RECENT ADVANCES IN INSERTION DEVICES

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ABSTRACT

The active development of third generation synchrotron radiation sources has resulted in a number of advances in the technology of insertion devices. Multipole and spectrum shimming of the magnetic field has now reached maturation and is routinely applied in a number of facilities. It results in devices having ideal spectral performances as well as minimum interaction with the stored electron beam. The development of phased segmented undulators has greatly simplified the manufacture and implementation of very long undulators. A great effort has been put into the generation of circularly polarised radiation resulting in a number of advanced helical undulators and ellipsoidal wigglers. An important issue is to reduce the magnetic gap, several directions are being followed including the use of a narrow fixed or variable gap vacuum chamber or placing the magnet blocks in the vacuum. A number of illustrations will be given of the ESRF Insertion Devices where a number of these recent developments have been pioneered.

1 INTRODUCTION

The insertion devices (IDs) known as undulators and wigglers are presently being intensively used in third generation synchrotron sources. The production rate of these magnetic structures has followed an exponential growth since 1980. Starting with about 5 IDs yearly manufactured in 1980, this rate is above 32 in 1996 and should be higher than 60/year at the end of 1998 with the start of operation of large facilities such as APS and SPRING-8. In the 1980s a large number of IDs were high field multipole wigglers. Nowadays , around 75 % of the IDs produced are low field undulators. The reason for this comes from both the high demand of the large high energy facilities which are optimised for undulators and from the recent advances in spectrum shimming which extend the accessible photon energy range. The magnetic design of IDs has also strongly benefited from the enormous progress made in computer hardware and software. The use of the very popular 2D PANDIRA code is being replaced by 3D magnetic codes. This concerns the design of the central period of the very large majority of the IDs presently under manufacture. A few laboratories also produce ab-initio 3D design of the extremities [7]. This result in lower cost devices with a reduction in volume of the expensive magnetic material needed and the down sizing or elimination of correction coils.

2 MAGNETIC SHIMMING OF INSERTION DEVICES

2.1 Motivation

In order to maintain the stability of the electron beam circulating in a storage ring, it is essential that an insertion device presents zero or very low integrated multipoles on the axis of the electron beam. To reach the smallest period for a given peak field and minimum magnetic gap, one uses permanent magnet alloys of type SmCo or NdFeB rather than electromagnets. The high remanence of these permanent magnet materials allow the construction of short period devices at reasonable cost. Nevertheless, the manufacturing methods of permanent magnet blocks (mainly the powder metallurgy) result in somewhat inhomogeneous blocks which present severe consequences for the field integrals and spectral performances of the device produced by assembling these magnet blocks. In most of the cases, even after careful pairing based on the measured magnetic moment of each blocks, the measured integrated dipole and quadrupole are often 10 to 100 larger than desired and the flux and brilliance on harmonics 5 and higher can be dramatically reduced. These field errors are now routinely corrected by sophisticated magnetic shimming processes.

2.2 Multipole shimming

The magnetic specification of insertion devices define maximum values for the integrated multipoles on the beam axis, the most demanding being the requirement for the integrated normal and skew dipole which is of the order of 50 G.cm and 20 G.cm respectively for the ESRF. The amplitude of the integrated multipoles can be strongly reduced by applying micro displacements on the magnet blocks and by using thin soft iron shims placed on the magnet’s surface. The first step of the process consists in placing the shims at various locations and measuring the field integral distortion induced. A signature table for each shim location is then obtained and, inverting the process, one derives the thickness and correct position of each shim to be placed for the reduction of the integrated multipoles A few iterations are usually required to reach a satisfactory result. This shimming technique, known as multipole shimming, is presently routinely used in several laboratories [1], [2].

