LBL-37503
UC-414

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the Cryogenic Engineering Conference, Columbus, OH, July 17–21, 1995, and to be published in the Proceedings

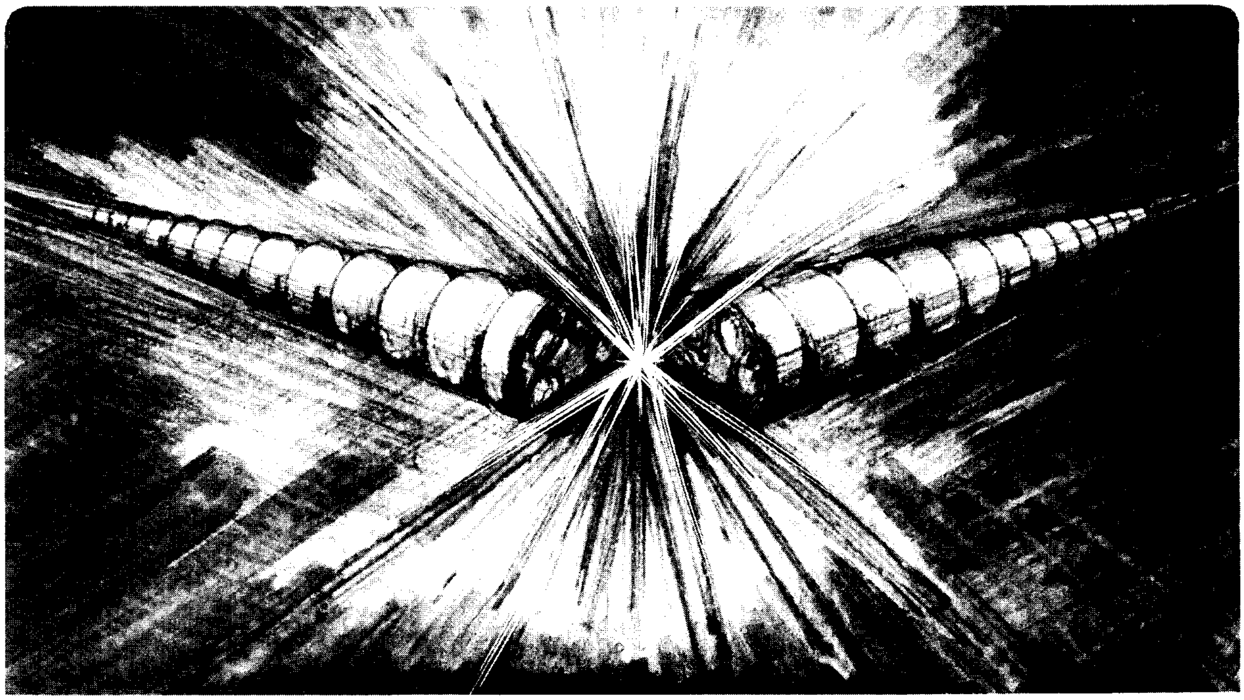
CERN LIBRARIES, GENEVA
SCAN-9602166

A Superconducting Bending Magnet System for a Compact Synchrotron Light Source

M.A. Green, A.A. Garren, E.M. Leung, D.D. Madura, D.B. Cline, J.J. Kolonko, and L.C. Schachinger

July 1995

Sw3603



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor The Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or The Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

Ernest Orlando Lawrence Berkeley National Laboratory
is an equal opportunity employer.

SC-MAG 523

LBL-37503

A SUPERCONDUCTING BENDING MAGNET SYSTEM FOR A COMPACT SYNCHROTRON LIGHT SOURCE,

M. A. Green and A. A. Garren

E. O. Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720

E. M. Leung and D. D. Madura

ADO Lockheed Martin
Rancho Bernardo, CA

D. B Cline and J. J. Kolonko, and L. C. Schachinger

Particle Beam Lasers, Inc.
Northridge CA 91324

July 1995

---

* This work was performed with the support of the Director of the Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, United States Department of Energy under contract number DE-FG03-94ER81826 and contract number DE-AC03-76SF00098.

