OVERVIEW OF HOT TOPICS IN INSERTION DEVICE DESIGN

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Abstract

Emphasis in insertion devices (undulators and wigglers) is evolving. Conventional designs account for the majority of devices in use as synchrotron radiation (SR) or free-electron laser (FEL) sources, but more is being demanded with each succeeding application. Totally passive field compensation, gap independence, and the perfecting of phase and spectral properties are areas of major interest. However, the shift toward specialty designs is increasingly important. Designs are tailored to achieve specific radiation characteristics. These range from SR sources with time-dependent polarization capabilities to long devices optimized for FEL operation in the X-ray regime. Strong focusing and other beam dynamics related characteristics are becoming extremely important for the next generation of FEL devices. As electron beam quality continues to increase, small-gap, small period, and unconventional field profiles are becoming necessary for compact sources. These areas of increased interest are examined.

1 INTRODUCTION

Since the last Particle Accelerator Conference in 1995 more than 140 papers concerning insertion device technology have been published [1]. As the recent literature is examined in detail, emphasis in insertion device work can be grouped into two broad categories. The areas can be referred to as conventional devices and specialty devices. This paper, being part of the section on magnet technology, will stress those devices that fall into this technology area. Wigglers and undulators based on plasma waves [2], electromagnetic waves including lasers [3], etc., are beyond the scope of this paper and will not be discussed.

2 CONVENTIONAL DEVICES

Conventional devices can be defined as those whose technology and geometry have been previously demonstrated and consistently implemented. Recent work in this area has emphasized improved performance characteristics from both spectral and beam dynamics aspects. There are three general technology areas that fall into this category: permanent magnet (PM), superconducting (SC), and electromagnet (EM) technologies.

PM technology has become the "workhorse" of insertion devices and accounts for the vast majority of devices being integrated at this time. Both pure-PM [4] and hybrid [5] (containing soft permeable material) are being regularly used. Improvement of spectral properties has been a major concern as more operational experience at major synchrotron radiation facilities continues [6-10]. Delivery of undulators with 1–2 degrees of optical phase error are becoming standard [11]. Passive compensation of undulators has become a major topic with an emphasis on gap independence while preserving good-field region. Illustrative of this is work done recently at STI [12]. Whereas, powered electromagnet coils were often used in the past, work has progressed so that by adjusting the final two magnets in a hybrid device a trajectory with near zero displacement from the axis results from entrance and exit field contributions. This has been achieved without loss of periods contributing to useful radiation or FEL interaction. Figure 1 plots the measured second integral of the field (proportional to the trajectory) of several gaps showing the lack of displacement from the axis over a wide range of gaps. The undulator is the APS U55#13, a 55-mm period hybrid device. By contrast, an "ideal undulator," one with a perfect sine wave and half amplitude first kick, produces an entrance offset proportional to 80% of the wiggle amplitude. Such enhancements simplify the integration of insertion devices for both SR and FEL applications.

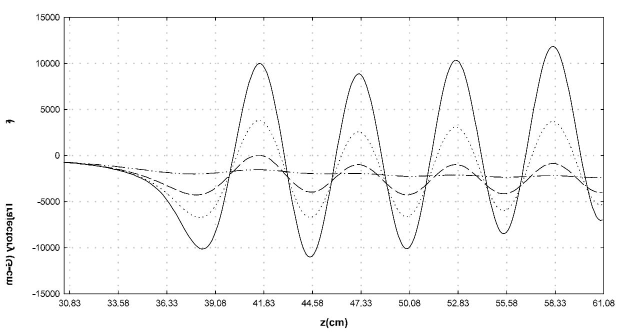

Figure 1: Entrance trajectories measured at several gaps for the APS U55#13 showing the gap independent zero-displacement configuration.

Another area that has received attention during the interim between conferences is the effect of ambient fields on performance. Magnetic performance has improved to the point that ambient field interaction is now a consideration. Pure rare-earth permanent magnet (REPM) devices are essentially transparent to ambient fields as the differential permeability of fully polarized REPM is only μ = 1.05. The presence of highly permeable material in hybrid devices, on the other hand, changes the characteristics of the ambient field as the gap

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is changed. The poles enhance the component of the ambient field that is in the principal field direction. The poles effectively shunt the ambient cross-field component. Figure 2 plots the relative enhancement of gap dependence of the change in the ambient field caused by a hybrid device. At minimum gap, the principal moment is increased by a factor of ~1.8 and the cross-field component is effectively shunted to zero. In addition to measurements this behavior has been confirmed in operational experience at APS and ESRF [13].