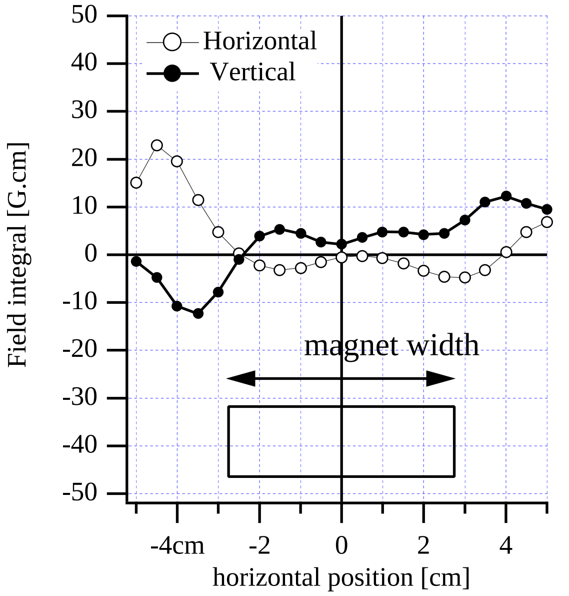

Figure 1: Horizontal and vertical field integral measured in the gap of 14 mm of an ESRF undulator (period 42 mm, N=38 periods) after shimming. The flatness of the curves as a function of the horizontal position ensure very low multipoles and small variations of these multipoles as a function of the magnetic gap.

2.3 Spectrum shimming

A second kind of field error is responsible for small fluctuations of the peak field and field profile from one period to the next. These errors are commonly called phase errors and result in severe losses of photon flux and brilliance on the high harmonic numbers. A phase or spectrum shimming can be applied to correct such errors. The principle is, in many aspects, similar to the multipole shimming. The figure of merit is, this time, the phase advance of each period which is locally increased or decreased by either moving a block vertically or placing a shim in a longitudinal position such that no field integral is induced while the phase is reduced. During the last three years the correction method has been clearly identified and applied routinely on many undulators [3], [4], [5]. Starting with a raw undulator including a rms. phase error of more then 10 degrees, it is possible to reduce it to below 2 degrees. As shown in Figure 2, the amplitude of the 15th harmonic of a 35 period undulator can be more than 80% of the ideal one expected from a purely sinusoidal field. Undulators are now produced with nearly ideal spectra. Note that spectrum shimming is made on the pessimistic hypothesis of a filament mono-energetic electron beam. The present performance reached by spectrum shimming is largely sufficient in view of the limitations imposed by the electron emittance and energy spread. As a result, the photon energy range covered by spectrum shimmed undulators has been multiplied by 2, resulting in increasing use of undulators, whereas, a few years ago, wigglers were preferred devices.

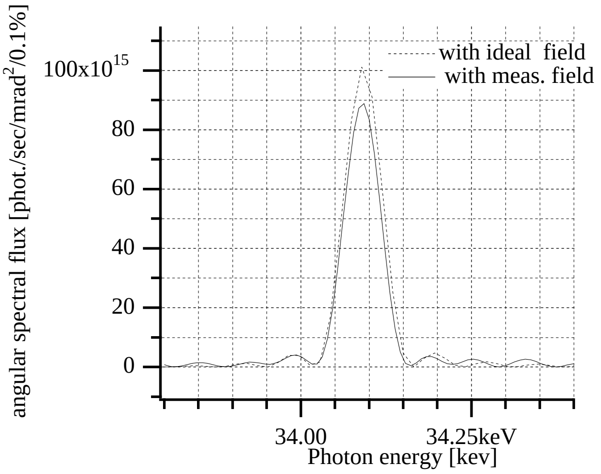

Figure 2: Spectra of the harmonic #15 computed for an ESRF undulator (period 46 mm, length 1.6 m and gap 20 mm). The plain curve corresponds to a spectrum shimmed undulator whilst the dashed curve corresponds to an ideal sinusoidal field. The calculations assume a filament mono-energetic electron beam of 6 GeV.

3 PHASING OF SEGMENTED UNDULATORS

The manufacture of long undulators is of particular difficulty because it is essential to achieve an accurate parallelism between the magnetic arrays positioned on each side of the electron beam. The supporting mechanical structure has to ensure the correct positioning of the magnetic arrays with a typical resolution of 1 micrometer. The longer the undulators, the more difficult the construction of the carriage. In third generation storage rings, the length of the straight sections is typically five meters. Two different strategies have been followed by different groups: the first consists in the fabrication of a single long undulator covering the total free length [6] , the second is based on the construction of several segments of one to two meters each. This second approach has been followed by ESRF and ELLETTRA because it strongly relaxes the required mechanical tolerances and significantly reduces the manufacturing costs. The main difficulty is the phasing of such segmented undulators. Although no simple phasing principle exists for hybrid undulators, solutions have been developed in the case of pure permanent magnet undulators. The most simple solution is shown in figure 3. The magnetic assembly is terminated with half length vertically magnetised magnet blocks. In order to properly recover the phasing between both segments, the half blocks have to be placed in contact [8] with no possible independent gap control of the individual segments. If one want to keep the control of the gaps independent in each segment, some longitudinal separation between the undulator segments must be provided which, for a short period undulator, result in a localised phase error which reduces the flux and brilliance on the high harmonics. In addition, due to the non unit permeability of the magnet blocks, field integrals are generated at the undulator junction which varies as a function of the magnetic gap of each segment. For such phasing, an active correction method using coils have to be envisaged in order to compensate the field integral [6].

