Permanent Magnet Work at Fermilab 1995 to Present

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Klaus Halbach

Klaus Halbach
1924 to 2000

Halbach made his reputation with his work on magnetic systems for particle accelerators. He and Ron Holsinger a Berkley engineer created the famous POISSON computer codes for magnetic system design, still in use after 30 years. Halbach went on to become one of the world's premier designers and developers of permanent magnets for use as insertion devices- wigglers and undulators in synchrotron light sources and free electron lasers. He also designed the magnets for the Berkeley Advanced Light Source storage ring.

Fermilab Contributors

There were a large number of people at Fermilab that worked on permanent magnets and the Recycler.

Bill Foster and Gerry Jackson
were the first to conceive of the Recyler and push it to a successful conclusion

There were many other including;

KJ Bertsche, BC Brown, CN Brown, J DiMarco, WB Fowler, HD Glass, DJ Harding, V Kashikin, MP May, TH Nicol, J-F Ostiguy, S Pruss plus many others

Layout of Talk

- Fundamental definitions
- Types of permanent magnets
- Temperature compensation
- Radiation damage
- Time dependence
- The 8 GeV transfer line at Fermilab
- The Recycler at Fermilab
- Adjustable Permanent Magnet Quadrupoles for the NLC
- Other permanent magnets

Sources of Information

- If you Google permanent magnets get 1,560,000 results -some of the better ones are:
- For theory Ferromagnetism by Richard Bozorth IEEE press
- For a how to guide International Magnetics Association
  - http://www.intl-magnetics.org/
- Papers on the Fermilab Recycler can be found in PAC 95, 97, 99, 2000 and 2003
- Dexter Magnetics
  - http://www.dextermag.com/
- Ugimag
  - http://www.ugimag.com/
- Hitachi
  - http://www.hitachimetals.com/product/permanentmagnets/

Important Definitions

- B residual B_r The magnetic induction after saturation in a closed circuit
- Remnant induction B_d The magnetic induction that remains after the removal of an applied field
- H_d is the value of H corresponding to B_d on the demagnetization curve
- Intrinsic Coercive Force H_{ci} indicates its resistance to demagnetization
- On a hysteresis curve of B vs H the B_r is where H_{ci} is 0 and the H_{ci} is where B_r is 0
- Load line has a slope equal to - B_d / H_d and is drawn in the 2^{nd} quadrant
- The product of B_d and H_d is the measure of how much energy can be supplied to the circuit and is measured in Mega Gauss Oersteds (MGO)
- The Curie temperature T_c is the temperature that the material demagnetizes
- Easy axis this is the direction of the field in the material
- A Fermilab Unit is Measured Field / Ideal Field * 10^4

Types of Magnetic Material

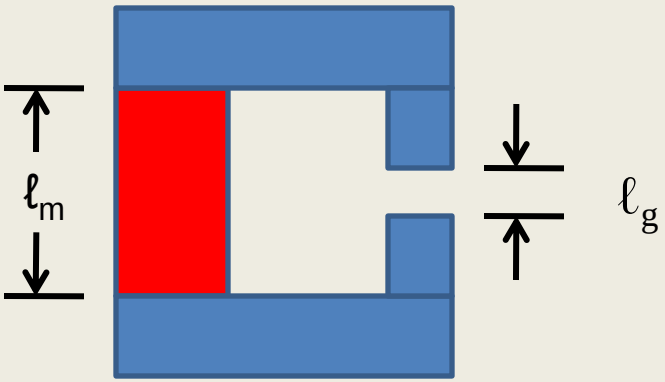
Alnico
Metal
Inexpensive
B_r 3,000 to 5,000 Gauss
Energy density 7 MegaGauss Oersteds

Strontium Ferrite
Hard ceramic
Inexpensive
B_r 3800 Gauss
Energy density 3.5 MegaGauss Oersteds

Samarium Cobalt
Rare earth
Expensive
B_r 9000 to 10,000 gauss
Energy density 26 MegaGauss Oersteds

Neodymium Iron Boron
Rare earth
Expensive
B_r 11,000 to 12,000 gauss
Energy Density 35 to 50 MegaGauss Oersteds

Load Line for a Simple Dipole



ℓ_m is the length of magnet
ℓ_g is the length of air gap
H_d magnetic potential of the magnet
H_g magnetic potential of the air gap
A_m is the area of magnet
A_g is the area of gap
B_d is the flux density of magnet
B_g is the flux density of gap

We can write two flux conservation equations about this dipole

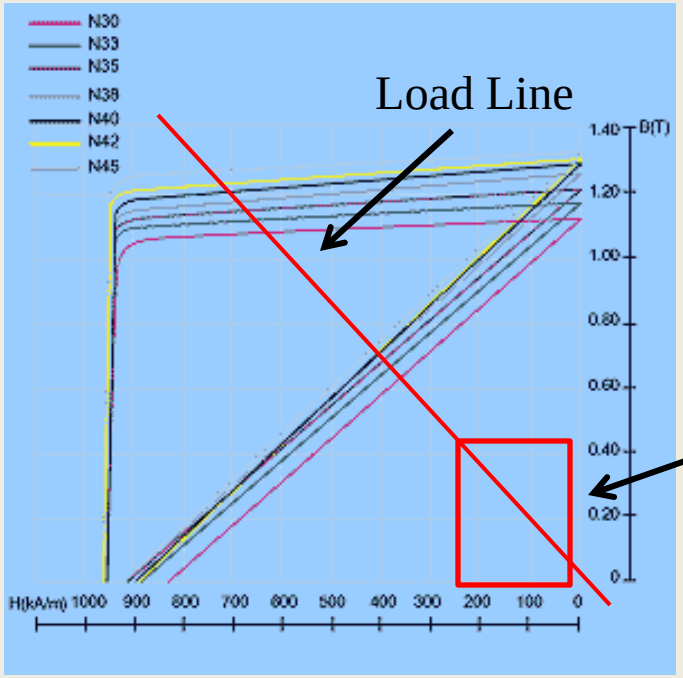
$$\ell_m * H_d - \ell_g * H_g = 0 \quad A_m * B_d = A_g * B_g$$

$$\Phi = \frac{\text{Magneto Motive Force}}{\text{Reluctance}} = B_d * A_m = \frac{H_d * \ell_m}{\ell_g * A_g}$$

$$B_d = H_d \frac{\ell_m * A_g}{A_m * \ell_g}$$

Load Line

$$B_d / H_d = \frac{\ell_m * A_g}{A_m * \ell_g}$$ This is the slope



B in Tesla

Energy Density

The different curves are for different grades of material

It is important to stay away from the knee of the curve.

H in Kilo Oersteds

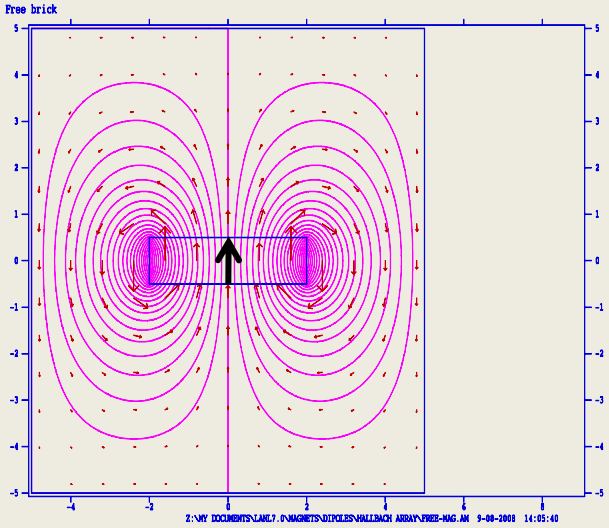
Magnet Modeling Software

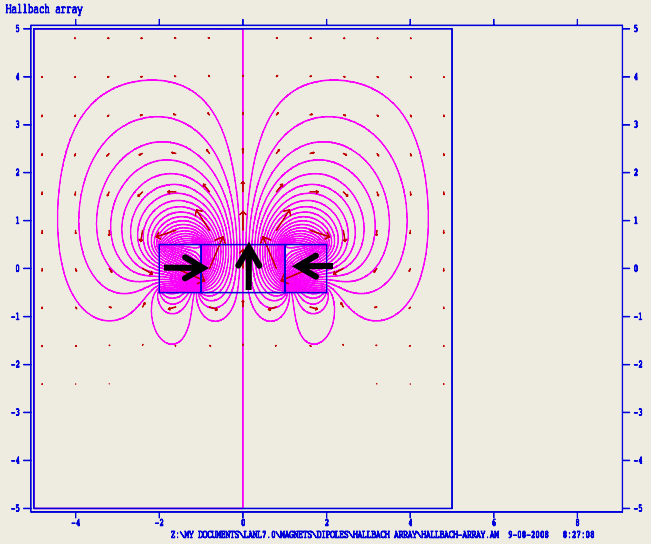
- There are many different magnet modeling programs available
  - ANSYS
  - Ansoft MAXWELL
  - Vector Fields OPERA and TOSCA
  - POISSON and PANDRIA

•I use POISSON and PANDRIA

- They are simple and free available from Los Alamos code group
  - http://laacg1.lanl.gov/laacg/services/download_sf.phtml
- Jim Billen and the Los Alamos code group has made a WINDOWS version
- They do 2 dimensional models very quickly and accurately
- Creates triangular mesh that can be densified in areas of interest
- Allow for different material steel and permanent magnets
- Graphical output helps to visualize program
- Can calculate harmonics
- Can be installed and working in less than 1 hour

Free Magnet and a Hallbach Array of the same size

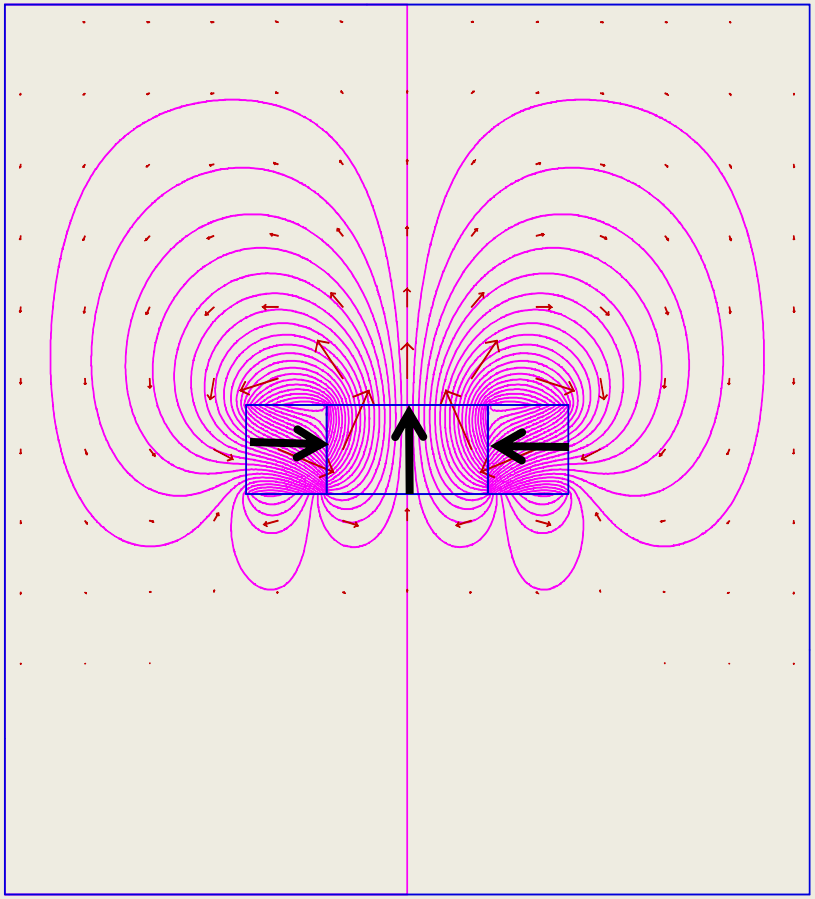




The free magnet is symmetric and disperses flux evenly.

The Halbach array concentrates the field by pushing the flux into the center magnet.

Halbach Array



This is a simple array of three magnets.

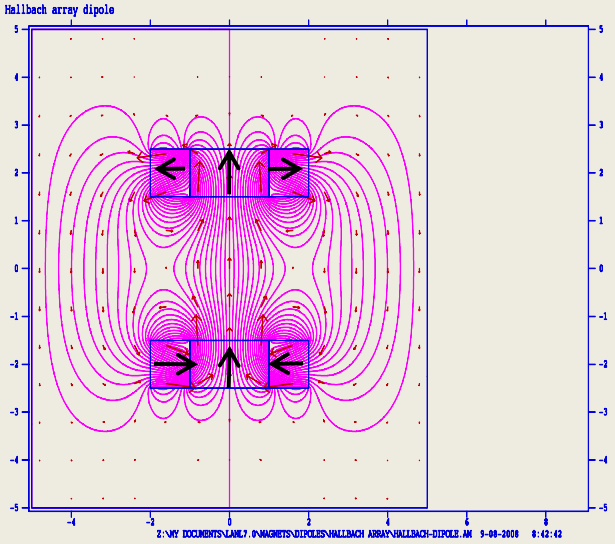
The black arrows indicate the direction of the easy axis.

The two outside magnets are pushing flux into the center magnet.

Sample POISSON Input for Halbach Array

```
Hallbach array
Original version from the 1987 User's Guide, Chapter 10.5
First pass simple 3 ferrite magnet Halbach array

; Copyright 1998, by the University of California.
; Unauthorized commercial use is prohibited.

&reg kprob=0,      ; Defines a POISSON or PANDIRA problem
conv = 2.54,       ; inches
dx = 0.05          ; mesh size
dy = 0.05          ; mesh size
nbslo = 0,         ; Dirchelt boundary condtion at bottom
ktype = 1,         ; symmetry midplane for this
nterm = 11,        ; number of harmonics terms
nptc  = 1440,      ; number of arc points
rint  = 0.4,       ; radius to calculate harmonics
angle = 360.0,     ; angle to calculate harmonics
mode=0   &         ; Materials have variable permeability

&po x=  -5.0,      y = -5.0 &      ;entire universe
&po x=  5.0,       y = -5.0 &
&po x=  5.0,       y =  5.0 &
&po x= -5.0,       y =  5.0 &
&po x= -5.0,       y = -5.0 &

&reg mat=6,mshape=1,mtid=6  &    ; RHS magnet
&po x =  1.000, y =  -0.500 &
&po x =  2.000, y =  -0.500 &
&po x =  2.000, y =   0.500 &
&po x =  1.000, y =   0.500 &
&po x =  1.000, y =  -0.500 &

&reg mat=8,mshape=1,mtid=4  &    ;Center magnet
&po x = -1.000, y =  -0.500 &
&po x =  1.000, y =  -0.500 &
&po x =  1.000, y =   0.500 &
&po x = -1.000, y =   0.500 &
&po x = -1.000, y =  -0.500 &

&reg mat=7,mshape=1,mtid=2   &      ; LHS magnet
&po x =  -1.000, y =  -0.500 &
&po x =  -2.000, y =  -0.500 &
&po x =  -2.000, y =   0.500 &
&po x =  -1.000, y =   0.500 &
&po x =  -1.000, y =  -0.500 &

&mt mtid=2,aeasy=   0,gamper=1,hcept=-3500,bcept=3800. & ; Sr Ferrite
&mt mtid=4,aeasy=  90,gamper=1,hcept=-3500,bcept=3800. & ; Sr Ferrite
&mt mtid=6,aeasy= 180,gamper=1,hcept=-3500,bcept=3800. & ; Sr Ferrite
```

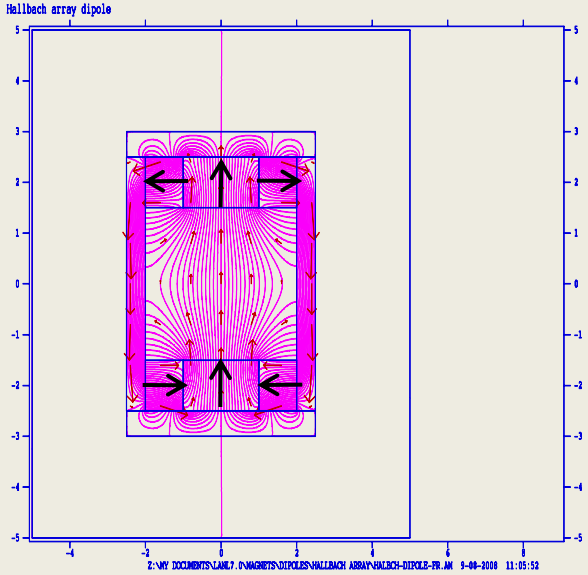
Halbach Array Dipole



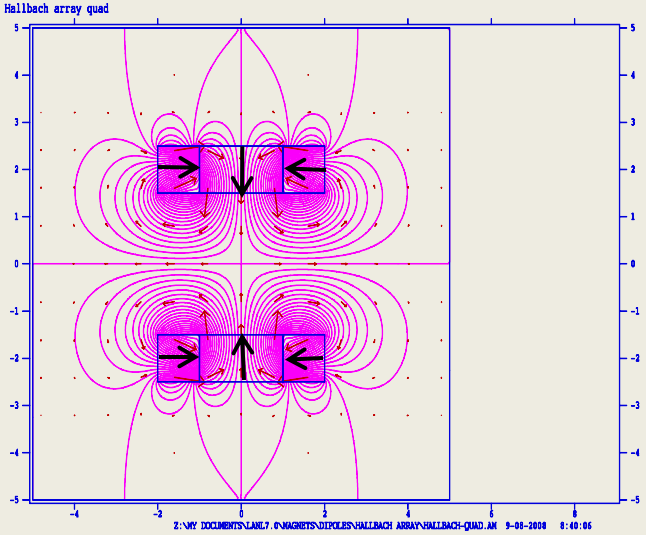
Two Halbach arrays used to make a simple dipole.

