Cryogenic Permanent Magnet and Superconducting Undulators

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Abstract

Cryogenically-cooled permanent-magnet-based undulators (CPMU) have been developed and built at many light sources 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). That investment has resulted in the design and fabrication of several SCUs which are currently operating on the APS ring.

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] [2] [3] [4] [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] [7] [8] [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.

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Undulators with cryogenically-cooled permanent magnets [10] (CPMUs) boost the field further. 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] [12] [13]) and successful operation over many years reflects the reliability of these devices.

Until recently there were very few cases of the successful construction and use of superconducting undulators (SCU) for light sources and free electron lasers (FELs). 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 section 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 Mainzer Microtron MAMI, and photon spectra were recorded [19].

In 2005, the first SCU (built by KIT and Accel GmbH) was installed at the KIT synchrotron [20]. It was in user operation until 2012. Several years ago, two SCUs were built by Babcock-Noell GmbH (currently Bilfinger Noell GmbH) per specifications set by the SCU team from KIT [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] [24] [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 (CPMUs), 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] [29] [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.

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:

$Nd_2Fe_{14}B$: $-0.08 \leq TC_r \leq -1.15\ \%\ /\ °C$ 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 Eq.2.(**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 $\varphi = arctan\left(2\, B_r^{perp}/B_r^{par}\right)$. Typical values are given in Table 1. The theoretic values refer to pure $Nd_2Fe_{14}B$ or $(Pr,Nd)_2Fe_{14}B$ crystals. Various magnet grades differ by the percentage of the added Dysprosium, which enhances the coercivity at the expense of remanence.

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

Cryogenically-cooled permanent magnet undulators (CPMUs), as proposed by Tanaka et al., make use of the large negative temperature coefficient of $Nd_2Fe_{14}B$ and $(Pr,Nd)_2Fe_{14}B$ magnets. Cooling from 300 K down to 77 K increases the remanence of $(Pr,Nd)_2Fe_{14}B$-magnets by 15%, whereas the coercivity increases by a factor of 2.5. Thus, the coercivity at room temperature must only provide enough stability for a safe magnet assembly at room temperature, and a high remanence (low coercivity) grade can be chosen. The radiation hardness is gained at low temperatures.

$Nd_2Fe_{14}B$ magnets exhibit a spin reorientation transition (SRT) below 135 K [34] [35] [36] [37], and the remanence drops at lower temperatures (the coercivity still increases). Thus, $Nd_2Fe_{14}B$-based CPMUs must be thermally stabilized at around 135 K. A direct liquid nitrogen cooling of the magnet girders is impossible in this case. The SRT temperature depends upon the rare earth (RE) involved in a $RE_2Fe_{14}B$ crystal [36]. $Pr_2Fe_{14}B$ does not show a SRT at all, and hence, this material is very interesting for CPMUs. Vacuumschmelze developed a new $(Pr_{0.8},Nd_{0.2})_2Fe_{14}B$ magnet grade dedicated for use in CPMUs [38] [39]. Meanwhile, it is available as Vacodym 131 TP or DTP. Only recently, Hitachi developed a grade with a similar magnetic performance (NMX-68CU). The data are summarized in Table 2.

Table 2: PrFeB grades as used in CPMUs.

Supplier	Vacuumschmelze	Hitachi		SANVAC
Grade	Vacodym 131 DTP, 77 K	NMX-53CR, 85 K	NMX-68CU, 77 K	P50SH
B_r^{typ}	1.62 T	1.57 T	1.66 T	under development
H_{cJ}	≥ 3185 kA / m	5888 kA / m	6300 kA / m	

The remanence is close to theory (within 10%), whereas the coercivity is still an order of magnitude lower than theory. Here, an improvement with further metallurgical optimization may be possible (e.g. grain size optimization). On the other hand, only the assembly at room temperature is critical for CPMUs. Grades of higher remanence can be used, if the magnets are stabilized with a so-called Grain-Boundary-Diffusion (GBD) process utilizing Dy or Tb. GBD enhances the coercivity by ≥4 kOe up to a depth of 2 mm with no loss in remanence [40] [41]. The first CPMU-9 prototype at BESSY had to be assembled in a cold store [42] (no GBD). Today, many SPUs are routinely treated with GBD, which alleviates the risks during assembly of CPMUs and also the operation of high performance room temperature devices [43].

Within a wide range of gap/λ_0 the field of a hybrid undulator is well approximated by Eq.3.

$$B = a \cdot \exp\left(b \cdot \frac{gap}{\lambda_0} + c \cdot \left(\frac{gap}{\lambda_0}\right)^2\right) \quad (3)$$

In the context of the evaluation of various undulator designs for X-FEL applications, a thorough analysis and parametrization of various undulator designs was done [44]. The figure of merit was the peak field B_{peak}, which is justified in most cases. For small ratios of gap/λ_0 (valid for many of the CPMUs) a third field harmonic shows up. In this case the figure of merit is the effective field B_{eff}, which directly correlates to the trajectory length and, hence the resonance wavelength. The higher field harmonics contribute only little to the effective field (Eq.4).

$$B_{eff} = \sqrt{\sum_{i=1,3,5\ldots} \frac{1}{i^2} B_i^2} \tag{4}$$

The fields of hybrid type CPMUs have been parametrized according to Eq.3 at the APS [45] and at the HZB. In the APS-model the pole and magnet transverse dimensions are fixed, whereas in the HZB-model, these dimensions are scaled with gap/λ_0. At $gap/\lambda_0 = 0.3333$ the pole width and height is 40 mm and 30 mm and the side and top/bottom magnet overhang is 5 mm. Non-scalable geometric details such as slits between magnets and poles, dead layers of magnets and chamfers have been ignored to achieve smooth scaling curves. When these details are included, the field drops by approximately 2%. At the HZB, the code UNDUMAG [46] was used, which was tested extensively vs. RADIA [47] [48]. Pole and magnet material is Vacoflux and Vacodym 131 DTP. The parameters *a*, *b* and *c* were fitted from simulations over a wide parameter space including gaps of 3, 5 and 7 mm and period lengths of 9, 11, 13, 15, 17, 19 and 21 mm.

The results are summarized in Table 3 together with data from independent simulations. The results with an identical figure of merit (B_{eff} for APS- and HZB-models) agree well within a few percent (Figure 1). Part of the deviation is due to different magnetic materials.

The optimized pole thickness *D* is well described by Eq.5 with $\bar{a} = 5.939$, $\bar{b} = -11.883$, $\bar{c} = 16.354$ and $\bar{d} = -8.550$.

$$D = gap \cdot \bar{a} \cdot \exp\left(\bar{b} \cdot \frac{gap}{\lambda_0} + \bar{c} \cdot \left(\frac{gap}{\lambda_0}\right)^2 + \bar{d} \cdot \left(\frac{gap}{\lambda_0}\right)^3\right) \tag{5}$$

In a real device with slits, dead layers and chamfers the values may deviate slightly.

Table 3: Fit parameters of hybrid type undulators. Simulations are based on Vanadium Permendur poles.

Magnet material of model undulator	B_r (T)	Code	Figure of merit	a	b	c	Reference
$Nd_2Fe_{14}B$, in-air	1.20	RADIA [47] [48]	B_{peak}	3.694	-5.068	1.520	[44]
$Pr_2Fe_{14}B$, 77 K NMX-68CU	1.67	OPERA [49]	B_{eff}	3.502	-3.604	0.359	[45]
$Nd_2Fe_{14}B$, 150 K NMX-S45SH	1.50	OPERA [49]	B_{eff}	3.341	-3.606	0.300	[45]
$(Pr,Nd)_2Fe_{14}B$, 77 K Vacodym DTP 131	1.62	UNDUMAG [46]	B_{eff}	3.598	-3.840	0.631	HZB

An optimization of B_{peak} yields higher values, but B_{eff} does not grow accordingly. Even worse, it is always smaller, and it drops significantly for small ratios of gap/λ_0 (Figure 1). The slope of B_{peak} vs. gap/λ_0 is steeper, similar to the results in [44].

2.3 Full scale CPMUs dedicated for light production in modern light sources

Several CPMU-prototypes based on $Nd_2Fe_{14}B$ and $Pr_2Fe_{14}B$ have been built for the exploration of technical limits (summaries in [5] [13] [45]). A few of them have seen electron beam [50] [51]. Table 4 gives an overview of full scale CPMUs, in operation and under construction, that are dedicated to light production in modern light sources. The operational temperatures are taken from the literature. It depends strongly on the actual fill pattern and the gap, and may vary between 138 K (no beam) and 177 K (hybrid filling pattern, gap 15 mm) as demonstrated with the first CPMU at the ESRF [52] [53].

In the last years, CPMUs turned into the workhorses of 3rd generation storage rings. They will be of major importance in DLSRs as well [54]. Additionally, they are well suited as radiators in compact light sources, such as FELs at laser plasma accelerated electron sources [55] [56]. Test experiments employing full scale CPMUs are already being prepared [57] [58] [59].

Table 4: Full-scale CPMUs in operation and under construction. Magnet suppliers: Vacodym grades: Vacuumschmelze; NMX and Neorem grades: Hitachi; P50SH: SANVAC; N48H: Zhejiang Innuovo. The magnetic gap is listed. The physical gap is 0.2 mm smaller, which is needed for the RF-shielding CuNi-foil. T is the operational temperature. Br and Hcj-values are given for the operational temperature except for the numbers in *Italic* type, which refer to room temperature. Most of the fields are peak fields, except for the ones labelled with e for effictive field.