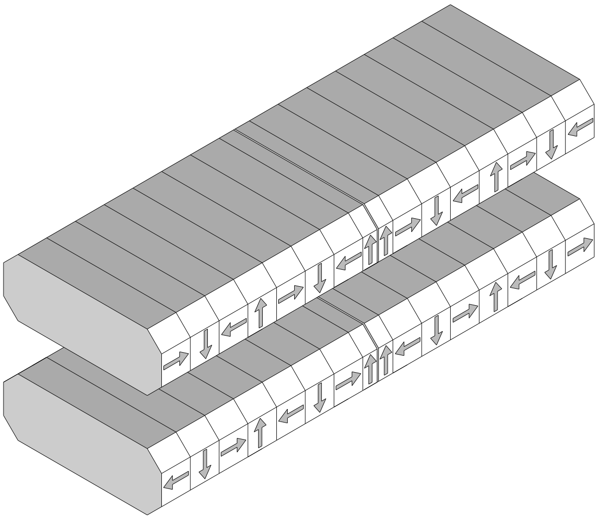

Figure 3: Conventional phasing of pure permanent magnet undulators. The last magnet block of each segment is a half block vertically magnetised. The arrows indicate the direction of the magnetisation.

An alternative to the conventional phasing has been developed at the ESRF in order to eliminate the problems described above [7]. The new structure for the end field part of each segment is shown in Figure 4. It includes special magnet blocks magnetised at 45 ° with respect to the vertical axis. The important feature is the non zero longitudinal separation of the segments for a perfect phasing. Typically, a separation of 6 mm is obtained for a 40 mm period. These phasing sections eliminate the phase error and reduce the field integral variation with gap by a factor three. In addition, it is less sentitive to longitudinal mis-positioning of the undulator segments by a factor 3 and allows a fully passive tuning of the magnetic gap independently on each segment .

4 POLARISATION

Conventional planar field insertion devices generate radiation which is essentially linearly polarised in the plane of the orbit. Since 1990 significant developments have been carried out on exotic insertion devices capable of producing circularly polarised light with flexible polarisation. A number of different undulator and wigglers have been proposed and/or successfully operated to achieve this goal.

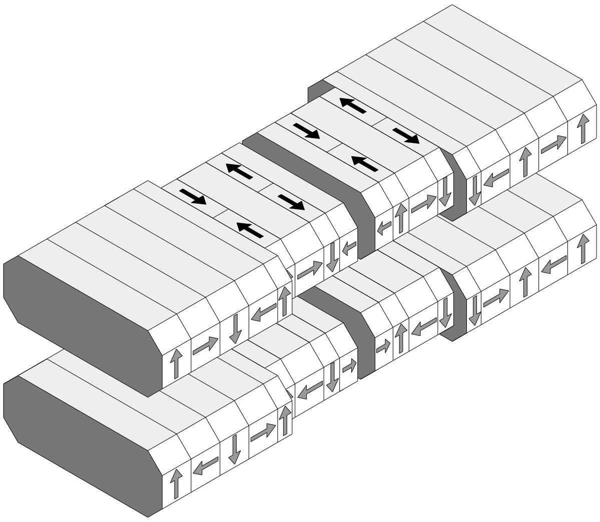

Figure 4: ESRF end field structure for the phasing of pure permanent magnet undulators. The vertical median plane between both segments is an antisymmetry plane. The optimum phasing is obtained with a segment separation of several millimetres.

4-1 Undulators

The production of circularly polarised radiation can be achieved using helical undulators.Various magnetic designs have been produced [9], [10], [11]. The common point between all these devices is the existence of at least one magnet array which is translated along the beam axis in order to modify the state of polarisation. The polarisation can be changed from circular left to circular right within a few seconds by the appropriate translation of a magnet block assembly. The most popular configurations concern the planar devices which can be installed with conventional vacuum chambers. Three such undulators are presently in extensive use at ESRF. At the present, the structure proposed by Sasaki has been adopted in the large majority of the facilities due to its mid-plane symmetry which ensures a minimum closed orbit distortion as a function of gap. However, harmonics higher than one cannot be used without breaking such symmetry. Recently, interest has been given to long period electro-magnet devices to produce such flexible polarisation with short flipping time [12].