Note the change in the easy axis for the side magnets.

The addition of steel on the top and sides increases the field in the gap by 32%. Again the black arrows are the easy axis.

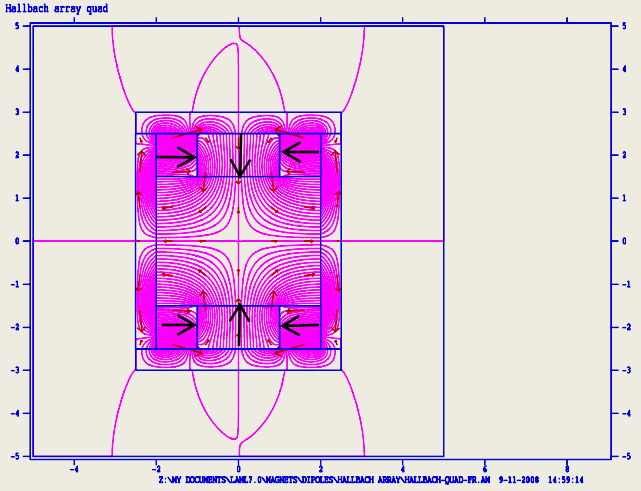


Halbach Array Quadrupole

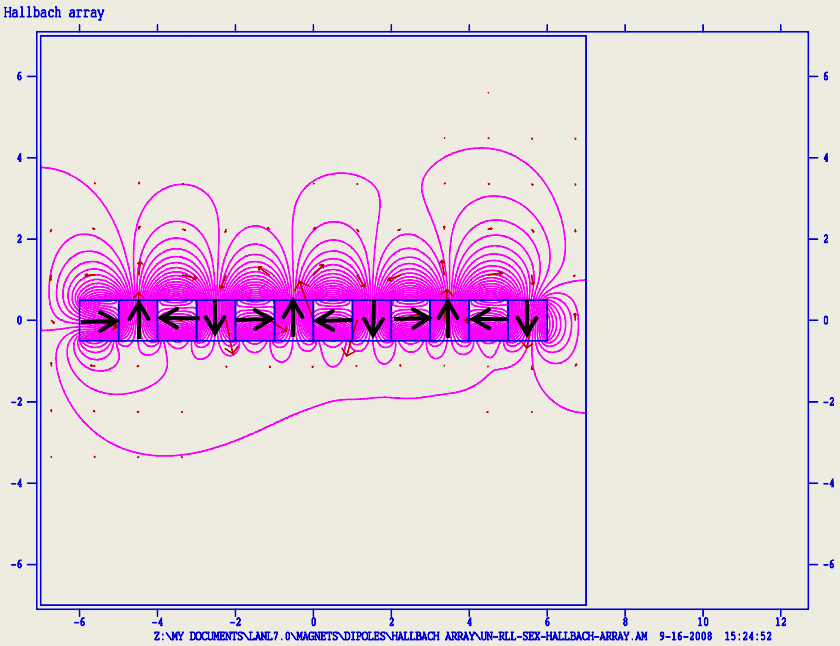


This is two Halbach arrays facing each other to make a quadrupole field.

Adding flux returns increases flux by 21%

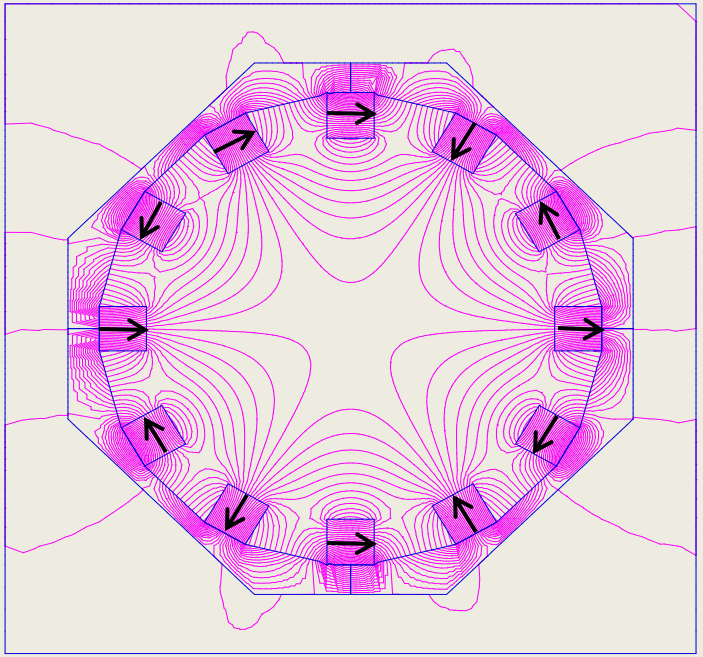


Halbach Array Sextupole



The black arrows point in the direction of the easy axis.

Sextapole



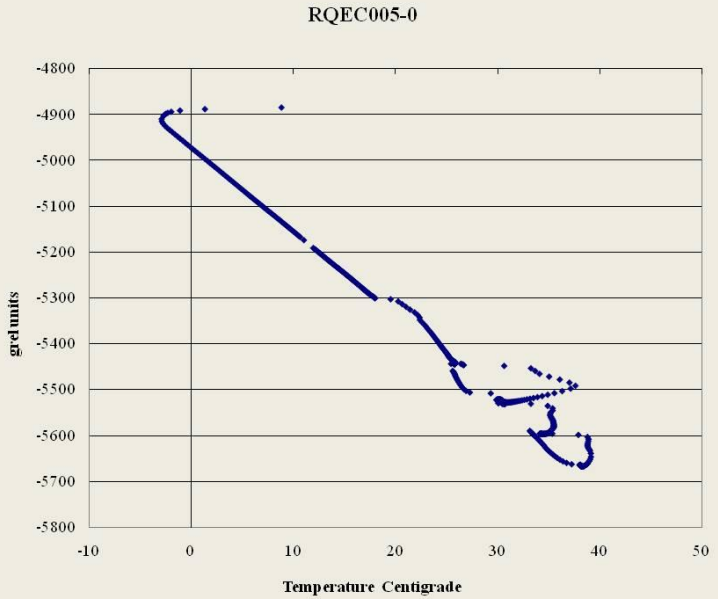
Temperature Variation

The magnetic field B_r varies with temperature.

As the magnets get hotter the B_r decreases.

For Sr Ferrite the variation is 0.18% per degree C.

For Samarium Cobalt the variation is 0.11% per degree C.



This is a plot of Temperature vs gradient strength for a recycler quad. The field falls off 720 units over a 40 C temperature change.

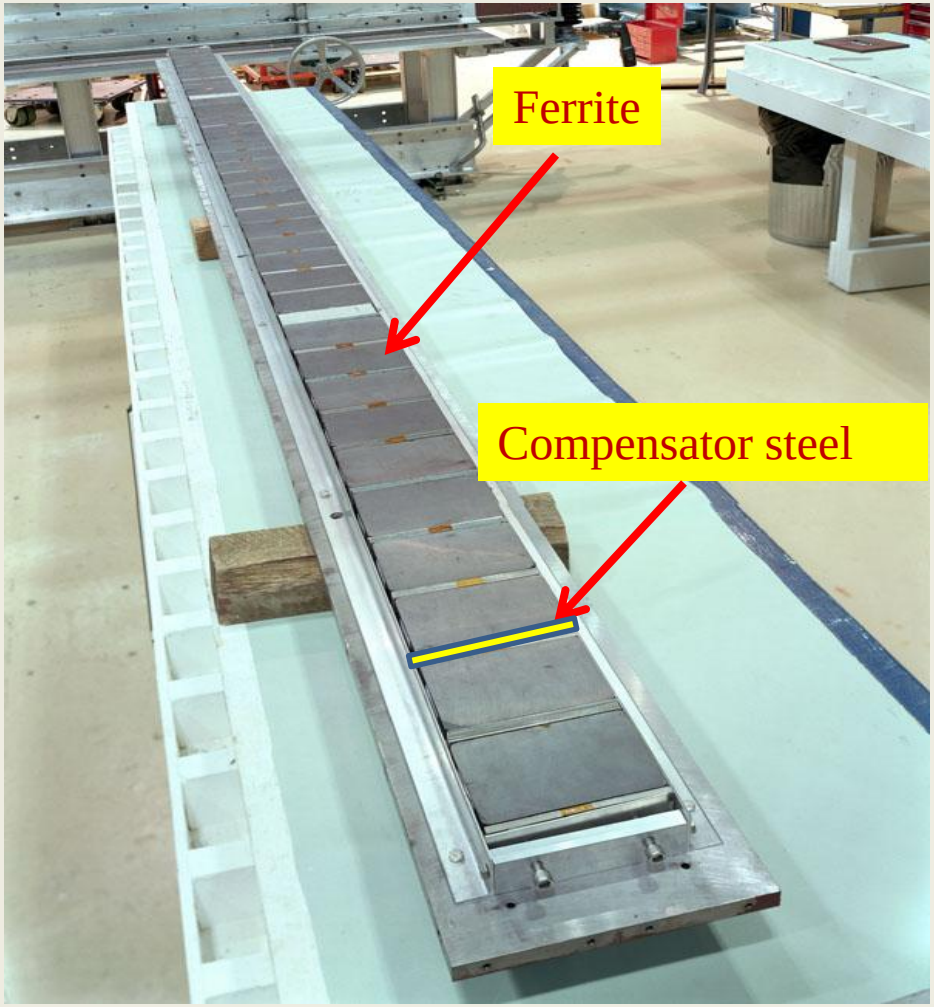
Temperature Compensation

The solution is to use steel with 28% Nickel added. The T_c (Curie temperature) of the steel is 55 C.

The material is placed between the pole pieces and the flux return.

As the temperature decreases the μ of the steel increases and acts like an iron shunt removing flux from the gap. As the temperature increase the μ goes to unity and acts like air allowing more flux into the gap.

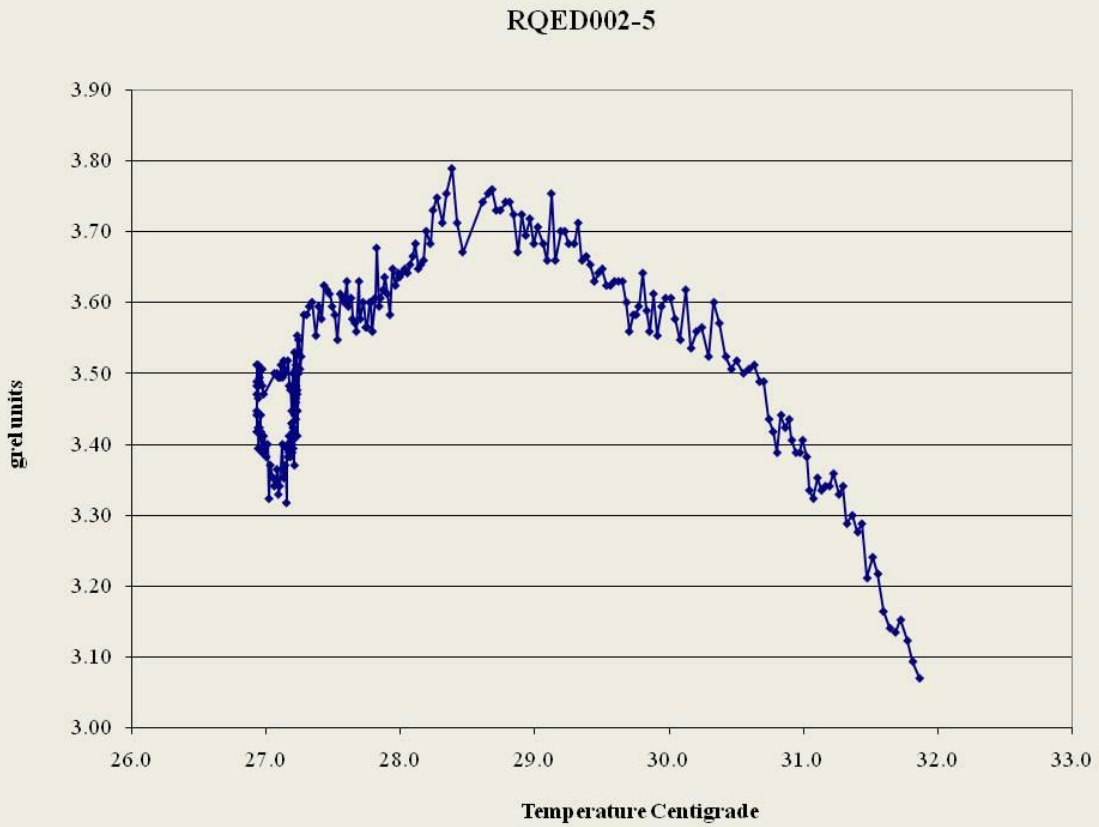
Empirically determine the correct ratio compensator steel to ferrite. This varies from batch to batch.



Temperature Compensated Magnet

This has undergone a 5 degree C temperature change.
A n un compensated magnet would change by 90 units.

This magnet changes by 0.7 units.



Radiation Damage

Large amount of literature on radiation damage see

http://www-project.slac.stanford.edu/lc/local/notes/dr/Wiggler/wiggler_rad.html

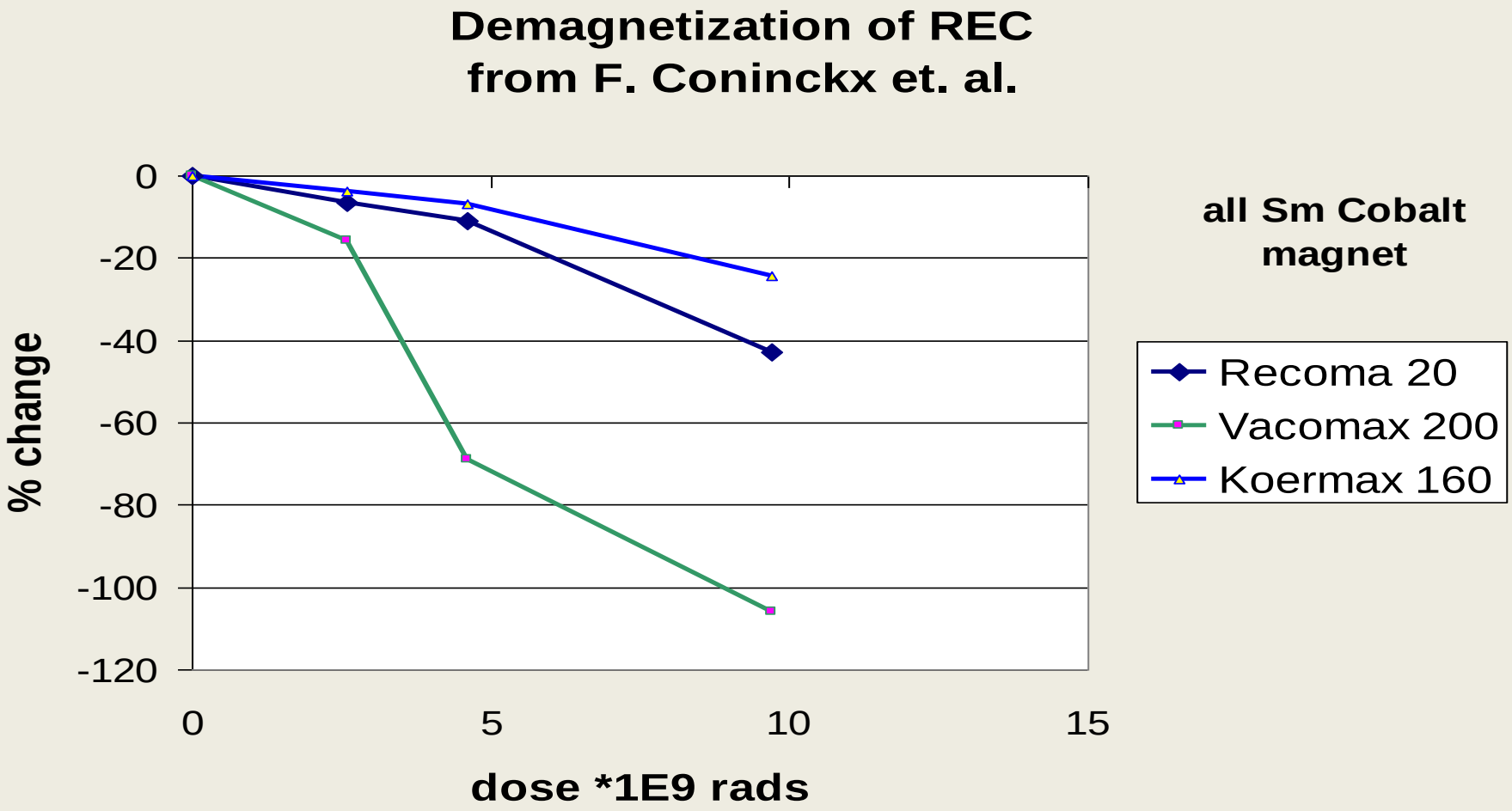
All studies are on rare earth magnets

Many different types of exposures protons, neutrons, gammas

Many different manufactures and materials

No consistent results

Demagnetization due to Radiation



Summary from Luna et al

Sample	Alloy	Type of Irradiation	Maximum Dose GRad	Remanence loss %	H_c kOe	H_{ci} kOe
CERN 1983						
RECOM 20 VACOMAX 200 KOERMAX 60 Krupp WIDIA	$RECo_5$ $SmCo_5$ $SmCo_5$ Sm_2Co_{17}	400 Gev protons	9.7 10.4 11.4 10.5	-42.7 -106.1 -24.2 -2.6	8.8 8.9 to 9.5	30.0 12.5 to 19.0
TRIUMPH 1985						
HICOREX 90 B HICOREX 96B CRUCORE 18 CRUCORE 26 NeIGT 27	$SmCo_5$ (SmPr)Co5 $SMCo_5$ Sm_2Co_{17} Ne-Fe-B	500 MeV protons	3.02 1.53 5.81 5.94 0.003	-13.5 -6.5 -1.64 -0.30 -55.40	 8.4 9.6	 16.0 10.0 17.0
LANL 1986						
CRUMAC 282 NeIGT 27	Ne-Fe-B Ne-Fe-B	Gamma	48.8 Mrad 48.8 Mrad Max fluence 10^8 n/cm^2	-0.00 -0.00	10.8	28.2
LANL 1982						
HICOREX 90B HICOREX 96B	$SmCo_5$ $SmCo_5$	Nuetrons from 800 MeV protons	1.10 1.20	-1.88 -2.21		
LANL 1986 Omega West reactor						
CRUMAX NeIGT 27H HICOREX INCOR 18 INCOR 22HE	Ne-Fe-B Ne-Fe-B Nd_2-Fe_{14}-B Sm_2Co_{17} Sm_2Co_{17}	Reactor neutrons	2.50 2.50 3.80 2.60 2.60	-79.10 -86.80 -14.00 -0.00 -0.20	10.8	28.2 17.0

