

UNDULATOR OPTIONS FOR SOFT X-RAY FREE ELECTRON LASERS*

S. Prestemon[†], R. Schlueter

Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

Soft X-ray free electron laser sources require significant photon energy tuning and ideally provide variable polarization to users. The proposed LBNL facility will provide multiple FEL lines with varying spectral characteristics to satisfy a broad array of soft X-ray physics. A variety of undulator technologies are being investigated to satisfy these requirements. We evaluate the performance characteristics of the key competing technologies, including superconducting options, and outline the impact of technology choice on overall facility design and cost. We review the key R&D issues that must be addressed to validate the different technologies for soft X-ray FEL application.

INTRODUCTION

The development of soft and hard x-ray free electron lasers (FEL's) is actively being pursued at a number of laboratories around the world. The recent successful commissioning of the LCLS free electron laser can be viewed as the first in an upcoming series of user facilities for ultra-fast, ultra-bright sources for a variety of science applications.

Photon energy tunability at the LCLS is provided by changing the electron energy emanating from the linear accelerator (linac). It is however preferable to tune the photon energy by varying the magnetic field, thereby allowing for fine tuning of the beam quality from the gun and linac; this is particularly true for facilities incorporating multiple FEL lines, since variation of photon energy by one user should not impact other FEL lines. The next FEL facilities expected to be commissioned, including XFEL [1], Spring8 [2], and Fermi [3], will have variable-gap permanent magnet undulators to provide photon energy tunability, although in each case the detailed undulator technology is different, with XFEL using planar undulators, Spring8 using in-vacuum planar devices, and Fermi incorporating planar and elliptically polarizing devices.

A concept for a multi (~ 10) FEL-line soft X-ray user facility has proposed at LBNL [4], operating at high (1 MHz) gun repetition rate yielding ~ 100 kHz FEL pulse repetition rate from each FEL line. Key interconnected design parameters include the peak electron energy provided by the linac and the undulator technology, period and gap, which combined define the resulting B-field capability and thus the minimum photon energy and energy tunability.

Here we review performance characteristics of existing

and potential undulator technologies and the impact of the technology choice on the electron beam energy, both in terms of photon energy tunability and overall system cost.

PERFORMANCE CHARACTERISTICS OF UNDULATOR TECHNOLOGIES

The workhorse undulator technologies for FEL applications are based on permanent magnet systems using the Halbach array concept. A number of variations exist, from the baseline pure-permanent magnet planar device to the high-performance in-vacuum hybrid (permanent magnets with steel or Vanadium-Permendur poles) designs, to variable-polarization devices [5].

The synchronicity condition for undulator radiation relates the emitted electromagnetic radiation wavelength λ_1 to the electron energy E and the undulator spatial period λ_u . For planar undulators the condition is

$$\lambda_{1,planar} = \frac{1 + K^2/2}{2\gamma^2} \lambda_u \quad (1)$$

where $\gamma = E/E_0$ is the (electron) relativistic mass ratio; the deflection parameter K is defined with B_0 the undulator maximum on-axis field, m the electron rest mass, and c the speed of light, as

$$K = \frac{eB_0\lambda_u}{2\pi mc} \quad (2)$$

The photon production is a strong function of the deflection parameter, peaking around $K = 1$.

Performance of undulators is characterized by the function $B(g_m, \lambda_u)$, where g_m is the magnetic gap. We will denote g_v the beam vacuum aperture. Here we provide a performance comparison of a variety of competing technologies: pure permanent magnet elliptically polarizing undulators, hybrid permanent magnet in / out vacuum planar undulators, superconducting helical, planar, and elliptically polarizing undulators, and a new planar undulator concept using high-temperature superconductors operating at low temperature. The performance curves will then be used to evaluate the influence of technology on the selection of operating energy and undulator period for an FEL facility.

