Resistive & Permanent Magnets for Accelerators

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Introduction

- Magnets are an important part of accelerator technology
  - Many accelerators are “mostly magnets”
- Particle accelerators operate with charged particle beams (e.g. electron, protons, ions, positrons, antiprotons etc)
  - Interaction of these charged particles and the magnet field allows manipulation of the beam

$$\overrightarrow{F} = e\vec{v} \times \vec{B}$$

Uses of Magnets in Accelerators

- Bending or Directing of Beam
  - Dipoles
- Focusing of Beam
  - Quadrupoles
- Beam Correction
  - Sextupoles and higher
- Beam "Compression" or Energy Separation
  - Chicanes using dipoles
- Background field for detectors
  - Solenoids
- Moving charged particles to create synchrotron light
  - Wigglers, Undulators

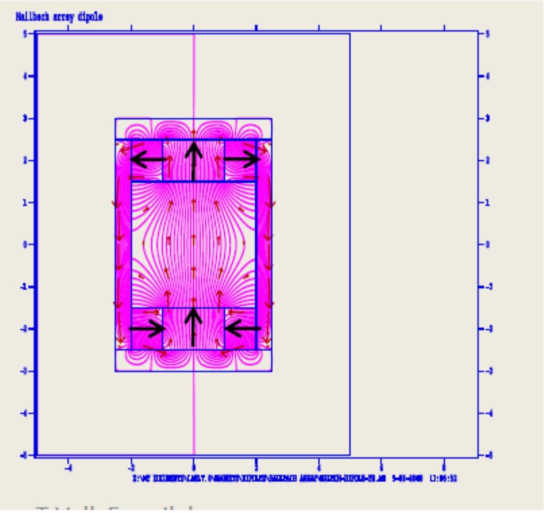
A key issue is field uniformity
<u>Having the right field in the right place</u>

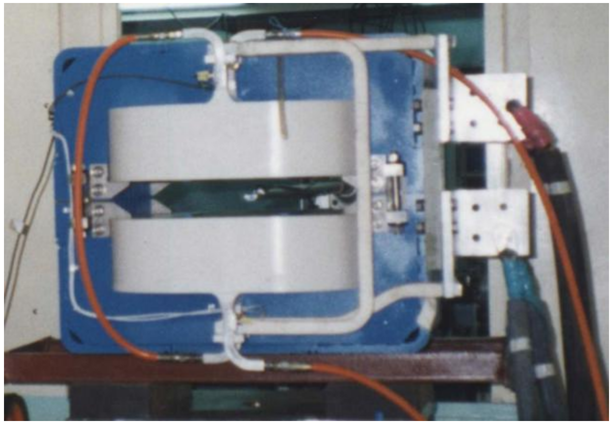
Magnetic Design

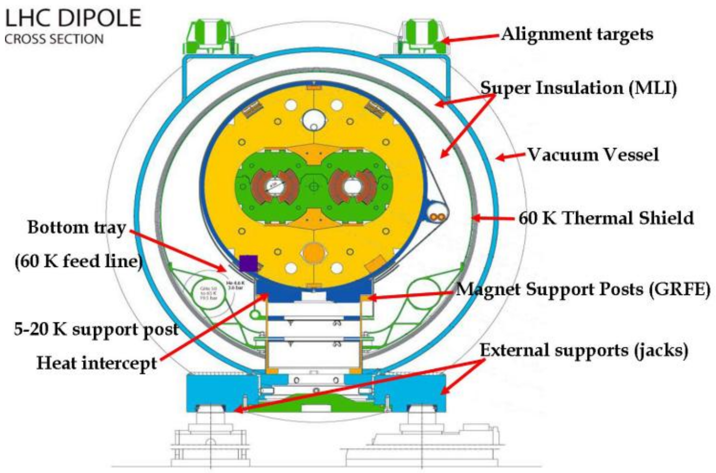
- Modern magnets are designed using a variety of modeling software (both 2D & 3D)
  - ANSYS
  - MAXWELL
  - TOSCA
  - POISSSON and PANDRIA
  - OPERA
- Programs are based on standard EM theory and most use Finite Element Analysis (FEA)
- Programs take into account material properties
- Some approximate equations will be given later

Magnet Technology Choices

- Permanent
- Resistive
- Superconducting







Relative Merits

Type	Advantages	Disadvantages
Permanent	Compact Low cost (in small low field magnets) No utilities required No maintenance Simple to operate – no adjustments required Can result in very precise fields (FEL undulators)	Constant field (mostly) Limited in field
Resistive	Variable field No need for complicated cryogenic or vacuum systems Can be built in house or through existing industrial base Relatively low capital cost	Limited in field (up to ~ 2 T) May require large amounts of electrical power and cooling water – complicated Possible tritium issue Possible large operating costs for power & water

Relative Merits

Type	Advantages	Disadvantages
Superconducting	High field Variable field Lower operating costs Reliability Cold beam tubes yield very high vacuums Can be made compact	High capital costs Limited industrial base Requires complicated ancillary systems – cryogenics, vacuum, quench protection

- Technology choice depends on accelerator requirements
  - All design is compromise
- Requirements for higher energy beams frequently dominate
- Permanent and resistive magnets discussed in this talk
- Next talk discusses superconducting magnets

Permanent Magnets

- Much of this material is taken from Jim Volk Fermilab Physicist
- Permanent magnets are used in very sophisticated ways in particle accelerators
  - Fermilab 8 GeV recycler ring is almost entirely permanent magnets
  - Precision fields in undulators
- Used where high field strength or field variation is not a requirement
  - Required field must be well known and unchanging

Permanent Magnet Materials

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

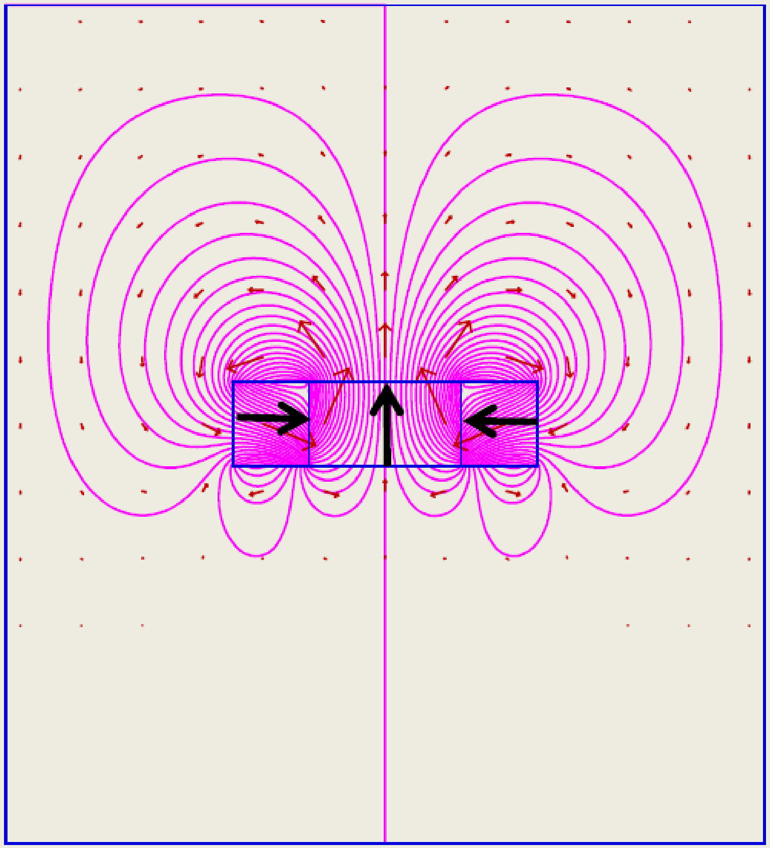
Samarium Cobalt
Rare earth
Expensive
B_r 9000 to 10,000 gauss
Energy density 26 MegaGauss Oersteds

