Short Period Undulators for Storage Rings and Free Electron Lasers

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Abstract. Short period undulators have the potential to enhance the spectral performance of synchrotron radiation sources significantly. These devices open the range of brilliant hard X-rays at medium energy storage rings, their implementation may reduce the facility length of linac based FELs and they are an essential prerequisite for laser plasma accelerator based FELs. The development of cryogenic permanent magnet undulators has started and the first devices, employing period lengths around 18mm, have been installed in 3rd generation storage rings. Ambitious magnet designs permit even smaller period lengths which improve their performance further. The paper discusses the performance of cryogenic permanent magnet undulators in comparison with superconducting undulators.

1. Introduction

Permanent magnet undulators are the workhorses of 3rd generation synchrotron radiation light sources and soft / hard X-ray FELs. At long period lengths they are complemented with electromagnetic undulators / wigglers. The high energy range is extended with NbTi and Nb3Sn based superconducting wavelength shifters of lower brightness. The highest undulator photon energy is defined by the shortest period length and the electron energy. The costs of a synchrotron radiation facility scales with the electron energy and, thus, it is beneficial to push the undulator design to shorter period lengths rather than enhancing the electron energy. Since in-vacuum undulators (IVUs) permit smaller period lengths the IVU technology has been developed over many years, mainly at SPring-8 [1]. Today, the technology is mature and IVUs are installed in many 3rd generation storage rings. Recently, SACLA, the first IVU-based FEL, demonstrated saturation at 0.15nm. An IVU is planned also for the SwissFEL [2]. Rare earths based magnets gain in performance at lower temperatures which has triggered the development of cryogenic permanent magnet undulators (CPMUs) [3]. These devices employ a remanence increase of 15-20% and an increase in coercivity of a factor of 3-4. A few devices are already in operation at 3rd generation storage rings [4] [5] [6] [7] and the development of these devices is ongoing. These devices have period lengths of \( \lambda_0 = 18 \text{mm} \) (ESRF, SOLEIL), 17.7mm (DIAMOND) and 14mm (PSI). A 9mm period length 20 period prototype has been built at HZB [8]. Another technology for short period undulators uses superconducting coils. The first FEL was based on an iron-free \( \lambda_0 = 32 \text{mm} \) superconducting undulator (SCU) with helical windings [9]. A shorter period of \( \lambda_0 = 24 \text{mm} \) (iron yoke) was realized with a helical SCU operated at BINP [10]. 20 years ago short period planar SCUs (\( \lambda_0 = 8.8 \text{mm} \) and 18mm) were developed at the ATF, Brookhaven for a 500nm SASE FEL [11] and a high gain harmonic generation experiment [12], respectively. A \( \lambda_0 = 3.8 \text{mm} \) 100 periods SCU was tested with the 855MeV electron beam of MAMI [13]. The only planar
SCU operated at a 3rd generation storage ring is the SCU14 at ANKA delivering photons since 2005 [14]. SCUs are part of the APS upgrade project [15] and the installation of a $\lambda_0 = 16$mm prototype at the APS is planned for 2012 [16]. Further developments of planar SCUs for 3rd generation storage rings are ongoing at ANKA [17] and DIAMOND [18]. Joint activities of STFC RAL and Daresbury Lab. on helical SCUs are related to the development of an efficient positron source for ILC [19].

In this paper we present a comparison of CPMUs and SCUs both planar and helical. The comparison is based on technologies which are already available or close to maturity, i.e. (Nd,Pr)FeB based CPMUs and SCUs with NbTi or Nb$_3$Sn coils. Pulsed electromagnetic undulators [20] or devices employing new superconducting materials such as bulk high temperature superconductors (HTSs) and HTS tapes are beyond the scope of the paper (for overviews of HTS based concepts see [21] [22]).

The minimum vacuum aperture, a crucial parameter in any design, will certainly shrink in the near future depending upon small gap experiences at SACLA and later SwissFEL. Valuable information about the impact of wakefields on FEL dynamics will be available soon and extensive studies of heat load effects at storage rings started [23] [24]. Thus, in this paper we will not discuss the issue of minimum gap but rather assume reasonable limits for the proposed designs which can be scaled to smaller gaps. In the following we will use the term gap for magnetic gap and aperture for vacuum gap.

