NOVEL UNDULATORS: THE LONG AND WINDING ROAD TO BRIGHTNESS

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Abstract

Storage rings and free electron lasers use undulators to produce high brilliant X-ray photon beams. In order to increase brilliance and photon energy tunability it is necessary to enhance the undulator magnetic peak field on axis by reducing its period without decreasing the electron beam stay clear. Undulator technologies aiming to reach this goal are presented.

INTRODUCTION

Undulators are arrays of bending magnets in which electrons travel a very gentle sinusoidal path and emit photons. Undulators are mainly operated in synchrotron light sources and free electron lasers (FELs) to produce extremely bright photon beams, which are used to study:

- Biological science investigating as for example mechanisms at the basis of diseases and virus replication (including covid-19) relevant for medical and pharmaceutical industry (see e.g. Ref. [1, 2])
- Material science analysing cracks, electrodeposition, magnetic memories for magnetic recording industry, diagnostics of micro-chips for semiconductor industry, etc…(see e.g. Ref. [3])
- Environmental science to develop better catalysts for industrial processes, electric cars, as well as to deepen the understanding of mineral extraction, waste disposal and climate change (see e.g. Ref. [4])
- Planetary research and geoscience (see e.g. Ref. [5])
- Human heritage and paleothology (see e.g. Ref. [6]).

The brightness of a light source is defined as follows:

$$Brightness = \frac{Flux}{4\pi^2 \Sigma_x \Sigma_y \Sigma'_x \Sigma'_y} \tag{1}$$

where the $Flux$ is the number of emitted photons per sec within a spectral bandwidth of 0.1%, and $\Sigma_{x,y}$ and $\Sigma_{x,y}$ are respectively the source size and divergence, determined by the size and divergence of both electron and photon beams. Electron beams with small size and divergence travelling in undulators generate highly collimated photon beams (see Fig. 1).

With the goals of increasing the photon energy tunability reaching harder X-rays and of realizing more sustainable accelerators with lower electron beam energies, there is a quest for short period undulators with a high maximum magnetic peak field on axis B_{max}. The undulator equation below indicates that, to produce a certain wavelength λ with lower electron beam energy it is necessary to decrease the undulator period λ_U:

$$\lambda = \frac{\lambda_U}{2n\gamma^2}\left(1 + \frac{K^2}{2}\right) \tag{2}$$

where n is the harmonic number, γ is the Lorentz factor, $K = 0.9336\lambda_U[\mathrm{cm}]B_0[\mathrm{T}]$ is the undulator parameter and B_0 is the peak field on axis. Short period undulators allow to reduce the dimension of storage rings and linacs, since lower electron energies are needed to produce a given photon energy. Moreover, for FELs, also the total length of the undulator line can be reduced. According to the 1D FEL theory [7], the gain length L_G:

$$L_G \propto \lambda_U^{1/3} f(K), \tag{3}$$

where $f(K)$ is a function of K. For a fixed electron beam energy and K, L_G is smaller for shorter λ_U. By decreasing λ_U, the same or an increased photon energy tunability is obtained by increasing B_{max}.

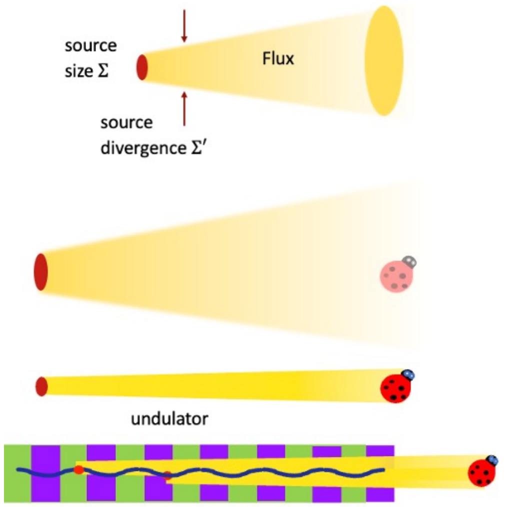

Figure 1: Sketch showing the meaning of bright source. A brighter source with a more collimated photon beam can better resolve the details of the probe under investigation. Electron beams with small size and divergence travelling sinusoidal paths along undulators (consisting of a series of dipole magnets) produce collimated photon beams.

