

CHALLENGE OF IN-VACUUM AND CRYOGENIC UNDULATOR TECHNOLOGIES

Jui-Che Huang[†], Chin-Kang Yang, Cheng-Hsing Chang, Ting-Yi Chung, Yung-Teng Yu,
Cheng-Hsiang Chang, Ching-Shiang Hwang,
National Synchrotron Radiation Research Center, HsinChu, Taiwan
Hideo Kitamura, Harima Institute, RIKEN, SPring8, Hyogo, Japan

Abstract

An in-vacuum undulator (IVU) opens the utilization of high-brilliance X-rays in the medium energy storage rings. The development of a short-period undulator with low phase error becomes important to bring X-ray into a new unprecedented brilliant light source in an ultimate storage ring (USR). NdFeB or PrFeB cryogenic permanent magnet undulators (CPMUs) with a short period have been developed worldwide to obtain high brilliance of undulator radiation. A CPMU has high resistance against beam-induced heat load and allow to operate at a narrow gap.

In a low emittance or ultimate storage ring, not only the performance of an undulator but the choice of the lattice functions is very important to obtain high brilliance of synchrotron radiation. The optimum betatron functions and zero dispersion function shall be given for a straight section at IVU/CPMUs.

In this paper, the relevant factors and design issues for IVU/CPMU will be discussed. Many technological challenges of a short-period undulator associated with beam induced-heat load, phase errors, and the deformation of in-vacuum girders will also be presented herein.

INTRODUCTION

To obtain short wavelengths of undulator radiation, a short period undulator or high beam energy is necessary; the former option is cost-effective to shift the spectrum to higher energy. Short period undulators, such as an in-vacuum undulator, cryogenic permanent magnet undulator and superconducting undulator (SCU) comprise a recent and future trend in the development of insertion devices. The advantage of using a short period undulator is that the number of periods can be increased for an undulator of a given length and more photon flux is obtained. To provide sufficient magnetic flux intensity, a small undulator gap is necessary. An in-vacuum undulator is thus suitable for short period undulator development. The operation of an IVU is more economical than that of a CPMU or SCU.

First true in-vacuum undulators were developed at KEK in 1991[1]. The entire magnet gap is fully used as a physical aperture for electron beam. Up to the present, in-vacuum undulators have been developed around the world [2-8], mostly based on KEK IVU design.

IN-VACUUM UNDULATORS

The research and development of an in-vacuum undulator were undertaken at KEK since 1986. At present, the technologies of an IVU are mature and technological challenges focus on the development of a short period/small gap devices.

Magnet and Coating

The first priority in the development of an IVU is to realize the UHV condition. Of two approaches toward UHV compatible magnets [9], the first is to have magnet material resistant to UHV baking. $\text{Sm}_2\text{Co}_{17}$, the Curie temperature of which is higher than that of NdFeB, is easily broken to powder, which may cause a contamination problem in UHV systems. In addition, NdFeB has higher remanent field than $\text{Sm}_2\text{Co}_{17}$. (for NdFeB, 1.05~1.15 T, whereas for $\text{Sm}_2\text{Co}_{17}$, 1.0~1.4 T) [10]. NdFeB with high coercivity, therefore, is preferable to $\text{Sm}_2\text{Co}_{17}$ for IVUs. A choice of NdFeB with high coercivity (H_{cj}) shall satisfy that H_{cj} is greater than 2000 kA/m to avoid demagnetization at UHV baking and radiation damage. Implementation of deposition Dy-diffusion/Grain-boundary diffusion technologies in NdFeB magnet, coercivity can be enhanced without sacrificing remanent field.

The second approach is coating on permanent magnets (PMs) for reducing outgassing from surface of rare-earth PMs. TiN ion-plating is favorable for a short period IVU because of small volume errors resulting from thin coating (5 μm thickness) and a hard coat property. A magnet with a TiN coating has better vacuum property than that of nickel electroplating.

Realization of UHV without Baking

UHV for an IVU is achieved through two strategies, plans A and B. Plan A is a baking approach, high temperature baking of PMs. On the other hand, plan B is a non-baking option to cool down PMs to cryogenic temperature. In adopting 'aging process' on PMs, plan A was found to be applicable, therefore, plan B was withheld till first CPMU proposal [11] in 2004. Furthermore, less cost and manpower are required in plan A. For an IVU, thermal treatments (aging process) and choice of PMs having high coercivity both improve not only the resistance against demagnetization during UHV baking (flux loss <0.1%) but resistance against electron irradiation [12][13].