Facility	#	Status	λ_0	Gap	N	L	Magnets	Grade	Br	HcJ	T	B	Cryogenics	References
			(mm)	(mm)		(m)			(T)	(kA/m)	(K)	(T)		
Diamond LS	1	operation	17.7	5.0 4.0	114	2.0	$Nd_2Fe_{14}B$	Vacodym 776 TP	*1.32*	*>1670*	147	1.04 e 1.26 e	thermosiphon	[60] [61] [62] [63]
Diamond LS	2-4	construction	17.6	5.0			$(Pr,Nd)_2Fe_{14}B$	Vacodym 131 DTP	1.62	>3185	80	1.20	cryocooler LN	[63] and private communication
Diamond LS	5	construction	16.6	4.5			$(Pr,Nd)_2Fe_{14}B$	Vacodym 131 DTP	1.62	>3185	80	1.25	cryocooler LN	private communication
ESRF	1	operation baked at 120°	18.0	6.0	107	2.0	$Nd_2Fe_{14}B$	Nerorem 595t	*1.16*	*>2400*	150	0.88	cryocooler LN	[64] [65] [11] [52] [53]
ESRF	2	operation	18.0	6.0	107	2.0	$Nd_2Fe_{14}B$	Vacodym 764 TP	*1.37*	*>1275*	150	0.99	cryocooler LN	[66] [67] [68]
ESRF	3	operation	14.4	5.0		2.0	$(Pr,Nd)_2Fe_{14}B$	Vacodym 131 DTP	1.62	>3185	80	1	cryocooler LN	[68] [54]
HEPS-TF/ IHEP	1	construction	13.5	5.0	140		$Pr_2Fe_{14}B$	P50SH	under development		< 85	1	cryocooler LN	[69] [70] [71] [72]
HZB	1	construction	17.0	5.5	80		$(Pr,Nd)_2Fe_{14}B$	Vacodym 131 DTP	1.62	>3185	80	1.12 e	cryocooler LN	[73] [74] [75]
HZB/ UHH/ Desy	1	construction	15.0	2.0	127		$(Pr,Nd)_2Fe_{14}B$	Vacodym 131 DTP	1.62	>3185	80	2.08 e	2 x coldhead	[73] [57]
NSRRC	1	construction	15.0	2.8 3.8	133		$Pr_2Fe_{14}B$	NMX-68CU GBD	1,67	6200	77	1.77 e 1.32 e	2 x coldhead	[5] [76] [77] [78]
SOLEIL	1	operation	18.0	5.5	107		$Pr_2Fe_{14}B$	NMX-53CR	1.57	6090	77	1.15	cryocooler LN	[79] [80] [81] [82] [13] [83]
SOLEIL	2	operation cryo-ready	18.0	5.5	107		$Pr_2Fe_{14}B$	NMX-53CR	1.56	6090	77	1.15	cryocooler LN	[81] [82] [83] [84]
SOLEIL	3	construction	18.0	5.5	107		$Pr_2Fe_{14}B$	NMX-53CR	1.56	6090	77	1.15	cryocooler LN	[83] [84]
SOLEIL	4	construction	15.0	3.0	200		$Pr_2Fe_{14}B$	NMX-53CR	1.56	6090	77	1.74	cryocooler LN	[58] [59] [81] [82] [83] [84]
SPring-8	1	beam tests 2013 at SPring-8	15	3.0	93	1.4	$Nd_2Fe_{14}B$	NMX-49CH	1.48	3025	140	1.64	2 x coldhead	[51] [5]
SPring-8/ SLS	1	operation at SLS	14	3.8 5.0	120	1.7	$Nd_2Fe_{14}B$	NMX-S45SH	> 1.5	> 4000	135	1.186 0.835	cryocooler LN	[12] [85] [86] [87]
SSRF	1	operation 2015	20	6	80		$Nd_2Fe_{14}B$	N48H	1.53	4000	135	1.06 1.03 e	cryocooler LN	[88]

2.4 Design considerations

2.4.1 Cryogenic concepts

Several technologies are suitable for the magnet cooling. The use of a cryocooler with liquid nitrogen is straightforward. The cooling capacity of more than a kWatt relaxes the design. The first CPMUs employing $Nd_2Fe_{14}B$ magnets required an indirect side cooling at about 135 K. Utilizing $Pr_2Fe_{14}B$ magnets, the first directly cooled CPMU to be operated at 77K was built at SOLEIL. This will be the preferred design in the future. If several CPMUs are installed in a facility, an elegant thermosiphon system can be adopted, as discussed with the installation of the first CPMU at DIAMOND [62]. Very tiny temperature gradients along the structure come along with reduced running costs. Cryocoolers with liquid nitrogen appear to be very reliable, since they have run for nearly a decade at various facilities without major problems (SOLEIL, ESRF, PSI, DIAMOND).

The other cooling concept is based on coldheads. Depending on the supplier, the cooling capacity at 77 K of a single stage coldhead can be about 180–200 Watts (50 Hz). A 77 K-design with two coldheads is a feasible solution at a high current storage ring, and a full-scale device is under construction [5] [78]. A vaccuum-isolated coldhead chamber with a thermo-feedthrough guarantees a smooth maintenance of the coldhead without venting the CPMU [51].

For temperatures below 77 K coldheads are the most efficient choice, although the cooling capacity drops by a factor of 4–5 at 30K. The remanence gain vs. 77 K operation is only 1%. The gain in coercivity is larger, but the magnets are already safe at 77 K. However, a low temperature (30 K is has the advantage of a high thermal conductivity of Cu) is essential in specific designs that make use of Dy-pole tips or HTSC-coils.

The cryogenics at temperatures $T << 77$ K are challenging. All potential heat leaks must be minimized, utilizing hollow and insulated columns as for the TPS ID, sophisticated flexible taper sections, and a shielding of the cold mass and electro-polishing of the inner surface of the vacuum tank, for example. Geometric and resistive wall heating in a high average current facility with short bunches needs specific care, and synchrotron radiation from upstream magnets must be blocked.

The number of girder supporting columns can be reduced by a factor of two with interlaced columns on the upper and lower magnet girder [87]. This configuration keeps the required gap accuracy, whereas the gap center, which is less critical, follows a sinusoidal wave.

A further significant reduction of the number of columns and the column cross section can be achieved with any kind of force compensation, which acts directly on the in-vacuum magnet girder. The first force compensation scheme was realized in a room temperature in-vacuum revolver undulator [89], where two compensation magnet arrays of the same periodicity as the center array are implemented. The force compensation can be realized with so-called Multipole Monolithic Magnets (MMM) at either side [90]. In another approach, the forces of a pure permanent magnet Halbach undulator are reduced by a factor of 50 with a specific rearrangement of magnets [91]. However, in this design the maximum field is reduced by $\sqrt{2}$ as compared to the original Halbach configuration. Therefore, it is less attractive for CPMUs, which aim for the highest fields. Another design with in-vacuum springs was adopted for an in-vacuum wiggler [92].

2.4.2 Magnet girder and column design

Most of the full-scale CPMUs are assembled from single keepers, which typically carry half a period. With the first 9 mm-prototype built at HZB, the mechanical structure was simplified [42]. Keepers are skipped and magnets and poles are inserted into slots of the magnet girders. This technique greatly reduces the number of parts and simplifies the assembly, if the girders are fabricated to tight tolerances. The alignment of pole height and roll angle is accomplished with pole clamps of the appropriate height. The CPMU-17 (HZB) and CPMU-15 (HZB/UHH) follow a similar approach. Due to fabrication issues the transverse slots for magnets and poles are realized with comb-shaped gauges, which are bolted onto the magnet girders [75]. Several gauges are used along the device (CPMU-17: 4x2; CPMU-15: 4x3). The relative longitudinal positions are measured on a CMM, and the distances are adjusted with special keys employing a few 10 microns of displacement (Figure 3). The so-called block keepers of the room temperature U15 of the Swiss-FEL employ a similar idea in combination with a more comfortable field tuning knob. The block keeper is made from extruded Aluminum profiles in this case [93].

For reliable operation of CPMUs, the reduction of the number of columns and the number of bellows is beneficial. Similar to the SwissFEL-U15 design, one instead of two columns are realized in transverse direction in the HZB CPMU-17 and CPMU-15. The magnet girder stability is maintained with a thicker column diameter.

The magnet arrays are covered with a CuNi-foil for RF-shielding, as adopted from the IVU experience over two decades [94]. A water cooling of the flexible tapers is not necessary due to the huge cooling capacity of the magnet structure.

2.4.3 Gap measurement system

A precise gap measurement and positioning of about ±1 µm is an important issue for modern SPUs with many periods, particularly when higher harmonics are used. It is essential in the so-called continuous mode, where the undulator and the monochromator are moved simultaneously in parallel over a scan. The operation is simplified, if the gap positioning precision is independent of the gap history and the moving direction. This task is difficult to achieve with indirect in-air measurement tools such as linear or rotary optical encoders. In a CPMU the shrinkage of the magnet structure during the cool down aggravates the situation, because it exceeds the desired accuracy by two orders of magnitude. A direct measurement technique is needed.

With the SLS-CPMU14, as built in collaboration between SPring-8 and the Swiss Light Source, a Keyence optical micrometer LS7600 has successfully been tested for a direct gap reading independent of the shrinkage during cool down, but it is not used in normal user operations. At HZB Keyence optical micrometers have been chosen as the main gap measurement systems for the CPMU-17 and the CPMU-15. A transmitter and receiver are located outside of the vacuum chamber, and a replacement in case of failure is simple. A vertical light band of 40 mm height enters the chamber through a window. Two blades at the magnetic structure cut out a part the light band, the trimmed beam leaves the chamber through a second window and is analyzed in the receiver. The optical micrometer signals are transformed to sin/cos-signals via specific electronics as developed at HZB. They can be interpreted by any modern motion controller. The signals are used in a feedback loop of the gap drive system with a cycling frequency of 1 kHz.

