Magnetic Field Tolerances for Insertion Devices on Third Generation Synchrotron Light Sources*

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Abstract

The nearly four orders of magnitude increase in brightness expected for insertion device (ID) x-ray sources on the next generation low-emittance synchrotron facilities will have a tremendous impact on many areas of research. However, in order to deliver the expected performance, the IDs will need to satisfy stringent magnetic and mechanical requirements. Errors in real devices affect both the spectral performance and storage ring. For example, one source of random magnetic field errors relating to the peak field in the device has a direct effect on the peak spectral brightness of undulator harmonics. Other errors result in with the higher moment fields (sextupole, quadrupole, etc.) in the device which can effect the performance of the low-emittance storage ring. Both effects are discussed in terms of the next generation synchrotron facilities.

1. INTRODUCTION

The next generation of low-emittance high-brilliance for synchrotron facilities such as the 7-GeV Advanced Photon Source (APS), 1-2 GeV Advanced Light Source (ALS), the European Synchrotron Radiation Source (ESRF), and SPring 8 (Japan), etc., will have insertion device undulator and wiggler x-ray sources with unique spectral properties. These properties will open new possibilities for scientific research in essentially every area of science and technology. Existing and new techniques utilizing the full potential of these sources, such as their enhanced spectral coherence, unique polarization properties, and high spectral brilliance, will permit experiments not possible with existing sources.

The enhanced performance predicted for ideal undulator sources on the low-emittance rings over that on present synchrotron sources is, in most cases, remarkable, and a considerable amount of effort has been spent over the past years to understand the spectral properties of these devices. During this time, it has become clear that the performance of actual devices will depend not only on the quality of the low emittance particle beam, but also on the achievable magnetic and mechanical tolerances. In addition, the error fields for real devices may introduce deleterious effects on the storage ring and, as a consequence, indirectly affect the undulator spectral performance.

In general, the magnetic field quality or tolerance for actual devices is determined by the storage ring requirements and the acceptable spectral performance. In the following, a summary of these tolerance requirements for typical planar permanent magnet undulator IDs on the new third generation synchrotron facility storage rings is presented. In addition, some recent results for APS prototype undulators are discussed.

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The major emphasis of this article is to identify the sources of magnetic field errors in real IDs and to describe the effects of these errors on the spectral performance of the device and on the storage ring.

2. CHARACTERISTICS OF IDEAL PLANAR IDs

A. Baseline Spectral Properties

Both undulators and wigglers are composed of magnet arrays in a planar geometry that set up a spatially oscillating magnetic field along the length of the device [1,2]. These arrays can either be made up of permanent magnets, with or without high-permeability steel poles such as vanadium permendur, or electromagnets. For the new low emittance storage rings with ring energies between 1 and 8 GeV, the majority of IDs have periods less than 20 cm in order to achieve the required spectral energies. This is the optimum range for permanent magnet structures. In almost all cases, rare-earth-transition metal magnets, especially Nd-Fe-B, are used because of their enhanced field strength. The magnetic structures of a pure permanent magnet (PPM) and a hybrid device with vanadium permendur poles are compared in Fig. 1. In both cases, the vertical component of the magnetic field along the z-direction of the ID varies periodically with a period λ_0. For the PPM ID, the field variation along the centerline of the midplane is nearly sinusoidal. For the hybrid structure, the field has higher harmonics determined by the detailed structure of the pole and magnet array.

The slope angle for the sinusoidal field is $\theta = K/\gamma$, where γ=1957 E_r , and E_r is the ring energy in GeV, and K is the deflection parameter given by $K = 0.934\lambda_0(cm)B_0(T)$, where B_0 is the peak magnetic field. In the undulator regime, defined by $K \sim 1$, interference effects occur within the synchrotron radiative opening angle, $\psi=1/\gamma$, which cause spatial and frequency bunching of the radiation. This gives rise to the typical undulator spectrum consisting of narrow bands of radiation called harmonics.

