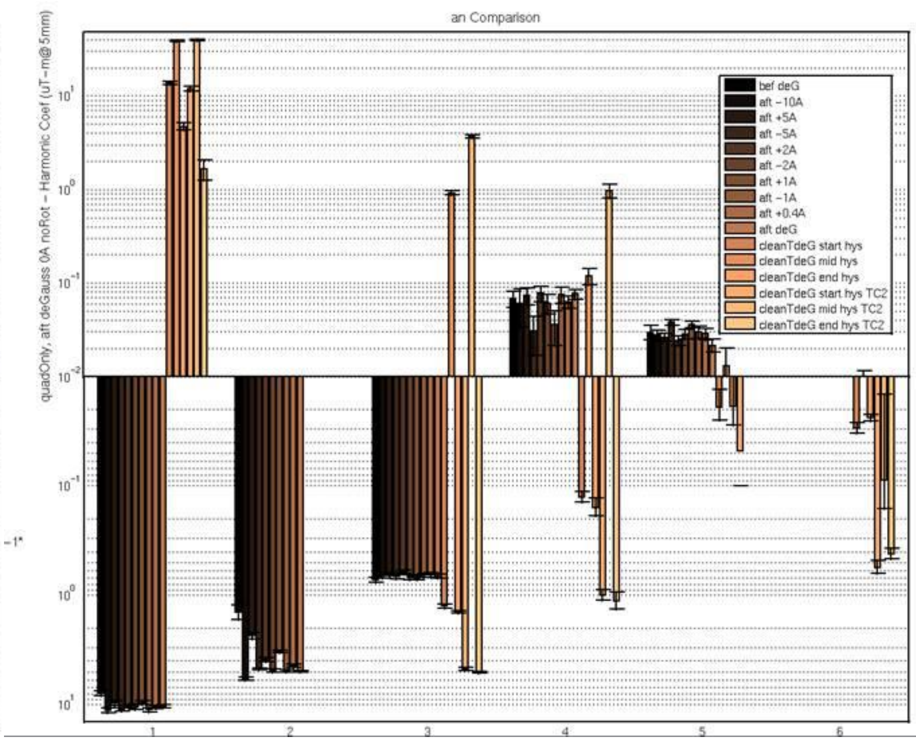
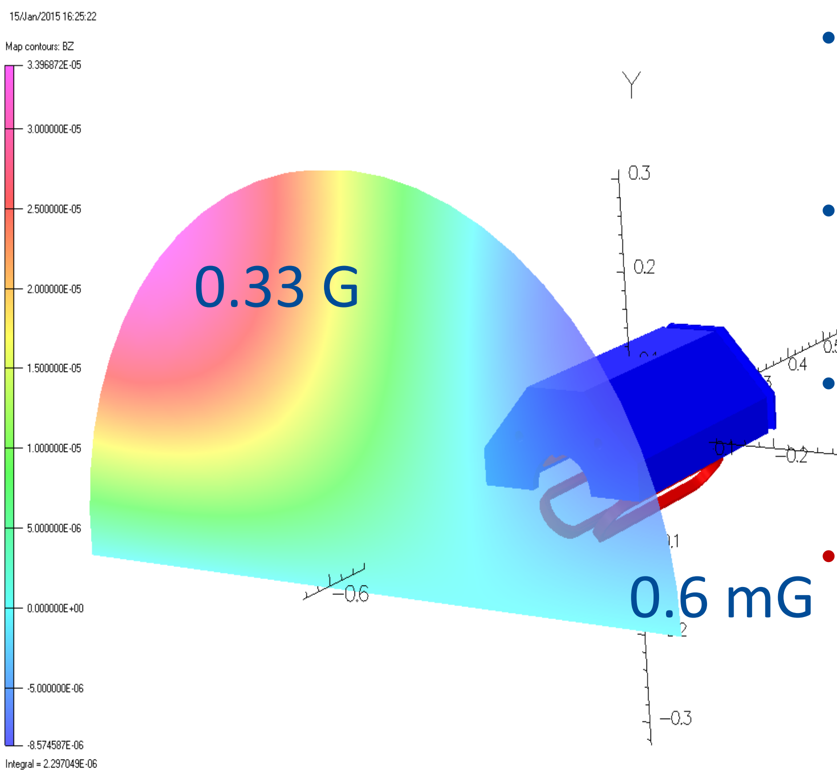
Residual Integrated Quadrupole Field at Zero Current





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.

