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FLUX SHUNTS FOR UNDULATORS

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Abstract

Undulators for high-performance applications in synchrotron-radiation sources and periodic magnetic structures for free-electron lasers have stringent requirements on the curvature of the electron's average trajectory. Undulators using the permanent magnet hybrid configuration often have fields in their central region that produce a curved trajectory caused by local, ambient magnetic fields such as those of the earth. The 4.6 m long Advanced Light Source (ALS) undulators use flux shunts to reduce this effect. These flux shunts are magnetic linkages of very high permeability material connecting the two steel beams that support the magnetic structures. The shunts reduce the scalar potential difference between the supporting beams and carry substantial flux that would normally appear in the undulator gap. Magnetic design, mechanical configuration of the flux shunts and magnetic measurements of their effect on the ALS undulators are described.

I. INTRODUCTION

Periodic magnetic structures for undulators and free electron lasers have stringent requirements on the average magnetic field. The average dc field should be very small so that the long-range deflection of a beam is insignificant compared to the amplitude of the oscillatory motion caused by the periodic magnetic field. If a larger dc field is present over the central region, the curved trajectory may become greater than the amplitude of the oscillations associated with the periodic magnetic structure; this may be unacceptable in many applications. Possible sources of the dc field component are the earth's magnetic field, other environmental fields, and improper device design. Methods available to reduce this dc component include active coils that buck the dc field, external ferromagnetic shielding and flux shunts.

Active coils mounted around, or adjacent to, the magnetic structure must be powered by an external power supply, and energized with a current that depends on the magnetic gap of the insertion device and its physical orientation and location in the local environmental magnetic field. Significant temperature variations may result from coil heating. Excessive heat can cause mechanical distortions, variation of the magnetization of the permanent magnet materials, and, if an excessive temperature excursion occurs, permanent damage to permanent magnet material. Cooling is probably necessary for active coils.

Providing external magnetic shielding for the entire device is rather complicated because of its physical size and appendages, and because of the low-field levels. Reducing field levels to sub-gauss levels requires special magnetic materials with low coercivity and very high permeability at low field, e.g., high nickel alloys.

In this paper we describe a new method, the Flux Shunt, for reducing the dc component of magnetic fields in undulators and other types of magnetic structures that use support members made of a soft magnetic material. The approach is straightforward, a magnetic coupling is made between the top and bottom support structures. This connection reduces the scalar potential difference between the two structures. The flux shunt forming this coupling must be made of a material with a very high permeability at low fields, have a low coercivity, and a low residual field in the operational state. The advantages of this technique are that it can be passive, with no need for a power supply, and the method is effectively independent of the source of external field. The application of flux shunts to the 4.6 m long ALS undulators, Figure 1, is described below.

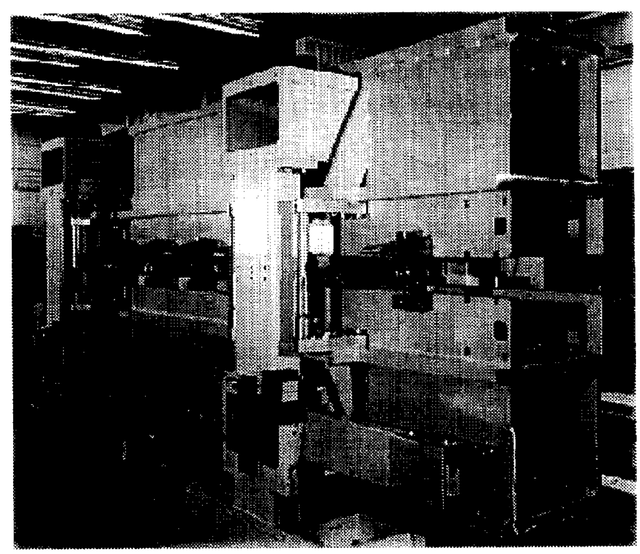

Figure 1. U5.0 Undulator support structure with flux shunts .

II. FLUX SHUNT MAGNETIC DESIGN

One objective in undulator design is to achieve as low an average dc magnetic field as possible in the region of the electron beam. Maintaining the upper and lower structures at the same scalar potentials requires that they be magnetically shorted together by a low reluctance material, a flux shunt.

However, assembly tolerances and finite permeabilities limit the minimum achievable scalar potential difference. Requirements for the flux shunt design and performance are based on the allowable vertical magnetic field integral, which is 100 G cm in the 4.6 m long ALS undulators [1]. Half of this tolerance is budgeted to environmental field effects that can be controlled by the flux shunt. An average dc field of 0.11 G is thus allowed. Because the fields are roughly sinusoidal, the maxima under the poles is about 0.17 G. This field corresponds to a pole scalar potential of 0.121 G cm with respect to the midplane.