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HICOREX 90B HICOREX 96B	$SMCo_5$ $SMCo_5$	800 MeV protons to neutrons	1.10 1.20	-1.88 -2.21		
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CRUMAX NeIGT 27H HICOREX INCOR 18 INCOR 22HE	Ne-Fe-B Ne-Fe-B Nd_2-Fe_{14}-B Sm_2Co_{17} Sm_2Co_{17}	Reactor neutrons	2.50 2.50 3.80 2.60 2.60	-79.10 -86.80 -14.00 -0.00 -0.20	10.8	28.2 17.0

Kähkönen et al. Jyväskylä Finland

Journal Phys Cond Mat 4 (1992)1007

Local heating of domains by knock atoms

Solve Laplace's Equation

$$\partial T/\partial t = \alpha \nabla^2 T$$

Use a Green's function to get

$$T = T_o + (T_c - T_o)(2 \pi R^2/3d^2e^{-1})$$

Gives the heat needed to heat a radius R above the Curie temperature

The energy of a knock on atom is

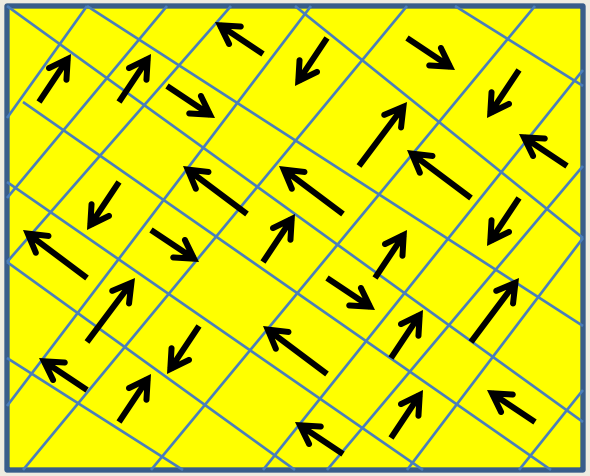
$$E_{kin} = 3/2\ k_B\ (T_1 - T_o)$$

An atom of material when hit will vibrate, it can flip direction If there is a demagnetizing field present this will help to push it over. There is always some demagnetizing filed present. It all depends on how the material was processed and how big the grains are.

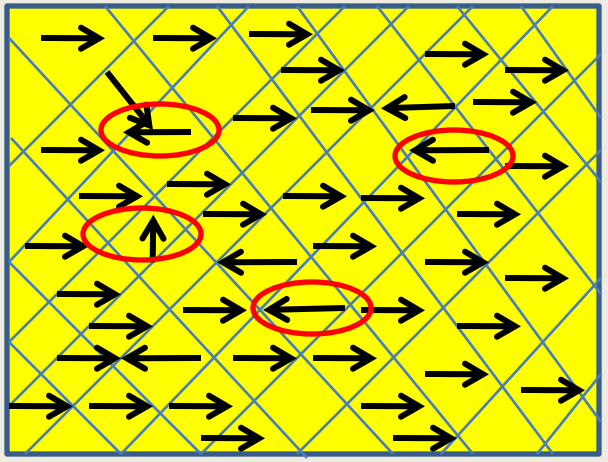
Radiation Damage

Un-magnetized material

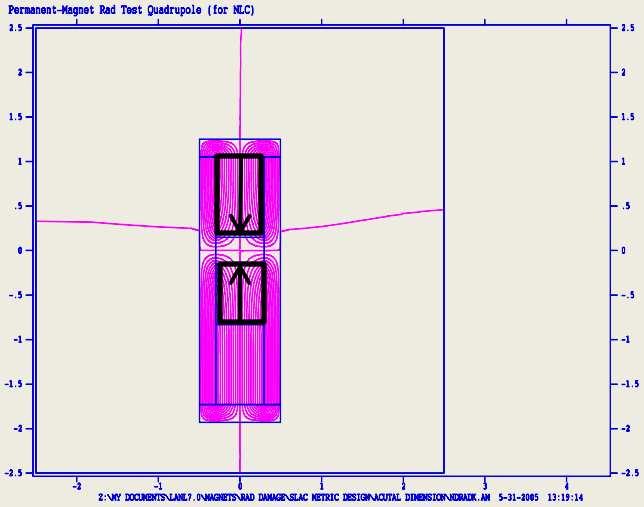
Arrows indicate direction of field in each grain.
Note a domain is 10^{15} atoms 0.1 micron or less
Grains are larger 1 micron or so



Magnetized material arrows indicate direction of field in each grain. Not all domains line up in each grain In Rare earth magnets domain wall can move in a grain



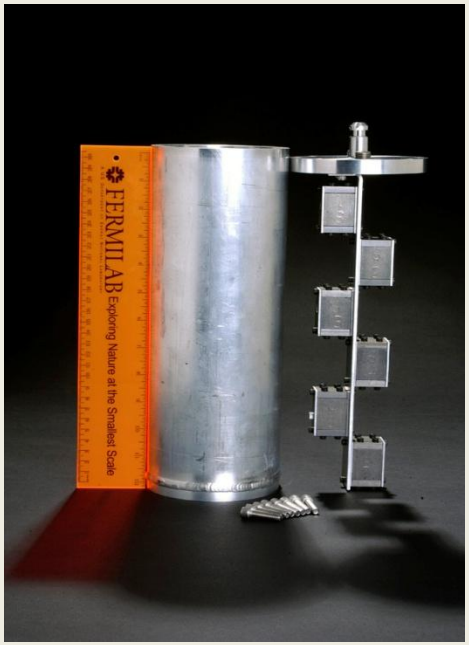
Test Quad Magnets



Test quads with a gap of 2 mm wide by 3 mm high able to fit into Rabbit hole in McCellan Reactor in Sacramento California.

Could vary load line by changing gap.

Irradiated different grades of materials from different manufacturers at the same time and same flux.



From S Anderson et al

Neutron irradiation at the McCellan reactor

Alloy	Manufacturer	Mx Gauss	dMx/dD Gauss/Gray
SmCo HS36EH	Hitachi	35	0.00
SmCo HS46AH	Hitachi	128	-4.65
Ne-Fe-B N34Z1	Shin Etsu	266	-0.11
Ne-Fe-B N50M1	Shin Etsu	17	-2.28

What we found by looking at radioactive half lives was many different doping elements

Rare Earth Elements such as Tb, Pm, Pr, Dy all in different quantities for different manufactures

This work was stopped when the decision was made to use superconducting RF

Practical Radiation Damage

- Strontium Ferrite is good to 10^9 Grays
- Rare Earths are harder to characterize
  - Different manufactures add different materials
  - It is important to understand what material is in the magnets
  - It is also important to test the magnets to ensure that the material is what you expect

Time Dependence

In 1960 Konenberg and Bohlmann published in Journal of Applied Physics Long Term Stability of Alnico and Barium Ferrite Magnets

$$\Delta M = aT\log(t/t_0)$$

Where t is time and T is absolute temperature

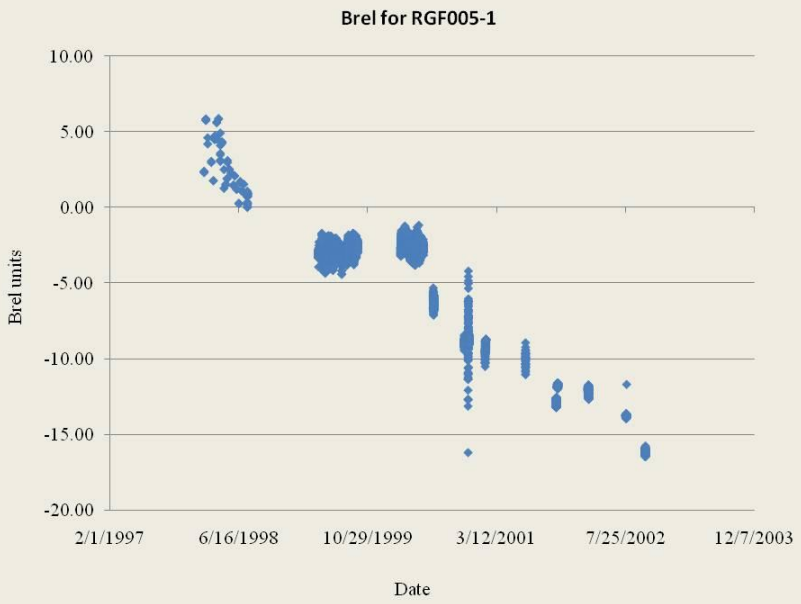
Theory developed by Louis Neel in 1950 and Street and Wooley in 1949

External shocks, temperature change can cause domains to flip thereby decreasing the field.

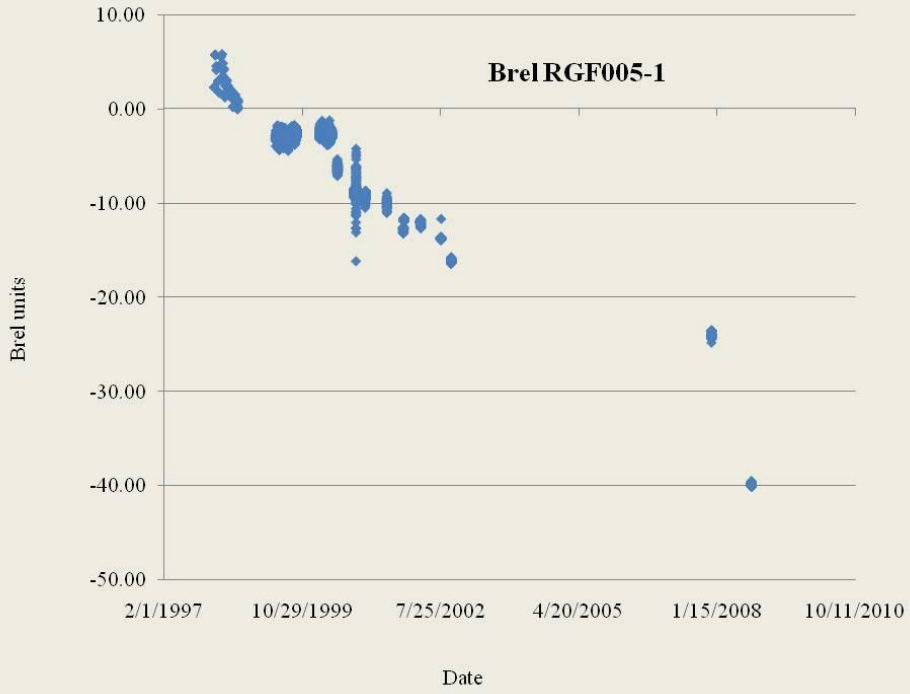
Time Dependence of Fields

This is a plot of B_{rel} for the first production gradient magnet vs. time. From 1998 to 2002 the field has decayed 0.2%. The decay is logarithmic with time.

This is not enough to cause problems with the recycler.



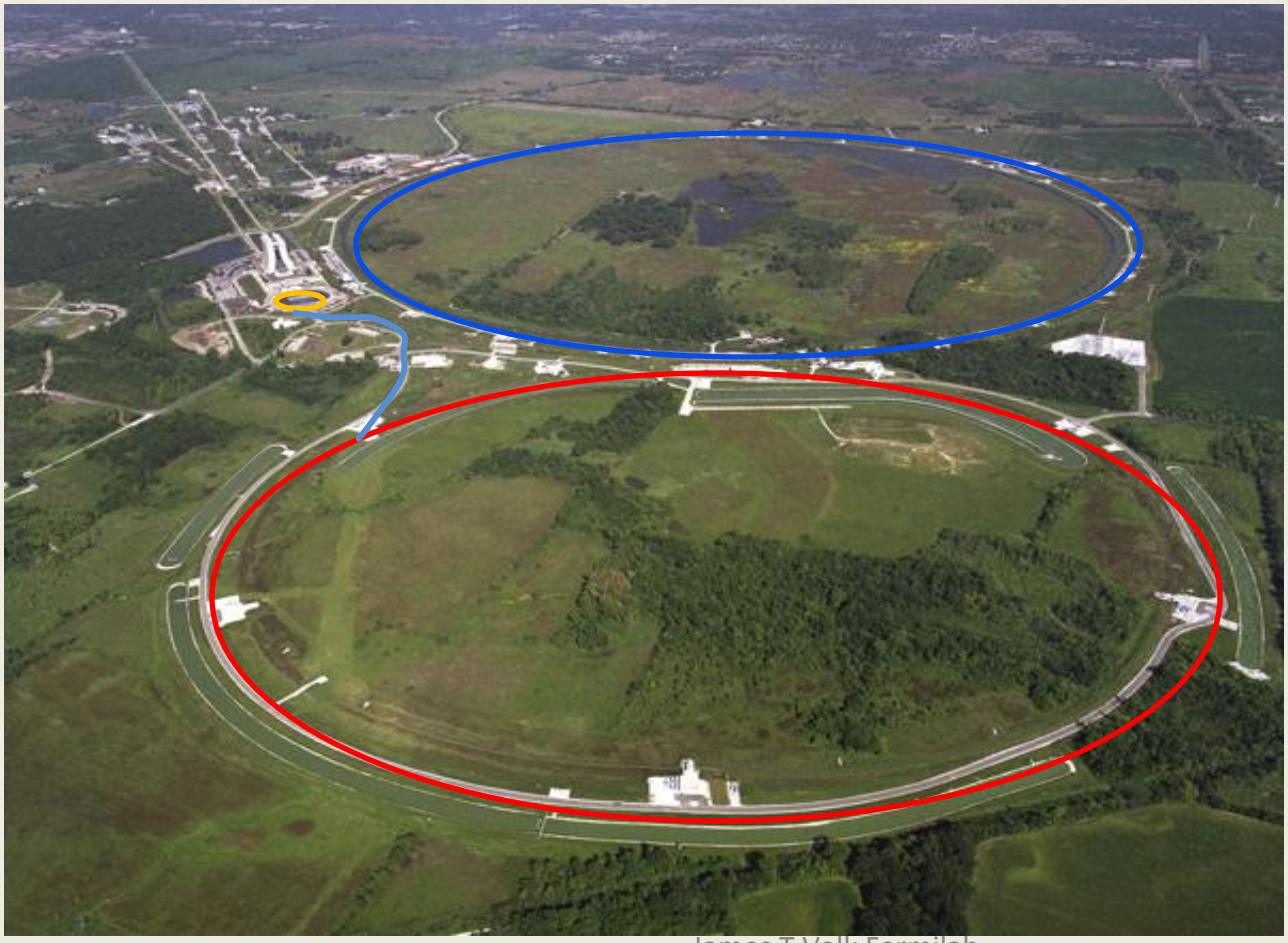
More Time dependence



The same magnet premeasured again in 2007 and 2008.