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

Note 10,000 Gauss = 1 T

Courtesy
J. Volk

Hallbach 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.

The easy axis is the direction of field in material

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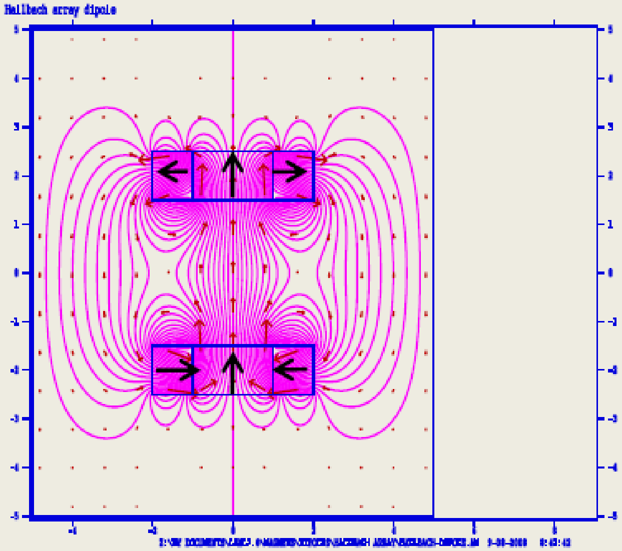
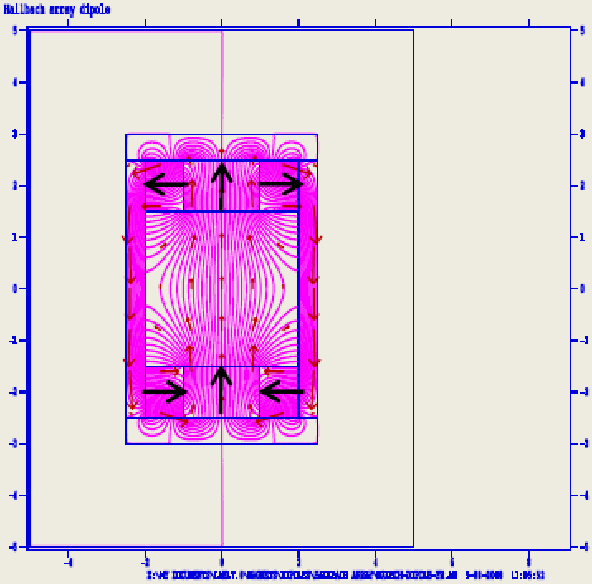
Hallbach Dipole



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.



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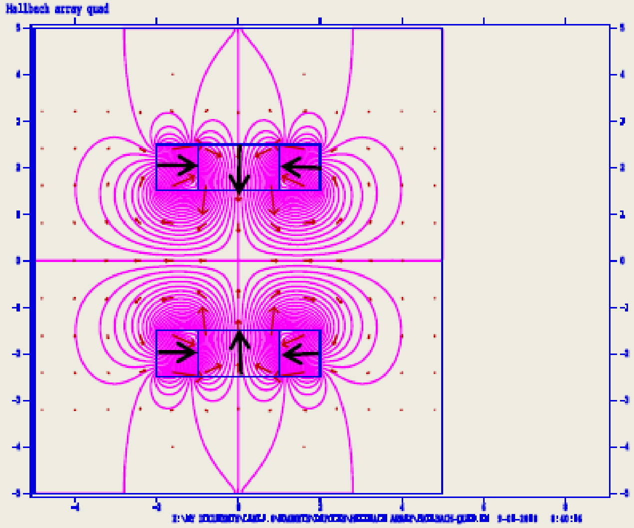
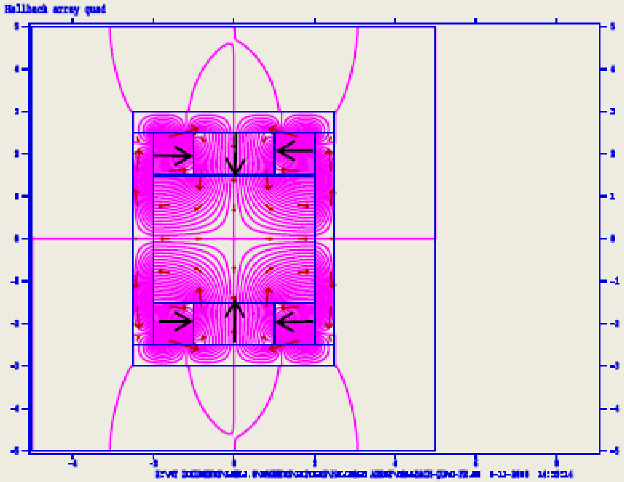
Hallbach Quadrupole