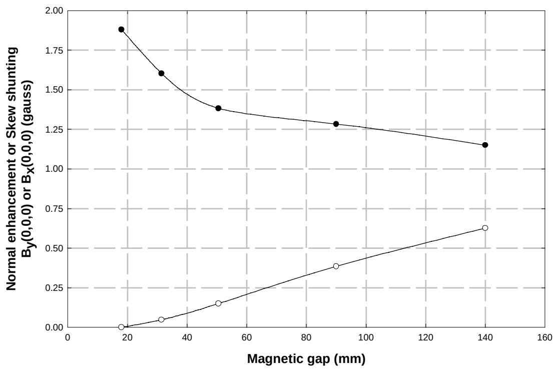

Figure 2: Plot of the relative enhancement for principal and shunting of skew ambient fields in a hybrid undulator.

In PM technology, additional work has been done in the phasing of multiple short devices mounted on the same straight section [14].

Superconducting devices are of interest in two major areas. They have proven useful as wavelength shifters in order to produce substantial quantities of hard x-rays on lower energy synchrotron radiation storage rings [15-17]. In FELs, small period superconducting undulators are being implemented to allow access into field regimes not well served at present by PM technology [18,19].

Additional aspects relating to conventional devices is the push toward small gap devices and very long straight sections for synchrotron radiation applications [20-23]

One application of undulators that have received more attention recently is their use as beam diagnostic devices. The magnetic performance has improved to the point that devices are being built and installed which are specifically dedicated for this purpose [24,25].

3 SPECIALTY DEVICES

Though progress and achievements in performance of conventional devices has been notable, activities in specialty devices have increased dramatically. These devices are optimized and designed for specific spectral or interaction characteristics. Three main areas appear among these devices: elliptical polarization devices for SR sources, devices optimized for self amplified spontaneous emission (SASE) FELs and compact source undulators for both FEL and SR sources.

Elliptical polarization devices have dramatically increased in number and application. These include pure REPM systems [26,27] which provide continuous or near CW elliptical polarization and electromagnet and hybrid combinations that are capable of polarization modulation of order 100 Hz or better [28-30].

SASE FEL undulators are another hot topic in insertion device technology. These devices are characteristically long, approaching 100 meters in length [31,32]. The issues associated with long undulators were first explored in the context of high power FEL oscillators and amplifiers [33,34]. Issues identified in that context remain significant concerns. Diagnostics that ensure tight overlap between the electron and photon beam are essential. If such diagnostics cannot simultaneously measure both photon and electron beams, alignment tolerances become extremely tight. The long undulators must provide, or allow, strong focusing to maintain interaction strength. This focusing is provided within the undulator structure or with external quadrupoles. External quadrupoles can either superimpose the focusing, in the case of pure-REPM designs, or be provided in longitudinal gaps in the undulator. Such gaps, whether for focusing, diagnostics, or vacuum pumping are a source of concern in SASE FEL design [35,36]. Focusing can also be provided by either arrangements of magnets within the undulator or the shaping of poles either longitudinally or transversely [37-41].

Another topic of interest is the push toward compact sources. Two areas of the many being explored for compact sources are micro-undulators and optical mode tapering. Micro-undulators are loosely defined as those devices with a period less than 10 mm. Activity in this area has extended over several years. Several approaches have been pursued including the use of LIGA technology [42-44].

Optical mode tapering is a specific application of constant resonant-energy tapering [45]. In normal tapering of undulators and wigglers the period and/or field is adjusted to change the resonant photon wavelength or electron energy subject to the resonance equation:

$$2\gamma^2 \lambda_p = \lambda_w \left(1 + K^2 / 2\right) \tag{1}$$

In constant resonant-energy (CRE) tapering the period, λ_w, and magnetic field, B, of the wiggler, ($K = eB\lambda_w/2\pi mc$) are adjusted in order to maintain the product of the square of the electron energy, γ, and optical wavelength, λ_p, constant. This formulation of the resonance equation assumes an essentially constant period undulator. If one examines the general wiggler field and particle motion equations and maximizes the on-axis spontaneous emission, there is a modification of the wiggler parameter K,

$$K = \sqrt{\left(\frac{eB\lambda_w}{2\pi mc}\right)^2 - \left(\frac{\lambda_w}{2\pi}\frac{dK}{dz}\right)^2} \qquad (2)$$

This divides constant resonant energy tapers into two broad categories: one where the changes in B and λ_w are small within a wiggler period (and the derivative term can be ignored), and the other where changes are large within a wiggler period.