Impedance Reduction

Magnet covers and flexible tapers are designed to reduce the impedance of an IVU. Without a magnet cover, single bunch instabilities are excited at high bunch current and beam lifetime are decreased by half [14]. In an early development, a magnet cover of type 304 stainless steel was melted by the combination effect of image current and synchrotron radiation (SR) heating [15], since then a copper nickel-plating magnet cover has become a standard solution. Several accidents in IVUs were associated with avalanche meltdown of magnet cover [15-17]. SR is responsible for avalanche meltdown of the magnet cover, and the image current mainly decreases the threshold of power to cause an avalanche meltdown. To avoid an avalanche meltdown accident on a magnet cover, the linear power density absorbed on a magnet foil should be less than 10 W/m, based on the operational experience of an in-vacuum undulator at Spring-8[18]. The thickness of nickel layer of a Cu-Ni magnet cover must be decided by condition of beam-induced heat load. A thin nickel layer provides small contact force and high thermal contact resistance between a PM and a cover. A thick nickel layer would cause loss of a valuable undulator gap. A typical thickness of nickel layer for storage ring IVU is 50 μ m and thinner nickel layer might be possible in a XFEL IVU.

A flexible transition is necessary between the entrance/exit of undulator vacuum chambers and the IVU gap to avoid wake field instability. The flexible transition must have a displacement allowance for gap change and thermal expansion during UHV baking. A water cooling pipe on flexible taper is essential to remove the heat derived from SR coming from upstream bending magnet or image current heating. A flexible taper with high cooling capacity (~100W) is used in SLS (cellular radiator type with BeCu ribbon) [19]. The TPS flexible taper is made of 5mm OFHC plate with a sliding mechanism. The cooling capacity, estimated around 10W, is not high but enough [20]. In SPring-8 BeCu woven strip [21] is designed to transform geometry from an elliptical ring vacuum chamber and an undulator magnet array. The thin BeCu strips cause low cooling capacity, about a few watts.

CHALLENGES OF SHORT PERIOD UNDULATOR

Magnetic field correction for an IVU is performed without vacuum chambers. After re-assembly of magnet arrays with vacuum chambers, undulator gap reproducibility is typically around 10~20 μ m. This assembly accuracy is effective only for a period longer than 30mm. For a short period IVU, the magnetic field is more sensitive to the gap value. Figure 1 shows the relation between field variation $\Delta B/B_0$ along the vertical position. The assembly errors might have serious impact on undulator magnetic field and phase error performance, when the period length is shorter than 20mm. Thus, using an in-situ measurement system [22] to verify the magnetic field becomes necessary. Local field variation resulting from gap errors can be

corrected with a differential adjusters developed in SPring-8 [23].

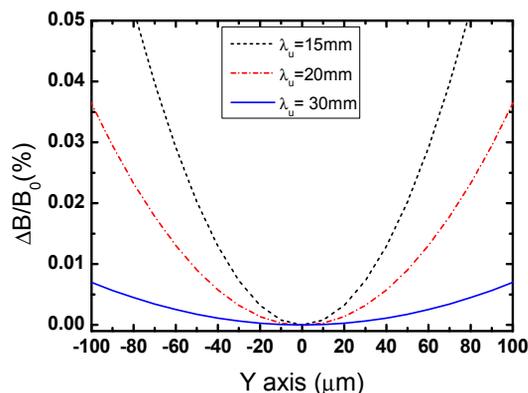


Figure 1: Relation of vertical position and field variation in various undulator period lengths. Results are calculated by RADIA code[24].

Phase Error Issue

In a low emittance or ultimate storage ring with medium beam energy, the utilization of higher harmonics of undulator radiation is thought to be major for hard X-ray beamlines. Therefore, low phase error performance of IVUs is quite essential. For a short period IVU, the phase error performance becomes degraded due to the assembly errors, deformation of an in-vacuum girder, Permendur pole saturation at a small gap and manufacturing errors of PMs and poles. A strong attractive force results in large girder deformation and gap errors, thus a phase error becomes prominent at a small gap. The strong attractive force can be compensated with a counter force system, described in the next section. Regarding Permendur pole saturation at a small undulator gap, this material, commonly used in a hybrid-magnet-structure IVU, is saturated at 2.3T. Before pole saturation, magnetic flux of earth field is corrected by the Permendur poles and the magnetic field intensity increases, but at a small undulator gap the poles become saturated and the permeability become unity. The earth field is no longer corrected by a pole. From the behavior of earth field, the changes of magnetic flux intensity at small gap would result in the excitation of phase error. Therefore, it is difficult to maintain low phase error through entire small gaps. Regarding manufacturing errors of PMs and poles, the machining errors of PM keepers is, at best, ~10 μ m. The magnetic field errors of an undulator increase with an increasing ratio of gap-error to period. The machining and assembly error may result in an increase of phase error when undulator gap becomes small. The situation deteriorates for a shorter period IVU.