The structure of the undulator distorts the external magnetic field, as shown in Figure 2 (note that only the vertical component of the external magnetic field need be considered), and it is concentrated by a factor of 1.36 at the electron beam position [2]. Thus, the 0.3 G external vertical field at the ALS will produce an integrated field of 187 G cm (0.3 G x 1.36 x 4.6 m). In addition, the ALS undulator geometry (1.4 cm gap) is such that the scalar potential of the structure is 10.3 times that of the poles, a factor 3.7 too high. To reduce this minimum gap undulator field to 0.11 G, the structure scalar potential from the midplane must not exceed 0.121 G cm x 10.3 =1.25 G cm.

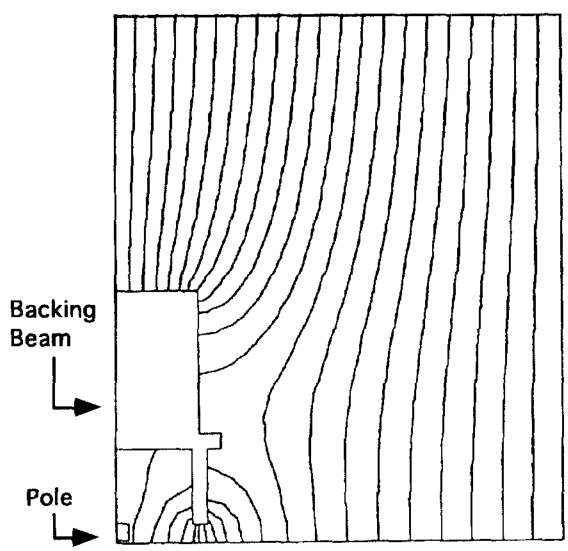

Figure 2. Field distribution around the undulator structure due to a background field.

The maximum flux that can enter the structure, again the Figure 2 configuration, occurs when the support structure is shorted to the midplane and for a 0.3G background field is 4.30×10^4 G cm^2.

Maximum total flux and allowable scalar potential difference determines the mechanical configuration of the flux shunt. For the ALS undulators, 6 flux shunts per device were selected, each flux shunt is a linkage because the undulator gap opens and closes to change field. The material selected for the linkage is 50% Ni-Fe because of its very high permeability at low field and its low coercive force. Using a 5 cm x 7.5 cm cross-section for the Ni-Fe shunt members, the computed scalar potential drop is 0.65 G cm for the Ni-Fe and 0.30 G cm for the air gaps for a total of 0.95 G cm, which is less than the allowable 1.25 G cm limit.

III. DESIGN AND CONSTRUCTION

The design requirements for the flux shunts include an undulator gap change of 20.2 cm, no effect on the precision motion of the magnetic structures and meet the reluctance goal of the design. The linkage design shown in Figure 3 was selected. There are five members and six spring-loaded, rotary hinge joints in this design allowing six degrees of freedom.

Hot rolled, 50% Ni-Fe was used for the linkage members annealed at 1200 degrees C for four hours after part fabrication to achieve the high permeability. The annealed state makes the material soft and gummy, resulting in galling at the joints. To ameliorate this problem, parts were plated with 15 µm thick electroless nickel and molykote grease was applied on all mating surfaces. To achieve the maximum surface contact, the faces were ground to 16 micro inch and hand lapped to a mirror finish before plating. To hold the adjoining faces together and allow motion, spring washers were installed on the ends of a hinge pin. A complete array of six flux shunts installed on the IDB U5.0 Undulator is shown in Figure 1.

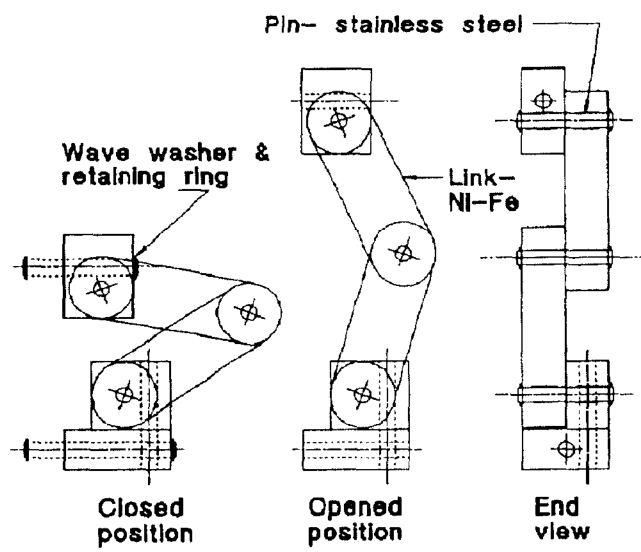

Figure 3. Flux shunt linkage.

IV. MAGNETIC MEASUREMENTS

The first measurements were carried out with a single flux shunt attached to two 80 cm square by 5 cm thick 1010 steel plates, Figure 4, to simulate 1/6 of an ALS undulator [3]. With a 22.5 cm plate spacing and the flux shunt disconnected from the plates, the average central field above the top plate was 0.36 G and between the plates 0.42 G for a field enhancement of 1.17. With the flux shunt connected, the field at the top increased to 0.49 G and the internal field dropped to 0.11 G, a reduction of a factor 3.82, which verified that the concept works. The shunt carried 3750 G cm^2 flux. Qualitatively, when the gap is increased, the field above the plate increases, the internal field decreases but the field integral between the plates increases. A 31,500 cycle life test of the flux shunt decreased the magnetic performance. by 6.6%.

