Superconducting Magnet Program for X-Ray Lithography Source at Brookhaven National Laboratory*

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Abstract

Brookhaven National Laboratory is funded by DOD-DARPA to develop a compact electron storage ring to be used as a X-Ray source for producing high density computer chips. The circumference of this machine is 8.5 meters, the machine lattice consists of four quadrupoles, two sextupoles and a pair of air-core combined function 3.87 Tesla superconducting dipoles. BNL is developing the superconducting dipoles in collaboration with its industrial partners GDSSD and GSED. This paper will describe the field characteristics and engineering realization of these magnets and present the current status of the program.

I. INTRODUCTION

Synchrotron based X-Ray Lithography is recognized as a promising method to produce large quantity of sub-micron size computer chips at an affordable cost. Brookhaven National Laboratory was funded in 1988 to develop a compact storage ring for industrial use, so that the U.S. semiconductor producers can compete world wide effectively.

BNL's project is divided into two phases, the first phase is to build a conventional machine with an energy of 200 MeV. Its lattice is identical to that of second phase high energy machine except that the two dipoles are of a resistive type. The goal of the first phase is to study the low energy injection and the accelerator physics. This low energy machine has been built and installed in the NSLS Department of BNL. The second phase of the program is to build a pair of 3.87 Tesla superconducting dipoles to replace the resistive dipoles of the first phase machine. The Phase II machine will operate at an energy of 700 MeV after the conversion is completed.

II. GENERAL DESCRIPTION

Figure 1 shows the cutaway view of the magnet. The SXLS superconducting dipole is a warm bore magnet, both the electron vacuum chamber and the photon exit ducts are at room temperature. RHIC conductor was adopted for the superconduting coils after confirming that the magnetization is not a problem at low injection field. The cold mass is supported by three low heat leak columns, the vacuum vessel is a bottomless one piece construction, magnet is assembled on a cryostat base plate and the superinsulation and heat shields is accomplished and the vacuum vessel is slipped over the whole assembly. The current leads are of a commercially available gas cooled type, the service stack is designed to enable easy servicing of the current leads and other components. The fiducial marks are external to the cryostat and serve as a means to locate the assembly during magnetic measurement and machine alignment. There are nine photon ports available from each of the dipoles.

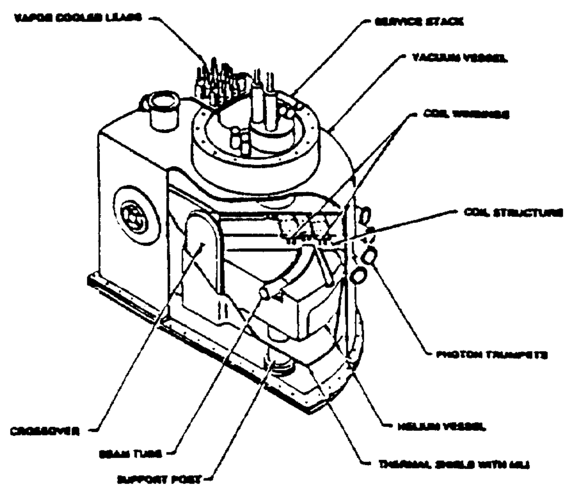

Figure 1. Magnet cutaway view.

III. COIL DESIGN AND FIELD CALCULATION

The magnetic lattice of this machine consists of two FODO cells incorporating 180 degrees combined function dipole magnets which contain both gradient and sextupole components. The SC dipole is designed to produce a bending field of 3.87 Tesla, a quadrupole of -1 T/m and sextupole of -9 T/m^2. All the other higher multipoles are undesirable and only reduce the dynamic aperture of the machine.

A set of three rectangular superconducting coil packs, A, B, and C (Figure 2) are arrayed around the beam tube to produce the required vertical dipole field. Coils A and B, which are placed as close to the mid-plane and the central

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trajectory as mechanically feasible, generate most of the dipole component of 3.87 Tesla. These two coils, however, also produce unacceptably large octupole and decapole components. Coil C in the magnet is used primarily to eliminate these higher order multipoles. The geometric configuration of the three coils was optimized to meet the field specifications given above. Trim windings are included in the magnet to provide for closed orbit correction, betatron tune and chromaticity variations. The strength of the trim windings are such as to provide adequate tuning as well as to account for changes in the desirable multipole content of the magnet due to coil placement errors.