The positioning accuracy of the system has been tested in a dedicated setup via a comparison with an incremental, optical, linear encoder (Heidenhain ULS300). A measurement reproducibility of ±1 µm has been demonstrated [73]. The accuracy is maintained with the insertion of two thick plane parallel glass blocks mimicking the entrance and exit windows. Unfortunately, they cannot be welded into a standard CF-flange for a reasonable price. On the other hand, off-the-shelf optical windows, which are already welded into an UHV-flange, distort the light beam non-linearly over the gap range by about 14 µm (Figure 4), and the transmission is only about 85%. Each window has its own characteristics which also depends on the orientation of assembly. Luckily, the distortion of the light band is reproducible on the level of ±1 µm, and the non-linearity can easily be corrected with lookup tables. The overall transmission of 70% does not have an impact on the reliability.

2.5 Field measurement

The field measurement and tuning of IVUs is done with conventional in-air systems, i.e. heavy granite benches with inherent passive positioning accuracy and with in-air motion control. After optimization, the magnet structure is cleaned and installed into the vacuum chamber. Control measurements were not done in the early days. Only later was it discovered, that phase errors may occur after disassembly and reassembly of the structure. In parallel, there was also the demand for a compact and portable Hall probe bench, in order to do in-situ measurements (in the vacuum tank, but not in-vacuum). Such a system is also suitable for magnetic checks at the place of installation (e.g. detection of demagnetization). For this purpose, the SPring-8 group developed the SAFALI system (Self-Aligned Field Analyzer with Laser Instrumentation) [95]. A carriage on a rail inside the vacuum tank holds the Hall probe. Two Pinholes are mounted on the carriage, which are illuminated with two laser beams. The trimmed beams hit two two-dimensional position sensitive detectors (2D-PSDs), which measure the transverse motion and the roll of the Hall probe. Three 2-axes-tables support the rail. In feedback mode these tables correct for the transverse Hall probe movements.

In parallel, another SAFALI-based system was optimized for the characterization of CPMUs at low temperatures. It was not clear at all whether the magnetic performance would degrade during the cooling process. This question was answered with the characterization of a 0.6 m prototype structure with the new system [96]. It relies on the precision of a granite bench, which moves the in-vacuum Hall probe via a long, 16 mm diameter, free-standing pipe (O-ring sealing). One in-air 4-axis stage permits a transverse displacement and pitch and yaw alignment. Transverse corrections are performed in feed-back mode during the measurement (reproducibility: 5 µm rms). The high precision set-up (phase error reproducibility: 0.1°) demonstrated that the phase error and the central trajectory stay constant during the cooling, and a room temperature shimming of the CPMUs is sufficient. Minor changes may occur in the end structures, where the poles are only partially saturated. This can easily be corrected based on simulated data at different temperatures.

With longer CPMUs (typically 2.0–2.5 m) a full-scale upgrade of the in-vacuum bench became mandatory [85]. Here, the in-vacuum guiding rail is supported by two in-air 2-axis tables. These stages enable a feed-back or feed-forward correction of transverse displacement, yaw and pitch. The Hall probe is pulled from an in-vacuum motor, and for the in-vacuum cables a specific cable rewinder was constructed.

At the same time, the ESRF group developed a different Hall probe bench [65]. Utilizing a special vacuum chamber, the Hall probe carriage sitting on an in-vacuum rail is moved from an in-air granite bench system via a magnetic coupling. In real-time, two laser interferometers measure the Hall probe's longitudinal position and yaw angle. The yaw data are used for an offline yaw correction.

The SwissFEL in-vacuum bench is based on the SAFALI arrangement. The rail is supported by six in-air 2-axes-tables along the bench. Beforehand, they are optimized individually for a minimum overall transverse displacement of the Hall probe. During field scans, they accomplish a transverse displacement correction in a feedback loop. Yaw, pitch and roll can be derived off-line from the rail profile, and a yaw-correction of the data is possible.

The SOLEIL in-vacuum bench is supported by seven 2-axes-tables from outside. The yaw and pitch errors of the rail are measured with a laser interferometer angle optic and the roll is measured with a Leica nivel 20. The angles are minimized with the tables and mechanic shims. The vertical position is measured with a laser tracker. If necessary, height corrections can be applied to the field data off-line.

All three U18 devices are characterized with this system. For the U15, the bench will be upgraded with a SAFALI system and with piezo crawlers for a Hall probe's fine positioning [84].

The in-vacuum bench at HZB [97] [73] aims for on-line fast position and angle corrections close to the Hall probe. It incorporates the measurement of all six degrees of freedom of the Hall probe, utilizing two 2D-PSDs (SAFALI like system) and a 3-axis interferometer. The Hall probe position and angle deviations are corrected on the fly by means of six in-vacuum piezo crawlers. Assuming a smooth movement of the Hall probe carriage, the transverse displacements can also be derived via integration of the pitch and yaw angles as derived from the laser interferometer data. This is a beneficial redundancy of the PSD-based displacement data.

The relative angle alignment of the two independent PSD-lasers is time-consuming, and the two parallel beams are therefore generated from a single one, utilizing specific in-vacuum optics. It consists of a beamsplitter, providing two parallel beams at 20 mm distance and two retroreflectors, which extend the distance to 70 mm. The alignment of the initial single beam (and the in-vacuum beam pair) is performed via two motorized in-air 2-axes-tables. For the safe movement of many in-vacuum cables during the scans, a compact cable tray has been developed at HZB [98]. The Hall probe carriage and the cable tray are pulled independently via steel cables and two in-air servo motors that are magnetically coupled into the vacuum.

Apart from the local measurements, integrated measurements are indispensable for a precise determination of the transverse field integral distribution. In-vacuum moving wire systems are used for this purpose. The designs at various laboratories are similar. Usually, the motion control and linear bearings operate in air, and the translation is coupled into the vacuum via metal bellows. Preliminary performance data of the new HZB-moving wire are given in [75]. The in-vacuum wire alignment relies on two 2D-fiducials, which are assembled onto the girder ends.

This section concentrated on only a few examples. Similar systems are in operation at several laboratories, which cannot be discussed in detail here.

Pulsed wire measurements are another interesting option for CPMUs, particularly if the space is limited. Important issues at short period lengths are wire dispersion and the impact of the pulse width. With a sophisticated dispersion and pulse width correction scheme, excellent results have been obtained for a 0.2 m long test structure [99]. An extrapolation to full scale devices (typically, 2 m) still has to be done. It is worth mentioning that the pulsed wire is a great tool for 1st and 2nd integrals. Fields and phase errors, however, cannot be determined with sufficient accuracy.

2.6 Field tuning strategies

The undulator field tuning hopes to meet two goals: i) best spectral performance, ii) minimum impact to the electron beam. The first issue is related to the phase error of the central trajectory, whereas the second one defines the off-axis field integral tolerance. According to Walker, the phase error can be broken up into three terms which add quadratically [100]: smooth errors, oscillatory errors, and local random errors. The smooth errors add up in a random walk process. They are mainly addressed during the shimming. The oscillatory term is compensated during trajectory straightening. Luckily, the local random phase error is only of minor importance and thus it is neglected during shimming.

Usually, in-air undulators are shimmed with small pieces of soft iron on top of the magnets for the optimization of magnetic performance [101]. In contrast, magnets and poles of IVUs and CPMUs are covered with a thin copper-coated foil with a smooth shape for the reduction of RF-losses, which excludes the conventional shimming. Instead, a careful initial characterization of the magnets (keepers, i.e. magnet pole assembles) before assembly is crucial. The magnetic characterization is done either with a flip coil [102] at various magnet (keeper) transverse positions or with a wire mimicking the electron beam [103] [104]. Different from a moving wire system, the magnets are moved relative to a fixed wire in order to exclude environmental fields from the data. These data are used in a sorting procedure, which delivers the initial configuration. Now and then during assembly the structure is re-measured magnetically, and the remaining magnets (keepers) are resorted. Alternatively, Tanaka proposed an in-situ sorting, which omits the initial magnet (keeper) characterization. The individual magnet (keeper) data are extracted from measurements of the completely assembled structure, and based on these data the keepers are swapped accordingly [105].

A precise and efficient shimming technology for IVUs and CPMUs is applied at the ESRF. Poles (in a hybrid) or vertically magnetized magnets (pure permanent magnet) are ground by small amounts (less than 100 μm) with a high spatial resolution (a few mm) [68].

In the following, we briefly describe the HZB method for the example of the CPMU-17 in which a high precision initial magnet characterization in combination with an efficient sorting and precise assembly yields good field performance without any intermediate measurement and resorting. All magnets are characterized for dipole errors and inhomogeneities with an automated Helmholtz coil and a mini stretched wire, respectively, as described in [103]. The HZB-simulated annealing code SORT evaluates a figure of merit, i.e. a weighted sum of 28 terms as derived from Helmholtz coil and wire measurements including peak fields, 1st and 2nd field integrals at various transverse positions, central trajectory straightness and phase error. Magnets are exchanged or rotated, where the figure of merit may become worse according to a virtual Boltzmann factor, which is steadily decreased. SORT offers the choice of the cooling regime via a temperature reduction factor T_{red} with $T^{new} = T^{old} \cdot T_{red}$. $T_{red} = 0$ represents a quench run, where only improvements between successive configurations are allowed. Sorting has been done with reduction factors between 0 and 0.95 (Figure 5Figure 4). As expected, the sorting procedure lasts longer for a slower cooling rate, but it delivers better results.

In the first step, the magnets were assembled onto the girders without further alignment. Then, Hall probe maps were taken from the individual girders. After subtraction of the periodic field, a comparison of the field integrals with the predicted values shows excellent agreement (Figure 6). This underlines the quality of the sorting procedure.

Afterwards, the poles were inserted and straightness measurements of the pole height and roll angle were done. Based on the geometry data only, the pole height and angles were adjusted to a band of $\pm 50 \mu m$ (Figure 7). Field integral measurements with a moving wire were performed before and after a transverse alignment of the poles (Figure 8). The magnet girder ends are not compensated, yet. The field integral distribution (red curve) closely follows the simulation. The difference between the blue and the red line shows the sensitivity of the field integrals on the transverse pole position. This proves the hypothesis that the magnet's property can predicted from single magnet block measurements to a high accuracy without a complicated numeric error analysis inside a hybrid structure. Part of the success may be the combined use of dipole data (long range errors) and wire data (short range errors). Further improvement is expected, if wire measurements at more than one distance are included (so far, only the distance of half the minimum gap is regarded).

