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Author
Halbach, K.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

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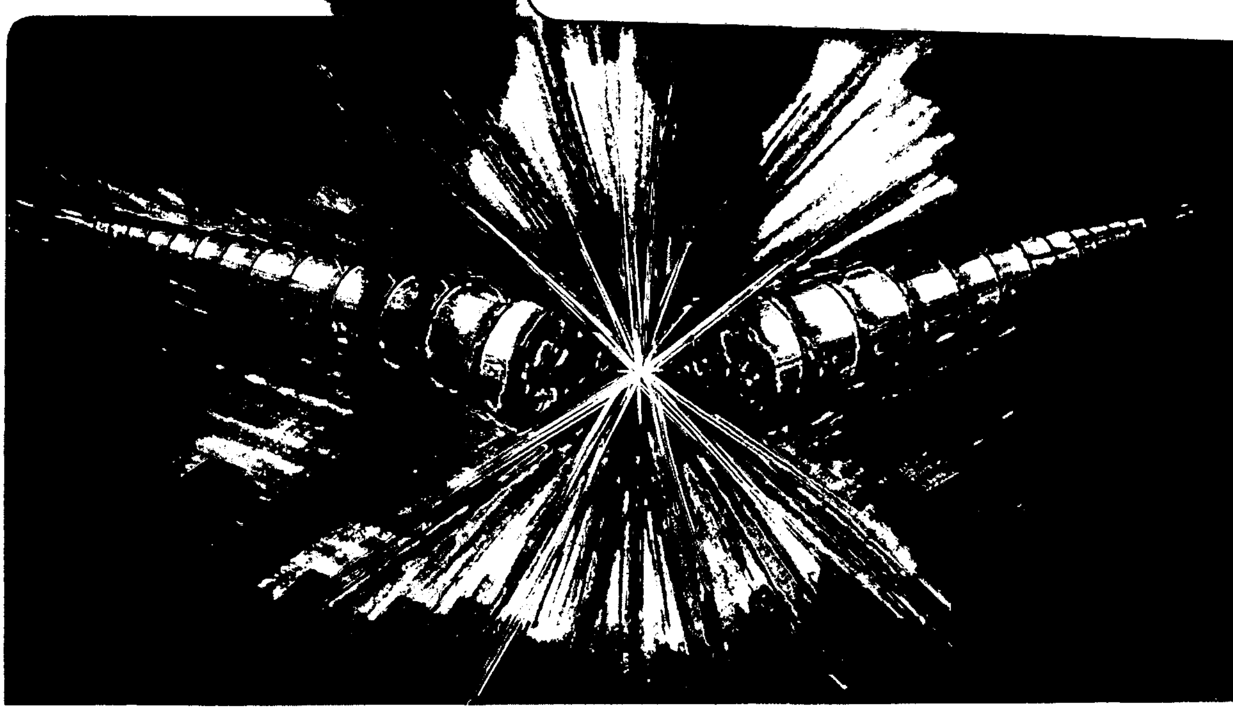

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DISCLAIMER

PERMANENT MAGNET UNDULATORS

Klaus Halbach

Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

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Resumé - Purs Terre-Rare-Cobalt (TRC) undulateurs et hybrid undulateurs, qui utilizent TRC et acier, sont décrits et comparés l'un avec l'autre aussi bien qu'avec des undulateurs superconductrices.

Abstract - Pure Rare Earth Cobalt (REC) undulators and hybrid undulators, using both REC and steel, are described and compared with each other and with conventional and superconducting undulators.

1. INTRODUCTION

Permanent magnet undulators have become widely used in recent years. I will describe briefly the major reasons for preferring, under some circumstances, permanent magnets over conventional magnets or superconducting magnets, and then describe the design and properties of pure REC undulators and hybrid undulators. Even though only undulators will be discussed, nearly all comments apply to wigglers as well.

2. COMPARISON BETWEEN PERMANENT MAGNETS AND MAGNETS EXCITED BY COILS

When one takes a magnet that is excited by coils and scales all linear dimensions while keeping the fields constant, one finds readily that the current density in the coils is inversely proportioned to the linear dimensions. This means that at some small size, the largest possible current density in a superconductor is exceeded (if one does not get into trouble earlier because of the size of cryostat components), or the current density in a conventional coil becomes so large that cooling of the coil becomes an insurmountable task. If, in magnets that use steel, one tries to avoid these problems by increasing the coil size, one changes the flux distribution in the steel in an unfavorable way, leading to performance deterioration because of saturation of the steel. Permanent magnets obviously don't have these problems, making them the preferred choice when one needs magnets that have magnetically important dimensions that are very small. Since it is generally desirable to have a fairly small period length in undulators, permanent magnet undulators are very attractive. There are, of course, additional benefits: Undulators do not require coils, power supplies, cooling, and all the paraphernalia that come with these things. When one considers that some undulators use more than 500 kW of power, permanent magnet undulators become quite attractive for economic reasons alone.