Adding flux returns
increases flux by 21%

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



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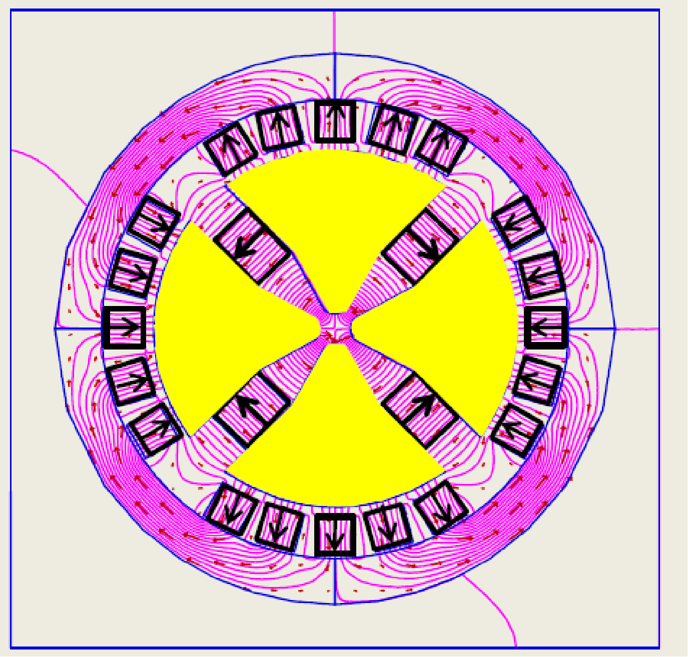
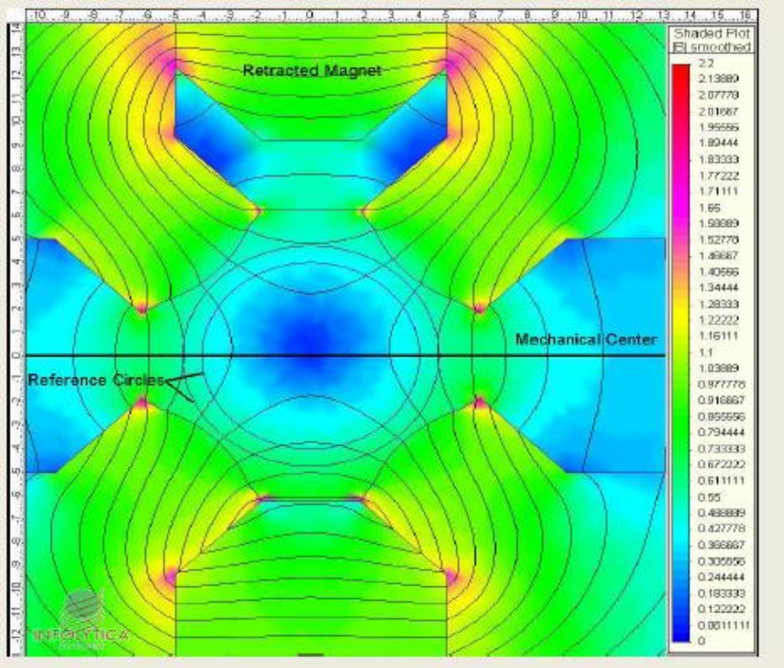
2 proposals for adjustable field permanent magnets





Hallbach Ring Quad
Rotating out ring of magnets
Changes field
Proposed for NLC

Moveable magnetic
Material adjusts field of quad
S. Gottschalk et al.

Courtesy
J. Volk

Effect of Temperature

- Field Dependence: Depending on the material, effect can be significant with moderate temperature change (tens of degree C)
- Even smaller temperature changes can impact alignment & thus function of FEL undulators
- Solutions
  - Tight environmental controls (LCLS, FLASH)
  - Temperature compensated design to reduce field dependence
- Actively cooled devices (s/c & resistive magnets) may have fewer issues - cryostat

Example
Fermilab Recycler Ring

The Recycler is an 8.9 Gev/c Anti proton storage ring in the Main Injector tunnel 3.3 km Circumference.

There are 488 permanent Magnets in the ring.

362 Dipoles
124 Quadrupoles
8 Mirror magnets
5 Lambertson
6 Sextapoles

Gerry Jackson and Bill Foster
In the Main Injector tunnel.

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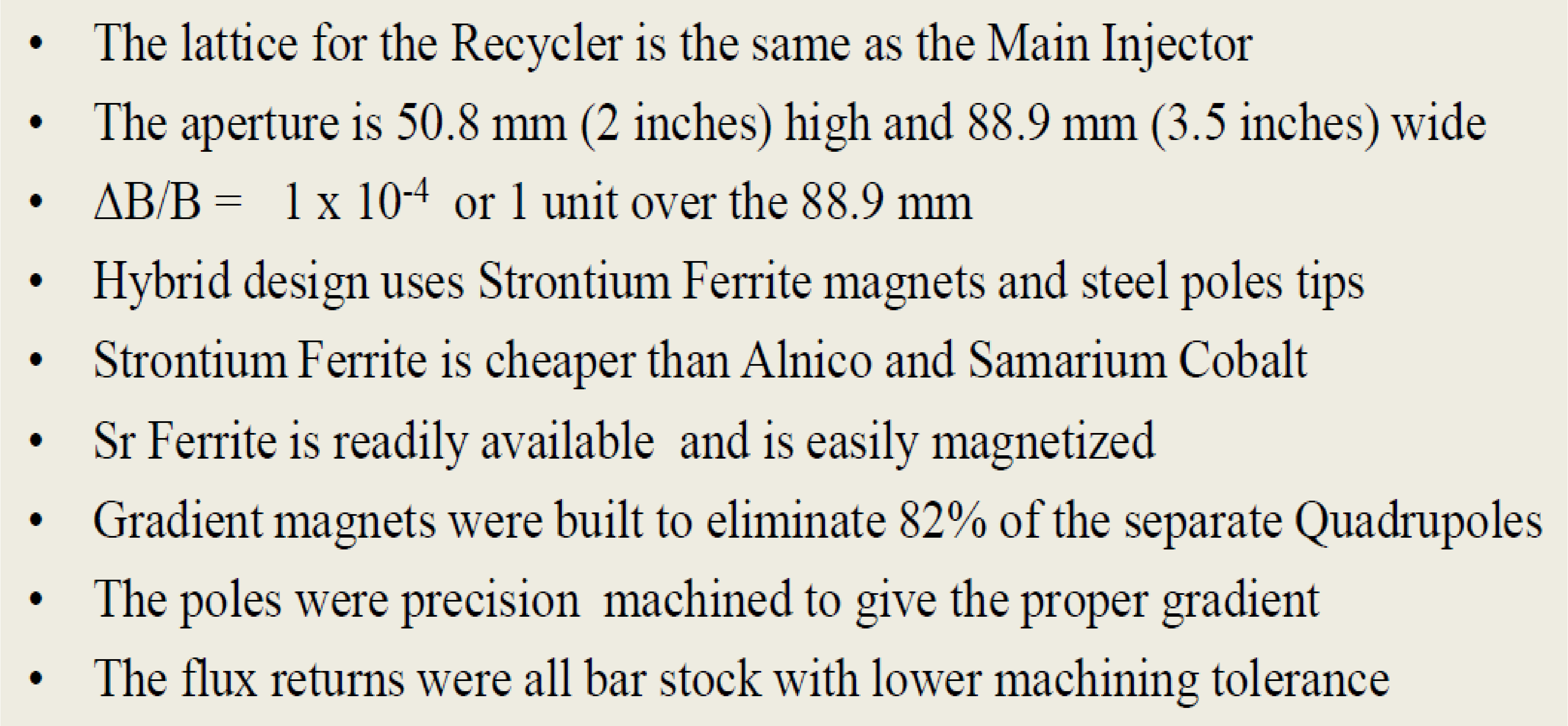
J. Volk

Recycler Design



- 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 x 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

