Proton Driver Magnets

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Snowmass 2001

Salient Features

- Large Aperture
- High Field (1.5 T)
- Large Stored Energy
- Separated Functions
- Stranded conductors for 15 Hz operation
- High Voltage-to-Ground Operation ($\simeq 5$ kV)
- Quad/Dipole on common bus for tracking
- Horizontal correctors integrated into main dipoles
- External vacuum skin - no vacuum pipe

Aperture

Physical aperture is a primary cost driver and is determined by two considerations:

- The ability to accommodate the large beam size (3.5 in $\times$ 5.5 in, 100%) necessary to keep space charge tune shift within reasonable limits.
- The need to keep losses at a level compatible with safety requirements

Notes:

- The horizontal aperture allows to keep losses $<$ 10% @ 3 kW (injection).

Quadrupole/Dipole Tracking : How good should it be ?

Due to different saturation behavior in the dipole and quadrupole magnets, the quadrupole/dipole strength ratio varies during a machine cycle. The net tune shift experienced by a particle of momentum $p + \Delta p$ is given approximately by

$$\Delta\nu = \xi_{\text{uncorrected}} \left[\frac{\Delta G}{G} - \frac{\Delta B}{B}\right] + \xi_{\text{corrected}} \frac{\Delta p}{p}$$

How much $\Delta\nu$ can be tolerated is arguable. We conservatively assume $\Delta\nu_{\text{max}} \sim 0.01$, based on the ISIS experience. This leads to the requirement

$$\left[\frac{\Delta G}{G} - \frac{\Delta B}{B}\right] \sim 0.001$$

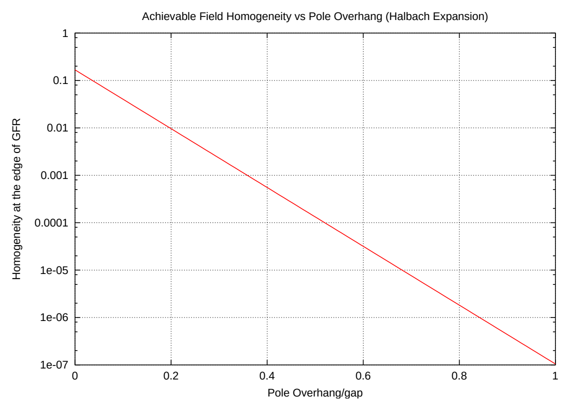
Dipole Field Quality Requirement

The field must be as uniform as possible at injection, taking into account the fact that aperture is a main cost driver. As saturation sets in, the distortion becomes sextupole dominated.

At injection:

$$\frac{\Delta B}{B} < 1.0 \times 10^{-3}$$

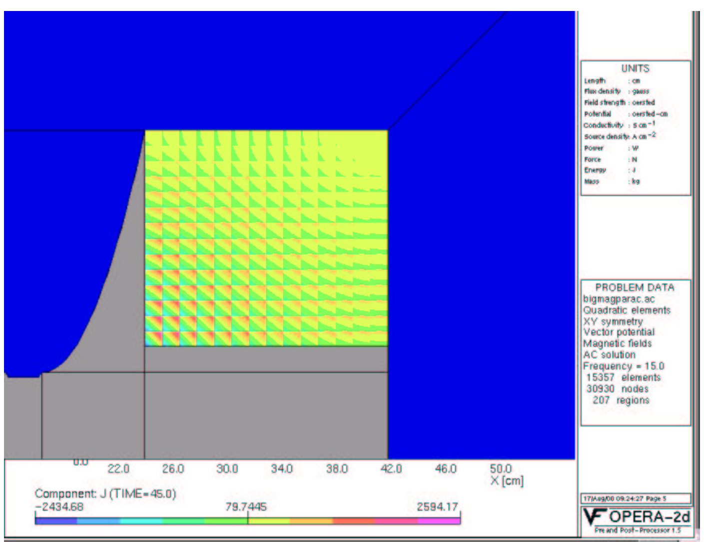
This is a conservative prediction from Halbach's formula for shimmed magnets.