There has been no change in the RF in the recycler indicating no change in the orbit and therefore no change in the field of the magnets

Over View of Fermilab Site



8 GeV Booster

8 Gev
Transfer line

Main Injector
And
Recycler

Tevatron

8 Gev Transfer Line
Booster to Main Injector

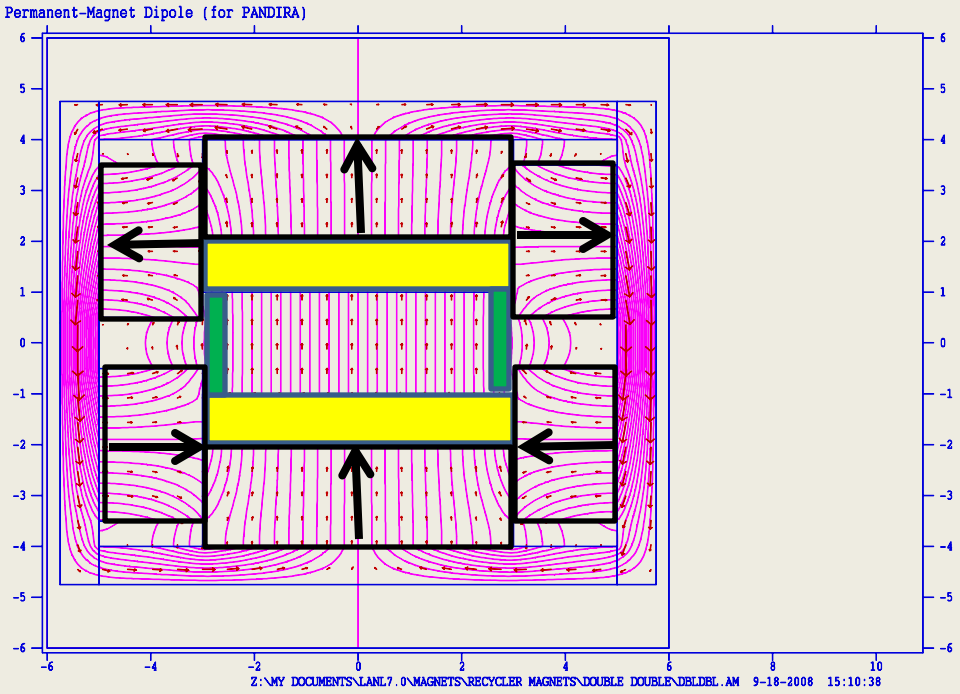
First proof of principle that permanent magnets work.

45 Dipoles
65 Gradient magnets
9 Quadrupoles

Beam transmitted on third pulse.

No “beam line physicist” assigned to the beam line.

Double Double Dipoles



Pandria model of Double Double dipole

Poles

Strontium Ferrite magnets

Temperature compensator material

Position of side bricks can change the sextupole moment of the magnet

The Recycler

The Recycler is an 8.9 Gev/c Anti proton storage ring in the Main Injector tunnel 3.6 km Circumference.

There are 488 permanent Magnets in the ring.

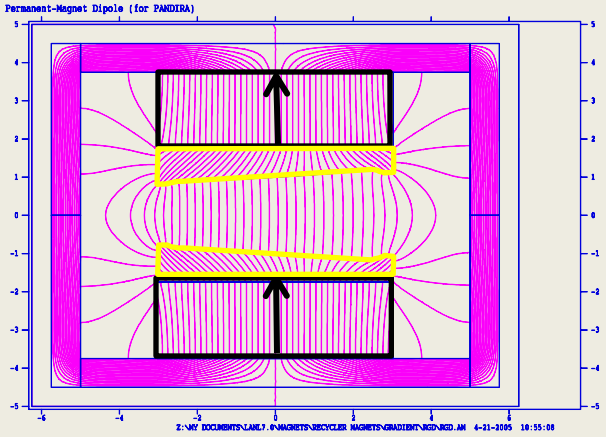
362 Dipoles
109 Quadrupoles
8 Mirror magnets
5 Lambertson
4 Sextapoles

Gerry Jackson and Bill Foster In the Main Injector tunnel.

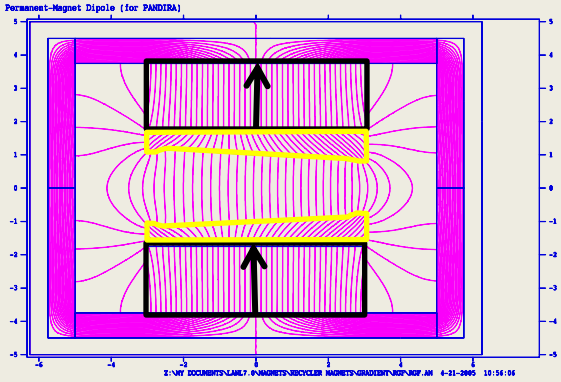
Design Parameters

- The lattice for the Recycler is the same as the Main Injector
- The aperture is 50.8 mm (2 inches) high and 88.9 mm (3.5 inches) wide
- $\Delta B/B = 1 \times 10^{-4}$ or 1 unit over the 88.9 mm
- Hybrid design uses Strontium Ferrite magnets and steel poles tips
- Strontium Ferrite is cheaper than Alnico and Samarium Cobalt
- Sr Ferrite is readily available and is easily magnetized
- Gradient magnets were built to eliminate 82% of the separate Quadrupoles
- The poles were precision machined to give the proper gradient
- The flux returns were all bar stock with lower machining tolerance

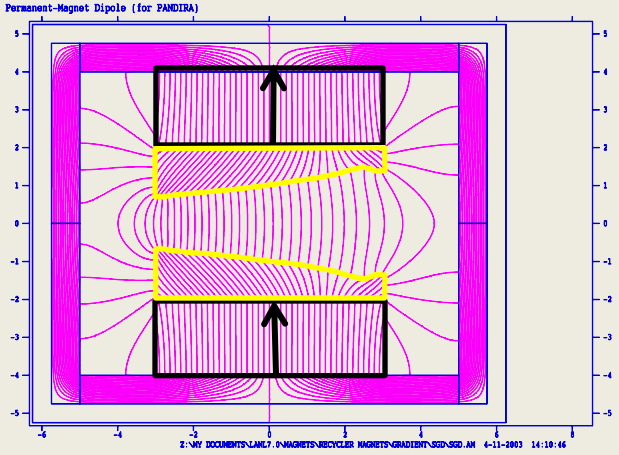
Recycler Gradient Magnets



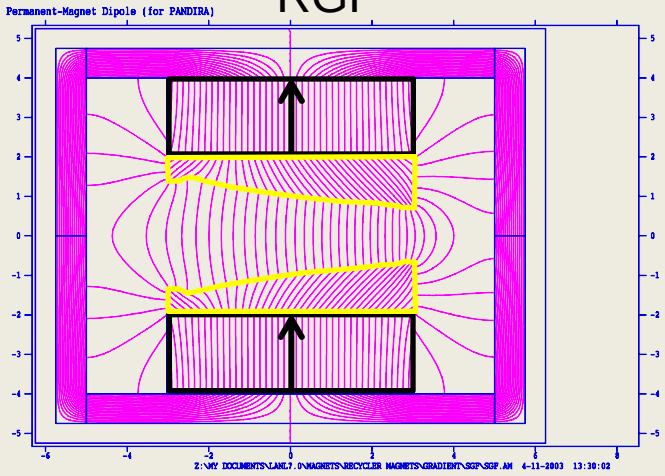
RGD



RGF



SGD



SGF

Recycler Parameters

Type	Total Pole width	Pole height At center	Pole length	B field	Quadrupole	Sextapole
units	mm	mm	m	Tesla	units	units
RGF	152	50.8	4.496	0.1375	619.7	8.7
RGD	152	50.8	4.496	0.1375	-598.1	-15.1
SGF	152	50.8	3.099	0.1330	1276.0	0.0
SGD	152	50.8	3.099	0.1330	-1303.1	0.0

Assembly

- Characterize batches of Strontium Ferrite magnets
  - Test one box from skid to determine if weak or strong
- Magnetize Strontium Ferrite magnets
  - Used old beam line dipole to provide the field built a transport system with PLU to drive magnets in and out and ramp the dipole
- Devise stacking plan
  - Changed the amount of Ferrite used in the magnets based on strong or weak magnets
- Place magnets on flux returns
  - All magnets held in place mechanically not by epoxy
- Build on assembly table
  - Needed for safe assembly of magnets

The magnet factory

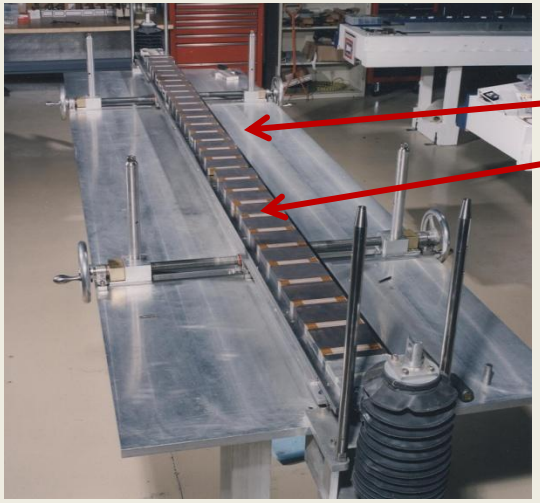
Assembly area

Test stand

Magnetizer

Storage

Assembly of a Gradient magnet



Bottom plate magnets and compensator

Pole assembly On magnets

Top plate with magnets lower into place

Side plates Ready to install

Assembly of Gradient

Side plates
Ready to install

Technicians
Cranking in
Side plates

Finished
Magnet
With traveler

Field Measurements

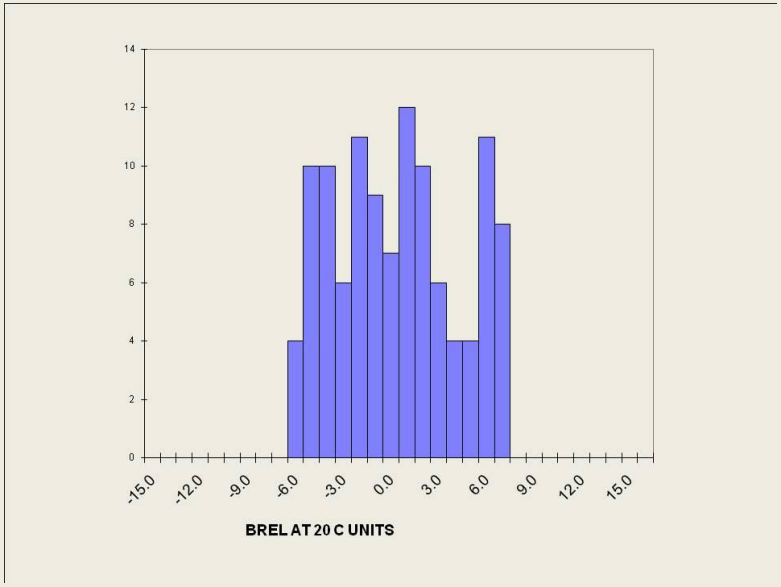
RGF 005 on test stand
at Magnet Test Facility

A Morgan coil was used to measure field strength and harmonics through 12 pole

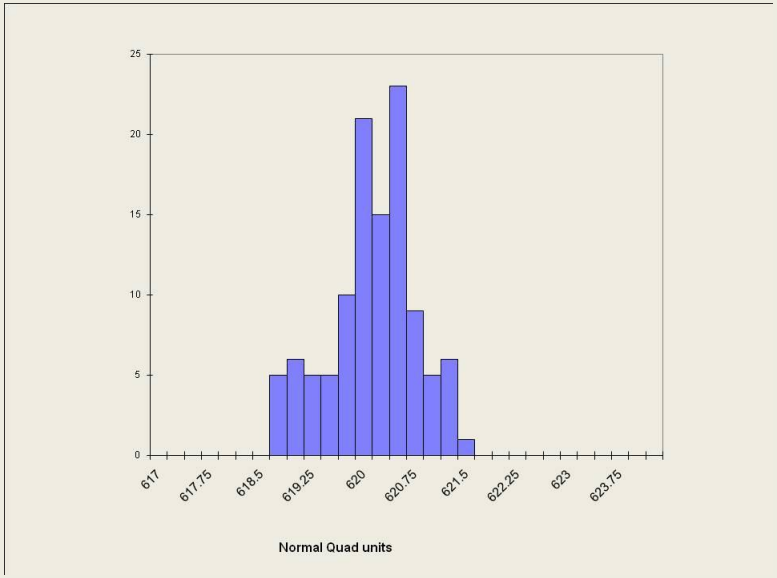
Measure and Adjust Magnets

- Measure with a flip coil to check temperature compensation
  - Each magnet was frozen over night
  - B field measured at 0 C and 22 C
  - Compensation calculated
  - Strips of compensator steel were added or subtracted
- Measured with Morgan coil to Adjust B field
  - Add or subtract magnetic material to achieve proper B field
  - used pieces as small as ½" by ½" by 6"
- Tune harmonics
  - Use Morgan coil to measure harmonics through 12 pole
  - Calculate shape of end shims to correct higher harmonics
  - Bill Foster wrote a program that took data and generate machine code for wire EDM cut shims directly
- Measured longitudinal field
  - Used hall probe on track to measure longitudinal field

Brel and Normal Quad

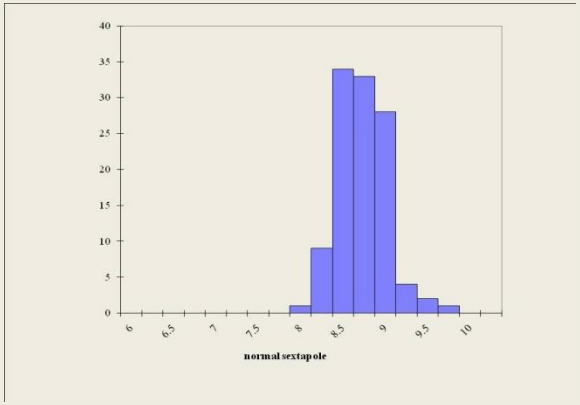


Histogram of
Quad gradient
measured/ ideal x 10^4
Specified 619 2 units
Held 619 -1 +2 units

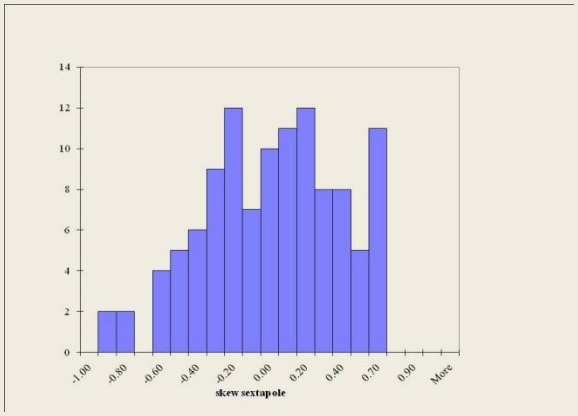


Histogram of
B measured/B ideal x 10^4
Specified 10 units
Held -6 + 8 units

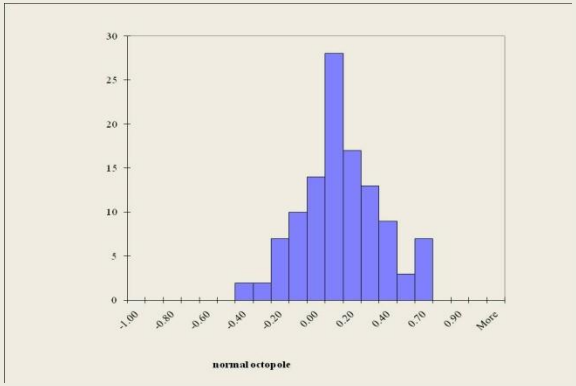
Higher Harmonics



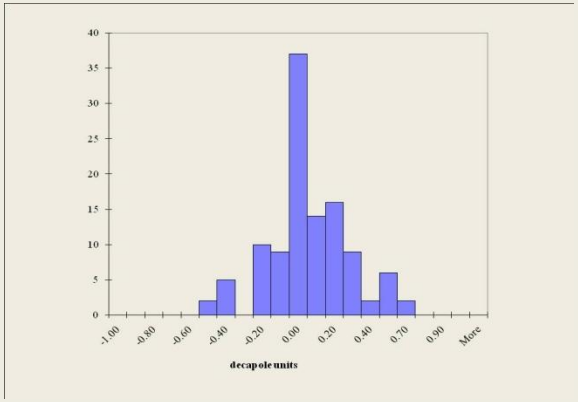
Normal Sextapole
Specified 8 ± 1 units
Held 8 ± 1 units



Skew Sextapole
Specified 0 ± 1 units
Held 0 ± 1 units

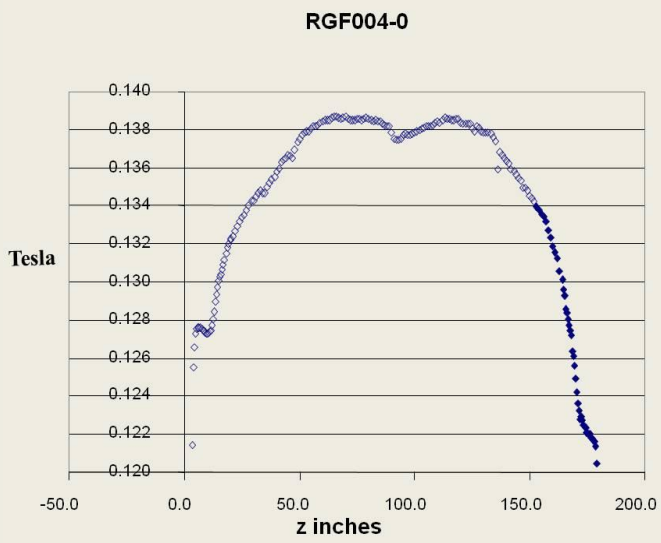


Normal Octopole
Specified 0 ± 1 units
Held 0 ± 0.5 units



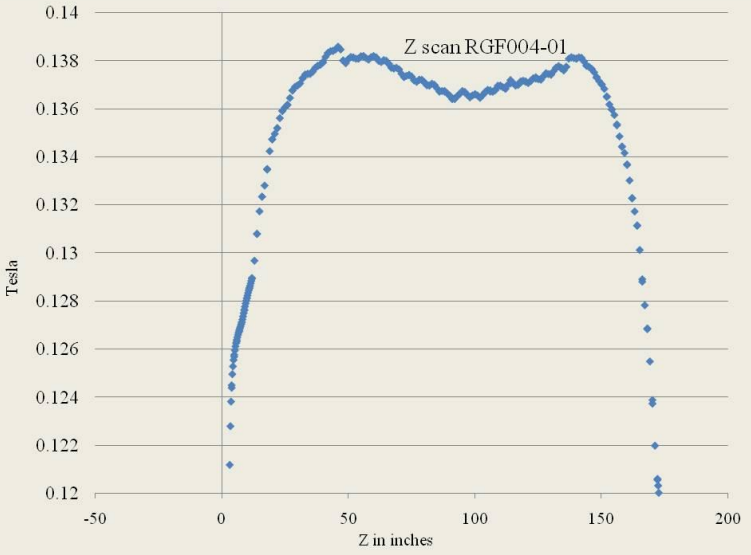
Decapole
Specified 0 ± 1
Held 0 ± 0.5

Longitudinal field

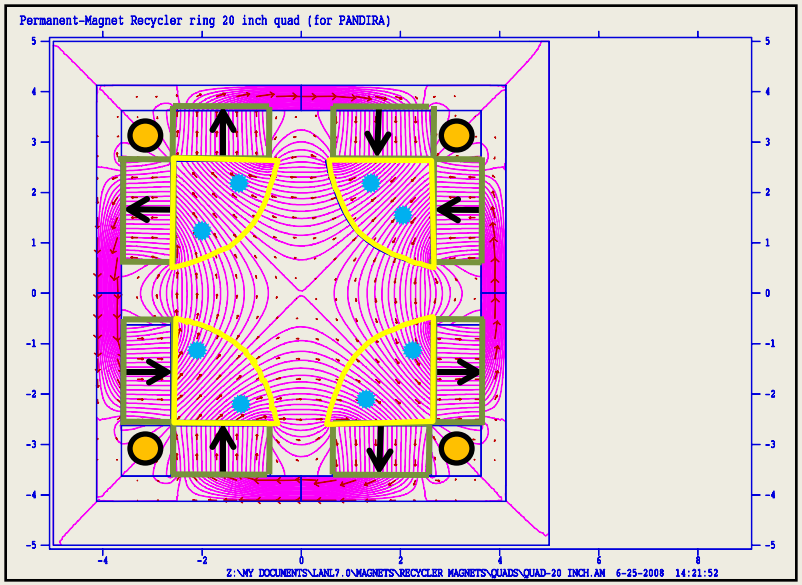


Even number of compensator strips between each magnet.

