Development trends for insertion devices of future synchrotron light sources

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(Received 3 September 2010; published 28 April 2011)

The in-vacuum undulator with a permanent magnet at room temperature is a mature technology and is widely used; with a short period length in a medium-energy facility, it can enhance photon brilliance in the hard x-ray region. A cryogenic permanent magnet has been investigated as an in-vacuum undulator; this undulator will become the best prospective device to satisfy the requirements of a photon source with great brilliance in the hard x-ray region. For the further hard x-ray region, a superconducting wiggler can provide great flux with a continuous spectrum, whereas a superconducting undulator will provide great brilliance with a discrete spectrum. High-temperature superconducting wires are highly promising for use in the development of superconducting undulators; unique algorithms for their development with an extremely short period in a small-magnet gap have been devised. Some out-of-vacuum planar undulators with special functions must also be fabricated to enable diverse applications in various light-source facilities. This article describes current and future developments for insertion devices in storage-ring and free-electron-laser facilities and discusses their feasibility for use therein.

DOI: 10.1103/PhysRevSTAB.14.044801 PACS numbers: 29.20.−c, 41.60.Ap, 41.85.Lc, 41.60.Cr

I. INTRODUCTION

A third- or fourth-generation synchrotron facility focuses mainly on either enhancing output at the greatest photon energies or extending the range of tunable photon energy at medium electron-energy facilities. Minipole (short-period undulator) insertion devices (ID) are hence essential instruments in facilities of the accelerator storage ring (SR), the energy-recovery linear accelerator (ERL), the free-electron laser (FEL), and even laser-plasma-based sources. Table I lists the status of storage-ring synchrotron-radiation facilities that have come online in the past decade or are tentatively planned to do so. In most medium-energy facilities, a short-period undulator with a small magnet gap is the only way to attain the hard x-ray range. Despite the frequent use of an out-of-vacuum insertion device with a hybrid or pure structure in the past two decades, the period length and magnet pole gap in these ID are large, making impossible the achievement of great photon brilliance at hard x-ray energies in the medium-energy facilities. Third-generation synchrotron light sources with high energy—ESRF (6 GeV), APS (7 GeV), and SPring-8 (8 GeV)—were consequently constructed in 1988, 1990, and 1991, respectively. Making the period length as small as practicable is critical to provide a source of harder x rays in advanced medium-energy facilities. A compromise between total length and magnet gap of the undulator should be concurrently made to satisfy the requirement of the electron-beam lifetime. ERL- or FEL-based synchrotron-radiation facilities have an electron-beam emittance smaller than of a SR facility, and no additional aperture for residual oscillation of the injected particles. The horizontal beam aperture can thus be made as small as the vertical beam aperture in the ERL and FEL facilities, such that the magnet gaps in horizontal and vertical directions can be the same, and smaller than that in the SR facilities. Most ERL and FEL facilities currently exploit the out-of-vacuum design.

The in-vacuum undulator (IU) [1–3] with a permanent-magnet or hybrid structure at room temperature is a mature technology and has been widely used in the past decade. This IU can support a short-period-length undulator (minipole undulator) in a medium-energy facility (about 3 GeV), subsequently enhancing the photon brilliance in the hard x-ray region. A medium-energy storage ring (less than 4 GeV) (Table I) has thus been planned at many institutions, such as Soleil (2.75 GeV), Diamond (3 GeV), SSRF (3.5 GeV), ALBA (3 GeV), NSLS-II (3 GeV), TPS (3 GeV), and MAX-IV (3 and 1.5 GeV). The photon energy can attain around at 35 keV (brilliance $\geq 10^{18}$) in a medium-energy facility (3 GeV) with an in-vacuum undulator at room temperature. A cryogenic permanent magnet has been used in an in-vacuum undulator to enhance the remanence field and the coercivity force. In the future, a cryogenic permanent-magnet undulator (CU) [4–6] will provide hard x rays around 65 keV (brilliance $\geq 10^{18}$) in a 3-GeV storage ring. The period length can accordingly be decreased from about 25 mm (IU) to about 15 mm (CU). Figure 1 shows possible energy spectra in a

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TABLE I. Current status of storage-ring synchrotron-radiation facilities constructed worldwide in the past decade and in the future.

Date	Facility	E/GeV	Emittance/nm rad	Current/mA	C/m	Straights/m × No.	Cell	Status
1994	ESRF	6	4.0	200	844	6 × 32	16 MBA	Operating
1996	APS	7	2.51	100	1104	4.8 × 40	40 DBA	Operating
1997	SPring-8	8	3.4	100	1436	7 × 36 + 30 × 8	44 DBA	Operating
2001	SLS	2.4	4.8 (4.1)	400	288	11.8 × 3 + 7 × 3 + 4 × 6	12 TBA	Operating
2006	SOLEIL	2.75	3.7	500	351	12 × 4 + 7 × 12 + 3.6 × 8	16 DBA	Operating
2006	DIAMOND	3.0	6.5 (2.7)	300	562	11.34 × 6 + 8.34 × 18	24 DBA	Operating
2008	SSRF	3.5	7.8 (3.0)	200	432	12 × 4 + 6.7 × 16	20 DBA	Operating
2009	ALBA	3.0	4.2	400	268	8 × 4 + 4.2 × 12 + 2.6 × 8	16 DBA	Commissioned
2014	TPS	3.0	1.67	500	518	12 × 6 + 7 × 18	24 DBA	Construction
2015	NSLS-II	3.0	2.0 (0.6)	500	792	9.3 × 15 + 6.6 × 15	30 DBA	Construction
2015	MAX-IV	3.0	0.33 (0.24)	500	528	5 × 20 + 1.5 × 40	20 MBA	Construction

3-GeV storage-ring light source with various insertion devices. The calculation of these spectra is based on a short-period length with a short length of undulator, which could be operated in a light-source facility (CU9 with magnet gap 1.5 mm will be operated in the FEL facility). Figure 2 displays possible maximum magnetic-flux densities of various undulator types in magnet gaps. The maximum magnetic-flux density of a superconducting undulator (SU) in a reasonable operating gap still exceeds that obtained using other insertion devices.

