DESIGN CRITERIA AND TECHNOLOGY CHALLENGES FOR THE UNDULATOR OF THE FUTURE

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Abstract

Demands for short-period undulators as X-ray sources are very urgent particularly in the medium-scale facilities. Accordingly, a great many efforts have been paid to develop short period undulators such as an in-vacuum undulator, a superconducting undulator and a cryogenic permanent magnet undulator. The paper describes briefly the status of the developments.

INTRODUCTION

Nowadays, undulators are essential devices for synchrotron radiation (SR) facilities [1,2,3] since they generate a quasi-monochromatic radiation with various features such as high brightness, high energy and special polarization characteristics. Particularly, demands for high-energy radiation in the X-ray region have become much stronger in many research fields. Accordingly, a short-period undulator design has been developed since they increase the number of periods in a unit undulator length and as a consequence, they generate brilliant SR [4]. Also, short undulator periodicity enables emission of high-energy photons, and it opens the way for X-ray beamline operation in medium scale SR facilities [5], such as NSLS (USA, 2.8 GeV), SLS (Switzerland, 2.4 GeV) [6], ALS (USA, 1.9 GeV) [7], PLS (Korea, 2.5 GeV), SOLEIL (France, 2.75 GeV), DIAMOND (UK, 3 GeV), CLS (Canada, 2.9 GeV), AS (Australia, 3 GeV), SSRF (China, 3 GeV) and so on. From the same reason, a short-period undulator is very attractive for SASE-FEL or ERL facilities, since it lowers the electron beam energy necessary for X-ray operation [8]. As a result this design makes a whole facility design compact and economic. Therefore, a great many efforts have been paid to develop short period undulators such as an in-vacuum undulator [9,10], a superconducting undulator (SCU) working around liquid helium temperature [11,12], and a cryogenic permanent magnet undulator (cryoundulator) [13].

IN-VACUUM UNDULATORS

Basic principle

The dimensions of each magnet piece for short-period undulators become smaller and consequently, the undulator should be operated at small magnetic gaps in order to obtain sufficient magnetic fields. One big advance to realize such a requirements has been an in-vacuum design, which accommodates permanent magnet arrays inside vacuum and eliminates a physical limitation of the magnetic gap due to a vacuum chamber. The magnetic gap can be controlled via bellows coupling with a mechanical driving system working in the atmospheric environment, and the achievable minimum gap can be designed to be almost zero. The first in-vacuum undulator (IVU) was developed at KEK in 1990 [9]. Since then, IVUs have been successfully operated for years in many synchrotron radiation facilities.

Permanent magnets

As a permanent magnet (PM) material for IVUs, NdFeB magnets with high coercivity or Sm_2Co_{17} magnets are generally used. The PMs for IVUs are arranged in the ultrahigh vacuum (UHV) connected directory to the storage ring vacuum system, which is the most important characteristic of IVUs. However, there are two difficulties arising from PM materials. One is out-gassing from the surfaces of the rare earth PMs due to their porous structure, which can be solved by the coating on the PM surface by nickel electroplating or titanium nitride (TiN) ion-plating. Particularly, the TiN coating is suitable for short-period undulators where small PM pieces are adopted. The thickness of TiN coating is as this as 5 micron, and the hardness is very high. Accordingly, we can expect small volume errors in PM pieces. The other difficulty, particularly for NdFeB, is irreversible demagnetization of PMs during UHV bakeout at the temperature higher than 380 K . To solve it, we have to adopt permanent magnets having very high coercivity. In addition to that, it is necessary to apply aging process to the PMs at the temperature somewhat higher than that of UHV bakeout. The choice, NdFeB or Sm_2Co_{17}, depends on the concept of each SR facility. At SPring-8, NdFeB has been used because this material is much more substantial as well as has higher remanent field compared to Sm_2Co_{17} which is easily broken to powder. On the other hand, ESRF has chosen Sm_2Co_{17} having a good resistance against radiation damage as is described later.

Here, let us show an important problem, radiation damage of PMs in undulators. The demagnetization of PMs is thought to be caused by neutrons produced by electron beam irradiation. It has been reported from several SR facilities that the demagnetization of NdFeB PMs in undulators often occurred. Since the demagnetization has been found in ordinary out-of-vacuum undulators, the demagnetization problem is thought not to be a specific issue for IVUs. And furthermore, we know that any demagnetization has not been found in SPring-8 whereas 20 IVUs have been operated under the unfavorable condition with respect to the radiation damage. To solve such a fact looking contradictory, we performed a demagnetization test on various PM materials using the 2-GeV electron linear accelerator at Pohang Light Source [14,15].