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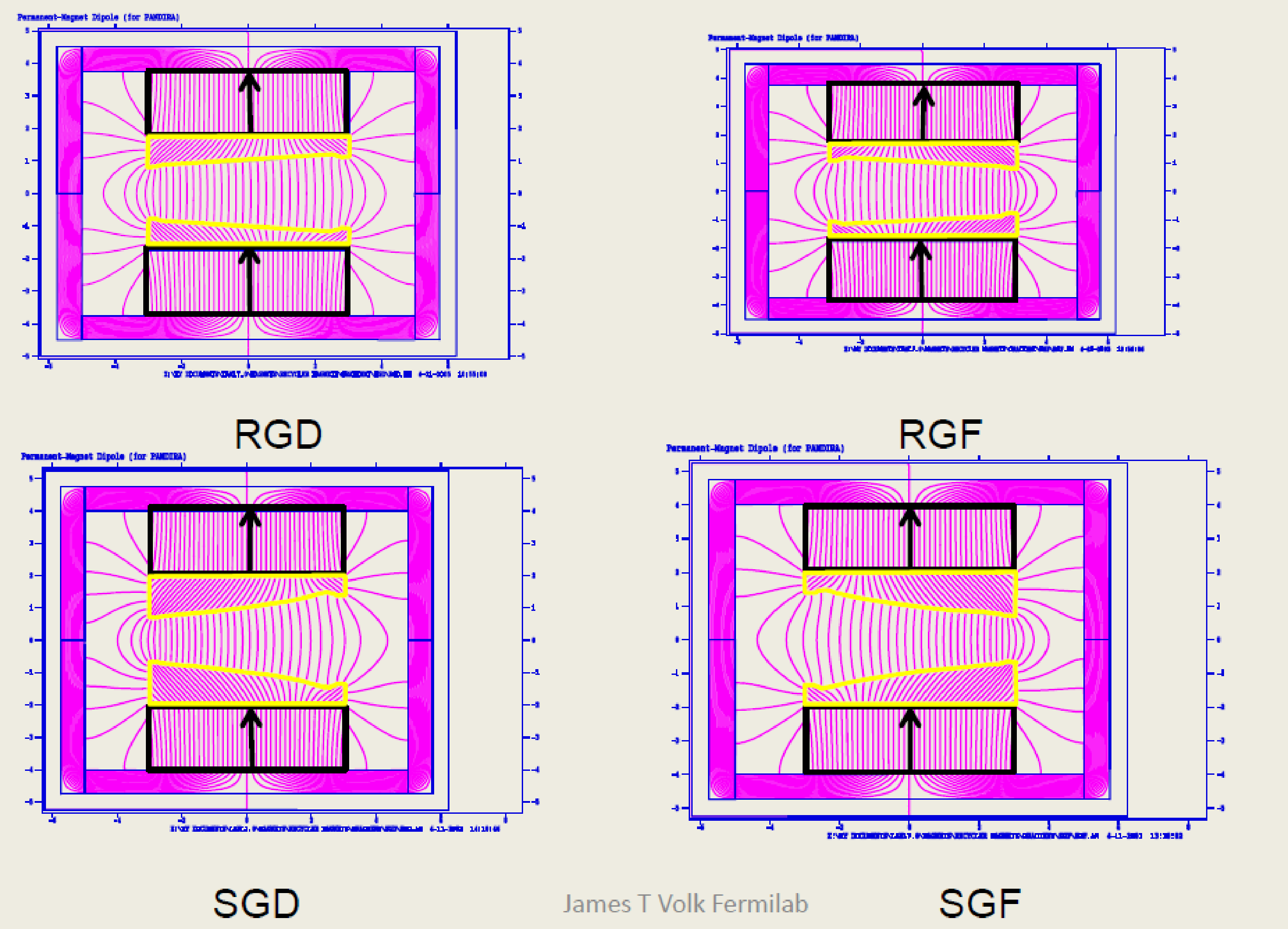
Recycler Gradient Magnets



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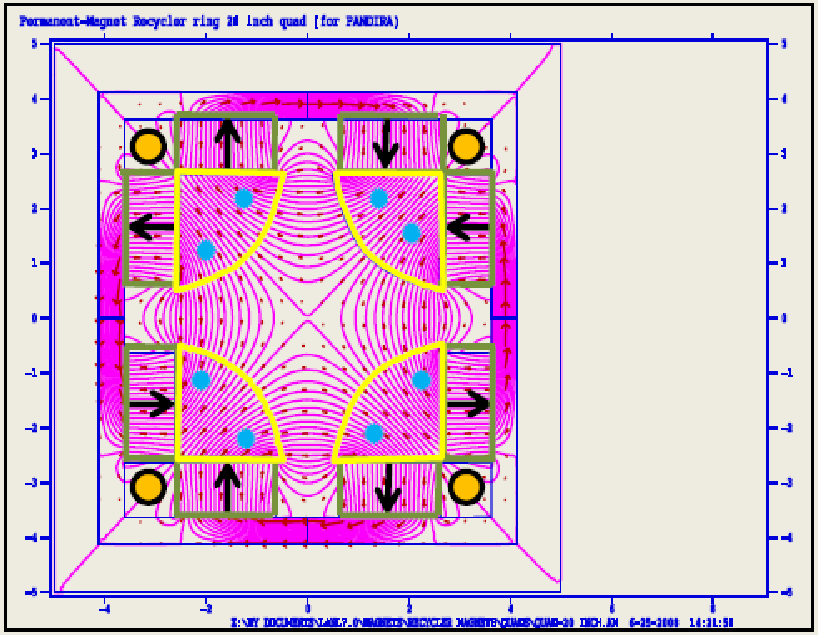
Recycler Quads