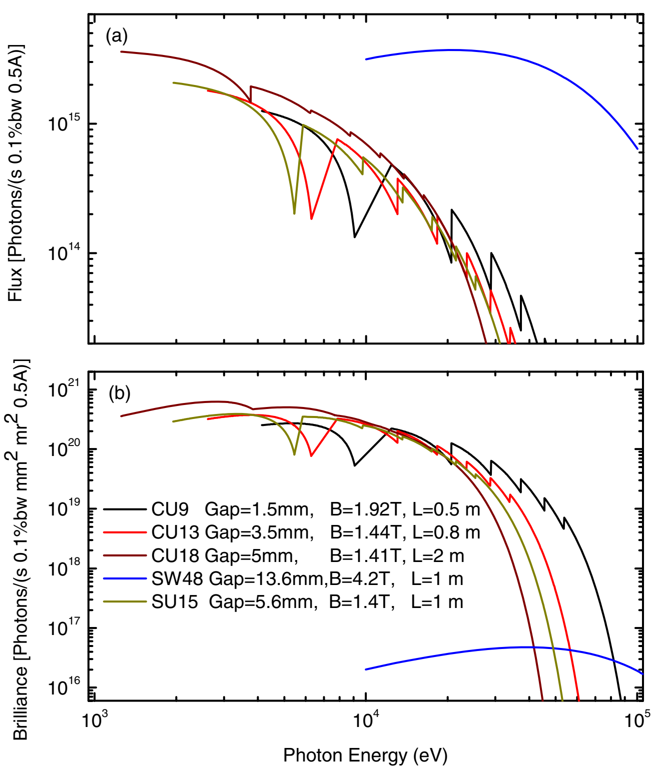

FIG. 1. Possible hard x-ray energy spectrum in an advanced medium-energy storage-ring facility: (a) flux, (b) brilliance. Energy spread 0.1% and phase error 2° were used to calculate the flux and brilliance in the TPS lattice parameters.

Superconducting wigglers (SW) [7–10] are also a mature technology that provide a great photon flux of hard x rays in a facility with medium-energy facilities (Fig. 1). Although a superconducting wiggler with low-temperature superconducting (LTS) wire is used in several synchrotron-accelerator facilities, there is still much scope for improvement. A superconducting wiggler is limited not only because much useless power is radiated from it that adversely affects the stability of optical components in the beam line, but also because it causes a tune shift, requires the use of further rf systems, increases the emittance, and increases the cost of the accelerator facility. Optimizing a large photon flux with a small radiative power in a synchrotron-accelerator facility must thus be considered [11]. Superconducting technology with high-temperature superconducting (HTS) wires is highly promising for use in developing undulators in coming decades. Several superconducting undulators [12–14] have been developed, and the first superconducting undulator [15] has been installed in the ANKA storage ring. Some critical issues, including

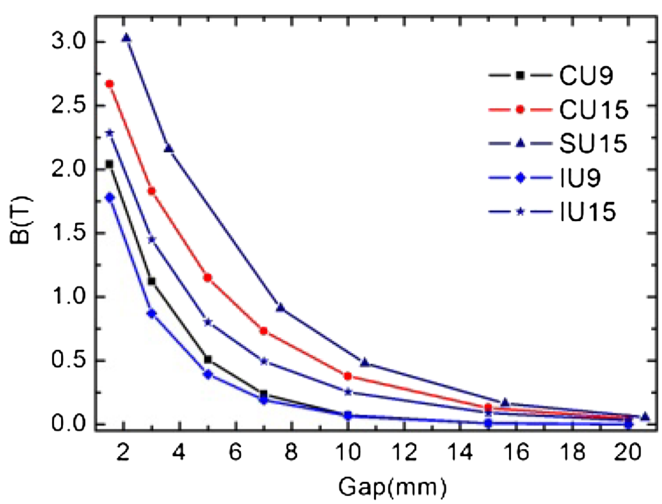

FIG. 2. Maximum magnetic-flux density in magnet gaps of various undulators with a short period length.

the heat-load problem and field-shimming mechanism, must be solved in the design and operation of such superconducting undulators. Some out-of-vacuum planar undulators, such as Apple-II undulators or an electromagnet elliptically polarized undulator (EPU), remain popular for use in a circular-polarization experiment with low- or high-frequency switching, respectively.