The remaining field integral errors would certainly have been smaller for tighter geometric pole alignment tolerances. The already very small phase error of one girder (no magnet shimming yet) would also shrink further, since the phase errors (Figure 7) shows some correlation with the geometric errors. This result is in agreement with the observation at SOLEIL for CPMU-2 and -3, where a pole position accuracy of $\pm 15 \mu m$ yields a sufficiently small phase error below 3° for a girder pair [83]. In case of the CPMU-17, the pole clamps have large fabrication errors, which will be improved with the next CPMU.

After magnet and pole assembly, a minor magnetic shimming started. Based on the phase errors, the pole height was adjusted at a few locations via an adaption of the pole clamp height. All these measurements were done at the naked magnet girder. Due to repelling magnet forces, the girder showed a bow of about 0.2 mm. This bow is subtracted in Figure 7. The single girder initial phase error of 2.55° is already pretty small, since no phase tuning via the girder supporting column has been done yet. This knob will be used when both girders are mounted into the vacuum tank.

All CPMUs worldwide are tuned for small phase errors via a length adjustment of the girder supporting columns (threaded rods). The columns of the PSI-U14 were tuned efficiently with specific differential screw assemblies [85]. An improved version was implemented in the SwissFEL U15, and it significantly reduced the tuning time. Other laboratories accomplish the column adjustment with mechanical spacers (e.g. Soleil [83], HZB). A phase error fine tuning is possible with distributed heaters along the in-vacuum girder. So far none of the laboratories have used this knob regularly.

Generally, the field optimization is done manually. The SwissFEL group develop a tuning robot for a fast and precise vertical pole adjustment of the SwissFEL U15 modules. The optimized robot needs less than two hours for one iteration of a 3.5 m long structure. Meanwhile, a compact robot that is dedicated to in-situ tuning inside the vacuum chamber is under discussion.

2.7 Operational issues

2.7.1 Local lattice modification for IVUs and CPMUs

Short period IVUs and CPMUs provide the best performance at small gaps. A trend for local lattice modifications for mini-β_y sections is visible at several facilities (e.g. HZB EMIL [106], Diamond [107]). A modern flexible light source provides different operation modes adopted to the needs of the users. If a mini-β_y section is implemented only in specific modes, the minimum magnetic gap might be larger in other modes (e.g. low-alpha mode at BESSY II). Though interesting for in-vacuum applications, an adjustable phase undulator (fixed gap) design [108] [109] [110] is not an option is these specific cases, neither for planar, nor for variably polarizing devices.

2.7.2 Specific operation modes

Specific operational modes, which modify the bunch length or the vertical beam size, must be implemented carefully: i) in the low-alpha mode [111] (short bunches of 2-3 ps rms) the usual high- and low-beta periodicity of BESSY II disappears by detuning the quadrupoles, and the vertical betatron-function in the former low-beta section increases from 1.2 m to 2.5 m. Thus, the minimum magnetic gap of the narrow gap undulator CPMU-17 increases from 5.5 mm to 7.8 mm. A new accelerator optics may help in the future; ii) BESSY-VSR [112] will routinely provide short (few ps) and long bunches simultaneously. Wake fields will grow in this mode, and flexible tapers must be designed appropriately. Other specific user modes at BESSY II, such as femto-second-slicing including horizontal bumps [113] or Pulse Picking by Resonant Excitation (PPRE) [114] for long bunch separation times or Transverse Resonance Island Buckets (TRIBS) [115], are less of concern because they act mostly on the horizontal phase space. In the TRIBS-mode, also called twin-orbit mode, two stable orbits are populated simultaneously with electrons. On the off-axis orbit, the electrons travel at displacements and angles up to a few mm and mrad, horizontally, which is not critical for CPMUs as long as the coupling is small.

It must be emphasized that short bunches in combination with short range geometric structures such as steps or grooves can hardly be simulated with the required accuracy due to computer hardware limitations. Measurements for cross-checks are always welcome. A thorough study of heat dissipation effects dependent upon bunch length, bunch charge, and filling patterns was possible at DIAMOND utilizing the COLDDIAG setup [116] [117] [118]. In this specific case, RF losses due to geometric effects at imperfect thermal transitions were detected. Alhough dedicated to the cryogenic design of superconducting undulators with a much more stringent heat budget, the comparison of simulations and measurements also provides valuable insights for the CPMU design. In the future, bERLinPro [119] may provide the chance for detailed RF loss studies with short bunches in complicated geometries.

2.7.3 Machine protection system

Most critical is the failure of a magnet power supply that may introduce large vertical orbit deviations. The synchrotron radiation of mis-steered electrons can easily destroy the downstream end of a CPMU. The local melting of the RF foil or the flexible taper, it is called avalanche melt through [120], may occur. At SOLEIL the upstream undulator in a canted double undulator system burned holes into the RF foil of the downstream undulator [121], which initiated two countermeasures to avoid future damages in case of large beam orbit deviations: i) beam displacement and angle interlock, ii) collimator in front of delicate undulators [121].

2.7.4 Radiation damage

Radiation damages of room temperature undulators in modern light sources are still an issue (e.g. LCLS [122], PETRA III [43] [123], SACLA [124]). The magnets can be re-magnetized, but this requires an expensive removal of the undulator from the accelerator and a loss of beamtime. The radiation hardness is heavily improved in CPMUs operated at 77 K due to the enhanced coercivity. After many years of operation in several facilities, a demagnetization of CPMU magnets has not been reported, and this aspect will therefore not be discussed further in this paper. Operation at even lower temperatures does not offer a big advantage, since the heat capacity shrinks rapidly with a decreasing gain in coercivity [42].

2.8 Pushing CPMU-fields further with specific designs

Besides the RE-families $Nd_2Fe_{14}B$, $(Pr,Nd)_2Fe_{14}B$, $SmCo_5$, and Sm_2Co_{17}, no new high performance magnet material is visible on the horizon, and therefore the magnetic performance limit of CPMUs is clearly defined. Achievable fields of planar and helical CPMUs have already been presented in [42], and the numbers are still valid today. However, several strategies have been discussed for a mild field enhancement of CPMUs, each of them providing a gain between 15%–20%. These strategies can be somewhat combined, yielding a substantial field enhancement. Considerable effort was spent in some of the technologies. Although the preliminary results looked very promising, the projects were terminated due to budget and manpower constraints. In view of the increasing popularity of CPMUs, it is worthwhile to consider a continuation of these studies.

Wedged poles: A hybrid undulator employs an inhomogeneous pole saturation, yielding fully saturated pole tips and non-magnetized or reversely magnetized pole areas at the opposite side. In a wedged pole design [125], the pole length (parallel to the undulator axis) increases inversely with the distance to the beam, resulting in a quasi-homogeneous magnetization. More flux lines are guided to the electron beam.

Side, top, and bottom magnets: Hara et al. [10] proposed a field enhancement of hybrid IVUs with side and top/bottom magnets attached to the poles. For good efficiency, the pole pieces of high permeability must be narrow in transverse direction, which reduces the good field region. This is less critical for single pass devices such as Free Electron Lasers (FEL), but also feasible in low horizontal beta sections of 3rd generation storage rings with a horizontal injection. Narrow poles may become standard with the advent of DLSRs with on-axis swap-out injection [126] [127]. Even with straight poles, the field gain is 15-20% [73] as compared to a conventional Halbach II undulator. The gain is even higher with a transverse trapezoidal pole shape. The clamping mechanics for these sophisticated arrangements is challenging, particularly at short period lengths. But new fabrication technologies have been tested successfully at the HZB CPMU-9-2 prototype, such as soldering of magnetized blocks [73] [128].

Dy-pole tips: CoFe (e.g. Vacoflux) with a saturation magnetization around 2.35 T is mostly favored over soft iron pole material. In a straight pole design, it is beneficial to replace the deeply saturated pole tip with a material of higher saturation magnetization. Oriented Dysprosium or Gadolinium are of particular interest at low temperatures. Single crystals employ saturation fields of 3.4 T and 2.7 T, respectively, however, crystals of an appropriate size are not available. Thus, studies at RadiaBeam Technologies concentrated on textured Dysprosium hybrid materials, as composed of thin foils with a thickness of a few 10 µm [129]. The studies were dedicated to CPMUs, although an application in SCUs might be interesting as well.

In contrast to a Dy-single crystal, polycrystalline Dy has a low initial permeability and a low saturation magnetization. In contrast, oriented (textured) polycrystalline Dy combines a large initial permeability and an enhanced saturation magnetization, and the fabrication technology is feasible. A Dy-crystal (hcp-structure) has a very hard axis perpendicular to the basal-plane and a hard and a soft axis in the basal plane. Ideally, the soft axis is oriented parallel to the magnetic field. The optimum crystal orientation in a horizontally wiggling undulator is: (x,y,z):([0001],<11$\underline{2}$0>,<10$\underline{1}$0>) where y is parallel to the main field and z is the electron propagation direction.

The texture is produced via a proper combination of cold-rolling and annealing, which results in a secondary re-crystallization [130]. Subsequently, the foils are stacked, pressed and annealed again to form a solid block of high density where the pole pieces are cut from [129].

Very promising tests with a five pole 9mm period prototype demonstrated a gain of 3% at 77 K against CoFe-poles. A higher gain is expected: i) at lower temperatures; ii) with side and top magnets, iii) for larger period lengths. Despite the promising results, RadiaBeam Technologies eventually terminated the studies, because the batch to batch performance reproducibility of the textured Dy-foils was too low for a safe construction of a full scale undulator.

