High-Field Strong-Focusing Undulator Designs for X-Ray Linac Coherent Light Source (LCLS) Applications*

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Abstract

Linac-driven X-Ray Free Electron Lasers (e.g., Linac Coherent Light Sources (LCLSs)), operating on the principle of single-pass saturation in the Self-Amplified Spontaneous Emission (SASE) regime typically require multi-GeV beam energies and undulator lengths in excess of tens of meters to attain sufficient gain in the 1Å-0.1Å range. In this parameter regime, the undulator structure must provide: 1) field amplitudes B_0 in excess of 1T within periods of 4cm or less, 2) peak on-axis focusing gradients on the order of 30T/m, and 3) field quality in the 0.1%-0.3% range. In this paper we report on designs under consideration for a 4.5-1.5 Å LCLS based on superconducting (SC), hybrid/PM, and pulsed-Cu technologies.

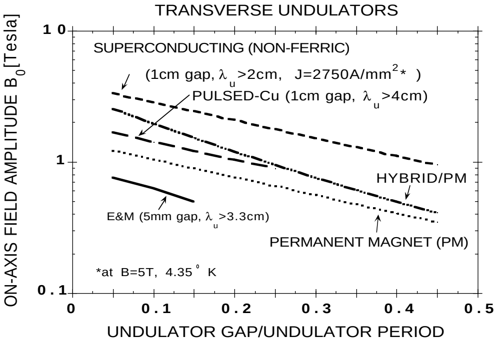

Figure 1. On-axis field performance of selected technologies.

I. INTRODUCTION

In recent years, a multi-institutional study group has been considering the use of a portion of the 3km S-band linac to drive a 4.5-1.5 Å LCLS at the Stanford Linear Accelerator Center (SLAC) [1]. The idea is to accelerate and compress a low-normalized-emittance beam from a laser-driven photocathode rf gun to peak currents in the 2.5-7.5 kA range and emittances approximating $\varepsilon \le \lambda / 4\pi$ (where λ is the output wavelength), and then induce gain saturation by passing the beam through a sufficiently long undulator with superimposed strong focusing. In modeling lasing performance at 4.5-1.5Å, undulator periods in the range 2cm< λ_u <4cm, K parameters ($K = 0.934\lambda_u B_0[T]$) in the range 2.5<K<4, and quadrupole focusing with gradients ranging from 25-75 T/m, have been studied [2]. In view of the single-pass mode of operation and 120 Hz repetition rate of the linac, a wide range of undulator technologies, a number of which are depicted in Fig. 1, can in principle satisfy the given field and period requirements. In considering these technologies, a number of practical factors must be taken into account. These include: 1) fabrication cost (proportional to length); 2) operating cost; 3) attainable field quality; 4) tunability; 5) means for implementing strong focusing; and 6) stability in the linac environment.

In outlining a research and development program expected to culminate in the construction of a 4.5-1.5 Å LCLS at SLAC, technologies that promise the highest on-axis undulator fields (viz., the shortest structures) and focusing gradients have been emphasized. Thus, despite a strong base of experience in E&M (DC) technology at LLNL [3] and a prior study of pure PM structures for a longer-wavelength LCLS [4], the r&d effort at SLAC is currently centered on (non-ferric) SC [5], hybrid/PM [6], and pulsed-Cu [7] technologies, with a practical emphasis on the first two. To date, ferric SC technology [8,9] has not been pursued due to as-yet-unresolved methods for attaining the desired focusing. In this paper we report on the following design studies currently underway in the three cited technologies: 1) a bifilar helical SC undulator [10]; 2) a new hybrid/PM design with monogenic dipole/focusing fields[11]; 3) a weakly-focusing hybrid/PM design with superimposed strong PM focusing [12,13]; and 4) a pulsed-Cu design. For definiteness, we restrict each design to λ=1.5 Å and an electron beam energy of 14.3 GeV ($\gamma \cong$ 28,000). The (transverse) undulator period is then $\lambda_u[cm] \cong 24/(1+K^2/2)$, with $K \to 2^{1/2}K$ for a helical structure.

II. SC BIFILAR HELICAL DESIGN

In the past two decades high-current-density accelerator magnets up to 17 m long have been built, achieving 4-10 Tesla central fields with error levels in the 10^{-4} range. Made of superconducting NbTi and nested in a two-layer “cosine-theta” fashion, these electromagnets employ “Rutherford” cable, include a large return iron yoke, and are restrained with a thick structural shell [14]. Operating at temperatures between 1.8-4.2 K and at currents of several thousand Amperes, these magnets attain a stored energy of several tens of kJ/m and require an insulator that can withstand several kV. With a current-carrying capacity of 3000 A/mm^2 (at 5 Tesla), these components require special attention to ensure their safety in the event of a quench.