To avoid affecting the electron-beam lifetime, beam stability, beam losses, and injection efficiency, a small magnet gap must be investigated. The minimum gap is determined by the safety tolerance of the electron beam in terms of wakefields, physical aperture, beta function, and the amount of radiation that magnets can sustain before incurring irreversible damage. Some unique algorithms have thus been developed to satisfy the strong demand for minipole insertion devices. HTS bulk magnets with magnetic-flux density 17 T are applicable even for a superconducting undulator [16]. Because of its great magnetic-flux density on HTS bulk material; such a magnetic-flux density will promote the shorter-period undulator to get higher field strength as compared with the longer-period undulator. An undulator of extremely short-period length (about 5 mm) that operates at a small magnet gap has been studied using a stacked layer of thin HTS tapes [17] for a superconducting undulator. Such studies might contribute to the establishment of low-cost synchrotron-accelerator facilities (less than 4 GeV) that use an undulator with extremely short-period length. Such facilities provide great photon brilliance in the hard x-ray region, but such assumptions warrant further testing to confirm their feasibility. Here we describe current and future developments of insertion devices for a medium-energy storage ring and FEL facility, and discuss also the feasibility of development of various insertion devices and related technical issues.

II. IN-VACUUM UNDULATOR

In-vacuum technology is at a mature stage, and several accelerator facilities, especially those of medium energy, use an in-vacuum undulator as the light-source device. Although in-vacuum undulators in storage rings can be operated in a small magnet gap, such a small gap affects the beam lifetime due to elastic scattering by residual gas atoms. The smallest practicable gap is proportional to the square root of the vertical betatron function inside the undulator. The total length of the undulator associated with an extremely small gap must hence be optimized to maintain an acceptable electron-beam lifetime. Table II lists typical parameters of the smaller gap of in-vacuum undulators in some facilities. The beam instability and injection efficiency must be carefully examined and tested when an undulator with small gap (less than 5 mm in SR facility) was operated at a top-up operation mode. Radiation damage to the magnet block in an extremely small magnet gap should be a major concern; experimental data at various facilities reveal the degradation of the magnet block due to radiation [18]. The resistance of the magnet block to radiation depends on the manufacturing process and the annealing stabilization; an aging treatment must be applied to each NdFeB magnet block by maintaining permanent magnets at a temperature 145°C for 24 h in a vacuum to enhance a large coercive force [18]. A company (Hitachi Metal, Neomax) developed a high-performance NdFeB sinter magnet on depositing Dy by diffusion [19]; the remanence field was enhanced to more than 400 G and the coercivity force to more than 4 kOe at room temperature.

Meanwhile, the heat load on the magnet block caused by the weak-field effect in in-vacuum undulators with extremely small gaps (less than 5 mm) is serious, especially in a few-bunch mode of operation with a short bunch length, which creates a large peak-image current that damages the magnet block. To prevent damage from a weak-field effect on the resistive surface of the magnet block, a nickel-copper (CuNi) sheet [20] should be attached to the face of the magnet block to reduce the resistive surface of magnet, and a rf finger should be installed carefully on both sides in the in-vacuum undulator. Long chamber tapers can also serve as the transition taper to decrease the impedance. The design of a rf transition taper should minimize any impedance discontinuity and allow for a longitudinal degree of freedom for baking. Installing a scraper can diminish the beam losses on the magnet block of undulator, but the scraper should be located carefully to avoid it becoming the source of a neutron shower that could produce

TABLE II. Minimum period length and gap of in-vacuum undulators in light-source facilities.

	Diamond	Soleil	ESRF	KEK-PF	NSLS
E_e/GeV	3	2.75	6	2.5	2.8
Beam current/A	0.3	0.5	0.2	0.45	0.28
Minimum period length/mm	21	20	17	12	12.5
Minimum gap/mm	5	5.5	5	4	3.3
Pole field/T at minimum gap	0.86	0.97	0.56	0.7	0.95
Undulator length/m	1.974	2	2	0.48	0.36
Lifetime decrease/%	10–20	3	<10	<1	<10

demagnetization of the magnet block. In particular, the scraper must not be located right in front of the undulator.

Most operational failures that arise in an in-vacuum undulator are related to the vacuum, the installation of the CuNi sheet [21], leaks from the water pipes, and the rf transition finger. A rf transition finger of taper design with an enlarged area of thermal contact should be considered, and the CuNi sheet should be fastened carefully to tolerate thermal expansion during baking. A rf taper of the SPring-8 type (flexible transition with woven strip CuBe) [22] or SLS type (flexible transition with rigid CuBe) [23] is selected, depending on the available space and the extent of the heat load. To ensure that the nickel-copper foil contacts smoothly the iron pole and the magnet block that decreases the heat load from the wakefield of the resistive wall, there must exist no recess between the magnet block and the iron pole. The hybrid structure must be designed with an overhang to diminish the 3D leakage flux and to detente the magnetic-field roll-off [24]. The extra magnetic-flux density of the overhang area compensates for the decrease of the fringe field.

