

INSERTION DEVICES OF NEXT GENERATION

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Abstract

One direction of the recent insertion device development is the pursuit of short periodicity. After the advent of in-vacuum undulators, short period undulators have been widely used at small gaps in many synchrotron radiation facilities. In order to pursue shorter periodicity, however, further improvement of the magnetic performance is needed. Although a superconductive device is a prospective candidate, there still remains technological R&Ds such as the thermal budget problem and new magnetic field correction methods. In this paper, we propose a new approach for the construction of a high performance short period undulator, in which the permanent magnets are used at cryogenic temperatures. In this so-called cryogenic permanent magnet undulator (CPMU), the magnetic field performance is improved by roughly 30 % compared with the current in-vacuum undulators. Since the CPMUs are operated at the temperature of liquid nitrogen or higher, a cryocooler with sufficient cooling capacity (several hundred watts) is available and the thermal budget is no more a problem. Moreover, there is no quench in the CPMUs and stable operation of the undulator can be expected. Design examples and expected performance of the CPMUs are given in the paper.

INTRODUCTION

Short periodicity in an undulator brings a number of benefits as a synchrotron light source. It increases the number of undulator periods and produces brighter radiation. At the same time, high energy radiation becomes available at synchrotron radiation facilities of medium or small size. In SASE-FEL (Self-Amplified Spontaneous Emission) facilities, a short period undulator is also attractive, because it lowers the electron beam energy necessary for FEL operation and reduces the size of the facility. On the other hand, a short period undulator should be operated at small magnetic gaps in order to obtain sufficient magnetic fields due to its small magnet size. From this aspect, high performance magnet materials are indispensable for the development of short period undulators.

One prospective technology is superconductive magnets. Since the superconductive magnets can produce very high fields, they have been commonly used as wigglers in synchrotron radiation facilities. Meanwhile superconductive undulators (SCUs) has been developed for more than twenty years [1, 2, 3], they have not become popular as an insertion device because of its technological difficulties. Unlike wigglers, the dimension of the undulator magnetic structure is small and high precision is necessary in the field

alignment of undulators. Although the latest SCU achieves 1.3 T with a undulator period of 14 mm [4], careful consideration is necessary in the thermal budget problem to prevent a quench [5].

In this paper, we propose new strategy of the short period undulator development, so-called the cryogenic permanent magnet undulator (CPMU), using permanent magnets at the temperature of liquid nitrogen or higher [6]. Compared with conventional in-vacuum undulators [7], the CPMUs are superior not only in the magnetic performance, but also in the hardness against demagnetization caused by electron beam irradiation. The construction of the CPMUs simply requires small modification in the currently used in-vacuum undulator design [8].

Table 1: Parameters of commercially available rare earth magnets. B_r and $\mu_0 iH_c$ are the values on the catalogue at room temperature. NEOMAXs are the products of Sumitomo Special Metal and VACOMAX is from Vakuumschmelze.

Magnet (type)	B_r (T)	$\mu_0 iH_c$ (T)
NEOMAX 50BH (NdFeB)	1.39-1.45	1.4
NEOMAX 48H (NdFeB)	1.36-1.42	1.6
NEOMAX 35EH (NdFeB)	1.17-1.25	2.5
NEOMAX 53CR (PrFeB)	1.3	1.2
VACOMAX 240HR (Sm ₂ Co ₁₇)	1.05-1.12	0.8-1.0

PERFORMANCE OF PERMANENT MAGNETS AT CRYOGENIC TEMPERATURES

The material of permanent magnets commonly used in undulators is NdFeB or SmCo magnets. NdFeB magnets have higher remanent fields (B_r) whereas SmCo magnets show better radiation resistance against electron beams. In case of using NdFeB magnets, particularly in the in-vacuum undulators, it is necessary to choose a large coercivity (iH_c) material in order to prevent demagnetization due to electron beam irradiation [9]. In general, large iH_c NdFeB magnets show small B_r , therefore, the undulator magnets can not take full advantage of the magnetic field performance of NdFeB magnets. However, the remanent field and coercivity of NdFeB magnets increase as lowering the temperature, and high B_r magnets become to have sufficiently large iH_c under the circumference of cryogenic temperatures. By using this characteristic of NdFeB magnets, high magnetic fields can be achieved with radiation resistant magnets in undulators.

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Magnetic field performance of rare earth magnets at cryogenic temperatures

In order to investigate the characteristics of B_r at cryogenic temperatures, the magnetic fields of five commercially available magnets were measured (table 1), including three different types of rare earth magnets, NdFeB, PrFeB and SmCo magnets.

