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DEVELOPMENT OF AN UNDULATOR MAGNET FOR THE DARESBUURY SYNCHROTRON RADIATION SOURCE

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Résumé - On décrit le projet d'un onduleur de 1 m de longueur constitué de blocs de matériau terre rare-cobalt ainsi que les méthodes utilisées pour calculer la distribution de champ à 3 dimensions ainsi que les forces magnétiques. On expose une méthode de test des blocs de manière à déduire l'information concernant les erreurs sur l'aimantation. Des résultats sont présentés et évalués en termes d'effets sur la trajectoire du faisceau d'électrons.

Abstract. The design of a 1 m long undulator composed of rare earth cobalt blocks and the methods used to calculate 3-dimensional field distributions and magnetic forces are described. A scheme for testing the blocks to derive information on magnetisation errors has been developed. Results are presented and evaluated in terms of the effect on the electron beam trajectory.

1. **Introduction.** An undulator is a periodic structure producing a transverse field distribution varying sinusoidally along its axis. The resultant undulating trajectory of an electron beam passing through the device leads to emission of synchrotron radiation with modified properties that are attractive for experimental usage. Design of an undulator for the SRS storage ring is complete and all components are available for assembly which will be completed before the end of 1983; installation in the ring will follow at the first available opportunity.

A previous MT-7 paper [1] reviewed general limitations on the design of such magnets. Since then greater emphasis has been placed on the use of rare earth cobalt (REC), usually SmCo_5 , permanent magnet material rather than on electro-magnetic devices and this is particularly true of free electron laser magnets. A companion paper in these proceedings [2] deals with this latter topic.

2. Magnet Design.

2a. **Optimization of parameters.** Fig.1 shows the conventional arrangement of REC blocks as first used on the Stanford undulator [3]. The peak field on axis for the case of infinitely wide blocks [1] is given by:

$$B_o = 2B_r \frac{\sin \pi/M}{\pi/M} (1 - e^{-2\pi h/\lambda_o}) e^{-\pi g/\lambda_o} \quad (1)$$

where B_r = remanent field of material, M = number of blocks per period, λ_o = magnet period, h = height of blocks and g = magnet gap.

In this case $M = 4$; a larger field can be produced with more blocks per period but there is a difficulty in magnetizing the blocks at an angle to the edges. Use of square cross-section, $h = \lambda_o/4$, allows maximum flexibility in selecting block locations. A period of 100 mm optimises the radiation intensity in the range 10-100 Å at the SRS operating energy of 2 GeV and provides visible light output at lower energies for diagnostics [4]; the magnet gap normally will remain fixed at its minimum value of 42 mm and 10 periods can be fitted in the available length.

Although an analytical method exists for investigating the effect of finite block width [5] it was convenient to use an existing general computer program, PMU3D

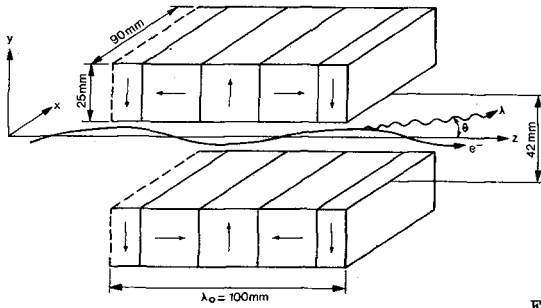


Fig.1 Basic SRS undulator geometry

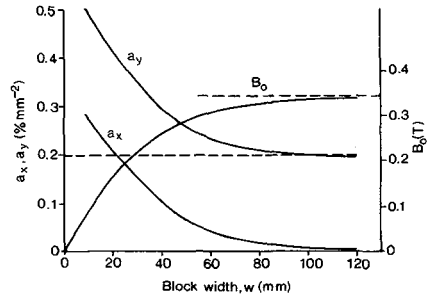


Fig.2 Variation of field strength and homogeneity with block width.

[6], the basis of which is the calculation of the field from a single block derived with a 3-dimensional current sheet model:

$$B_i = \frac{\mu_0}{4\pi} \sum_{\substack{j=1 \\ k \neq i \neq j}}^3 M_i \left[\tan^{-1} \left(\frac{r_{i r_k}}{r_j r} \right) \right] \begin{matrix} r_{i2} r_{j2} r_{k2} \\ r_{i1} r_{j1} r_{k1} \end{matrix} + M_j \left[\ln(r_k + r) \right] \begin{matrix} r_{i2} r_{j2} r_{k2} \\ r_{i1} r_{j1} r_{k1} \end{matrix} \quad (2)$$

Indices i, j and k take values 1, 2 or 3 respectively for the x, y and z coordinates of block corners. The transverse field distribution is approximately quadratic [7]:

$$B_y = B_0 (1 - a_x x^2)(1 + a_y y^2) \quad \text{with } a_y - a_x \approx \frac{1}{2} \left(\frac{2\pi}{\lambda_0} \right)^2 \quad (3)$$

Fig.2 shows the dependence of a_x, a_y and B_0 on block width. As the electron motion is not strongly effected by the inhomogeneity [8] a somewhat arbitrary width choice of 90 mm was made, providing a field amplitude close to the 2D limit indicated in the figure.