An extremely short-period length and a small-magnet gap of the in-vacuum undulator are used in a medium-energy SR facility. Table II lists the extremely short-period undulators that have been installed and tested in SR facilities. Three in-vacuum undulators—i.e. two with period length 12.5 mm and another with period length 18 mm—were installed at the NSLS synchrotron light source [5,25]. The total length was only 0.36 m for a period length 12.5 mm and 1 m for a period length 18 mm, with operating magnet gaps 3.3 and 5.6 mm, respectively. The beam lifetime was decreased only from 14 h to about 12.7 h when the undulators were operated with vertical beta function 0.3 m [25]. At ESRF, the decrease of the lifetime remained less than 10% when the magnet gap of the undulator was decreased to 5 mm (vertical beta function 2.5 m) [26]. The extremely short-period undulators in other facilities are revealed in Table II [27,28]. These IU were fabricated also for SCSS XFEL (Japan-SPring-8); eighteen segments of in-vacuum undulators are installed. The magnetic length of each segment is 5 m and the magnetic period is 18 mm; the magnetic circuit is a hybrid type, with iron pole pieces that are made of Permandur (Fe-Co alloy) and NdFeB magnet material. A maximum K value 2.2 is obtained at gap 3.5 mm, and this magnet gap is adjustable to vary the photon energy over a wide range, as in a SR facility. Between two undulator segments is a drift space of width 1.2 m in which quadrupole magnets for betatron matching, steering magnets for orbit correction, electron beam-position monitors, and phase-shift magnets are inserted, to adjust the optical phase between two adjacent undulators [29]. The IU for SPring-8 XFEL has been installed, and its field performance has been verified using a system for field measurement *in situ* [29].

An in-vacuum hybrid wiggler [30,31] was developed to replace the superconducting wiggler in a medium-energy facility in which no cryogenic system was available. The SOLEIL facility investigated an in-vacuum wiggler to radiate at greater photon energy; this wiggler consists of 38 periods of length 50 mm, subsequently producing 2.1 T at minimum gap 5.5 mm, and a compensating mechanical system composed of springs was developed to minimize the large magnetic forces (10 tonnes) in the vacuum. The same mechanism of a spring system is applicable for an in-vacuum undulator to decrease the deformation (which creates an extra phase error) of a girder as the gap is varied.

A cryogenic permanent magnet is usable in an in-vacuum undulator to enhance the remanence field (B_r) in the material NEOMAX50BH above 1.6 T and the coercivity force above 3000 $\mathrm{kA\,m^{-1}}$. The material NEOMAXH45SH has a coercivity force, 1671 $\mathrm{kA\,m^{-1}}$, greater than that of NEOMAX50BH at room temperature, but the remanence field is small ($B_r = 1.5$ T) at cryogenic temperature. Both materials have a large remanence field and a large coercivity force, which resist radiation damage and demagnetization at cryogenic temperature. A cryogenic permanent-magnet undulator has hence been developed and constructed for use with a short-period length in a SR light source [4–6,32]. Table III presents the features of various permanent magnets between room and cryogenic temperatures. Various facilities have selected the magnet materials that are also shown in Table III. For a situation in which dual modes of operation at room and cryogenic temperatures in an extremely small magnet gap are considered, or even when the magnet assembly in the hybrid structure is considered, the material NEOMAXH45SH is then operated more safely

TABLE III. Parameters of permanent magnets between room temperature (RT) and cryogenic temperature (CT) (NEOMAX are products of Hitachi Metal).

Model No. of PM	NEOMAX-50BH	NEOREM-595t	NEOMAX-42AH	NEOMAX-53CR	NEOMAX-45SH
Material	NdFeB	NdFeB	NdFeB	PrFeB	NdFeB
Type	Pure	Hybrid	Hybrid	Hybrid	Hybrid
RT/CT/K	300/140	300/110	300/150	300/150	300/135
B_r/T at RT/CT	1.45/1.6	1.17/1.31	1.3/1.45	1.3/1.45	1.33/1.5
iH_c/kOe at RT/CT	14/38	30/58	24/53	12/50	21/50
Facility	SPring-8	ESRF	NSLS	SOLEIL	SLS

at an extremely small magnet gap. The optimal temperature to operate the magnet block of NEOMAXH45SH is about 135 K, such that the deviation of the remanence field is insensitive to the temperature of the magnet block. The typical maximum field strength and coercivity of CU obtained with NEOMAX45SH can exceed those obtained using a conventional IU by 28% and 78% [33], respectively. CU is thus highly promising for use in an undulator with a small gap. The PrFeB-based cryogenic undulator for a laser-plasma-accelerated e-beam is currently utilized in the tabletop free-electron laser (TT-FEL) [34] at Ludwig Maximilian University. The TT-FEL with a 1-GeV electron source is associated with the CU9 [34] at a magnet gap 2.5 mm and produces keV photons. A prototype with 20 periods is currently under construction at BESSY. The greater photon energy is obtainable with an extremely short-period undulator, but its thinner magnet block is readily demagnetized; careful design of the magnet circuit is thus required to resolve this issue. Although more robust than thin magnets, for thick magnets it is difficult to provide an extremely short-period undulator. An optimal period length 9 mm with a magnet gap 1.2 mm was therefore studied [35], and considered for the FEL facility.

Any variation in the gap of the CU induced by thermal shrinkage of the supporting shaft should be monitored, and compensatory adjustments should be made. For this purpose, in SPring-8 and NSLS an optical micrometer (KEYENCE, LS-7000) is used to monitor the variation of the gap. To compensate for the temperature gradient and to correct the subsequently increased phase error, a method has been proposed at SPring-8 in which the gap variation is corrected with a differential adjuster in the out-of-vacuum shafts, which supports the in-vacuum beam [29]. CU was measured with a system called SAFALI [29], based on the dynamic feedback of the position of a position-sensitive detector sensor. Preliminary measurements of the magnetic field indicate that the field errors are independent of temperature; no extra phase error is hence observed when the magnet array is cooled to a low temperature. A conventional undulator field-shimming method, made at room temperature, is thus still effective at cryogenic temperatures for CU. Another issue is that the cryogenic temperature is obtained with either a cryogen-free cryocooler or a low-temperature gas controlling the liquid nitrogen. Whether a cryocooler or liquid nitrogen is used depends on the number of CU; when one or two CU are operated, the cryocooler becomes preferable.

