

## A PERMANENT MAGNET UNDULATOR FOR SPEAR

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### SUMMARY

A 30 period permanent magnet ( $\text{SmCo}_5$ ) undulator has been designed, built and tested. The period is 6.1 cm, overall length is 1.95 m, and the gap is variable from 2.7 cm to 6.0 cm. Magnetic measurements at the mid-plane with a 2.7 cm gap show that the field is sinusoidal with a peak value of .28 T. Construction details and magnetic measurements are presented along with the spectral distribution of radiation produced by 3.0 GeV electrons traversing the undulator.

### INTRODUCTION

Undulator magnets<sup>(1)</sup> are of scientific interest because, when used in an electron storage ring, they generate quasi-monochromatic synchrotron radiation with higher brightness (flux into a small solid angle) than can be obtained using the ring bending magnets or wigglers. An undulator has an alternating periodic transverse field designed so that the maximum deflection of the electron is about  $\gamma^{-1} = m_0 c^2/E$ , which is also the natural opening angle for radiation emission. Ring bending magnets and wigglers produce much greater angular deflections and hence the intrinsic high brightness in the plane of the deflection is lost. Furthermore, because only a small deflection is wanted in an undulator a large number of periods is possible in a reasonable length. Interference effects in the radiation emitted at many co-linear source points result in enhancement of the radiation at certain wavelengths and suppression at others.

The device reported here was designed, constructed and tested at LBL for use at SSRL. It was installed in the SPEAR storage ring at SLAC on Dec. 10, 1980 and the first radiation was measured a few days later. The device produces high-brightness, tunable, quasi-monochromatic synchrotron radiation with first harmonic peaks at photon energies up to about 2 keV. Higher harmonics (up to the 9th harmonic) have been observed with reduced intensity. Preliminary measurements of the radiation indicate that the undulator performs about as expected. At photon energies around 1 keV the undulator provides a brightness that is about 2 orders of magnitude higher than that produced by the ring bending magnets. Higher brightness should have a major impact on studies in the soft x-ray region including x-ray microscopy and surface physics.

The properties of rare-earth cobalt (REC) materials<sup>(2,3)</sup> are ideally suited to the design and construction of short period undulators resulting in high performance with considerably less construction cost and complexity as well as operations simplicity and economy (e.g. no power required) compared with other approaches. Future REC undulators on SPEAR ( $E < 4$  GeV) could reach photon energies of about 8 KeV and on PEP ( $E = 15$  GeV) they could reach about 50 KeV.

### II Design Criteria

To gain experience with an undulator without the cost and delay of building a new beam line for it, the undulator was designed to make use of existing wiggler beam lines.<sup>(4)</sup> Anticipating undulators, new wiggler magnets were designed to be split along the median plane and the top and bottom halves separated and stored in place. This permits the "C" shaped undulator

to be inserted without disturbing the vacuum chamber used by the wiggler. The overall length of the undulator was set by the 1.95 m between the chamber flanges. The minimum usable gap of the undulator is set by the chamber height, 2.9 cm. For high brightness the value of  $K = .934 B_0(T) \lambda_u(\text{cm})$  should be  $\geq 1$ , where  $B_0$  is the peak magnetic field and  $\lambda_u$  is the undulator period. The wavelength of the first harmonic is given by

$$\lambda = \frac{\lambda_u}{2\gamma^2} [1 + \frac{K^2}{2} + \gamma^2 \theta^2]. \quad (1)$$

$\theta$  is the angle of the radiation relative to the beam direction. Thus to obtain short wavelength radiation  $\lambda_u$  should be as small as possible consistent with  $K \geq 1$ .

The peak magnetic field of a linear undulator made of REC material is given by<sup>(2)</sup>

$$B_0 = 2B_r \frac{\sin \pi/M}{\pi/M} [1 - e^{-2\pi h/\lambda_u}] e^{-\pi g/\lambda_u} \quad (2)$$

where  $B_r$  is the remanent magnetic field,  $M$  is the number of blocks per undulator period (in each half of the undulator),  $h$  is the height of the blocks and  $g$  is the full gap height. The choice of 4 blocks per period ( $M=4$ ) and  $h=\lambda_u/4$  makes all blocks identical, resulting in considerable cost savings at only a small sacrifice in peak magnetic field. With  $\lambda_u=6.1$  cm and  $B_r \approx .8$  T the undulator could have 30 periods and a peak magnetic field of .23 T is expected at 3.0 cm gap according to eq. (2). The highest value of  $K$  is then 1.3 and the wavelength of the first harmonic at 3.5 GeV is about 12 Å according to eq. (1).