For a synchrotron light source application, the material is challenging to handle due to several reasons: i) Dy shows two phase transitions: ferromagnetic at T < 85 K; antiferromagnetic at 85 K < T < 179 K; paramagnetic at T > 179 K. Hence, a conventional temperature independent undulator field compensation is hard to achieve; ii) Dy outperforms CoFe only if the pole saturation level is already rather high. In other words, the driving fields must be strong enough to push the material to the region of high saturation magnetization. This implies narrow poles and side magnets; iii) a significant gain is achieved only well below 77 K, which requires a sophisticated cryogenic design employing coldheads.

HTSC-rings: In 2004, the SPring-8 group started the investigation of a so-called cryoundulator plus, i.e. a CPMU with integrated high temperature superconducting current loops (HTSC-loop) [131] [132] [133]. The racetrack-shaped induction loop is located around the pole tip. The superconducting current is induced in the following procedure: i) the gap is closed above the critical temperature $T > T_c$; ii) the temperature is reduced to $T < T_c$; iii) the gap is opened again. A substantial field gain is expected from simulations with critical current densities $J_c \gg 1kA/mm^2$ [131]. The scaling of J_c is described by Eq.6.

$$J_c(T) = J_0\left[1-\left(\frac{T}{T_c}\right)\right]^m \qquad (6)$$

J_0 is the critical current density at $T = 0K$, and m quantifies the pinning mechanism with a value within $1 < m < 3$. A high SC current density with a substantial field gain is expected at an operational temperature around 30 K. Today, the temperature can be achieved with modern coldheads.

Two technical challenges were reported [131] [132] [133]: i) with the HTSC current switched on, the HTSC loop is exposed to an enormous magnetically induced mechanic stress. The stress could be handled more easily in a circular loop, which, however, is not feasible in a planar undulator. A reinforcement of the HTCS loop (joining the loop and a pole piece) is essential to avoid micro cracks and magnetic performance degradation. The reinforcement must be UHV-compatible and it must withstand the stresses due to different thermal expansion of the HTSC loop and the pole piece. Numerous temperature cycles and many magnetic cycles are expected during the lifetime of cryoundulator plus. Resin impregnation of the sintered material and stiffening the loop with glued soft iron pole pieces have been tested successfully as reinforcement techniques. Soldering techniques may be helpful in this context, too; ii) the mechanic and magnetic homogeneity of the HTSC-material and the lifetime are crucial for the reliable operation of a cryoundulator plus in a multiuser facility. The potential of a cryoundulator plus is pretty high, and it is worthwhile to develop a safe reinforcement technology and to optimize the bulk HTSC material further.

Inhomogeneous magnetization: Transversally die-pressed magnets are usually chosen for CPMUs. The non-avoidable magnetic inhomogeneities, which are introduced during fabrication, can easily be sorted out because their spatial distribution is amazingly well reproduced [134]. On the other hand, in aiming for the highest fields, inhomogeneities can be introduced intentionally during fabrication via an appropriately optimized pressing die. This has been proposed for the Athos APPLE X undulator magnets of the SwissFEL [T. Schmidt, private communication, 2017]. An overall field gain of at least 5% is expected.

New APPLE designs: Variably polarizing devices in FELs and DLSRs with on-axis injection can be realized with APPLE III [135], Delta [136], or APPLE-X [137] magnet arrangement. The field boost vs. an APPLE II is at least factor of 1.4, depending upon the vertical gap needed for the chamber support. An in-vacuum APPLE II design that permits a cryogenic option for a future device is currently developed at HZB.

2.9 Variably polarizing in-vacuum and cryogenically cooled undulators

So far we have discussed planar, linearly polarizing devices. SPUs with helical, elliptical or arbitrarily polarized light are needed as well. Planar helical / elliptical fixed polarization undulators can easily be converted to CPMUs. Generally, polarization switching is possible with a double undulator system employing local orbit bumps [28] [29] [30]. On the other hand, polarization switching in a single IVU is challenging, since the following four key components must be considered (assuming an APPLE II structure):

i) Special arrangement of motors, gear boxes, screws, linear bearings
ii) UHV-compatible fabrication technology and assembly strategy for magnet pairs
iii) RF-shielding of neighboring magnet rows, which permits a relative longitudinal motion
iv) Flexible taper, which permits a large phase motion

So far, no variably polarizing IVU (i.e. IVUE) has been built, not even for room temperature (RT). For single pass devices a round chamber with a wall thickness of only 0.2mm is feasible (galvanic fabrication), which reduces the gap loss. This concept is not applicable in storage rings with a large horizontal aperture for injection, but it may become interesting for DLSRs with swap-out injection [126] [138].

As an analogy to the development of IVUs, the development of variably polarizing devices will proceed in two steps: i) room temperature device, RT-IVUE; ii) cryogenically cooled device, CPMUE. The key issues will be solved with an RT-IVUE. Remaining challenges are the differential thermal expansion coefficients of materials and cryo-compatible clamping of a more complicated magnet structure including 3D-forces.

Currently, a full scale planar in-vacuum APPLE II undulator is being developed at HZB. It is dedicated to two RIXS and one microscopy beamline. The status of the four above-mentioned key components is: i) all gap and phase driving parts are operated in air, and hence, standard components are used. Large diameter columns connect the UHV-magnet girders with the in-air girders. Gap and phase measurement is accomplished with in-air optical micrometers similar to the HZB-CPMU-17. A force compensation is implemented to minimize girder bending; ii) a magnet-soldering technique based on reactive foils was developed at HZB [73]. It is currently adopted to larger magnets and extended to UHV compatibility; iii) two strategies are evaluated by means of simulation and prototyping: a) two independent foils with an overlap cover the individual magnet rows; b) one common, shaped foil attached to one of the magnet rows, shields both rows; iv) prototyping of various designs including lifetime tests under vacuum is on-going.

The described technology with an in-air motion control is well-suited for cryogenic application. The critical issue is the thermal budget, which depends heavily on the shape and cross section of the columns. An accurate force compensation in all three directions is indispensable in this context.

Once, the technology is mature, the choice of the appropriate magnet structure is free, e.g. APPLE II [32] and APPLE III [135] including a gap drive; Delta [136] with a fixed gap and adjustable phases; APPLE X [137] and Delta II [H.-D. Nuhn, private communication, 2017] with four transverse degrees of freedom (e.g. realization of a transverse gradient undulator).

3 Superconducting Undulators

As it was already stated in the Section 1, SCUs are currently operated only at two light sources: ANKA/KIT and APS. For this section APS SCUs have been chosen to illustrate status of SCU technology and to present several directions for future developments mostly due to the full access of one of authors (EG) to all details of their design, construction and operations.

There were four very important milestones achieved in the process of developing SCU technology at the APS. First of all, it was experimentally demonstrated that SCU magnets could be built to the technical specifications for undulators set by most advanced light sources and FELs. And there is no shimming required to achieve this high level of magnetic performance. Second, the engineering of SCU cryogenic systems matured enough to design and build robust and affordable cryostats. These cryostats, that house SC magnets and a beam vacuum chamber, could operate as a stand-alone system, or become a part of the large cryogenic facility. In either case, their cooling capacity has enough margin to handle heat loads from storage ring- and FEL-based light sources. It was also shown that the beam vacuum chamber is exposed to well-predicted heat loads from e-beam and synchrotron radiation. Third, it was demonstrated that SCUs could be aligned under operational conditions, and the accuracy of such an alignment matches the one of conventional, in-air permanent magnet undulators. Finally, the operational reliability of several SCUs has been confirmed by their practically flawless performance at the APS storage ring. This section of the paper summarizes the results of the latest SCU advances in all four areas and outlines the most important future directions in SCU development.

3.1 APS SCUs

3.1.1 SCU magnet

A typical planar APS SCU magnetic structure in many ways emulates one of a hybrid permanent magnet undulator. This structure, schematically shown in Fig.9, has two magnets separated by a gap. Each magnet is made of a multitude of SC coils wound around the iron core with poles in between the coils. The winding of any two adjacent to one pole coils are run in opposite directions, as are the electrical currents. This configuration results in an array of alternate polarity magnets that feed their field through the poles to the undulator gap. It is a complete equivalent of the hybrid permanent magnet undulator magnetic structure. Magnetic modeling of such a structure is straightforward and could be accomplished by using the Radia or Opera magnetic simulation codes. There are other possible designs for SCU magnetic structures, but the one presented here that is used for APS planar SCUs is the most efficient for small period undulators. The regular, periodic part of the SCU, shown in Fig.10, includes identical coils, made of single SC wire that is wound in the set of equally distanced slots/grooves machined in the soft iron magnet core. The design of the non-periodic part, i.e. the ends of the SCU, also shown in Fig.10, follows the recipe for the end design of hybrid permanent magnet undulators: a gradual decrease of magnetic field, i.e. a number of turns in several coils, toward the end of the device. Ideally, such a design should deliver completely uniform periodic magnetic structure and nullify both 1st and 2nd integrals of the SCU magnetic field. But there are several factors preventing the construction of an ideal SCU. The most significant factor is practically achievable tolerances in the manufacturing of SCU magnet cores.

Details of the mechanical design of the APS SCU magnet cores can be found elsewhere [139]. The connection between the mechanical tolerances of SCU magnet fabrication and its magnetic performance has also been partially analyzed in the past [140]. Based on the results of this and later analysis, the straightforward approach in the design and fabrication of APS SCUs was established. That approach calls for precise fabrication of the magnet core, an accurate and consistent winding procedure, and precise control of the gap in the assembled magnet [26]. As long as well-defined tolerances and specifications for fabrication and assembly procedures are met, the SCU is able to meet all magnetic, and consequently, all radiation specifications required for undulators at 3rd and 4th generation light sources, as well as those for any FEL. It is important to emphasize that the process of fabrication and final APS SCU tuning doesn't include any magnetic shims.

