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Magnets for High Intensity Proton Synchrotrons

J.-F. Ostiguy, V. Kashikhin and A. Makarov

Fermi National Accelerator Laboratory, Batavia, IL, USA[1]

Abstract. Recently, there has been considerable interest at Fermilab for the Proton Driver, a future high intensity proton machine. Various scenarios are under consideration, including a superconducting linac. Each scenario present some special challenges. We describe here the magnets proposed in a recent study, the Proton Driver Study II, which assumes a conventional warm synchrotron, roughly of the size of the existing FNAL booster, but capable of delivering 380 kW at 8 GeV.

INTRODUCTION

One of the principal considerations in designing a high intensity proton synchrotron is to limit losses to prevent activation. Typically this translates into a requirement on the maximum fractional particle losses: on the order of 10^{-4} to as low as 10^{-6}. In order to provide sufficient dynamic stability, it is necessary to limit both space charge induced tune shift and tune spread. This is accomplished in two ways: by keeping the machine circumference small and by spreading out the proton distribution transversely. The former strategy implies rapid cycling, the latter implies large aperture; both have an impact on magnet design.

Aperture is a principal cost driver since magnet overall size, fabrication, power consumption and power supply hardware costs are directly proportional to stored magnetic energy. Magnet physical aperture, as opposed to available beam aperture, is determined not only by space charge considerations but also by the type of vacuum pipe employed. Because of the very substantial eddy current induced losses associated with rapid cycling, a conducting beam pipe generally cannot be used. One possible solution is a ceramic beam tube with thin conducting strips disposed on its inner surfaces to minimize beam impedance. This is costly in terms of physical aperture because for mechanical reasons, ceramic walls have to be considerably thicker than metallic walls. The Proton Driver magnets sidestep the difficulty by putting the entire magnet inside an evacuated enclosure an approach employed for the Fermilab Booster magnets. One drawback is that due a larger desorption area, achieving satisfactory vacuum in order to prevent gas scattering induced losses requires special care.

The presence of a large energy dependent space charge tune shift and tune spread dictates the need for tight tune control during the entire acceleration cycle. For this reason, dipole/quadrupole tracking errors are a special concern. A tracking error is equivalent to momentum offset error and results in a tune shift of magnitude

$$\Delta\nu = \xi_{\text{uncorrected}} \left[\frac{\Delta(G/B)}{(G/B)} \right] \qquad (1)$$

where $\frac{G}{B}$ is the ratio the gradient to main dipole field. Note that the tune variation is proportional to the *uncorrected* chromaticity because, in the context of a focusing error, there is no closed orbit error and the chromaticity correction sextupoles have no effect. The magnitude of the tolerable tune shift is debatable. At ISIS (RAL, U.K.), the ability to control the tune to within a part in 100 proved necessary, mostly to stay clear of specific resonances at extraction. While it is conceivable that this criterion can be relaxed, it provides a sense of what needs to be achieved.

Some rapid cyclic machines (e.g. the Fermilab Booster) use combined function magnets. This economizes space and naturally provides good tracking as long as the operating field is kept below ~ 1 T. The Fermilab Proton Driver study II assumes an aggressive 1.5T bending field and separate function magnets. The field strength is determined by two requirements. First, the circumference ratio between the Proton Driver and the Main Injector should be a simple rational fraction to allow synchronous beam transfers. Second, the total circumference should be as small as possible in order to minimize the space charge tune shift. Dipoles and quadrupoles are on a common bus; the residual tracking error (on the order of a percent) is handled by an independently powered active quadrupole correction system capable of compensating for the tune shift dependence on energy during acceleration.

DIPOLES

The Proton Driver dipole is a conventional H-magnet design. Field homogeneity is preserved at high excitation by profiled pole edges and by the presence of circular

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TABLE 1. Proton Driver II Main Dipole Magnet Parameters