2b. End design. To ensure that the electron beam emerges from the undulator with no net deflection or displacement requires a field distribution symmetric about the magnet centre and end poles contributing half the field integral $\int B_y dz$ produced by the central poles. The properties of REC mean that use of end blocks of half length (see Fig.1) meet this requirement exactly. Figure 3 shows the computed field distribution, B_1 , with this arrangement with the left hand physical end of the magnet at $z = 0$. B_2 is the field of an identical magnet whose right hand end is located at $z = 0$. By superposition [9] the sum is the sinusoidal distribution, B , which exists in the centre of the magnet. Integrating over the end field region ($\pm \lambda_0$) then gives the following result:

$$\int_{-\lambda_0}^{\lambda_0} B_1(z) dz + \int_{-\lambda_0}^{\lambda_0} B_2(z) dz = 0 \quad (4)$$

By symmetry however $B_2(z) = B_1(-z)$ and so both integrals must be zero as required. This scheme avoids the complication of a rotatable full block used in previous designs [3] and also has the advantage of being independent of gap setting. In practice however differences between the magnetization strengths of half and full blocks will require some additional compensation by means of small trim coils.

2c. Magnetic force calculations. The force acting between two REC blocks can in principle be calculated by analytical means with a current sheet model. For the simple case illustrated in Fig.4 a 2-dimensional model gives the result:

$$\frac{\text{Force}}{\text{length}} = \frac{B_r^2}{\pi \mu_0} \left\{ (2a+b) \ln \left[\frac{(2a+b)}{((2a+b)^2 + a^2)^{1/2}} \right] - 2(a+b) \ln \left[\frac{(a+b)}{((a+b)^2 + a^2)^{1/2}} \right] \right. \\ \left. + b \ln \left[\frac{b}{(b^2 + a^2)^{1/2}} \right] - a \tan^{-1} \left[\frac{2a+b}{a} \right] + 2a \tan^{-1} \left[\frac{a+b}{a} \right] - a \tan^{-1} \left[\frac{b}{a} \right] \right\} \quad (5)$$

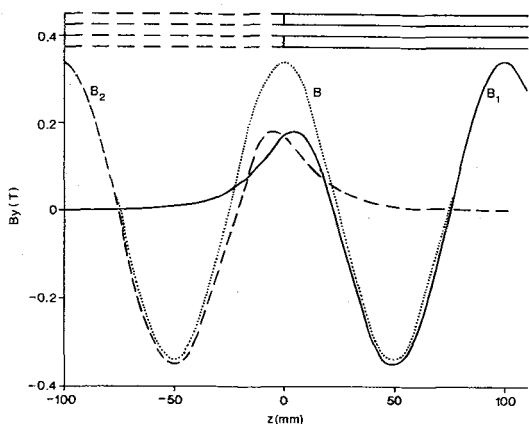


Fig.3 Field distribution near the end of the undulator.

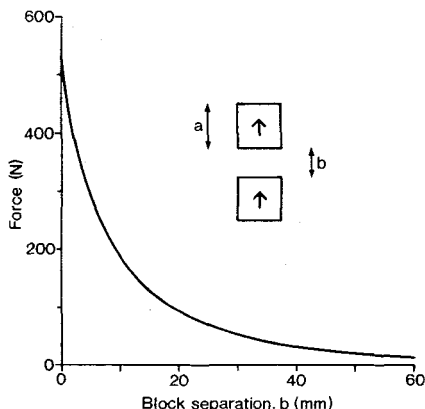


Fig.4 Magnetic force between two blocks.

For $a = 25$ mm, width = 90 mm and $B_r = 1.0$ T Fig.4 shows the rapid force increase at short distances, rising to 532 N for blocks in contact. At larger separations it falls as $(a+b)^{-4}$ since blocks can be represented by elementary dipoles situated at the block centres. A simpler numerical calculation has been undertaken for the undulator, summing forces between surface element pairs and moments about block centres. The total attractive force between arrays is about 2650 N and the end blocks experience the largest couple, about 1 Nm.