LBL-37503

A SUPERCONDUCTING BENDING MAGNET SYSTEM FOR A COMPACT SYNCHROTRON LIGHT SOURCE

M. A. Green and A. A. Garren

E. O. Lawrence Berkeley National Laboratory
University of California
Berkeley, CA 94720

E. M. Leung and D. D. Madura

ADO Lockheed Martin
Rancho Bernardo, CA 92125

D. B Cline and J. J. Kolonko, L. C. Schachinger

Particle Beam Lasers, Inc.
Northridge CA 91324

ABSTRACT

High intensity, high energy X-rays for use in protein crystallography, nano-machining and medical applications, such as non invasive coronary angiography, can be produced by a 1.2 to 1.5 GeV electron storage ring compact light source with 6 to 8 tesla superconducting bending magnets. Because the bending magnets are to be superconducting, the storage ring energy can be over factor of two lower than a conventional storage ring that delivers same photon energy. The ring, which has superconducting bending magnets, is smaller in circumference and has the advantage of having fewer particles in the ring for a given x ray source intensity. The proposed storage ring is a separated function accelerator ring with six superconducting bending magnet units. Conventional quadrupoles and correction elements would be located between the bending magnets. Because the synchrotron radiation is generated in the bend, the superconducting bending magnets must have a warm vacuum chamber for the electron beam. Variations of a superferric magnet design have been studied for this application. This report presents a superferric H magnet design that can produce good quality magnetic field in a region that is 50 mm high by 100 mm wide. This modified superferric H magnet design has saturated iron poles but the magnetic flux is returned from one pole to the other through an unsaturated iron return path. The dipole magnet required for a compact storage ring must be physically short (380 mm long), and the field must fall off rapidly at the ends of the magnet. This report describes a preliminary design for a pair of 6.894 tesla, thirty degree bending magnets in a common vacuum vessel for use in a 1.5 GeV compact storage ring light source.

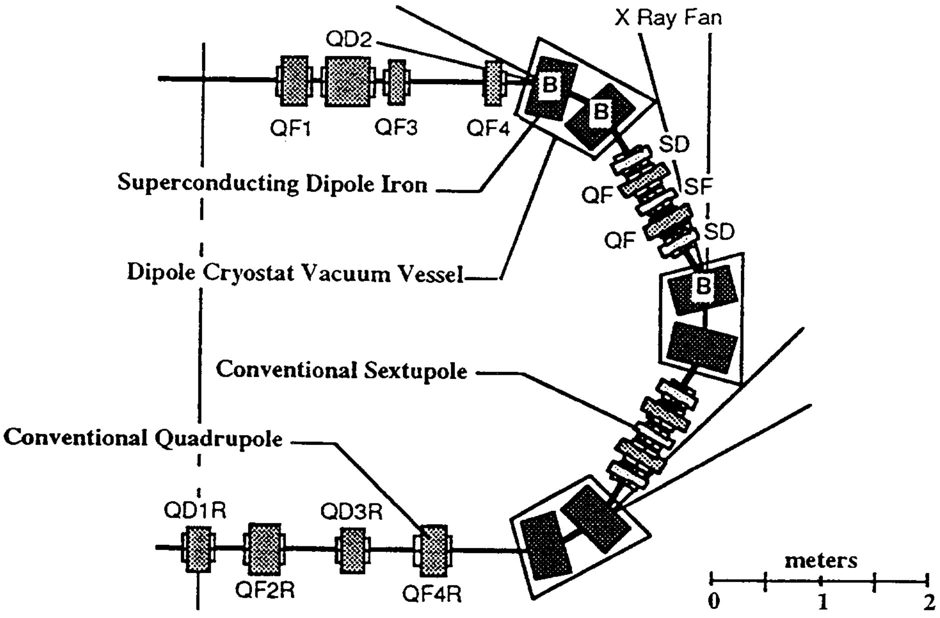


Figure. 1 Half of a 26 meter Circumference Compact Storage Ring Showing the Superconducting Dipoles, and the Conventional Quadrupoles and Sextupoles