2. Cryogenic Permanent Magnet Undulators

The limitations of CPMUs are closely related to the limitations of the material. The maximum possible remanence can be evaluated from the crystal structure. Today, high performance material reaches 90% of the theoretical value [25] and further improvements are rather unlikely. On the other hand the coercivity is still about a factor of ten below theory (Brown’s Paradoxon [26]). In CPMU designs, however, the coercivity is not the limiting parameter, and, thus, existing materials can be considered of having ultimate performance. The critical step in the CPMU fabrication is the assembly at room temperature where high reverse fields are encountered and demagnetization due to low coercivity at 300K may occur. This assembly is safe if the material is treated with a grain boundary diffusion (GPD) process, which enhances the coercivity by about 3kOe [25]. In this process Dy diffuses along the grain interfaces into the bulk without entering the grains, thus, enhancing coercivity without sacrificing remanence.

Nd$_2$Fe$_{14}$B material has a spin reorientation at about 135K causing a decrease in remanence below 135K. In contrast, the remanence of (Nd,Pr)$_2$Fe$_{14}$B is monotonically increasing with decreasing temperatures. This material in combination with high saturation CoFe poles is the preferred material combination (e.g. CPMU at SOLEIL). A new (Nd$_{0.2}$Pr$_{0.8}$)$_2$Fe$_{14}$B magnet grade has been developed by Vacuumschmelze within a collaboration of Ludwig Maximilian University Munich and Helmholtzzentrum Berlin [8] (Figure 1). Single pass devices permit special designs: Side magnets attached to narrow trapezoidal / rectangular shaped pole pieces enhance the field by 10-20% [27] [25]. With textured Dy or Ho pole tips the field can be enhanced further (20% for gap / period = 0.1 [25]).

The technology of cryogenic undulators is well developed. The cryogenic system which adds to the established IVU technology is defined by the material constraints. (Nd,Pr)$_2$Fe$_{14}$B devices can be cooled directly with liquid N$_2$ (SOLEIL) whereas Nd$_2$Fe$_{14}$B devices (ESRF, PSI, DIAMOND) require either a sophisticated cryogenic design or an active temperature stabilization of the magnets. The use of Dy / Ho requires lower temperatures (<80K / <10K) and no experience is available, yet. So far, only planar CPMUs have been built, but the technology is applicable to helical devices as well. Fixed polarization undulators are easy to build whereas variable polarization CPMUs are challenging. So far, the DELTA undulator prototype [28] is the only variably polarizing IVU. The implementation of cryogenics while keeping full operational flexibility is ambitious and not solved yet.

3. Superconducting Undulators

PMUs scale differently with period length as compared to electromagnetic undulators (EMUs) which is due to the specific current distribution (infinitely thin “surface currents” versus “thick” current windings). EMUs are limited by the cooling technology to approximately 5A/mm$^2$ (averaged over
complete coil section). Thus, EMUs are restricted to long period lengths and they are outperformed by PMUs at shorter dimensions where EMUs loose tuning flexibility with K<2.5 (Figure 2). SCUs are limited by the field and temperature dependent critical current (Figure 3). Over a wide range SCUs are superior over PMUs but at low period lengths PMUs gain in performance for the same reason. It has to be discussed whether this crossover lies in a region of physical interest.

**Figure 1.** (Nd,Pr)FeB grades from different magnet vendors. The VAC grade (red line [8]) operated at 77K is used in the simulations. Data of CRxx taken from [29] [30].

**Figure 2.** Comparison of PMUs and EMUs for different period lengths and gaps. Magenta: K-ratio of devices based on the two different technologies.

**Figure 3.** Critical current densities at 4.2K (averaged over a rectangular cross section incl. insulation, Cu, air) of the wires as used in the simulations below.

For highest on-axis fields iron yokes are indispensible. Today, SCU coils are usually made from NbTi wires. The critical current of Nb3Sn in the superconducting phase is a factor of two higher as compared to NbTi. Technical limitations such as the required activation at 700°C and the required thicker insulation reduce this advantage to a factor of 1.4. Nb3Sn Prototypes have successfully been built and tested [31] [32] [33] but longer devices have not been built. Only recently, short samples of NbTi wires with artificial pinning centers became available [34] which promise a factor of 1.4 increase in the critical current.