Figure 1 is the measured B_r of the five magnets as a function of temperature. The magnetic fields were measured by fixing a hall probe at the surface of the magnet samples. Then, the measured fields at the position of the hall probe were converted to B_r . The magnet samples were magnetized at room temperature and the variation of the magnetic field was followed. Note that the field changes in Fig. 1 are completely reversible with respect to the temperature.

As well known, B_r of the NdFeB magnets has a negative temperature coefficient, roughly 0.1 %/K around room temperature. As cooling down the magnet, B_r increases as shown in Fig. 1. Below a certain temperature around 140 K, however, B_r starts decreasing due to a spin reorientation [10]. In case of the SmCo and PrFeB magnets, this field decline was not observed.

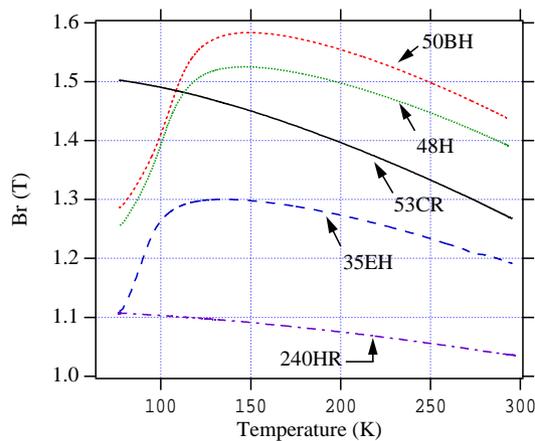


Figure 1: Temperature dependence of the remanent fields (B_r) of five commercially available magnets (table 1).

Coercivity of NdFeB magnets at cryogenic temperatures

iH_c of the NdFeB and PrFeB magnets in table 1 were measured using a superconductive magnetometer, which can apply ± 7 T to the sample under temperature controlled atmosphere. The measured temperature dependence of iH_c is shown in Fig. 2.

NEOMAX 35EH, which has large iH_c but medium B_r , is the magnet used in the conventional in-vacuum undulators at SPring-8. From Fig. 2, it is figured out that iH_c of all magnets goes beyond the room temperature iH_c of 35EH

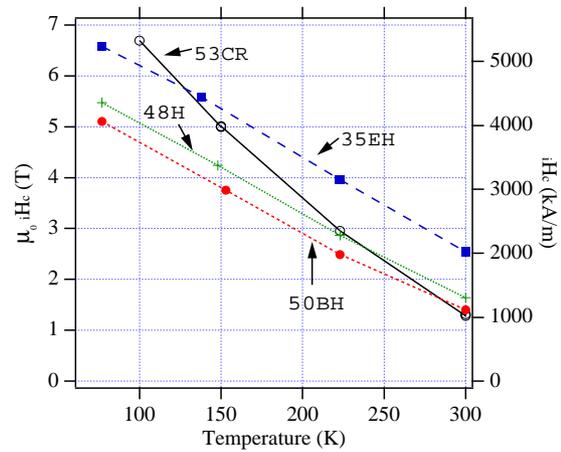


Figure 2: Temperature dependence of the coercivity (iH_c) of the sintered NdFeB and PrFeB magnets in table 1.

($\mu_0 iH_c \sim 2.5$ T) below 200 K, and the high B_r magnets become to have sufficient iH_c at cryogenic temperatures.

The radiation resistance of NdFeB magnets is related to iH_c and large iH_c magnets have higher resistance. Recent work reveals that the NdFeB magnet with $\mu_0 iH_c = 3.6$ T (Sumitomo Special Metal NEOMAX 27VH) has the same resistance as $\text{Sm}_2\text{Co}_{17}$ magnets [9], which were believed to be most resistant against electron beam irradiation among rare earth magnets. The improvement of radiation resistance at low temperatures was already confirmed for NdFeB magnets using proton beams [11] and the same result can be expected against electron beams.

DESIGN EXAMPLES OF THE CPMUS

Figure 3 is examples of the CPMU design. Since the magnet arrays of the in-vacuum undulator are already located inside vacuum (Fig. 3 (a)), the CPMU can be realized by simply adding some refrigerant channels (Fig. 3 (b)) or cryocoolers (Fig. 3 (c)). Supposing the CPMU operation in SPring-8 with a 203-bunch mode, the estimated amount of heat load of a 1.5 m long CPMU is about 130 W: 100 W incoming through the beam shafts, 30 W due to thermal radiation of inner chamber surfaces, synchrotron radiation and resistive wall effect. Unlike superconductive undulators, the CPMUs are assumed to be operated at the temperature of liquid nitrogen or higher. Therefore cooling capacity of a few hundreds watts can be easily obtained and the expected heat load can be covered with a compact cryocooler of Gifford McMahon type.

