STATUS OF THE MAGNETIC DESIGN OF THE INSERTION DEVICES FOR ELETTRA

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Abstract

The status of development of insertion devices for ELETTRA is described, including pure permanent magnet undulators, a hybrid multipole wiggler and devices producing circularly polarized radiation.

Introduction

A 1.5-2 GeV third generation synchrotron radiation source, ELETTRA, is under construction in Trieste, Italy [1]. The storage ring design has been optimized for the inclusion of up to 11 insertion devices that will provide radiation beams from undulators with extremely high brightness in the photon energy range 0.01-2 keV, and radiation from multipole wigglers up to 30 keV. The general performance of insertion devices in ELETTRA has been described previously [2,3]. So far, four beamlines have been defined for the first phase of operation - undulator beamlines for super-ESCA, photoemission amd surface science, and a multipole wiggler for diffraction. Under study are two further insertion device beamlines for microscopy and circular dichroism.

This report summarizes the design constraints and recent work on undulator field errors, wiggler design and new structures for producing circularly polarized radiation.

Design Constraints

The straight section length between quadrupoles is 6.0 m, however, after space is allocated for other equipment the available space for insertion devices becomes 4.8 m [4]. In order to simplify construction, handling and testing, the IDs will be constructed in three independently controllable sections. This also allows the possibility for devices to be rapidly interchanged, and for different ID types to be installed in one straight. In order to overcome phase errors between sections that can reduce the source brightness [3,5] the undulators will be constructed using the pure permanent magnet technology, while hybrid technology will be used for the multipole wiggler. For reasons of cost and flexibility, the mechanical support system for all ID types will be the same, with a length of 1.5 m. A prototype carriage is nearing completion, and will be delivered in June [4].

The requirement for good beam lifetime has defined vertical electron beam apertures in the insertion device straight of 20 mm at 1.5 GeV and 15 mm at 2 GeV, from which magnet apertures of 25 mm (1.5 GeV) and 20 mm (2 GeV) have been defined [3]. The storage ring will be operated initially at the lower energy for some period of time, before 2 GeV operation is established. Decisions on insertion device parameters will be taken on an individual basis, and will either be optimized for 2 GeV, or where appropriate, permit operation at either energy. Design of a 4.8 m long narrow gap vacuum vessel has been completed and construction of a laboratory model will begin soon [4].

Undulator Design

The main parameters of the design of pure permanent magnet undulators can be determined easily using standard techniques [6]. So far, detailed design has only be carried out for the Super-Esca beamline [7], for which a period of 56 mm was selected in order to obtain a good tunability using first and third harmonics even with the larger magnet gap of 25 mm. In this case, because of the large gap to period ratio, use of the hybrid design would have increased the field strength by only 9%, for which the improvement in performance is negligible. A block height of one half of the period length and a width of 70 mm were chosen to give within 10% of the maximum field amplitude for such a structure, with a suitable transverse field homogeneity ($k_x = 13\ m^{-1}$).

In the pure permanent magnet structure errors in the strength and direction of the magnetization in the individual blocks have a direct influence on the field quality of the final magnet. Calculations have been carried out to estimate the effect on the field integral errors [8]. Firstly, the field integral $\int B_y dz$ was calculated (z = beam axis) at a number of transverse positions (x,y) on a circle of a given radius about the beam axis, for a single block. Fourier analysis then yielded the integrated multipole components for the single block, given in Table 1. A simple statistical estimate could then be made of the expected (rms) total error in a sample undulator with given magnetization errors. For example, a 1% rms error in all blocks would yield the estimates given in Table 2. On this basis it is clear that the main concerns are the dipole and quadrupole errors, whereas higher order mutipole errors meet the requirements for ELETTRA [9]. Block measurement and sorting can be used to reduce the multipole errors, however some care must be taken in the algorithm used since, for example, a pairing of two blocks with the same M_y error above and below the median plane can cancel the dipole error, but double the skew-quadrupole error of an individual block, and similarly for M_x errors.

Table 1. Integrated multipole fields along the beam axis (z) introduced by a single permanent magnet block, of size 70 mm (x-horizontal) x 28 mm (y-vertical) x 14 mm (z) with a magnetization of 1 T along the y direction; block centre 24 mm above the beam axis. In the case of a magnetization along the x-axis, the normal and skew components are reversed.