Water-Cooled Stranded Conductor

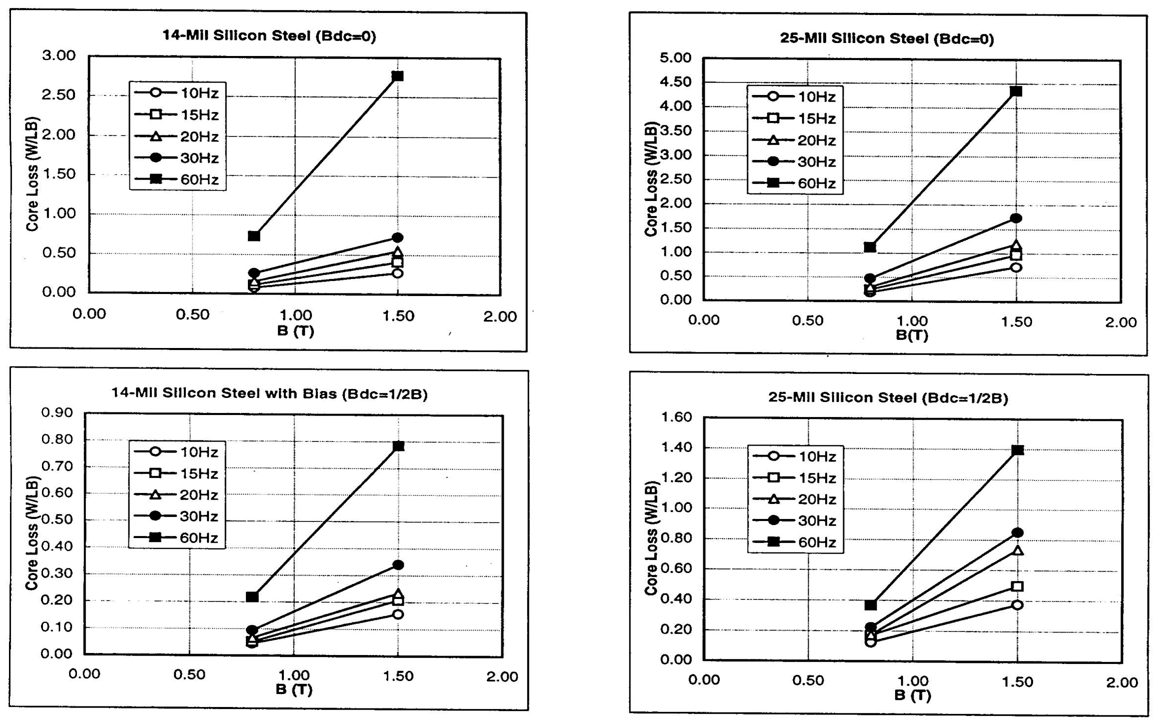
The PD high field and high frequency lead to unacceptable eddy losses in solid water-cooled conductors such as used in the FNAL Booster.

$$\begin{aligned} \mathcal{R} &= R_{\mathrm{AC}}/R_{\mathrm{DC}} \\ &= 2 \text{ (Fermilab Booster. 0.45 in conductor, 0.7 T, 15Hz)} \\ &> 8 \text{ (Proton Driver, 0.45 in conductor, 1.5 T, 15 Hz)} \end{aligned}$$



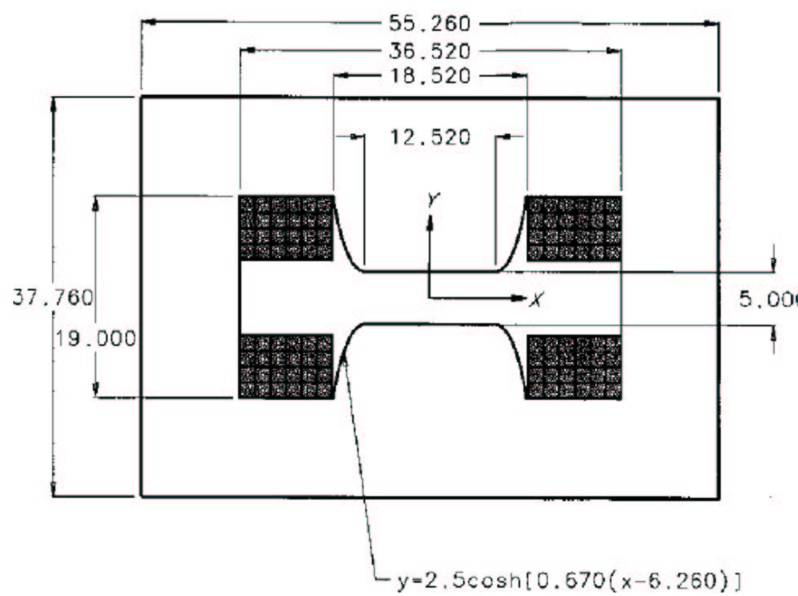
Lamination Steel

We use 0.014 in (29 gauge) thickness M17 Si-Fe laminations to minimize eddy current losses ($\delta \simeq 0.040$ in). Manufacturer's data refers sinusoidal excitation at 50 or 60 Hz. Loss measurements were performed for 10 to 60 Hz biased excitations for 14-mil and 25-mil samples, confirming that biased excitation results in lower losses.