For ultra-high vacuum compatibility, the magnets of the conventional in-vacuum undulators should be baked out before installation. But the CPMU operation at cryogenic temperatures significantly decreases the outgassing rate from the magnets and the bake out is no more necessary. In addition, field alignment techniques developed for conventional undulators can be directly applied to the CPMUs.

Regarding the magnet material, there are two choices,

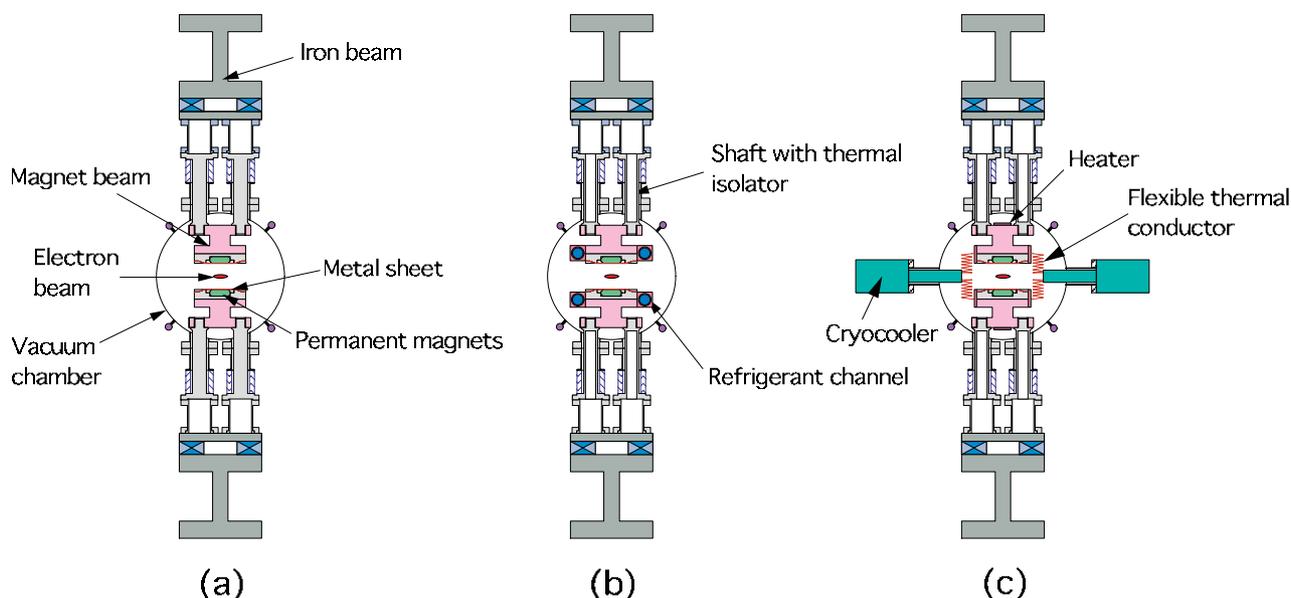


Figure 3: Design examples of the CPMU, (a) conventional in-vacuum undulator, (b) CPMU with refrigerant channels and (c) CPMU with cryocoolers.

NdFeB or PrFeB magnets. If the high B_r NdFeB magnets are used, operating temperature should be maintained at the optimum temperature, which is around 150 K for 50BH as shown in Fig. 1. Since the temperature dependence of the magnetic field becomes smaller at cryogenic temperatures, better field stability can be expected compared with the undulator operation at room temperature. In case of the PrFeB magnet (53CR in Fig. 1), the magnets can be cooled down to 77 K using liquid nitrogen as a refrigerant. In both cases, the magnetic field of the CPMU gains a 25-30 % increase and iH_c becomes more than 50 % higher compared with the conventional in-vacuum undulators at room temperature.

EXPECTED PERFORMANCE OF THE CPMUS

CPMUs as a synchrotron radiation source

A short period undulator is a very important tool for the x-ray beamline operation in medium size synchrotron radiation facilities, such as SLS and Soleil [12, 13]. Figure 4 compares the peak magnetic fields of a 19 mm period hybrid undulator between a conventional in-vacuum type ($B_r = 1.2$ T) and a CPMU ($B_r = 1.58$ T). The conventional in-vacuum undulator produces a magnetic field of 1.2 T at 4 mm gap, but the same field can be obtained at 5.2 mm gap in the CPMU.