A prototype CU was developed and operated for more than two years with electron-beam testing in the ESRF storage ring [36]. Measurements of the magnetic field revealed that the field quality varied slightly with temperature; such variation is to be avoided. A differential adjuster design [29] is important to ensure that the phase error is small when there is a temperature gradient in the CU system. In the future, a phase error 2° rms will be obtainable in CU operation in a SR facility, and the CU might replace the IU in future light-source facilities.

III. SUPERCONDUCTING INSERTION DEVICES

Several superconducting wigglers are used in synchrotron light sources: this technique is mature. An advanced superconducting multipole wiggler SW48 [10] with a short-period length was fabricated at BINP; one was installed in CLS, another in the Diamond light source. The 27 poles of SW48 with period length 48 mm under the magnet gap 13.9 mm can produce a field strength 4.2 T. Four superconducting multipole wigglers SW60 [7] with field strength 3.2 T at magnet gap of 18 mm were fabricated by NSRRC and Wang NMR Inc. and installed in the 1.5-GeV Taiwan Light Source; their operational performance is excellent [7,37]. A superconducting wiggler with 3.5 T [8] was installed in MAX-II. Three design philosophies have been implemented at BINP, MAX-II, and NSRRC: NSRRC used a 100-K aluminum beam duct and an even number of poles, whereas BINP and MAX-II used a 4.2-K stainless-steel beam duct and an odd number of poles. The 100-K aluminum chamber improves the thermal conductivity and decreases the electric resistance of the beam duct. Another benefit of the 100-K aluminum beam duct is that the number of reabsorbed molecules is small: H_2 and CO are not then frozen on the surface, but are pumped away when the beam duct is kept over 100 K. The pressure of the beam duct is hence independent of its temperature, but the end-tapered transitions should be constructed of stainless steel to decrease the thermal conductivity. The even-pole design of NSRRC SW can keep no trip of the electron beam when the magnet is quenched [7]. To overcome the image-current effect and to decrease the heat load from scattered light, a copper-strip liner of the BINP superconducting wiggler kept at 20 K was installed inside the 4.2-K stainless-steel beam duct. According to the design of MAX-II SW, the 4.2-K stainless-steel beam duct has a copper coating on the surface of the beam duct to replace the copper-strip liner. The beam-duct designs of BINP and MAX-II have magnet gaps 13.9 and 10.9 mm, respectively, that are smaller than that of NSRRC. Because of the compromise between the pressure condition in the UHV system and the minimum practicable gap, the design of the beam duct of BINP is preferable. A superconducting wiggler generates more useless heat load and has a small brilliance (see Fig. 1); for this reason it is not the best photon source for use in a future light-source facility. Nevertheless, a superconducting wiggler is the only remaining choice if one seeks to obtain hard x-ray photon fluxes at a facility with a small electron energy.

A superconducting undulator for a SR light source or a FEL facility has been developed, but its operation in a small gap is still a critical issue in a SR facility. The institutes of ANKA (SU14) [12], NSRRC (SU15) [14,38], and APS (SU16) [39] have launched a feasibility study of a superconducting undulator with period lengths (magnet gap) 14 mm (5–10 mm), 15 mm (5.6 mm), and 16 mm (9 mm), respectively. The SU14 [15] was built by ACCEL and installed in the ANKA storage ring to test its performance; the heat load of the beam was greater than expected. Under an electron-beam test, the coils sustained a smaller current than those without a beam. The calculated and measured photon fluxes differ by a factor 2 in some regions at a large magnet gap [40]. The heat load on an SU15 [14] was studied to survey the operational issues in the storage ring; detailed analyses are available [14,41]. Some heat load is produced by electron bombardment [42] and the scattering of light on the beam duct. The heat load associated with radiation from the bending magnet can be decreased with a photon absorber of sawtooth shape in front of an ID, a soft-end design of the dipole magnet, or a chicane mechanism in front of the ID [43]. A large residual resistivity ratio of the beam-duct material that is used with operation in a long-bunch mode, with a low-frequency rf cavity or a Landau cavity, can minimize the heat load from the image current. The tolerance of the heat load of the coil in the beam duct is inversely proportional to the magnetic-field strength. An analysis of the heat load [43] based on synchrotron radiation and the image current also took into account the parameters of the TPS lattice. The quenching behavior on heating the beam duct was measured in a test Dewar with an extra heater, which was wound with non-magnetic $Ni_{80}Cr_{20}$ wire (dimension 0.1 mm) on the beam duct; this test served to simulate the heat load from the image current and the synchrotron radiation from the bending magnet. Figure 3 shows the heat-load tolerance of NSRRC SU15 at varied magnetic-flux density as measured in a test Dewar; the quenching experiment shows that the tolerated power density at the design field strength, 1.4 T, is $0.79\ \mathrm{mW\,mm^{-2}}$. The measured power density, $0.79\ \mathrm{mW\,mm^{-2}}$, has a tolerance greater than the calculated power density, $0.38\ \mathrm{mW\,mm^{-2}}$ [43].

