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Phasing Multi-Segment Undulators

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An important issue in the manufacture of multi-segment undulators as a source of synchrotron radiation or as a free-electron laser (FEL) is the phasing between successive segments. The state of the art is briefly reviewed, after which a novel pure permanent magnet phasing section that is passive and does not require any current is presented. The phasing section allows the introduction of a 6 mm longitudinal gap between each segment, resulting in complete mechanical independence and reduced magnetic interaction between segments. The tolerance of the longitudinal positioning of one segment with respect to the next is found to be 2.8 times lower than that of conventional phasing. The spectrum at all gaps and useful harmonics is almost unchanged when compared with a single-segment undulator of the same total length.

Keywords: undulators; insertion devices; X-ray sources; angular spectral flux; harmonics; ideal performance; measured performance.

1. Introduction

The manufacture of very long undulators with more than 100 periods capable of generating ideal brilliance up to harmonics 5 of the radiation spectrum is a technological challenge. The requirement for a high photon energy of the fundamental peak of the undulator spectrum or high critical energy of the wiggler spectrum forces the manufacturer to use permanent magnets rather than electromagnets. The large majority of insertion devices in use as a source of synchrotron radiation are made using permanent magnets. The permanent magnet blocks are attached to two long rigid girders symmetrically placed above and below the vacuum chamber. In order to tune the magnetic field, the girders are fixed on a carriage structure which permits a remotely controlled variation of the magnetic gap and sometimes taper with a resolution of the order of 1 μm over a gap range between 10 and 300 mm depending on the period length. The carriage supporting the magnet arrays is in many cases a delicate high-precision piece of mechanical engineering. The longer the carriage the more delicate it is. A study of the choices made by the various facilities in the world reveals two different approaches. One is to build a long single-piece undulator magnet (single-segment approach) with a length of ~4–5 m or longer, the other is to segment the undulators into small segments 1 or 2 m long (multi-segment approach). In 1987, the ESRF selected the multi-segment approach for the following reasons: it strongly relaxes the specification of straightness and rigidity of the girders over the single-segment length of 1.6 m; it reduces the weight of the carriage to less than 2 tonnes (including magnet array) from the typical value of more than 10 tonnes in the single-segment approach; it reduces the specifications on the straightness of the vacuum chamber since each segment is separately aligned on the chamber. A bending of the chamber can be compensated by a bending of the undulator field, which can be tolerated to some extent. Finally, the high energy of the ESRF implies a high heat load on the beamline components, and the gradual increase of the undulator length by adding more segments is a convenient way to operate the beamline whilst developing optics capable of withstanding the full heat load. The result of this segmentation is a significant flexibility. At present, 32 segments are in operation and the installation time of a single segment in the storage ring tunnel is, typically, half a day. Moving an insertion-device segment with its carriage from one place in the tunnel to any other takes less than one day and has been used a number of times for test purposes or for reasons of convenience. One of the most delicate issues in the segmentation is the phasing between the segments to ensure full brilliance on the lowest-order harmonics of the spectrum such as 1, 3 and 5. This article describes a novel phasing scheme recently developed and tested at the ESRF.

2. Conventional undulator phasing

As yet, no simple method exists to phase two segments of hybrid magnet arrays. In principle, it is always possible to open a longitudinal gap between the segments and to place an electromagnet three-pole section that must be tuned according to the gap of each undulator. The added complexity and the space lost between the segments has not convinced any designer to select this option. This is not the case for pure permanent magnet arrays, however. Segments can be phased by terminating each undulator by a half-length vertically magnetized block (half block). This is illustrated in Fig. 1. The half blocks from two adjacent undulator segments must be placed in contact. The two half blocks are equivalent to one full block and the field geometry to that of a full undulator with twice the length without any interruption in the middle. Nevertheless, this scheme presents a few limitations. Bringing the half blocks into contact practically eliminates the possibility of independent gap-tuning of both segments because of mechanical friction. Therefore, the gap must be changed synchronously on all segments installed, which is an undesirable complication. Taking the ESRF's case of phasing two undulator segments, each made of 41 periods of 40 mm operating at a magnetic gap of 15 mm, the opening of a 1 mm (2 mm) longitudinal gap between the half blocks reduces the angular flux on harmonics 5 by 20% (40%), which is also undesirable. If NdFeB magnet blocks are used, one must also face a vertical field integral variation as high as 90 G cm which occurs at the junction between the segments when the gap of a single-undulator segment is moved from 15 to 60 mm (see Fig. 2). This field integral is due to the permeability of the NdFeB blocks, which is slightly larger than 1. Their values have been measured as 1.06 (1.17) for the component of field parallel (perpendicular) to the easy axis of magnetization. Such field integrals introduce some distortions on the closed orbit which are detrimental to the majority of the users. Corrections must be made using electromagnets.