In order to estimate the spectral performance, the beam parameters similar to the SLS storage ring are taken as an example: beam energy = 2.4 GeV, beam current = 400 mA, emittance = 5.0 nm rad. Using these parameters, brilliance is calculated up to 9th harmonic for a conventional hybrid

in-vacuum undulator with λ_u (undulator period) = 19 mm, a hybrid CPMU with $\lambda_u = 16$ mm and a hybrid CPMU with $\lambda_u = 12$ mm. The results shown in Fig. 5 indicate that the CPMUs can provide access to higher photon energy range with higher brilliance because of short undulator period and high magnetic performance.

CPMUs as a SASE-FEL source

Short period undulators are also attractive for SASE-FELs, since they lower the required electron beam energy and shorten the facility length. As an example, the parameters of the SCSS are used for the estimation. The SCSS is a SASE-FEL project aiming at 3.6 nm radiation using the 1 GeV-1 kA electron beams in the first phase [14]. In the SCSS, an in-vacuum undulator of 45° tilted pure magnet type with $\lambda_u = 15$ mm is used at the gap of 3.6 mm to obtain a deflection parameter (K) = 1.3 [15].

Figure 6 shows achievable K parameters at 3.6 mm gap of a conventional in-vacuum undulator and a CPMU as a function of the undulator period. In Fig. 6, about 30 % higher K is obtained at the same gap or the same field is obtained at a larger gap when using the CPMU. As a consequence, the undulator period can be made shorter. Figure 7 compares the 3-D gain length of SASE [16] between the two undulators as a function of the undulator period. With $\lambda_u = 12$ mm in the CPMU, the gain length becomes shortest and the required energy is decreased from 1 GeV to 0.87 GeV for 3.6 nm radiation.

The short period CPMU is also beneficial in a high-gain harmonic-generation scheme for exploiting shorter wavelengths [17, 18].

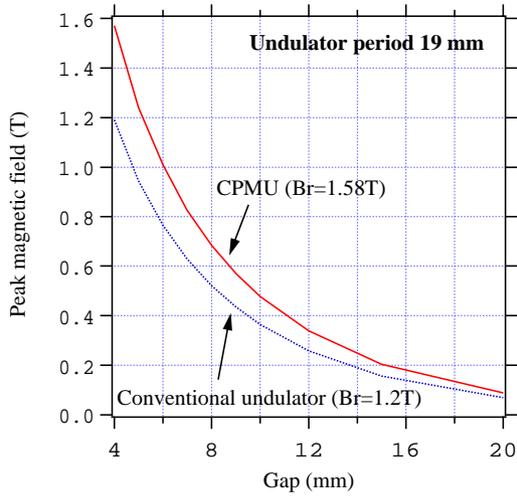


Figure 4: Comparison of the peak magnetic fields between a room temperature in-vacuum undulator (blue dotted line) and a CPMU (red solid line). Both undulators have the same hybrid structure with $\lambda_u = 19$ mm.

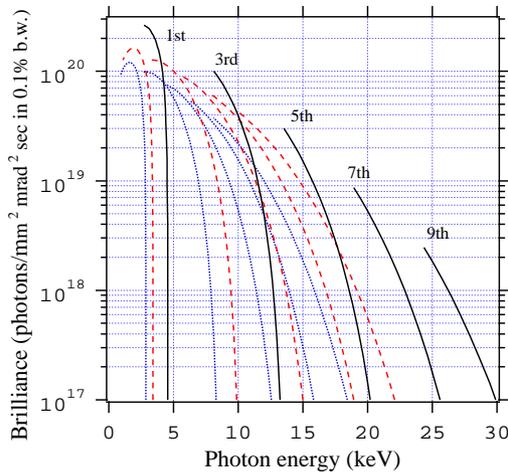


Figure 5: Calculated spectral performance of a conventional in-vacuum undulator with $\lambda_u = 19$ mm (blue dotted line), a CPMU with $\lambda_u = 16$ mm (red dashed line) and a CPMU with $\lambda_u = 12$ mm (black solid line). All undulators are the same hybrid type and the minimum gap is fixed at 4 mm. Brilliance up to 9th harmonic is shown in the figure.