This paper reviews different technological developments aiming to reduce λ_U and enhance B_{max}. In particular I will focus on superconducting undulators (SCUs) and their present and upcoming applications in storage rings, FELs

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and compact light sources. In the last section I will present few examples on proposed concepts based on alternative technologies.

TECHNOLOGY COMPARISON

Considering the same geometry, that is λ_U and beam stay clear/vacuum gap, SCUs can produce higher B_{max} with respect to permanent magnet undulators (PMUs).

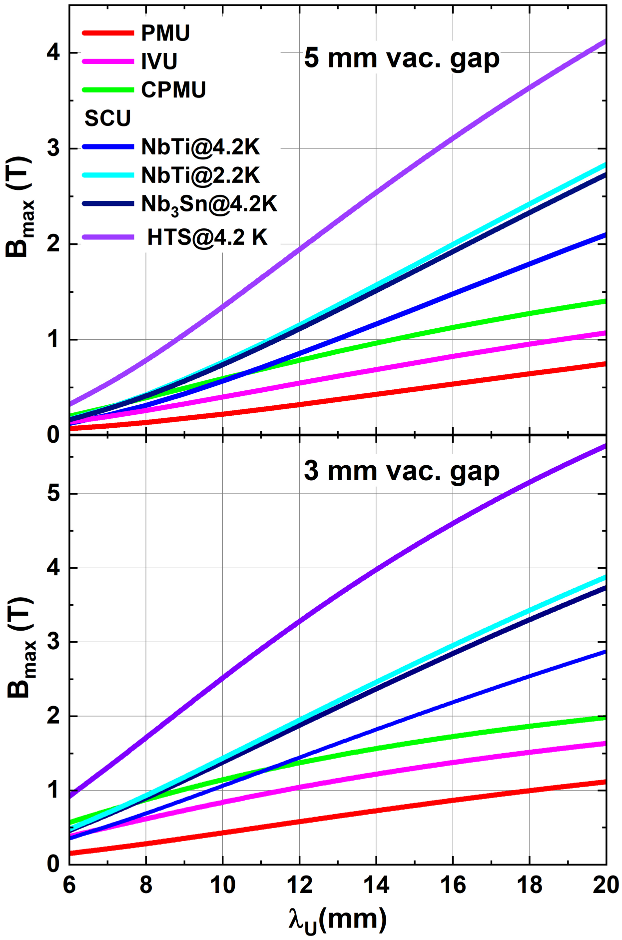

Figure 2: Comparison in terms of magnetic field as a function of the λ_U at a beam stay clear/vacuum gap of 5 mm (top) and of 3 mm (bottom) for different undulator technologies. Adapted from Ref. [8]

In Fig. 2 is reported a comparison between these technologies for vacuum gaps of 5 mm and 3 mm. In vacuum undulators (IVUs) are an evolution of the PMUs: to increase B_{max} the magnet arrays are placed closer to the electron beam and share the same vacuum. The B_{max} of PMUs depends on the field remanence, which by cooling them down to about 100 K reaches a maximum of about 1.7 T. Such IVUs are called cryogenic PMUs (CPMUs), and allow to reach even higher B_{max}. While SCUs have the potential to reach higher fields by using superconducting materials with higher current density, PMUs have reached their limit [9]. The curves reported in Fig. 2 are obtained by the following parametrization curves. For the B_{max} of the PMUs and IVUs with, respectively, a magnetic gap g equal to the beam stay clear plus 2 mm and 0.2 mm, the function [10] below holds:

$$B_{max} = 3.381 \exp\left(-4.73\frac{g}{\lambda_U} + 1.198\left(\frac{g}{\lambda_U}\right)^2\right) . \quad (4)$$