The results are summarized in Fig. 1, where we can found two important tendencies; the resistance against electron beam irradiation is higher for NdFeB PM material with higher coercivity, and it can be improved by thermal treatment. Therefore, we can understand the contradictory fact found in the IVUs at SPring-8. The choice of PM material and the thermal treatment for IVUs are also reasonable to obtain a high resistance against radiation damage. As shown in Fig.1, Sm_2Co_{17} and NEMAX-27VH shows the best resistance, but their remanent field is not so high. NEOMAX-35EH, adopted for the IVUs at SPring-8, has a higher remanent field performance but a lower resistance compared to that of Sm_2Co_{17}/27VH. Considering the practical case or actual results, however, we think that there is no problem in the use of 35EH since the irradiation dose of 150E13 (the maximum of the graph in Fig. 1) is almost equal to the number of electrons being 500 times higher than that stored in the SPring-8 ring at 100 mA. Anyway, the choice, high remanent field or high resistance, is a trade-off issue.

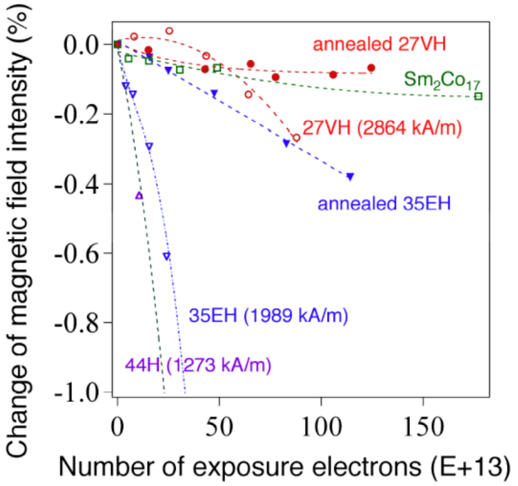

Fig. 1: Radiation-induced demagnetization curves of NEOMAX-27VH (with/without annealing), 35EH (with/without annealing, 44H and Sm_2Co_{17}

Metal cover for magnet arrays

When a bunched beam passes through the gap of an IUV, the image current flows in the facing sides of the magnet arrays with a power generated according to the simple Joule's law [18]. Therefore, the magnet arrays of an IVU should be covered with a thin metal foil, which is also necessary to screen the periodic structure of undulator magnets. Considering the skin effect, the power of the image current heating is given approximately [17] with SI unit by

$$P = MI_b^2\left(\frac{L_u}{\pi G}\right)\frac{\Gamma(3/4)}{\omega_0\sigma_t^{3/2}}\sqrt{\frac{\mu_0\rho}{2}}$$

where M is the number of bunches, I_b: the beam current per bunch, ρ: the resistivity of the foil, L_u: the length of undulator, G: the magnetic gap, ω_0: the revolution frequency, σ_t: the bunch length. Therefore, the image current heating is not negligible when the gap is very narrow, the bunch current: very high, and the bunch length: very short. For an example, when we suppose I_b = 6 mA, M=16, σ_t = 30 psec, G = 4 mm, ω_0 = 1.3 MHz (SPring-8), ρ = 2E10-8 ohm.m (copper), the power may exceed 30 W for a 1 m IVU. The best choice for such a metal cover is Ni-plated copper foil. The thickness of copper foil is typically 50 micron with the Nickel layer thickness 10 micron. The reason for Ni-plating is that magnetic attraction is necessary to obtain good thermal contact. The magnetic flux loss is negligibly small as 0.01%. There is another choice for a magnet cover, Cu-plated Ni foil. In this case, the thickness of Cu layer is 10 micron, which is sufficiently thick to reduce image current heating since the skin depth is very short, typically, less than 1 micron. However, this thickness is not enough against resistive wall instability. In case of this instability, lower frequency components play an important role.

Another heat source for the magnet array is a synchrotron radiation coming from the upstream bending magnet. Since the magnet arrays of an IVU are thermally isolated by vacuum, they should be equipped with water-cooling channels.