Varied number of compensator strips between each magnet
More strips close to center less at the ends.



Recycler Quadrupoles



PANDRIA model of the Recycler quadrupole

Poles

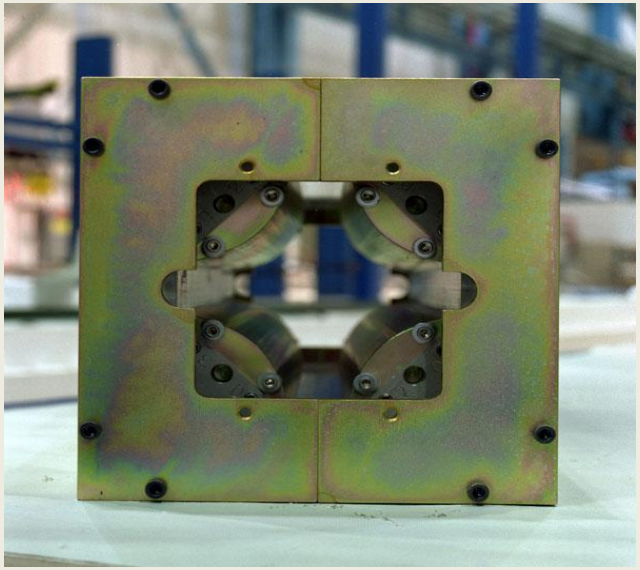
Magnets arrows show easy axis

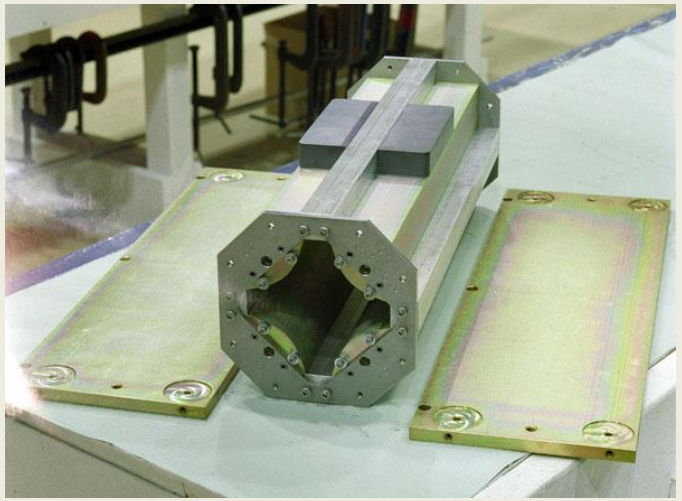
Washers to tune harmonics

Smaller washers were used on the pole faces to kill the decapole

Recycler Quads

End view showing poles





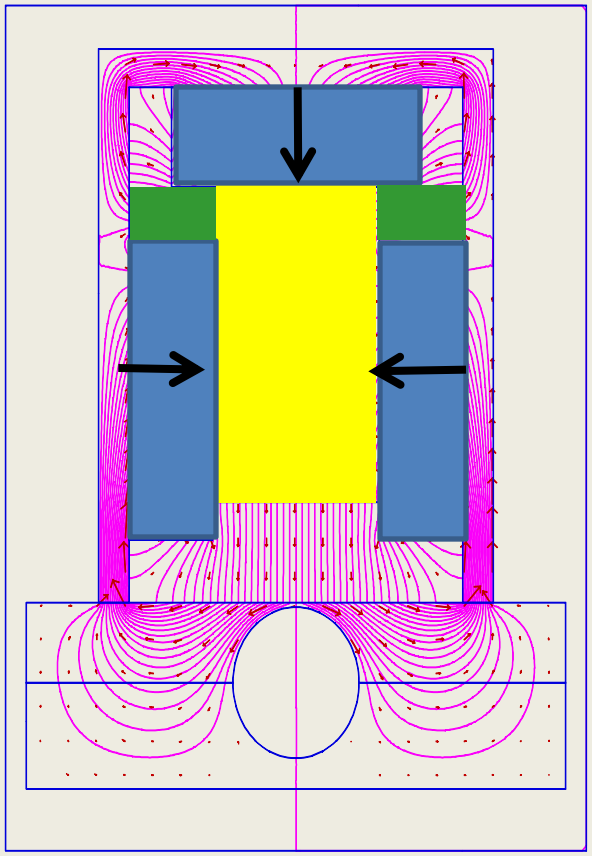
Flux returns open showing magnets

Tuning the Quads

- In each corner there was a tube 25.4 mm in diameter
- Steel washers were inserted on a SS threaded rod to adjust the gradient, sextupole and octopole.
- A program was written using the Morgan coil data to determine the correct number of washers to add
- The process converged in 3 to 5 attempts
- Small screws and washers were added to the pole face to eliminate the 10 pole

Lambertson Magnets

You need to get the beam in and out of the Recycler



Poles 101 mm wide 152 mm high

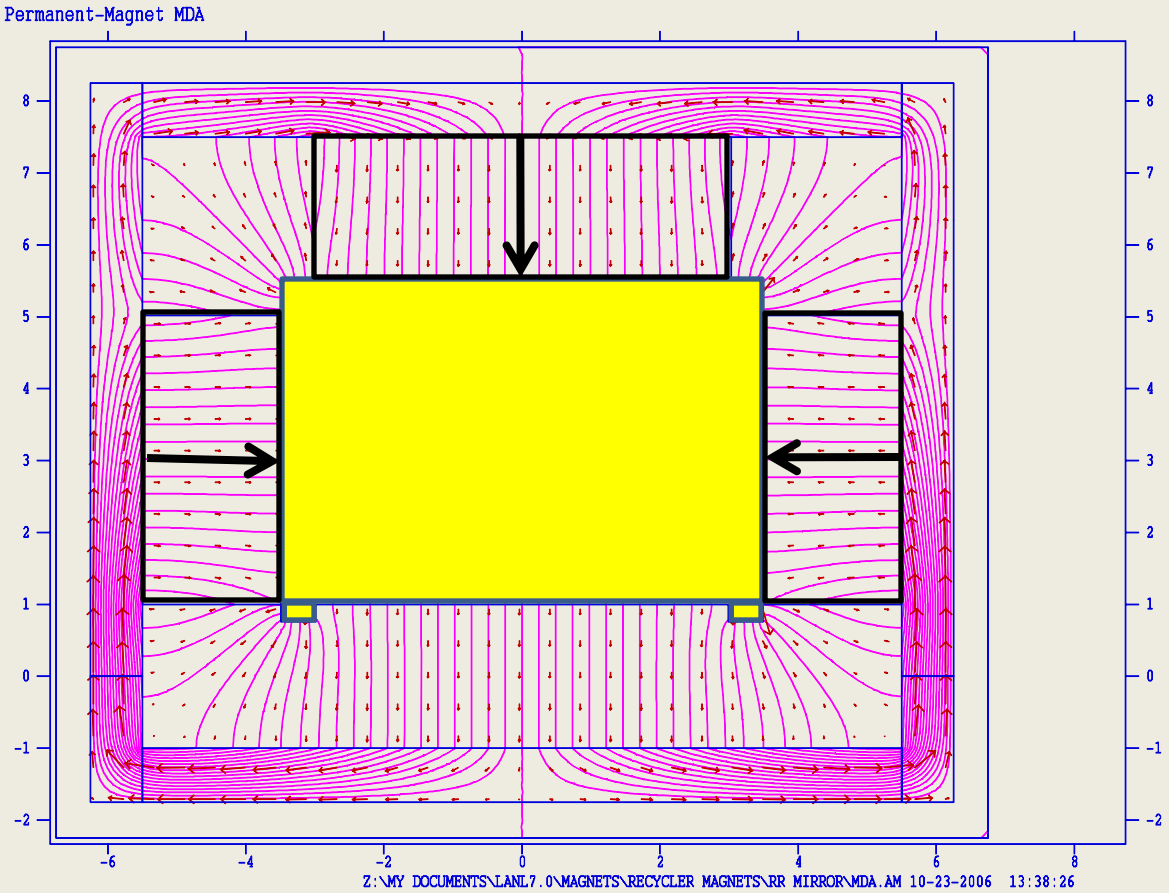
Strontium Ferrite
Used position of side bricks to adjust sextapole

Compensator

1700 Gauss in field region
5 Gauss in field free region

Mirror Magnets

Six of these were made for the injection and extaction

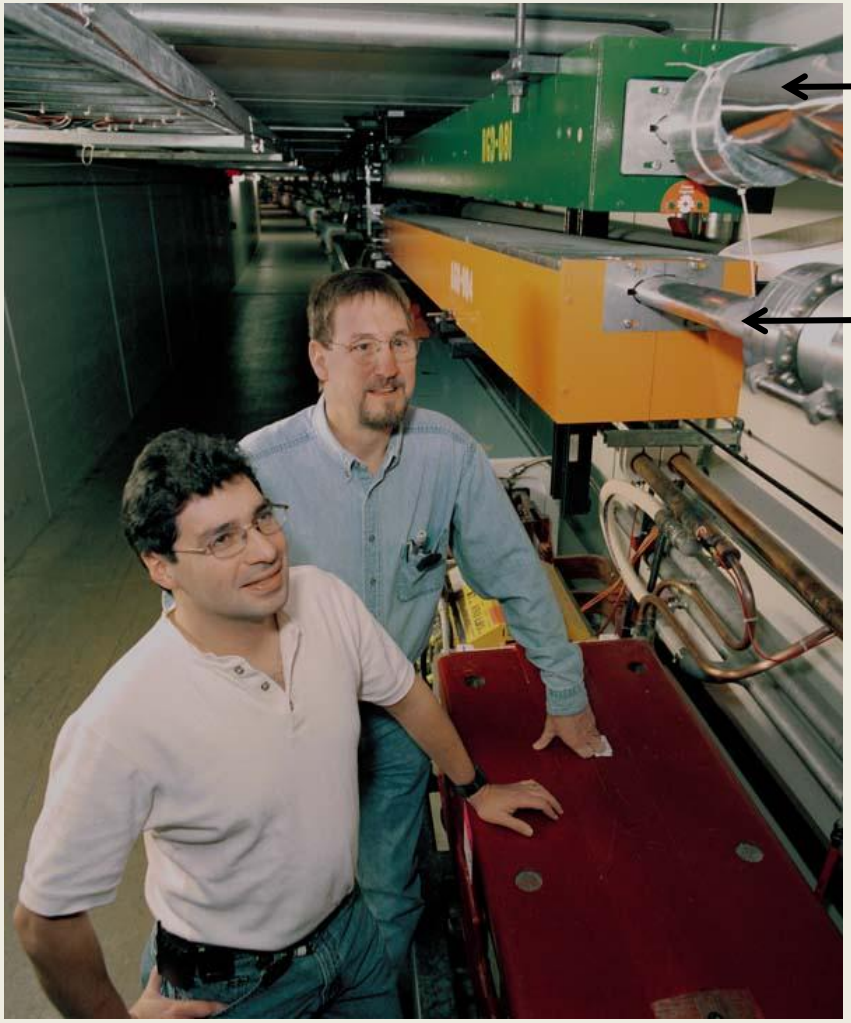


Gap is 50.8 mm by 152 mm

Pole note the small pieces were to reduce sextupole

Strontium Ferrite

Mirror Magnets

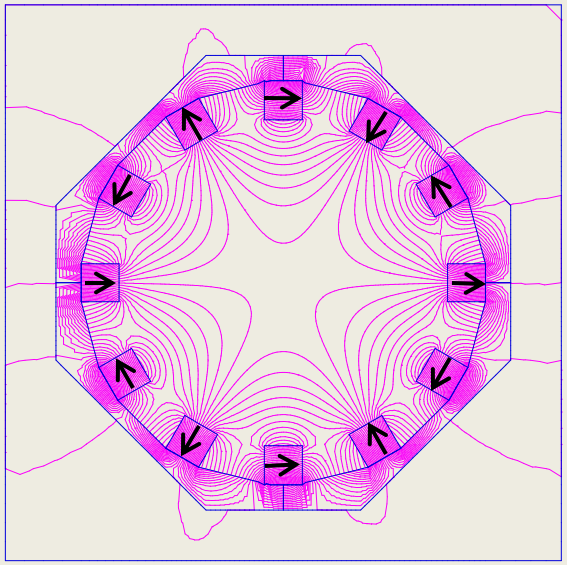


Recycler

Mirror magnet in transfer line

Dave Johnson and Cons Gattuso in the tunnel showing the recycler and mirror magnet.

Sextupole



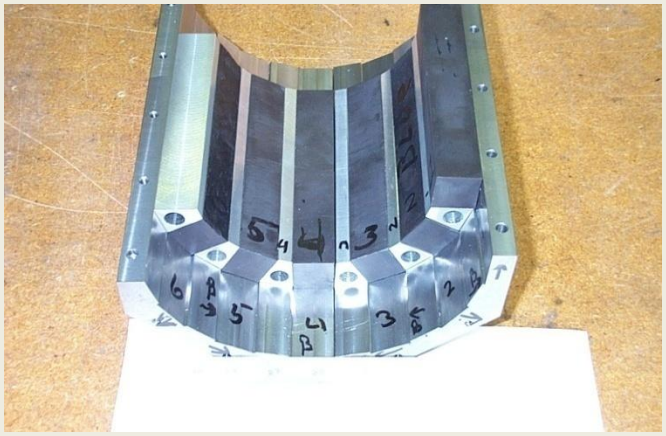
There was a need to cancel the sextupole moments of 4 recycler gradient magnets. To do this 4 permanent magnet sextupoles were built.

These were Halbach array style magnets with the easy axis alternating around a ring.

The gradients were between 300 and 400 Kilo-Gauss/m^2

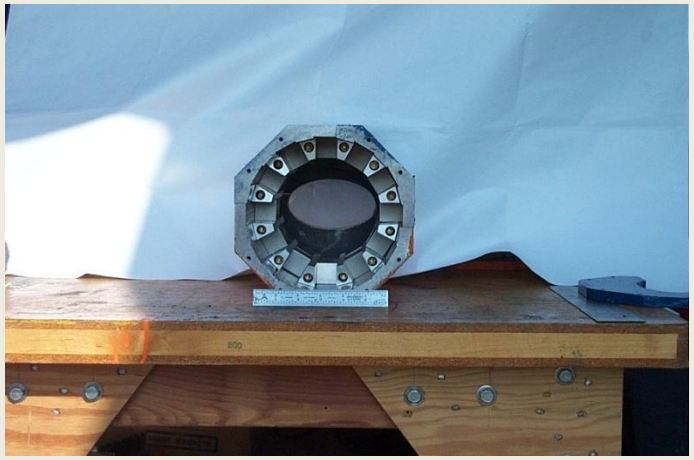
In the spaces between the magnets washers were placed to tune the harmonics

Construction of Sextupoles

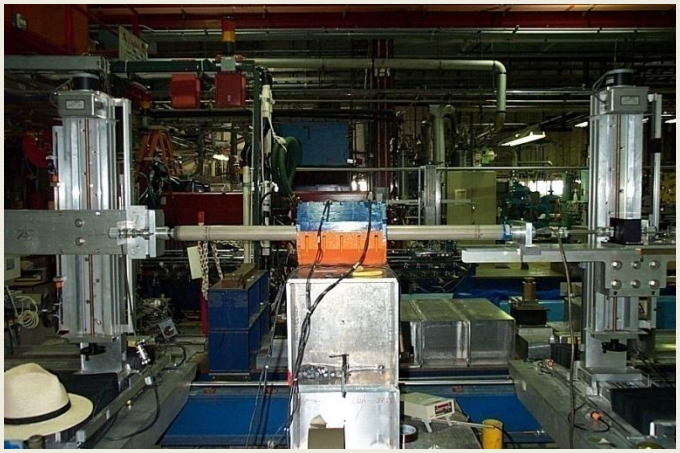


There were Aluminum spacers between each brick. The holes held steel rods and washers to allow for strength adjustments.