Optical mode tapering (OMT) is a specific application of CRE to address two problems related to the operation of compact FELs. The gap of the undulator used in an FEL is often limited by the size of the optical beam at the ends of the undulator. The length of the optical cavity is often dictated by matching to the undulator and maintaining a large spot size on the resonator mirrors to limit damage. By adjusting the undulator gap throughout its length to be as small as permitted by the optical mode the interaction strength and number of periods in an undulator can be maximized. The variation in period and field needed to maintain resonance is not significant until the Rayleigh range is on the order of the undulator length or smaller.

To illustrate the types of performance enhancement that can be achieved with OMT, it is useful to examine an analytical system with a nominal values: 1 meter undulator length, L_w, a photon wavelength, λ_p = 10 µm, an electron beam energy γ = 50, and a mode limitation that the local gap must not be less than 4 times the optical mode radius. For illustration the system is assumed to have low gain and the mode is described by a TEM_{00} mode. With this example system, one can examine two regimes: the Rayleigh range for a fixed undulator length, and the undulator length for a fixed Rayleigh range. Figure 3 is a plot comparing the small signal gain of the fixed 1-meter OMT undulator and the equivalent-length uniform-gap device. The optimum Rayleigh range for the uniform gap device is ~L_w/3 whereas the OMT optimizes at ~L_w/5. The maximum gain of the OMT is 40% higher than that of the uniform gap and the Rayleigh range can be shortened by more than a factor of 3 without losing gain compared to the maximum for the uniform gap device. Figure 4 plots the small signal gain for a fixed Rayleigh range = 0.5 meter for both the OMT and uniform-gap undulators. With the uniform-gap device as periods are added the K must decrease to accommodate the optical mode. The loss of the wiggler length eventually exceeds the benefit of the additional periods. For the OMT as periods are added the interaction strength of the central periods are not diminished and a stronger interaction is maintained so gain is enhanced for a significantly longer undulator. This continues until the additional periods have such a weak field that they no longer contribute to the gain.

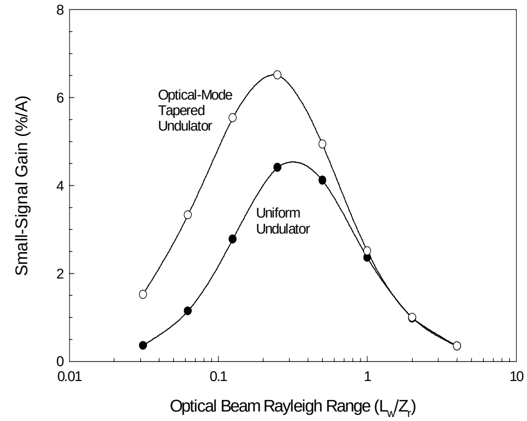

Figure 3: Small signal gain for OMT and uniform undulator for a 1-meter wiggler for various Rayleigh ranges.

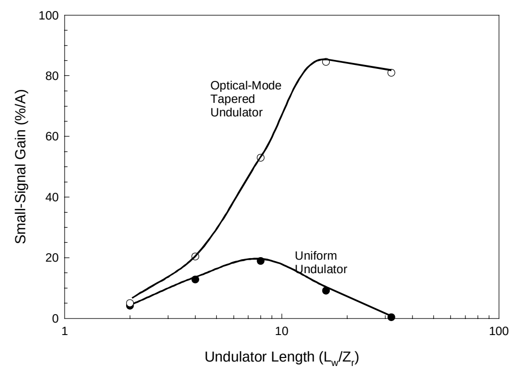

Figure 4: Small signal gain as a function of undulator length for the OMT and uniform undulator for a fixed Rayleigh range of 0.5 m.

4 CONCLUSION AND ACKNOWLEDGMENTS

From an examination of the activities in undulators and wigglers it is clear that it is an area still alive with interest and a great deal of potential for progress in providing radiation sources and diagnostics with improved characteristics. The technology has advanced and the variety of approaches increased that devices specialized for specific characteristics are becoming more commonplace. One area that is also important to gauging the success of an insertion device is the development of precise measurements that accurately determine its optical characteristics [46].

This paper can only scratch the surface of the activity and the works cited are illustrative only and must not be viewed as all encompassing. The absence of a citation in no way indicates the author's opinion of its significance to the field.

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