Recent Advances in Insertion Devices

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ABSTRACT

The demand for more and better insertion devices (IDs) at new third-generation synchrotron radiation facilities has prompted significant advances in ID technology. Since the advances are being made at different laboratories around the world, an overview is given here of this progress. The focus is on those results that apply to IDs in general rather than to those from one specific ID or laboratory. The advances fall into two general categories: those that reduce the net effect that the ID has on the particle beam, and those that enhance the quality of the emitted light spectrum. The need for these advances, the factors that are most important in achieving them, and the current state of the art are discussed.

I. INTRODUCTION

Significant progress has been made in the field of insertion devices, particularly during the past three or four years, because of the construction and initial operation of third generation synchrotron radiation sources. New developments have been reported at recent PAC/EPAC conferences, Synchrotron Radiation Instrumentation conferences, and in review articles. [1-5]

In the late 1970's, the first insertion devices (IDs) were installed on first-generation synchrotron radiation sources. Their radiation properties were studied, and it was shown that IDs can be compatible with storage rings. [6] Ten years later, a wide variety of IDs occupied straight sections on almost all existing storage rings. With the advent of third-generation synchrotron radiation sources in the early 1990's, there has been a dramatic increase in the number of insertion devices (IDs) installed or planned worldwide, as shown in Fig. 1. These new storage rings may be designed to have ten times as many IDs installed as was typical for older sources. ESRF has been running for the past two years with more than a dozen IDs installed; it is the first machine so far to operate with so many IDs.

Fig. 1 also shows that undulators are increasingly preferred over wigglers. This is because many experiments today require very high brilliance. This high brilliance can be achieved without unnecessary power loads from unneeded wavelengths of light by using undulators, because high-quality undulators have very sharply-peaked emitted-light spectra. Recent significant advances in the ability to build and tune high-quality undulators have encouraged this trend. The magnetic field of an undulator can now be tuned so that the spectrum of emitted light has sharp and strong harmonic peaks out to very high harmonic numbers.

The magnetic field tuning techniques that have been developed not only ensure a high-quality spectral output, but also minimize the net effect that an ID has on the stored particle beam. This has become increasingly important with the newer small-emittance storage rings that have many IDs installed, since the cumulative effect of all the installed IDs must be considered.

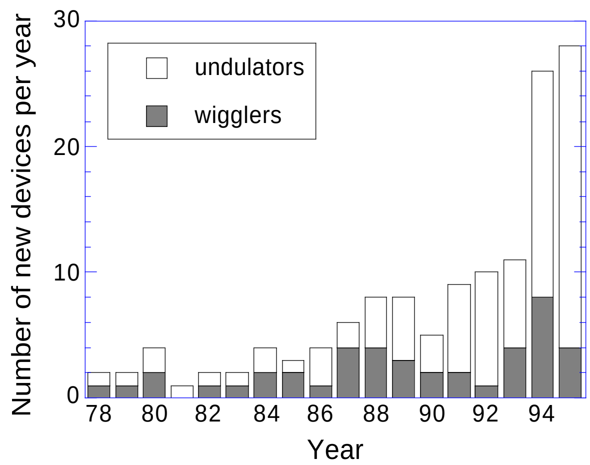

Figure 1. Number of new insertion devices constructed per year, worldwide, from 1978 to 1995. (This does not include free-electron lasers.)

Of the many IDs [3] that have been built or proposed, some are optimized to produce specific radiation characteristics, such as variable polarization. Other IDs have particularly short or particularly long period lengths. Some of these special IDs have been installed on older synchrotron radiation sources, where they can produce useful light and also serve as prototypes for IDs for newer storage rings.

In what follows, we will discuss recent progress in both reducing the net effect that IDs have on the stored particle beam and in tuning IDs for high-quality spectral output.

II. ID-STORED BEAM INTERACTION

Insertion devices that are installed into storage rings can have undesirable net effects on the closed orbit in the ring. Such effects have been a major concern since the first insertion device was installed into a storage ring [7]. In addition, IDs can cause betatron tune shifts, decreased beam lifetime due to dynamic aperture changes, and vertical-horizontal coupling. In first and second generation sources, various local and global feedback schemes were used to correct closed-orbit distortions. [8, 9]

The requirements of new third-generation sources are more stringent, however. The emittance of the stored particle beam and the physical aperture of the beam are smaller, so that allowable ID-related orbit distortions are smaller. This smaller allowable effect is distributed among a much larger number of insertion devices, making the requirements for each individual ID more demanding.

Orbit distortions are also, in general, a strong function of the magnetic gap of the insertion device. An undulator needs to have its gap changed whenever its user wants a different photon energy. With an increase in the number of undulators on a storage ring, there is also an increase in the frequency of gap-change requests. Users of the synchrotron radiation facility rapidly lose patience with "orbit correction" interruptions or beam instabilities that are due to gap changes in someone else's ID. Third-generation storage rings therefore demand IDs that are "fully compensated", i.e., that have negligible effect on the stored beam at any magnetic gap.