DIPOLE REQUIREMENTS FOR A COMPACT STORAGE RING

Figure 1 shows a diagram of an industrial 1.2 to 1.5 GeV compact electron storage ring with superconducting bending magnets and room temperature quadrupoles and sextupoles. The light source ring design shown in Fig. 1 resulted from cost optimization studies that were combined beam dynamics studies[1,2] The required central induction of the dipole at a ring energy of 1.5 GeV is 6.894 T. The dipoles that are shown in Fig. 1 and that are presented in this report have a design central induction commensurate with 1.5 GeV storage ring energy. The peak critical energy of the x rays generated by the ring shown in Fig. 1 is 10.4 keV (at a beam energy of 1.5 GeV). Intense synchrotron x rays with an energy up to 40 keV are produced at six points around the ring. The ring is compact; its circumference is 26 meters. There is adequate room in the straight sections for rf cavities and a system to inject a 100 MeV electron beam into the ring. The ring shown in Fig. 1 has a design beam current of 20 mA. As a result, the synchrotron x rays are extracted from the downstream dipole of the pair. The x rays from the upstream dipole of the pair will be absorbed by the vacuum chamber passing through the dipoles. If the dipoles are separated (with focusing elements between them), the x ray beam intensity can be increased over an order of magnitude, but the ring circumference and cost will increase.

Each dipole in the pair shown in Fig. 1 has a magnetic length of 380 mm along the beam orbit. The dipoles are straight magnets so that the lattice defocusing comes from the edge of the dipole. The key to making a compact electron storage ring is the fabrication of short high field dipoles that have the end field characteristics similar to room temperature, copper and iron dipoles. Within the magnetic length magnet, the integrated field quality has to be very good. Beam dynamics studies suggest that the integrated field has to be good to one part in 10000 over a region that is ±20 mm wide around the electron beam.

Picture frame magnets have a very good field uniformity over the entire width of the magnet pole until the iron in the pole and return yoke saturates. The design for the dipole presented here is based on a modified picture frame dipole proposed by Pavel Vobly at INP Novosibirsk[3,4]. The Vobly dipole has saturated iron in the poles, but shield coils keep the magnetic flux in the pole until it can be returned by an unsaturated iron return yoke. As a result, the end field fall off is similar to that of conventional iron dominated dipoles. This is very important for a dipole with a magnetic length of only 0.38 meters.

THE SUPERCONDUCTING DIPOLE

Figure 2 shows a quarter cross-section through the center (in the longitudinal direction) of a Vobly type of dipole designed to produce a central induction of 7.0 tesla. Fig. 2 shows the flux lines generated by the magnet when the field is uniform across the pole and the central induction is 7.0 tesla. The dipole shown in Fig. 2 has three different coils: 1) The gap coils will generate the magnetic field within the gap. The current in the gap coils will be linear with the magnetic induction within the gap. 2) The crossover coils will carry the current from one side of the gap to the other side of the gap. This coil, which is in series with the gap coil, acts in a way similar the end crossover coils in a conventional H dipole magnet with unsaturated iron poles. The gap and crossover coil currents cancel each other, away from the magnet gap. 3) The primary function of the shield coil is to keep flux from leaking out of the pole when its iron becomes saturated. The flux lines from gap stay perpendicular to the pole face even within the pole iron, when the current in the shield coil is set to the proper value. The shield coil current will be nearly zero when the iron in the pole is unsaturated. As the pole iron saturates, the current in the shield coil increases linearly as the central induction minus the saturation induction of the iron. The shield coil will be powered separately from the gap and crossover coils.