The typical list of SCU specifications is quite long, but the most important parameters to meet are peak field on the SCU axis and the phase errors. Both these parameters are critical for delivering close to theoretical radiation performance. A comprehensive compilation of calculated and experimental results for achievable on axis peak fields by SCUs has been accomplished recently [45]. Experimental data on peak fields that were actually achieved were compiled for most of the operating in-vacuum undulators, as well as for the operating SCUs. Calculations and experimental results, presented in Fig.11, show that NbTi-based SCUs with periods of 15 mm or larger provide higher on axis peak field than most advanced, ultimately cryogenically cooled in-vacuum hybrid undulators. There are no experimental results yet on the performance of Nb_3Sn-based SCU, but if such an undulator is successful it could shift an advantage in the peak field of SCU versus IVU even further, down to 10 mm period IDs. If there was very little doubt about the ability of SCUs to reach record high peak fields, there was always a strong perception about the inability to build SCUs with low phase errors. That perception was based on an erroneous assumption that SCUs, as hybrid IDs, would require magnetic shimming to achieve low phase errors. But contrary to this assumption, it was shown experimentally that an SCU with phase errors as low as 2.3 degrees could be built without any field shimming [26]. The analysis of the main factors contributing to an undulator phase error shows that systematic deviations from the required magnetic gap (along many undulator periods) that result in systematic deviation from the desired peak magnetic field are a key contributor to the rise of phase errors. Statistical deviations in the magnet gap (from one pole to the next pole) are also important, but because of averaging along the device, they contribute less compared with systematic deviations, unless they are exceedingly high. In permanent magnet undulators, these gap deviations are corrected by mechanical shimming at one of the selected undulator gaps. The most important issue for permanent magnet undulators is maintaining the same gap uniformity for all undulator gaps. An SCU on other hand has a fixed gap and therefore such an issue doesn't exist. In the APS SCUs, the role of mechanical shims, that establish the gap uniformity, serves the set of adjustable mechanical clamps shown in Fig.12. The combination of fixed spacers and clamps allows for the adjustment of the mechanical, and as a result the magnetic undulator gap to the desired precision, and that process is applicable to undulators of any practical length. Fig.13 shows the results of magnet measurements for a 1.5-meter long SCU with a period of 2.1 cm and magnetic gap of 7 mm that was built at the APS as a part of the R&D project in collaboration with SLAC [141]. In this device the uniformity of the magnet gap of the SCU was partially controlled by the set of six gap spacers and only three clamps: two at the ends and one in the middle of the magnet. It was the first attempt to use this gap adjustment technique to minimize phase errors, and it was successful but only brought phase errors down slightly below 5^0. The next SCU built at the APS was a 1.2-meter long device with a 1.8-cm period that had a set of 16 spacers and eight clamps. This device has been tuned to a low phase error as is shown in Fig.13. An optimal number of spacers and clamps would allow for tuning of phase errors of shorter or longer SCUs to the same level.

Compensation of the 1st and 2nd field integrals of SCUs is a pretty straightforward process. Each end of an SCU magnet is equipped with extra coils, shown in Fig.12, that are placed in one or two of the last grooves of the magnet core. Each coil is powered independently and provides the "knob" for electron beam orbit steering. There are also set of corrector coils in upstream and downstream ends of the magnet, as well as two coils, one on the top and another on the bottom along the magnet, to correct small vertical component of the field. This comprehensive set of corrections makes SCU fully transparent to the electron beam.

There is a vacuum chamber placed between the magnet cores of an SCU shown in Fig.12. APS vacuum chambers for planar SCUs are made from extruded Al, and the cross-section of the internal opening typically has an elliptical shape. Such a shape is optimal for mechanical and thermal conductivity reasons. A long, thin wall vacuum chamber is very flexible and fragile without supports. Therefore, in several areas along the chamber the horizontal wall is much thicker, and these extended beyond the magnet hardware plates make the vacuum chamber stiffer. The same extensions are used to support and align the vacuum chamber. By adjusting the position of each extension, the outer surface of the vacuum chamber is maintained straight with a uniform slot of about 0.4 mm from each SCU magnet core. The vacuum chamber is terminated by flanges on both sides of the SCU magnet. The engineering design of the SCU vacuum chamber is defined not just by straightforward mechanical tolerances. Very important requirements for the optimal design, which will protect the vacuum chamber from unwanted heat sources, are derived from the thermal conductivity, beam physics, and multiple heat source considerations. Some of these requirements will be discussed in the next chapter.

3.1.2 Cryogenic and vacuum system

The very first APS SCU cryogenic system was a standalone cryostat with four Sumitomo cryocoolers, shown in Fig.14. The original concept and main engineering solutions for the first APS SCU cryostat came from the experienced team of SC wigglers designers/builders at Budker Institute of Nuclear Physics in Novosibirsk, Russia [22]. The cryogenic system [142] of this cryostat (see Fig.14) consists of three thermal circuits, each operating at its nominal temperature of approximately 4, 20, and 60 K.

The lowest temperature circuit includes an SCU magnet, liquid helium tank, and a low temperature part of current leads. The intermediate temperature circuit consists of the vacuum chamber and internal thermal shield, and the highest temperature circuit includes an outer thermal shield and "high temperature" part of current leads. The two types, two of each Sumitomo cryocooler, provide the required refrigeration for all three circuits. This cryostat was successfully used to build and operate the first three SCUs at the APS, and two such cryostats are currently in operation.

The cooldown process of the APS SCU cryostat is preceded by its vacuum evacuation. After that, all four cryocoolers go into action and the relatively slow cooldown process starts. It takes about 75–80 hours until the lowest temperature circuit comes close to 4.8–5K, and at that time liquid helium is added to the liquid helium tank. That process takes about an hour and after that, the SCU is ready to be powered. The typical representation of the APS SCU cooldown process is shown in Fig.15. In the steady state process of the operation, He gas pressure is maintained at the constant level and the same amount of evaporated He brought back to liquid state within a closed loop. While powered and with e-beam present, the excess of cooling power in the 4K circuit is relatively small and does not exceed a few parts of W. This margin is very important for reliable SCU operation and it is important and quite possible to increase it up to the level of 1W or even better in the future.

The original APS SCU cryostat has been used for three SCUs installed in the storage ring. It was also used for testing of the FEL SCU prototype. The hardware populated the cryostat has been always equipped with multiple thermocouples. And in the period of several years it allowed to accumulate very detailed temperature maps of all components in the cryostat under different cryogenic conditions. This comprehensive construction and operational experience with the original SCU cryostat was the basis for very accurate benchmarking of the thermal model of such a cryostat. Analysis of this well-established and proven model indicated that the cryostat could be significantly simplified without loss of efficiency in the cryogenic performance. In fact, the performance efficiency could be noticeably improved. That analysis led to the development and construction of a simplified and cryogenically better performing cryostat [143]. Fig.16 shows rendering images of this cryostat layer by layer. The most important improvement is the elimination of one thermal shield. That makes the total mass to be cooled noticeably smaller, and as a result, the cooldown time drops as well. Fig.17 shows the typical cooldown timeline for this cryostat. It is an important operational improvement that makes the assembly-disassembly turnaround process substantially shorter. There were also improvements made in the system delivering liquid helium in the liquid helium tank. The vacuum vessel of newly designed cryostat has a diameter that is almost twice as small as the original one. That makes this cryostat compatible, dimension-wise, with practically all existing light sources and FEL accelerator and undulator tunnels.

It should be noted that the actual cooling power of the 20K circuit, which includes the SCU vacuum chamber, typically does not exceed 40 W, and for reliable SCU operation, the budget of all thermal losses occurring in the SCU vacuum chamber should stay well within that limit. Therefore, for the engineering design of all cold-to-warm hardware transitions, as well as transition sections that control and mitigate e-beam wake-field losses, the choice of the material and cross-section configuration of the vacuum chamber are important parts of the overall design of reliable SCU vacuum chamber directly connected to the storage ring vacuum system. The main elements and the cross-section of the APS SCU vacuum chamber are shown in Fig.18. The SCU vacuum chambers were thoroughly tested at the APS storage ring prior to SCU installation [144]. The vacuum chambers have been equipped with multiple thermosensors and temperature elevations as a function of e-beam current and e-beam peak current. Synchrotron radiation missteering angles and e-beam displacements have also been measured. Only after the confirmation that heat loads and effects on e-beam at the SCU vacuum chamber are well understood and controlled can an SCU be installed on APS storage ring.

3.1.3 Magnetic measurements

Since the vacuum chamber is an integral part of the SCU vacuum system, the direct magnetic measurements of fully assembled and operational SCUs become possible. Internal volume of the vacuum chamber, as shown in Fig.19, accommodates special tubing that guides and houses multiple magnetic sensors. These last ones are mechanically supported and their motion controlled by the set of linear translation stages installed on the precise long bench. This concept was introduced by the BINP SC wiggler team [145] and has been adopted for the APS's SCU magnetic measurements. The set up utilizes the same types of magnetic sensors, such as Hall probes, rotating coils, etc., as the ones used for the magnetic characterization of out-of-vacuum permanent magnet undulators. The same set-up used for conventional undulators could be used for any SCU by installing a guiding tube with the required diameter in the SCU's vacuum chamber. The access to the magnetic gap is limited by only one longitudinal direction, however. The APS's SCU magnet measurement system [146], shown in Fig.20, is currently 3.5 m long and could be extended if longer undulators are measured. This magnet measurement system has been routinely used to verify magnetic performance of the APS's SCUs and to generate look-up tables for SCU corrections coils.

One of the main challenges for SCU in-situ magnetic measurements is the ability to accurately correct measured data for the sagging of a guiding tube and long coil or single wire sensors. The purpose of this correction is to extract the magnetic field distribution along the SCU longitudinal axis from measured data. Several techniques have been developed and applied to overcome this challenge. One is based on the use of a sensor with at least two Hall probes built-in. Another is based on accurate measurements of the sagging profile of the rotating coil and correcting the data according to these measurements. Results of measurements with different types of sensors are cross-checked for consistency.

