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A SIX-TESSLA SUPERCONDUCTING DIPOLE MAGNET DESIGN AND DEVELOPMENT PROGRAM FOR POPAE*

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ABSTRACT

POPAE, the proposed Proton-Proton Intersecting Storage Ring Facility at Fermi National Accelerator Laboratory, will require some 1400 superconducting 6.0 T DC dipole and quadrupole magnets. The dipoles are 6.17 m long and consist of coils of rectangular cross section clamped directly onto the 6 cm inner diameter bore tube. Aluminum is used to support the coils, and they are wound from a rectangular monolithic 2:1 copper to NbTi filamentary conductor. An experimental program has been undertaken to test and select the size, type and internal support scheme of the conductor. Full-sized coils of the POPAE dipole design, for shortened to 0.5 m but supported similarly to the full-sized magnet are being tested in the field of a 2.2 T backing magnet modeled after the Argonne ASD magnets. We also describe the large-scale cryogenics installation needed for the facility.

I. INTRODUCTION

POPAE, an intersecting storage ring facility of 1000 GeV on 100 GeV protons has been proposed¹ for construction at Fermilab. In terms of cost and reliability, the dipole magnets are a major part of the project. For the chosen 6.0 T magnetic field and 6.17 m effective length, each ring requires 570 dipoles. These dipoles must have a field quality which permits the storage of a beam of 5.0 A for many hours.

II. POPAE MAGNET PARAMETERS

The bending of a 1000 GeV beam of protons into a closed circle requires an $\int B dl$ of 21,100 Tm. It is instructive to examine the cost of the machine for various choices of dipole field B . Stronger fields entail greater cost per unit length for the magnet system, but fewer meters of magnets and other components. The POPAE reference design entails some 35.3 millions of dollars of components with cost independent of the choice of field B , and some \$46.2 M of items with cost proportional to the machine's circumference, in addition to the magnets themselves.

Costs for the POPAE dipoles are calculated for various values of B assuming cold iron and cold bore, including superconductor, iron yokes, construction labor, cryostats, and aluminum coil support material. The results appear in Fig. 1.

Fig. 1 Dipole cost as function of field.

In each case, a current density of 20 kA/cm² in the windings was assumed, and enough iron to contain the return flux. A set of 12 pancake layers closely approximating a 'displaced elliptical' dipole was used in the study. The quadrupoles are presumed to scale in cost as the dipoles.

The cost (before AEM, EDIA, contingency, and escalation) of the storage ring facility for the various choices of dipole field B are summarized in Table I.

B	Fixed Costs	Dipole and	Total Cost
T	Costs	Quadrupole	\$M
	\$M	Magnet Cost, \$M	
3	35.3	48.7 + 6.3	182.7
4	35.3	53.6 + 6.9	165.1
5	35.3	57.5 + 7.4	155.6
6	35.3	64.9 + 8.5	154.9
7	35.3	82.8 + 10.6	168.3
8	35.3	116.7 + 14.9	201.6

It is seen that the cost of POPAE is relatively insensitive to the choice of field with a broad minimum around 6.0 T. Siting considerations favor a high value of B and a smaller ring, and reliable 6 T dipoles are a reasonable extrapolation beyond present experience.

The geometry chosen for the windings permit the choices of magnet current and average current density to be made on the basis of cost and reliability. Up to about 30 kA/cm², the higher the current density the more efficiently the conductor is used and the less costly the magnet as shown in Fig. 2. Cable of NbTi and copper is now obtainable that carried in excess of

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Fig. 2 6T dipole magnet cost.

43 KA/cm² at 5 T, but this falls to about 32 KA/cm² if peak fields of 6.6 T are desired. Such current densities are further reduced by about 20% if temperature excursions above 4.2 K or 0.5 K or so are considered.

Figure 2 also shows the relative expense of increasing the beam aperture for whatever reason. If, for example, a warm bore were specified and an additional 1 cm annulus for insulation thereby required, the magnet cost would increase by fifty percent.