Flexible transition

The dimensions of each magnet piece for short-period undulators become smaller and consequently, the undulator should be operated at small magnetic gaps in order to obtain sufficient magnetic fields. One big advance to realize such a requirements has been an in-vacuum design, which accommodates permanent magnet arrays inside vacuum and eliminates a physical limitation

Since the path for an electron beam should be smooth in the longitudinal direction, much attention should be paid to the space between the vacuum chamber and the end of the magnet arrays. If not so, unexpected parasitic mode would be excited with a beam instability. To reduce this excitation, we have to adopt a special transition between the undulator magnet array and entrance/exit of the vacuum chamber [10]. This transition should be flexible since the gap is variable, and have a water cooling channel against image current heating just described.

SUPERCONDUCTING UNDULATORS

Another candidate for shorter-period undulator development is a superconducting undulator (SCU) working around liquid helium temperature (LHeT). The first SCU for an electron storage ring was developed at

LURE a quarter of a century ago [11]. This SCU had a vacuum duct kept at liquid nitrogen temperature (LNT) inside the magnetic gap. For the thermal insulation space between the vacuum duct and the magnetic pole at LHeT, therefore, the magnetic gap was designed to be very wide as 22 mm compared to the inner height of the vacuum duct, 12 mm. As a result, the achievable magnetic field applied on the electron beam was not so high compared to that of a permanent magnet undulator, the performance of which was successfully demonstrated at SSRL a few years later. Since then, therefore, the mainstream in the undulator developments has been based on the permanent magnet technology. Recently, however, a new type of SCU using NbTi conductor has been developed with a 14 mm period at a magnetic gap of 5 mm [12]. This SCU has no vacuum duct inside the magnetic gap (in-vacuum type) so that a very high magnetic field of 1.3 T can be applied on the electron beam. The development of SCU is in progress all over the world [18, 19]. However, there is still a thermal budget problem as discussed previously in IN-VACUUM UNDULATORS. Although a high RRR (residual resistivity ratio) value in SCUs is expected against image current heating, the cooling capacity of SCUs is generally limited to several watts at the temperature of liquid helium. Serious consideration is needed against the heat brought by the electron beam.

It is noticeable that a 3.5 T SC wiggler of cold-bore type has been developed at MAX Lab [20]. Since this device has a vacuum duct inside of the magnetic gap, the concept is different from that being developed at ANKA. The total length of the wiggler is 1.47 m with a periodic length of 61 mm (47 poles). The duct with an inner aperture of 10.2 mm is coated inside with copper against image current heating. The power brought by the electron beam was measured as 1.59 W under the condition (beam current I= 200 mA, bunch length σ = 25 psec, multi-bunch mode, RF frequency f_{rf}=500 MHz, circumference C = 90 m). The image current part of the above value was 1.37 W and the rest part (SR): 0.26 W. If scaling the above result to the small number bunch operation of SPring-8 (I = 100 mA, σ =30 psec, 16 bunch mode, f_{rf} = 508 MHz, C = 1436 m), the calculation result for the image current heating is very high as 41 W. Therefore, we can say that the realization of in-vacuum/cold-bore type SCUs depends on the operating condition of an accelerator. As a matter of course, we have another choice to adopt a warm bore design, but it results in considerable deterioration in field performance in terms of a physical aperture for electron beams.

CRYOUNDULATORS

Motivation

As well-known, NdFeB PM exhibit negative dependence of remanent-fields or coercivity against temperature, typically -0.1 %/K or –0.6%/K around room temperature, respectively. According to this constant, the magnetic field or coercivity is expected to increase as cooling the magnets down to cryogenic temperature around liquid nitrogen temperature, which is a motivation to develop a new concept in undulator developments, called a cryogenic permanent magnet undulator, or “cryoundulator” [13].

Differently from SCUs, the important advantage of the cryoundulators (CRUs) is allowing very high heat load of several hundred watts, which can be covered by a compact cryocooler of Gifford McMahon type. And furthermore, the advantages of the CRUs over SCUs are not only saving of electricity but also stable operation without any quench. In addition, all techniques of field correction developed for PM undulators can be applied to the CRUs without any significant modification.