Recently there were advances made in the use of a single pulsed wire technique for SCU magnetic characterization [99]. This technique was introduced quite some time ago and used mostly to measure a variety of accelerator-based magnets. In the last few years there were several attempts to apply this technique for magnet measurements of undulators. Some of them were more successful than others, but this technique is still not ready to compete with Hall probe-based or other well-established methods. Nevertheless, the advancement of pulsed wire magnetic measurements is quite important for SCUs and for any undulator with limited magnetic gap accessibility and very small magnetic gaps. Therefore, the development of this technique continues at the APS, where most of the pulsed wire hardware duplicates one designed at the LBNL, but the data processing is quite different [147]. Recent tests of this technique performed on the APS's helical SCU showed very promising improvements in measurements of the magnetic field profiles and field integrals.

3.1.4 Alignment of the APS SCU "cold mass"

Repeatable and accurately controlled positioning of the SCU magnet with respect to e-beam orbit/trajectory is critical for the performance of the undulator as a light source or an element of the FEL amplifier. Therefore, development of a reliable and economically viable technique of SCU alignment is quite important. Alignment of the first APS SCUs was based on the ability to measure the position of the SCU vacuum chamber extensions protruded from the upstream and downstream of the SCU magnet and visible through the window on the cryostat vacuum vessel. These extensions followed the motion of the SCU magnet through cooldown and warmup processes since the vacuum chamber is embraced by the SCU magnet, but thermally separated from it. After the repeatability of these motions was confirmed through multiple cooldowns and warmups, the procedure of the SCU cryostat and SCU magnet alignment was established. That procedure provides the alignment accuracy within 50 microns, which is enough to satisfy the positioning requirements for the SCU installation at the APS storage ring.

For the next generation of light sources, such as the APS-U, as well as the current and future FELs, this level of accuracy is not adequate. Therefore, a new alignment approach has been introduced for the new APS SCU cryostat. Four optical windows with the direct optical path to a target (but a very small solid angle) on the cold mass have been added in the cryostat [148]. The alignment technique itself utilizes a newly developed "cryoscanner" that could be easily removed from a window and installed back or moved to another window with a very high degree of positioning reproducibility. The "cryoscanner" readings collected on three or four windows will fully define the position of the SCU magnet with respect to external fiducials. Eight invar rods support the SCU magnet inside the cryostat. The position of each rod is adjustable and controlled from the outside. As a result, the feedback loop for the cold mass positioning during the operations could be implemented. A new alignment system has been tested with the new APS helical SCU. The alignment accuracy of 10 microns for the APS helical SCU installed in the new cryostat has recently been demonstrated [149]. A relatively simple extension of this alignment system for multiple cryostats and SCUs represents the potential solution for the alignment challenge of the FEL SCU undulator line. There is also a potential option to use fiber optics to deliver optical signal to "cold mass" targets, and bring the alignment accuracy down to several microns.

3.1.5 Operation of APS SCUs

There are three SCUs that have operated at the APS, each for different a period of time. SCU0 has operated from January 2013 to August 2016, and has been replaced at the APS Sector 6 by SCU18-2 in September of 2016. SCU1, now called SCU18-1, has operated at the APS Sector 1 from January 2015 to the present day. And recently, the HSCU started its first year of operations at the APS Sector 7. Overall, thousands of hours of operational experience with SCUs has been accumulated. The first and most important takeaway from this experience is that the SCUs didn't cause even a single beam loss in the storage ring through all these years. Each SCU is equipped with a system that prevents catastrophic and uncontrolled beam motion during a quench. Another important result is that even the total number of quenches for all operational SCUs through all these years was 148, the majority of these events were related to unexpected beam dumps at the storage ring, whereas the total number of self-induced quenches was only 10. To prevent beam dump-related quenches in SCUs by controlling beam loss locations, an abort kicker system triggered by the machine protection system could be used [24]. Such a kicker has been installed at the APS in January 2016, and since then the number of beam dump-related quenches drastically decreased.

The operational statistics of the APS SCUs are practically the same as for the APS hybrid magnet IDs. The average APS SCU availability is close to 99.57% due to very stable SCU operation conditions and the relatively short recovery time of about 0.5h after extremely rare instances of self-induced quenches. And all APS SCUs, similar to hybrid IDs, are fully controlled by beamline users.

The performance of one of APS's SCUs – SCU1(SCU18-1) – as a radiation source has been studied in details [24]. The absolute flux measurements of monochromatic beam have been performed for undulator radiation harmonics from 1 to 9 and those data were compared with calculated values. These results are presented in Fig.21. The measured flux is ≅ 2/3 of calculated flux, which is quite reasonable given the nontrivial nature of absolute flux determination. What is more important is that the ratio of flux at high harmonics to flux at first harmonic, at both calculated and measured tuning curves, is quite close. That quite accurately confirms the value of phase errors obtained in the SCU's magnetic measurements.

The parameters of operational SCUs at two light sources: ANKA and APS are summarized in the table 5.

Table 5: Full scale SCUs for 3rd generation storage rings. The real gap loss of the KIT/Accel device was much larger when re-measured at room temperature after removel from the storage ring.

Facility	Start-Finish of Operations	λ_0 (mm)	# of periods	Vacuum aperture (mm)	Gap loss (mm)	B (T)	Cooling	References
APS 2 SCUs	2015-current 2016-current	18	59.5	7.2	2.3	0.97	4 cryocoolers, LHe closed circuit	[23] [24] [25]
APS	2013-2016	16	20.5	7.2	2.3	0.8	4 cryocoolers, LHe closed circuit	[23] [150]
APS Helical	2017-current	31.5	38.5	26	5	0.45	4 cryocoolers, LHe closed circuit	publication in preparation
APS-Upgrade	Planned – one example	16.5	216	6	2	1.07	4 cryocoolers, LHe closed circuit	private communication
KIT/ Accel	2005-2012	14	100	8,12,16 25 (open)	0.6 (?) (design)	0.3	3 cryocoolers	[20] [151] [152]
KIT/ Noell	2014-2015	15	100.5	7, 16 (open)	1	0.73	4 cryocoolers	[153]
KIT/ Noell	2017-current	20	74.5	7, 15 (open)	1	1.18	4 cryocoolers	[154] [155]

3.2 SCU – source of radiation with variable polarization

Planar SCUs deliver linearly polarized radiation, and the direction of the polarization vector is perpendicular to the direction of the magnetic field in the SCU. Non-planar SCUs could be built as a pure helical undulator, or by combining two planar SCU magnets in one magnetic structure of an undulator that produces variably polarized radiation. As was mentioned in the introduction, two purely helical SCUs were successfully built and used quite some time ago: one for pioneering FEL experiments, and another one at the low energy storage ring VEPP-2M, to characterize the polarization properties of e^- and e^+ beams. But a purely helical SCU can only produce circular polarization. In 1976, a scheme to combine two purely helical coils in one SCU with the purpose of generating variably polarized radiation was proposed [156]. A storage ring compatible planar SCU with horizontal access was built at NSRRC [157]. The undulator employs nested canted coil pairs. Another proposal of a planar variably polarizing SCU is based on four rectangular coils in an APPLE like arrangement (without longitudinal motion) [158]. All these designs suffer from low fields because they do not have iron poles for flux concentration. At the same time, conventional electromagnetic undulators that produce variably polarized radiation have been successfully built and utilized at various light sources and FELs [159]. Following some of their design solutions and by taking advantage of small outer dimensions of vacuum chambers for FELs and the 4th generation of light sources, a new design for a variably polarized SCU has been proposed at the APS [160]. The device, called SCAPE, consists of two pairs of “planar” superconducting magnets including iron poles assembled around a vacuum chamber. A rendering of the SCAPE, with assembled and exploded views, is shown in Fig.22. Each pair of “planar” SC magnets produces independently linearly polarized radiation in two perpendicular planes. By independently varying the amplitude of the magnetic field in each pair of SC magnets, one can control polarization and change it from completely linear to fully helical. Recently, a 0.5-m long SCAPE prototype was built and it is currently being tested at the APS SCU construction facility. By design, each SCAPE can generate only one chirality of circular polarized light. In order to change the chirality from left to right or right to left, two SCAPE-type devices should be placed in line.

An important performance parameter of variably polarized undulators is the frequency of polarization reversal. In the case of a single SCAPE, such frequency is low: a reversal per minute. But a special combination of SCAPE devices and their particular modes of operation, as well as the use of different SC wire in the future, promises to bring that frequency to the level of 1Hz or higher.

3.3 Future directions of SCU developments

Several decades of development efforts at many synchrotron radiation facilities around the world have resulted in the mature technology of permanent magnet undulators. Recently, after more than two decades of developments, this technology has evolved to embrace in-vacuum cryogenically cooled devices. SCU technology, on the other hand, is much younger and, even more importantly, has never been supported with the same dedicated efforts and investments as permanent magnet undulators. Nevertheless, in the last several years significant progress in SCU technology has taken place as well. This progress has demonstrated that the magnetic and radiation performance of SCUs matches the performance of the best permanent undulators.

The successful construction and operation of NbTi-based SCUs with periods of 16 mm and above encourages the consideration of the future designs of undulators with smaller periods, down to 10 mm. That in turn requires adaptation of different types of SC wire with higher critical currents for SCU technology. One of these wires, Nb_3Sn, has already been used for building short SCU prototypes [161], but none of these developments have produced a truly functional device that could be installed and operated at an existing light source facility. Since Nb_3Sn cables and wires have been successfully used for commercial and research magnets, it is clear that with the right approach this material could be adopted for the construction of SCUs. The benefits of such developments are illustrated in Fig.11. The best possible technical solutions for CPMUs and NbTi-based SCUs are inferior to Nb_3Sn-based undulators with periods between 10 and 15 mm. Therefore, developments toward Nb3Sn wire tailored for the SCUs' designs and the establishment of the robust technology of Nb_3Sn SCU construction would be one of priorities for the APS's SCU developers.