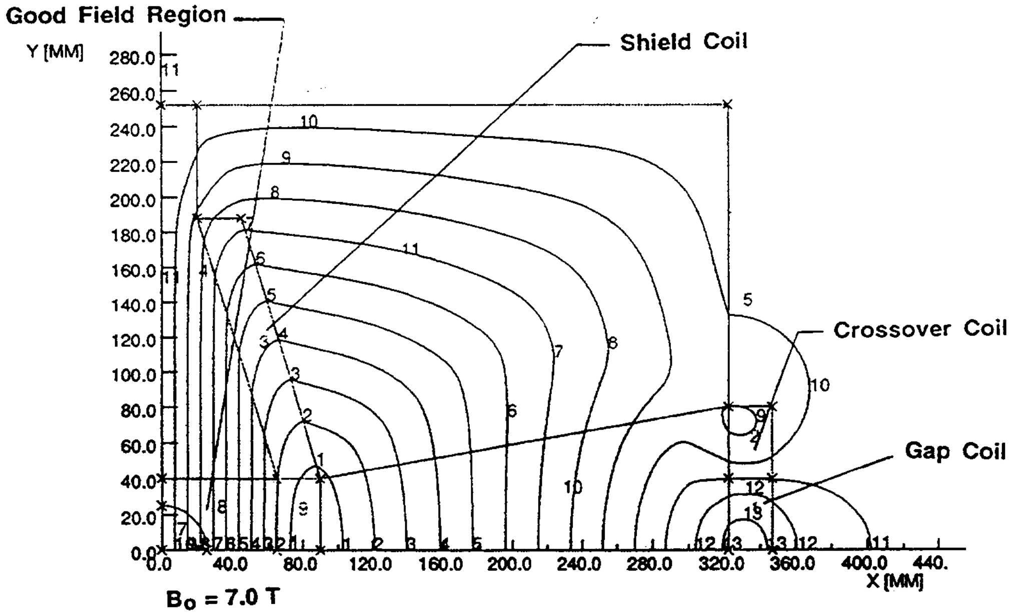


Figure 2 A Quarter Cross-section of the Compact Light Source Dipole Showing the Magnetic Flux Lines at a Central Induction of 7.0 T

Figure 3 shows a three dimensional view of the three coils. The iron boundary is shown as dashed line. The arrows in Fig. 3 show the direction of current flow in each of the coils. From Fig. 3, one can see that coils are not complex in their construction. All of the bends occur in a single bend. Features such as turned up ends have been avoided. Figure 4 shows the iron assembled around the dipole coils

The dipole shown in Fig. 2 through 4 will generate a uniform field over a wide range of central inductions, provided that the current density in the shield coil system is correctly chosen with respect to the current density in the gap and crossover coil system. Fig. 2 shows that the flux density in the pole is the same as the flux density within the gap. The field in the magnet gap is very uniform. The current density in the shield coil is 166.6 MA per square meter while the current density in the gap and crossover coils is 270.0 MA per square meter. The excitation function for the shield coil can be modified by changing the height and slope angle of the shield coil[5].