Pure and Hybrid Permanent Magnet Devices

The family of undulator technologies based on permanent magnet material forms the basis of most undulators in use on storage ring light sources, and will be used in the first X-ray FEL's to come online in the next few years. Hybrid devices, incorporating magnetic poles placed on a scalar potential by neighboring permanent magnets, are

* This work was supported by the Director, Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

[†] sprestemon@lbl.gov

typically used for planar devices [6]. These can be "traditional" out of vacuum devices (OV) or in-vacuum (IV). From a magnetic performance point of view the difference between the two technologies is simply due to a difference between the feasible magnetic gaps of the IV technology vs. OV technology, the latter's g_m being larger so as to sit outside of the vacuum chamber (with its gap g_m being $\sim 1.5\text{mm}$ larger than the g_m of the IV technology). Herein, both pure and hybrid device performance functions are modeled as homogeneous, with field strength a function of the nondimensional parameter g_m/λ .

Pure permanent magnet (PM) devices that rely on the direct PM flux are used predominantly for devices providing variable polarization (EPU's). A common configuration is the APPLE II devices [5], which allows variable linear and variable elliptic polarization control while maintaining a planar gap for the vacuum chamber. A recent alternative EPU design (" Δ ") leveraging the linear characteristic of an FEL/ERL line is described in [7]. All of these configurations can be reasonably modeled using the functional form [6],[8]

$$B(g_m, \lambda_u) = B(g_m/\lambda_u) = aB_r e^{b(g_m/\lambda_u) + c(g_m/\lambda_u)^2} \quad (3)$$

where B_r is the remanent field of the permanent magnet material and the coefficients a , b , and c are provided in Table 1.

Table 1: PM Based Undulator Fit Coefficients (see Eq. 3). EPU APPLE data fit from [9]. All EPU fits assume linear horizontal polarization mode.

Type	a	b	c
PM (planar)	1.55	$-\pi$	0
Hybrid, van. Perm. (planar)	3.44	-5.08	-1.54
PM (EPU, "APPLE")	1.47	-2.77	-0.37
PM (EPU, " Δ ") [7]	1.51	-0.82	-3.31

Superconducting Helical Undulators

Bifilar helical undulators using low-temperature superconducting wires have been used since the 1970's [10]. The on-axis field of a bifilar helical coil with cross-section of dimension $(r_0, r_1) \times \lambda_u/2$ can be estimated as [11], [12]

$$||B(\lambda_u, r_0)|| = \frac{\alpha r_0}{\sqrt{r_0^2 + \lambda_u^2/4\pi^2}} \frac{2\mu_0 J_E}{\pi^2} [\lambda_u F_1 + \pi F_2] \quad (4)$$

with

$$F_1 = K_0\left(\frac{2\pi r_0}{\lambda_u}\right) - K_0\left(\frac{2\pi r_1}{\lambda_u}\right)$$

$$F_2 = 2r_0 K_1\left(\frac{2\pi r_0}{\lambda_u}\right) - 2r_1 K_1\left(\frac{2\pi r_1}{\lambda_u}\right).$$

Here K_0 and K_1 are modified Bessel functions. The coefficient α has been added to account for a realistic winding former; assuming a former coilpack separation of $\delta z =$

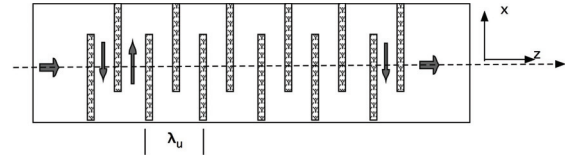


Figure 1: Tape undulator concept. The current path is dictated by patterned cuts in the superconductor.

$\lambda_u/5$ results in $\alpha \approx 0.8$. The variation in pitch angle with radius is not accounted for in Eq. 4, although the effect is small, typically 1 – 5%.

Superconducting Planar Undulators

The performance of planar superconducting undulators has been described elsewhere (see for example [13]). The performance of a superconducting undulator is dictated by the engineering current density J_E , defined as the total Amp-turns of the coilpack divided by the coilpack cross-sectional area. Among the low-temperature superconductors, NbTi and Nb₃Sn are available commercially for applications. For real undulator applications Nb₃Sn typically yields an increase in J_E of $\sim 40\%$ over NbTi. More novel "artificial pinning center" (APC) NbTi conductors are competitive with Nb₃Sn, but suffer from lack of reliable commercial availability and reduced temperature margin as compared to Nb₃Sn: the latter has a critical temperature T_c of $\sim 18\text{K}$, whereas APC NbTi has a $T_c < 11\text{K}$.

