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Cryogenic permanent magnet and superconducting undulators

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ABSTRACT

Cryogenically-cooled permanent-magnet-based undulators (CPMUs) have been developed and built at several places around the world in the last decade. They currently operate successfully at many synchrotron radiation facilities, and they are planned as radiators in compact light sources based on laser plasma accelerated electrons. CPMUs have become the undulators of choice at medium energy storage rings. In the past few years, the performance of CPMUs has been brought closer to the physical limit; future incremental improvements will allow the limit to be reached.

Superconducting undulators (SCUs), however, despite having a longer history than CPMUs, had not attracted the same level of investment. SCU programs have only relatively recently been given significant funding priority at the Advanced Photon Source (APS). The investment at APS has resulted in the construction of the specialized SCU facility, and in the design and fabrication of several SCUs which are currently operating on the APS ring. KIT invested in the development of a cold vacuum chamber (COLDDIAG) for beam heat load studies, in a precise horizontal conduction cooled magnetic characterization facility as well as in a strong collaboration with the industrial partner Bilfinger Noell. This led to the production of two undulators successfully tested in the KIT synchrotron light source.

The combination of mature CPMU technology and developing SCU technology will provide significant flexibility in the choice of advanced undulators for new and upgraded light source facilities. This review paper covers the status of operations and development of CPMUs and SCUs.

1. Introduction to CPMUs and SCUs

Permanent magnet-based in-vacuum undulators (IVUs) have been in operation for more than 20 years. Based on the pioneering work of the SPring-8 group [1–5], today IVUs are operated in nearly every modern synchrotron radiation facility, including 3rd generation storage rings, diffraction limited storage rings (DLSRs) and free electron lasers (FELs). Short period IVUs (SPUs) push the photon energy spectrum to higher photon energies in a cost-efficient manner. Furthermore, a shorter period length permits a larger number of periods. Generally, an overlap of the 1st and 3rd undulator harmonic is demanded by the users, which defines the lower limit of the undulator parameter K as $2.5 \leq K$. The lowest magnetic gap is a key parameter, which defines the period length lower limit. The vertical betatron function as optimized for smallest magnetic gap is $\beta_{y0} = L_{und}/2$, with the undulator length L_{und}. Both smaller magnet gaps at the center and longer devices are possible in an adaptive gap undulator (AGU) [6–9], where the gap is related to vertical betatron function β_y,

$$gap \sim \sqrt{\beta_y} = \sqrt{\beta_{y0} + s^2/\beta_{y0}} \tag{1}$$

where s is the distance to the straight section center.

Two elaborate technologies are available for the fabrication of short period undulators: Cryogenically cooled permanent magnet undulators (CPMUs) and superconducting undulators (SCUs). This article reviews both technologies and tries to look toward the future.

Undulators with cryogenically-cooled permanent magnets [10] (CPMUs) boost the field beyond that of IVUs. The magnet cooling is only a small add-on to the well-established technology of IVUs, but its benefit is huge. Besides the higher fields, CPMUs provide higher radiation stability, and furthermore, the problem of RF- and synchrotron-radiation heating is pretty much alleviated when compared to that in IVUs due to the large cooling capacity of the magnet structure. The first CPMU has been in operation for nearly 10 years, and a number of further CPMUs have been built and are operated at several 3rd generation storage rings. The smooth commissioning (e.g. [11–13]) and successful operation over many years reflects the reliability of these devices.

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Until recently there were very few cases of the successful construction and use of superconducting undulators for storage ring based light sources and free electron lasers. The very first SCU (helical design) was used by J. Madey and his team for the demonstration experiments at the first FEL [14,15]. After that, a short helical SCU was used at the VEPP-2M storage ring, BINP, in Novosibirsk, for an unsuccessful attempt at creating a strong enough source of soft x-rays for electron beam polarization experiments [16]. The Madey undulators had a helical core and the wires were wound on two helices. This design is still beneficial for FELs due to the high field and the simple winding technology. However, it could not be transferred to storage ring devices, where a large horizontal aperture for injection is required. Therefore, in the 1990s, the development of planar short period SCU prototypes was initiated at Brookhaven [17,18]. Low phase errors between 1.2° and 3.4° were observed within three individual sections of 23 periods and a period length of 8.8 mm. The project was terminated eventually, before the devices have seen electron beam. Unsolved technical problems were the phasing between the sections and winding shorts. Another short period SCU (100 periods with 3.8 mm period length) was built at Karlsruhe. Although the magnetic field was pretty poor, the device was installed at the Mainz Microtron MAMI, and photon spectra were recorded [19].

In 2005, the first SCU (developed by KIT and Accel GmbH) was installed at ANKA (currently KIT synchrotron light source) [20]. It was in user operation until 2012. Several years ago, two SCUs were developed by the collaboration between KIT and Babcock-Noell GmbH (currently Bilfinger Noell GmbH) [21]. The SCU15 was successfully operated from 2014–2015 without a quench, before it was removed from the ring. The SCU20 was installed during Christmas 2017, and is in operation since then. At the same time, the technology of both large and small superconducting magnets used at accelerators and elsewhere has progressed significantly. Quite a few superconducting wigglers have also been built, mostly by BINP, and have been installed and used at multiple light sources [22].