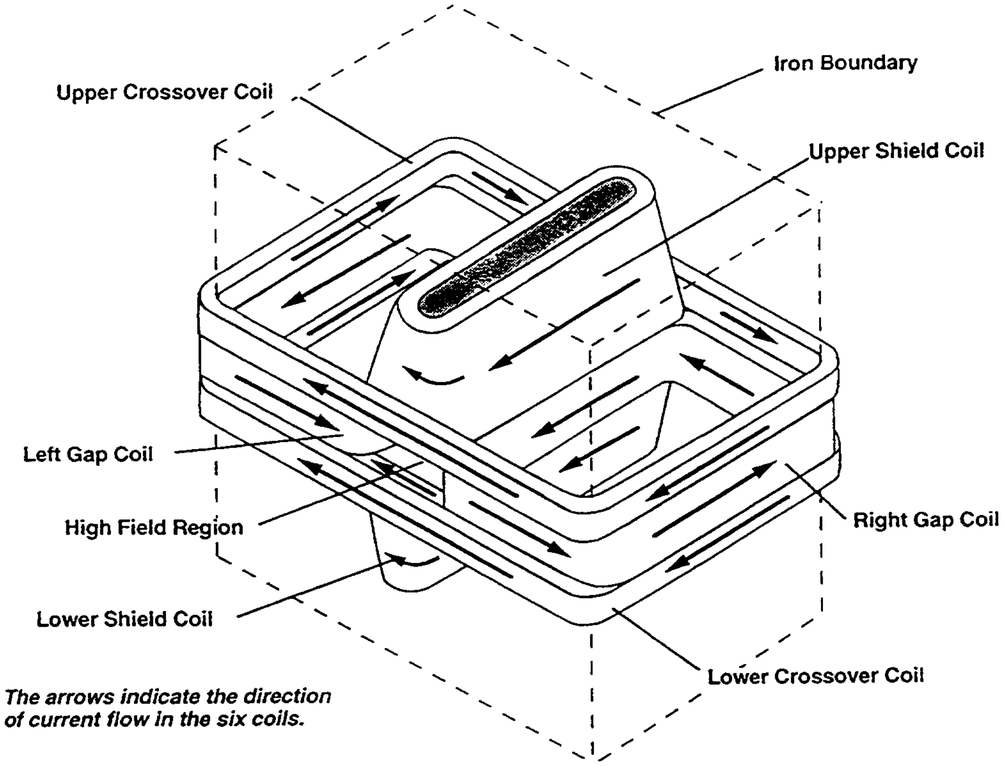


Figure 3 A Three Dimensional View of the Coils in a Compact Light Source Dipole

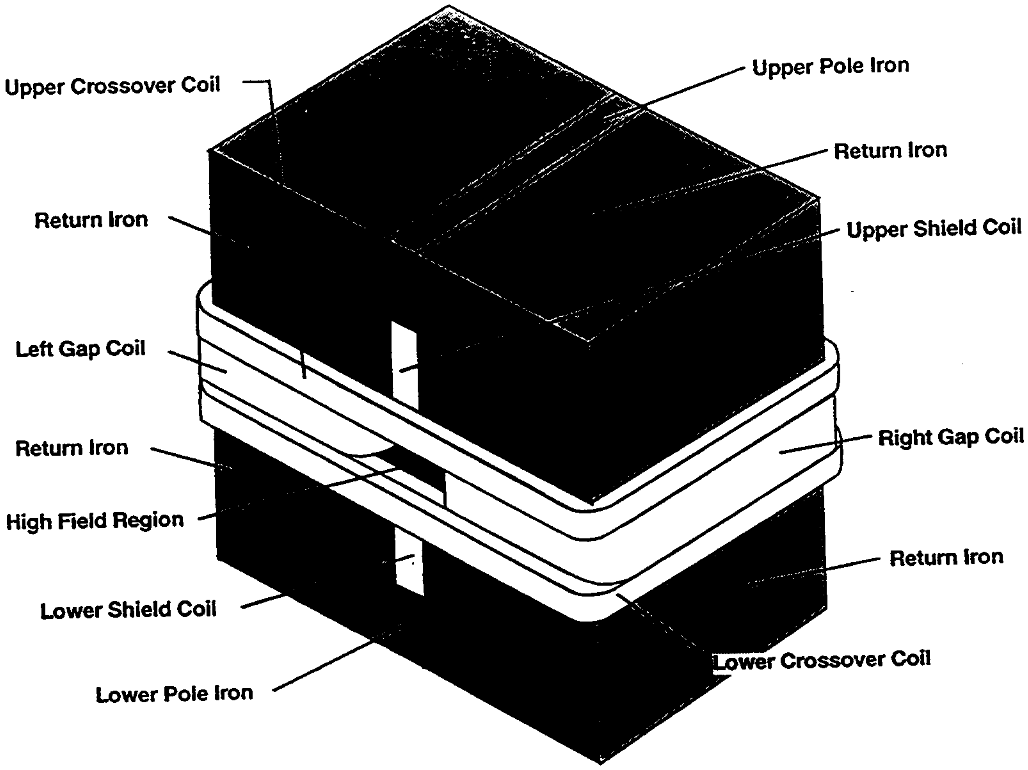


Figure 4 A Three Dimensional View of the Fully Assembled Light Source Dipole

Figure 5 shows the current density in the gap and crossover coils (The gap and crossover coils have the same current density.) and shield coils needed to produce a uniform dipole field as a function of the central induction of the dipole. One can adjust the current density in the shield coil with respect to the current density in the gap and crossover coils such that the sextupole generated in the gap is zero. If the gap