Magnet Fringe Field at Peak Strength



- *At peak magnet 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.*

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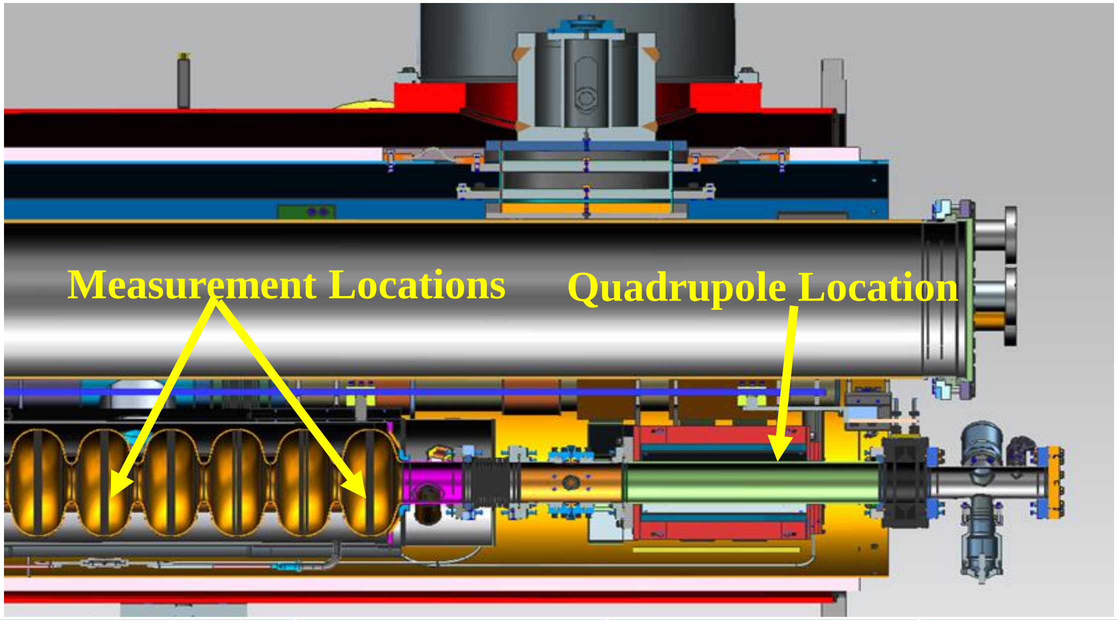
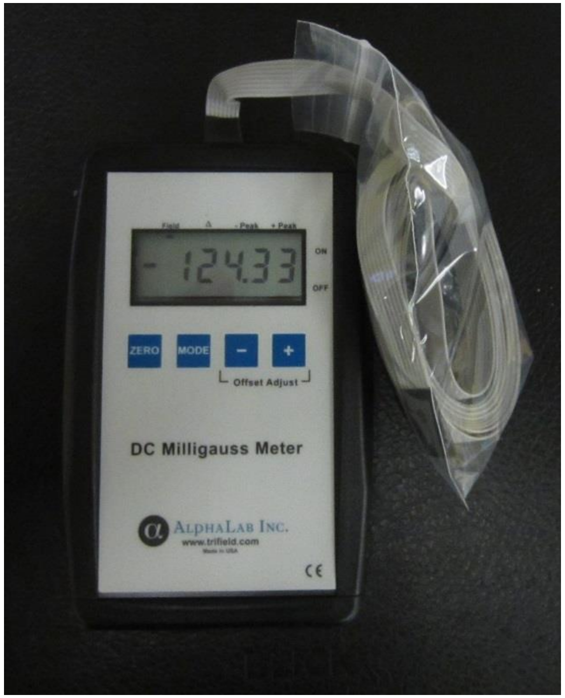
Magnetic Field inside the Cryoperm 10 Shield



