

Calculation of Eddy-currents Induced in a Compact Synchrotron Superconducting Magnet Structure During a Current Ramp¹

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Abstract

Under DARPA sponsorship, a compact Superconducting X-Ray Light Source (SXLS) is being designed and built by the Brookhaven National Laboratory (BNL) with industry participation from Grumman Corporation and General Dynamics. The SXLS machine employs two 180° curved 4 tesla superconducting dipole magnets. These magnets are required to produce a dipole field for bending the beam but at the same time they must produce finite amounts of higher multipoles which are required for conditioning the beam. In fact uniformity of the field to less than 1 part in 10,000 must be maintained under all operating conditions. When a superconducting magnet is ramped from zero to full field, the changing magnetic field produces eddy-currents in the magnet structure which in turn can produce undesirable multipoles. This paper discusses a simple method for estimating these eddy-currents and their effect on the field harmonics. The paper presents the analysis basis and its application to the SXLS magnet support structure and to the beam chamber components.

INTRODUCTION

As part of the DoD/DARPA sponsored U.S. National X-Ray Lithography Program, technology transfer from BNL to Grumman has been underway since the fall of 1988 with the end objective of having Grumman deliver a compact superconducting x-ray light source suitable for application in a semiconductor manufacturing environment. The SXLS is optimized for lithography work for sub-micron high density computer chips, and is about the size of a billiard table (1.5 m x 4.0 m). The machine has a racetrack configuration with two 180° bend dipole magnets being designed and built by General Dynamics under a subcontract with Grumman Corporation. Each magnet has 18 photon ports which

deliver light peaked at a wave length of 10 Angstroms.

The overall configuration of a superconducting magnet shown in Fig. 1. It produces a maximum field of 3.85 T in the beam region. The magnets are air-cored and employ warm beam chambers. In addition to the main dipole field coils, superconducting trim coils are also incorporated for generating quadrupole, sextupole and radial field components. The quality of field in the beam region is very critical. The field must have precisely controlled multipoles up to the decapole level during the whole range of operation of the machine. The superconducting dipole magnets are ramped up from zero field to the full-field (3.85 T) in 3 minutes during the start-up phase. During this ramping period, eddy-currents are generated in the structural components (magnet cold-mass, cryostat, beam chamber, etc.). These eddy-currents could generate undesirable field multipoles with deleterious effect on the beam quality.

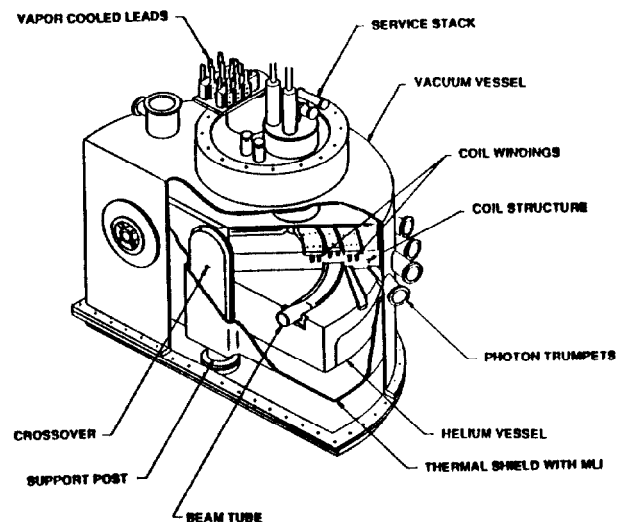


Figure 1: Superconducting Dipole Magnet

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This paper describes an analysis for computing eddy-currents in the structural components of a magnet during a current ramp. These currents are then used for computing the magnetic field in the beam region which is further resolved for obtaining the field multipoles. A sample set of calculations is presented in this paper as an illustration.

ANALYSIS

Fig. 2 shows the beam chamber assembly cross-section used as an example to describe the calculation technique. The beam chamber assembly consists of a beam chamber, NEG pumps, and ion pumps. During a current ramp in the dipole coils, the field in the magnet bore changes as a function of time. This changing field induces eddy-currents in all conductive components of the chamber assembly.