coil height and slope angles are correctly selected the higher multipoles from decapole on up will be very small. To check this, the two dimensional field uniformity was calculated at a central induction 7.132 T. A field uniformity of 0.6 parts in 10000 was calculated in a region that was ± 30 mm about the center of the dipole. (See Figure 6) This means that sextupole, decapole and 14 pole were very small. The even multipoles (quadrupole, etc) are zero by symmetry.

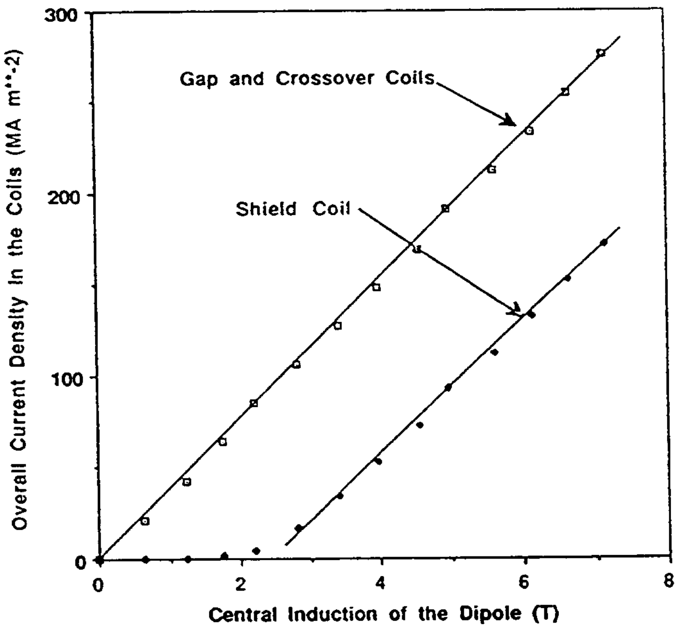


Figure 5 The Current Density in the Gap and Crossover Coils and the Shield Coils Needed to Achieve a Uniform Dipole Field as a Function of Central Induction