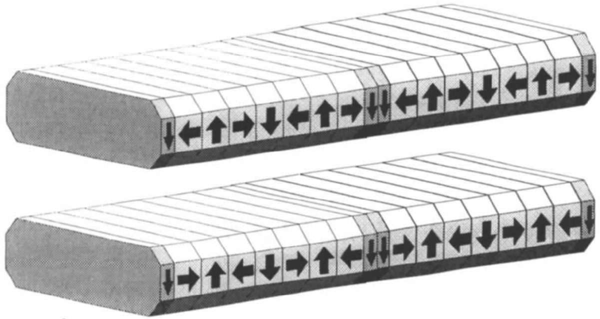

Figure 1

Conventional method for phasing two pure permanent magnet undulators. The undulator segments are terminated by half blocks magnetized vertically which are placed in contact.

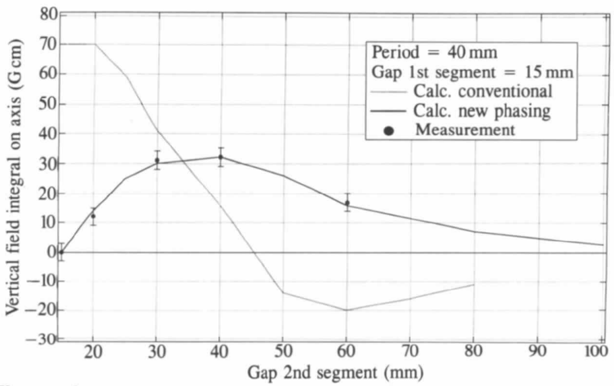

Figure 2

Field integral as a function of the magnetic gap of one segment leaving the gap of the other segment at a minimum of 15 mm. The dashed curve is the prediction for conventional phasing. The solid curve is the prediction for the new phasing sections. The dots are the measured values. The undulator period is 40 mm. The curves are the result of the subtraction of the contribution of both segments together from those of each of the segments alone at the same gap.

3. Phasing sections

To remove a number of the problems discussed above we have modified the termination of the undulator segments. A number of magnetic configurations were studied. For each design the three-dimensional magnetic field components and their integrals along the electron beam path were computed taking into account the permeability of the blocks. The most successful configuration is presented in Fig. 3. The two half blocks terminating the undulator segment, discussed earlier, are spaced at a distance from each other of 1.5 × period. The space between the half blocks is occupied by two magnet arrays of smaller transverse size which terminate each undulator segment. We shall call them phasing sections. The phasing sections are designed to operate with a longitudinal air gap of 6 mm between each other. The vertical component of the magnetization of the adjacent undulator segments, including the phasing section, is in the so-called antisymmetric configuration, resulting in a zero vertical field at any point belonging to the symmetry plane separating the two undulator segments. One of the most important issues in designing such a phasing section is maintenance of a constant optical phase per unit longitudinal distance in the phasing section as well as in the undulator segments. The optical phase is entirely due to the period at a large gap and to a mixture of the period and magnetic field at a small gap. The spacing of the undulators at a distance of 1.5 × period ensures a proper phasing at a large gap. At a low gap, some of the field is missing due to the absence of magnetized material in the 6 mm space between the phasing sections. This lower field in the junction between the phasing sections

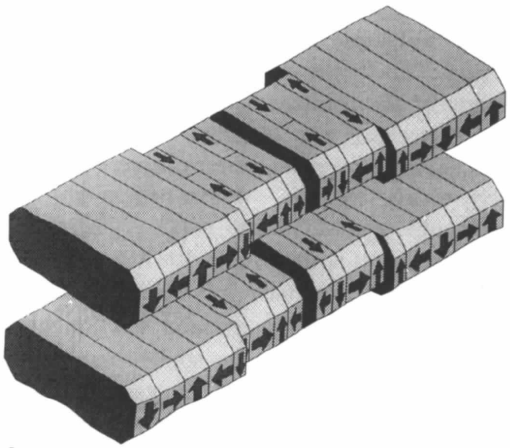

Figure 3

Magnetic configuration of the phasing sections.

is compensated by a larger field in the adjacent poles where special magnet blocks magnetized at 45° with respect to their faces are used. Note that since the vertical field is inverted from one segment to the next, the lack of field at the junction is attenuated by the fact that the expected field is low in this area. This is the reason why we selected the antisymmetric configuration. A symmetric field configuration would require additional field in the immediately adjacent pole to compensate for the missing field in the junction. This is illustrated in Fig. 4 which presents the measured magnetic field of two such segments. The slightly higher field in the pole immediately adjacent to the middle can be clearly noticed.

Fig. 5 presents the angular spectral flux [measured in photons $s^{-1}(0.1\%)^{-1}$ $mrad^{-2}$] obtained on the odd harmonics of the spectrum on axis. The electron energy is 6 GeV and the current is 100 mA.

