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 ∼ 100kHz 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-PermanDur poles) designs, to variable-polarization devices [5].

The synchronicity condition for undulator radiation relates the emitted electromagnetic radiation wavelength \( \lambda_1 \) to the electron energy \( E \) and the undulator spatial period \( \lambda_u \). For planar undulators the condition is

\[
\lambda_{1,\text{planar}} = \frac{1 + K^2/2}{2\gamma^3} \lambda_u \tag{1}
\]

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

\[
K = \frac{cB_0\lambda_u}{2\pi mc}. \tag{2}
\]

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 \( g_0 \) 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
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 ~ 1.5mm 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 \( g_m / \lambda \).

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 ("\( \Delta \)") 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]

\[
B(g_m, \lambda_u) = B(g_m / \lambda_u) = aB_r e^{b(g_m / \lambda_u) + e(g_m / \lambda_u)^2}
\]

(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).

<table>
<thead>
<tr>
<th>Type</th>
<th>( a )</th>
<th>( b )</th>
<th>( c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM (planar)</td>
<td>1.55</td>
<td>-0.82</td>
<td>-3.31</td>
</tr>
<tr>
<td>Hybrid, van. Perm. (planar)</td>
<td>3.44</td>
<td>-5.08</td>
<td>-1.54</td>
</tr>
<tr>
<td>PM (EPU, &quot;APPLE&quot;)</td>
<td>1.47</td>
<td>-2.77</td>
<td>-0.37</td>
</tr>
<tr>
<td>PM (EPU, &quot;( \Delta )&quot; [7]</td>
<td>1.51</td>
<td>-0.82</td>
<td>-3.31</td>
</tr>
</tbody>
</table>

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 \((r0, r1) \times \lambda_u / 2\) can be estimated as [11], [12]

\[
||B(\lambda_u, r0)|| = \frac{\alpha r_0}{\sqrt{\lambda_0^2 + \lambda_u^2}} \frac{2\mu_0J_E}{\pi^2} \left[ \lambda_u F_1 + \pi F_2 \right]
\]

(4)

with

\[
F_1 = K_0(\frac{2\pi r_0}{\lambda_u}) - K_0(\frac{2\pi r_1}{\lambda_u})
\]

\[
F_2 = 2r_0K_1(\frac{2\pi r_0}{\lambda_u}) - 2r_1K_1(\frac{2\pi r_1}{\lambda_u})
\]

Here \( K_0 \) and \( K_1 \) are modified Bessel functions. The coefficient \( \alpha \) has been added to account for a realistic winding former; assuming a former coilpack separation of \( \delta z = \lambda_u / 5 \) 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 Nb\(_3\)Sn are available commercially for applications. For real undulator applications Nb\(_3\)Sn typically yields an increase in \( J_E \) of ~ 40% over NbTi. More novel "artificial pinning center" (APC) NbTi conductors are competitive with Nb\(_3\)Sn, but suffer from lack of reliable commercial availability and reduced temperature margin as compared to Nb\(_3\)Sn: the latter has a critical temperature \( T_c \) of ~ 18K, whereas APC NbTi has a \( T_c < 11K \).

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 YBa\(_2\)Cu\(_3\)O\(_{7-\delta}\) (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 \( \lambda_u \) and \( g_m \). A comparison is provided in Fig. 2 for the important regime \( 10 < \lambda_u < 20\text{mm} \), for a beam aperture of ~ 4mm. Figure 3 considers the aggressive regime
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 \((\lambda_1, K_{min})\) and \((\lambda_2, K_{max})\) to yield

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

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

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

Equation 1 can be reformulated to yield \( \lambda_u = \lambda_u(\gamma; \lambda_1, K_{min}) \), where the minimum wavelength \( \lambda_1 \) 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 \( \lambda_2 \) can then be obtained as an implicit solution of the following equation:

\[
K_{max} = \frac{\varepsilon B_0(\lambda_u(\gamma; \lambda_1, K_{min}), g_m)\lambda_u(\gamma; \lambda_1, K_{min})}{2\pi mc}
\]

From eq. 2, 3, 4 etc. it is evident that \( K_{max} \) is a function of the allowable vacuum aperture \( g_0 \) and undulator technology. In Fig. 4 the minimum electron energy is plotted as a function of \( \lambda_2 \) assuming \( \lambda_1 = 1\)nm (typical of a soft X-ray facility) for the elliptically polarizing undulators, in-vacuum undulators, and Nb₃Sn 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

**FEL Technology II: Post-accelerator**

728
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 energy. 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**