The B_{max} of the CPMUs with a magnetic gap g equal to the beam stay clear plus 0.2 mm is described by [11]:

$$B_{max} = 3.502 \exp\left(-3.604\frac{g}{\lambda_U} + 0.359\left(\frac{g}{\lambda_U}\right)^2\right) , \quad (5)$$

and the one for the NbTi based SCUs by [12]:

$$\begin{aligned} B_{max} = &\\ &\left(0.28052 + 0.05798\lambda_U - 9. \times 10^{-4}\lambda_U^2 + 5. \times 10^{-6}\lambda_U^3\right)\\ &\times \exp\left(-\pi\left(\frac{g}{\lambda_U} - 0.5\right)\right), \quad (6) \end{aligned}$$

where λ_U and g are in mm and B_{max} in T. The blue curve shown in Fig. 2 for NbTi-SCUs is valid by operating at a temperature of 4.2 K with a temperature margin of 1 K for both following cases: a) a magnetic gap of 6 mm applying ≈ 80% of the critical current, and b) a magnetic gap of 6.5 mm applying ≈ 85% of the critical current. Applying superfluid helium cooling schemes, as done for the Nb superconducting radio frequency (RF) cavities, improves B_{max} by 35%. The cyan curve in Fig. 2 is obtained by multiplying the right term of Eq. 6 by 1.35 [8], still considering a temperature margin of 1 K. The dark blue curve represents the expected magnetic field for NbSn$_3$-SCUs at 80% of the critical current limit and it is obtained by multiplying the right term of Eq. 6 by 1.3 [11]. The application of high temperature superconductors (HTS) to undulators has the potential to reaching B_{max} of the order of 2 T with $\lambda_U < 15$ mm for a beam stay clear of 5 mm, doubling B_{max} with respect to NbTi-SCUs operating at 4.2 K. The violet line shown in Fig. 2 is a fit of the results from simulations performed in FEMM [13] for different λ_U and magnetic gaps ranging from 6 mm to 20 mm and from 4 mm to 8 mm, respectively. The geometry of the HTS tape SCU is shown in Fig. 3 considering 96 layers of 33 μm thick HTS tape with a width of $\lambda_U/4$. The lower part of Fig. 3 shows the loadlines of HTS-SCUs with $\lambda_U = 10$ mm and the critical current of a 2.5 mm wide HTS tape at 15 K. For an operating temperature of 4.2 K, there is a temperature margin of about 11 K for B_{max} described by the following parametrization:

$$\begin{aligned} B_{max} = &\\ &2.42\left(0.37 + 0.057\lambda_U - 0.0021\lambda_U^2 + 3. \times 10^{-5}\lambda_U^3\right)\\ &\times \exp\left(-\pi\left(\frac{g}{\lambda_U} - 0.5\right)\right), \quad (7) \end{aligned}$$

where λ_U and g are in mm and B_{max} in T. The critical current from Ref. [14] normalized to the different tape widths has been adopted.

The large temperature margin of the HTS allows to operate these coils at higher temperatures without losing in magnetic

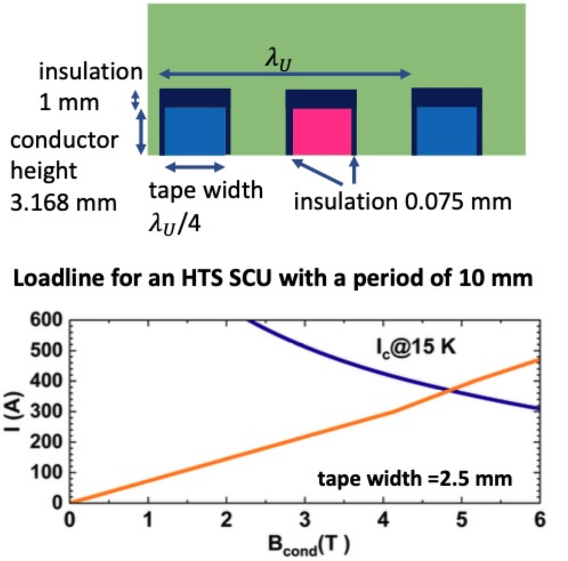

Figure 3: Top: Geometry of the HTS-SCU simulated with FEMM to obtain the loadlines needed to derive Eq. 7. Bottom: Example of the loadline of an HTS-SCU with λ_U = 10 mm and 6 mm magnetic gap, and the critical current of a 2.5 mm wide HTS tape at 15 K. The current at the crossing point is used to calculate B_{max}.

field performance, leading to more robust and/or sustainable operation with reduced cooling power.