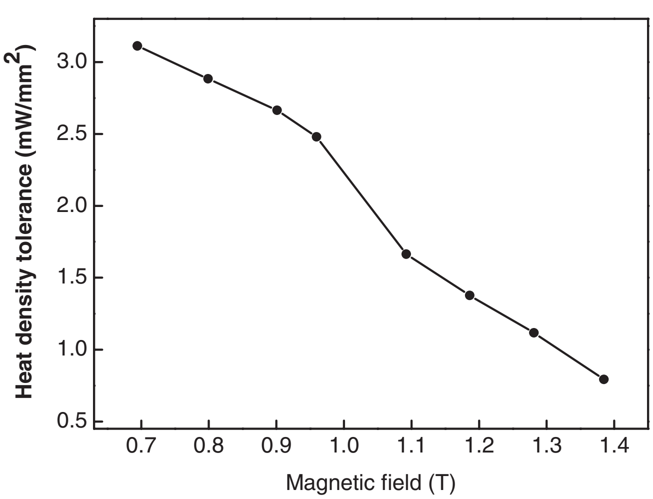

FIG. 3. Heat-load density as a function of magnetic-field strength at a coil-quenching condition.

A HeLiCal collaboration in the U.K. is developing a superconducting helical undulator [44] for the ILC project; this undulator with period length 11.5 mm at winding bore 6.35 mm can yield 0.86 T. The above wire designs apply NbTi that is associated with an iron pole in the superconducting undulator. Another helical undulator [45] using a superconducting wire or a staggered structure has been utilized to provide a helical field.

According to the theoretical calculation, in a long-bunch-length machine with a multibunch operating mode, the contributions to the heat load on the beam duct arise mainly from the bending radiation, the scattered light, and electron bombardment [42], but the main contribution to the heat load on the beam duct in a short-bunch-length machine under few-bunch operation [14,41] is from the image current. However, the experimental results at ANKA seem to indicate that the heat load on SU was greater than expected. A uniform cooling power from a cryogenic system is essential for a small-gap superconducting undulator. As liquid helium can rapidly remove the heat load on the beam duct, the design of a recondensing LHe bath cryostat with cryocooler is effective for cooling an SU. The heat load on the beam duct is still a serious issue when SU is operated at a small gap in a SR or FEL facility. Recently, commercially available HTS wires including bismuth strontium calcium copper oxide (BSCCO) (1-G) [46] and yttrium barium copper oxide (YBCO) (2-G) [47] wire have been improved, and have the potential to solve the heat-load problem. The critical temperatures of BSCCO and YBCO are 90–110 and 90–93 K, respectively. Although 1-G and 2-G HTS wires can be operated at liquid-nitrogen temperature, their critical current densities are not comparable with that of the currently used LTS wire unless the HTS wire is operated at 4.2 K [48]. Challenges must still be overcome to improve the maximum current density of the HTS wire, its length, uniformity of current density, bending radius, and cost. MgB_2 wire [49] with critical temperature 39 K is also used in superconducting magnets; this wire is much cheaper than HTS wire, but its critical current density is lower.

The other critical issue of a superconducting undulator is field shimming. Shimming methods were developed at ANKA [50] and NSRRC [51]. The SU at NSRRC was shimmed using iron-shim pieces and a low-temperature trim coil; the maximum field correction achieved using iron-shim pieces or a trim coil is approximately 2%. The trim-coil method is much easier to use *in situ* to find optimal field strength because the current is remotely variable and opening the cryochamber is not required. The method based on trim-iron pieces is more cost effective in terms of testing procedure, and no heat loss is caused by the additional current leads of the trim-coil method. A SU mockup with one undulator coil [50] was developed to test the field shimming in ANKA; an array of coupled HTS loops was attached to the surface of the SU. The maximum field correction obtained with this shimming method was approximately 1%. These methods require additional testing of the heat load to confirm the feasibility of the field-shimming tasks. Another issue is that the superconducting coils of the SU suffer from a hysteresis effect [52] caused by persistent currents within the filaments of the superconducting wire when the magnetic field of the SU is varied; a margin greater by several percent than the calculated maximum field strength of the ID is required to estimate accurately the energy spectrum.

IV. OUT-OF-VACUUM INSERTION DEVICES

Few transitional out-of-vacuum planar insertion devices are used in recent advanced light sources, such as the planar elliptically polarized undulator (EPU) of the Apple-II structure, which is still popular in medium-energy storage rings. To obtain circularly polarized light, most Apple-II EPU undulators are designed to be operated in a universal mode [53,54] in which all four rows are moved to produce a state of polarization [53]. The field strength can be varied also through the phase, so the magnet gap need not be altered [55]. According to this scheme, the maximum field is controlled by the relative motion of the magnetic arrays in the longitudinal direction (commonly described as an adjustable-phase undulator) [55], instead of varying the magnet gap to vary the photon energy. This scheme was used for the ADRESS beam line at SLS.