It is convenient to power several POPAE dipoles in series with bypass thyristors to shunt any magnet which might quench. If external quench resistors were part of the protection circuit, large voltages would appear across each dump resistor; if several magnets quenched before the string were discharged, unacceptable voltages would accumulate along the string of magnets. Thus it is desirable that each magnet be able to absorb its own stored energy if it should quench and not require an external dump resistor for energy removal.

To limit the temperature rise to 100 K and the potential buildup to 500 V, the current should be 2000 A or more, so that the heat generated in a quenched magnet equals the enthalpy of the coil mass. A more exact calculation in which the magnet resistance develops as the quenched region grows, using the computer code QUENCH,² predicts that 80% of the coil volume will be driven normal, the peak terminal voltage of the dipole will be 700 V and the peak temperature 300 K for an initial current of 2500 A and a current density of 20 KA/cm². This calculation of temperature and voltage maxima is conservative, but more analysis and testing of the quench aspects of the magnet are clearly needed.

III. LOCATION OF COILS

Adjustment of the conductor configuration in the presence of a shield of infinite permeability to produce nearly uniform fields in 2D or 3D is carried out by minimizing the area integral of H_x^2 or GG^* over a reasonable working region,^{3,4} where

$$H = H_x + iH_y$$

and G is the axial integral of H through the magnet. This is done in multipole form in which the lowest multipole corresponding to the desired field is removed from the multipole expansion. In this manner, all higher multipoles are minimized.

The effects of finite permeability are rather small. These effects on the multipole expansion are found in 2D by inserting the desired configuration of conductors into the magnetostatic code LINDA.⁵ The difference between the multipoles obtained with finite permeability and infinite permeability is applied as a correction to the multipoles obtained from the complex variable calculation both in the 2D and in the 3D form. This procedure is less certain for 3D since the actual iron configuration is not infinitely long. The magnetostatic code GFUN⁶ in its two- and three-dimensional forms has also been used and agrees with the above methods.

IV. INTERNAL SUPPORT

The choice of a 6.0 T field level requires that careful consideration be given to the support of the conductor. The design of 6.0 T magnets using NbTi superconductor is somewhat different from that for 4.0 to 1.5 T magnets, such as for the ES/D⁷ or Isabelle,⁸ in that one must properly arrange considerably more superconductor around the bore and at the same time make adequate provision for the increased forces on the coils. The strictly dc character of the POPAE magnet operation allows generous use of metal in the support structure.

In the ES/D design two relatively thick shells provide sufficient current, and the arc lengths of the shells are adjusted to remove sextapole and decapole terms for the central field. At 6.0 T, the shell thickness becomes so large that a simple multipole adjustment is no longer possible with two shells. More shells with differing arc lengths are needed to obtain a high-quality field and this geometry creates a difficult structure in which to provide the increased mechanical support required by high-field operation.

In the Isabelle design rectangular blocks are arranged in a radial pattern, with the spacing and current density adjusted to achieve a high-quality field. A flat-ribbon braided conductor with the full radial width is used, combined with dummy windings to reduce the current density as required. At 6.0 T, two layers of such blocks become necessary, with consequent support problems.

We have chosen a flat, rectangular coil design with a rectangular conductor, either monolithic or cable. The transfer of force across a coil should promote mechanical stability with such a geometry. In the reference design of the POPAE proposal (Fig. 3), there are six coils approximating an intersecting circles geometry and positioned to remove the sextapole and decapole components of the field.

Although this geometry becomes somewhat inefficient in low field designs, the wide coils required for high field strengths are easily accommodated, and lend themselves naturally to good mechanical support. This support is provided by machined aluminum extrusions, a feature of this design that is possible

because the operation is dry, we do not have to consider field distortion from eddy currents or heating in the coil structure.