In general, the spatial distribution of the radiation is complex [3]. Near a harmonic energy, however, it consists of a central radiation cone combined with structure off-axis. For a single particle, the radiative source size and divergence of the central radiation cone of the nth harmonic depend on the wavelength, λ_n, and the length, L, of the undulator, and are given by:

$$\sigma'_r=(\lambda_n/L)^{1/2} \qquad \text{and} \qquad \sigma_r=(1/4\pi)(\lambda_n L)^{1/2},$$

respectively.

In both ID structures, the spectral properties depend on the trajectory of the particle beam through the device which in turn depens on the magnetic field and the magnetic period of the device.

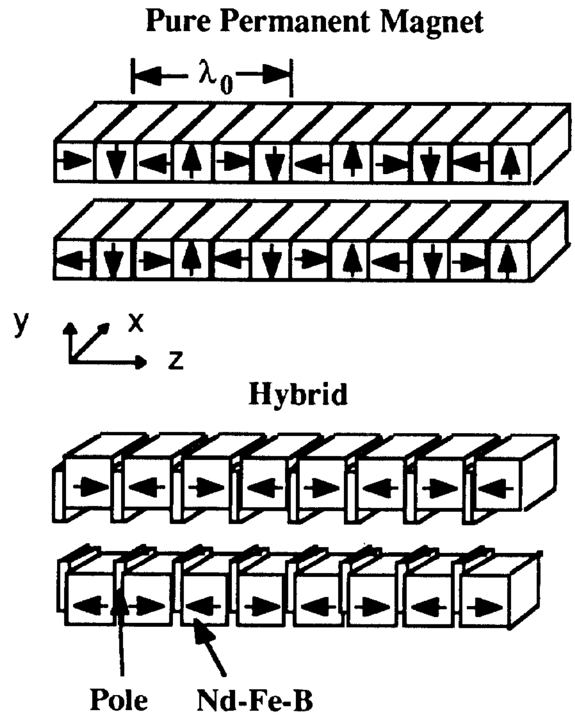

Fig. 1. A pure permanent magnet structure with four magnetic blocks per period compared to a structure with steel poles with approximately the same period.

The spatial and angular distribution of the stored particle beam determined by the emittance will affect the undulator spectral properties most severely. The particle beam distributions are approximately Gaussian and given in terms of the beta functions, β_x and β_y, at the undulator location in the lattice and the storage ring emittance, ε_x and ε_y. For the i=x,y directions, the particle beam size, σ_i, and divergence, σ'_i, are given by:

$$\sigma_i = (\varepsilon_i\beta_i)^{1/2} \quad \text{and} \quad \sigma'_i = (\varepsilon_i/\beta_i)^{1/2}.$$

The effective radiative source size, Σ_i, and divergence, Σ'_i, in the i=x and i=y directions is given approximately by the convolution of the natural single particle source parameters and the particle beam parameters, and

$$\Sigma_i = ((\sigma_i)^2 + (\sigma_r)^2)^{1/2} \quad \text{and}$$
$$\Sigma'_i = ((\sigma'_i)^2 + (\sigma'_r)^2)^{1/2}.$$

For third generation storage rings, natural emittances, ε, on the order of of ~1 nm rad will be achieved. Assuming a coupling of ~ 10% between the vertical (y) and horizontal (x) emittances, the magnitude of σ'_y and σ_y are on the order of ~ 5-10 μrad and 50-100 μm, respectively. This is to be compared to the natural radiative opening angle and size of the undulator photon beam, which depends on the x-ray wavelength of the harmonic chosen. For soft x-ray devices with harmonics in the range of 100-1000 Å, the natural undulator source divergence dominates. In the harder x-ray region, the source emittance effect becomes important near 1 Å radiation.