Superconducting Tape Undulators

A novel concept has recently been proposed to generate an undulator field by stacking in series a number of high-temperature superconductor tapes [12]. Traditional superconducting undulator concepts use layered windings on a machined former to generate the alternating fields. This approach is not readily applied with tape conductors, as some degree of "hard-way" bend of the tape is usually required, or a large number of joints must be made. The tape undulator eliminates the need for windings altogether by incorporating the current path directly onto the tape. Using micromachining, lithography or laser techniques, a flat YBa₂Cu₃O_{7- δ} (YBCO) tape conductor can be patterned with cuts in the superconductor that force the current in a defined path, as shown in Fig. 1. The YBCO tape properties can be leveraged by close proximity of the YBCO layer to the beam, resulting in efficient use of field-producing current. The tape concept promises very tight tolerances and low cost, making it very competitive for narrow gap, short period applications.

Performance Comparison

The different technologies excel in different regimes of λ_u and g_v . A comparison is provided in Fig. 2 for the important regime $10 < \lambda_u < 20\text{mm}$, for a beam aperture of $\sim 4\text{mm}$. Figure 3 considers the aggressive regime

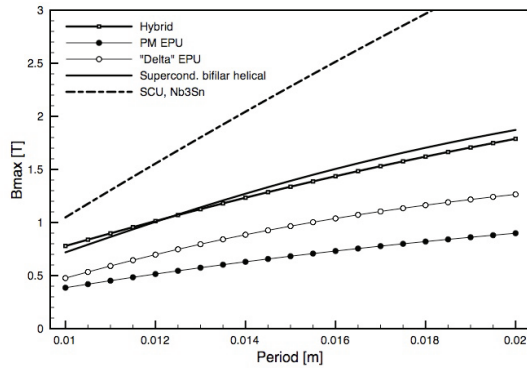


Figure 2: Performance comparison between multiple technologies: PM-hybrid, APPLE EPU, Δ -EPU, and superconducting bifilar, for a vacuum aperture of 4mm. Calculations of the bifilar helical SCU data assume an iron-free system with $J_E = 1500\text{A/mm}^2$, neglect $J_c(B)$ dependence, and are only reasonably valid for $B < 2T$. PM-based devices assume remanence field $B_r = 1.35T$. SCU data assume Nb_3Sn material. Note that the field values presented are maximum on-axis values.

$5 < \lambda_u < 10\text{mm}$, for a beam aperture of $\sim 2\text{mm}$. Due to the field dependence of the critical current of YBCO material, the tape concept excels in narrow gap, very short period regimes, e.g. $g_v < 3\text{mm}$, $\lambda_u < 10\text{mm}$, where the peak field on the superconductor is low $B_{max} < 3T$. SCU's based on low-temperature materials excel in the important regime $g_v > 3\text{mm}$, $\lambda > 10\text{mm}$. Note that in both regimes PM (pure or hybrid) are tough competitors, and have the advantage of being fairly mature technologies with known technical solutions to handle tolerances and field errors.

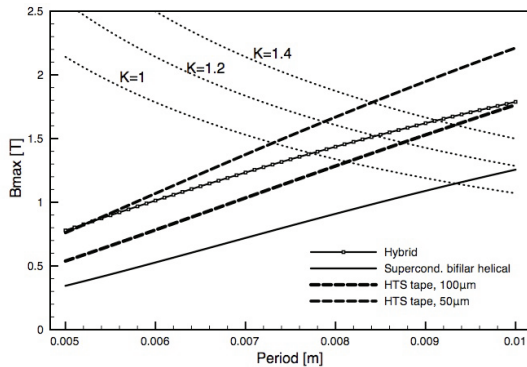


Figure 3: Performance comparison between in-vacuum PM-hybrid and the HTS tape concept. Calculations for the PM-hybrid are as in Fig. 2. "HTS tape 1" assumes $100\mu\text{m}$ thick tape. "HTS tape 2" assumes $50\mu\text{m}$ thick tape. In both cases the device operates at $\sim 4.2K$.