Counter Force System

It is well-known that the magnetic force increases exponentially as an undulator gap decreases. In a short period/small gap undulator, a counter force system may be necessary to maintain the girder deformation small or to make a compact gap-driven system. The design of the

counter force system shall have no effect on the magnetic field of beam center line and there must be no damage from upstream bending magnet (BM) SR. Simple structure shall be adopted in vacuum to avoid risk of fatal failure and to obtain good accessibility for field measurement system. Three types of force-cancellation systems have been proposed in insertion devices. 1) For a repulsive force generated by magnets, two-sided magnet arrays with opposite magnetization from the main magnet array are applied to a revolver undulator in Spring-8 [25]. According to this concept, a cost-effective multipole monolithic magnet has been tested for a small gap IVU [26]. 2) For a spring system for an in-vacuum wiggler in SOLEIL [27], nonmagnetic springs-coils with two spring coefficients are installed at the side of magnet arrays for force compensation. 3) A set of exponential characteristics of conical spring-system for an APS vertical polarization undulator can allow close fit to the magnetic forces for compensation [28]. Other spring configurations can be found in SALCA undulators [29].

Heat Load Issue

Beam-induced heat load (SR and image current heating) with the slope of a magnet cover from PMs manufacturing errors constrains the IVU operation as a large potential risk of avalanche meltdown on a magnet cover.

The heat load on a magnet cover, derived from SR coming from an upstream bending magnet, increases dramatically when the undulator gap is small, particular at the end of a magnet array. To avoid such a risk, a tight orbit interlock for orbit mis-steering is necessary. One must also take precautions about scattering SR. Regarding image current heating on the magnet cover, power on a cover is inversely proportional to the undulator gap [18]. The manufacturing errors of magnets or keepers create some level difference from adjacent magnets. The slope angle on a magnet cover increases due to those manufacturing errors. The local power density on a magnet cover is associated with ratio between a slope angle of a magnet cover and an incident angle derived from SR. As a result, local power density on the magnet cover may be 2~5 times larger than zero slope case.

CRYOGENIC PERMANENT MAGNET UNDULATOR

The development of CPMUs for short period undulators has become a recent trend. CPMUs in ESRF [30,31], DLS [32], SOLEIL [33], SLS [34] and SPring-8 [35] were constructed and installed in the ring. More new CPMU projects are in progress at DLS [36], HZB [37], TPS [38], SOLEIL LUNEX5 [39] and ESRF [31]. The development of a CPMU is motivated by KEK non-baking plan B. The CPMU technologies can be extended from IVUs and development has been advanced at SPring-8 [10][40][41].

The outgassing from PMs is suppressed at cryogenic temperature (CT). A CPMU operates at CT and PMs fabrication is at room temperature (RT), therefore, the

aging process is unnecessary. However, it should be noted that H_{cj} at RT shall be higher than 1000 kA/m to avoid demagnetization during magnet assembly at RT.

ESRF has demonstrated a non-baked CPMU can operate smoothly in the storage ring and beamline [31]. Another motivation is that the performance of rare-earth-based magnets has been improved at lower temperatures. Remanence and coercivity increases in accordance with the cooling, but the remanence of NdFeB reach the maximum around 150K. Because of 2~3 times increased coercivity at CT, aging process for PMs can be regarded as to be finished at room temperature, therefore, there is a little radiation damage to the magnet.

Magnet Choice for a CPMU

Magnets of NdFeB [40], PrFeB [42] and $(Nd_{0.2}Pr_{0.8})FeB$ [43] are commonly used in CPMUs. The well-known effect is that usage of the NdFeB is limited to temperature around 140~150 K due to magnet spin-orientation transition phenomenon, the PrFeB magnet has no such limit on contrary. After the performance of a PrFeB CPMU was proven in SOLEIL [33], PrFeB or $(NdPr)FeB$ magnet has become a favorable choice of magnets in a CPMU development, so adopting a higher remanence with low coercivity magnet become practical.

Figure 2 shows the field measurement for several magnetic materials that can be selected for a CPMU. The NdFeB magnet has a maximum magnetic field around 160 K. A PrFeB magnet has a good performance compare to NdFeB for a temperature below 200 K. The magnetic flux intensity at 77K increase 115% from 300K.