Compared to permanent magnet undulators, superconducting undulators can achieve much higher fields if the period length is large. Because of present magnetic properties of REC and steel, the highest fields that can be achieved with permanent magnet undulators are of the order 2.2T, compared to 6 - 10T with superconducting devices.

3. PURE REC UNDULATORS

Fig. 1 shows schematically a pure REC undulator. The performance of such a device that is infinitely long in the z-direction and in the direction perpendicular to the paper plane is in very good approximation given by (see ref. 1)

$$B_z - i\,B_y = 2i\,B_r \cdot \sum_{\mu=0} \cos\,(nk(z+iy) \cdot e^{-nkh} \cdot \frac{\sin\,n\epsilon\pi/M'}{n\pi/M'} \cdot (1-e^{-nkL}) \qquad (1)$$

$k = 2\pi/\lambda$ and $n = 1 + \mu \cdot M'$

In this formula, M' is the number of blocks per period in one half on the magnet, and it is assumed that the easy axis of the REC is rotated by $2\pi/M'$ when one goes from one block of REC to the next. It should be noted that one can easily write down a closed expression for the fields, but in the form of equ. (1) the essential and interesting properties of the fields are much more clearly visible. A formula and a graph that allows one to assess the effect of finite width (in the direction perpendicular to the paper plane) of a magnet is also given in ref. (1). If one ignores the finite differential susceptibility ($\mu-1 \sim .05$) of the material, as we do here, the three-dimensional (3D) fields produced by each individual finite size block can also be expressed with elementary transcendental functions.

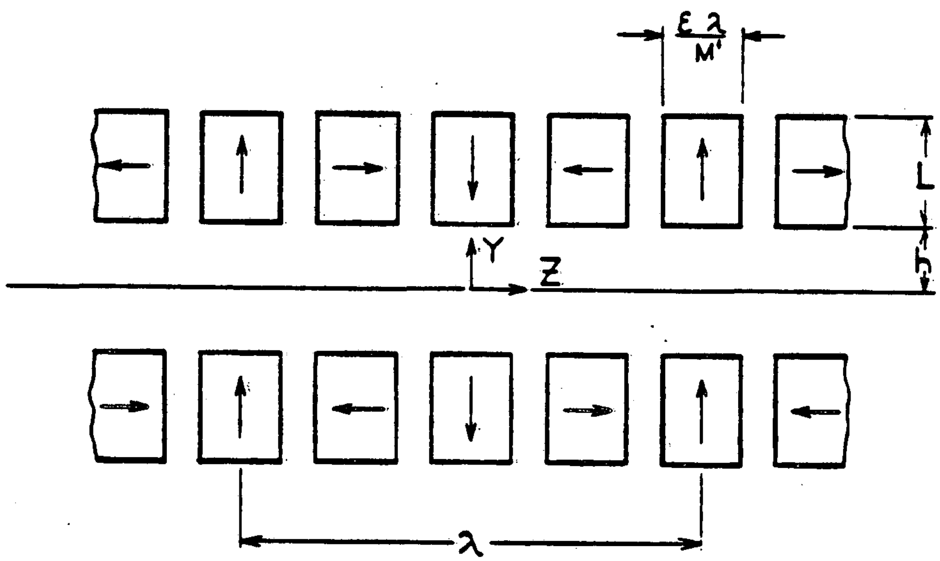

Fig. 1. Schematic Crossection through Pure REC Undulator

In most cases, the higher harmonics of the field expansion are not important. If one assumes the most frequently used value 4 for M', one for ϵ, and $L = \lambda/2$, equ. (1) becomes

$$B_z - i\,B_y = i \cdot 1.723 \cdot B_r \cdot e^{-kh} \cdot \cos\,(k(z+iy)) \qquad (2)$$

An early undulator of this design has been described in some detail in ref. (2). While no significant detrimental effects have been detected that are attributable to deficiencies in the manufacture of the REC blocks, the application of this undulator was not very sensitive to such errors. Other workers, however, had unpleasant experiences (ref. (3)). Instead of describing other group's remedies in detail, it is probably more useful to make some general remarks and recommendations about this topic:

A. Deficiencies in the production of REC blocks seem to depend very strongly on the manufacturer. The least damaging deficiency is variation of the total dipole moment of REC blocks. Much more damaging is an incorrect orientation of the easy axis, or worse, variation of the easy axis orientation and/or magnetization strength within a block. An even more insidious error would be a strong variation of the field level where the magnetization curve starts to deviate significantly from a straight line. Blocks that are suspect in this regard should never be used with the easy axis parallel to the z-axis. It should also be noted that different manufacturers use rather different methods to measure their blocks.

