Magnet Shielding at Low Fields

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Realistic Component Dimensions

- **Dipoles**
  
  25 M lb @ 1$/lb
  
  $A_{\text{cond}} \sim 0.001 \text{ m}^2$
  
  ~115 m long

- **Quadrupoles**
  
  13 M lb
  
  5 turns/pole req.
  
  > 10 m long
  
  ~4000 required

- **Synchrotron radiation absorbers**
  
  20 kW each
  
  Rad shielding req.
Heat dissipation by an air cooled bus

- Current = 500 A
- Height = 2 cm
- Width = 5 cm
- Resistivity = 2.80E-08 ohm m
- Air cooling = 1 mW/degC/cm²
- Circumference = 531000 m
- Conductors = 4
- Area = 0.00100 m²
- Power dep. = 7 W/m/cond
- Voltage = 7434 V/turn
- Temperature = 5 deg C
- Total power = 3.72 MW/cond

With return:
- Total power = 14.87 MW
- Total weight = 1.26E+07 lbs
- Cost rate = 1.6 $/lb
- Cost = 2.02E+07 $

Cooling the collider tunnel by conduction to the walls

- Power = 100 MW
- Circumference = 531000 m
- Typ. Area = 6 m²
- Typ. Dist. = 1 m
- Conductivity = 3 W/K/m
- Thermal Exp. = 8.00E-08 /deg K

- Temperature = 10.46 degrees K
- Expansion = 8.37E-05 meters/m

Dipole magnet yoke / mate's cost

LEP
- Circumference = 26500 m
- Maximum field = 0.135 T
- Pole Width = 0.225 m
- Lam. thick = 0.0015 m
- Spacers = 0.004 m
- Packing factor = 0.2727
- Return width = 0.13 m
- Max. yoke field = 0.88 T
- Yoke Area = 0.1879 m²
- Iron vol = 5.12E-02 m³
- Density = 491.88 lb/ft³
- Iron mass = 405 kg/m
- Packing fr = 0.9
- Weight = 2.12E+07 lbs = 12641 tons
- Cost rate = 1 $/lb
- Cost = 2.12E+07 $

PREP
- Circumference = 531000 m
- Maximum field = 0.012 T
- Pole Width = 0.225 m
- Lam. thick = 0.000635 m
- Spacers = 0.000635 m
- Packing factor = 0.0909
- Return width = 0.04 m
- Max. yoke field = 0.74 T
- Yoke Area = 0.0335 m²
- Iron vol = 0.0030 m³
- Density = 491.88 lb/ft³
- Iron mass = 24 kg/m
- Packing fr = 0.9
- Weight = 2.53E+07 lbs
- Cost rate = 1 $/lb
- Cost = 2.53E+07 $
Disposal of Waste Heat

- Heat deposited at the discrete absorbers can be conducted to the walls.

- Heat sinks would probably be large.

\[ P = \kappa A \frac{\Delta T}{\Delta x} \]

Gives \( \Delta T = P \Delta x / \kappa A \approx 10 \, ^\circ C \) for the following case if \( \kappa \approx 3 \, \text{W/m} / ^\circ \text{C} \), \( P = 200 \, \text{W/m} \). This gradient would take weeks to develop.
Hardware

- **Dipoles**
  Low field implies minimal iron, light structure.
  \[ B_{\text{max}} = \sim 0.014 \text{ T} \quad @ \quad E_b = 300 \text{ GeV} \]
  \[ B_{\text{inj}} = \sim 0.0023 \text{ T} \quad @ \quad E_b = 50 \text{ GeV} \]

  Remanent fields and external fields are a problem at injection.

  Low currents \( I = 0.5 * B l / \mu_0 \sim 500 \text{ A} \).
  Conductors (2 - 0000 rubber insulation) \( \Rightarrow \) air cooled.
  Commercial connectors could be used.

- **Quads**
  Constraints on damping in three dimensions require long quads, \( l_Q \sim 10 \text{ m} \)

  Pole tip fields (\( \sim 50 \text{ mT} \)), and currents are very low.

- **Vacuum System**
  Photodesorbed gas production / m is very low.
  \( 2 \text{ L/s/m} \Rightarrow 10^{-9} \text{ torr} \).

  The vacuum chamber can be designed so that synchrotron radiation never reaches it.
  Sagitta = 1.6 cm in 100 m. (pretty straight)

  No distributed radiation Pb shielding.

  Discrete absorbers can absorb all the gas and power loads. Heat sinks can go into the ground.
Parameterizations of the Field in a Magnet

- There are three sources on fields in magnets
  G. Fischer, SLAC-PUB 3726, (1985)
  K. Brown and J. E. Spencer, 1981 PAC, p2568
  H. A. Enge, Rev. Sci. Instr., 35 (1964) 278

The most detailed is Enge, who defines

\[ h(s) = \frac{B_{z,0}}{B_0} = \frac{1}{1 + e^S} \]

with

\[ S = c_0 + c_1 s + c_2 s^2 + c_3 s^3 \]

where \( s \) = the distance along the normal to the magnet gap in units of \( D \), the gap distance. The constants depend on the geometry, but the "short tail" numbers are typical,

\[
\begin{align*}
  c_0 &= 0.383 \\
  c_1 &= 2.388 \\
  c_2 &= -0.817 \\
  c_3 &= 0.200.
\end{align*}
\]
Penetration by External Fields

The penetration is primarily dependent on $c_0$, which changes slightly with geometry.
Fields in Gap

The resulting fields, when the physical gap is adjusted to be at zero look like,

\[ h(s) \]

\[ 1-h(s) \]

Assuming the zero is arbitrary, one can consider \( 1-h(s) \) as an error field penetrating a gap.
Error Fields

- Penetration of external fields can be estimated by comparing $\Delta B/B$ in the special case when $B_{ext} = 0$.

Brown and Spencer

$$\Delta B/B \sim 1 / (1 + e^S)$$
$$S = c_0 + c_1 x + c_2 x^2 + ...$$

Fischer

$$\Delta B/B \sim 10^{-ax}$$

Distance into magnet, [gaps]
Summary

The external fields outside the magnet are attenuated by two effects:

- The external fields are shunted around by the magnet yoke so that the field external to the gap is ~0.1 times the ambient field.

- The field in the gap is attenuated by the gap geometry and dies off rapidly within the gap.

The remanent fields in the gap were significant. The test magnet was not efficiently degaussed due in part to power supply limitations. The measured remanent fields were dependent on the probe location, and degaussing.