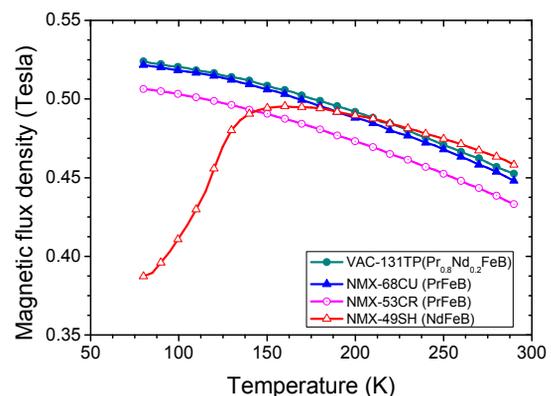


Figure 2: Dependence of magnetic flux density on temperature. All the samples have a same permeance of about unity. A Hall probe was used to measure the magnetic field at a selected distance.

Cryogenic Cooling Method

Two common methods, LN_2 cooling [30-34,36] and cryo-cooler cooling [35,38], have been adopted for CPMUs. Good magnetic performance for $(NdPr)FeB$ and PrFeB CPMU is obtainable with cryo-coolers because magnet can be cooled down to the low temperature below 77 K. Cryo-cooler is also an effective choice for a facility where LN_2 transfer line is not available. A system for LN_2 with stable pressure and closed-loop circulation LN_2 system can be adopted to be shared with monochromators

in beamlines. A thermosiphons arrangement with LN₂ [36] can provide a large cooling capacity and can be efficient for several CPMUs operated concurrently. The drawback of LN₂ cooling method is lack of flexibility to decrease PMs temperature below 77K.

Thermal Budget and Mechanical Issue

In the case of a CPMU operating at a small gap, the magnetic attractive force at low temperature can be high. For example, TPS CPMU (period 15mm) at the gap of 3mm, the magnetic force reaches 30 kN/m [38]. The counter force system presented at previous section might be an effective solution to construct a compact frame. In the optimization of the number of bellows shafts (BSs), we must take into account the in-vacuum girder deformation and conduction heat transfer via BSs. A special design of hollow BSs can reduce conduction heat transfer by a factor of 5~10.

The magnet temperature is balanced from conduction heat transfer via BSs, radiation, the beam-induced heat load and cooling power. To keep stable PMs temperature, heaters are used to compensate the beam-induced heat load (depending on beam current, undulator gap or filling patterns). Precautions must be taken for the deformation of in-vacuum girders caused by heating and cooling cycle of heaters.

Material contraction at low temperature causes a gap to widen by several hundred μm relative to 300K, mainly arising from shrinkage of in-vacuum girder. An optical gap measurement system [9] or a moving wire [44] to determine the physical gap at low temperature is necessary.

Temperature Variation of Magnet Array

The temperature variation of magnet array increases phase error because of the gap errors due to material contraction (magnet keepers, in-vacuum girder and bellows shafts) and variation of magnetic properties (remanent field). The phase error at CT hence may be increased from that at RT. From the practical experience at ESRF [45] and SOLEIL [46], the temperature variation on an aluminum-alloy girder with LN₂ cooling is about 1~2 K/m. For improvement to have small thermal variation (target <0.1K/m) of magnet arrays, one can adopt 1) OFHC girder, 2) increase of the cooling capacity, such as thermosiphons cooling arrangement, 3) distribution of several heaters with precise temperature controls or 4) optimization of cooling points with the cryo-cooler cooling method. A tapering function of mechanical frame might be necessary to correct residual linear temperature gradient. Differential adjusters may be implemented to correct such local gap errors.

In-situ Measurement System

One of main tasks in the development of CPMUs is to measure the magnetic field at cryogenic temperature and to correct gap errors due to temperature variations. A compact in-situ measurement system shall be located in the insulation vacuum ($P < 1 \times 10^{-4}$ Pa). As a Hall sensor is

cooled by its vicinity of cold magnets, a temperature-dependent calibration of a Hall probe is necessary. All the components of the system shall be vacuum compatible to avoid contamination. SPring-8 and TPS [22,47] in-situ measurement system is based on laser-positioning components and dynamic adjustment of rail positions to ensure that the Hall sensor moves in the magnetic field center. In the ESRF system, a hall probe moves on a linear guide rail and hall probe position errors caused by a rail is measured. The magnetic field is corrected on taking into account the rail errors [44]. HZB proposed a new structure of a system in which the hall carrier moves by stainless steel strings. All the degrees of freedom in hall probes (orientation and displacement) can be corrected by 5 piezo-motors. [48]. Precaution about minor issues might affect the results, such as signal wire bending, contact resistance at vacuum feed through and so on.