Comparison with a superconductive undulator

Table 1 is a comparison of the magnetic gaps among the latest SCU developed by ACCEL [4], a conventional pure magnet in-vacuum undulator and CPMUs under common conditions of $K = 1.8$ and $\lambda_u = 14$ mm. In case of the conventional in-vacuum undulator, the magnetic gap should be closed to 1.9 mm to fulfill the conditions. However, the gap is eased to be 3.2 mm for the CPMU of a pure magnet type. The necessary gap is further enlarged to 3.8 mm for the hybrid CPMU, in which additional magnets are

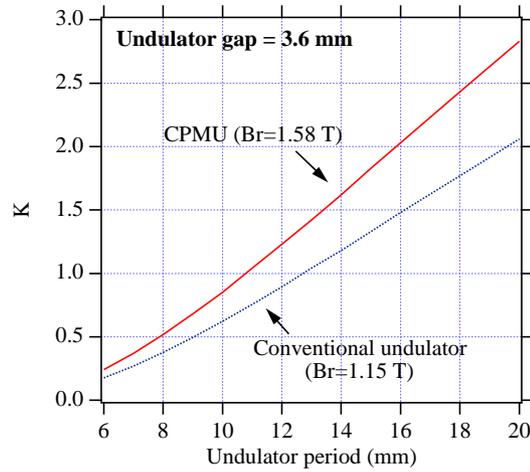


Figure 6: Comparison of K between a conventional undulator and a CPMU as a function of the undulator period. The undulator gap is fixed at 3.6 mm and both undulators are the 45° tilted pure magnet type [15].

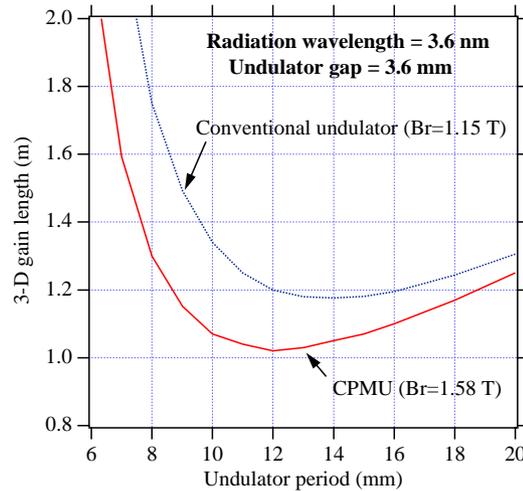


Figure 7: 3-D gain lengths of a conventional in-vacuum undulator and a CPMU as a function of the undulator period. 45° tilted pure magnet type is assumed for both undulators [15]. The undulator gap and radiation wavelength are fixed at 3.6 mm and 3.6 nm respectively, and the electron beam energy is changed accordingly.

placed beside poles in order to increase the magnetic field [6, 19].

DISCUSSIONS

When compared at the same magnetic gap, the magnetic field of the CPMUs is not as high as the SCU as shown in table 1, and there is room for higher magnetic fields for SCUs if using Nb_3Sn coils [20]. However, if comparing the magnetic performance in terms of the physical aperture for the electron beams, the performance of the CPMUs comes

Table 2: Comparison of the magnetic gaps among the SCU developed by ACCEL [4], a conventional pure magnet in-vacuum undulator and the CPMUs, under common conditions of $K = 1.8$ and $\lambda_u = 14$ mm. The magnet material of the CPMUs is 50BH assuming the operation at 148 K.

Type	Gap (mm)
ACCEL SCU [4]	5
Conventional in-vacuum	1.9
CPMU pure magnet	3.2
CPMU hybrid	3.8

close to that of the SCUs. There are two options for the cryogenic design of SCUs, either a cold bore exposing the magnets to the electron beam or a warm bore inserting thermal insulators between the magnets and the electron beam. Considering the capacity of current cryocoolers at the temperature of liquid helium, the heat load of the cold bore design should be smaller than a few watts to prevent a quench. With the warm bore design, the magnetic performance of SCUs is degraded depending on the effective gap loss due to the thickness of insulators. On the other hand, the magnetic gap of the CPMUs corresponds to the promised aperture for the electron beam except an additional 0.1 mm gap loss due to the metal sheets covering the magnet surface [8].

In the CPMUs, the thermal budget problem is not so serious because compact cryocoolers with large cooling capacity are available at the temperatures higher than the liquid nitrogen temperature. The operation of the CPMUs has the same reliability as conventional permanent magnet undulators, since there is no possibility of a quench. Although field measurements may have to be carried out at cryogenic temperatures, the field correction techniques developed for conventional undulators can be directly applied to the CPMUs. Thus the development of the CPMUs is straightforward from the current in-vacuum undulator technology.

In this paper, we showed the achievable performance of the CPMUs using the currently available technologies of permanent magnets. However, the performance of NdFeB magnets is still being improved. Particularly, PrFeB magnets have potential for higher magnetic fields, since they have been almost abandoned for more than ten years because of a lack of demands. If the manufacturing techniques accumulated on the improvement of NdFeB magnets are applied to PrFeB magnets, further improvement of the CPMU performance can be expected.

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