At the moment it is purely speculative to project the outcome of the use of HTS materials for SCU design and construction, but the first small steps in the direction of prototyping short HTS-based SCUs are being made [162]. With future improvements in the quality and quantity of HTS wire specially designed for SCU applications, the breakthrough in reaching record high fields at 10 mm and smaller periods could be quite dramatic.

It will be important for future SCU designs to focus on novel devices that produce variably polarized radiation with reasonably fast polarization switching capabilities. SCAPE is the very first step in that direction, but new SC materials and smart geometries could play a crucial role in dramatic performance improvements of the SCUs' capabilities in polarization control.

Another more incremental development is the demonstration of the capability– even with the existing technology– to design and construct SCUs as long as several meters. APS Upgrade project is designing and planning to build several four meter long SCUs, each consisting of two in line undulators. In the near future it would be also quite important to establish reputable vendors who are able to design and manufacture SCUs per user specifications.

The 3rd and 4th generation light sources, as well as FELs, require extremely high quality undulators. For storage ring-based light sources, they are necessary for covering a wide radiation energy range, and they minimize the length of undulator lines for FELs.

The SCU technology developed in the last decade at the APS is mature enough to be transferred to a company specializing in cryogenic instrumentation. Such a company could deliver affordable SCUs for existing and future storage ring-based light sources and FELs, and their developers would be able to fully capitalize on the advantages that SCUs provide.

4 Conclusion

For a comparison of the CPMUs of Table 4 and the existing full scale SCUs of Table 5, the fields of all devices were scaled to the same vertical aperture. Effective fields were used if available, otherwise peak fields were taken. The scaling is done differently for CPMUs and SCUs. For CPMUs the field at an individual gap was scaled to a common reference gap ($gap_{ref} = gap + \Delta gap$) applying Eq.7. The reference gap is 5.2 mm, regarding 0.2 mm for the CuN foil. The parameters a, b, and c of the HZB-effective field fit were used.

$$B_{ref} = B \cdot \exp\left(\left(b + \frac{c \cdot 2 \cdot gap \cdot \Delta gap}{\lambda_0}\right)\frac{\Delta gap}{\lambda_0} + c \cdot \left(\frac{\Delta gap}{\lambda_0}\right)^2\right) \tag{7}$$

The scaling of the SCUs was accomplished according to Eq.8 [163]

$$B = [0.28052 + 0.05798 \cdot \lambda_0(mm) - 9 \cdot 10^{-4} \cdot \lambda_0^2 + 5 \cdot 10^{-6} \cdot \lambda_0^3] \cdot exp\left[-\pi\left(\frac{gap}{\lambda_0} - 0.5\right)\right] \tag{8}$$

The gap loss of the KIT/Noell SCUs is 1.0 mm. These devices employ a thin liner at 10 K (thin insulation between coil and liner), which is part of the accelerator vacuum. The coils rests in a separate vacuum. A fixed vacuum chamber as for the APS SCUs cannot be utilized, because the SCUs have to be opened during injection. The liner and the flexible tapers are moving accordingly. The gap loss of the APS-SCUs is larger due to the chamber, being 2.3 mm for the existing devices and 1.8 mm for the future devices.

The scaled K-values are plotted in Figure 23. The blue line indicates the material limit for conventional planar CPMUs. The red line shows the limit of SCU designs utilizing modern NbTi wires, a gap loss of 1.8 mm, and applying 80% of the critical current density. The KIT/Noell SCU20 lays below the red line, because the operational current has plenty of margin to the critical current.

Both the conventional CPMU and SCU technology are mature. The choice of the technology depends partly on the period length, where CPMUs are chosen for shorter, and SCUs for longer period lengths. The crossing point is at a period length of about 14 mm. In the next decade both technologies will develop for higher fields by different measures. The CPMU fields can be boosted with specific designs beyond a conventional hybrid, e.g. wedged poles and magnets, side magnets, Dy pole tips, HTSC loops, or inhomogeneous magnetization as discussed in Section 2.8. The SCU fields can be raised with ambitious designs such as a 1 mm gap loss (KIT/Noell design), currents of 90% of the load line, or temperatures below 4.2 K. A wire optimization for SCU purposes also offers a big potential. Another factor of 1.3 can be gained with Nb_3Sn wires, once the fabrication technology is elaborated.

Variably polarizing cryogenic undulators will be developed within the next decade. As a 1st step, an in-vacuum room temperature APPLE II undulator is constructed at HZB. Based on the experience, a cryogenic device is planned. On the other hand, a prototype of a superconducting SCAPE device with variable polarization is on the way at APS. Shortly, a performance comparison in terms of magnetic field and polarization switching rate will be possible.

Today, field errors of CPMUs and SCUs are small. Phase errors below 3° are achieved, where an explicit shimming is not necessary for SCUs.

A fast wavelength tuning is an important issue for the user community. In SCUs the cycling time (time for a complete hysteresis loop) is limited by the coil cooling technology. If liquid Helium is involved, the cycling time can be as short as one minute (APS), whereas it takes five minutes with a cold head cooling (KIT/Noell-SCU20).

Once, the technologies of CPMUs and SCUs are transferred to industry, a fair price comparison will be possible. It is expected, that the SCUs will be less expensive.

This article concentrated on the comparison of planar cryogenic undulators for the use in 3rd and 4th generation storage rings. For FELs a round or four-fold symmetric magnetic structure is possible, and variable polarization is not required in the bunching section. Here, purely helical superconducting undulators are the preferred solution due to their superior high magnetic field, and the simply winding technology.

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6 Figure captions

Figure 1: Top: Optimized effective fields of CPMUs with various period lengths at three gaps as simulated with UNDUMAG (symbols) and fit according to Eq.3 (line). Bottom: Solid lines: Deviations of optimized effective fields from HZB-fit (symbols: HZB-optimization, no symbols: APS-optimization). For illustration, the data for optimized peak fields are plotted as well: dotted line: peak fields, dashed line: effective fields.

Figure 2: Magnet girder of CPMU-17 with integrated liquid nitrogen cooling. The comb-shaped gauges (TiN coated) define the longitudinal position of poles and magnets. Magic finger assemblies (at both ends of the magnet girder) are tuned after complete assembly of the girders in the vacuum tank.

Figure 3: Alignment of comb-shaped gauges. The deviation of the tooth position from the design value is plotted before and after gauges alignment. The residual deviation over the complete magnet girder (after a straight line subtraction) is within ±10µm.

Figure 4: Comparison of Keyence optical micrometer and Heidenhain linear encoder. Configuration A: two plane-parallel glass blocks plus two UHV compatible optical windows; configuration B: two plane-parallel glass blocks only. Thick line: the gap is opened and closed four times from 3 mm to 53 mm in steps of 1 mm; thin lines: differences of Keyence reading and Heidenhain linear encoder reading during the four cycles.

Figure 5: Cost development during the magnet sorting process. Five runs with different seeds have been done for each set of sorting parameters. Quench runs (left) and simulated annealing runs (right).

The numbers indicate the speed of cooling via the temperature reduction factor T_red. A factor close to one triggers a very slow cooling rate, whereas smaller factors speed up the cooling process.

Figure 6: Transverse distribution (-20mm < z < 20mm) of vertical (left) and horizontal (right) field integrals of single magnet girder at a distance of 2.75 mm. The poles are not inserted yet. Dotted lines: expected transverse field integral distribution for presorted configuration (for details see text); solid thin lines: predicted field integrals after sorting; thick lines: measured field integrals as extracted from Hall probe measurements. The periodic part is filtered out.

Figure 7: Pole height and magnet height measurements of lower magnet girder (laser interferometer, straightness optics). Values at two z-positions (dotted lines: z=-15.5mm, dashed lines: z=15.5mm) and averaged values (thick lines) are plotted. The phase error of the magnet girder after geometric pole alignment only is plotted as well.

Figure 8: Transverse field integral distribution (from moving wire measurement) of upper magnet girder after pole height adjustment based on straightness data only. Squares: before transverse pole alignment; triangles: after transverse pole alignment; circles: UNDUMAG simulation including contribution of vertical environmental field.

Figure 9: Rendering and picture of APS SCU magnet core.

Figure 10: Schematic of main and correction coils in SCU magnet core.

Figure 11: Calculated on-axis magnetic fields of two CPMUs (PrFeB, NdFeB), two SCUs (NbTi, Nb3Sn), and one IVU (SmCo) for a vacuum gap of 6.0 mm for period lengths from 8 mm to 30 mm.

Figure 12: SCU magnet with gap spacers and gap-adjusting clamps. The vacuum chamber extends from both sides of the magnet.

Figure 13: Phase errors as a function of magnet current for APS SCU18-2 and LCLS SCU prototype.

Figure 14: The cross section of the original APS SCU cryostat.

Figure 15: Cooldown curves, temperature versus time, for original SCU cryogenic system.

Figure 16: Rendering images (based on the engineering drawings) of new APS SCU cryostat with thermal shield, cold mass, undulator and vacuum chamber.

Figure 17: Cooldown curves, temperature versus time, for original (SCU18-2) and new style (HSCU) cryostats.

Figure 18: Cross-section of the APS SCU vacuum chamber: transition upstream and downstream sections.

Figure 19: Cross-section of the APS SCU vacuum chamber with tubing and magnetic sensors.

Figure 20: SCU Magnet measurement bench.

Figure 21: SCU18-1 calculated and measured flux for harmonics from n=3 to n=11.

Figure 22: SuperConducting Arbitrary Polarization Emitter-SCAPE. Two sets of “planar” undulator magnets are placed around vacuum chamber.

Figure 23: Effective K-values of built CPMUs and SCUs in comparison with theoretical curves (for details see text). The CPMUs are listed in table 4, and the SCUs are listed in table 5. All K-values are scaled to the same vertical aperture of 5.0 mm. The CPMU gap loss is 0.2 mm. The SCU gap losses are 2.5 mm (SCU18), 1.8 mm (SCU16.5) and 1 mm for the KIT/Noell devices.

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