Component	Integrated Strength	
dipole	0.0024	T m
skew-quadrupole	-0.059	T
sextupole	-0.056	$T\ m^{-1}$
skew-octupole	-29	$T\ m^{-2}$

Table 2. Expected (rms) integrated multipole fields (normal and skew) in an undulator of 81 periods with blocks of the type given in Table 1, assuming a randomly distributed 1% rms magnetization error in the x and y directions.

Component	Integrated Strength (rms)	
dipole	0.0006	T m
quadrupole	0.015	T
sextupole	0.014	$T\ m^{-1}$
octupole	7.3	$T\ m^{-2}$

Magnetization errors also have the effect of producing a variation in the field amplitude from pole to pole, which reduces the undulator radiation brightness. A simple method for calculating the expected field amplitude variation for given magnetization errors, gave good agreement with measurements on previous undulators [8]. A nominal limit of 0.5% rms has been established for the ELETTRA undulators, however, it is not possible to relate this directly to a reduction in radiation brightness using existing theories, because of the large statistical variations that occur for a given value of error and because the real effect depends also on the electron beam emittance and photon energy. A further complication is the fact that in a pure permanent magnet geometry correlations between the field error of adjacent poles can also have a significant effect on the radiation spectrum [8].

The calculations above were based on the assumption that the main errors are due to variations in the strength and direction of the magnetization from block to block. However, initial measurements on the NdFeB permanent magnet blocks for constructing a prototype 56 mm period undulator indicate that inhomogeneity in the magnetization is also a very important factor [10]. The extent to which block measurement and selection can be used in this case to improve the field distribution is presently under study. Alternatively, or in addition, once a magnet array or complete structure has been constructed and measured shimming techniques developed at the ESRF [11] can be used to improve the field quality.

Multipole Wiggler Design

In the case of the multipole wiggler, a constraint on the maximum field is set by the permitted opening angle of the radiation. The start of the radiation slot in the bending magnet, through which the ID radiation will pass, is 7.91 m from the upstream end of the ID. The vessel horizontal aperture is ± 40.5 mm, however, allowances have to be made for misalignment of the vacuum vessel position with respect to the electron beam axis, and for variations in the closed orbit at the ID during operation. Taking these factors into account results in an effective horizontal aperture of ± 38.9 mm. For very large K values, the radiation opening angle is given by $\pm K/\gamma$, however, since even small amounts of power can lead to a significant heating of the uncooled, insulated vacuum chamber, calculations showed that in the present case an aperture of $\pm 1.05\ K/\gamma$ is needed to reduce the absorbed power to less than 0.1% of the total. A further allowance must be made for deviations of the electron trajectory in the wiggler itself, even assuming that no net deviation in position or angle occurs, and for this a value of $\pm 0.05\ K/\gamma$ has been taken. As a result the requirement becomes that the opening angle must satisfy $K/\gamma < 4.47$ mrad, i.e. $K < 17.5$ (2 GeV) or $K < 13.1$ (1.5 GeV).

Optimization of the wiggler parameters to find the maximum field level that can be produced, with the given constraints on the gap and K value, has been carried out using a combination of 2-D and 3-D analysis using the POISSON [12] and HYBRID [13] computer codes respectively. The former allows steel saturation effects to be evaluated, assuming infinite pole width, while the latter gives an estimation of the effects of finite pole and magnet width, but with infinite steel permeability.

For the tranverse field homogeneity a conservative approach must be taken, because of the large aperture required in the ELETTRA lattice for Touschek scattered particles in order to preserve adequate lifetime [3]. Tracking studies using the standard 3-D field expansion with a cos $(k_x x)$ variation in the main B_y field component, gave a limit on the transverse variation of $k_x < 10\ m^{-1}$, for a nominal 1.5 T wiggler with 125 mm period and 4.5 m length [14]. The real transverse field distribution will however be quite different, especially at the smallest gap setting, with significantly higher order multipole terms. Until more detailed studies are performed, a preliminary specification has been set that within a good field aperture of ± 30 mm (scaled from that in the other lattice elements), the field deviation and the field gradient must be less than that of the cos $(k_x x)$ model i.e. $\Delta B/B < 4.5\ \%$, $B'/B < 3\ m^{-1}$ Studies using the HYBRID program, show that in order to achieve this a pole width of 90 mm is required.