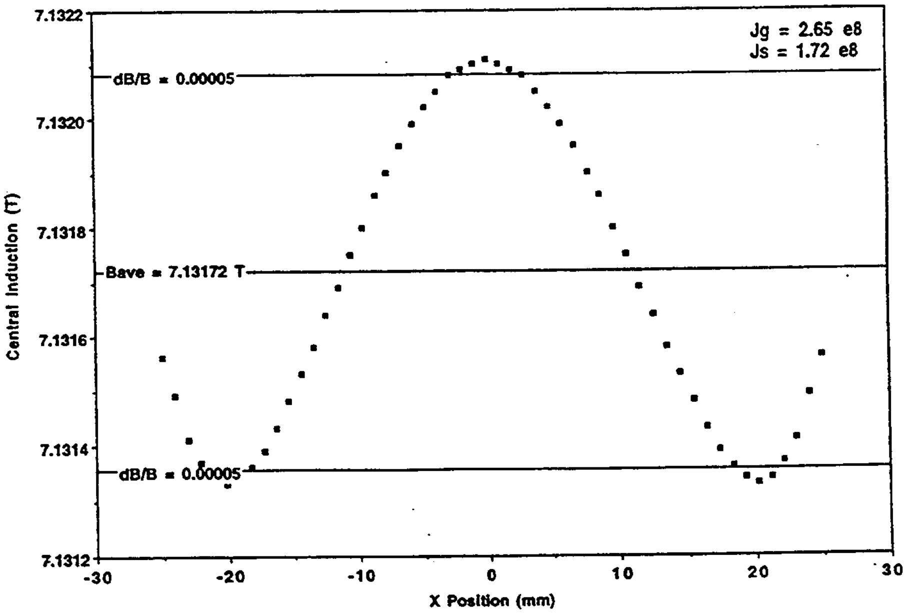


Figure 6 The Two Dimensional Magnetic Induction on the Beam Plane as a Function of X Distance along the Pole from the Magnet Center (The shield coil surrent is set for uniform Field.)

Table 1 presents the parameters for the 7 tesla dipole shown in Figs. 2, through 4. When the electron beam energy in the ring configuration shown in Fig. 1 is 1.5 GeV, the dipole central induction will be 6.894 T. The required integrated dipole for each of the twelve ring dipoles is about 2.62 T m If one bases the coil design shown in Figs. 2 and 3 on a cable made from SSC inner conductor (with a copper to superconductor ratio of 1.4), the dipole will operate at about 87% of its critical current along the load line (based on a metal packing fraction of 0.7 and an operating temperature of 4.4 K), when the dipole central induction is 6.9 T. It appears that the SSC inner superconductor can be cabled into conductor of almost any desired current for this application.

Table 1 Compact Light Source Superconducting Dipole Parameters

Number of Bending Units	6
Number of Dipoles per Bending Unit	2
Dipole bend Angle (degrees)	30.0
X Ray Fan Angle (degrees)	20.0
Required Integrated Induction (T m)	2.620
Design Induction at Center (T)	6.894
Magnet Cold Gap (mm)	80.0
Magnet Iron Pole Width (mm)	130.0
Nominal Pole Length (mm)	~376
Shield Coil Height (mm)	148.0
Coil Thickness (mm)	25.0
Stored Energy* (kJ)	~190
Peak Induction in Winding* (T)	~7.0
Iron Length (mm)	376.0
Iron Width (mm)	644.0
Iron Height (mm)	504.0
Estimated Cold Mass per Dipole (kg)	~1100