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

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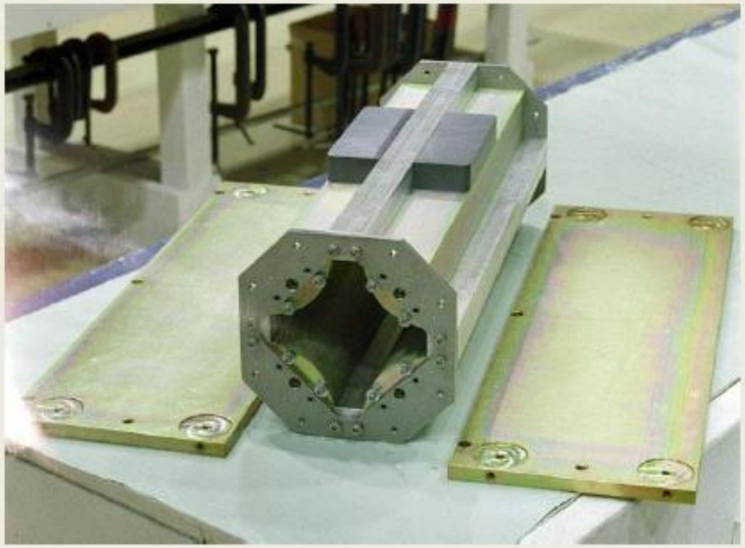
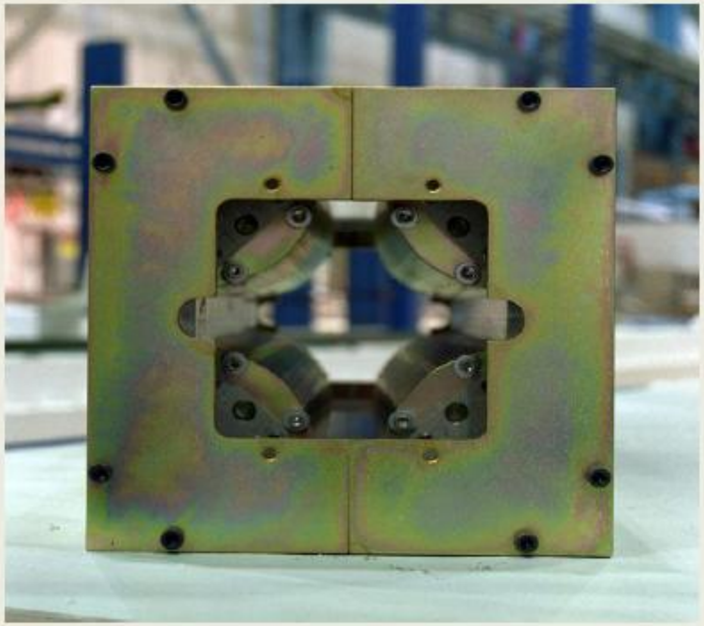
Recycler Quads



End view showing poles



Flux returns open showing magnets

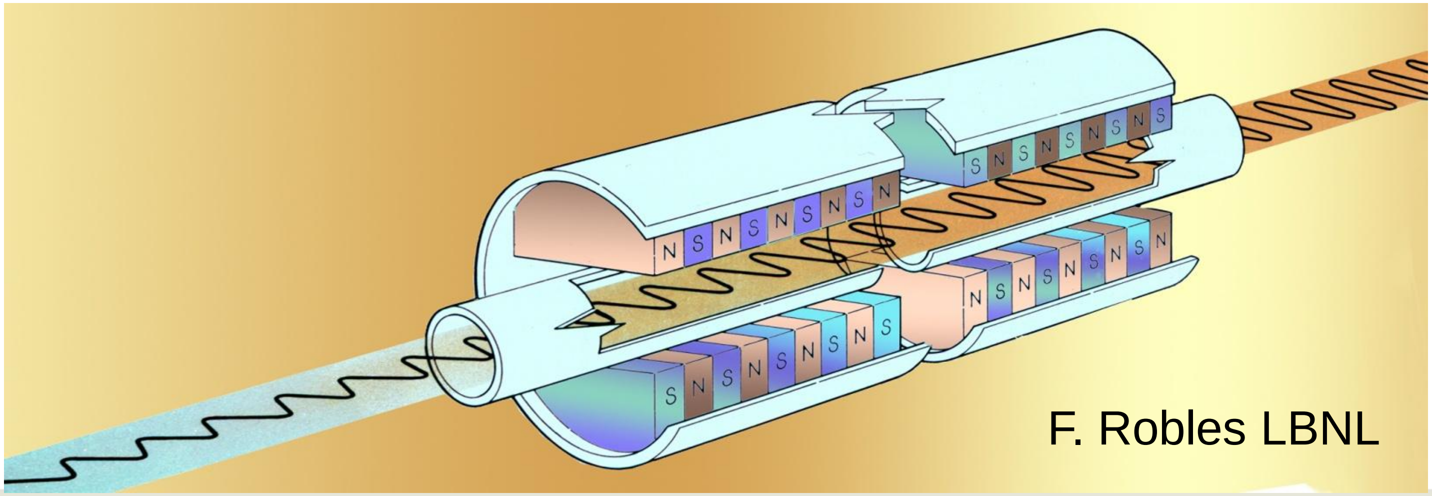
Problems with the Recycler

- 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

Note the recycler was
ultimately successful

PM Undulators

- Moves particle beam back and forth to create synchrotron light & possibly FEL
- Frequently use PM (though resistive & s/c versions also exist)
- Many different types exist (transverse, helical, with or without iron)

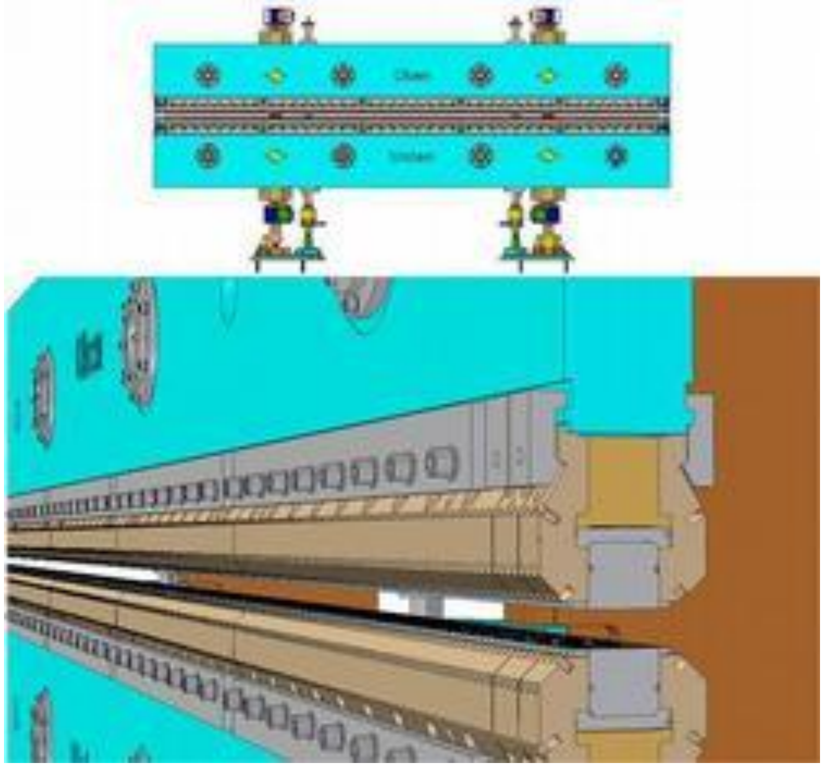


F. Robles LBNL

PM Undulators

- The magnets should be as close to the beam as possible
- The precision of the magnetic structure is very important to success
  - Requires high mechanical and thermal stability
    - Deformation limits of a few micrometers are common
    - Tends to result in large support structures and tight environmental controls
  - Requires precise magnetic measurements & precision alignment
- A wide variety of these devices have been built or proposed