	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

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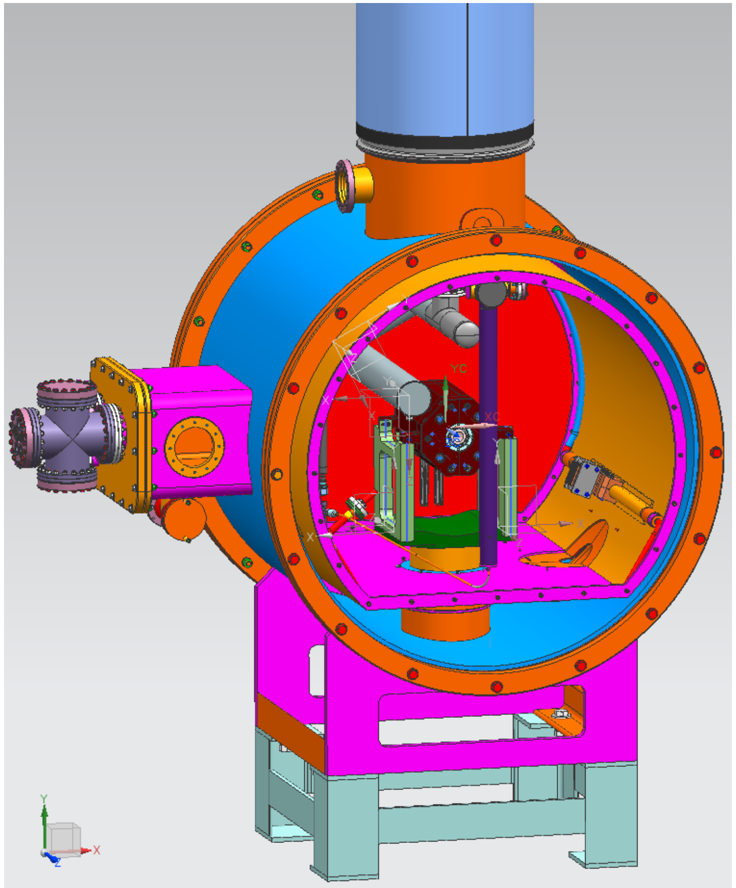
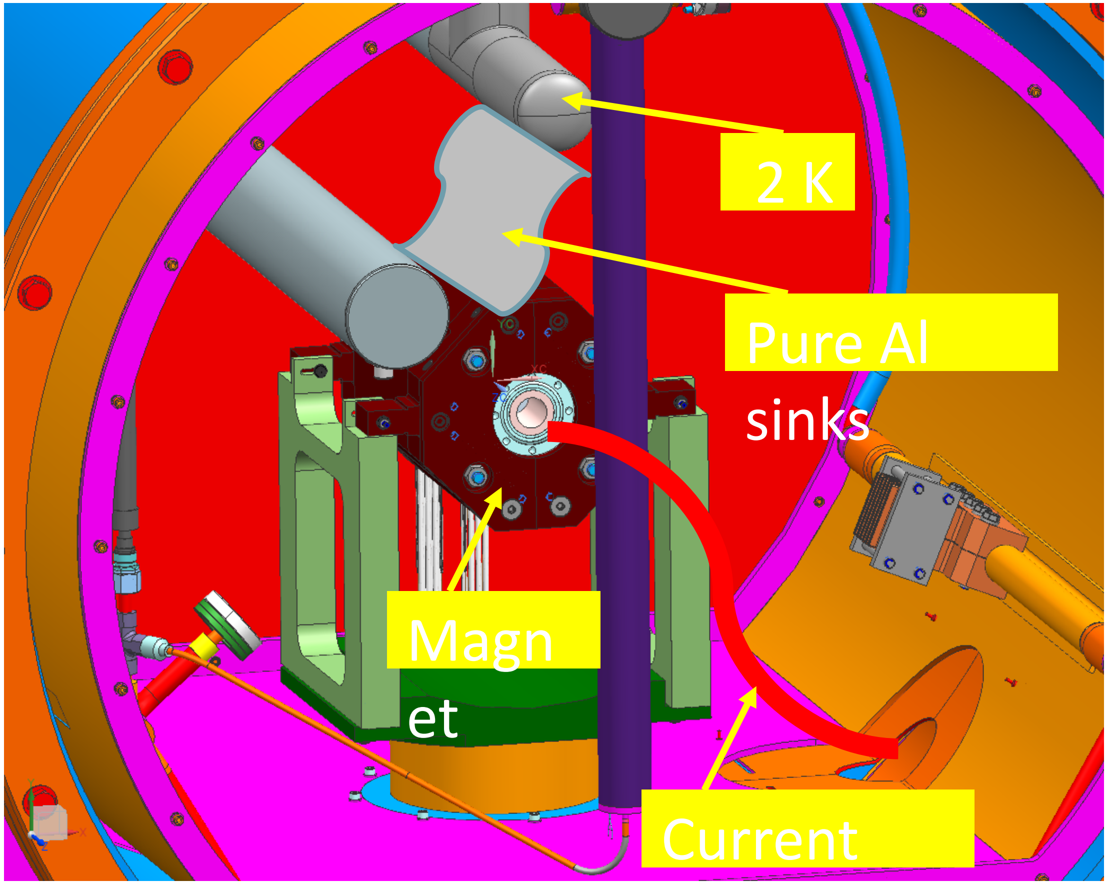
Conduction Cooling Test at STC cryostat