### III Design and Fabrication

The detailed undulator design was based on the following considerations:

1. Beam-optical considerations require that the variation of the magnetic field transverse to the undulator axis and perpendicular to the field direction at  $\pm 1$  cm from the beam should be less than the smaller of  $3 \times 10^{-3}$  T or 5% of the peak undulator field. Three-dimensional field calculations (graphs useful for this are given in reference 2) indicated that the undulator had to be 7.5 cm wide to satisfy this requirement. Since it is difficult to obtain REC blocks of that length with the desired magnetic orientation and to avoid a crack directly above the beam it was decided to use 3 blocks, each of 2.5 cm length, for each row.
2. After consultation with REC manufacturers a magnetic dipole moment per unit volume variation of  $\pm 2.5\%$  was chosen as a compromise between tolerance and cost.<sup>(5)</sup> The REC blocks were obtained from Hitachi Magnetics, Edmore, Michigan. A computer program assigned blocks to locations to optimize field uniformity and symmetry relative to the transverse midplane. The above variation in magnetic properties does not significantly broaden the peaks beyond the broadening due to the finite number of periods  $N$ , ( $\Delta\lambda/\lambda_n \approx 1/nN$ , where  $n$  is the harmonic number), and the angular divergence of the electron beam.
3. To minimize the net angular deflection and displacement of the beam by the undulator, a pair of rotatable REC block assemblies is located at each end. Their angular orientation is chosen to null the field integral through the undulator and to obtain symmetry relative to the transverse midplane. The members of each pair rotate in opposite directions.
4. To magnetically decouple the ends of the undulator from steel that might be nearby, and to sharply cut off the fields of the undulator at its ends in order to avoid the possible introduction of sextupoles or higher order multipoles, each end of the undulator has a pair of steel plates that act as field clamps. One surface is parallel to the undulator midplane. The plates comprising a pair are connected by a flexible steel cable, fixing them at the same scalar

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potential as the undulator midplane.

Design of the undulator is shown in Figure 1. The cut-away view shows the orientation of the  $\text{SmCo}_5$  magnet blocks and their position within the keepers. The  $\text{SmCo}_5$  blocks were glued to the keepers with 3M structural adhesive 2214 Hi-Temp. The following procedure was used to attach the magnet blocks to the keepers:

1. The blocks were numbered and sorted into lots for each keeper using the sorting routine.
2. Each block was cleaned with acetone, its direction of magnetization determined with a magnetic "stud finder", adhesive applied and inserted into a block holding fixture.
3. The block was placed in its assigned place in the keeper, clamped, and the holding fixture removed.
4. With all the blocks, usually 36, clamped into a keeper, the adhesive was cured at  $110^\circ\text{C}$  for 90 min.
5. Adhesive backed vinyl tape (.007") was used to protect the blocks from dirt and iron chips.

It was originally expected that the blocks could be hand-positioned. However, the strong magnetic forces, and resultant technician fatigue, caused us to change to the above procedure. The keepers are pinned and bolted to the upper and lower backing plates. After this installation we began to experience glue joint failures on the end of keepers when the field direction there was toward the midplane of the undulator. The end row of blocks would simply pop out. Failure was generally between the adhesive and the  $\text{SmCo}_5$  magnet bond. It is suspected that the end blocks failed because the adhesive there was essentially in a tension-peel mode. Purposely only the back sides of the blocks were glued in case they had to be removed. The interior blocks would have some adhesive in shear because the glue was squeezed up the sides in the clamping operation. Each end edge of the keeper was free of adhesive. We solved this problem by pressing additional adhesive into the crevices between the blocks on each end of the keeper, reclamping and curing the adhesive. With the added adhesive the forces on the end blocks can be taken in shear. There have since been no failures.

The undulator gap is varied by moving the upper and lower backing plates in opposite directions. This is accomplished with 4 right hand and 4 left hand ball screws which are driven simultaneously by one stepping motor through an arrangement of gears and shafts. Electrical switches limit the travel. To protect the drive train in case of electrical switch failure, a slip clutch was installed on the output shaft of the motor gear box. Stepping motors are also used to drive the end block assemblies described above. Since the gap is varied, each end magnetic block drive has a shaft section that must change in length and have angular flexibility at its ends (similar to the drive shaft of a car). This was accomplished by two longitudinally flexible couplings. Field terminators (blocks of soft iron) are located at the ends of the undulator. Flexible soft iron cables connect the terminators at each end for flux continuity. The three stepping motors (one for the gap and one for each pair of rotatable end assemblies) are driven by a single chassis with provision for future computer control. Each motion is read by an encoder and a digital display of position is provided. The completed undulator is shown in Figure 2. A total of 726  $\text{SmCo}_5$  magnet blocks (each  $1.5 \times 1.5 \times 2.5 \text{ cm}^3$ ) are contained in the 20 keepers and 4 end assemblies.