These magnets had to clamp around the beam pipe could not break vacuum. They were built in two sections that bolted together

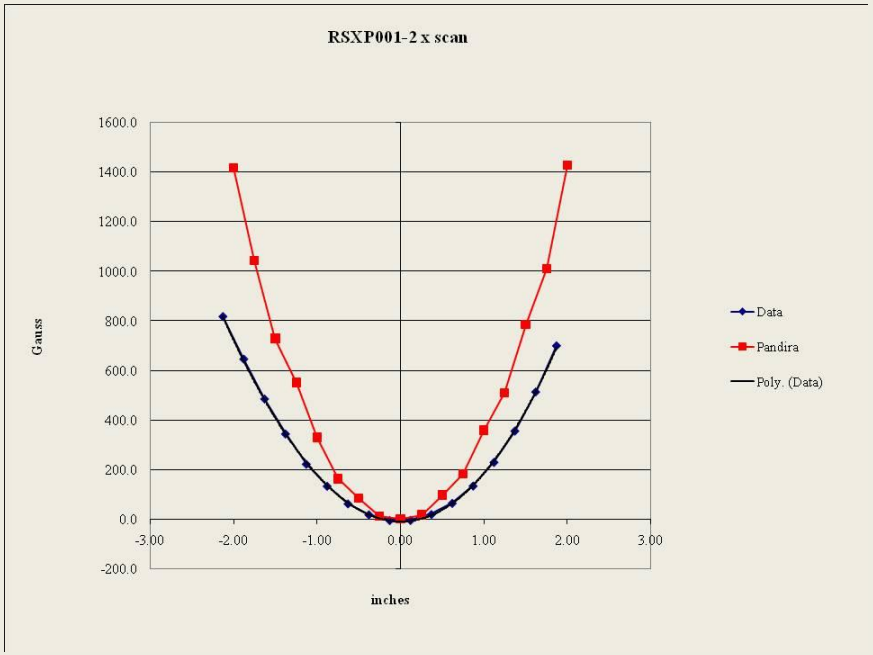


Measurements



Sextupole on the test stand at MTF.

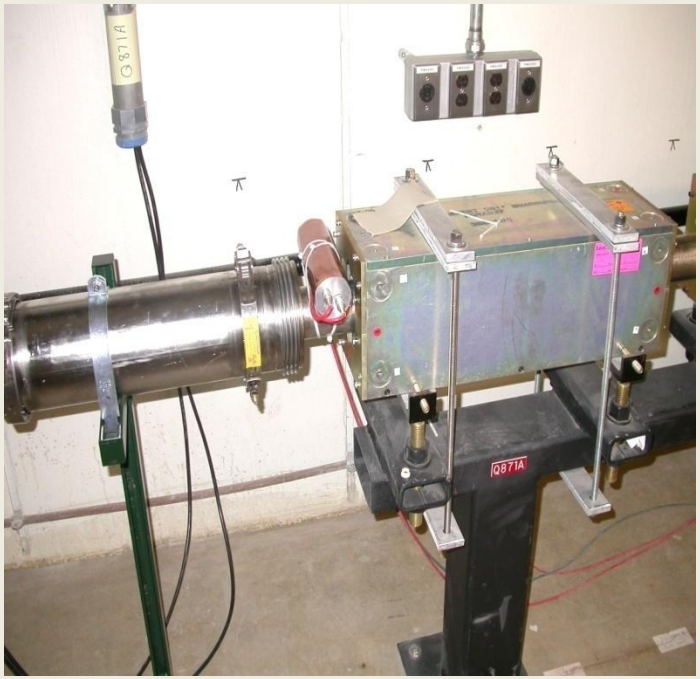
Hall probe scan of sextupole



Problems with the Recycler

- Heater tape
  - Stainless steel tape was added to the outside of the beam pipe for bake out
  - The μ of the tape changed as the tape work hardened
  - This introduced a sextupole moment that was un accounted for
  - The tape had to be removed and new tape installed
  - Should have tested field with beam pipe installed
- Vacuum
  - Vacuum took a long time to get to 10^{-11} Torr range necessary for storage ring
- Instrumentation
  - Not enough BPM and loss monitors at the beginning to determine orbits correctly

Mini Boone Beam Line

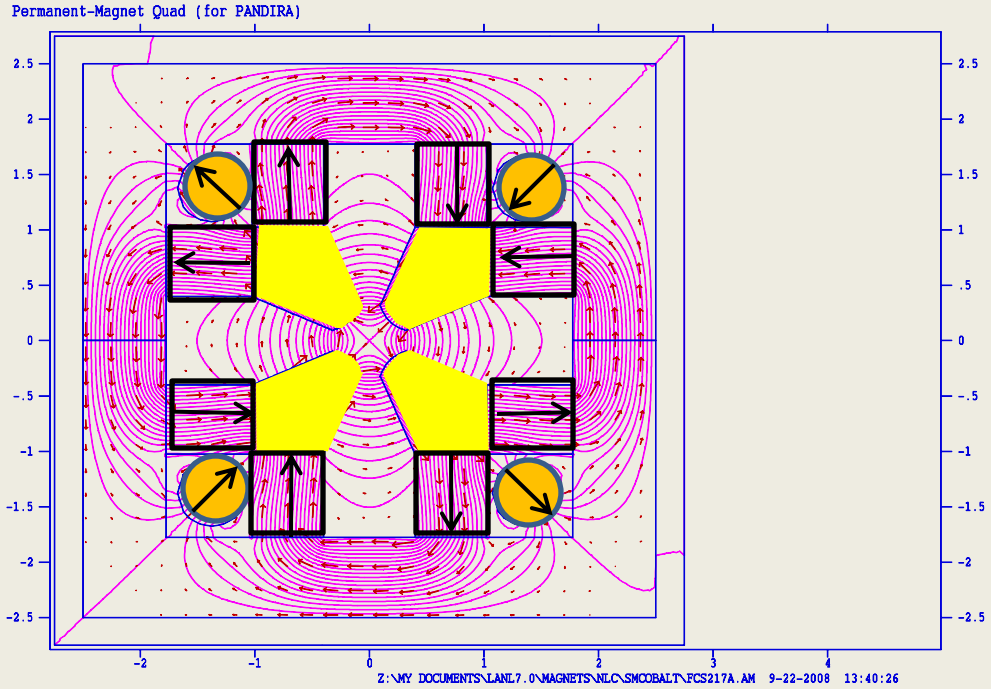


This is an 8 GeV transfer line from the booster to the Mini Boone target. PM quads were used with EM bends and trims

Adjustable Permanent Magnets Quadrupoles

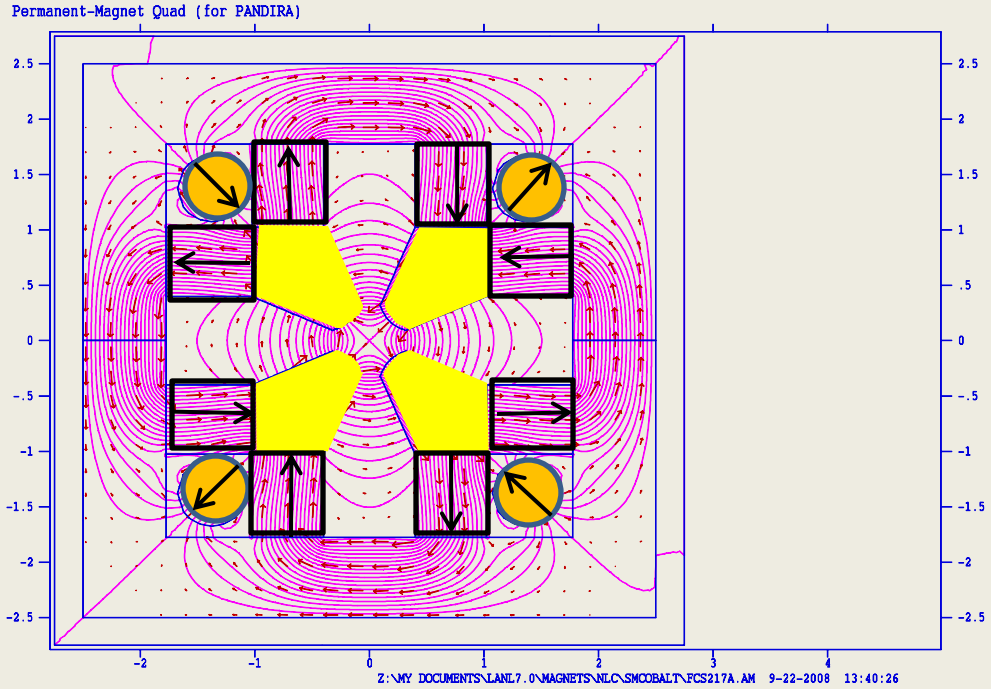
- Developed for the Next Linear Collider
- Quadrupoles were needed between RF cavities for focusing
- Also to be used for Beam Based Alignment (BBA)
- Aperture 12.7 mm
- Gradient on the order of 100 Tesla per meter
- Vary field by 20% for BBA
- Maintain center stability of field to within 1 micro meter

Corner Tuner based off of Recycler Quad



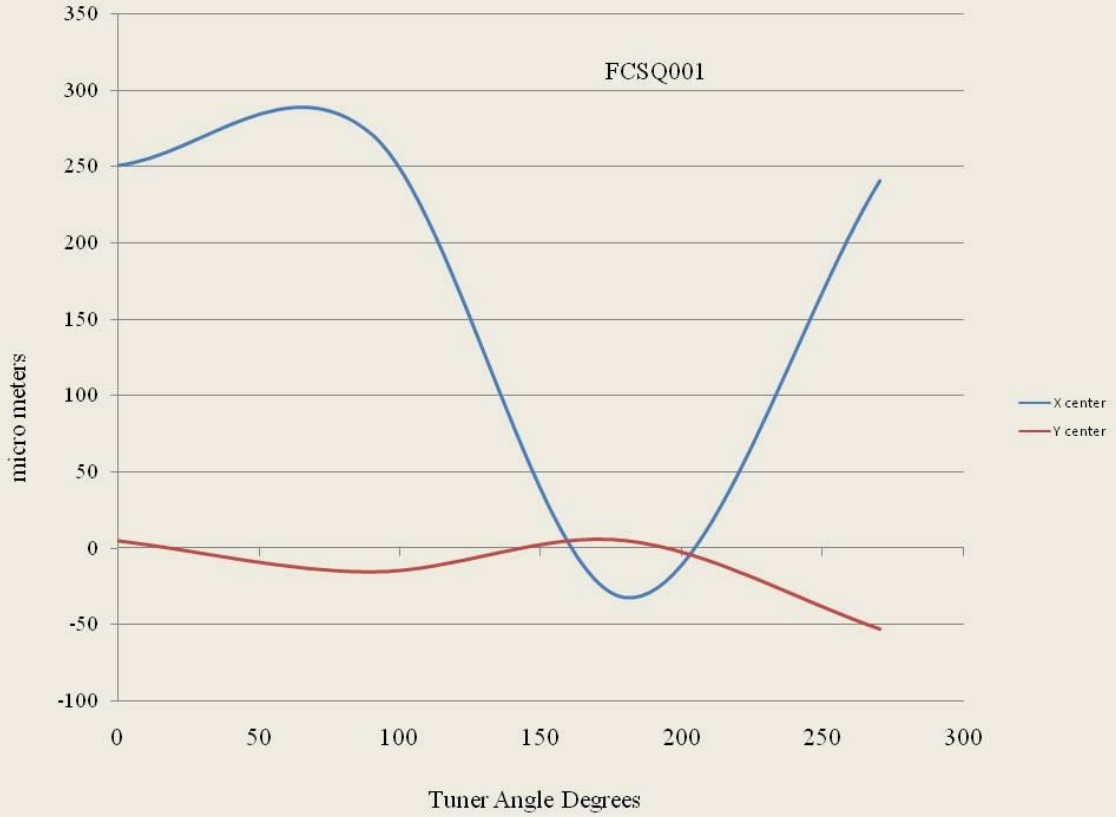
First try was a variation on the Recycler style quad. Instead of steel in the corners, rotating magnets were placed in the corners

Corner Tuner based off of Recycler Quad



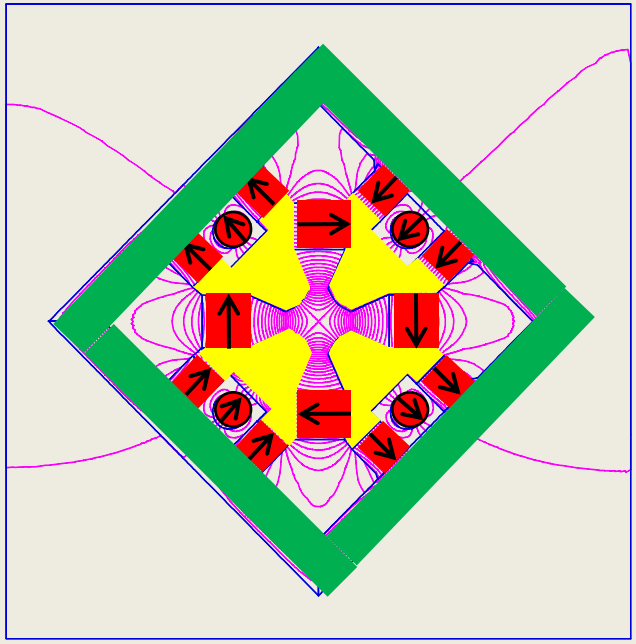
First try was a variation on the Recycler style quad. Instead of steel in the corners, rotating magnets were placed in the corners

Center Stability of Corner Tuner



Large variation of center with angle of tuning rod magnet was capable of 20% gradient change.