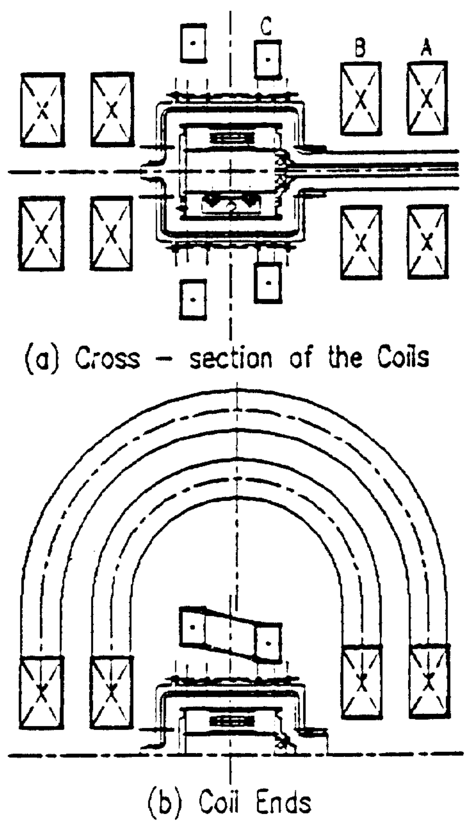

Figure 2 Cross section of the coils and coil ends.

The ends of the A and B coils are of the bedstead type as show in Figure 2. This choice was dictated by a desire to minimize the horizontal closed orbit distortion in the end regions of the magnet. Although a coil with race track type is easier to manufacture, the proximity of the coil ends to the magnet mid-plane produces the closed orbit distortions in excess of one centimeter. For the C coil, a flat end was deemed acceptable as it carries significantly less current than the other two main windings and thereby produces less deleterious effects on the orbit. There are nine photon ports distributed within an included angle of 100 degrees, therefore, the separation between the ports is rather limited.

Magnetic field calculations were performed by TOSCA that was interfaced with the optimization module of ANSYS. The optimization process in ANSYS was set by treating the coil locations as the design variables, and the multipoles calculated by TOSCA as the state variables. The differences between the calculated and specified multipoles were interpolated as penalty functions of the design variables. This results in a optimum set of coil locations that satisfied the required tolerances on the multipoles.

The coil locations were optimized based on the multipoles values at the mid point of the magnet. A Fourier Transform method corrected for the curvature terms was used in TOSCA to extract the multipoles from the calculated field values. Field derivative terms with respect to the arc length were ignored. Subsequently, the LBL ESG version of M. Berz's Differential Algebra [1] package was used in conjunction with TOSCA to obtain the multipoles as functions of the arc length (Figure 3). For an air core magnet, the magnetic field is given by an analytic expression, based on the Biot-Savart Law. The DA package is capable of performing arbitrary order derivatives with respect to any variable, either the position coordinates or the coil locations. In this way, the usual multipole coefficients or the sensitivity of these multipoles to the coil locations can be computed.

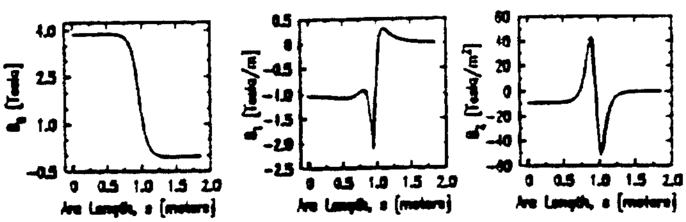

Figure 3 Multipoles as functions of the arc length.

IV. Engineering Considerations

1. Material Selections

The most critical materials for this magnet are current carrying conductors and their support structure. The conductor for the two main current blocks are of the same cable construction as BNL's RHIC project except that there is no keystoning requirement for SXLS magnet. By using the conductor that has been extensively used and characterized and using it in a conservative manner, the training of the coils at the beginning can be minimized. The operating current at 5.2 Tesla (max field) is 2800 amperes which is 70% of the current sharing value of 4000 amperes. The measured critical current of SXLS cable sample at 5.2 Tesla is in the order of 6900 amperes, therefore, the operating current is only 40% of the critical current. The critical temperature at 5.2 Tesla is 7.05 K, the current sharing temperature at 5.2 Tesla and 2800 ampere is 5.95 K, there is a temperature margin of 1.6 K for an estimated operating temperature of 4.35 K. The coil "C" has a flat race track end with a step-up configuration to obtain the proper gradient in the coil body. The coil "C" and the corrections coils are made from small diameter wires because cable type conductors are not sutiable for these coils due to their small bending radii. The total current in the correction windings is very low, the number of turns are kept low to reduce the complexity during the winding. The operating currents in the windings are generally 50% to 70% of the predicted quench currents and only 22% to 45% of critical current. There is at least a temperature safety margin of 1.65 K for the correction windings at their respective peak field locations.