B. To correct magnetic deficiencies, it is essential to measure the relevant magnetic properties of the blocks, and then assign each block to a location in the array such that the deficiency is least damaging. In some cases it may be necessary to make small corrections to the location and/or orientation of blocks. In order to check the quality of the fields produced by the array, one should measure the fields produced by each half of the array separately (preferably with some null method) and take further corrective action if necessary. Since REC has differential permeabilities that are close to one, the use of correction coils is possible.

It is also possible to superimpose fields onto the undulator in order to achieve beam optical effects that are needed even for a perfect undulator. A good example would be a quadrapole field that would introduce focusing in the undulator bend plane and reduce the undulator-produced focusing in the direction perpendicular to the undulator midplane. When doing this, one has to be sure that this superimposed field does not drive the working point of the REC too far into the second or third quadrant of the magnetization curve. The most "endangered" part of the array is the region closest to the z-axis of the blocks with their easy axis parallel to the z-axis. In the array described by (2), the field there can be 95 percent of the coercive field H_c. Depending on the H-value for which the magnetization curve starts to deviate significantly from a straight line, only a small field will cause deterioration of the magnetic properties of the REC there. The part farthest away from the z-axis of the blocks with their easy axis parallel to the y-axis is similarly vulnerable. But since that part is so far away from the z-axis, deterioration of the magnetic properties there is not nearly as damaging to the performance of the array.

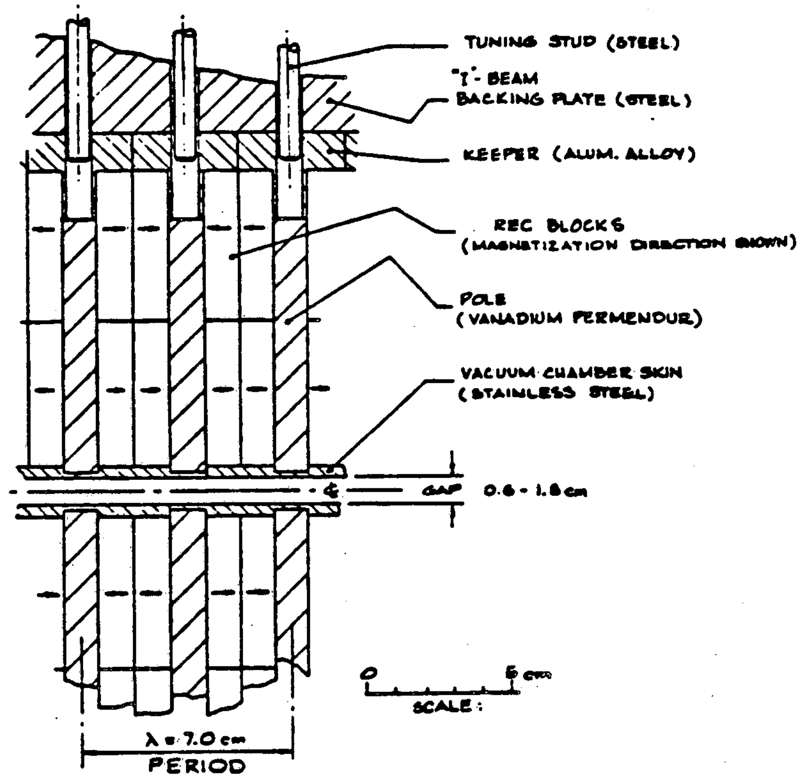

Fig. 2. Hybrid Undulator Crossection

4. HYBRID UNDULATORS

Fig. 2 shows the basic design of a hybrid undulator. The main thoughts behind this design are the following:

A. The REC is used only to excite the magnet, i.e., generate the magnetic flux in the gap, not to determine the field distribution in the gap.

B. Even if the steel is saturated, as long as its permeability is large compared to one, the magnetic properties of the steel have only a small effect on the field distribution in the gap. This, together with A., means that, in contrast to the pure REC undulator, the performance of the hybrid undulator depends only very weakly on the magnetic properties of the materials used. As a consequence of this, the hybrid undulator can use REC material that is considerably less expensive than that used for a pure REC undulator.

C. The field levels achievable with the hybrid undulator can be significantly higher than those obtainable with the pure REC undulator.

D. It is very easy, if necessary, to tune the strength of individual poles with the help of the tuning studs indicated in Fig. 2.

When using the hybrid design, one gives up two desirable properties that the pure REC undulator possesses:

A. It is not possible with the hybrid to (linearly) superimpose external fields.

B. The design of a specific hybrid is much more complicated than the design of a pure REC undulator since practically every magnetic property of a pure REC undulator can be calculated with analytical formulas, while optimization of a hybrid requires a significant amount of numerical analysis as well some magnetic measurements on a prototype. A lot of this work has been done for a specific hybrid undulator that is under construction at Lawrence Berkeley Laboratory (LBL), and can be applied to design other hybrids. Still, there will probably always be more design work associated with a hybrid than a pure REC undulator.