However, HTS tapes are still much more expensive than NbTi wire, up to about a factor 10. To use the high engineering current density of the ReBCO tape in the most effective location to increase B_{max} and take advantage of the larger temperature margin of HTS tapes, HybriSCU, a graded SCU combining NbTi and ReBCO tape has been proposed and studied. The geometry taken into consideration foresees the use of 4 mm HTS tape and λ_U = 16.8 mm. The improvement of B_{max} at λ_U = 16.8 mm for a magnetic gap of 6 mm and a temperature margin of 1 K for NbTi and 11 K for the ReBCO tape is of about 15% by adding 7 layers of ReBCO tape to the 15 layers of NbTi, and of about 37% by considering 13 layers of NbTi and 30 layers of ReBCO tape [15].

SCUs offer elegant solutions, using the same winding body, to duplicate or triplicate the period length, which can further increase the photon energy tunability range considerably [16].

NbTi-SCUs have, with respect to PMUs, the additional advantage of a higher radiation hardness, demonstrated in NbTi magnets used in different colliders.

SUPERCONDUCTING UNDULATORS

SCUs date back to the early 70s. A helical SCU wound with NbTi wire was used to demonstrate for the first time the FEL process [17]. After having been dismissed for more than 30 years, NbTi-SCUs are now successfully operated in synchrotrons and are commercially available [18–21]. A recent paper thoroughly reviews SCUs [22]. In the following I will limit to giving an overview of the SCUs operating in synchrotrons and of the planned SCUs for synchrotrons, X-ray FELs (XFELs) and compact light sources.

Three synchrotrons worldwide are operating SCUs: the Advanced Photon Source (APS), the KIT light source and the Australian Synchrotron. Before its upgrade, the APS was smoothly running two NbTi SCUs with λ_U = 18 mm, 7.2 mm vertical beam stay clear, B_{max} = 0.97 T and a magnetic length of 1.1 m [19], and a helical SCU with λ_U = 31.5 mm, 8 mm beam stay clear, B_{max} = 0.4 T and a magnetic length of 1.2 m [23]. The maximum rms phase error was reduced from 6° to 2° from the first to the second planar NbTi-SCU. A Nb_3Sn-SCU was tested in the APS during the last three months of operation before the long shutdown for the upgrade of the ring. This SCU has the same parameters as the planar NbTi ones except for an increased B_{max} = 1.17 T and a maximum rms phase error of 6°. The APS SCUs are cooled using a thermosyphon system. A liquid helium tank placed inside the cryostat is used as reservoir to flow helium along the coils. The tank is kept cold by cryocoolers in a closed loop cycle and needs to be filled before cooling [24]. This concept was developed by the Budker Institute of Nuclear Physics (BINP) and applied to the APS SCUs and to a superconducting wiggler developed for the CLIC damping ring tested at the KIT synchrotron [25].

KIT and its industrial partner Bilfinger Nuclear & Energy Transition GmbH (Bilfinger) have developed planar NbTi-SCUs, which are now commercially available [18, 20]. These SCUs are cooled only by cryocoolers, without need of additional liquid helium and nitrogen. The KIT light source is successfully operating a SCU with λ_U = 20 mm, 7 mm beam stay clear, B_{max} = 1.18 T and a magnetic length of 1.5 m [26]. After this development a SCU with λ_U = 16 mm, 5.6 mm beam stay clear, B_{max} = 1.084 T and a magnetic length of 1.6 m was built by Bilfinger for the Australian Synchrotron, and is now providing photons to the BioSAX beamline to study fundamental properties of biomolecules [21]. For both SCUs measurements of up to the 7^{th} and 5^{th} harmonics, respectively, have been reported, demonstrating the good magnetic field quality.