Peak Dipole Field	1.5	Tesla
Good Field Aperture	101.6×152.4	mm^2
Physical Aperture	101.6×273.1	mm^2
Field Homogeneity	±0.0005	
Magnet Length	5.72	m
Cycle Frequency	15	Hz
Peak Current	5170	A
Conductor Dimensions	20.2×15	mm^2
Conductor cooling hole diameter	10	mm
No of turns/pole (3 conductors & top/bottom coils in parallel)	12	
Lamination Thickness	0.35	mm
Lamination Material	Si-Fe M17	
Inductance	18	mH
DC Resistance	4.7	mOhm
Stored Energy	0.063	MJ
Coil Losses	115	kW
Core Losses	16.3	kW
Core mass	37,000	kg
Peak Terminal Voltage	4.85	kV
Water Pressure Drop	10	bar
Water Flow	1.7	l/s
Water Temperature Rise	17	deg C

holes in the center of the poles. The magnet cross-section is shown in Figure 1; a list of relevant parameters is presented in Table 1. The dipoles are excited so as to produce a magnetic field strength of the form

$$B(t) = B_0 - B_1\cos(\omega t+\phi) + 0.125 B_1 \sin(2\omega t + 2\phi) \quad (2)$$

where B_0 is the injection field, B_1 is the magnitude of the fundamental component, $\omega/2\pi = f = 15$ Hz and ϕ is a constant phase factor. The second harmonic component is introduced to reduce the maximum value of dB/dt, which determines the peak RF accelerating voltage and the overall RF system costs.

In an iron dominated dipole, good field homogeneity can be achieved over the entire extent of the physical vertical aperture g, that is, all the way to the pole surfaces. However, field homogeneity over the horizontal extent of the aperture requires a certain amount of pole overhang w. For a given field homogeneity, the required horizontal extent of the physical aperture is minimized by shimming the pole pieces edges. The optimality of a design can be accessed by comparing the achieved physical horizontal extent to a theoretical estimate developed by Klaus Halbach [2]. Figure 2 presents calculated field homogeneities achieved by the Proton Driver II dipole magnet.For this magnet, the ratio $g/w \simeq 0.6$ and we note that the achieved homogeneity is in good agreement with the prediction from Halbach's formula.

Eddy Currents

In a rapid cycling magnet, the presence of eddy currents is a source of technical difficulties. Eddy currents are induced both in the magnetic core and in the conductors. In the core, they are largely suppressed by a laminated core construction which impedes their flow in the longitudinal direction. As long as the lamination thickness is smaller than the skin depth, their is little impact on field quality and principal effect is to increased losses.

Eddy currents induced in conductors are potentially more problematic. If the current distribution is non-uniform, resistive losses can be substantial; furthermore, the field homogeneity can be affected. The latter problem is largely eliminated by avoiding to place conductors into or near to the magnet mid-plane.

For a rectangular conductor immersed in a uniform time-varying magnetic field $B_0\sin(\omega t)$, it can be shown that the power losses are given by

$$P = \omega^2 B_0^2 A a^2/16\rho \quad (3)$$

where A is the conductor area, a is the conductor width and ρ is the resistivity. Clearly, eddy currents can be reduced either by reducing conductor cross-section or the magnetic field in which the coils are immersed. Reducing individual conductor area increases the number of turns N and therefore the magnet terminal voltage, since the inductance scales like N^2. To keep the voltage at a reasonable level, it becomes necessary to connect multiple turns in parallel. The Proton Driver II magnet assumes groups of three conductors connected in parallel in each coil and the top and bottom coils also connected in parallel. The electrical and mechanical connections in the end regions are shown in detail in Figure 1. Note that the conductors are not transposed. Although transposition would reduce losses slightly, it would also render connections in the end region very complex and cumbersome.

In the Proton Driver Study I, eddy current power loss problems were completely side-stepped by the use of a special water cooled stranded conductor. Aside from the technology required to produce reliable electrical and mechanical joints, the main drawback of the stranded conductor is its high cost (about an order of magnitude more expensive than conventional copper conductor). For study II, the possibility of using conventional solid water cooled conductors has been revisited. Figure 3 presents the result of an eddy current computation.

Eddy current losses reach a substantial level in the conductors closest to the edge of the pole, in the fringe field region. To take advantage of the fact that the magnetic field is predominantly vertical in that region, a rectangular (as opposed to square) conductor is employed. Relatively high losses affect approximately 20% of the total coil cross section; however, localized heating should be prevented by good thermal contact between conductors. Conventional water-cooled solid copper coil is a well-understood technology. Compared with stranded conductors, the trade-off is reduced operational efficiency vs reduced up-front fabrication costs.