Most new accelerator facilities have been planned to use the Apple-II EPU, including those at institutes Soleil, Diamond, ALBA, SSRF, and TPS. Although the Apple-II EPU has the greatest rates of polarization and the maximum magnetic-flux density in the horizontal field, the field roll-off of the two transverse field components declines rapidly, adversely affecting the top-up injection and dynamic aperture. For this reason the vertical field (B_y) roll-off was improved with either a thin shim at the edge of the magnet block [56] or an optimal angle of magnetization with respect to the vertical axis [57] of the magnet block. Figure 4 displays the mechanisms by which those two solutions decelerate the rapid decline of field roll-off; Fig. 5 shows this improvement of the vertical field roll-off. The method that uses an end shim at the edge of the magnet manipulates the performance of the magnet block more readily than optimizing the angle of magnetization of the magnet, but the latter scheme provides a greater magnetic-flux density. Neither method can improve the field roll-off of the horizontal field (B_x). The integral multipole components of the two transverse fields can also be corrected using a magic finger [56]. Apple-II undulators produce strong dynamic multipoles in the elliptical and inclined mode, which can significantly decrease the electron-beam lifetime and dynamic aperture.

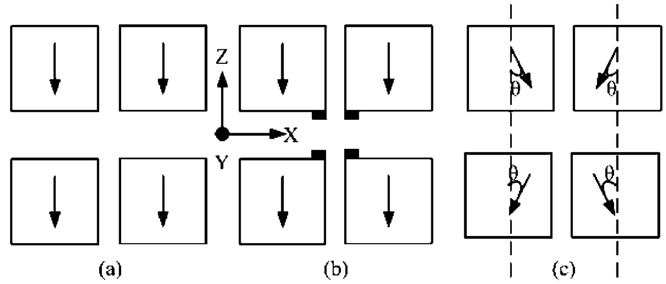

FIG. 4. Two algorithms to improve the homogeneity of the vertical field: (a) original concept without modification; (b) shim added at the magnet edge; (c) magnetization of the magnet block at an optimal angle.

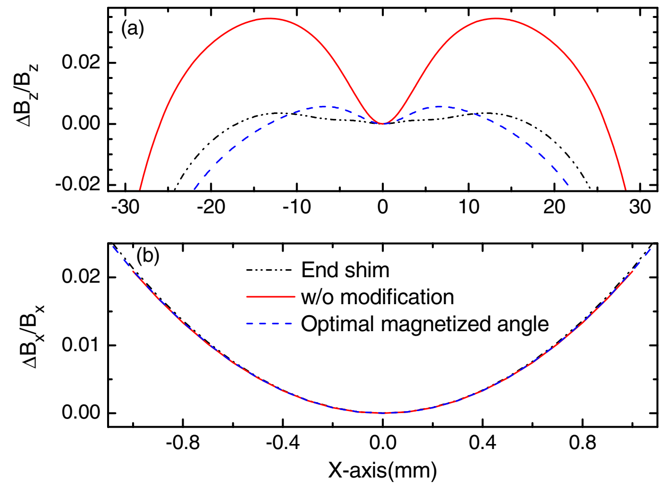

FIG. 5. Distribution of roll-off of (a) vertical field and (b) horizontal field, in the original design without modification, with an added shim at the magnet edge, and with an optimum angle of magnetization.

A shimming method [58] was therefore developed at ESRF to reenlarge the dynamic aperture for use at a small electron-energy facility (BESSY, SOLEIL), to compensate for the tune shift and the dynamic aperture correction. Passive shimming is invariably a preferable solution. Two strategies have been considered [59]—rotating permanent magnets at either end of the device, and a combination of individually powered flat wires above and below the vacuum chamber.

Another concern of an Apple-II EPU is the generation of an enormous force between two adjacent rows when the phase is altered. Each sector unit of the magnet array contains five or seven blocks; this arrangement can decrease the total force of each sector unit, facilitating installation and removal of each sector magnet array and avoiding the deformation of each sector unit. Another issue is that it is difficult for the Apple-II device to switch between opposite polarization states more rapidly than 1 Hz; the planar electromagnet undulator [60] using copper sheet as a coil is thus selected for rapid switching between opposite polarizations in insertion devices. If the experiment does not require a particular polarization, the circular-polarization mode of the EPU provides an advantage of a small heat load on the beam line. A quasiperiodic [60] mechanism can be applied for the elliptically polarized undulator with high harmonic energy to provide circularly polarized light. This circularly polarizing quasiperiodic undulator combines electromagnets to generate the vertical field and permanent magnets to generate the horizontal field. A quasiperiodic condition can be created when the vertical electromagnetic field is excited at the quasiperiodic poles; the heat load of the horizontal linear polarization is thus decreased when a quasiperiodic mechanism is applied on the elliptically polarized undulator. To obtain higher field strength on each pole when the period length is decreased, the in-vacuum Apple-II EPU should be studied and developed.

Several Apple-II EPU devices have been installed in a SR light source in the past decade, such as at BESSY, ELETTRA, ALS, and NSRRC; the operational performance of the Apple-II device [61] is satisfactory in these facilities. The largest Apple-II device UE65 [62] (length 5 m) was installed in the 6-GeV light source PETRA III at DESY, which generates enormous forces in a small gap, 11 mm. The support structure of UE65 is made from a single piece of cast iron and the Al girders for the magnetic structure are milled from solid blocks to avoid the welding of aluminum. Each magnet girder of UE65 is attached to the support structure with four transverse flexible joints and one longitudinal flexible joint that have been optimized for maximum stiffness in one particular direction and minimum stiffness in another direction, which allows for girder tapering without generating additional strong forces or torques.