All SCUs mentioned above have continuously wound vertical coils. Quenches are rare and do not prevent the further operation of the synchrotron. They are recovered within 1 hour at APS and within 30 minutes at KIT and at the Australian Synchrotron.

Plans for SCUs in Synchrotrons

For the APS upgrade, four cryomodules 4.8 m long with two SCU coils each are planned. Two of the cryomodules foresee in line coils 1.9 m long with λ_U = 16.5 mm, while the other two foresee a canted configuration with two 1.5 m and 1.3 m long coils and λ_U = 16.5 mm and λ_U = 18.5 mm, respectively [27]. The beam stay clear is 6.3 mm and B_{max} = 1.06 T and B_{max} = 1.32 T for the shorter and longer λ_U, respectively [28].

BINP developed a NbTi-SCU for the Diamond Light Source with $\lambda_U = 15.6$ mm, a beam stay clear of 6 mm, $B_{max} = 1.2$ T, a magnetic length of 1.9 m, and rms phase error of 2.5°. Because of the political situation, this SCU was never delivered. Before the conflict in Ukrain, BINP was working on NbTi-SCUs for their new diffraction limited storage ring SKIF, for which they did foresee a planar and performed R&D on a tapered and an elliptical SCU [29]. BINP has dominated the market of NbTi superconducting wigglers for the last decades [24]. Their SCUs are based on the same technology and use horizontal racetrack coils, connected by joints. This solution has the advantage of keeping the possibility to easily exchange the coils in case of failure, and the disadvantage of needing to cool down the joints. In case of a wiggler, where the coils are immersed in liquid helium this is not an issue. However, for undulators in which the coils are cooled via copper braids it might become challenging to cool all the joints.

The Institute of High Energy Physics (HIEP), Chinese Academy of Sciences, has designed and built a 1.5 m long planar NbTi-SCU with a short period of 15 mm and plans additional developments for applications both in storage rings and FELs [30].

The Paul Scheerer Institute (PSI) is developing a SCU based on bulk HTS blocks for the X-ray tomographic microscopy beamline at the Swiss Light Source 2.0 (SLS) to reach up to 60 keV. The concept of stacking HTS bulks in a solenoid with the function of magnetizing the blocks when they are cooled below their critical temperature was proposed by Kii et al. [31] and demonstrated for the first time experimentally by the same group with a six periods prototype [32]. PSI has demonstrated in collaboration with the University of Cambridge a magnetic field $B_0 = 2.1$ T for a magnetic gap of 4 mm, $\lambda_U = 10$ mm [33], in a ten period prototype and is now aiming to building the SCU for the beamline. This will have magnetic length of 1 m long with 4 mm vacuum gap, $B_0 = 1.8$ T, $\lambda_U = 10$ mm, with a solenoid in Nb_3Sn, designed and produced by Fermilab, providing a uniform field of 12 T allowing a maximum field variation in the bulks < 0.001 [34].

Plans for SCUs in XFELs

The Linac Coherent Light Source (LCLS), the Shanghai High Repetition Rate X-ray FEL and Extreme Light Facility (SHINE) and European XFEL (EuXFEL) are all planning to test and operate SCUs. SCUs allow XFELs to reach 2-25 keV with electron beam energies of 8 GeV, as planned for SHINE and LCLS-II-HE, and 25-70 keV with electron beam energies of 16.5 GeV as in use at EuXFEL. All three laboratories decided to apply planar NbTi-SCUs, since they have proven successfull operation in synchrotrons. The helical geometry can increase the efficiency of the FEL process up to 10-20%, but introduces additional complications on tolerances. XFELs need few thousands periods to reach saturation, and therefore long undulator lines. Those are segmented such that each undulator is few m long to allow economic manufacturable lengths and reasonable measurement benches. Each undulator is followed by a so-called intersection, including diagnostics elements, a quadrupole to keep the dimensions of the electron beam below few tenths of μm permitting the FEL process to occur, and a phase shifter to compensate the phase advance of the emitted photons with respect to the electron beam. Segmenting the SCU line in many cryostats few m long increases its length and the thermal losses but reduces the risks in case of possible failures and makes alignment as well as magnetic measurements easier. A segmentation of the SCU line in many cryostats allows also to keep the intersections at room temperature. When few cryostat modules are used cooling with cryocoolers is of advantage. For a complete SCU FEL line with few tens of modules, a cryoplant is a clear choice [35].