In contrast, a non-ferric SC helical undulator will most likely be: 1) lower-field (viz., 2-3 Tesla), 2) current-dominated, 4) small, and 5) self-protecting. A single wire strand will replace the cable while maintaining the “cosine-theta” configuration. On the other hand, since a SC device can

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be current and field limited, field non-linearities that are common in helical magnets are likely to cause the field at the conductor to increase at the expense of a reduced central field. Keeping the non-linearities as low as possible will require the use of magnets whose ratio of circumference to period is small (on the order of 1 or less), mitigating parasitic effects that can strongly alter the purity of the dipole field [15]. An undulator with a period of 27 mm would consequently imply the use of a coil with a diameter ≤8 mm. In a recent conceptual study a single SSC-type strand [16] has been used to structure a 2-layer helical bifilar magnet in a geometry designed to minimize the sextupole component (see Fig. 2). This (0.72 mm diameter) wire - with a Cu/SC ratio of 1.3:1 - carries about 900 A and generates a central field of 2 Tesla. Replacing it with an Artificial Pinning Center (APC) wire, which has a greater current carrying capacity at low fields (e.g., 5000 A/mm^2 at 3.5 Tesla), the maximum central field could be made to approach 2.5 Tesla..

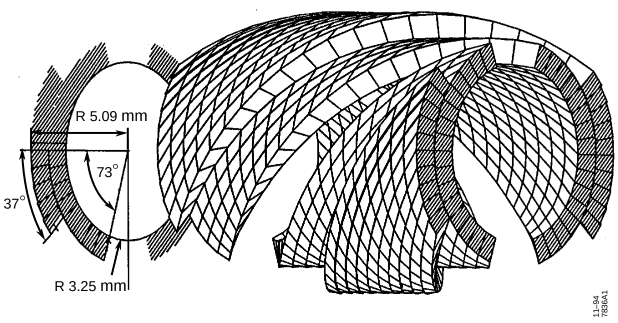

Figure 2. SC bifilar winding design with low field harmonics.

With regard to magnet safety and protection, present estimates are that with a low operating stored energy (on the order of 200 J/m) [17], and with a high current density in the copper (5000 A/mm^2), quench propagation may be fast and the magnet may dissipate its energy in about 13 ms while generating only several tens of Volts. To test the self-protection of the windings under these conditions, as well as to investigate issues of field quality, SC focusing, charging time, and specific quenching mechanisms, the construction of a short LCLS prototype is planned within the coming year.

III. HYBRID/PM SINGLE-STRUCTURE DESIGN

One hybrid/PM LCLS design under study is a novel strong-focusing configuration featuring vanadium permendur poles excited by NdFe/B permanent magnets, sections of which have poles that are alternately tilted in the +/- transverse direction with respect to the midplane and simultaneously wedge-shaped, as viewed from above. For example, such a device with a 4 cm period, a 0.6 cm gap on-center, a ±8.6° tilt, and a ±10.7° wedge could provide a 45 T/m gradient and an on-axis field strength of 0.97 T; => K=4. Minimum/maximum gap at transverse position x=±0.66 cm would be 0.4/0.8 cm.. Pole thickness at x=±0.66 cm is 1.0±0.25 cm. The iron pole pieces shape the field, affording better design quality than is possible with a pure PM device at this small gap.

The choice of simultaneous pole tilt with respect to the midplane and nonuniform pole thickness follows from a 3-D analysis of the ideal pole shape for the superposition of fields from an undulator and a quadrupole.. Let (x,y,Z) be the horizontal, vertical, and axial directions. Define complex variables $w \equiv Z + iy$ and $z = x + iy$. The desired wiggle field and focusing field are, respectively, $B^*_{wig}(w) = iB_0 \cos kw$ and $B^*_{foc}(z) = i2az$, where $k \equiv 2\pi / \lambda_u$ and a is a (focusing-strength) constant.The corresponding scalar potential in the gap is given by $V_{SD} = V_{wig} + V_{foc} = (B_0 / k)\sinh ky \cos kZ + 2axy$. A contour along which V is constant is an equi-scalar potential surface to which the magnetic field is orthogonal. Choosing the boundary of the vanadium permendur pole, whose permeability is effectively infinite, to lie along a constant-V contour specified by $V = f(B_0, 2a, \lambda_u, h)$, where h is the half-gap, gives rise to the wiggle and focusing fields described above. The equi-scalar potential contour along the ideal pole surface passing through the point $(0,h,0)$ is $V_{3D}(0,h,0) = (B_0 / k)\sinh kh$. Thus, the ideal pole contour lies along the surface defined by