The energy of a given undulator harmonic, n, is given approximately by:

$$E_n(\text{keV}) = 0.949\, nE_r^2(\text{GeV})/((1+K^2/2+\gamma^2\psi^2).\lambda_0(\text{cm}))$$

The natural energy band width is given by $\Delta E/E = 1/(nN)$, where N is the number of magnetic periods in the device. The bandwidth, ΔE, corresponds to an angular divergence, $\psi \sim \sigma'_r$. This natural energy band width is increased by particle beam parameters such as the emittance and energy spread. For a given storage ring, the baseline energy width will require numerical calculations that take into account the actual angular acceptance and the particle beam emittance. For perturbations that are not much larger than the natural undulator angular width σ'_r, the contributions to the energy spread, ΔE/E, of the harmonics from the particle beam divergence is given approximately by:

$$\Delta_i = (\sigma'_i\gamma)^2/(2(1+K^2/2))$$

where i=x,y. The energy spread of the particle beam will also contribute to the energy width of a harmonic.

The on-axis spectral brilliance, BL0 (sometimes referred to as brightness), in photons/(s 0.1%BW mm^2mrad^2) is defined as:

$$BL0 = F/(4\pi\Sigma_x\Sigma'_x\Sigma_y\Sigma'_y)$$

where F is the total flux at a given photon energy in a fixed band width (BW).

These intrinsic spectral properties of undulator radiation including emittance define the baseline performance of ideal devices for different storage ring conditions. This baseline is a convenient one from which to discuss the effects of magnetic field errors on the performance of real devices. One of the effects of particle beam emittance is to complicate the mathematical description of the effects of field errors of real devices on the spectral properties. For some types of errors such as phase errors discussed later, the spectral properties dcan be described approximately by a Gaussian convolution of the error field distribution with emittance. For steering errors, it is not clear whether this approximation can adequately describe the combined effects of error fields and emittance and numerical calulations using the actual magnetic field may be required.

B. Effect on Storage Ring

From the point of view of the storage ring, a perfect undulator with infinite width and plane poles will show some degree of vertical focusing of the particle beam [4]. This focusing is associated with the variation of the magnetic field from the device centerline in the midplane to the pole face and the transverse component of the particle trajectory. For a field with a sinusoidal dependence along the length of the undulator, this focusing is equivalent to a quadrupole component of the magnetic field and results in a tune shift of the storage ring. It is the smallest possible perturbation achievable with a device. The quadrupole component depends approximately on the square of the ratio of the peak field to the ring energy and is more important for high field devices in low energy storage rings. Non-linear octupole-like terms are also present. The sextupole term vanishes over one period.

There is no net steering given by $\int B \cdot dz$ in one period length of a perfect ID because of the periodic variation of the field. A net steering will occur for configurations of poles in which the net number of periods is a half integer. No net particle beam offset occurs through the device except in this case.

3. PERFORMANCE OF REAL UNDULATOR DEVICES

A. Sources of Magnetic Field Errors

As mentioned, the spectral properties of a given ID on a particular storage ring depend exclusively on the trajectory of the particle beam through the device. For planar devices, which is the focus of this article, the magnetic field is determined by the array of magnetic elements. The field variation along the length of the device for the hybrid structure can have odd harmonics of the field higher than the sinusoidal dipole term. The magnitude of these harmonics can usually be kept below 10% of the main sinusoidal field by appropriate choice of the pole dimensions. Optimization is required since the peak field also depends on the pole thickness. As mentioned, the variation of the magnetic field along the z-direction for a PPM ID is nearly sinusoidal.

For undulators, the presence of higher field harmonics affect the relative intensity and position of the energy harmonics of the device. For wigglers, they will modify the spatial distribution of the photons. These effects cannot really be considered as associated with magnetic field errors since the degree of purity of the fundamental can be controlled in most cases.