Some Examples

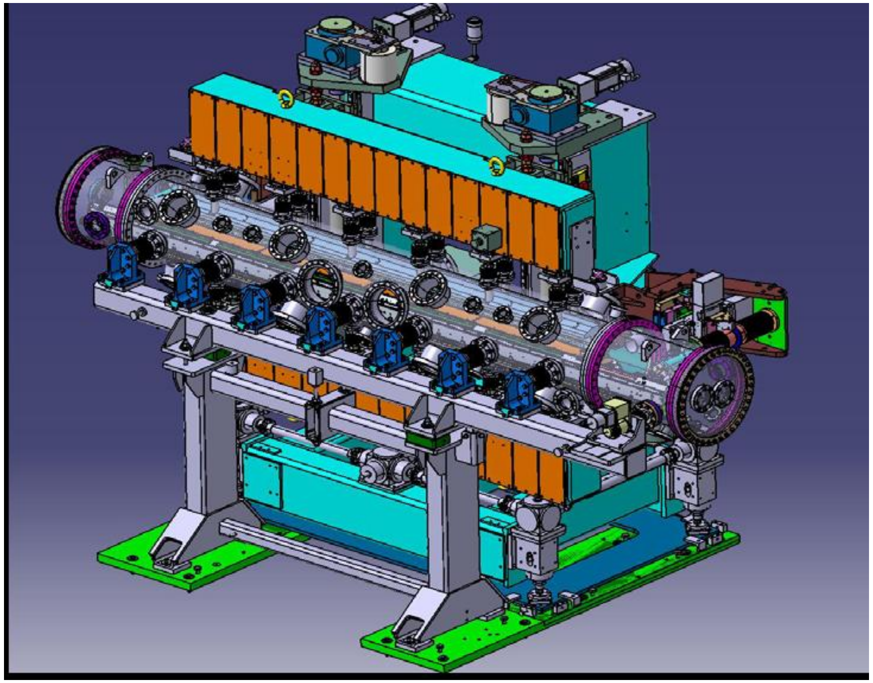


Undulator Design from HASYLab
DESY

Undulators for FLASH FEL
DESY

Cryogenic Permanent Magnet Undulator

- Lowering temperature to 140 K increases field by ~ 13 - 25 % to about 0.5 T(rare earth magnets NdFeB and PrFeB) Radiation damage a concern in NdFeB
- May also help in thermal stability



From “DEVELOPMENT OF A PRFEB CRYOGENIC UNDULATOR AT SOLEIL”

C. Benabderrahmane et al. *Proceedings of IPAC’10*, Kyoto, Japan

Resistive Magnets

- Electromagnets
  - Excitation is provided by current carrying conductors (generally Cu)
  - Field is shaped by Iron poles
  - Field in iron is less than the iron saturation value
  - Resistive losses in the conductor frequently require water cooling
- Basis of electromagnets is the Biot-Savart law

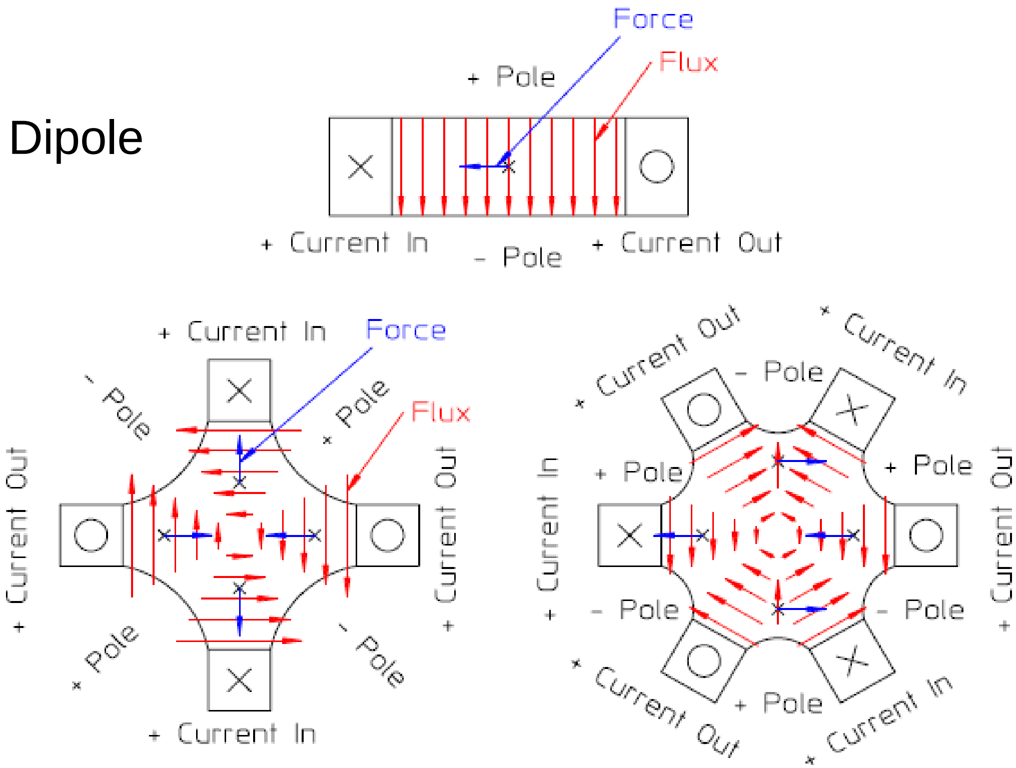
$$B = \frac{\mu_0 I}{2\pi R}$$

Examples of Ideal Magnets

Dipole

Quad

Sextupole



Coil Currents, Polarities and Force Directions for a Positive Beam Current

From
“Iron Dominated
Electromagnets”
J. Tanabe
SLAC-R-754

Some Approximate Equations (assumes iron not saturated)

	Dipole	Quadrupole	Sextupole
Field (B)	$B = \frac{2 NI \eta\mu_0}{h}$	$\frac{dB}{dr} = \frac{2 NI \eta\mu_0}{r^2}$	$\frac{d^2 B}{d^2 r} = \frac{6 NI \eta\mu_0}{r^3}$
Power Dissipated	$P = \frac{\rho B h j l_{avg}}{\eta\mu_0}$	$P = \frac{2 \rho r^2 j l_{avg} (dB / dr)}{\eta\mu_0}$	$P = \frac{\rho r^3 j l_{avg} (d^2 B / d^2 r)}{\eta\mu_0}$

Where

I = current, N = number of turns
h = gap height, r = radius from center
l_{avg} = average length of turn
ρ = resistivity
j = current density
η = efficiency (~ 0.99)
$\mu_0 = 4 \pi \times 10^{-7}$

From : Th. Zickler
Basic Magnet Design
CERN Accelerator School
Burges – 2009

http://cas.web.cern.ch/cas/Belgium-2009/Bruges-after.html

Comments on Resistive Magnet Cooling

- If the power dissipated via Ohms law is too high than the magnet will over heat and melt
- Thus
  - the current density must be keep low – yielding very large conductors or
  - Cool conductors actively with flowing water
    - Flow rates and thus pumping costs can be very high
    - LCW is generally used (expensive)
    - Tritium may be produced and have to be dealt with