SLAC and ANL joint forces to demonstrate the integration of a SCU prototype downstream with respect to the hard XFEL undulator line at LCLS. In order to achieve a high packing factor the cold mass in each module comprises a 1.5 m long planar NbTi-SCU and all the elements of an intersection. The prototype will consist of two modules each about 2 m long [36] for a total length of about 4 m. The aim is to perform the development for a complete SCU FEL line with no gaps in between, in which many modules are bolted together. The prototype allows integration with the existing beam-based alignment system, and FEL gain measurements. A cooling system as for the above described ANL SCUs is foreseen. SCU prototype coils with $\lambda_U = 21$ mm, a magnetic gap of 8 mm and 1 m long have been fabricated and reached the specified $B_{max} = 1.67$ T and rms phase error < 5° [37].

SHINE is planning a complete line with 40 SCUs. Each cryostat will be 4.5 m long with 4 m long SCU coils and a SC phase shifter in the middle. The intersections will be at room temperature and a cryoplant will be used to cool all 40 modules with the coils at≈ 4.2 K with a thermosyphon system. Horizontal race track coils with $\lambda_U = 16$ mm will be used. For a beam stay clear of 4 mm, $B_{max} = 1.58$ T is foreseen [38]. Prototype coils 4 m long have been built. Each m of the 4 m long coils is powered a different power supply. For 3 m length, $B_{max} = 1.53$ T was reached. The last section sustained smaller currents. These SCUs will be in vacuum, that is the coils will share the same vacuum as the electron beam. A copper tape 0.1 mm thick will screen image currents [39].

A total of six SCU modules are planned to be installed downstream of one of the hard XFEL lines at the EuXFEL. The Superconducting undulator PRE-SerieS mOdule (S-PRESSO) is anticipating the Free-Electron laser SuperconducTing undulator Afterburner (FESTA). Aim is to extend lasing above 30 keV up to 60-70 keV [40, 41]. A 5 m long cryostat contains two SCU coils about 2 m long separated by a SC phase shifter and corrections coils. The small-series production FESTA consists of five modules. The contract of S-PRESSO has been assigned to Bilfinger. S-PRESSO is completely cryogen free as the systems developed by KIT\Bilfinger: it will be cooled with six cryocoolers. The $\lambda_U = 18$ mm and $B_{max} = 1.82$ T have been chosen so that the fundamental of the SCU overlaps the one of the PMUs to demonstrate the further amplification of the FEL process. A magnetic gap of 6.5 mm is foreseen with a beam stay clear of 5 mm, leaving space for possible shimming coils. A copper vacuum chamber (h 10 mm x v 5 mm) made of 0.3 mm thick copper with a residual-resistance ratio ≈ 100 [8], separates the cold mass, placed in an insulation vacuum, from the electron beam vacuum. Prototype SCU coils 300 mm long have been built at Bilfinger and tested at KIT in a liquid helium bath test stand at 4.2 K. The prototype shows a very robust design reaching $B_{max} = 2$ T. The second field integral is well within specifications. The stability to the nominal current was tested for 8 h [42].

SCUs for Compact Light Sources

NbTi-SCUs with λ_U between 10 and 16 mm are also the choice for the up to come compact light sources. The first in vacuum planar NbTi-SCU was tested at CLARA (Compact Linear Accelerator for Research and Applications). The vacuum of the SCU reached a base pressure $P = 10^{-6}$ mbar and was separated from the rest of the accelerator with $P = 10^{-8}$ mbar by two thin foils placed inside manual valves letting the electron beam pass through. This SCU has $\lambda_U = 15.5$ mm and $B_{max} = 1.05$ T with a beam stay clear of 7.4 mm. The expected IR spectrum was not observed due to a strong kick to the beam even at low currents. Despite this, no electron beam induced quenches were observed [43]. EuPRAXIA plans to test a NbTi-SCU with $\lambda_U < 16$ mm, $B_{max} > 1.5$ T and a beam stay clear of 5 mm [27] under development at Fermilab, while STFC is developing a helical NbTi-SCU for CompactLight with $\lambda_U = 13$ mm, $B_{max} = 1.1$ T and a beam stay clear of 4 mm to reach 8-16 keV photon energies with 5.5 GeV electron beam energy [43].