This progress, particularly in the construction and successful operation of BINP superconducting wigglers, laid the foundation for the successful design, construction, testing and operation of SCUs at the APS in recent years. Three SCUs have been built, installed, and successfully used at the APS storage ring [23–25]. These undulators replaced or added to existing permanent magnets devices, and they noticeably enhanced the performance of three APS beamlines: two at the hard x-ray energy range and one at 6 keV. Two planar SCUs have operated at the APS for several years, and a third, helical SCU (HSCU) was commissioned and started operations in February 2018. The performance reliability of the APS SCUs matches the reliability of well-established permanent magnet devices. And the same is applied to their performance as radiation sources. The predicted brightness in the wide x-ray spectral range, which matches the measured magnetic performance of NbTi-based SCUs, has been confirmed experimentally [24]. Moreover, the SCUs' magnetic performance easily achieved design values, and in many instances, exceeded them. It was also recently demonstrated that an SCU could be built to meet both storage ring-based light source and x-ray FEL specifications [26]. These results not only established the high quality of SCUs, they also showed that NbTi-based SCUs, with a period of 15 mm and larger, produce an on axis magnetic field stronger than most advanced cryogenically cooled in-vacuum undulators for the same beam stay clear aperture. With the future advancements of Nb_3Sn-based undulator technology, this advantage could be extended for undulators with periods as low as 10 mm.

2. Cryogenically-cooled permanent magnet undulators

2.1. Introduction to CPMUs

This chapter reviews the development of cryogenically-cooled undulators, including related technologies, and offers an overview of potential developments in the next decade. Several incremental steps are possible, which may add up to significant improvements.

The magnet material utilized for these devices is well known, and the theoretical performance of conventional designs is limited by the material (Section 2.2). Section 2.3 gives a brief overview of full scale CPMUs, existing or under construction, at 3rd generation storage rings or FEL demonstrators. Most of the IVU technology can be utilized in a CPMU. However, several key components need to be adapted (Section 2.4), such as the cooling system, the magnet girder design, and the gap measurement system. The magnetic field measurement of cryogenic undulators is challenging, because an in-air measurement may not be sufficient. In particular, the undulator endpoles include partially saturated poles, and measurements at the temperature of operation is mandatory. Furthermore, the thermal shrinkage at low temperatures may disturb the field performance. Several in-vacuum (IV) Hall probe benches suited for cryogenic measurements will be presented in Section 2.5. The field tuning strategies of CPMUs are similar to those for IVUs. Various strategies will be discussed in Section 2.6. Most of the operational issues of CPMUs and IVUs are similar, although the low temperature of the magnets reduces the risk of damages during operation (Section 2.7). Existing CPMUs are conventional Halbach II hybrids [27], and the technology of this design is mature. Significant field gains can be achieved with specific add-ons beyond the hybrid type, which are discussed in Section 2.8. So far, polarization switching employing IVUs can be accomplished only with double undulator systems with fast electron orbit bumps [28–30]. Variably polarizing single device IVUs or even CPMUs (i.e. CPMUEs) have yet to be built. In Section 2.9, the trajectory for the development of a CPMUE will be briefly explored.

Table 1
Remanence reduction factors for $Nd_2Fe_{14}B$ and $(Pr,Nd)_2Fe_{14}B$ [Vacuumschmelze, private communication].

ρ/ρ_0	0.995
V_{mag}/V	0.96
$\cos(\varphi)$	0.98 isostatically pressed 0.96 transversally pressed

2.2. Magnetic material and field performance of cryogenic Halbach II undulators

A hybrid undulator design (Halbach II) is chosen for CPMUs, since it provides a higher field than a pure permanent magnet design (Halbach I [31]). High performance permanent magnet undulators are based on rare earth materials. Triggered by the Co-crisis in the 1970s, $Nd_2Fe_{14}B$-grades were developed. Today, this material is preferred due to the high remanence, mechanic robustness (as compared do Sm_2Co_{17}), and price, unless specific constraints in the magnetic design require a SmCo-grade. Such constraints in terms of magnetic design can include: radiation hardness or reduced temperature sensitivity. Typical temperature coefficients of the remanence TC_r at room temperature are:

$Nd_2Fe_{14}B$: $-0.08 \le TC_r \le -1.15\%/°C$ depending on the grade
$SmCo_5$: $TC_r = -0.03\%/°C$
Sm_2Co_{17}: $TC_r = -0.04\%/°C$.

Another advantage of $SmCo_5$ is the small transverse susceptibility (0.04 instead of 0.15), which reduces the field integral fluctuation during phasing of an APPLE device [32,33].

The theoretical limit of the remanence B_r^{sat} is reduced by several reasons to B_r as described by Eq. (2).

$$B_r(20\,°C) = B_r^{sat}(20\,°C) \cdot \frac{\rho}{\rho_0} \cdot \frac{V_{mag}}{V} \cdot cos\,(\varphi)\,. \quad (2)$$

The reduction factors are density reduction ρ/ρ_0 due to imperfect pressing and sintering, volume impurity V_{mag}/V, and averaged single crystal grain misorientation $\varphi = arctan\left(2B_r^{perp}/B_r^{par}\right)$. Typical values are given in Table 1. The theoretic values refer to pure $Nd_2Fe_{14}B$ or

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