3. Permanent magnet blocks. The material chosen was Hitachi Hicorex-22A samarium cobalt (SmCo_5). Because of the large dimensions each block comprises 4 smaller pieces glued by the manufacturer before magnetization. Block magnetic properties have been studied by taking point field measurements of the component B_y at positions indicated in Fig.5, enabling the magnetization strength and an offset between magnetic and physical centres for each coordinate direction to be calculated:

$$\begin{aligned} M_x &= \frac{B1-B3-B6+B8}{4 C_1} & M_y &= \frac{B2+B7}{2 C_2} & M_z &= \frac{B4-B5-B9+B10}{4 C_3} \\ \Delta x &= \frac{B1-B3+B6-B8}{4 M_y C_4} & \Delta y &= \frac{B2-B7}{2 M_y C_5} & \Delta z &= \frac{B4-B5+B9-B10}{4 M_y C_6} \end{aligned} \quad (6)$$

where C_1-C_6 are coefficients calculated using eqn.(2). After locating a block in a simple holder a set of data could be taken automatically in about 10 minutes with the Daresbury magnet test facility [10] employing a Hall plate.

The results of measurements carried out on 84 blocks are summarised below:

$$\begin{aligned} \sigma_{M_x} &= 0.0067\text{T} & \sigma_{M_y} &= 0.0051\text{T} & \sigma_{M_z} &= 0.0125\text{T} & \langle M_y \rangle &= 0.9235\text{T} \\ \sigma_{\Delta x} &= 0.07 \text{ mm} & \sigma_{\Delta y} &= 0.12 \text{ mm} & \sigma_{\Delta z} &= 0.13 \text{ mm} \end{aligned}$$

Fig.6 is a histogram of the main magnetisation component which shows a total spread of 2.5%, a factor of two better than the manufacturer's quoted spread. The same technique was applied to the half blocks. The major difference in this case was the higher remanent field strength, $0.936 \pm 0.001\text{T}$ for the 8 blocks measured.

4. Trajectory calculations. The most important effects arise from M_x and M_y errors which cause finite transverse field integrals along the magnet, calculated as $\sim 3.10^{-4}$ Tm for errors of 0.01 T in a single block. Beam deflections of 0.015 mrad in both transverse planes then occur at the lowest anticipated electron energies. Assuming a Gaussian distribution of errors ($\sigma_0 = 0.015$ mrad) the expected position and angle errors at the magnet output are, with $N = 80$ blocks:

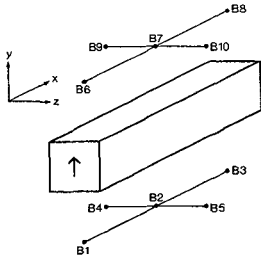


Fig.5 Scheme for magnetic measurements.

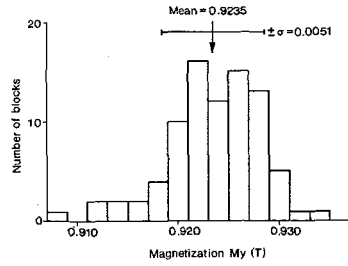


Fig.6 Variation in main magnetization strength.

$$\sigma_x = \sqrt{2} \frac{\lambda_0}{4} \sigma_\theta \left[\sum_{i=1}^{N/2} i^2 \right]^{1/2} = 0.08 \text{ mm} \quad \sigma_{x'} = \sqrt{N} \sigma_\theta = 0.13 \text{ mrad} \quad (7)$$

As a check field values obtained from PMU3D have been used to calculate the electron trajectory as follows (valid for $x' \ll 1$):

$$x'(s) = \frac{0.3}{E_{\text{GeV}}} \int_0^s B_y(z) dz \quad x(s) = \int_0^s x'(z) dz \quad (8)$$

Motion in the y plane was also checked although focusing forces in this plane [11] will modify the trajectory. A series of runs with random magnetization errors agreed with the simple model to within the statistical error. The effect of magnetic centre offsets of 0.1 mm was also found to be negligible.

5. Magnet construction. The necessary novel assembly techniques developed for a similar magnet [2] will again be utilised. Each block will firstly be glued into an individual holder and then bolted onto the baseplate using a special jig to overcome the large magnetic forces. Random block location will be possible because of the small computed trajectory errors, but the measured block dimensions imply an overall length ~ 3 mm greater than the nominal 1 m. Gap variation up to 100 μ m will be possible by manual adjustment on a lead screw mechanism and the whole magnet can be moved horizontally on linear bearings up to 300 mm away from the electron beam.

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