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.

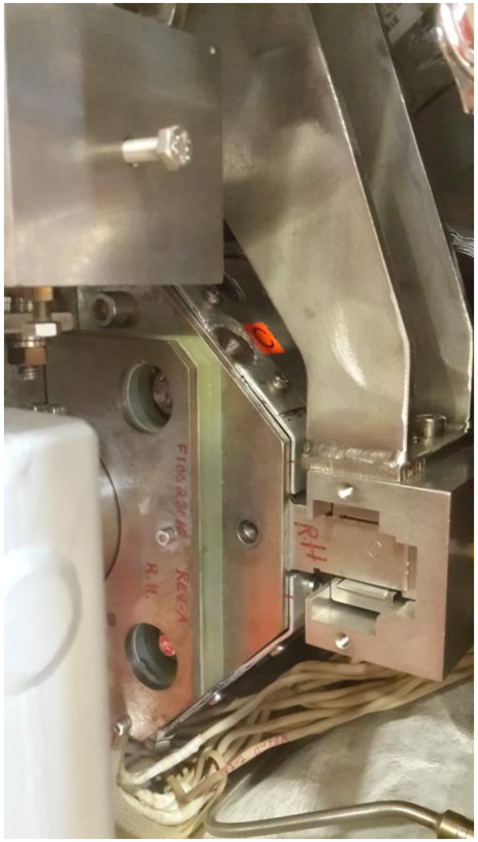
Test Results

- *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.