Real errors in the magnetic field of both PPM and hybrid IDs arise from several sources. One is the mechanical construction tolerances achieved in the fabrication of the device. These errors involve placement tolerances of pole pieces and magnets, as well as dimensional tolerances on the assembly or backing beams. A second source of field errors is orientation errors and block to block variations of the net magnetic moment of the permanent magnet blocks used in the construction of the device. Finally, the magnetic block can have inhomogeneities in the moment distribution that can be different for different blocks. All of these factors will give rise to magnetic field errors that have both a random and a systematic component. They introduce both particle beam steering, trajectory distortions, and focusing effects in both the vertical and horizontal directions. As a result, they affect the spectral properties of the undulators and the performance of the storage ring

These sources of errors should be distinguished from size effects in real undulators. In general, one predicts the magnetic arrays assuming IDs with infinite width so that the fields are two dimensional. Finite width effects for real devices can be estimated from either experimental results [5] or model calculations (6). In general, the width of a given ID requires optimization in order to maintain magnetic field quality and roll-off in the horizontal (x) direction. This roll-off for an error-free device, results in horizontal focusing as was the case for the vertical focusing as well as other non-linear terms. The width of the magnet and pole array can be readily controlled in order to achieve the price-performance criteria required.

Of the real error sources mentioned, the block properties are the most crucial in determining the final ID performance. In the initial stages of permanent magnet ID development, pure permanent magnet arrays were used to achieve the required field. In this case, the magnetic system is nearly a linear medium since the permeability of the magnet is approximately equal to 1. As a result, the quality of the resultant magnetic field depends directly on the quality of the blocks used in constructing the magnetic array. This means that, ultimately, the field quality depends on the materials properties of the magnets. In principle, this requires very tight fabrication tolerances on the magnetic properties of the blocks and careful sorting [2].

The hybrid structure, on the other hand, offers the advantage that, in principle, the magnetic field is achieved by exciting a steel pole such as vanadium permendur by permanent magnet blocks. The maximum flux in the steel pole should be kept below the saturation level and consequently the magnetic properties depend less on the detailed material properties of either the block or the pole. In addition, a certain amount of error cancelation is expected since the same magnet block excites poles of opposite sign. In actual fact, as will be discussed, the magnetic field errors and performance in both high quality PPM and hybrid structures devices required for the next generation IDs depend to some extent on the permanent magnet block properties in similar ways.

Presently, the fabrication of the Nd-Fe-B blocks that are used in the production of high quality, high field IDs involves a three step process consisting of orientation, pressing, and sintering of fine powder. Isostatic pressing of the magnet in the applied field produces the best performance and most uniform magnets. It also has the highest production cost. In addition, the dimensional tolerance and direction of the moment are more difficult to control because of the lack of a well-defined datum surface.

The bulk magnet properties depend on the average direction of the net moment and the uniformity of the magnetic moment distribution through the block. A perfect set of blocks will all have the same magnitude of the net moment and in the same orientation relative to some specified direction. For real blocks, orientation and magnitude errors in the magnetic moment occur. In the case of a hybrid magnetic structure, orientation errors can give rise to excitation errors in the pole adjoining the magnet since only the perpendicular component of the moment from the block's surface is important. The orientation can also cause a non-zero component of the field on the bottom face of the magnet that can affect the midplane field and zero crossing. In the PPM structure, they contribute directly to the field errors of the device. Errors such as these require careful measurement of the block moment and orientation with a Helmholtz coil arrangement, for example. Once measured, the data can be used in a sorting algorithm to properly select and distribute the errors over the body of the ID.

Block errors much more difficult to measure are associated with non-uniformities in the moment distribution. For the hybrid structure, they are suppressed away from the midplane. They are detrimental, however, on or near the surface of the block facing the particle beam near the zero crossing of the field, since they add net steering of the particle beam and contribute in a random way to the field error of the device.