Several out-of-vacuum planar undulators remain utilized in energy-recovery linac (ERL) and FEL facilities, such as SPARC, FLASH, and LCLS; they allow for use of a small electron-beam aperture on the horizontal and vertical axes in ERL and FEL. LCLS FEL has 33 segments of a planar hybrid undulator [63] with a fixed gap to form an undulator of length 120 m. Each segment undulator, of length 3.4 m and with period length 30 mm ($k = 3.5$), is operated at a fixed magnet gap, 6.8 mm. The taper shims serve to correct the horizontal and vertical trajectories between each segment. Made from titanium forgings, the undulator strongbacks are large and highly precise. The magnets are slightly canted with opening angle 4.5 mrad, allowing some k tunability. SPARC XFEL (European XFEL at BESY) has an undulator (maximum $k = 2.2$) [64] with six permanent sections and period length 2.8 cm; the magnet gap is variable between 25 and 6 mm. Therefore, the transitional planar undulators are thus still used in FEL and ERL facilities, but the operation of a SU or CU is preferable at a small-energy FEL facility.

V. ADVANCED DEVELOPMENT OF INSERTION DEVICES

When a tapered undulator is used, the magnitude of the central field varies linearly along the beam axis. The tapered undulator serves to compensate for the degradation of FEL gain caused by the energy chirp in a single-pass seeded FEL, such as in the NSLS SDL undulator [65]. The final 2.5 m of the 10-m NISUS undulator was linearly tapered so that the magnetic-field strength at the end of the undulator was decreased by 5%. A tapered undulator has also been adopted either to compensate for the loss of particle energy or to complete the suppression of amplification in the largest fraction of the electron bunch that is used for production of attosecond pulses in the XUV/ soft-x-ray regime of SASE FEL [66,67]. A tapered undulator [68] can also increase the spectral bandwidth for x-ray diffraction to produce additional reflection points, but such a tapered undulator is inadequate for operation at a higher-order harmonic spectrum energy because the photon flux becomes decreased much more than for an untapered undulator. For an in-vacuum tapered undulator, it is difficult to construct a taper larger than 2 mm.

A pure permanent-magnet structure of a Delta undulator [69] with period length 24 mm and magnet gap 5 mm was designed for the Cornell ERL to produce a universal polarization mode and to vary the phase for tuning the photon energy. To satisfy the vacuum condition, four slits of width 0.5 mm between the magnet arrays provide sufficient conductance for high-vacuum pumping, and the blocks are soldered to copper holders in the vacuum to yield an outgassing rate 2.77×10^{-7} Torr L s^{-1} and a vacuum 5×10^{-9} Torr.

A novel concept to generate an undulator field was introduced on stacking several HTS tapes in a series [17]. A flat $YBa_2Cu_3O_{7-\delta}$ (YBCO) tape conductor can be patterned in the superconductor to maintain the current in a defined path, with micromachining, lithography, or laser techniques. The properties of the YBCO tape can be leveraged by its close proximity of the YBCO layer to the beam. The HTS tape thus becomes a competitive application for a small gap with an extremely short-period undulator. In addition to HTS tape, HTS bulk [16,70] was used to develop an undulator. HTS bulk magnets that are made from YBaCuO bulk can trap a magnetic field up to 17 T [71] through the "pinning" effect, which is much greater than from a permanent magnet. A unique mechanism for use in a very-high-field magnetization system must thus be developed to magnetize the HTS bulk. In the future, HTS bulk magnets can, moreover, be operated at a temperature above the boiling point of liquid nitrogen; this feature can overcome the problem of a large heat load on the beam duct of the superconducting undulator. Although currently available cryogenic systems enable HTS bulk magnets to be used in the undulator, the method of magnetization and the quality of bulk HTS dominate their applications for insertion devices. Further work is thus warranted to improve the performance of either HTS bulk or HTS tape until it can be practically used in an undulator [72].

IV. CONCLUSION

Many in-vacuum undulators have been utilized in insertion devices—especially at advanced medium-electron-energy facilities. In the future, the CU will replace the IU and become a common usage at advanced medium-electron-energy facilities. To satisfy the requirements of great brilliance and a wide energy spectrum at such facilities, an extremely short-period CU operated at a small magnet gap is necessary, but the CU should be installed in an optimized length of straight section that has a small betatron function lattice. According to empirical results from NSLS, ESRF, KEK PF, and SPring-8 [25–28], three different lengths (3, 6.5, and 13 m) of straight section are the best lattice design for installing ID, with a period length about 10 mm, to be installed in the straight section of length about 3 m that has extremely small β_y (about 0.2 m) at the center, or for an ID with a period length about 20 mm to be installed in a straight section of length about 6.5 m that has small β_y (about 2 m) at the center; alternatively, two IDs might be installed in a straight section of length about 13 m that has a double minimum β_y. Conventional planar helical undulators with a pure Apple-II structure or an electromagnet are still used to produce circularly polarized radiation in SR, ERL, and FEL facilities. A SU with HTS wire might have the best potential for use after the next decade if the timetable for the development of HTS wire is favorable. In particular, HTS tape or HTS bulk can be applied for the development of an undulator only after further tests have been undertaken to demonstrate its feasibility for use in insertion devices.

ACKNOWLEDGMENTS

National Science Council of Taiwan supported this research under Contract No. NSC99-2221-E-213-004. We thank Dr. H. Kitamura (SPring-8), Dr. T. Tanabe (NSLS-II), Dr. J. Bahrdt (BESSY), and Dr. J. Chavanne for valuable discussions. Dr. John Ogilvie is appreciated for his editorial assistance.

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