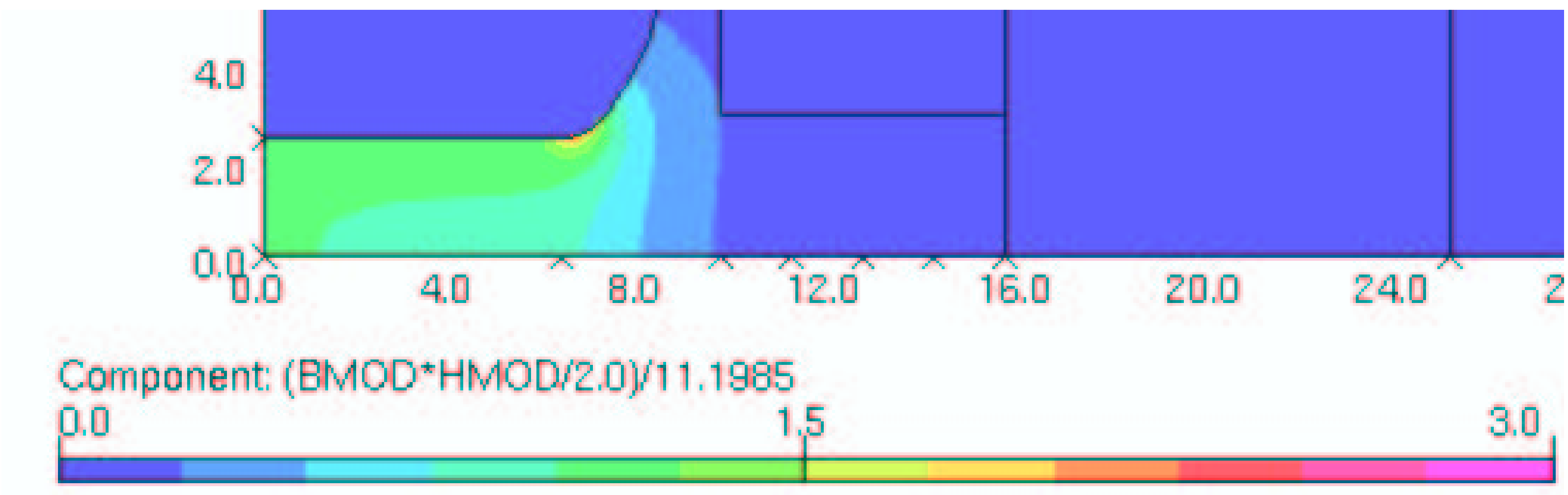
Dipole Magnet

Max Stored Energy (5.1655 m)	0.336 MJ
Inductance (low field)	3.07 mH /m
Inductance (@ 1.5 T)	2.88 mH /m
No of Turns/pole	2(parallel) $\times$ 12 $=$ 24
Transfer Constant	2.365×10^{-4} T/A
Peak Dipole Field	1.5 T
Peak Current (M17)	6720 A
Steel Length	5.1655, 4.1924 m
Conductor Dimensions	37×37 mm^2
Cooling tube dimensions	8 ID, 10 OD mm
Conductor Packing Fraction	80% (approx)
Physical Aperture	5×12.5 in^2
Good Field Aperture	5×9.0 in^2
Coil Area	0.105 m^2
Lamination Area	1.109 m^2
Lamination Thickness	0.014 in
Lamination Material	M17 Steel
Core mass (5.1655 m magnet)	44,900 kg
Coil mass (5.1655 m magnet)	10,700 kg
Maximum Terminal Voltage	5 kV