#### IV Magnetic Measurements

Magnetic measurements are summarized below:

1. At the undulator midplane, the magnetic field is sinusoidal along the beam axis as expected. Averaged midplane magnetic fields for peaks and valleys at various gap positions are summarized below.

Gap (cm)	Average Peak & Valley Fields (Gauss)	Std. Dev. (Gauss)
2.7	2808	55
3.5	1863	35
4.5	1110	21
6.0	504	19

2. The two rotatable end magnetic blocks of each rotator were oriented such that midplane symmetry of the rotator vertical field was achieved.
3. The end rotator orientations were determined for various gaps such that the field integral was less than 200 Gauss-cm. End rotator range (sinusoidal) is 3500 Gauss-cm for a 2.7 cm gap; 3250 Gauss-cm for a 3.5 cm gap. End rotator sensitivity near the integral null is 7 Gauss-cm for the smallest angular increment with a 2.7 cm gap; at a 3.5 cm gap the sensitivity is 10 Gauss-cm/increment.
4. Transverse field measurements verified the three dimensional field calculations for the good field aperture (the lesser of 30 Gauss or 5% of the field over  $\pm 1 \text{ cm}$ ). Good field aperture width measurements made on 2 adjacent peaks and the in between valley are summarized below:

Gap (cm)	Peak Magnetic Field (Gauss)	Aperture Width (cm)	Basis
2.7	2848	2.3	30 G
3.5	1877	2.3	30 G
4.5	1110	2.6	30 G
6.0	508	3.0	$\pm 5\%$

#### V Radiation Measurements & Effects on Stored Beams

The spectrum and intensity of the radiation produced by the undulator have been measured over the range 500-7000 eV. Above 3000 eV measurements were made using a high resolution ( $\Delta\lambda/\lambda \geq 10^{-4}$ ) Si(111) 2 crystal monochromator, operating in a He system separated from the storage ring vacuum by 533  $\mu\text{m}$  of Be. An example of these results is shown in Figure 3. Peaks corresponding to the 3rd through 6th harmonics can be seen varying as expected with the changing value of K as the undulator gap is changed. Measurements of the more intense fundamental and 2nd harmonic have also been made below 3 keV (the Be window cutoff) by removing the Be windows and measuring the energy distribution of photoelectrons emitted by the undulator radiation striking a polycrystalline graphite sample in a high vacuum system connected directly to the storage ring. Analysis of the data obtained over the entire spectral range (500-7000 eV) is now in progress.

As the undulator gap is closed a new coherent horizontal oscillation of the beam is observed which is not yet understood. No other effects (e.g. on stored beam orbits, tunes, lifetime, etc.) are observed. Further study of the new effect is planned.

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## References

- (1) The following are general review articles on undulator magnets and undulator radiation:  
A. Hofmann, Nucl. Instr. & Meth. **152**, 17-21 (1978).  
D.F. Alferov, Yu A. Bashmakov, K.A. Belovintsev, E.G. Bessonov and P.A. Cerenkov, Particle Accelerators **9**, 223-236 (1979).

- J. Spencer and H. Winick; Chapter 21 in "Synchrotron Radiation Research", H. Winick and S. Doniach (eds.) Plenum Press, New York 1980.
- (2) K. Halbach, "Physical and Optical Properties of Rare-Earth Cobalt Magnets", Nucl. Instr. & Meth. (to be published).
- (3) K. Halbach, IEEE Trans. Nucl. Sci. **NS-26**, 3882 (1979).
- (4) H. Winick and J. Spencer, Nucl. Instr. & Meth. **172**, 45-53 (1980).
- (5) K. Halbach, Magnetized Rare-Earth Cobalt Blocks, LBL Specification M 616, 1980.