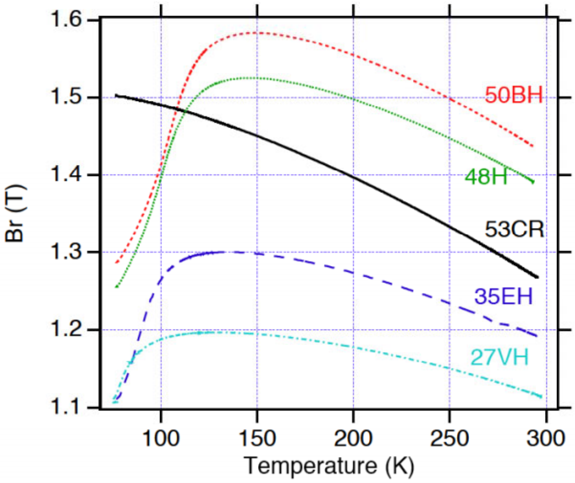

Fig. 2: Temperature dependence of remanent fields of the NdFeB and PrFeB magnets, NEOMAX-27VH, 35EH, 48H, 50BH and 53CR (NEMAX Co., Ltd.).

Performance of NdFeB PMs at cryogenic temperatures

In NdFeB PMs, there is a turning temperature around 140 K and the magnetic field starts decreasing below this temperature due to the spin reorientation. In order to find the optimum temperature, the remanent fields of commercially available NeFeB and PrFeB magnets are measured. Figure 2 shows the temperature dependence of remanent fields of the NdFeB and PrFeB magnets, NEOMAX-27VH, 35EH, 48H, 50BH and 53CR (NEMAX Co., Ltd.). The last material, NEOMAX-53CR, a PrFeB magnet containing Praseodymium (Pr) in substitution for Neodymium (Nd), was developed by NEOMAX Co., Ltd. 15 years ago. NEOMAX-35EH, which has high coercivity but a medium remanent field, is used for conventional in-vacuum undulators as SPring-8. NEOMAX-50BH and 48H are typical magnets with a high remanent field but low coercivity at room temperature. NEOMAX-27VH has a high resistance against radiation damage as mentioned previously. The optimum temperatures for NdFeB PMs (27VH, 35EH, 48H and 50BH) are slightly different, but they show similar behavior; the magnetic field decreases below a certain temperature. In contrast, the remanent field of

53CR continues increasing at low temperatures. It should be mentioned that the change of the magnetic fields in Fig. 2 is entirely reversible with respect to the temperature.

Meanwhile, the coercivity of these five magnets significantly increases at low temperatures. In order to measure coercivity (iHc), a superconductive magnetometer (Quantum Design MPMS XL7), which can supply -7 ~ +7 T under an atmosphere of precisely controlled temperature, is used. Figure 3 is the measured coercivity (iHc) of NdFeB and PrFeB magnets as a function of temperature.

As shown previously, the resistance of magnetization against electron beam irradiation relates to coercivity in case of NdFeB magnets. For an example, a NdFeB magnet with large coercivity (NEOMAX 27VH) has the same resistance as Sm2Co17 magnets, which were believed to be the most resistive against electron irradiation among rare earth magnets. The coercivity of 27VH is about m_0iHc=3.6 T at room temperature. Comparing this value to those in Fig. 3, even the coercivity of 50BH, which is the smallest among the measured five magnets, exceeds 3.6 T below 150 K. From these results, the magnets of CRUs are expected to have not only better magnetic performance, but also better endurance against electron beam irradiation compared with room temperature in-vacuum devices.

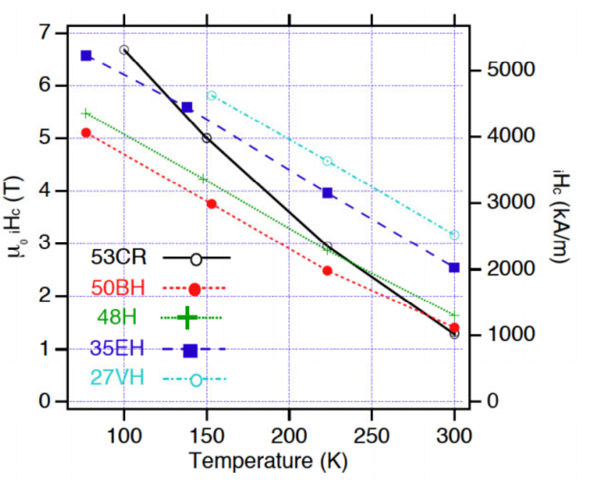

Fig. 3: Temperature dependence of coercivity of the NdFeB and PrFeB magnets, NEOMAX-27VH, 35EH, 48H, 50BH and 53CR (NEMAX Co., Ltd.).