$$1 = \cos kZ\left(\frac{\sinh ky}{\sinh kh}\right) + \left(\frac{y}{h}\right)\left(\frac{x}{g}\right)\left(\frac{kh}{\sinh kh}\right),$$

where $g \equiv B_0 / 2a$. The complicated 3-D curved pole shape is approximated by the canted, wedged pole having flat surfaces described at the beginning of this section.. This practical design has the desirable feature that the PM material placed between poles remains a simple cuboid. TOSCA [11] modeling of the canted, wedged, flat-surfaced pole achieves very nearly the performance attained in the ideal analytical design.

Hybrid technology is proven, and PM forces for the LCLS design are small. Modular construction of a 55m-long device is convenient, possibly being in-vacuum. The PM cost for 1000 periods, each consisting of four 1cm x 3cm x 3cm blocks at ~$4/cm^3 is only $144,000. Alternating gradient focusing can be achieved by having a ~0.5m-long focusing section, followed by "drift" and defocusing sections. The wiggle field is matched throughout the sections (see Fig. 3).

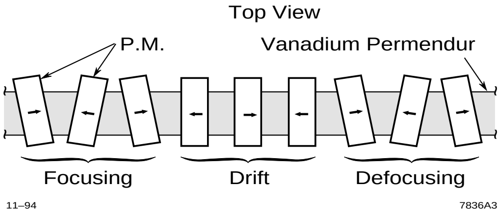

Figure 3. Wedged/canted hybrid/PM undulator section.

IV. HYBRID/PM SEPARATED-FUNCTION DESIGN

A second hybrid/PM LCLS design utilizes a conventional array of simple cuboid poles and NdFe/B magnets to generate a weakly-focusing undulator field, with strong quadrupole focusing provided by superimposed arrays of PM pieces. In one version of this design the PM pieces comprise simple block-pairs inserted into the gap from the sides [13]; in another version the PM pieces are thin strips (1-2 mm) arranged into planar quadrupoles [12] and affixed, along with Beam Position

Monitors (BPMs), to the vacuum duct, which remains mechanically independent of the undulator structure [18]. Potential advantages of this approach include: 1) easier lateral access to the beam, 2) higher attainable undulator fields (1.2-1.4 T), 3) amenability to undulator tuning with shunt plates, and 4) quadrupole field tuning with mechanical actuators.

V. PULSED-Cu DESIGN

Based on prior work on pulsed-Cu undulator prototypes at LANL [7,19], estimates of the operating parameters of a pulsed-Cu LCLS indicate that such a design, in principle, could be realized with existing technology. For example, for a 30m structure operating at 120 Hz, a Pulse Forming Network (PFN) would need to generate 120 2μs current pulses (with tops sufficiently flat over a 0.2μs interval) per second. For a total bifilar wire cross section of 0.25 cm^2 and a resistance of 0.15Ω, pulsing with a peak current of 50 kA would require peak and average powers of 375 MW and 90 kW, respectively. As suggested by the cited research, prototype r&d for the LCLS would need to focus on field quality issues stemming from: 1) impulsive and oscillatory stresses, 2) longer-term (irreversible) strains, and 3) thermal loading.

VI. SUMMARY

A summation of critical parameters and r&d areas associated with the undulator technologies described above is listed in Table 1. Over the next two years the LCLS program plans to address these issues, either at SLAC or in collaboration with laboratories specializing in the individual technologies. Problems common to all technologies, such as, e.g., undulator modularization [21,22], field metrology, and field and e-beam alignment strategies will also be addressed.

Table 1	SC	Hybrid/PM	Pulsed-Cu
Minimal Period[cm]	2	3	2
Sat. Length [m]	30	55	30
Minimal Gap [mm]	6	6	6
K at Minimal Period	~3.5	~3.5	~3.5
Focusing Methods	SC, PM	PM,PS[a]	Pulsed, PM
ΔB/B	~0.01% (in dipoles)	~0.2% (at 3rd gn. sources)	>2% (attained at LANL)
Advantages	Shortest	Proven Technology	Short, No Rad. Damage
Potential Problems & Engineering Issues	Tolerances Quenching Rise Time	PM Damage[b]	Field Quality Mech&Thrm. PFN[c]

[a]Pole Shaping [11]; [b]Ref. [20]; [c]Pulse Forming Network

VII. ACKNOWLEDGMENTS

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