Quadrupoles

The Proton Driver quadrupoles are four-fold symmetric magnets. Both horizontal and vertical focusing

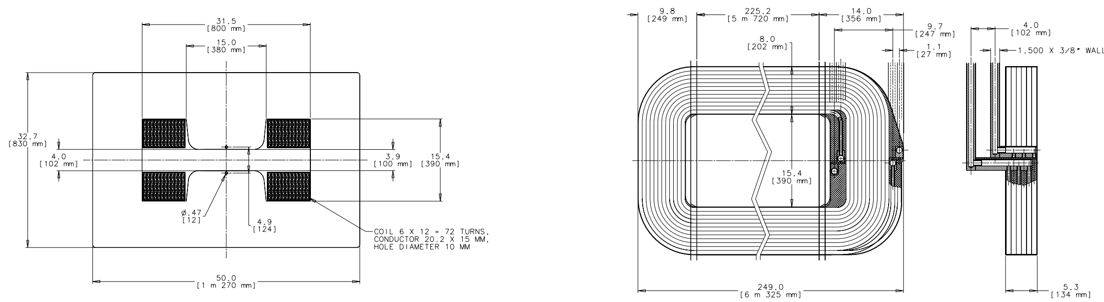

FIGURE 1. Proton Driver dipole cross-section and coil detail. Note the circular holes in the center of the poles. Note also the parallel connections at one of the coils extremities.

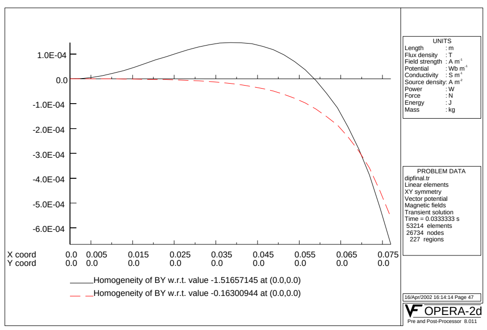

FIGURE 2. Proton Driver dipole field homogeneity at minimum and maximum excitations.

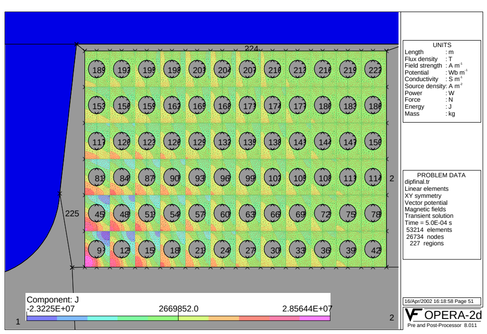

FIGURE 3. Eddy current distribution in the conductors. Note that the distribution is most uneven in conductors located near the pole edge.

quadrupoles are identical and the aperture radius is set to accommodate a rectangular good field region of the same size as the dipoles'. A common current bus provides dynamical tracking between the quadrupole gradient and dipole field. The number of turns and length of the quadrupole are selected so as to match optical and physical requirements at injection. At higher energies, the gradient/dipole strength ratio must not deviate by more than a percent or two; this effectively limits the maximum achievable gradient. For the required aperture, when the quadrupole pole tip field reaches 0.84 T, the field at the edges of the truncated hyperbolic profile reaches approximately 1.5 T, and saturation begins to affect the linearity of the relation between quadrupole strength and excitation. Note that saturation in backleg region also affect nonlinearity; however, this effect can be minimized by adjusting the backleg width. Note that for a four-fold symmetric quadrupole saturation does not adversely impact field quality since all harmonics except those of order 4n (8n-pole) are suppressed: the first allowed harmonic is the 12-pole. At 8 GeV, the deviation is on the order of 2.0%.

CONCLUSIONS

High voltage operation is a serious concern. The dipole magnets have a maximum terminal voltage on the order of 5 kV; in the proposed resonant configuration, the maximum voltage to ground reaches approximately 3.3 kV. Another source of concern in the fact that the entire magnet is be placed inside an evacuated enclosure. Special precautions will be needed during the assembly process to avoid excessive degassing.

An interesting avenue for future R&D would be an investigation of super-ferric magnet technology. In recent years, a new generation of Nb-Ti superconducting cable has been developed for applications in power generation and transmission. The cable has insulated filaments with a diameter as small as 0.1 μm embedded in a Cu-Ni alloy matrix. Superconducting coils would result in substantial savings in overall magnet size and power consumption; these savings may be substantial enough to offset the additional costs and complexity engendered by the cryogenic system.

REFERENCES

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