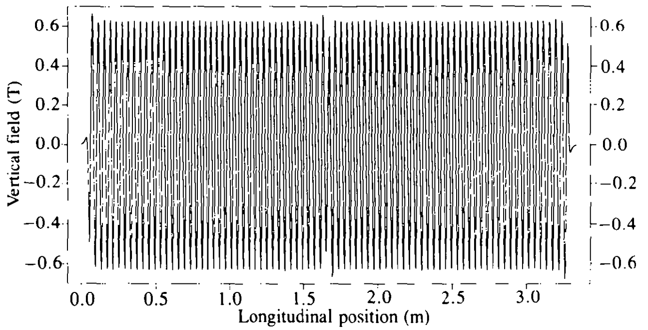

Figure 4

Measured field of two segments of 41 periods. The gap and period are 15 and 40 mm. The field modification introduced by the phasing section is clearly visible in the middle where extremes above and below the average peak field are recorded. The higher peak field compensates for the lower peak field to maintain a proper optical phase in the crossing of the phasing sections.

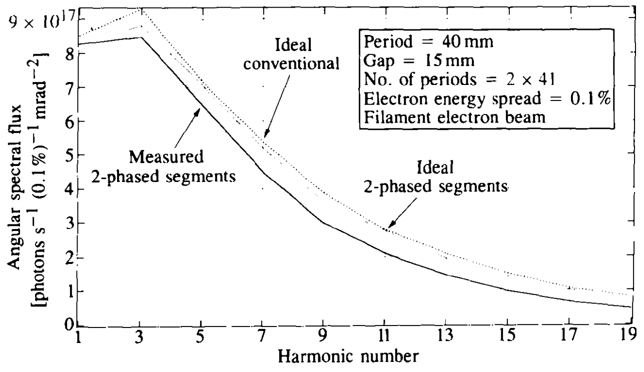

Figure 5

Angular spectral flux generated on-axis as a function of the odd harmonic number. The computation is made assuming a filament beam and a 0.1% electron energy spread. The gap is 15 mm. The curve labelled 'Measured 2-phased segments' is predicted from the measured field shown in Fig. 4. The curve labelled 'Ideal conventional' is a prediction from the field obtained from three-dimensional modelling of a single-piece undulator of the same physical length as the two segments. The curve labelled 'Ideal 2-phased segments' is a prediction from the field obtained from three-dimensional modelling of the phased segments.

The curve labelled 'Measured 2-phased segments' is computed from the measured field shown in Fig. 4. It is compared with two ideal devices. The curve labelled 'Ideal 2-phased segments' corresponds to a computation from the magnetic field of a three-dimensional modelling of the phased segments. The curve labelled 'Ideal conventional' corresponds to the field of a three-dimensional modelling of a single-piece undulator of the same physical length as the two segments but terminated in the conventional way as shown in Fig. 1. A small difference is noticed between the two 'ideal' curves. The phased segments are usually slightly below the conventional design depending on the harmonic number. This is due to the fact that one pole in each phasing section is not properly in phase with those of the undulators, resulting in constructive or destructive interference depending on the harmonic number. Nevertheless, the poles of the two undulator segments are properly phased with respect to each other. As a result, the average (maximum) reduction of the angular spectral flux is simply 1/*N* (2/*N*), where *N* is the number of periods per segment. It reaches 2.5% (5%) in our configuration. We have seen cases (specific gap and harmonic numbers) where the phased segments give 1 or 2% more flux than the

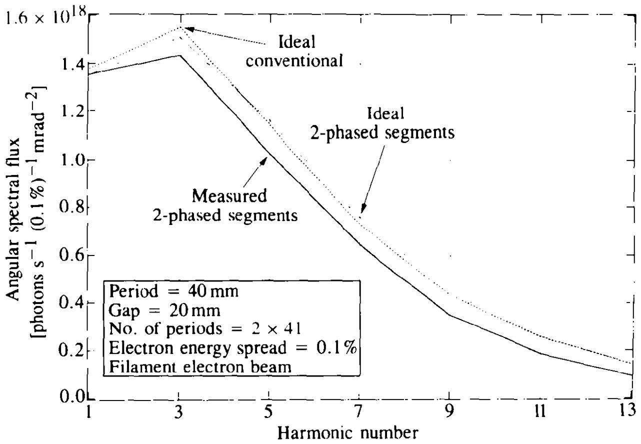

Figure 6

As Fig. 5 but for a gap of 20 mm.