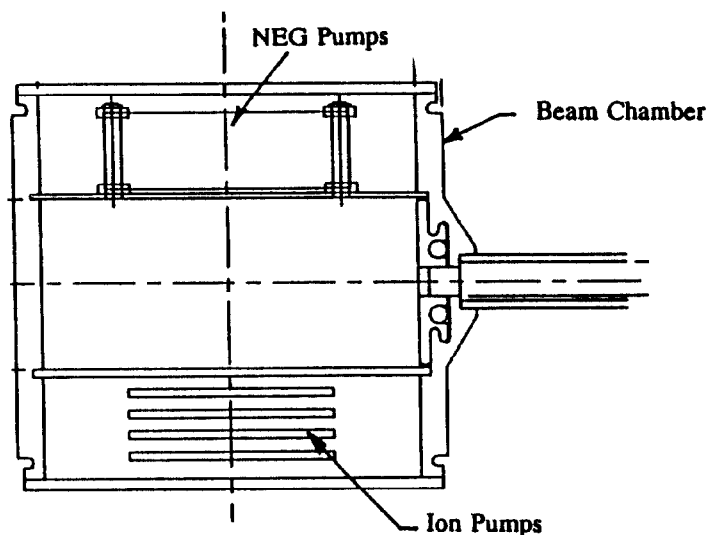


Figure 2: Beam Chamber Assembly

Each dipole is bent 180°. However, for the purpose of calculations, the beam chamber and the dipole coils are assumed to be toroidally continuous. All beam chamber components are made from 304 stainless steel with the exception of ion-pumps which utilize titanium. Each component of the beam chamber is sub-divided (for eddy-current calculations) into a number of circular sub-elements. All dipole coils and the vacuum chamber circuits are inductively coupled to each other. An inductance matrix is calculated which has self- and mutual-inductances for all circuits (including the superconducting coils). Resistance of each circuit is also calculated. Time varying magnetic field due to the dipole current ramp induces voltage in all beam chamber circuits. A set of algebraic equations are developed to satisfy the relationship between the induced currents and the induced voltages. Since the dipoles are only half circles, the net current in all circuits formed by the circular beam chamber elements must sum to zero. Fig. 3 shows circular eddy-current circuits which are physically broken and

therefore the sum of all circuit currents is constrained to be zero.

The circuit equations to satisfy the above constraint are described below:

$$\begin{aligned} R_1 I_1 - R_2 I_2 &= V_1 - V_2 \\ R_2 I_2 - R_3 I_3 &= V_2 - V_3 \\ &\vdots \\ R_{n-1} I_{n-1} - R_n I_n &= V_{n-1} - V_n \end{aligned} \quad (1)$$

$$I_1 + I_2 + I_3 + I_4 + \dots + I_n = 0$$

Inductive voltage drop ($L \, di/dt$) is ignored because it is negligible for the current ramp values considered in this case. R_1, R_2 , etc. are circuit resistances.

The total voltage (V_1, V_2 , etc.) induced in each beam chamber circuit is calculated from the current ramp imposed on the superconducting coils with the following relations:

$$\begin{aligned} V_1 &= M_{11} i_1 + M_{12} i_2 + M_{13} i_3 + \dots + M_{1m} i_m \\ V_2 &= M_{21} i_1 + M_{22} i_2 + M_{23} i_3 + \dots + M_{2m} i_m, \text{ etc.} \end{aligned} \quad (2)$$

where i_1, i_2 , etc. are current ramp-rates (rate of change of current with respect to time) and m is the number of superconducting coils. M_{1m} , etc. are mutual inductances.

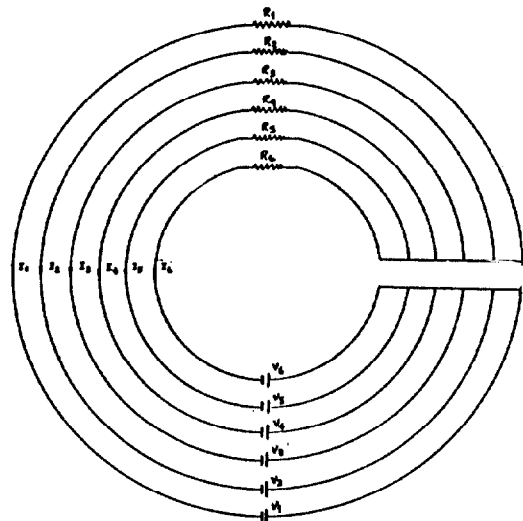


Figure 3: Eddy-current Circuit Concept

For calculating the eddy-currents, first circuit voltages are calculated from Eqn. (2) using the known current ramp-rates in the superconducting coils. These circuit voltages are then used in Eqn. (1) for calculating n -currents in the beam chamber circuits. These circuit currents are next utilized for calculating magnetic field on the mid-plane of the dipole magnet at 31-radial locations. The field can be calculated with any standard code that can handle circular coils with rectangular cross-sections. The magnetic field distribution as a function of radial distance from the beam reference orbit is given in Table-1.

Table 1
Magnetic Field Distribution

Radial Distance (m)	Radial Field (T)	Vertical Field (T)
-0.030	9.888E-08	4.573E-06
-0.028	1.017E-07	4.528E-06
-0.026	1.032E-07	4.489E-06
-0.024	1.028E-07	4.455E-06
-0.022	1.005E-07	4.426E-06
-0.020	9.584E-08	4.400E-06
-0.018	8.881E-08	4.379E-06
-0.016	7.935E-08	4.361E-06
-0.014	6.752E-08	4.346E-06
-0.012	5.348E-08	4.333E-06
-0.010	3.747E-08	4.321E-06
-0.008	1.977E-08	4.311E-06
-0.006	7.427E-10	4.301E-06
-0.004	-1.924E-08	4.292E-06
-0.002	-3.978E-08	4.284E-06
-0.000	-6.046E-08	4.275E-06
0.002	-8.087E-08	4.266E-06
0.004	-1.006E-07	4.258E-06
0.006	-1.192E-07	4.249E-06
0.008	-1.363E-07	4.240E-06
0.010	-1.516E-07	4.231E-06
0.012	-1.647E-07	4.222E-06
0.014	-1.755E-07	4.214E-06
0.016	-1.836E-07	4.207E-06
0.018	-1.890E-07	4.200E-06
0.020	-1.916E-07	4.193E-06
0.022	-1.917E-07	4.187E-06
0.024	-1.894E-07	4.180E-06
0.026	-1.849E-07	4.172E-06
0.028	-1.787E-07	4.161E-06
0.030	-1.711E-07	4.145E-06