An additional factor for the Nd-Fe-B magnets is the temperature behavior of the magnetic moment. Because of their lower magnetic transition temperature, the magnets have a larger temperature coefficient than the cobalt-based alloys. Representative data for the temperature variation of a typical Nd-Fe-B magnet used in the construction of IDs shows a relative variation of the magnetic moment of the block of approximately 12 parts in 10^4 per °C. For the undulator, this translates into a systematic variation in the K-value and, hence, the harmonic energy. The harmonic energy variation of the undulator with respect to the magnetic field corresponds to:

$$\Delta E/E=-(K^2/(1+K^2/2))\Delta B/B.$$

For a K-value of 1, the temperature variation in B results in approximately the same magnitude shift in the harmonic energy. This should be compared with the width of the harmonic, which depends primarily on the number of periods, the harmonic, the emittance of the storage ring, and the limiting apertures of the experiment. For a hundred-period device, the variation in the energy caused by a 1 °C change in temperature corresponds to approximately 1/10 of the natural bandpass ($\Delta E/E$) for the 3rd harmonic with no emittance.

For the wiggler, the temperature variation in the moment will result in the same magnitude shift in the critical energy of the device.

B. Effect on Spectral Properties

In a perfect ID with infinite width, the magnetic field can be completely described in terms of a unique peak field and magnetic period. The errors mentioned above introduce both systematic and random variation in the field. In the simplest picture, the field is assumed to be described by a peak field B_0 plus an error field ΔB_i, which depends on the pole considered. As an approximation, the error fields are assumed random with a Gaussian distribution.

Kincaid [7] did the pioneering work of predicting the effect of random non-correlated errors on the spectral properties of undulators. There are two effects resulting from field errors distributed in the device. The first is that the net steering of the particle beam through the device will not be zero. Each pole will contribute steering due to the error field of $\int \Delta B_i dz$. An example of the steering introduced by a 1% difference in a peak field at a given pole is shown in Fig. 2 As can be seen, the error field will cause a kick in the particles trajectory angle and result in a displacement.

Such displacements are detrimental if the magnitude of the kick angle is larger than the intrinsic divergence of the undulator given in Section 2. For the case of a zero-emittance particle beam, this can be shown [8] to result in an allowable integrated dipole field error of < $1704/N^{1/2}$G-cm. This, in effect, is equivalent to maintaining steering kink to within the natural divergence cone of the undulator.

With emittance, the kick will depend on the divergence of a given particle in the beam and, as a result, an analytical convolution of the beam emittance effects and fields causing steering is not possible. Full numerical calculations are required.

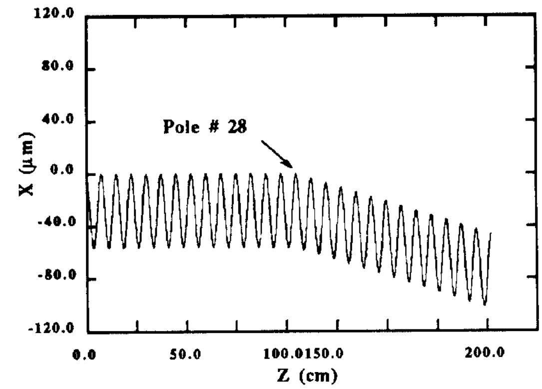

Fig. 2 Steering caused by an 1 % increase in a pole for a hybrid structure with a peak field of 0.46 T and period of 7.5 cm.

The error field, ΔB_i, also contributes to a phase error associated with the difference in the time the particle spends in each pole region. This phase error exists whether steering is present or not and introduces statistical fluctuations in the photon pulse trains and, for the undulator, results in a loss of intensity and broadening of the harmonic. For small steering errors (<0.5%), the phase errors can be convoluted with the emittance to obtain the combined effect. In general, however, calculations for the specific error field distribution are required if the performance is to be predicted accurately. Numerical calculations [9] have shown that the degradation not only depends on the error field but also on the detailed distribution. In any case, random field errors will be less than 0.5% in most cases for the new storage rings [10]. Table 1 shows typical values achieved for an APS prototype undulator installed on the VUV ring at the National Synchrotron Light Source. Also shown are field requirements expected for the undulators at the APS. Similar results have been obtained for a 3.3 cm period prototype undulator.