4-2 Wigglers

The production of circular polarisation at high photon energy (above 20 KeV) cannot be achieved efficiently with helical undulators. For this purpose several kinds of special wigglers have been designed. Asymmetric wigglers [13], [14] have been built and successfully operated. In these devices, the magnetic field is not symmetric as shown on figure 5: large positive peaks alternate with negative one of smaller amplitude. As for bending magnet, the radiation in the orbit pane is linearly polarised, while it becomes right-handed (left-handed) circularly polarised if one collects the radiation at a sufficiently high energy from above (below) the orbit plane. The engineering difficulty associated with asymmetric wigglers is the control of the field integral which is induced by the asymmetry of the magnetic field. In this case, 3D magnetic design is essential. The use of an elliptical wiggler is another possibility [15], [16], [17] . It is derived from a conventional vertical field wiggler by adding a small horizontal field with same period phase shifted longitudinally by $\pi/2$. The radiation produced on the axis of such a device is strongly circularly polarised left or right depending on the sign of the horizontal field with respect to the vertical field . Because only a small horizontal field is required (associated K value of the order of one), an electromagnet AC structure can be envisaged. The benefit is a fast switching time between left and right circularly polarised radiation

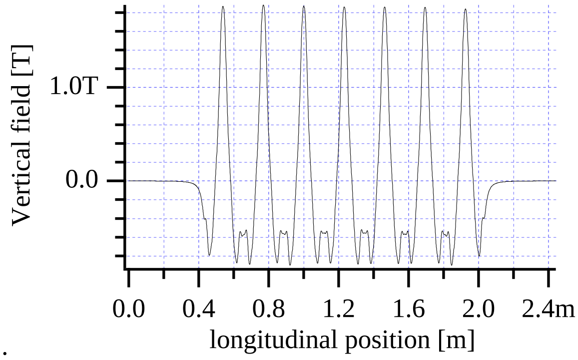

Figure 5: Magnetic field of an asymmetric wiggler installed on the ESRF storage ring. The gap is 20 mm and the period of the device is 230 mm. The large asymmetry of the magnetic field allows the production of circularly polarised radiation away from the orbit plane.

5 SMALLER GAPS

The very large majority of permanent magnet insertion devices are operated with the magnet block placed in air outside the vacuum. A vacuum chamber is placed inside the magnetic gap. This is the simplest and therefore most economical choice. It is also extremely flexible since it allows an easy replacement of the magnet array or ID without breaking the vacuum. Five meter long vacuum chambers allowing a magnetic gap as small as 11 mm have been installed at APS. This thickness is not far from the minimum tolerable by the electron beam compatible with a reasonable lifetime. A penalty is paid in the fixed gap chamber since the minimum magnetic gap operated is typically 4 to 5 mm larger than the effective electron beam stay clear. These 5 mm originating from the material thickness, manufacturing process and alignment errors, can be important for short period undulators aimed at producing a high energy of the fundamental for a given electron energy. With a variable gap chamber the free aperture for the electron beam can be adapted to the operation mode of the ring. Gaps as small as 6 mm have been reached [18], [19]. One device of this type has been in operation at the ESRF since January 1995. The manufacture of such vacuum chambers is complicated and it is a challenge to build undulator segments longer than one metre. Another possibility is to place the permanent magnet blocks inside the ultrahigh vacuum [20]. The magnetic gap can therefore be identical to the electron beam stay clear. However, there are serious engineering difficulties to overcome. They include a proper coating of the magnet block to limit the degassing, a baking temperature limited to 130 ° to avoid a demagnetisation of the permanent magnet blocks and possible lateral Higher Order Modes resonances and electrical continuity to avoid excessive heating by the return current of the chamber. SPRING-8 is presently producing a large number of such in vacuum undulator.

6 CONCLUSION

Undulators produced nowadays have residual negligible field errors both in terms of multipoles and spectra. Producing flexible circularly polarised radiation is becoming routine in a number of laboratories. Large efforts in the development of high quality insertion devices have been produced in a number of facilities. The transfer of this knowledge to industry is an important issue in the near future.

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