Initial calculations established a relationship between the maximum field in the steel in the 3-D calculation (HYBRID) and the saturation (reduction in B_0 due to finite permeability) in the 2-D case (POISSON). Since a low saturation is desired in order that pole-to-pole field variations do not change with gap setting, a saturation of 2 % was specified. The coresponding limits on the maximum field in the pole were 2.1 T for iron, and 2.4 T for iron-cobalt poles. Then, using HYBRID solutions were sought for a range of period lengths that gave the maximum allowed B_0 (with K=17.5) with the minimum magnet volume (V) per half period. In this way, the most efficient solution is obtained with the longest period, smallest pole thickness (p) and pole height (h), for each field value. A magnet overhang of 25 mm was found to be close to the optimum in all cases. The results (Table 3) indicate that despite the high cost of iron-cobalt compared to iron, this is the still the most cost effective solution. Since the achievable photon flux at 30 keV does not vary very rapidly with B_0 (25% between 1.45 and 1.5 T) a reasonable choice is therefore a period of 125 mm. In this case, a total of 21 full strength poles, plus two end poles, can be accommodated in each 1.5 m section.

Table 3. Optimized wiggler parameters with the constraint K=17.5, gap=20mm.

λ_0 (cm)	B_0 (T)	p (cm)	h (cm)	V (cm^3)	Pole material
13.0	1.44	2.5	10.0	700	iron
12.75	1.47	2.8	19.0	1076	iron
12.5	1.50	2.8	29.0	1521	iron
13.0	1.44	1.8	5.5	526	iron-cobalt
12.75	1.47	1.9	7.0	595	iron-cobalt
12.5	1.50	2.0	9.0	684	iron-cobalt
12.25	1.53	2.15	12.8	849	iron-cobalt
12.0	1.56	2.35	24.0	1354	iron-cobalt

The effect of various changes in the pole geometry has also been investigated using POISSON. A pole overhang reduces B_0 and increases the field in the pole, but also reduces the area in the magnet that experiences a reverse field component. A pole chamfer mainly has the effect of reducing the maximum field level at the pole tip, while a magnet chamfer "cuts-out" the region of reverse field. An optimum magnetic configuration to avoid pole saturation and magnet demagnetisation is therefore a combination of pole and magnet chamfers, without a pole overhang. However, since a pole overhang is of benefit mechanically, to provide a means for securing the magnet block, and since a magnet chamfer reduces the flexibilty for selection of the smaller blocks that are usually used to form the large composite block, the solution adopted is a 2 mm pole overhang with a pole chamfer. Figure 1 shows the field distribution for the proposed geometry, with B_0=1.54 T. The calculated saturation is 1.3%, and so the estimate for the final field amplitude is 1.48 T. This procedure should in principle give a pessimistic result, since 3-D effects lower the field in the pole and hence reduce the saturation.

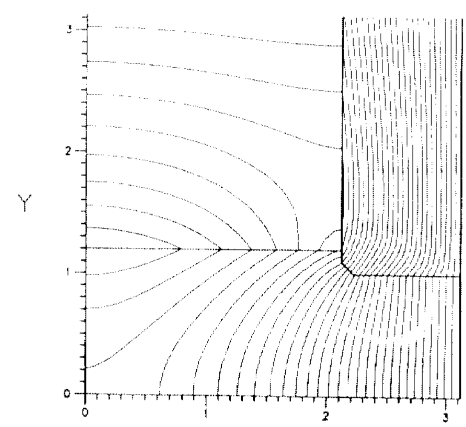

Fig.1 Field distribution in the multipole wiggler magnet.

Circularly Polarized Radiation Source

In addition to the requirement for conventional insertion device radiation that is polarized in the horizontal plane, there is also a desire for circularly polarized radiation for particular experiments. Initial studies concentrated on the new planar device proposed in ref. [15] for generating circularly polarized radiation with variable helicity. This scheme is more simple than the earlier crossed undulator design [16], but also relies on a mechanical adjustment in order to switch between right- and left-handed polarization. Studies of the linear [17] and non-linear [18] effects of this device have shown that it is more suited to a higher enrgy ring than ELETTRA. A related structure [17], is more efficient but is of fixed polarization, and would require therefore a complicated optical system to switch between beams of opposite helicity. Since these studies it has become clear that in the present case, a fast switching of the polarization between right- and left-handed is desired, which can only be achieved using the double undulator scheme [19] and so recent work has concentrated on this device.

