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A PERMANENT MAGNET UNDULATOR FOR SPEAR

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SUMMARY

A 30 period permanent magnet (SmCo5) 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 midplane 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(1) 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 occurs as y' = μ0Bx • 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, it is the deflection per period or period of the beam by the undulator. A pair of rotatable REC block assemblies is located at each end. The above variation in magnetic properties makes it possible to obtain REC blocks of the desired magnetic orientation and to avoid a crack directly above the beam it was decided to use 3 blocks, each 2.5 cm length, for each row.

3. To magnetically decouple the ends of the undulator 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 = 0.934 B0(T)λ0(cm) should be ≥ 1, where B0 is the peak magnetic field and λ0 is the undulator period.

The wavelength of the first harmonic is given by

λ = \frac{u}{2\gamma^2 [1 + \frac{\gamma^2}{2} + \frac{\gamma^4}{2}]} \tag{1}

θ is the angle of the radiation relative to the beam direction. Thus to obtain short wavelength radiation aλ0 should be as small as possible consistent with K ≥ 1.

The peak magnetic field of a linear undulator made of REC material is given by

B0 = 2ρ \frac{\sinh(M)}{ρ} \frac{1}{\cosh(M)} \frac{1 - e^{-2\pi h/\rho}}{e^{-2\pi h/\rho}} \tag{2}

where B0 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 aλ0/4 makes all blocks identical, resulting in considerable cost savings at only a small sacrifice in performance. A magnetic field of 3.6 T at the chamber height, 2.9 cm for high brightness 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 A 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 ± 1 cm from the beam should be less than the usable spread of 3 x 10^{-5} σ ≈ 1% 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 ± 5.2% was chosen as a compromise between tolerance and cost. (3) 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, (Δx/N) = 1/(2hN), where N is the harmonic number), and the angular divergence of the electron beam.

3. To minimize the 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 integral of 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 sides 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...
Magnetic Measurements

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.

<table>
<thead>
<tr>
<th>Gap (cm)</th>
<th>Average Peak &amp; Valley Fields (Gauss)</th>
<th>Std. Dev. (Gauss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7</td>
<td>2808</td>
<td>55</td>
</tr>
<tr>
<td>3.5</td>
<td>1863</td>
<td>35</td>
</tr>
<tr>
<td>4.5</td>
<td>1110</td>
<td>21</td>
</tr>
<tr>
<td>5.0</td>
<td>504</td>
<td>19</td>
</tr>
</tbody>
</table>

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 ± 1 cm). Good field aperture width measurements made on 2 adjacent peaks and the in between valley are summarized below:

<table>
<thead>
<tr>
<th>Gap (cm)</th>
<th>Peak Magnetic Field (Gauss)</th>
<th>Aperture Width (cm)</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.7</td>
<td>2848</td>
<td>2.3</td>
<td>30 G</td>
</tr>
<tr>
<td>3.5</td>
<td>1877</td>
<td>2.3</td>
<td>30 G</td>
</tr>
<tr>
<td>4.5</td>
<td>1110</td>
<td>2.6</td>
<td>30 G</td>
</tr>
<tr>
<td>6.0</td>
<td>508</td>
<td>3.0</td>
<td>±5%</td>
</tr>
</tbody>
</table>

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 (Δλ/λ ≥ 10⁻⁶) Si(111) 2 crystal monochromator, operating in a He system separated from the storage ring vacuum by 533 μm 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.

Acknowledgements

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(1) The following are general review articles on undulator magnets and undulator radiation:
K. Halbach, "Physical and Optical Properties of Rare-Earth Cobalt Magnets", Nucl. Instr. & Meth. (to be published).
K. Halbach, Magnetized Rare-Earth Cobalt Blocks, LBL Specification M 616, 1980.

References

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Figure 1

LBL - SSRL UNDULATOR

Figure 2

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 x 10^{-6} radians horizontal by 8.8 x 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.