To assess the field levels that are achievable with a hybrid undulator, a computer design study was undertaken with the following assumptions: The REC has a remanent field of .9T, and the bulk of the REC material is run at B = .18T Although this seems to be a rather low working level, it is a reasonable figure for determining the upper limit of economically achievable field levels. Since saturation of the steel is important, the B(H) curve of Vanadium-Permendur was used for the steel, and it was further assumed that the magnet is very wide in the direction perpendicular to the paper plane of Fig. 2. Optimizing the width of steel for a number of ratios of gap/period g/λ leads to data that can be accurately described by the following expression:

$$B = 3.33 \cdot \exp\left(-\frac{g}{\lambda} \cdot \left(5.47 - 1.8 \cdot \frac{g}{\lambda}\right)\right) \qquad (3)$$

In equ. (3), B is the peak field (in T) in the midplane of the undulator, and equ. (3) is valid over the range $.07 < g/\lambda < .7$, giving a maximum field of 2.3T for $g/\lambda = .07$. Fig. (3) shows a plot of the fields produced by a hybrid and those of an undulator according to equ. (2) with a remanent field of also .9T.

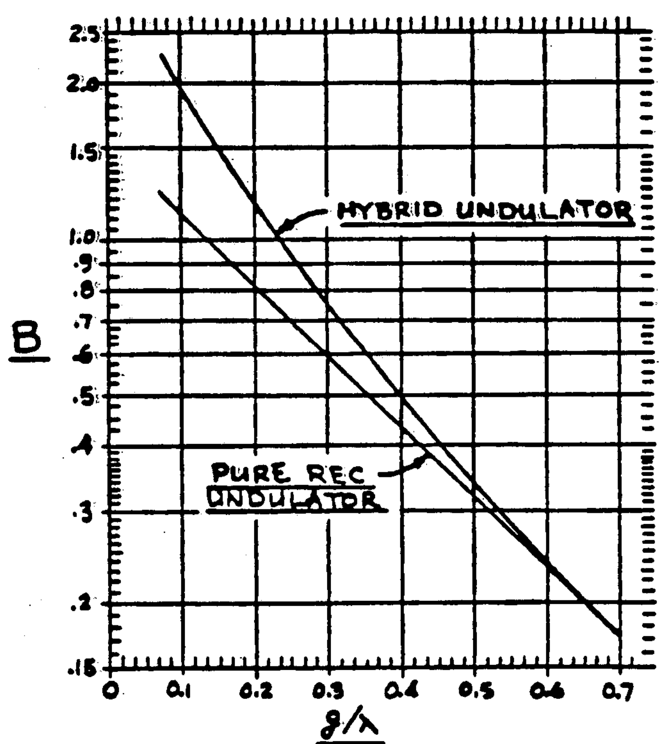

Fig. 3. Peak Midplane Fields in Hybrid and Pure REC Undulators

The field distribution in the hybrid has some third and fifth harmonics present. Their size is such that the field is more peaked than a pure sine curve. The relative amplitude of the harmonics increases with the maximum field level and reaches, in the midplane, 28 percent and 7 percent for the third and fifth harmonics at 2.3T. These harmonics could be reduced, if necesary, with only minor impact on the peak field. Reference 4 describes in some detail a hybrid wiggler that will be part of a synchrotron light facility at SSRL.

5. CONCLUDING REMARKS OF INTEREST FOR BOTH TYPES OF PERMANENT MAGNET UNDULATORS

In order to make it possible to reduce the period length of undulators, it has frequently been proposed to put undulators inside the vacuum vessel. Measurements made at SSRL have shown that REC has a remarkably low out-gassing rate of $< 10^{-10}$ Tl cm^{-2} sec^{-1} (see ref. 5).

Although I am not aware of any completed studies of radiation damage, preliminary results indicate that REC is remarkably radiation damage resistant. Because of highly anisotropic thermal expansion coefficients, the material is very sensitive to thermal shock, which may be generated by irradiation. As long as the temperature of REC is kept below 200°C, there is only a small "first time only" irreversible loss of magnetization when reaching elevated temperatures, and the reversible losses are very small also. Similarly, aging effects are too small to be of concern.

First time users are usually taken aback by the material cost, being of the order \$1.5 cm^{-3} for blocks of the size used in hybrid and undulators, and considerably more for the pieces of REC made to order with tight tolerances. However, in the parameter range of interest for free electron lasers, it seems that the cost for the REC does not amount to more than 10 percent of the total undulator cost.

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TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720