This scheme consists of two undulators with orthogonal field polarization separated by a magnet that adjusts the relative phase of the radiation emitted in the two sections. A possible method of construction is to mount a pair of conventional undulators at ±45° with respect to the horizontal plane, in order to achieve as small a gap as possible. The disadvantage however is that the gap must still be considerably larger than that of a conventional device, which restricts the tunabilty of the output radiation, and in addition a different mechanical structure is required compared to the other insertion devices. To overcome these difficulties, the possibility of using a planar magnet to produce the horizontal field undulator is being considered.

Such a magnet, consisting of two arrays of the type used in ref. [15], but with the addition of a separation between the left- and right-hand sides, is shown in fig. 2.

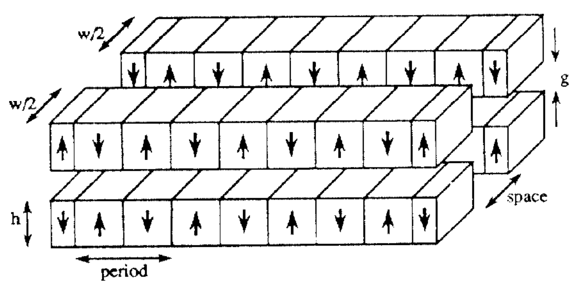

Fig.2 Planar permanent magnet array producing a periodic horizontal field distribution.

Calculations show that a total magnet width (w) of about 70 mm, and a height (h) equal to one half of the period length is sufficient to obtain close to the maximum field amplitude on axis. Figure 3 shows the field amplitude achievable as a function of magnet period for a 20 mm gap, for comparison with the field achievable in a conventional design with various gaps. It can be seen that with zero separation the new design gives similar performance to that of a conventional magnet with a gap of 30-40 mm.

Preliminary dynamic aperture studies for a double undulator scheme in ELETTRA, incorporating a conventional vertical field undulator and a horizontal undulator of the above type, have shown that significant dynamic aperture reduction occurs [20]. In order to reduce the effect of the horizontal field undulator, the possibility of modifying the transverse field variation by introducing a space between the magnet arrays is being considered. Figure 4 shows the field variation in one case as a function of the block separation. It can be seen that as the separation increases the field amplitude decreases, however the variation of the field in the horizontal direction (and hence the vertical also) decreases. Initial results suggest that a suitable dynamic aperture may be able to be achieved by such a technique. Figure 3 shows that a separation which gives k_x=0 still gives a performance equivalent to that of a conventional device with approximately a 40 mm gap.

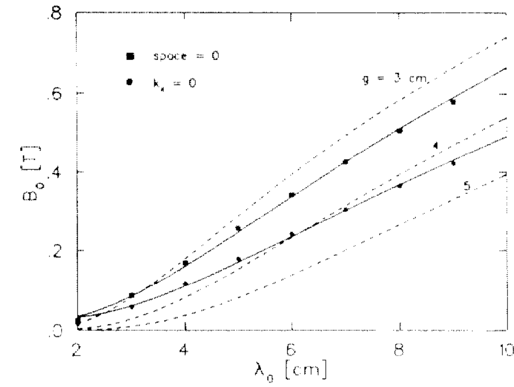

Fig.3 Field amplitude in a horizontal field undulator of the fig.2 type (g=20 mm) for different block spacings, and in a conventional undulator geometry (various gaps); Br=1.1T, h=period/2, 2D limit in both cases.

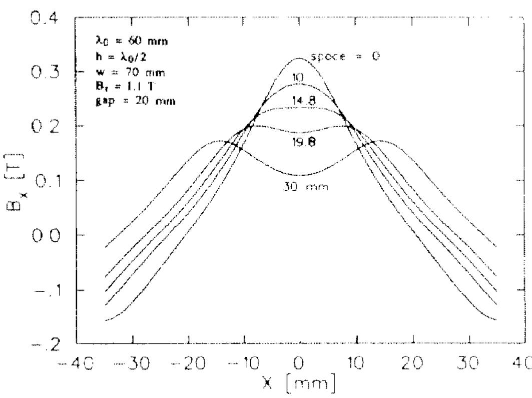

Fig.4 Field variation in the transverse direction for various block spacings

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