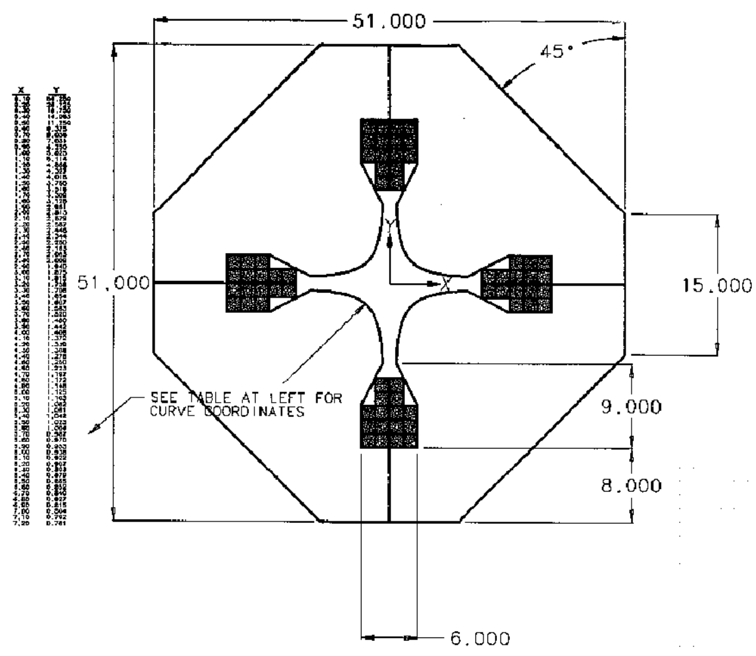
Stored Energy

Surprisingly, approximately 40% of the magnetic energy is stored **outside** of the gap region. It may be possible to reduce this fraction and the overall magnet volume by modifying the pole profile and/or the conductors placement.



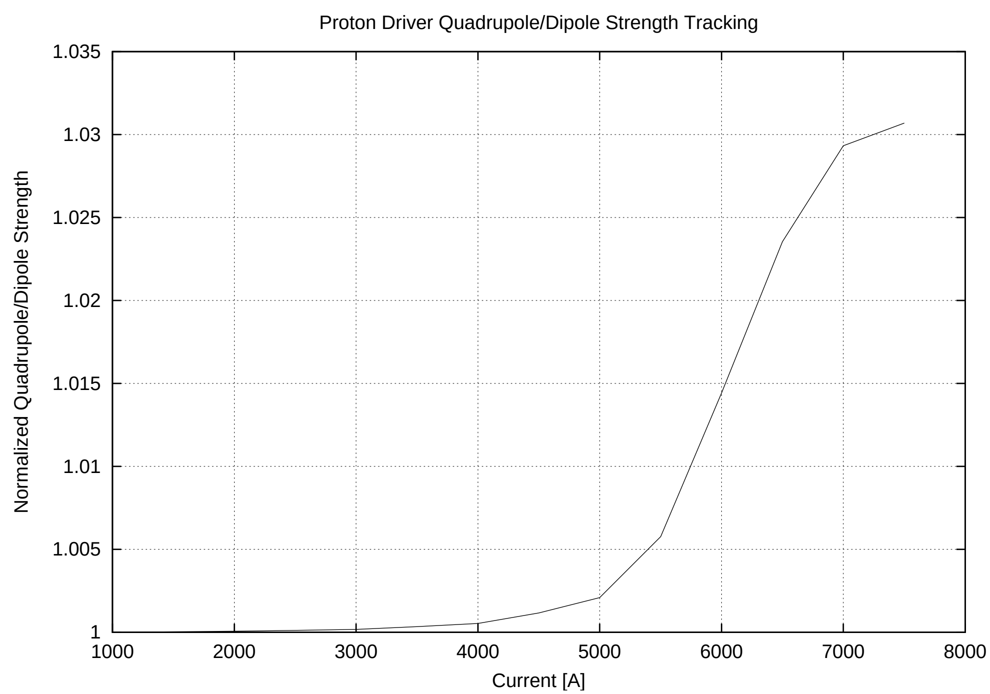
Quadrupole Magnet

Aperture	3.3541 in
Peak Gradient (16 GeV)	8.7494 T/m
Peak Current (M17)	6500 A
Steel Length	1.6824 m
Transfer Constant	1.37865×10^{-3} T/m/A
Stored Energy (1.6824 m)	0.052 MJ
Inductance	1.481 mH/m
No of Turns/pole	8
Conductor Dimensions	37×37 mm^2
Cooling tube dimensions	8 ID, 10 OD mm
Conductor Packing Fraction	80%
Lamination Area	1.095 m^2
Coil Area	0.0929 m^2
Lamination Thickness	0.014 in
Lamination Material	M17 Steel
Core mass (1.6824 m)	14,500 kg
Coil mass (1.6824 m)	1,400 kg
Max Terminal Voltage	0.425 kV