Wedge Quadrupole



Pole tips

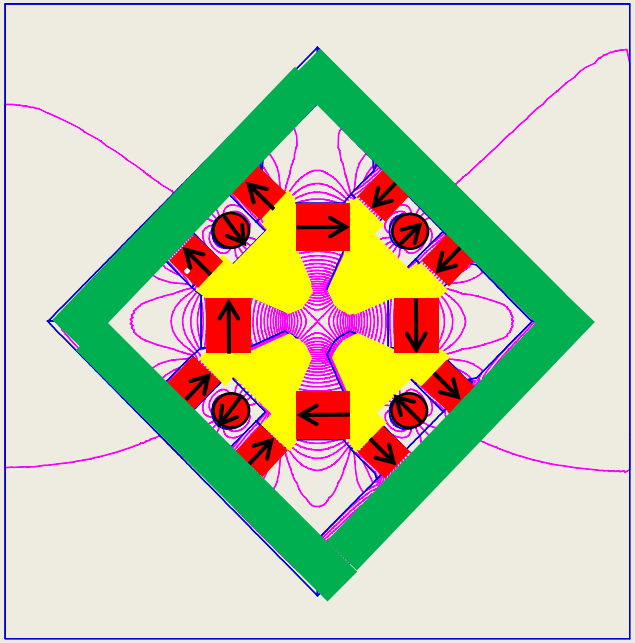
Wedge magnets

Pole magnets

Tuning rods shown in max field position

Flux returns

Wedge Quadrupole



Pole tips

Wedge magnets

Pole magnets

Tuning rods shown in max field position

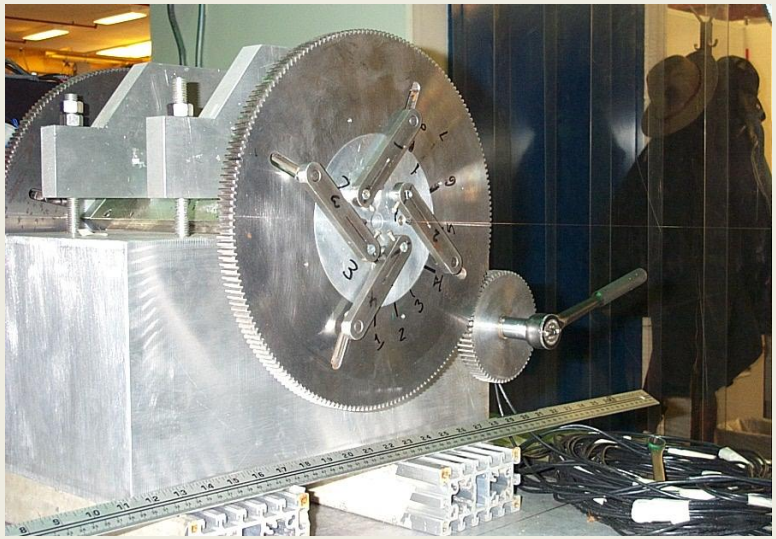
Flux returns

Wedge Quad Assembly and Test

Side view of magnet showing tuning rod

Quad setup for stretched wire measurements at MTF

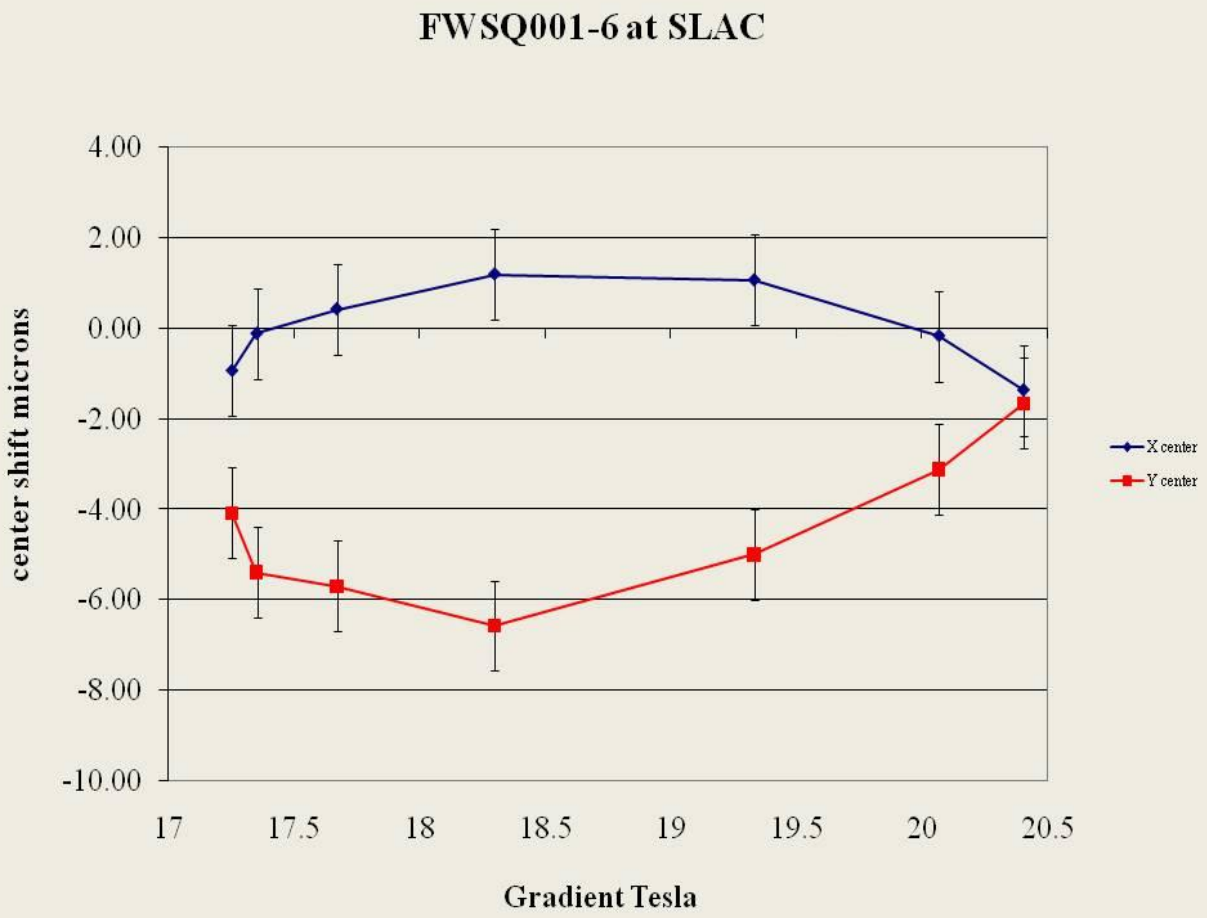
Measuring Wedge Quad at SLAC



Wedge quad on rotating coils test stand at SLAC

End of Wedge quad showing the rod turning mechanism

Center Stability of Wedge Quad



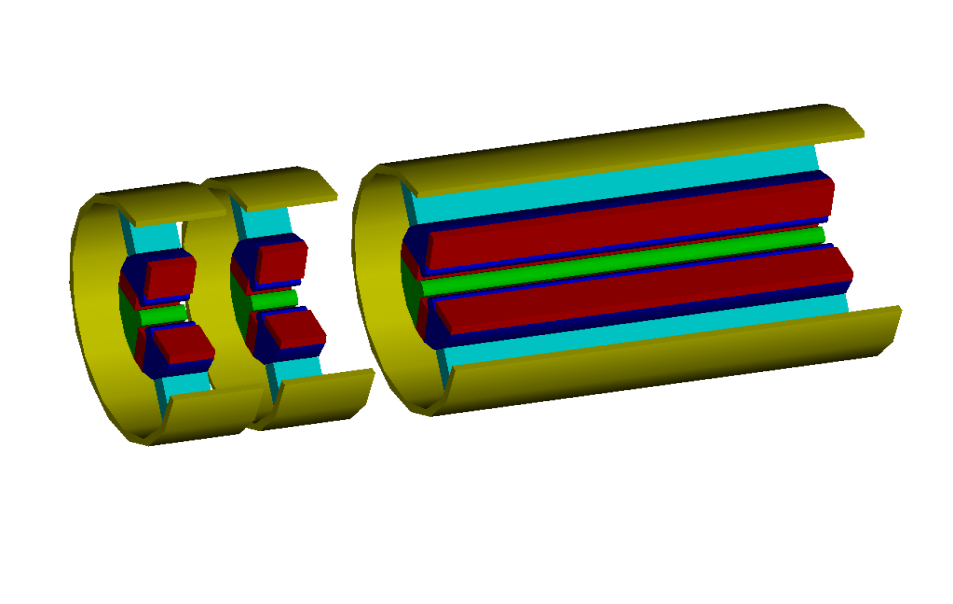
Data taken at SLAC with rotating coil

X center varies by 2 micro meters for 20% change in gradient

Y center varies by 4 micro meters for a 20% change in gradient

Magnets in rods not totally balanced

Counter Rotating Quads

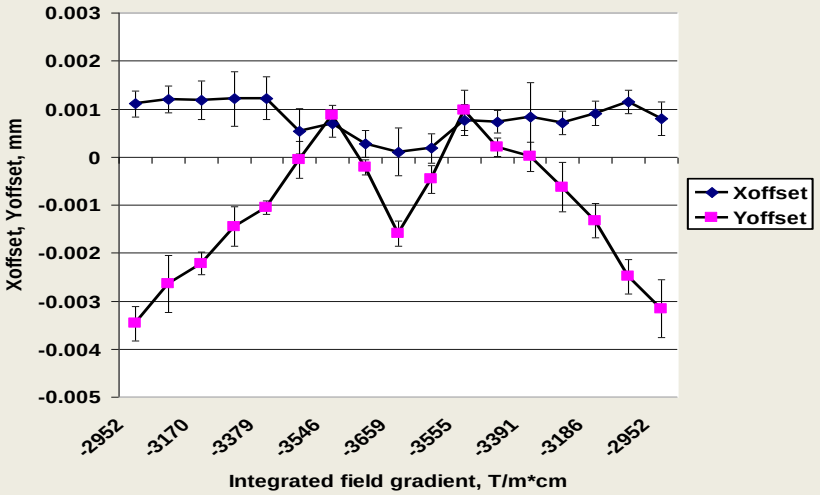


Use fixed permanent magnet quad and two smaller rotating quads to adjust the gradient

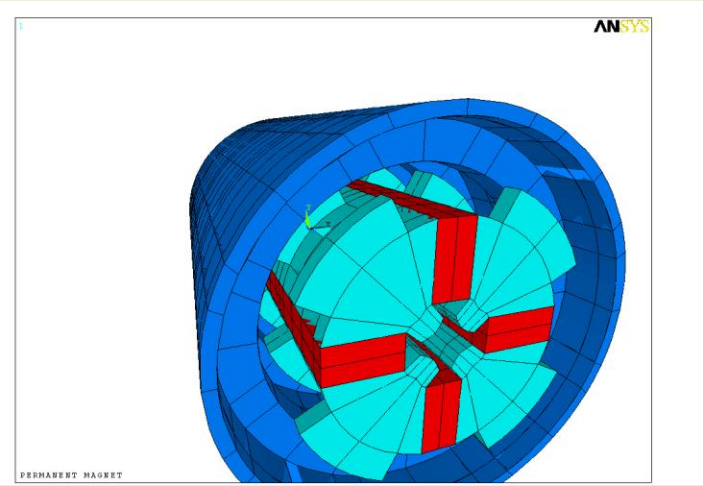
Counter Rotating Quadrupoles

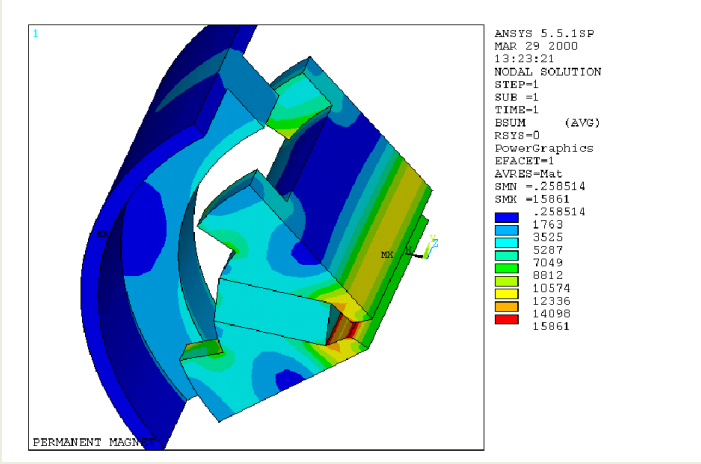
Vladimir Kashikhin of Fermilab developed a set of counter rotating quadrupoles. The two inner quads rotated on a stand relative to the outer quads to vary the field.

The center stability was better than 5 micro meters over the 20% change in fields

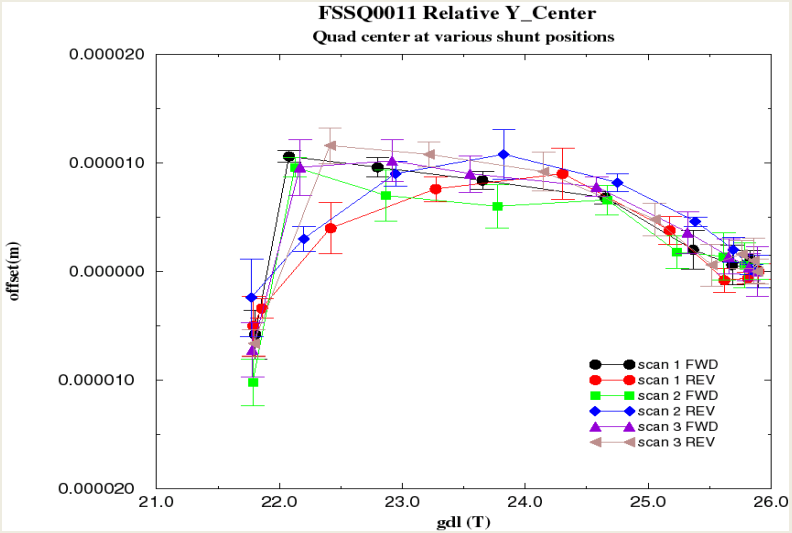


Rotating Shunt Quadrupole



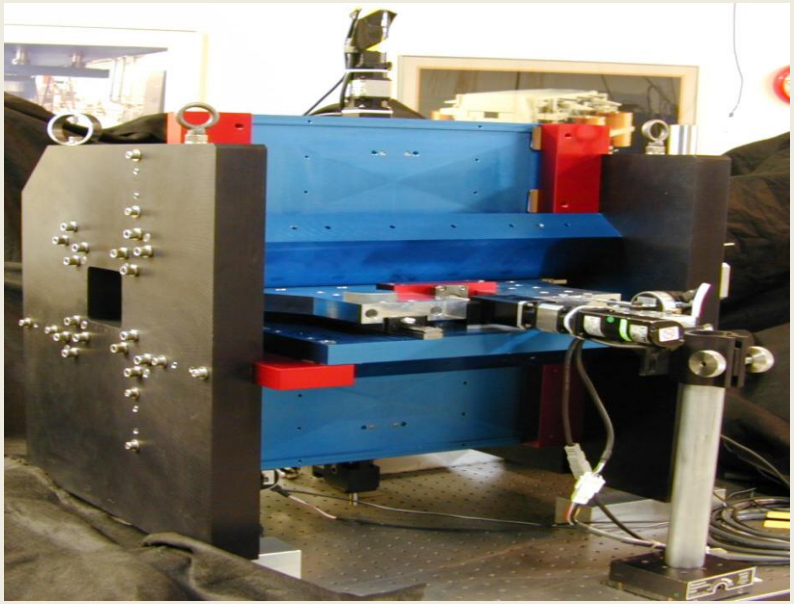


Vladimir Kashikhin of Fermilab developed a rotating shunt quad. The permanent magnet material is in red and the steel shunts are blue

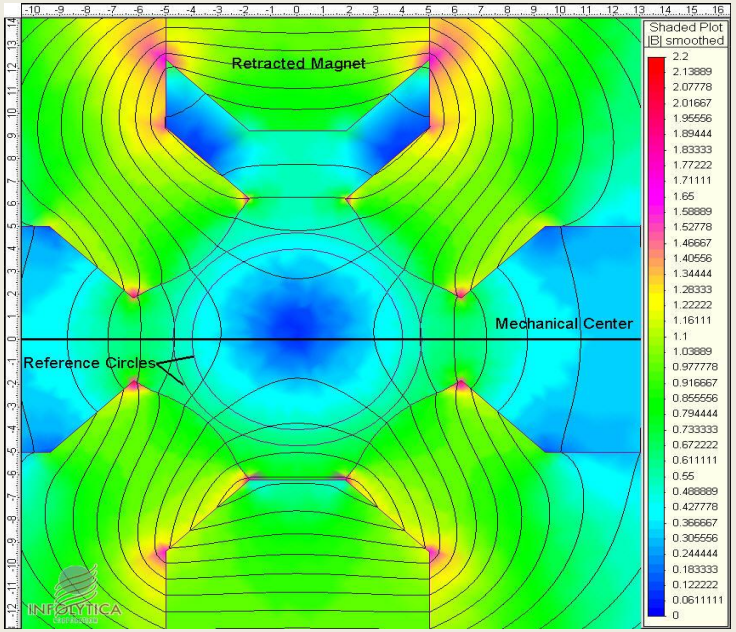


The center stability less than 1 micron
See Magnet Technologies 17 for paper

Moving Magnetic Material to Change the Gradient

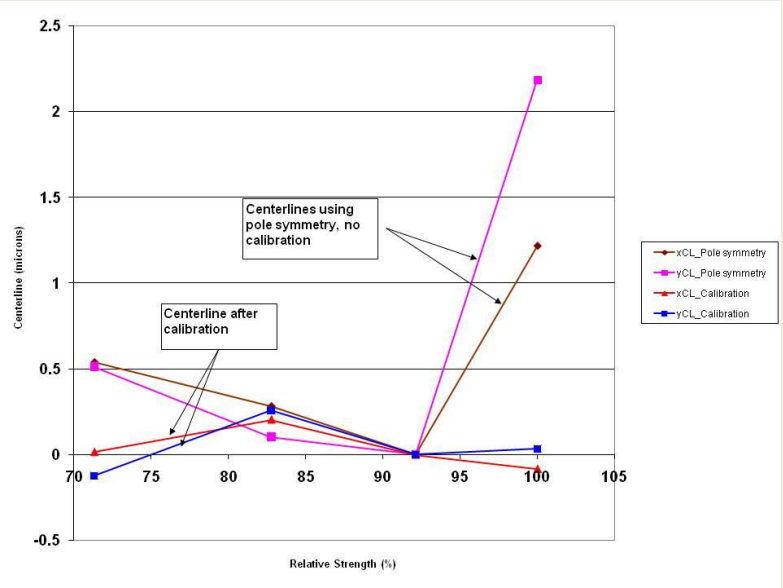


Steve Gottschalk of STI Optronics
Seattle Washington developed an adjustable quadrupole based on moving the magnetic material.
See PAC 2005 for paper

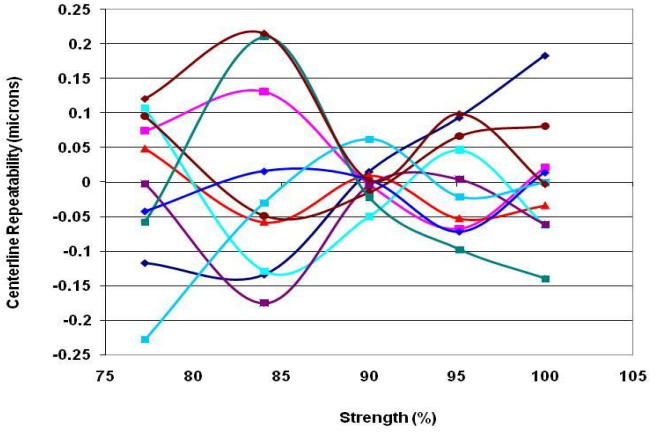


They were able to balance the different fields in the magnet material by placement of the magnets. The magnetic center stability is better than 0.5 micrometers over a 20% change

Center Line Shift

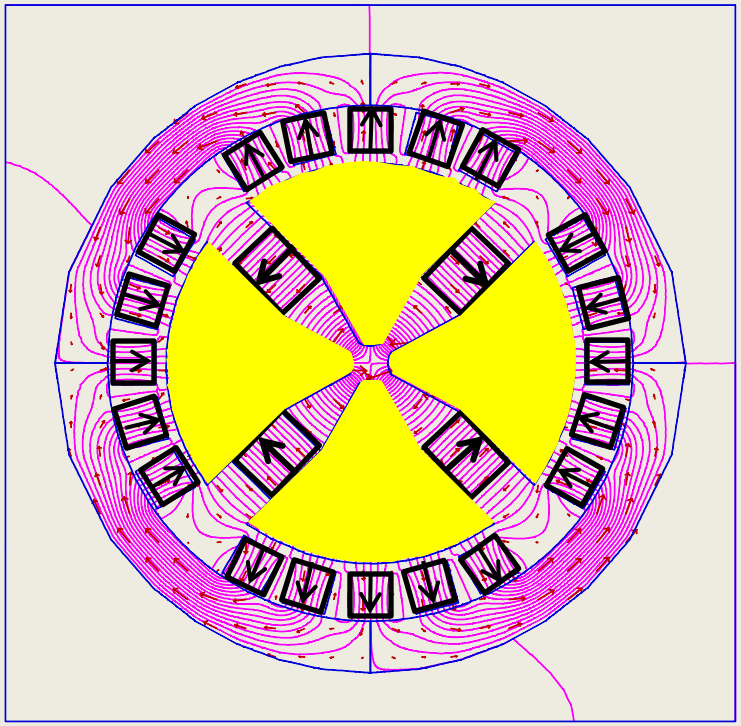


Multiple passes varying strength by 30% total shift less than 0.5 micro meters



Variation in strength for tuners before and after adjustment of position

Halbach Ring Quad



Another type of adjustable quad, the outer ring of magnets rotates to change the field.