Table 1. Measured parameters of the APS prototype undulator at a minimum magnet gap of 34 mm.

	Measured (NSLS)	APS
Period	7.5	-
Number of Periods	27.5	-
Minimum Gap (mm)	34.0	10
Peak Field (kG)	4.60	-
$(\Delta B/B)$rms (%)	0.22	0.3
Gap Resolution (µm)	4	2.5
Transverse Rolloff (%) in ±1cm	0.1	0.1
Steering Error (G-cm)	13	<100
Integrated Quadrupole (G)	7	<40
Skew Quadrupole (G) <	10	<20
Integrated Sextupole (G/cm)	60*	<100

Both the steering and phase errors effects are the result of field errors, which depend on several parameters. First, they depend on the mechanical tolerances of the pole and magnet placement and pole shape. Variations in the effective gap between poles, for example, can result in variations in the magnetic field. The mechanical tolerances on pole and magnet placement and dimensions are between 20 and 100 μm for third generation IDs [11,12]. Field errors are also associated with magnet block properties. Upper limits on moment distributions and orientation errors are on the order of 1% and 1 degree. These values, combined with the required remanent field, B_r, and the third quadrant behavior of the coercive force, H_c, are stringent specifications for the Nd-Fe-B magnet blocks. Limits on the inhomogeneities are under investigation and attempts to measure surface fields are in progress [13].

C. Effect of Errors on Storage Ring

As mentioned, a perfect ID with a finite width will show both horizontal and vertical focusing of the particle beam. In general, the y-component of the field, B_y, can be given as a series expansion:

$$B_y(x,y=0,z)=B_y(x=0,y=0,z)(1+Qx+Sx^2+...)$$

where Q is the quadrupole and S, the sextupole component. The full quadrupole field involves both x and y as well as a skew component with principle axes rotated by 45°. The skew quadrupole mixes x and y and results in a larger coupling constant and, hence, vertical emittance. The sextupole component involves terms like x^2-y^2 and xy. In a real device, the multipoles result from errors in the magnetic structure. The quadrupole, for example, is the result of pole canting errors. For a hybrid device, the B_x component is suppressed at the pole surface resulting, in principle, in a reduced skew quadrupole.

Of interest to the performance of the storage ring is the integrated multipoles over the length of the ID within some specified good field region of the device. The acceptable values depend on the sensibility of the storage ring to the ID, and its ability to correct the effects of the higher moments. Since many IDs will be installed on the new rings, the combined perturbation to the lattice must be considered.

Measurement of the integrated multipoles by scanning point probes or rotating coils are difficult and require in many cases, a precision slightly beyond the state of the art. Measurements of these moments using the storage ring for the APS 7.5 cm prototype undulator are in progress. For an earlier APS prototype device with a 3.3 cm period and 2 m length installed on the Cornell High Energy Storage Ring operating in a special low-emittance mode, the moments determined by the storage ring measurements were consistent with magnetic field measurements. Correlations of this type are necessary if reliable predictions concerning the performances of IDs on the new storage rings are required.

For the case of the APS, the values of the integrated moments are given assuming 34 devices on the storage ring. The values are within the correction capabilities of the magnets within the lattice. Only the sextupole component is significantly different with a value of 0.5 T/m compared to 1 T/m for the APS.

The origin of the higher moments for real devices is still under intense scrutiny. Both the sextupole and skew quadrupoles require further evaluation for the hybrid structure where suppression of the moments should occur. This is most likely the result of the detailed spatial distribution of the error field near the surface of the magnets.

A new three dimensional model that treat these effects has recently been developed [13]. If successful, the model will permit the prediction of higher moments and error fields from localized perturbations in the magnet block.

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