ALTERNATIVE TECHNOLOGIES

Microwave undulators (MUs) have been first proposed in the 80s by Shintake et al. [44]. It is possible to use the standing or travelling wave produced by a metallic RF structure generating a periodic transverse magnetic field. The λ_U depends on the wavelength of the cavity in free space λ_0 and on the wavelength of the guide λ_g ($\lambda_g > \lambda_0$ to allow the wave to propagate): $\lambda_U = 1/\lambda_w + 1/\lambda_g$. The long period undulation with period given by the difference of the terms in the above equation is suppressed by choosing a $\lambda_g \approx \lambda_0$. For a standing wave MU $B[T] \propto \sqrt{P[GW]Q_0}$ and for a travelling wave or so-called flying undulator $B[T] \propto \sqrt{P[GW]}$. where P is the input power and Q_0 is the quality factor. Standing wave MU require less power to produce the same B as the flying undulator. MUs are not sensitive to radiation, allow relatively larger apertures than PMUs and SCUs and the polarization can be controlled by the one of the input wave.

Tunable spontaneous emission and seeded coherent radiation at the Next Linear Collider Test Accelerator (NLCTA) at the SLAC National Accelerator Laboratory have been measured using a MU based on a copper structure with $Q_0 = 91000$ with $\lambda_U = 13.9$ mm, $B_{max} = 0.65$ T and a beam stay clear of 12 mm. The MU was powered by a klystron with an output power of 75 MW at 11.424 GHz and flat top pulse 1.6 μs long [45]. With quality factors up to 3-4 orders of magnitude larger than copper cavities, superconducting ones can boost B_{max}. In order to reduce λ_U higher frequencies are needed. Unfortunately for higher frequencies the output power of possible driving sources drops significantly. A proposal for CompactLight was made aiming to reducing $\lambda_U = 4.35$ mm with $B_{max} = 1.25$ T and a beam stay clear of 4.8 mm, requiring a source with a frequency of 36 GHz and output power 50 MW. The biggest challenge of application of MUs is the lack of commercially available high frequency driving sources with sufficient stability and lifetime [46]. A possible issue in reaching high B_{max} is microwave breakdown.

Different technologies have been proposed to achieve submillimeter λ_U for ultra compact XFELs: the periodic electric field of a laser with μm wavelength (Ti:Sa or CO) can be used to form an optical cavity using a similar principle as the MU [47, 48]; micro-electromechanical system (MEMS) fabrication technologies to reach 100 μm gap, $\lambda_U = 400$ μm and $B_{max} = 0.135$ T, which combined with 200 μm gap quadrupoles with an ultra high gradient of 1400 T/m can enable producing hard X-rays with sub-Gev electron beams [49]; a laser focused on a gas jet used to accelerate electrons in its wake can be used to ionize Si nano-wires periodically arranged and acting as an undulator with $\lambda_U = 24$ μm and $B_{max} = 270$ T. This could generate X-ray beams with adjustable energies in the range 10–100 keV and a peak brightness of the order of 10^{23} photons/s mm^2 mrad^2 0.1% bandwidth [50].

SUMMARY

SCU technology provides short period and high field undulators. Tremendous progress has been made in the past years on SCUs. Planar NbTi-SCUs are becoming a mature technology and they are commercially available. The number of laboratories working on SCUs is increasing as well as the interest of the light sources community in this technology.

Alternative concepts to reach short period high field undulators are proposed and some tested. None of them is yet ready to be applied in user facilities.

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