This was designed but the NLC was canceled before it was built

Permanent Magnets and CLIC

PARAMETER SCAN FOR THE CLIC DAMPING RINGS

Y. Papaphilippou, H.H. Braun, CERN, Geneva, Switzerland M. Korostelev Cockroft Institute, UK

EPAC 2008

Parameter Unit	Symbol	New value 2005	Old value 2007
beam energy [GeV]	E_b	2.424	2.424
circumference [m]	C	360	365.2
bunch population [10^9]	N	110	312
bunch spacing [ns]	T_{sep}	0.533	0.5
bunches per train	N_b	110	312
number of trains	N_{train}	4	1
store time / train [ms]	t_{store}	13.3	20
rms bunch length [mm]	σ_z	1.547	1.53
rms momentum spread [%]	σ_δ	0.126	0.143
final hor. emittance [nm]	$\gamma\varepsilon_x$	550	381
hor. emittance w/o IBS [nm]	$\gamma\varepsilon_{x0}$	134	84
final vert. emittance [nm]	$\gamma\varepsilon_y$	3.3	4.1
coupling [%]	κ	0.6	0.13
vertical dispersion invariant	$\mathcal{H}_y$	0	0.248
no. of arc bends	n_{bend}	96	100
arc-dipole field [T]	B_{bend}	0.932	0.932
length of arc dipole [m]	l_{bend}	0.545	0.545
arc beam pipe radius [cm]	b_{arc}	2	2
number of wigglers	n_w	76	76
wiggler field [T]	B_w	1.7	2.5
length of wiggler [m]	l_w	2.0	2.0
wiggler period [cm]	λ_w	10	5
wiggler half gap [cm]	b_w	0.6	0.5
mom. compaction [10^{-4}]	α_c	0.796	0.804
synchrotron tune	Q_s	0.005	0.004
horizontal betatron tune	Q_x	69.82	69.84
vertical betatron tune	Q_y	34.86	33.80
RF frequency [GHz]	f_{RF}	1.875	2
energy loss / turn [MeV]	U_0	2.074	3.857
RF voltage [MV]	V_{RF}	2.39	4.115
h/v/l damping time [ms]	$\tau_x/\tau_y,/\tau_s$	2.8/2.8/1.4	1.5/1.5/0.76
revolution time [μs]	T_{rev}	1.2	1.2
repetition rate [Hz]	f_{rep}	150	50

Permanent Magnets and CLIC

PARAMETER SCAN FOR THE CLIC DAMPING RINGS

Y. Papaphilippou, H.H. Braun, CERN, Geneva, Switzerland M. Korostelev Cockroft Institute, UK

EPAC 2008

Parameter Unit	Symbol	New value 2005	Old value 2007
beam energy [GeV]	E_b	2.424	2.424
circumference [m]	C	360	365.2
bunch population [10^9]	N	110	312
bunch spacing [ns]	T_{sep}	0.533	0.5
bunches per train	N_b	110	312
number of trains	N_{train}	4	1
store time / train [ms]	t_{store}	13.3	20
rms bunch length [mm]	σ_z	1.547	1.53
rms momentum spread [%]	σ_δ	0.126	0.143
final hor. emittance [nm]	$\gamma\varepsilon_x$	550	381
hor. emittance w/o IBS [nm]	$\gamma\varepsilon_{x0}$	134	84
final vert. emittance [nm]	$\gamma\varepsilon_y$	3.3	4.1
coupling [%]	κ	0.6	0.13
vertical dispersion invariant	$\mathcal{H}_y$	0	0.248
no. of arc bends	n_{bend}	96	100
arc-dipole field [T]	B_{bend}	0.932	0.932
length of arc dipole [m]	l_{bend}	0.545	0.545
arc beam pipe radius [cm]	b_{arc}	2	2
number of wigglers	n_w	76	76
wiggler field [T]	B_w	1.7	2.5
length of wiggler [m]	l_w	2.0	2.0
wiggler period [cm]	λ_w	10	5
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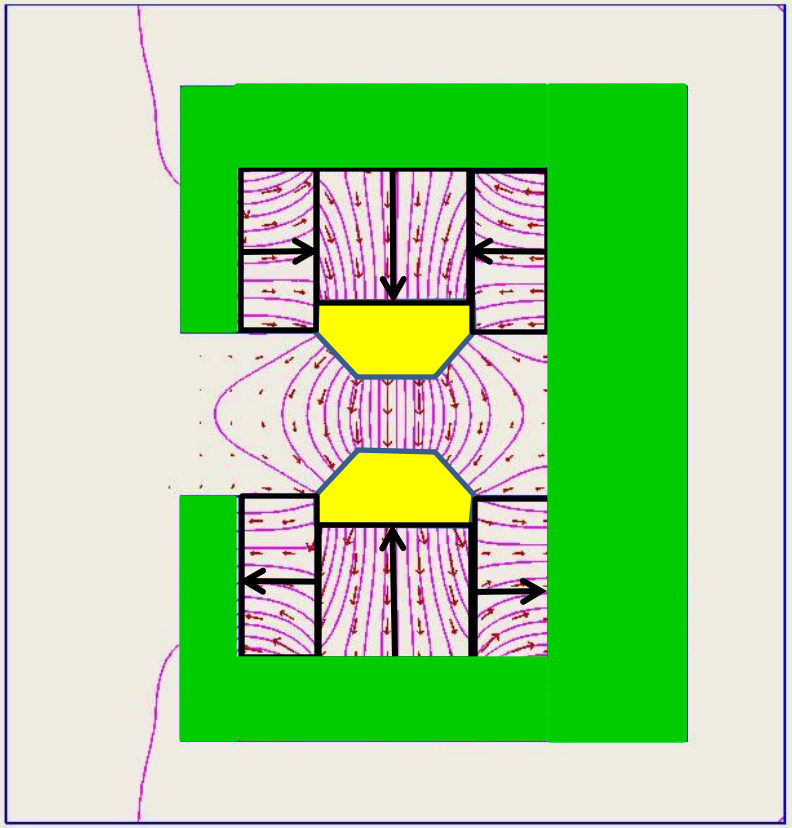
h/v/l damping time [ms]	$\tau_x/\tau_y,/\tau_s$	2.8/2.8/1.4	1.5/1.5/0.76
revolution time [μs]	T_{rev}	1.2	1.2
repetition rate [Hz]	f_{rep}	150	50

0.932 Tesla bend field

2 cm pipe radius

23 mm Gap C Magnet



Poles

Magnet material samarium Cobalt

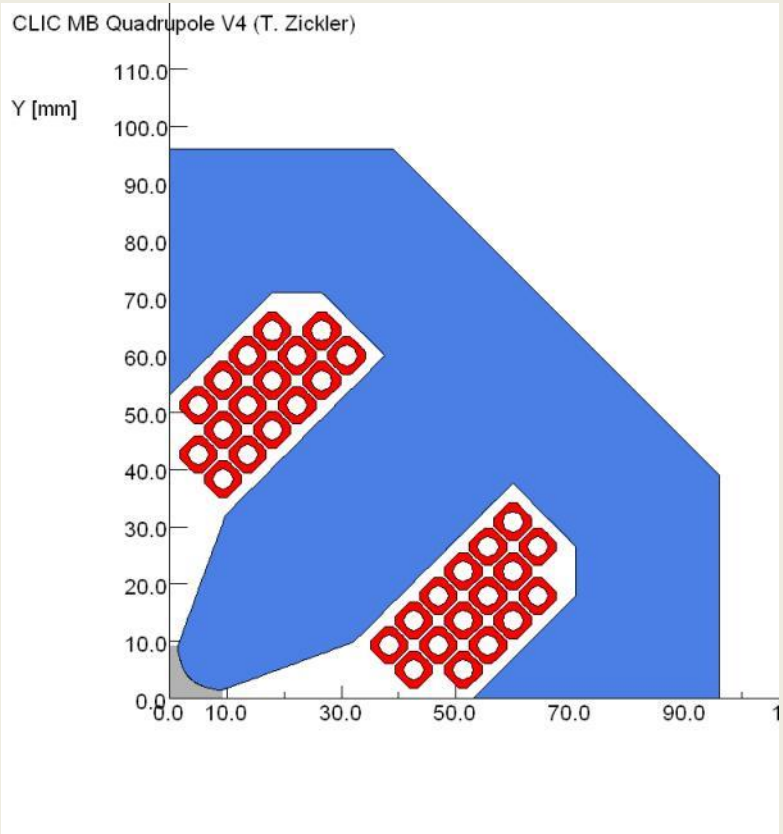
Flux returns

23 mm gap
1.08 Tesla 13% higher
35 units of sextapole
20 units of decapole
These can be fixed with pole shaping and end shims

From CLIC Nano Stablization page

Thomas Zickler

Quadrupole Magnet	
Nominal Gradient	200.1 T/m
Nominal integrated Gradient	370.0 T/m
Aperture radius	5.0 mm
Iron Length	1844.0 mm
Effective length	1849.0 mm
Total magnet weight	393.3 kG
Total magnet width	192.0 mm
Total magnet height	192.0 mm



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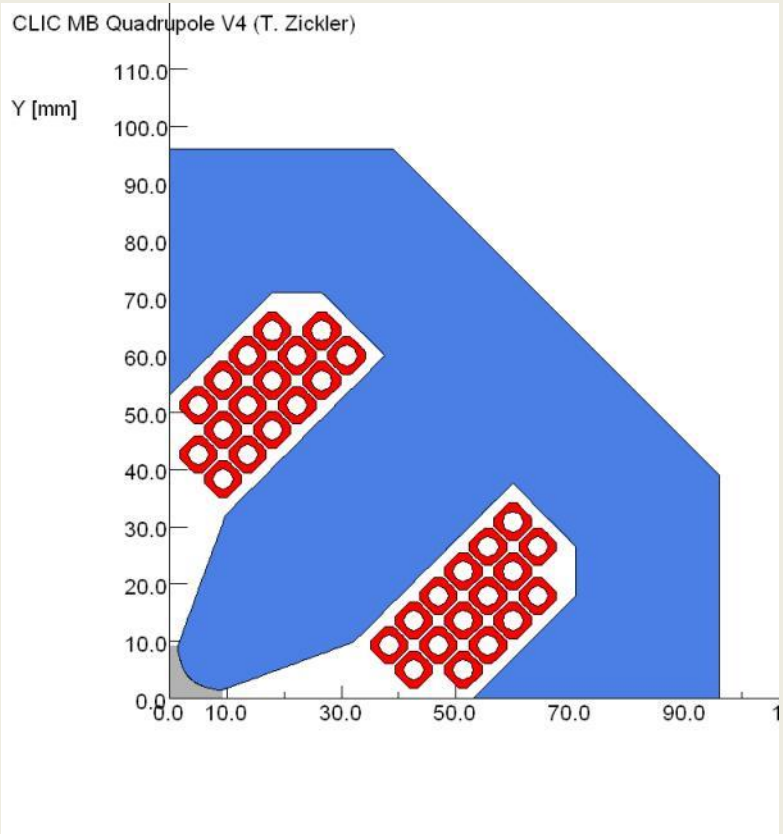


CLIC Quadrupole

Nominal Gradient 200.1 Telsa/meter
Aperture radius 5 mm

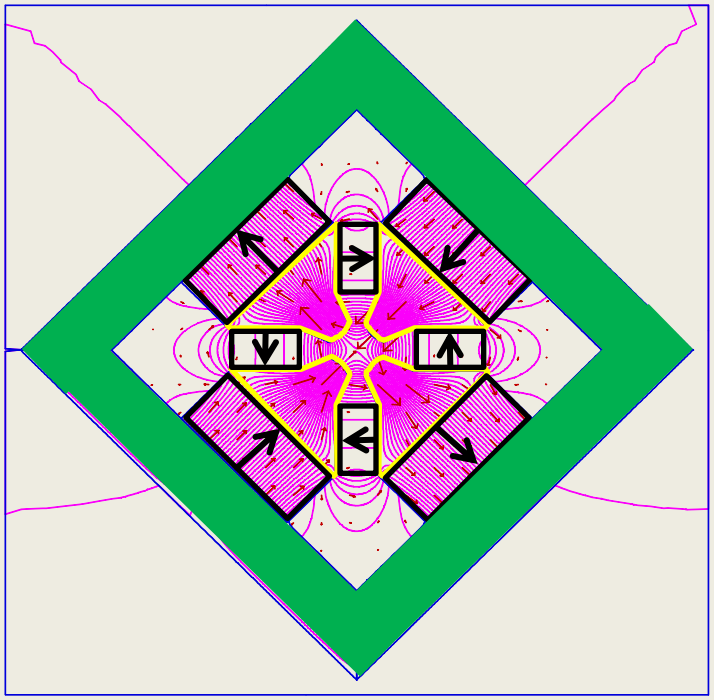
Variation on Wedge quad
developed for NLC

Poles with 6.25 mm aperture radius

Magnet material Ne-Fe-B magnets

201.1 mm outside dimension

208 Tesla/m gradient



An Adjustable Quad

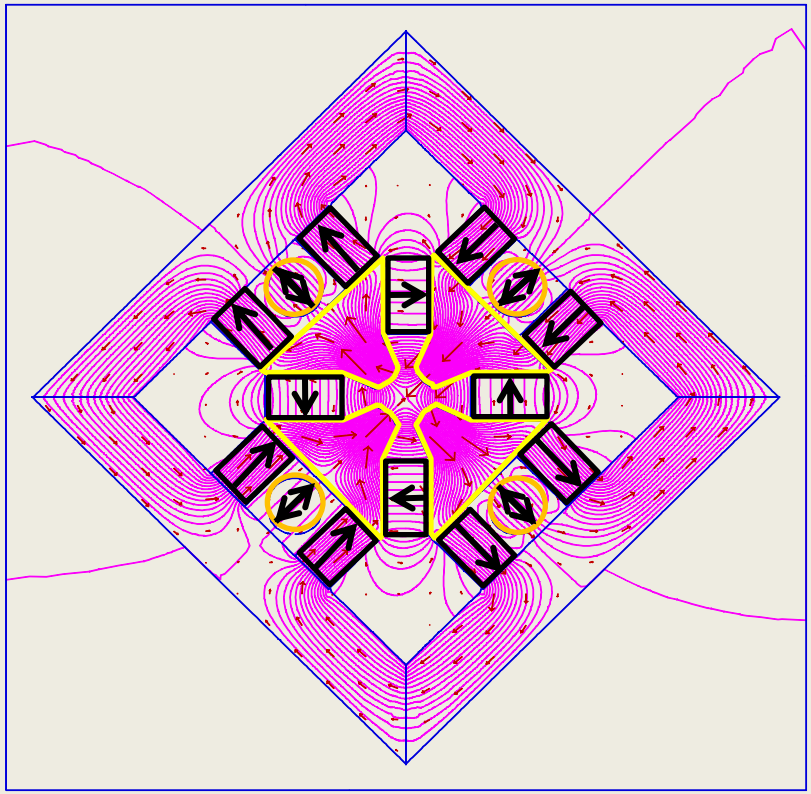
Same as before

12.5 mm gap

Ne-Fe-B magnets

200 T/m tuners forward

180 T/m tuners reversed



Conclusions

- Permanent magnets are the solution for fixed energy beam lines and storage rings
  - Permanent magnets are stable in both time and temperature
  - Permanent magnets are radiation hard
  - For any fixed energy beam line or storage ring permanent magnets are the first choice; the use of electromagnets must be justified!
  - No power supplies or LCW -- this means no vibrations very important for storage and damping rings

- Adjustable permanent quads can be made that are equal to if not better than electro magnets
  - Several different styles of adjustable quads were designed and built for the NLC
  - Several met the spatial stability specifications
  - One exceeded the spatial stability specifications

Thank you

Questions?