Fig. 4 shows the vertical field in a graphic form as a function of the radial distance measured from the reference beam radius. Fig. 5 shows the radial component of the field. The vertical field component in Table -1 is analyzed to determine field multipoles with the LOTUS program.

The calculated harmonics (multipoles) are listed below:

Multipole Coefficient	Value	Unit
Dipole	4.273E-6	T
Quadrupole	-3.919E-6	T/m
Sextupole	5.665E-5	T/m ²
Octupole	-2.027E-2	T/m ³
Decapole	1.874	T/m ⁴

These values of multipoles are small to be of any concern. Since the vacuum tube assembly is asymmetrical about the horizontal plane, the eddy-currents in the beam chamber components produce a net radial field. This field component is 6×10^{-8} which is negligible for all practical purposes. It is safe to conclude that the eddy-currents induced in the vacuum tube are not likely to impact the beam performance.

Similar calculations could be made for the magnet cold mass to study impact of eddy-currents on the field harmonics. The cold mass would have to be divided into a number of small circuit elements.

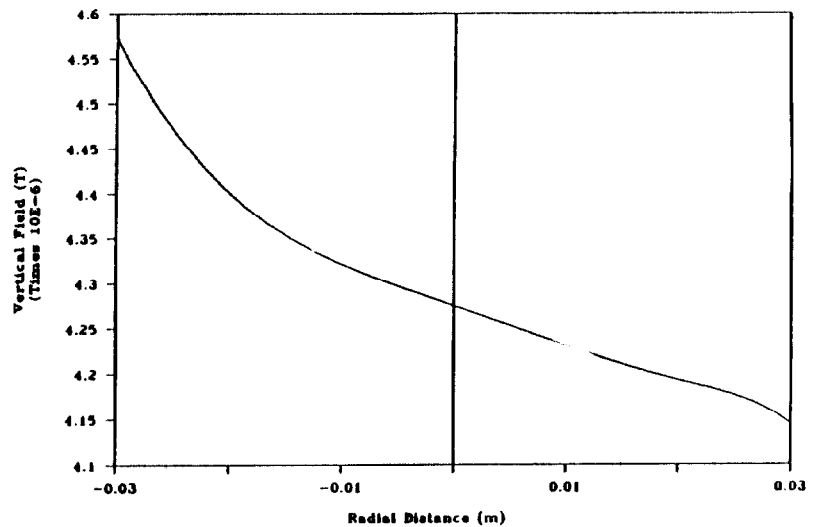


Figure 4: Vertical Field due to Eddy-currents

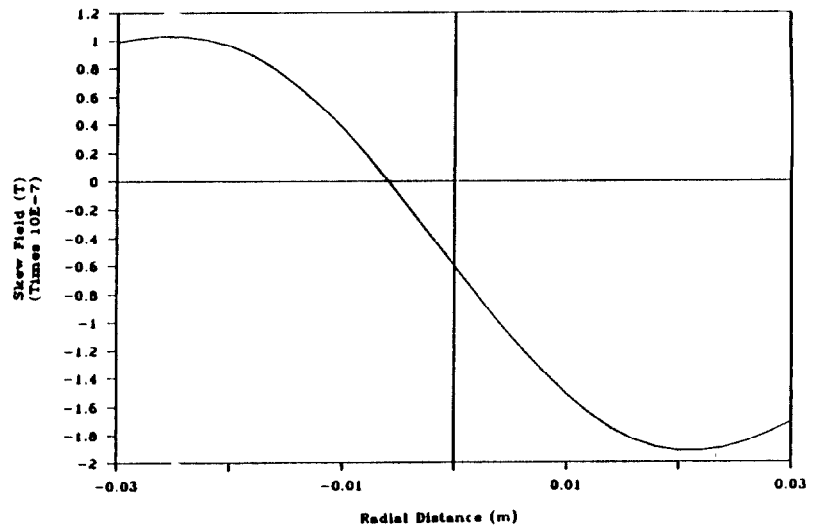


Figure 5: Radial Field due to Eddy-currents

CONCLUSIONS

A method has been described for calculating eddy-currents in the structural components coupled with the dipole coils. The method is very general and could be used for studying other similar problems such as currents and forces generated in the cold mass, cryostat and beam tube chamber components during an abrupt quenching of the superconducting magnet coils.