A magnet of similar design, and reaching 6 T, has been built and operated at Saclay by H. Desperter.¹ The cold-bore diameter is 9.2 cm and the length is 60 cm. After the coil ends were strongly clamped, the magnet was able to reach a central field of 6 T without iron (7% of short-circuit current). The median-plane field uniformity was close to that required in storage-ring magnets.

Fig. 3. POPAI reference dipole design.

V. EXTERNAL SCREENING

The POPAI coils are wound in extruded aluminum bolins. The conductor is clamped by aluminum blocks pressed into place along the outer edge of the bolin and tack-welded into place. The effects of the differential contraction of the aluminum and the conductor during cool-down are accommodated in this design.

The bolins and coils are assembled onto the bore tube extension which has steps to position the bolins. The assembly is clamped and then machined to accept a shrink fit aluminum tube which is segmented for ease of fabrication and assembly.

The completed coil assembly is inserted into the iron yoke, which is split along the vertical median plane and joined with aluminum plates so that on cool-down the iron follows the coil assembly inward. Teflon-coated pads position the coil assembly in the yoke and allow for differential longitudinal contraction.

VI. IRON

The POPAI dipole reference design (Fig. 3) incorporates cold iron with inner radius 12.7 cm and thickness 17.8 cm, but thinner at the top and bottom where the flux is less. This iron yoke contributes mechanical support to the coils, enhances the central field, and shields the central bore against stray external fields.

However, this iron is expensive and is the heaviest component of the magnet, and if it is included

inside the cryostat, it greatly increases the time and expense of cool-down. Moreover because of saturation effects the multipole components change with current setting and require current-dependent corrections. It is therefore instructive to examine in detail the effects of moving the inner iron radius outward, while maintaining sufficient iron thickness to return the flux beyond that radius. An air-core dipole was configured which produced 6 T with a current density in the windings of 20 kA/cm^2 . For each inner radius r_1 chosen, a thickness b of iron was calculated which contained the flux with a flux density of 1.8 T. The air flux was then corrected to account for the field enhancement due to the iron, and the current density therefore reduced so that the central field remained 6 T. The iron thickness was reduced correspondingly to the increase in current density. Table II shows the results of the calculations for various r_1 and b for the cost of conductor and iron for each configuration.

TABLE II

Conduct	Current	Screen	Cost	Cost	Cost
Inner	Density	Thickness	Area	\$/m	\$/m
Radius	kA/cm^2	cm	cm^2		
r_1 cm					
10.0	15.6	21.8	27.6	1608	1246
15.0	16.5	15.4	25.6	1498	1117
20.0	17.9	14.2	24.8	2110	21.0
25.0	18.6	11.8	22.8	2100	20.0
35.0	19.5	8.7	21.5	2200	2.00
∞	20.0	6.0	1.85	2700	2.00

The effect of the outer size of the bore was determined by use of the program BFL. For a bore of μ of 10,000 and for a realistic field relation, the central field and field harmonics were calculated. To test the screening effect of the iron, the field at 60 cm was also calculated. To test the screening against an external field, two dipoles with two-dimensional dipole moment $13.4 \times 10^6 \text{ A cm}$ were placed 100 cm from the center of the magnet, and the field and sextupole moment recalculated. Finally all calculations were repeated with 2 cm less thickness of iron.

The results show that screening was almost complete for $\mu = 10,000$ with either 18.8 cm or 15.4 cm for iron. However for variable μ , 15.5 cm was fairly effective at screening, but 15.5 cm was little better than no iron at all. Combining these results with the results in Table II, that the combined cost of conductor and iron is almost independent of iron location, forces the conclusion that the cost of screening is necessarily high. This further suggests that the feasibility of eliminating the iron shield completely as a means of reducing the cost of the magnet should be examined. Experience with the FNAL 15-foot bubble chamber suggests that equipment can be operated in the POPAI tunnel even with unshielded magnets.

VII. CRYOGENICS

For reasons of economy a central large liquid-helium-refrigerator facility, located near the center of the rings, has been proposed for POPAI. Both liquid helium and liquid nitrogen refrigerants are