Orbit perturbations can be limited by setting maximum values for the first and second integrals of the magnetic field through the insertion device, and by setting maximum values for the higher order integrated magnetic moments (i.e., how the first integral of the field varies as one moves away from a line through the exact center of the ID). The first field integral through the ID determines the angle between the pre- and post-ID trajectories of a particle, while the second field integral determines the displacement. The maximum allowed first and second integrals can be chosen using the following expressions so that the effect of the ID is much less than the beam emittance:

$$\frac{\int B_{x,y} dz}{B \cdot \rho} << \sqrt{\frac{\varepsilon_{y,x}}{N \cdot \beta_{y,x}}}$$

$$\frac{\int\int B_{x,y} dz'\, dz}{B \cdot \rho} << \sqrt{\frac{\varepsilon_{y,x} \cdot \beta_{y,x}}{N}}$$

where $B_{x,y}$ is the horizontal or vertical magnetic field, $B \cdot \rho$ is the rigidity parameter for the storage ring, $\varepsilon_{y,x}$ is the vertical or horizontal emittance, $\beta_{y,x}$ is the vertical or horizontal beta function, and N is the number of IDs on the storage ring. Table 1 shows the first and second integral tolerances for the APS storage ring.

Table 1. APS Insertion Device Tolerances

Quantity	Normal	Skew
First integral (G-cm)	20	20
Second Integral (G-cm^2)	20 000	20 000
Quadrupole (G)	50	50
Sextupole (G/cm)	200	100
Octupole (G/cm^2)	300	50

These same requirements for beam size stability also determine the maximum allowed integrated quadrupole moments. Requirements for higher moments that affect the dynamic aperture can be determined by using storage ring tracking codes [10] to evaluate the effect of these moments. The integrated multipole tolerances for the APS storage ring are included in Table 1. In general, however, these numbers depend on the good field region required for the ID because the higher order moments are a description of how the field integral varies as the line of integration is moved laterally within the good field region. Typical good field regions are less than a few centimeters horizontally and less than a centimeter vertically.

A number of different ID designs and fabrication techniques have been tried in order to meet these challenging magnetic field quality requirements. At some labs, the approach has been to demand very high mechanical and magnetic precision for everything that goes into an ID and to sort the magnets very carefully, with the goal of producing a device whose field is so good that it needs no post-assembly shimming. [11] At other labs, inexpensive components have been a greater priority. The magnets are carefully sorted, but large field errors remain after assembly. Much work then goes into magnetic shimming in order to achieve a high-quality field. [12, 13]

In order to be able to measure the properties of IDs sufficiently precisely, the accuracy and reliability of magnetic measurements has had to improve. New techniques and improved old techniques now make the necessary measurements possible [14]. For example, first field integrals through a 5-meter-long ID are now measured with a reproducibility of less than a Gauss-cm, as required for accurate higher-order multipole measurements.

There is now a better understanding of how to suppress magnetic moments, both by maintaining high tolerances during the selection of magnetic materials and during fabrication, and by using shimming techniques to correct the effects of imperfections in an assembled device. Impressively small ID magnetic moments have been achieved. In Table 2, experimental results for an ESRF and an APS planar ID are shown.

Table 2. Multipole moments achieved [15]

Moment	at ESRF	at APS
Dipole (G-cm)	<20	15
Quadrupole (G)	<10	20
Sextupole (G/cm)	<10	40
Octupole (G/cm^2)	<10	10

For non-planar IDs, such as sources of elliptically or circularly polarized radiation, magnetic tuning is even more challenging. Nevertheless, two such devices — the helical undulator Helios [16] and the Elliptical Multipole Wiggler (EMW), which has an AC electromagnet [17] — have been successfully operated at ESRF and NSLS, respectively. In Helios, the vertical positions of the upper and lower jaws can be moved independently (one jaw produces a vertical field, the other a horizontal field), and a relative longitudinal displacement is possible. The polarization and wavelength are altered by moving the magnetic arrays so as to change the 3-D magnetic field distribution. In the EMW, the horizontal field component from the electromagnet changes at frequencies of up to 100 Hz so that a dynamic compensation system is required. For both devices, however, the closed orbit displacements are negligibly small. For Helios, the closed orbit distortion was less than 6 μm, and for the EMW it was less than 1 μm.

The few examples above show the substantial progress that has been made in minimizing the effects that IDs have on a storage ring. The next goals are to eliminate the need for a local feedback system and, once it has been demonstrated that a gap change will have no effect on other beamlines, to allow synchrotron radiation users to change their ID gaps freely.

III. ID SPECTRAL PERFORMANCE

Magnetic field errors also affect the spectral performance of an undulator. Errors can arise from such things as non-uniformities in the magnetic properties of the materials used and finite mechanical tolerances on the magnetic structure components. The effect of these errors on the spectrum of the undulator is to decrease the brilliance of the harmonic peaks. Higher harmonics suffer greater decreases than lower harmonics. Therefore, the spectral quality of an undulator can be defined by how close the brilliance of the emitted spectrum is to than of an ideal undulator.