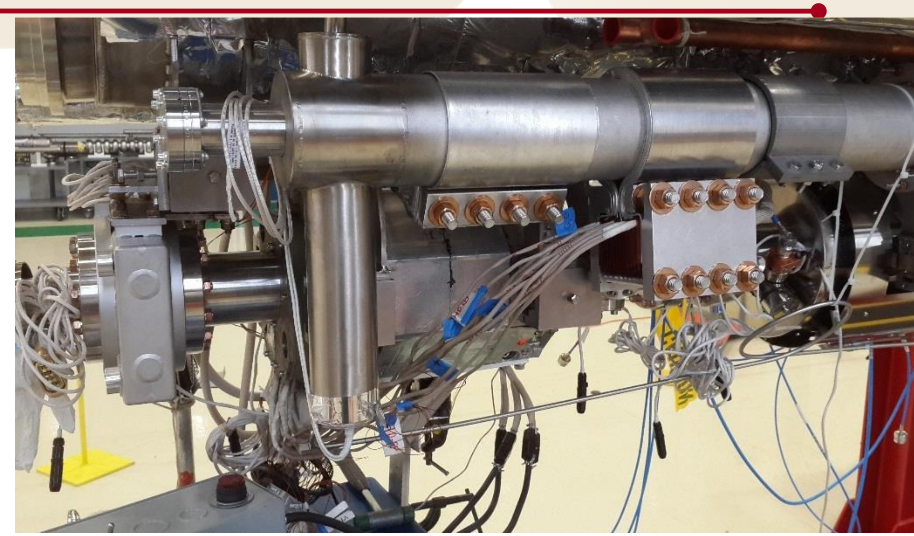
Magnet on adjustable bearings.

Sub-assembly in central Bld.

Thermal sink clamps.

Magnet Installation in Cryomodule (2)

Magnet leads and instrumentation wiring.

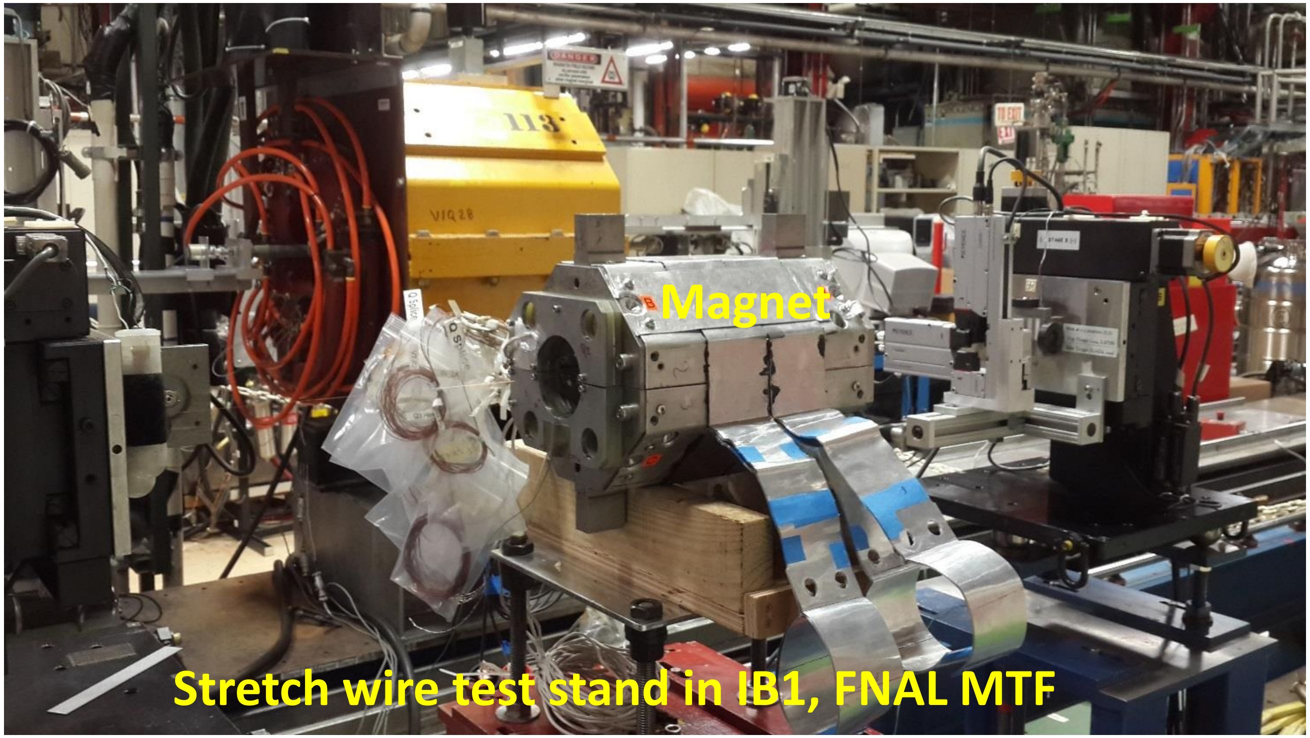


Magnet heat sinks clamps installed.