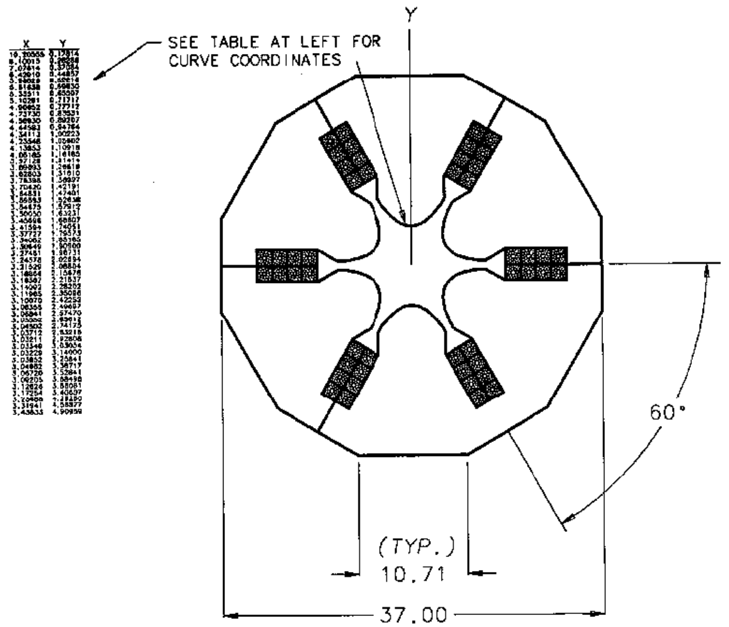
Tracking Error

Dipole and Quadrupole are on the same current bus. The transfer functions of both magnets are matched as well as possible. The residual tracking error (below) is compensated by an active correction system.



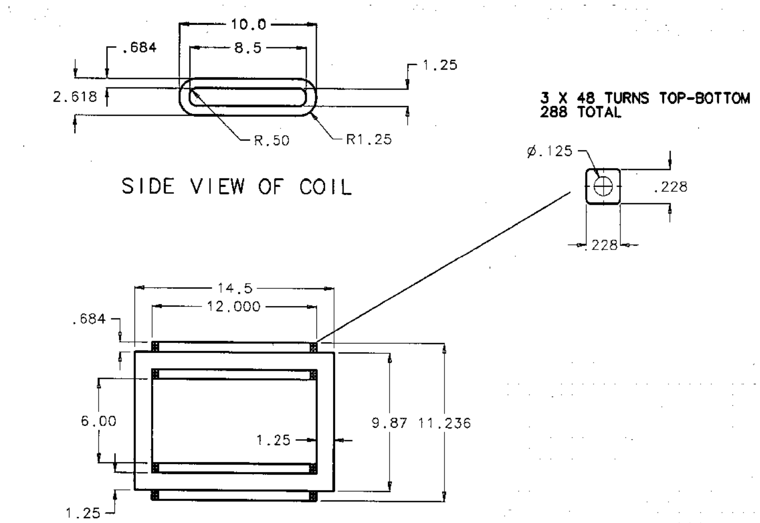
Sextupole Magnet

Aperture (Inscribed circle radius)	3.818	in
Peak Sextupole (H,V)	35,47.5	T/m^2
Peak Current	2850	A
Steel Length	0.3	m
Max Stored Energy	2980	J
Inductance	2.448	mH/m
No of Turns/pole	4	
Transfer Constant ($\mu = \infty$)	0.016667	$T/m^2/A$
Conductor Dimensions	1.5×1.5	in^2
Lamination Thickness	0.014	in
Lamination Material	M17 Steel	
Lamination Area	0.5676	m^2
Coil Area	0.0696	m^2
Core Mass	1,340	kg
Coil Mass	190	kg



Vertical Corrector Magnet

No of Turns/pole	3×48	
Max Current (including saturation)	400	A
Max Field (including saturation)	0.25	T
Steel Length	0.25	m
Lamination Material	M17	
Lamination Thickness	0.014	in



R&D Requirements and Conclusion

No fundamental obstacle, but the magnets are challenging !

Prototyping of a large aperture dipole and quadrupole will be necessary for the following reasons:

- Stranded conductor water-cooled coils is a new technology. Ends need to be carefully engineered for space (limited bending radius) and insulation. Procedures to make good mechanical and electrical joints need to be developed.
- Insulation typically fails in regions that are not homogeneous. The exact location of weak spots is hard to predict with accuracy and as a result, high voltage insulation requires experimental validation.
- Residual frequency dependent effects impacting the transfer function and/or field quality need to be experimentally assessed.