The cooling concepts comprise conduction cooling by cryocoolers (ANKA), indirect liquid He cooling in a thermosiphon arrangement cooled by cryocoolers (APS), and liquid He-bath cooling (ATF) with the use of cryocoolers (ILC, DIAMOND). Coil temperatures are usually 4.2K except for the DIAMOND device where 1.8K is planned. The design of the vacuum chamber is a key part since it defines the minimum magnetic gap. Apart from the ILC device which has a cold chamber (4.2K) all devices have an individually cooled chamber or liner with a temperature between 10K and 20K allowing for a relaxed heat budget. The APS and DIAMOND devices are based on an individually supported vacuum chamber, which causes a magnetic gap to vacuum gap difference of Δ = 2mm. ANKA follows the concept of a thin liner squeezed between the coils allowing for Δ = 1mm. Thin layers of low thermal conductivity separate the coils from the liner in this case. A cold bore (4.2K) guarantees the smallest value of Δ = 0.5mm as demonstrated with the ILC device.

### 4. Comparison of CPMUs and SCUs

#### 4.1. Field Levels

The parameter space for the following comparison of the two technologies is λ₀ = 5-15mm and vacuum aperture = 2-4mm. The CPMU models are based on the (Nd₀.2Pr₀.8)₂Fe₁₄B material as described in [8] and CoFe poles. Two NiCu foils of 0.1mm each are assumed. The SCU models are evaluated for round wires: Supercon NbTi (http://www.supercon-wire.com), Φ = 0.44mm and Hyper Tech Research Nb₃Sn (http://www.hypertechresearch.com), Φ = 0.64mm, with critical currents as plotted in Figure 3 (simulations at 4.2K). An ambitious magnetic to vacuum gap difference of Δ = 0.5mm is chosen (cold bore). Planar and helical arrangements have been simulated. The CPMU helical device is based on the DELTA arrangement with 0.5mm slits between neighboring magnet rows. The helical SCU is modeled as a double helix device since it provides highest fields. All data are given for
90% of the loadline. Planar helical SCU designs including iron for field boosting are only 10-20% better than APPLE II devices for equal apertures [35]. An iron-free planar variably polarizing SCU has been proposed [36]. The field does not exceed the field of an in-vacuum APPLE II undulator with a similar aperture, however, it has the advantage of being independent upon moving mechanical parts in vacuum.

Using NbTi wires wide pole (storage ring compatible) SCUs and CPMUs provide similar field levels below $\lambda_0 = 9$mm (Figure 4). For single pass devices such as FELs or ERLs the pole width of CPMUs may be smaller. Trapezoidal poles and additional magnetic material at the pole sides [25] boost the field by 14% for $\lambda_0 = 5$mm, aperture = 2mm and 18% for $\lambda_0 = 15$mm, aperture = 2mm, respectively (bullets in Figure 4). The iron pole tips of the SCUs are highly saturated. The replacement with CoFe pole tips enhances the field of a $\lambda_0 = 5$mm SCU (magnetic gap = 2.5mm) by 5%. At the time being, the ANKA SCU15 demonstrator currently under fabrication is the only SCU having CoFe poles. Planar Nb$_3$Sn based SCUs are attractive even below $\lambda_0 = 9$mm.

Figure 4: $K_{eff} = 93.4 \cdot \lambda_0 \cdot \sqrt{B_z^2 + B_y^2}$ vs. $\lambda_0$ of planar CPMUs and SCUs at various vacuum gaps; NbTi-wire (left) and Nb$_3$Sn-wire (right). Magenta: K-ratio of the two technologies. Coloured data are evaluated for wide poles. Black bullets: trapezoidal poles with side magnets for the four cases: $\lambda_0$=5mm, 15mm and gap=2mm, 5mm.