Superinsulation applied.

External power leads flags.

Quadrupole Magnetic Center Position

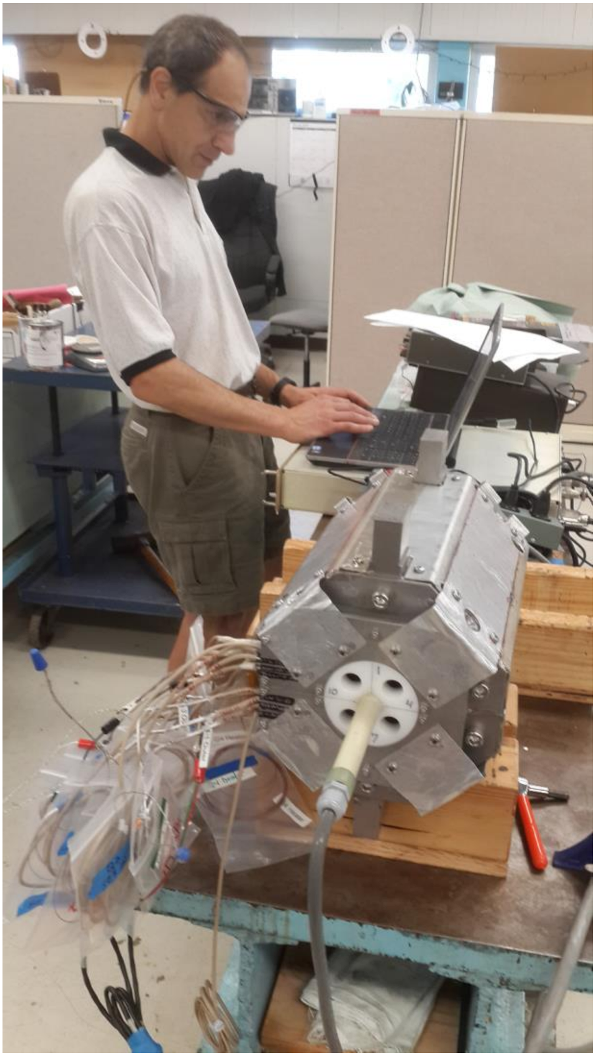


- *Each magnet will be tested at room temperature by a stretch wire technique.*
- *The quadrupole magnetic center position will be transferred on 8 reference points at magnet ends.*

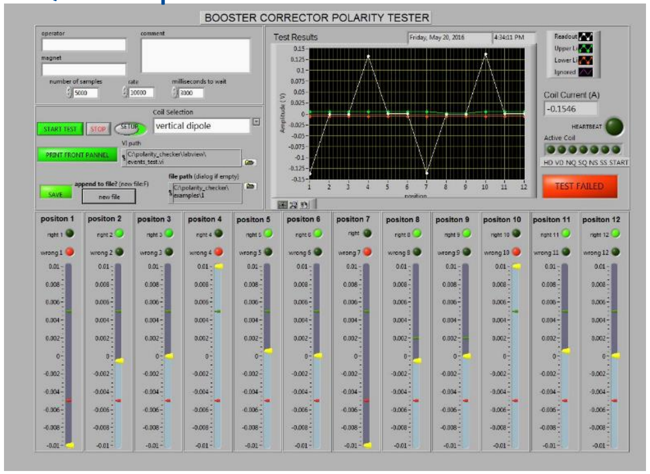
Technical status

- 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 are 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.