The PM in-vacuum data suggests strong performance at short periods. Although devices with periods of 10mm or less have been built, their fabrication requires precise

machining of magnetic material and of poles, followed by labor-intensive assembly and shimming. These issues become more severe as the period and gap decrease. Strengths of the HTS concept are that a) periodicity can be accurately maintained using existing micromachining capabilities, b) the assembly is fairly simple, and c) the device cost is therefore expected to be low. These issues are particularly important for large-scale FEL applications that may require 10 – 100m of undulators.

It should be noted that for any cryogenic narrow gap technology, and in particular for superconductor technologies, heat loads associated with beam wakefields and radiation must be addressed. This is of particular concern for high-repetition rate, high-current FEL's. Detailed modeling and experiments are currently being considered to estimate these loads and their impact on undulator technologies.

IMPLICATIONS FOR FEL DESIGN

For an FEL design to yield wavelength tunability $\lambda_1 < \lambda < \lambda_2$ with a given technology, eq. 1 can be applied with (λ_1, K_{min}) and (λ_2, K_{max}) to yield

$$K_{max} = K_{max}(\lambda_1, \lambda_2, K_{min})$$

(see [9]). For planar fields this yields

$$K_{max} = \left[2 \left(\frac{\lambda_2 - \lambda_1}{\lambda_1} \right) \left(1 + \frac{K_{min}^2}{2} \right) + K_{min}^2 \right]^{1/2} \quad (5)$$

Equation 1 can be reformulated to yield $\lambda_u = \lambda_u(\gamma; \lambda_1, K_{min})$, where the minimum wavelength λ_1 and minimum deflection parameter $K = K_{min}$ are considered fixed. A reasonable choice is $K_{min} = 0.8$, as sufficient on-axis flux density is still produced to only marginally impact the FEL performance. Using eq 2 and 5, the minimum electron energy needed to achieve a maximum wavelength λ_2 can then be obtained as an implicit solution of the following equation:

$$K_{max} = \frac{eB_0(\lambda_u(\gamma; \lambda_1, K_{min}), g_m)\lambda_u(\gamma; \lambda_1, K_{min})}{2\pi mc} \quad (6)$$

From eq. 2, 3, 4 etc. it is evident that K_{max} is a function of the allowable vacuum aperture g_v and undulator technology. In Fig. 4 the minimum electron energy is plotted as a function of λ_2 assuming $\lambda_1 = 1\text{nm}$ (typical of a soft X-ray facility) for the elliptically polarizing undulators, in-vacuum undulators, and Nb_3Sn superconducting undulators.

Impact of Electron-energy Reduction

For CW operation superconducting RF is essential. The cost of an SCRf system is driven by traditional infrastructure (e.g. tunnel, shielding, etc), cryogenic infrastructure (e.g. liquifiers, storage capacity, transfer lines, etc.), and SCRf cavities (number, gradient, etc). Each of these cost drivers is expected to scale roughly linearly with electron

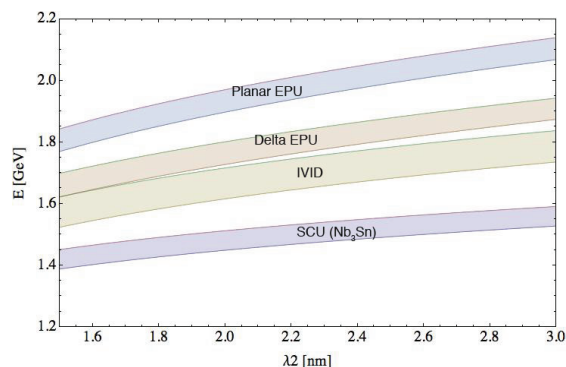


Figure 4: Electron energy needed to produce radiation in the range $1nm < \lambda < \lambda_2$ for various undulator technologies. In all cases planar modes were assumed. For each technology the calculations were made for vacuum apertures of 4 to 5mm to illustrate the gap-dependence.

energy. The linac and associated infrastructure will be a/the leading cost driver for a future FEL user facility.