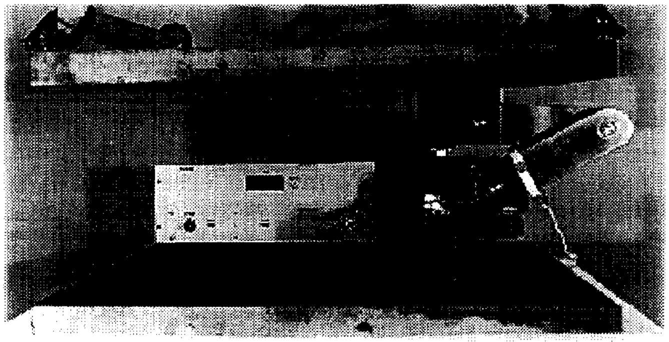

Figure 4. ALS prototype flux shunt in test configuration.

Tests were carried out with the assembled undulator support structure/drive system and the magnetic structure backing beams, but without the periodic structure installed, as shown in Figure 1 [4]. Results show that the near midplane vertical field integral, due to the environmental fields, is 115–150 G cm over the undulator operating range without the flux shunts. Calculations of this configuration using the Figure 2 model, without the pole, yields field integrals of 160–200 G cm, which suggests that approximately 25% of the flux is shunted through the large vertical members of the support structure. With the six flux shunts attached to the backing beams, the field integral is reduced to 70 G cm for all gaps or an average gap field of 0.15 G. Based on calculations, with and without the pole installed in the magnetic structure, at 1.4 cm gap, field integral with poles would be 80 G cm for an average field reduction factor of 2.57. This field integral is greater than the predicted 50 G cm and is probably due to saturation in the backing beams (annealed 1005 steel). As the shunts were added, the amount of flux carried by the shunts increased, though the flux carried in each individual shunt decreased with the distribution of flux among these shunts being fairly uniform.

Magnetic measurements on the completed IDB-U5.0 Undulator showed that the six flux shunts reduced the magnetic field integral by 110 G cm over the range of magnetic structure gaps from 1.4 cm to 21 cm. However, the measured field integrals are dominated by magnetic structure errors and the ends of the undulator so the environmental fields only make a partial contribution to the field integral in this case.

Energizing the flux shunts was explored to cancel the field integral at any gap. Because the coil excitation is outside the magnetic structure, the effects of coil heating will not affect the magnetic field.

A coil was put on each flux shunt to change the undulator vertical magnetic field integral. Measurements carried out with individual shunts, energized at a given current, show that the undulator centerline vertical field integrals generated by the shunts on the ends of the undulator are about 20 % higher than those generated by the shunts located in the center of the undulator. This is believed to be due to the end configuration of the magnetic structure, in particular the shorting of the outermost poles to the backing beams.

With all six flux shunts energized in series, the change in the undulator vertical magnetic field integral is only 87% of the change that is obtained when the field integral changes of the individual shunts are added together when excited with the same current.

Data was obtained for the six flux shunts energized that gives the changes in the centerline vertical magnetic field integral as a function of ampere-turns for several gaps. The results show, for a given excitation, that the field integral change increases with gap closing until the permanent magnet structure begins to saturate at about 2.2 cm, after which it decreases. The ampere turns required to null the vertical magnetic field integral as a function of undulator gap are determined .

V. SUMMARY

Tests demonstrate that the flux-shunt concept effectively reduces the average dc magnetic field in the undulator. For the IDB-U5.0 support structure alone, the vertical support members shunt approximately 25% of the flux between the backing beams and the flux shunts carry 35% more resulting in a 70 G cm field integral and an average field of 0.15 G. Flux shunts reduced the field integral for the completed device to 110 G cm, but the environmental field effects are a fraction of the periodic structure field errors. In this case, the field integral can be canceled by energizing coils on the flux shunts.

VI. ACKNOWLEDGMENT

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VII. REFERENCES

[1] "U5.0 Undulator Conceptual Design Report," LBL PUB-5256, (Nov. 1989).

[2] E. Hoyer, "Flexible Yoke Design," LBL Engr. Note M7039B (July 1990).

[3] E. Hoyer, "Flexible Yoke and Prototype ALS Flux Shunt Tests," LBL Engr. Note M7229 (Oct. 1991).

[4] E. Hoyer and K. McCabe, "Flux Shunt Magnetic Meas. on the SDS," LBL Engr. Note M7285 (July 1992).

[5] E. Hoyer, "Flux Shunt Magnetic Measurements on IDB," LBL Engr. Note M7350 (April 1993).