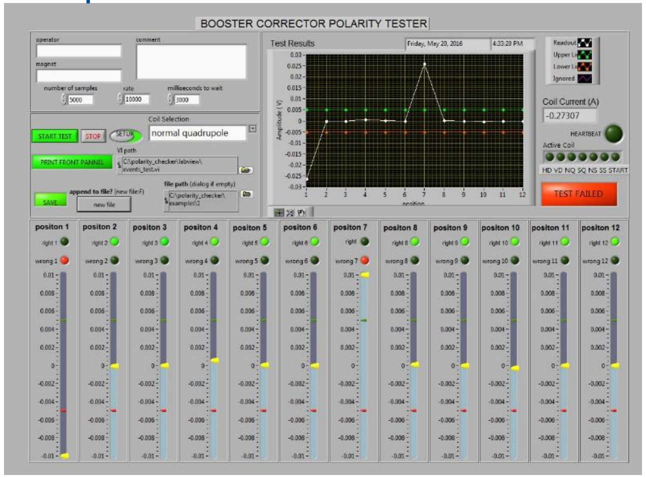
Magnetic Field Polarity Checker



Quadrupole Field

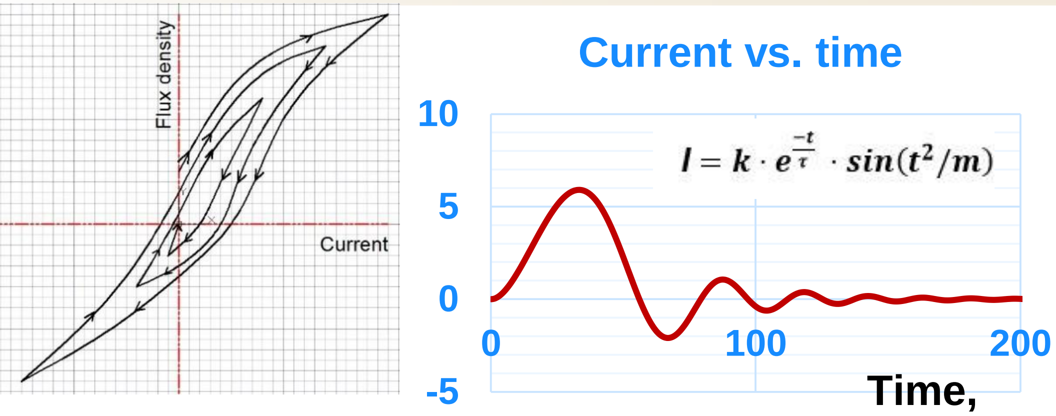


Dipole Field

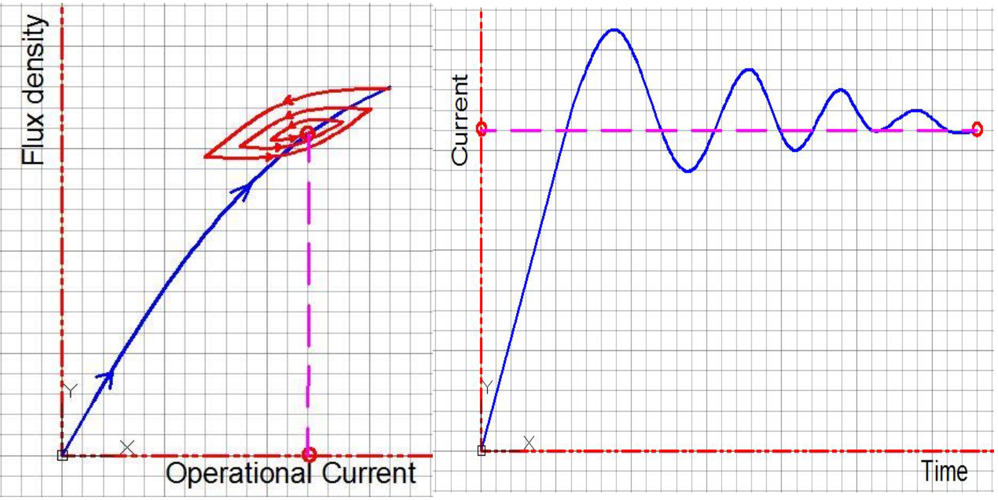


- *Magnet have 24 coil leads.*
- *Leads must be spliced correctly to form a quadrupole, and dipole configurations.*
- *The polarity check is a critical step for the verification.*
- *This check is included in the acceptance of magnet delivered from industry.*