Fabrication of Resistive Magnets

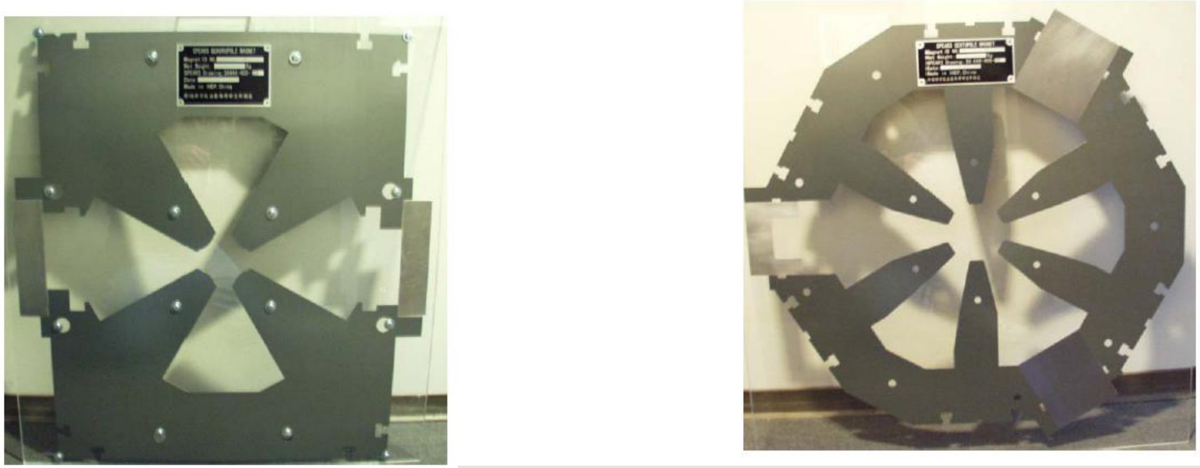
- Proper fabrication of resistive magnets is a very complicated issue and success requires a great deal of experience
- A very detailed and useful guide here is “Iron Dominated Electromagnets” J. Tanabe, SLAC-R-754 (included in your materials)
- Basically, fabrication can be divided into 3 areas : the yoke, the coil and assembly and installation

Yoke Fabrication

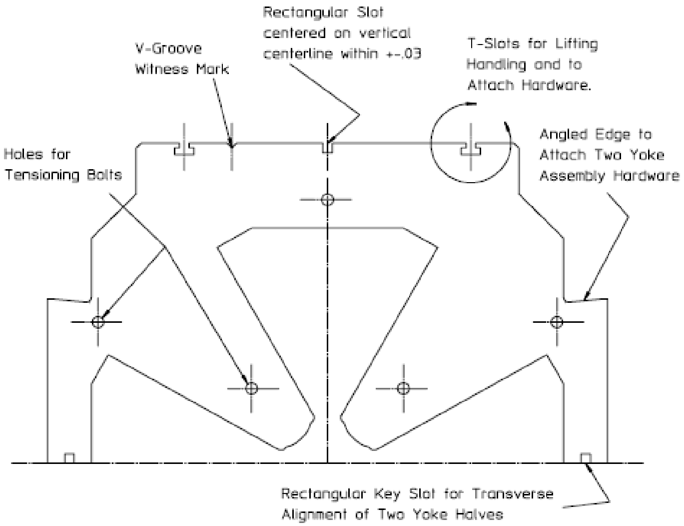
- A fundamental requirement is that resistive magnets should have reproducible performance under excitation & have limited multipole fields
- This requirement is met largely by the iron (steel) yoke
  - Avoid saturation in the yoke

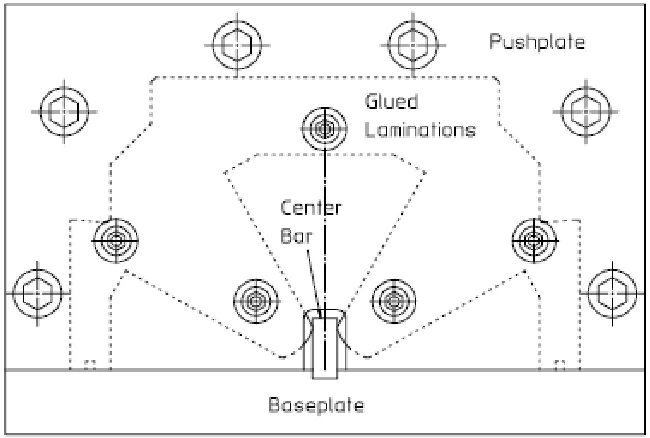
Yoke Laminations

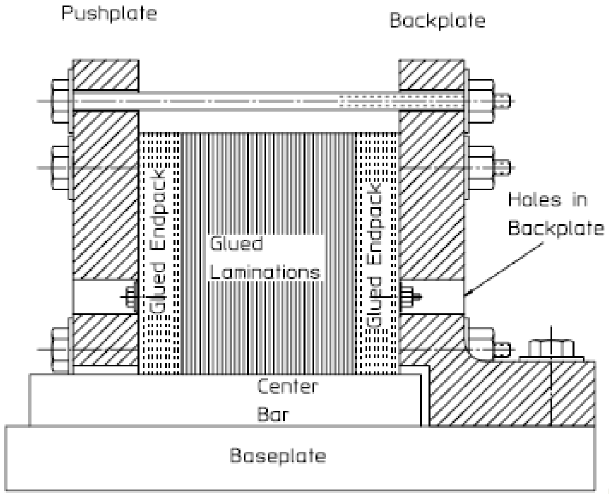
- Yokes are generally made out of laminations to reduce eddy currents thus improving field quality and reducing hysteresis
- Laminations are generally shuffled or sorted to allow similar material properties in each magnet
- Laminations are carefully shaped to avoid saturation and to deliver the correct field shape
- Laminations can be assembled using glue, welding or via mechanical fasteners
- For small numbers of magnets with low AC use solid material rather than laminations is frequently used



Yoke Assembly







From
“Iron Dominated
Electromagnets”
J. Tanabe
SLAC-R-754

Coil Fabrication

- Wind copper to produce desired field
- Insulate via glass tape mylar or other materials to prevent turn to turn shorts
- Install water & electrical connections
- Finished coils are typically potted in epoxy to prevent damage, maintain the coil shape and prevent shorts to ground