One of the other critical problems for this program is the selection of proper structural material. A very stringent requirement for low permeability has been established since the beginning of this program. The SXLS magnet will be ramped during acceleration process, therefore, the eddy current generated in the structure can also degrade the desired multipole contents. The significant Lorentz forces acting on the support structure are in the order of 250 tons radial and 170 tons vertical. The mechanical properties of the material is a great concern, especially the Young's modules and the fracture toughness at the operating temperature of 4.35 K. The coil packs have to be properly prestressed at room temperature in order to prevent conductor motion under the heavy Lorentz force during the ramping cycle and at the full field. The yield strength of the structure and the bolting material at room temperature have to be carefully selected so that they will not fail under the cool-down and warm-up repetitive stress cycles. The matching of the contraction coefficients of these materials to that of coil packs should be reasonably close so that the prestress will not be drastically reduced at the operating temperature.

2. Structural Analysis

Because of the asymmetry inherent in the magnet structure and the truly three dimensional nature of the coils and the stringent coil position stability during the ramping and operation period, it is necessary to perform the detailed structural analysis by using computer codes, such as NASTRAN, TOSCA, and ANSYS. The analysis was based on three loading conditions, namely, 3.87 Tesla Lorentz force, thermal distortion, and 43 psia internal helium pressure. The combined displacement due to all the loads is in the order of 3 mils and the stresses on the coil, as expected, are very low. The prestresses of the coil packs at room temperature and at the operating temperature of 4.35 K were carefully examined by taking into account the differences in integrated contraction and stiffness of all materials.

3. Thermal Analysis

The thermal load of the magnet assembly was estimated in detail, the refrigeration requirement at 4.5 K is 15 watts per magnet, 30% of this load is the contribution from warm bore beam tube. The thermal insulating space between 4.35 K and 300 K surfaces in this region is only in the order 0.4 inches, the implementation of thermal shield is deemed impractical. The boil-off due to all the current leads and the other diagnostic wiring is in the order of 10 liters per hour. The thermal loads due to heat shields and intercepts is approximately 31 watts at 80 K.

One of the special features of this magnet is warm (temperatures higher than 280K) electron and photon tubes, therefore, the true temperature profile of these two components is considered an important factor in the system design. The current design requires a wrapped 0.4 inches of double aluminized Kapton NRC-2 thermal blanket over most of the beam tube. Each photon duct will be surrounded by a 0.37 inches of the same superinsulation material. A Kapton substrate was chosen to accommodate the potentially high radiation doses and bake out temperature. To maintain the positional accuracy, the beam tube assembly is supported from the interior wall of the surrounding helium plenum by G-10 structures. In order to equilibrate temperature along the beam tube, the beam tube and the photon ducts are thermally shunt to the cryostat vacuum vessel wall.

4. Electrical Design

As mentioned before, the SXLS magnet utilizes the RHIC's wire and cable as conductor material, the intended currents in the conductors are very conservative, the penalty of this type approach is the slow quench propagation velocity and thereby increased degree of difficulty in quench protection of the coil packs. The longitudinal quench propagation velocity of sample cable (made by LBL group) was measured by W. Sampson's group of BNL, it is in the order of 4 meter per second at 2800 amperes and 5 Tesla. The lateral propagation velocity was estimated from literature sources for SSC conductor. The external dump resistors are provided to protect all coils, the maximum voltage to switch on a resistor circuit is in the order of 600 volts. The maximum temperature of the coil after the quench is less than 300 K. Quenching of the smaller correction coils would not affect the performance of the main coils, while if one of the mail coils quenches, induced voltages will quench all the coils.

V. PRESENT PROGRAM STATUS

The magnet program has gone through various stages of review by an outside expert panel. It has so far passed the comparative studies review, conceptual design review, preliminary design review. The final design review will take place at the end of July, 1991. The first dipole will be completed in April of 1991 and the second magnet will be completed in March of 1993.

VI. REFERENCES

[1] M. BERZ, "The Description of Particle Accelerators Using High Order Perturbation Theory on Maps", AIP Conference Proceeding, 184, (1989).