Magnet Degaussing and Standardization



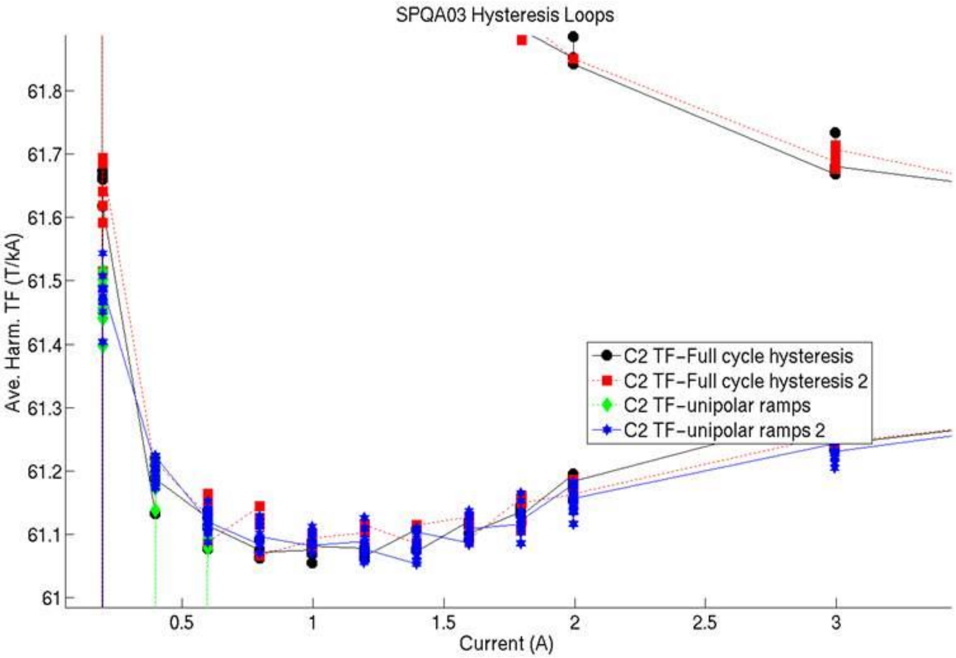
Degaussing cycling



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)*

Recent 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.*

Magnet System Failures (1)

- *Most dramatic failures were caused by not proper sub-systems integration:*
  - Pulsed toroidal system because of slow heating, and resistance rise;
  - HGQ – air pressure test;
  - LHC – splices, protection, etc…
- *Mistakes in the design:*
  - Weak electrical insulation;
  - Not proper stabilized superconductor;
  - High fringe flux;
  - Permanent magnets overloaded.

Magnet System Failures (2)

- *Wrong material choice:*
  - *- Magnetic heaters in the gap;*
  - *- Ferromagnetic bronze close to the magnet gap;*
  - *- High Hc or Hc fluctuations of iron yoke steel.*
- *Extrapolation of known design to higher parameters without margins:*
  - *- Water cooling to 90 C;*
  - *- 2 T field to 7 T .*
- *Risky tests:*
  - *- Too high voltage tests;*
  - *- SC magnet test at abnormal conditions.*

Lessons Learned

- *"In the best case you will be unnoticed".*
- *Always request magnet specification.*
- *"The job takes so long time as you have".*
- *Do not present results without careful verification.*
- *Always check manually simulations, design, test results using simple formulas.*
- *Do not believe anybody, even yourself. Double check results.*
- *First test results often in the contradiction with the design, and simple formulas.*
- *Proposing a novel approach carefully investigate previous designs and drawbacks.Often New*
- *Sub-system integration is very often overlooked.*

First LCLS-II Cryomodule Successfully Tested !