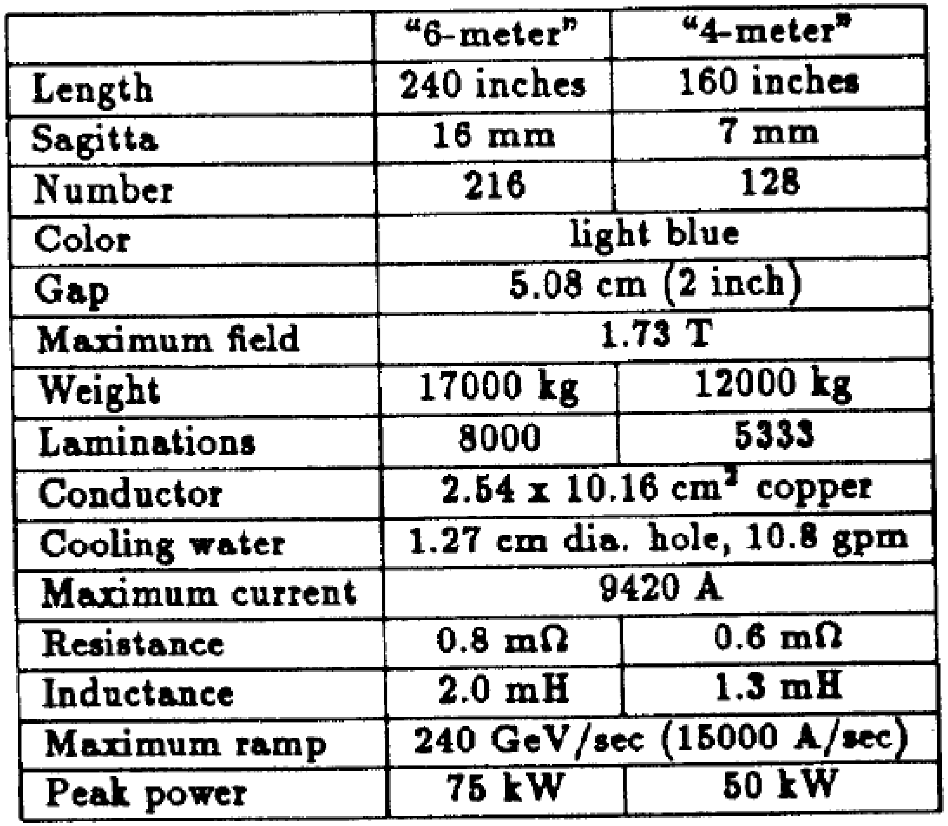
Assembly & Installation

- The coil, yoke, beam tube and other assembled together
- The magnet fields are carefully measured and references are installed to allow precise alignment of the magnet with the beam center
- Other tests such as checking water flows and HiPotting (testing for shorts to ground) are done

Example 1
Fermilab Main injector Dipole

- Principle bending magnet in Fermilab Main Injector
- Required to ramp from 0.1 T to 1.73 T at 2.4 T/s
- 344 dipoles were required

Example 1
Fermilab Main injector Dipole



	“6-meter”	“4-meter”
Length	240 inches	160 inches
Sagitta	16 mm	7 mm
Number	216	128
Color	light blue	
Gap	5.08 cm (2 inch)	
Maximum field	1.73 T	
Weight	17000 kg	12000 kg
Laminations	8000	5333
Conductor	2.54 x 10.16 cm^2 copper	
Cooling water	1.27 cm dia. hole, 10.8 gpm	
Maximum current	9420 A	
Resistance	0.8 mΩ	0.6 mΩ
Inductance	2.0 mH	1.3 mH
Maximum ramp	240 GeV/sec (15000 A/sec)	
Peak power	75 kW	50 kW

Table 1: Main Injector Dipole Parameters

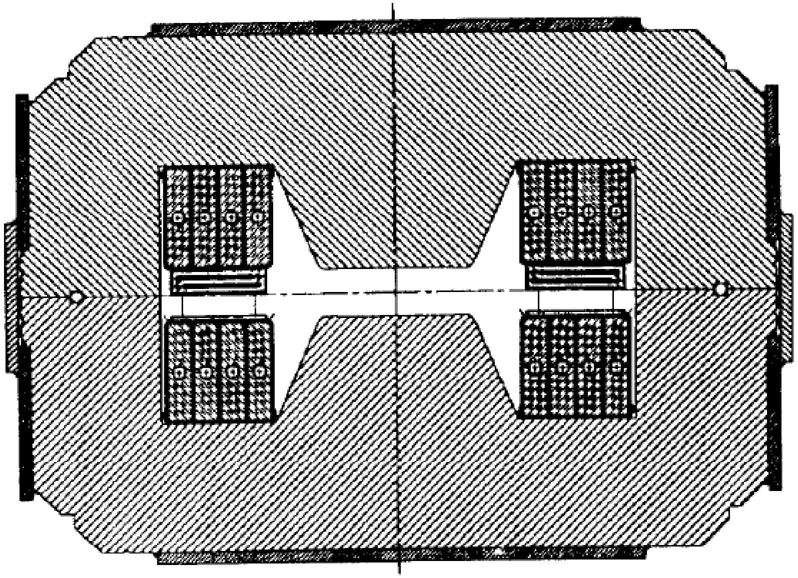


Figure 1: Cross section of Main Injector Dipole

From “Design Considerations & Prototype Performance of the Fermilab Main Injector Dipole” D. Harding et al. (PAC 1991)

Example 1
Fermilab Main injector Dipole

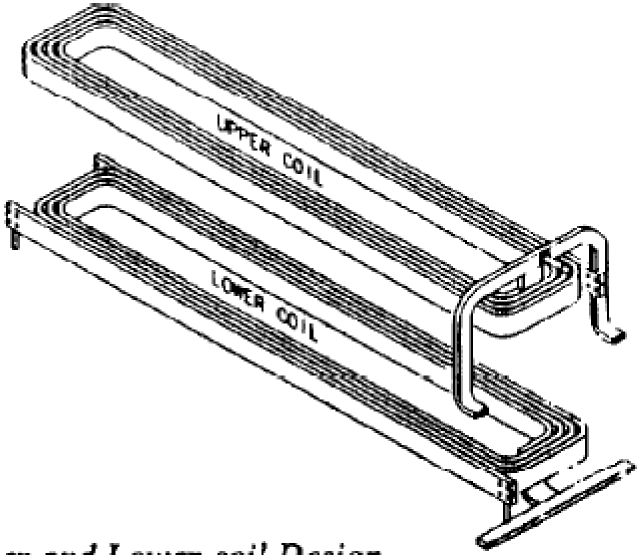


Fig. 2. Upper and Lower coil Design

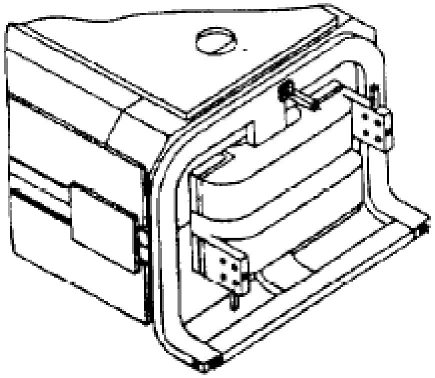


Fig. 3. Completed Magnet Connections

From "The Design & Manufacture of the
Fermilab Main Injector Dipole" B. Brown. (EPAC 1992)

Main Injector and Recycler Magnets in Fermilab Tunnel