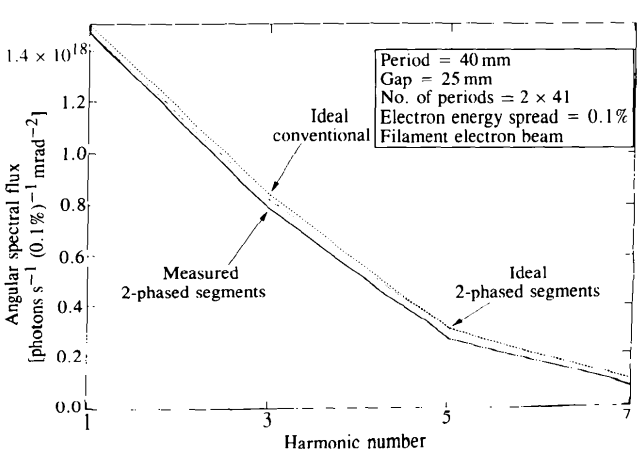

Figure 7

As Fig. 5 but for a gap of 25 mm.

conventional single-piece undulator. This can be explained by the fact that the phase of the last half pole of the conventional termination is not optimum for all harmonics. Note the smaller angular spectral flux obtained from the measured field as compared with the predicted one. The most important contribution to this discrepancy is related to the residual imperfect spectrum shimming present on one of the segments. [The first development of spectrum shimming was by Chavanne & Elleaume (1994); see also Chavanne & Elleaume (1995). A similar technique called phase shimming has been reported more recently by Diviacco & Walker (1996).] Figs. 6 and 7 present a similar comparison for magnetic gaps of 20 and 25 mm. We can therefore conclude that the consequences of such phasing sections on the undulator spectrum are negligible for all useful values of the magnetic gap.

An error in the longitudinal positioning of one segment with respect to the other induces a reduction of the angular spectral flux. Nevertheless, because of the choice of the asymmetric field configuration, the three-dimensional field computation predicts that a 2.8 mm mispositioning would result in the same distortion of the spectrum (20% reduction on harmonics 5) as that predicted for a conventional termination with a 1 mm spacing between segments. In practice, for a three-segment device, an accuracy of relative longitudinal positioning of 6 ± 1 mm is sufficient to maintain the angular spectral flux on harmonics 5 to better than 95%. The guideline used in the magnetic design is to separate the phasing sections as much as possible whilst keeping an almost ideal spectrum. The opening of such a 6 mm gap dramatically reduces the magnetic and mechanical interaction between each of the segments. The gap of each segment can be controlled completely independently. Fig. 2 presents the expected vertical field integral as a function of the gap of one undulator segment while the other stays at 15 mm. A good agreement is obtained between the measurement and the prediction by three-dimensional modelling. The maximum vertical field integral excursion is 32 G cm, obtained when the gap of the second segment is 40 mm. This is low and does not require any active electromagnet correction. A consequence of the independent gap setting of each segment is that one can phase undulators of the same or slightly different period, made with magnetic blocks, with slightly different magnetization or temperature response. The fine tuning will be obtained by maximizing the angular spectral flux recorded on the beamline.

Finally, one should mention another improvement with respect to the conventional termination related to the vertical field integral. Fig. 2 presents the field integral predicted for two segments, each one being symmetrical, which means that on any single segment the terminations have the same field polarity. It should be noted that the conventional termination results in a non-zero field integral for a gap of 15 mm while the proposed termination has zero field integral. This effect is (as discussed in the previous section) due to the permeability of the magnet blocks being slightly different from 1. In a sinusoidal periodic structure, the vertical field integral originating from such permeability cancels from one pole to the next except in the terminations. The conventional termination suffers from an imperfect cancellation of the field integral. In the proposed phasing sections, the terminations do not add any field integral at any gap value except those due to the interaction from one segment to the next, which have been reduced to 32 G cm.

4. Conclusions

We have described the benefits of using a new type of passive phasing section between undulator segments. The insensitivity of the spectrum combined with the large tolerance in the error in the longitudinal placement of the segments and the negligible magnetic interaction between segments makes such phasing sections very attractive for the manufacture of very long undulators for free-electron laser (FEL) or synchrotron radiation applications. For example, a 40 m long undulator with a period of 40 mm could be built from 20 segments and expected to give full performance on the fundamental of the spectrum assuming each segment is properly spectrum-shimmed. The spectrum shimming of the individual segments gives an almost ideal performance up to harmonics 21 of the spectrum. Phasing 20 of these segments by the proposed method results in an almost ideal performance on harmonics 1. Any temperature or small field gradient present along the structure can easily be compensated by a small adjustment of the gap of each segment without inducing any angle or displacement to the electron beam. These phasing sections can be viewed as a means of building a variable length undulator. The length is simply a multiple of the segment length. This is useful not only for FELs but also for high-energy synchrotron sources, which produce a tremendous heat load in the beamline. Currently, there are plans to make systematic use of these phasing sections at the ESRF.

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