* at the design central induction for a 1.5 GeV storage ring

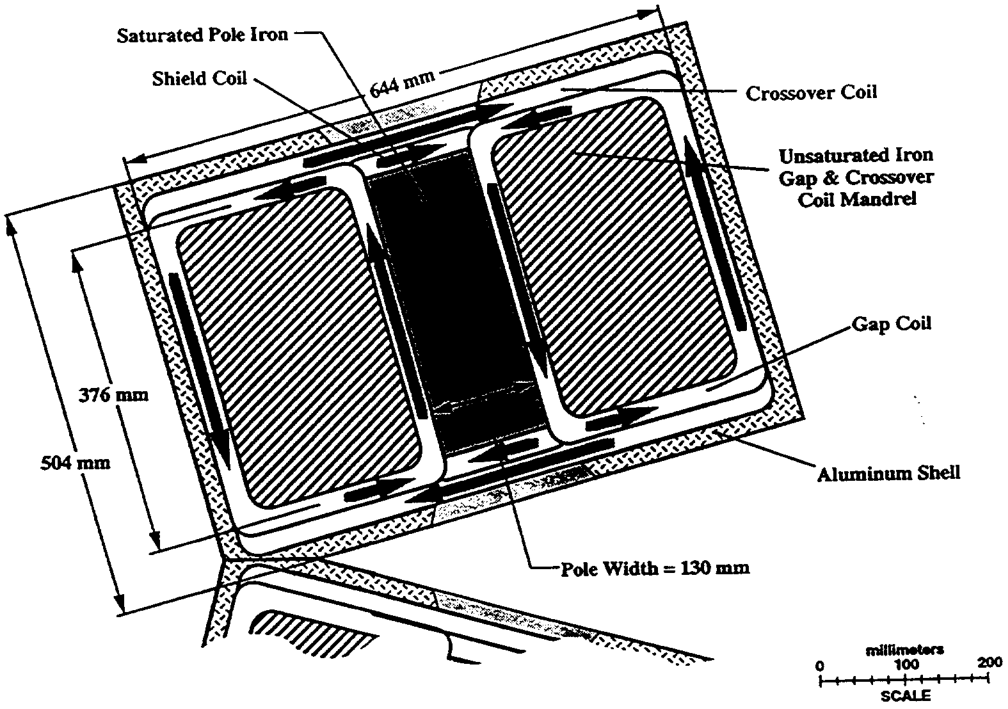


Figure 7 Dipole Cross-section in the Plane of the Electron Beam

Figure 7 is a Cross-section of the dipole on the electron beam orbital plane. Fig. 7 shows that the cap and crossover coils can be wound as flat pancakes with small radius bends in the corners. The shield coils are more difficult. These coils can be wound in a stair like structure and still have the dipole meet its field uniformity requirements. The primary magnetic force acts in a direction to force the two gap coils apart. There is a strong force on the iron pole pieces to draw them together. Preliminary force calculations suggest that the magnetic forces can be carried by a 19 mm thick aluminum shell. The shell can also insure that the coils maintain contact with the iron during cool down and excitation

.

The cost of a short compact light source dipole is primarily a function of the pole width, not the gap between poles. Since most of the iron in the magnet is unsaturated, the overall iron height and width are functions of the pole width and the saturation induction of the iron. Most of the dipole cold mass in the dipole is iron. The Vobly type dipole is not very efficient in its use of superconductor. Unlike most superconducting dipoles, the cost of the superconductor is not a large part of the capital cost of this magnet.

CONCLUSION

A compact synchrotron with 6.9 tesla superconducting bending magnets appears to be feasible. A short high field dipole magnet is the key element for a compact synchrotron light source storage ring. The short high field bending magnet must have end field characteristics that are similar to short conventional low field magnets. The magnetic flux must be constrained in the poles, even when they are saturated while the magnet is running at high field. The modified picture frame magnet design presented in this report has this characteristic. The primary disadvantage of the magnet design presented in this report is that it requires two separate power supplies in order for the magnet to produce good field quality over a range of inductions. At low field, when there is almost no current in the shield coil, the shield coil current can be used to eliminate the remnant field sextupole due to magnetization of the iron and persistent currents in the superconductor. The Vobly dipole design concept, discussed here, appears to be viable for dipole magnets that have a length to gap ratio of greater than four.

ACKNOWLEDGMENTS

This work was performed with the support of the Director of the Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, United States Department of Energy under contract number DE-FG03-94ER81826 and contract number DE-AC03-76SF00098.

REFERENCES

1. A. A. Garren, et al, "A 1.5 GeV Compact Light Source with Superconducting Bending Magnets," to be published in the Proceedings of the 1995 Particle Accelerator Conference, Dallas TX, USA, 1-5 May 1995
2. M. A . Green and A. A. Garren, "Optimization of Superconducting Bending Magnets for a 1.0 to 1.5 GeV Compact Light Source," to be published in the Proceedings of the 14th Magnet Technology Conference, Tampere, Finland, 11-16 June 1995
3. G. N. Kulipanov, N. A. Mezentsev, L. G. Morgonov, et al, "Development of a Superconducting Compact Storage Rings for Technical Purposes in the USSR," Rev. Sci. Instrum. 63 (1), p 731 (1992)
4. P. D. Vobly, private communication concerning compact synchrotron dipole magnet designs
5. M. A. Green, "Superconducting Dipole Magnets for Compact Light Source Storage Rings," Lawrence Berkeley Laboratory Internal Report LBID-2005, 9 Feb. 1994