The real test of spectral performance for an undulator is, of course, measurement of the absolute flux of radiation emitted as a function of frequency. Even before the device is installed in the storage ring, however, its performance can be predicted from magnetic field measurements. The magnetic field map is used to calculate particle trajectories through the undulator and, in turn, the brilliance of the light that will be emitted as a function of wavelength.

It has been shown that the best predictor of brilliance reduction is the rms value of the phase error [18]. Walker [19] showed the quantitative relationship between the two. Phase error arises from differences in the time intervals between successive wiggles in the particle trajectory. The real trajectory is calculated from measurements of the magnetic field along the undulator. The phase in this real trajectory is then compared with the phase for an ideal undulator to obtain the rms phase error, which is in turn used as a figure of merit for optimizing the undulator magnetic field. Walker [19] found that the decrease in brilliance compared with the ideal case varies like exp $(-(n\cdot\phi)^2)$,where n is the harmonic number and ϕ is the phase error.

In order to optimize the undulator magnetic field, the magnet blocks are carefully measured, then sorted into an arrangement that will give as perfectly periodic a field as possible. For a hybrid undulator that uses high-permeability pole pieces, the poles can be sorted by size as well. Once the undulator is assembled, it can be shimmed to correct the field integrals, the moments of the field integrals, and the trajectory as a function of undulator magnetic gap. Shimming is also used to minimize the phase errors. The typical result is an rms phase error of several degrees, leading to a reduction in the fifth harmonic brilliance of about 20%. Post-assembly shimming along the ID has not been used much during ID fabrication at ALS, nor is it planned to be used at BESSY II. Nevertheless, very impressive performance results have been achieved by careful selection and sorting of magnets and by maintaining extremely tight mechanical tolerances in the magnetic structure. Some of these results are shown in Fig. 2. [20] Fig. 2 shows the on-axis flux measured from the ALS U8.0 undulator at K=5.24, along with the flux calculated from the measured magnetic field. For comparison, the flux density calculated for an ideal ALS U8.0 magnetic field is also shown. The harmonics shown start at the 18th.

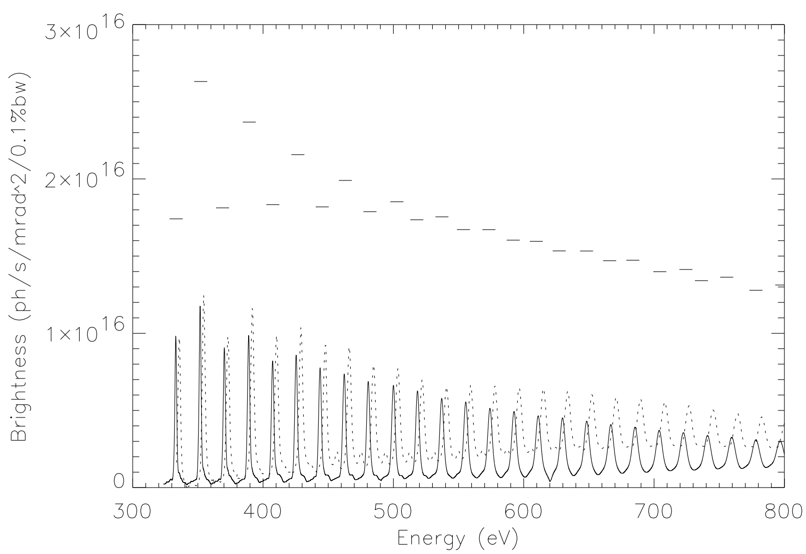

Figure 2. High-harmonic flux from the ALS U8.0 undulator at K=5.24. The dotted line shows the flux measured from the installed device. The solid line shows the flux calculated from the measured magnetic field. The calculated peak flux values from an ideal U8.0 magnetic field are also indicated by the dashed lines. The harmonics shown start at the 18th.

Recently, a phase-shimming technique was used to achieve rms phase errors of less than a degree. This small phase error leads to the 20% reduction in brilliance not occurring until about the 27th harmonic. [21] Similar results have been achieved at ESRF using their 'spectral shimming' technique. At ESRF, radiation from harmonics up to the eleventh will be used. These techniques have both been applied to pure permanent magnet IDs. At APS, a phase-shimming approach has been used to optimize the spectrum of a hybrid undulator. The phase errors were reduced to 4°, which corresponds to a seventh harmonic brilliance of about 80% of ideal.

With these advances, undulators are now being built whose spectral performance is very close to what is theoretically possible. Future effort will probably be directed towards the development of specialized IDs.

Many different types of advanced IDs have been described in recent papers. Third-generation storage rings still have many straight sections that are as yet unoccupied by IDs. Therefore, a wide and long (particularly at Spring-8, with its 30-meter-long straight sections) field is open for future developments that will also benefit the fourth-generation synchrotron radiation sources.

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