Examples of cryoundulators

For a long time, a high remanent field PM such as NEOMAX-50BH has been believed to be unsuitable for practical undulators since its coercivity is very low at room temperature. However, the situation has drastically changed by the CRU concept. Here, we show the performance of an example of a CRU where NEOMAX-50BH is adopted. We consider two undulator types, pure and hybrid configuration types, with a periodic length of 14 mm. The pure permanent magnet undulator is supposed to be of Halbach type (magnet size: 35 mm in width x 10 mm in height). The other undulator is hybrid undulators using permendur as a pole material. Figure 4 compares the peak fields of two 14 mm period undulators as a function of magnetic gap calculated using RADIA [21]. As a reference, a plot for a room temperature pure magnet undulator made with 35EH magnets (B_r=1.19 T) is also added in the figure. Comparing with a room temperature in-vacuum undulator, the performance of the magnetic fields is improved by roughly 30 % for the CRU of a pure magnet type and by 50 % for the CRUs of hybrid types.

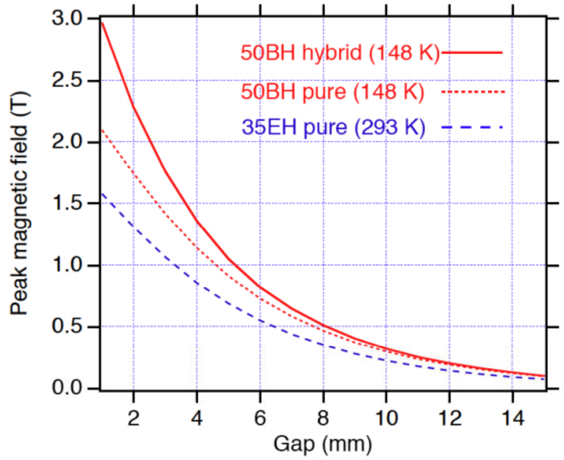

Fig. 4: Peak fields of 14 mm period undulators as a function of magnetic gap

The actual CRU can be designed as an extension of IVU design. Since the magnet arrays of an in-vacuum undulator are placed under good thermal isolation with vacuum, the undulator operation at the cryogenic temperature of liquid nitrogen or higher simply needs some additional cooling channels or cryocoolers. Figure 5 shows an examples of the CRU design, which resemble the ordinary in-vacuum undulator design except having cryocoolers attached to the magnet beams.

CONCLUSION

It can be said that the concept of a medium-scale SR facility has been established, which is strongly supported by the successful routine operation of SLS (Swiss Light Source). The key feature of the concept is a combination of short-period undulators and low emittance ring with moderate beam energy. In other words, the X-ray performance of such a facility may be comparable to that of the exiting large-scale facilities. Accordingly, constructions of SR faciliies based on this concept have been proposed all over the world, and some of them are now under construction. Therefore, the short-period undulator development such as SCUs or CRUs is a matter of great urgency. To meet the above demand, SCU development should aim at the realization of stable and reliable operation under the severe condition brought by the electron beam, and in case of CRU development, the concept should be verified as soon as possible.

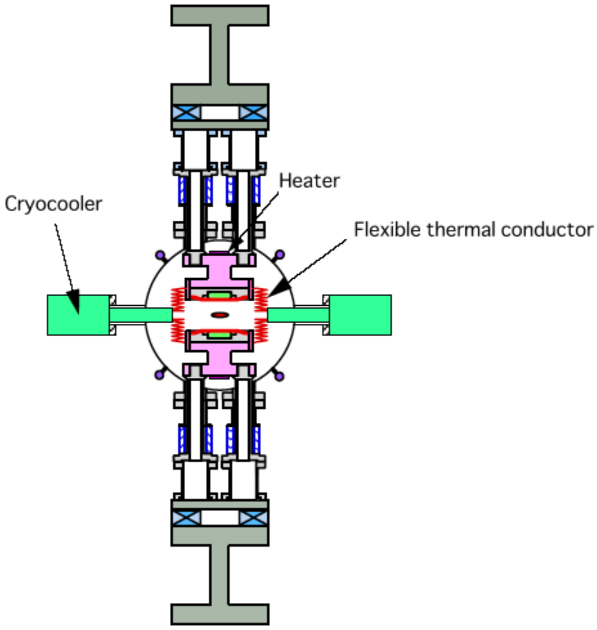

Fig. 5: Example of a cryoundulator with cryocoolers.

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