LATTICE FUNCTIONS FOR IVU/CPMUS

Low emittance, low emittance coupling and low energy spread is essential to realize a high brilliance undulator radiation. The most important goal of USR is to obtain high brilliance of SR not low emittance of electron beam, and the lattice function for IVU/CPMUs at straight sections shall be considered to have an optimal betatron function and zero desuperation function. The perfect matching of the betatron function to an insertion device shall satisfy $\beta_{x,y} = L_u / 2\pi$, where L_u denotes undulator length, to have maximum brilliance. The design of betatron function becomes very important for a USR, where emittance of electron is comparable to intrinsic photon beam emittance of 8 pm.rad (for radiation wavelength of 1Å). In Fig. 3, the decrease of brilliance is very sensitive to the choice of betatron function in a low emittance case.

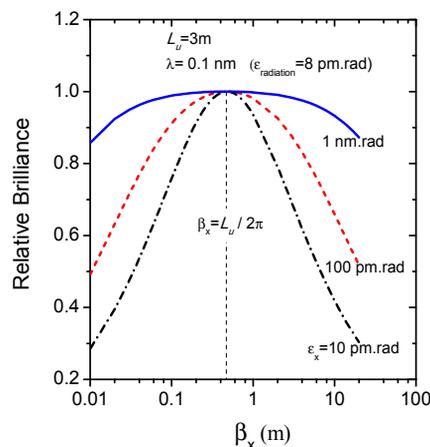


Figure 3 : Dependence of the relative brilliance on horizontal betatron function in various electron emittance.

In a low β_x case, a pole width of magnet can be reduced and low attractive force is generated. Therefore, a compact mechanical frame and low cost of IVU/CPMUs become possible. If we consider injection at straight section, β_x shall be high to maintain high injection efficiency. For a choice of vertical betatron function, β_y must be a

half of undulator length to have long beam lifetime, and this is particular important for a small gap undulator operation. As a result, $\beta_x = L_u / 2\pi$ and $\beta_y = L_u / 2$ is recommended for IVU/CPMUs to have a high brilliance with long beam lifetime.

Emittance can be lowered by finite dispersion at straight sections, however this is not always effective for high brilliance undulator radiation. The lattice function must have zero dispersion function, η_x at straight sections for IVU/CPMUs. A dispersion free straight section can avoid reduction of brilliance due to the increase of source size by energy spread. In addition, emittance growth can be avoided and one can expect emittance reduction derived from damping effect. Operation of multiple high magnetic-field undulators can reduce emittance furthermore and higher brilliance can be expected in all the undulators.

IN-VACUUM UNDULATOR FOR XFEL

On adopting IVUs having a short period, the beam energy can be decreased and the facility become compact. (SACLA (8 GeV) [49], and Swiss FEL (5.6 GeV) [50]). The design criteria of an IVU depends on the accelerator type. The consideration of IVUs design criteria based on LINAC-based XFEL with a single pass electron compared with multi-turn re-circulating electrons in storing

ring is shown in table 1. In LINAC-based XFEL, the heat load and injection issue becomes less critical, and the small gap around 2mm operation become practicable. Narrow poles and vacuum pressure requirement make the low cost of XFEL undulators. In general, the requirement of undulators in storage ring is more stringent than that in XFEL one and all the components in storage rings must be high temperature resistance for UHV baking and UHV compatible.

SUMMARY

The development of IVU/CPMU is a recent trend for short period undulator as X-ray source. For an in-vacuum undulator, the technologies of IVU are mature and the main challenge in the development is phase error issue. For a CPMU, the performance is proven and related technologies are developing. CPMU has high resistance against thermal budget compared to superconductive undulator and very narrow gap may be allowed. Low temperature variation to ensure low phase error performance. High magnetic field performance of short period IVU or CPMU may cause high heat load problem for beamline components.

Table 1: IVU Requirements for LINAC-based XFEL and Storage Ring

Design criteria	LINAC-based XFEL	Storage Ring
Vacuum requirement	P<1E-6 Pa (No-baking) Vacuum compatible components can be used	P<1E-8 Pa (Baking is necessary).Components shall have strong thermal resistance
Phase Error	Critical	Very critical for high harmonics operation
Heat load associate to average beam current	~nA Not critical	~100mA /Very critical at small undulator gap operation.
Minimum Gap	G _{min} ~2mm and limited by electron beam loss	G _{min} ~4mm and limited by beam lifetime and beam heating
Magnet design	Narrow pole pieces	In high β_x case, wide pole necessary to keep high injection efficiency

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