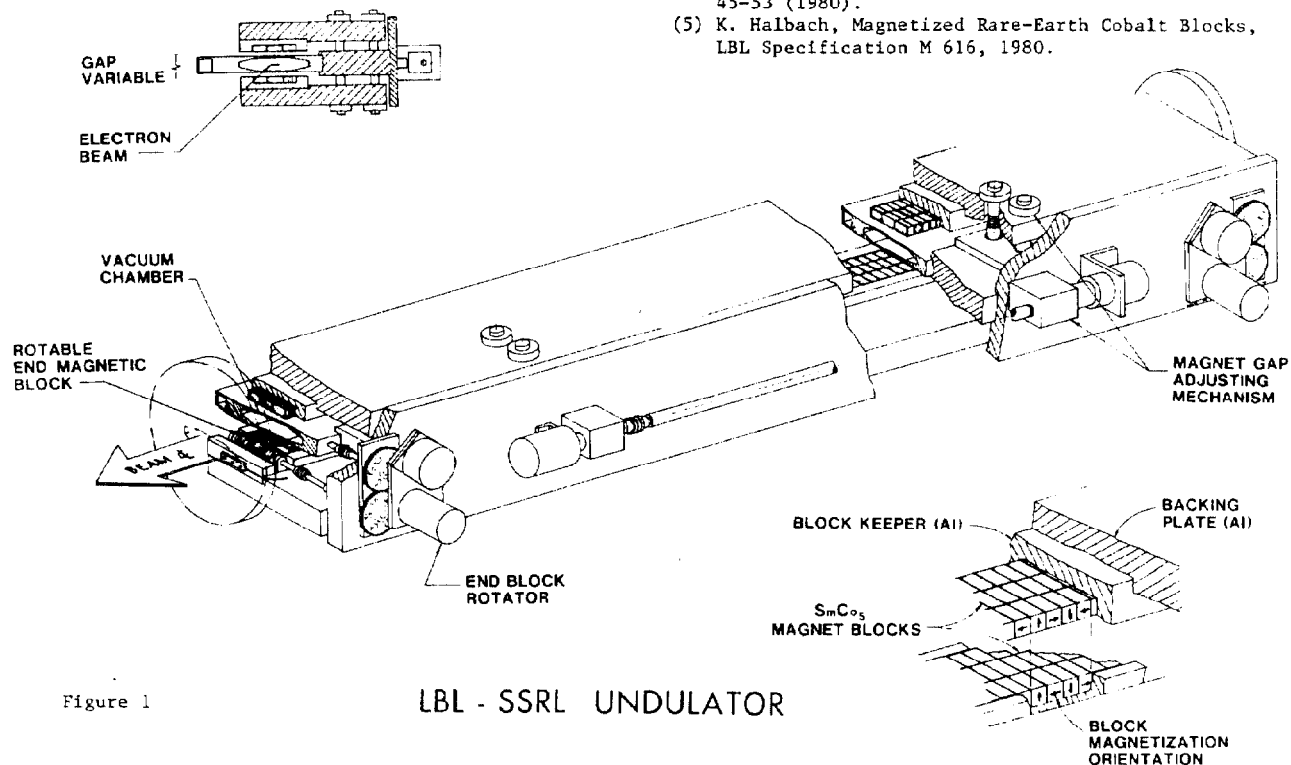


Figure 1

## LBL - SSRL UNDULATOR

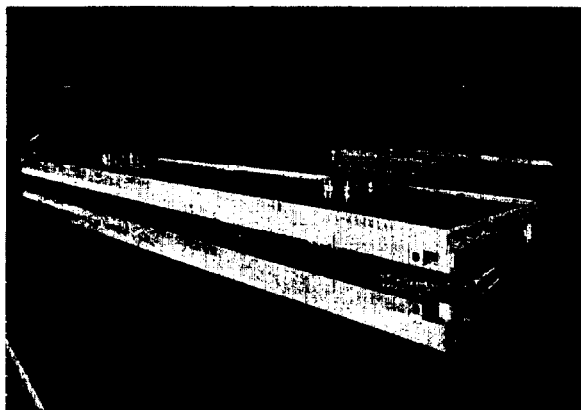


Figure 2

Photograph of Completed Undulator

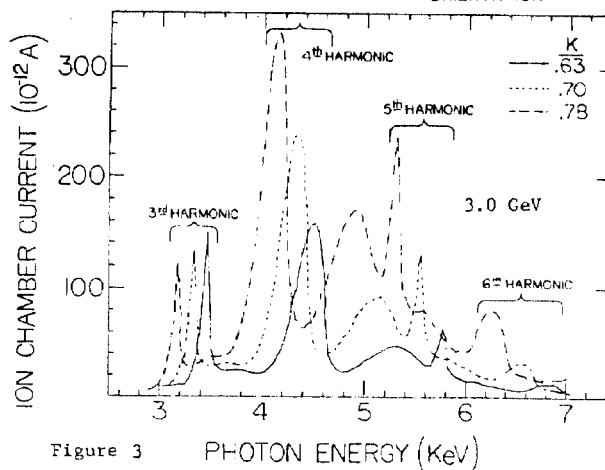


Figure 3 PHOTON ENERGY (KeV)

The results of measurements with a crystal monochromator and a 12 cm long air ionization chamber are shown. Slits were used to define a very small angular acceptance ( $18 \times 10^{-6}$  radians horizontal by  $8.8 \times 10^{-6}$  radians vertical). Only higher harmonics (3rd through 6th as indicated by the numbers on the figure) can be seen because of severe attenuation below 3 KeV by Be windows and other material in the beam line. The peaks vary as expected with the value of K as the undulator gap is varied. No corrections have been made for attenuation or monochromator efficiency. See text.