Impact of Period Reduction

Aggressive undulator performance translates into selection of shorter period for a given wavelength range and hence a lower electron energy. Since the FEL saturation length is to first order $\propto N$, where N is the number of undulator periods, high-performance undulators result in shorter FEL sections.

Shorter undulator length is expected to result in reduced cost. Although one might expect cost to scale roughly with total undulator length, the cost savings may be difficult to achieve if the reduced period is accompanied by tighter tolerances and/or more complex assemblies.

TOLERANCES AND CORRECTION

Undulator field quality requirements for FEL's are predominantly associated with steering and phase-shift/shake [14]. For PM-based undulator designs existing shimming techniques are applicable, although the merit criteria differ from that used typically in storage ring light sources. In particular, the accurate control of gap variation of the magnet structures necessary to provide energy tunability while maintaining trajectory constraints is expected to be difficult for soft X-ray FEL's due to the lack of beam stiffness.

For superconducting devices a reliable shimming methodology has yet to fully demonstrated. Both active and passive schemes are under investigation. The lack of moving components, however, should be a significant advantage, both for accurate, reproducible field error correction and for long term reliability.

CONCLUSIONS

The undulator design parameters for a soft X-ray FEL are closely coupled to the selection of electron beam en-

ergy. A methodology has been presented to aid in the energy selection process, and an initial comparison of undulator technologies provided. Although reduction in vacuum aperture can impact the energy selected, a far greater impact can be had if new high-performance undulator technologies can be implemented. Leveraging the promise of new technologies will require investing in their development, including the prototyping of devices, thorough analysis of their performance, and the development of associated systems including passive/active field corrections and highly accurate field measurement systems.

REFERENCES

- [1] M. Alterelli and et al., "The European X-ray Free-electron Laser Technical Design Report",
- [2] T. Tanaka, K. Shirasawa, T. Seike, H. Kitamura, "Development of the Short-period Undulator for the X-ray FEL Project at Spring-8", *AIP Conference Proceedings*, Jan 2004.
- [3] R. Walker, D. Bulfone, F. Cargnello, "The Fermi FEL Project at Trieste", *Nuclear Instruments and Methods in Physics Research ...*, Jan 1996.
- [4] J. Corlett, A. Belkacem, J. Byrd, "Design Studies for a High-repetition-rate FEL Facility at LBNL", *Lawrence Berkeley National Laboratory*, Jan 2009.
- [5] S Sasaki, "Analyses for a Planar Variably-polarizing Undulator", *Nuclear Instruments and Methods in Physics Research-Section ...*, Jan 1994.
- [6] R. Schlueter, "Wiggler and Undulator Insertion Devices", *Synchrotron Radiation Sources: a Primer*, pages 1–17, Feb 2009.
- [7] A. Temnykh, "DELTA Undulator for Cornell Energy Recovery Linac", *Physical Review Special Topics-Accelerators and ...*, Jan 2008.
- [8] P. Elleaume, J. Chavanne, B. Faatz, "Design Considerations for a 1Å Sase Undulator", *Nuclear Inst. and Methods in Physics Research*, Jan 2000.
- [9] A. Zholents, "The Recipe for a Choice of the Electron Beam Energy Needed for Operation of an X-ray FEL", Oct 2007.
- [10] L.R. Elias, J.M. Madey, "Superconducting Helically Wound Magnet for the Free-electron Laser", *Review of Scientific Instrumentation*, 50(11):6, May 1979.
- [11] B. Kincaid, "A Short-period Helical Wiggler as an Improved Source of Synchrotron Radiation", *Journal of Applied Physics*, Jan 1977.
- [12] S. Prestemon, D. Dietderich, A. Madur, S. Marks, R.D. Schlueter, "High Performance Short-period Undulators Using High Temperature Superconductor Tape", *PAC proceedings*, pages 1–3, May 2009.
- [13] R. Schlueter, S. Marks, S. Prestemon, "Superconducting Undulator Research at LBNL", *Synchrotron Radiation News*, Jan 2004.
- [14] Y. Li, B. Faatz, J. Pflueger, "Undulator System Tolerance Analysis for the European X-ray Free-electron Laser", *Physical Review Special Topics-Accelerators and Beams*, Jan 2008.