Helical SCUs gain 60-70% over planar SCUs for the same aperture whereas helical pure permanent magnet CPMUs are only 10% better than high end hybrid designs (Figure 5). Helical hybrid undulators where permanent magnets replace the SC current wires inside a helical iron yoke would provide higher fields. However, such a device has not been built yet because the engineering aspects are rather challenging. Thus, helical SCUs are still unrivaled in the considered period length range.

Figure 5 (left): Comparison of helical CPMUs and helical SCUs for various period lengths and vacuum apertures of 2.0mm (solid) and 5.0mm (dotted).

Figure 6 (right): Related loadlines of Figure 5 for $\lambda_0$ = 5, 9, 15mm. Vacuum apertures: 2.0mm (solid), 5.0mm (dotted). The noise at low currents is due to incomplete relaxation.

4.2. Shimming Techniques
Magnetic field error corrections, i.e. undulator shimming, is a mature procedure for permanent magnet devices. Trajectory errors compatible with 1 Angstrom SASE FEL operation have been achieved and phase errors around 2° are state of the art. Various techniques are used, such as soft iron shims or permanent magnets on top of the structures, so-called magic fingers (individual permanent magnet arrays at the undulator ends), virtual shimming (block movement on transverse direction) and correction coils. Additionally, magnet block sorting before and relocation after assembly are employed.

Except for correction coils all these techniques do not apply for superconducting devices, and, hence, the strategy for optimization is different. Field errors of superconductors are due to geometric errors,
i.e. fabrication errors of the yoke and coil winding errors. Below saturation winding errors are covered by the iron yoke whereas they may show up with iron saturation. An increase of field errors above saturation from 0.15-0.2% rms to 0.33% rms has been observed at the ATF 18mm period SCU [37]. The so-called induction shimming technique has been proposed and successfully tested at ANKA [38] [39]. Significant error reduction has been demonstrated with loop shaped HTS films deposited on a 500µm sapphire substrate [39]. For a real device the substrate thickness has to be reduced because it contributes to the minimum gap. It is worth mentioning that the induction shimming corrects for flux changes within the HTS loops. Thus, this technique does not provide the full flexibility of usual central trajectory shimming or local phase shimming. It has been demonstrated that phase errors can be suppressed with appropriate machining and winding techniques. The three ATF $\lambda_0 = 8.8$mm, 23 period prototypes showed initial phase errors of only 1.2°, 2.7° and 3.4° below saturation [40] and the 21-periods APS prototype has a phase error of 1.5° only, even at saturation. Magnetic measurements of the new 1.5m long SCU15 demonstrator of ANKA demonstrates the possibility of achieving 3.5° phase error [41]. Including emittance and energy spread of the MAX IV storage ring even a phase error of 5.6° reduces the 15th harmonic brightness by only 25% [42]. Thus, phase errors do not limit the performance of SCUs. Appropriate shimming techniques for the on axis trajectory which are appropriate for FEL applications have not been demonstrated, yet.

4.3. Operational Issues
Photon energy tuning with SCUs has to follow a well-defined hysteresis loop in order to control remanence effects of the iron yoke. Doing so, the reproducibility of the field integrals is in the order of a few 0.01Tmm. For the APS SCU the complete cycle can be scanned within 1 minute. Tuning an SCU in parallel with a monochromator is still challenging, even in stop-and-go motion.

5. Conclusion
NbTi based SCU technology permits excellent spectral performance such as PMUs, even at higher harmonics. Strategies for FEL trajectory shimming still have to be elaborated. Above 10mm period length SCUs produce the highest fields. For period lengths in the sub-cm regime high end CPMUs can compete with NbTi type planar SCUs whereas Nb3Sn or NbTi / APC based devices are still superior. Helical SCUs are superior over helical CPMUs even at short period lengths. Today, variable polarization is not available, neither with CPMUs nor with SCUs. In the future longitudinal magnet motion in a CPMU seems to be feasible providing variably polarized light such as conventional in-air APPLE II type devices. Certainly, substantial engineering effort is necessary to gain this flexibility. Helical SCUs do not incorporate this option since the helicity is fixed by the design, but double SCU schemes are possible. CPMUs will dominate the short period undulator technology for the next years, but SCUs will become the preferred devices as soon as operational issues have been demonstrated in a multi-user facility.

6. References
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