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Undulators for Short Wavelength FEL Amplifiers

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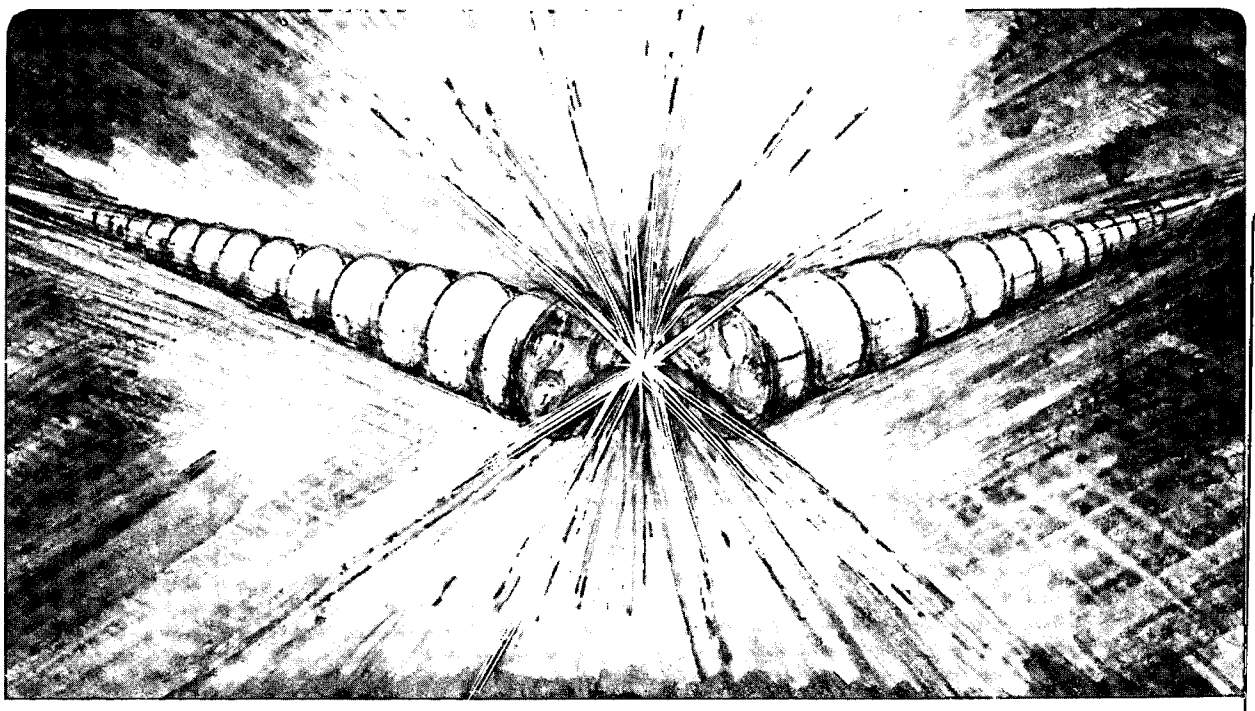

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UNDULATORS FOR SHORT WAVELENGTH FEL AMPLIFIERS*

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ABSTRACT

Issues critical to the design of undulators for use in short wavelength FEL amplifiers, such as attainable on-axis field strength, device compactness, field quality, required magnetic gap, and strong focusing schemes, are discussed. The relative strength of various undulator technologies, including pure permanent magnet, hybrid, warm electromagnetic, pulsed, and superconducting electromagnetic devices in both helical and planar configurations are reviewed. Favored design options for proposed short wavelength FELs, such as the Linac Coherent Light Source at SLAC and the DUV Free-Electron Laser at BNL, are presented.

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1 Introduction

Achieving desired FEL action in SLAC's proposed Linac Coherent Light Source (LCLS) necessitates an undulator with of the order of 1000 periods. The electron beam must be focused over the device length, while the on-axis field strength should provide a desired deflection parameter $K \simeq 2-6$ [1]. In general, a shorter period would result in a shorter undulator length, but a lower attainable K. Typical focusing required for a 2.7-cm-period device at $K = 4$ is that of a quadrupole FODO system with 40-cm-long, 50-T/m-gradient quadrupoles separated by 40 cm.

Relative strength of various undulator technologies in short period linear polarized devices for feasible LCLS gaps 0.4-0.6 cm are shown in Fig. 1 [2,3,4,5]. The LCLS specifications preclude small-period conventional electromanget devices, since the level of current density required to attain the requisite field strength exceeds cooling capability. Short-period pure permanent magnet (P-M) devices could accommodate superposed external quadrupoles but the large quadrupole bore would preclude the large gradient desired. Canting of PM pieces likewise can produce only weak on-axis gradients [6].

2 Short-Period Pulsed Undulators

At Los Alamos, a variety of short period (1 mm - 30 mm) pulsed devices have been developed [7,8]. The general aim there was to push down the period as much as possible, yet still maintain $K_{rms} \simeq 1$. Performance limits of these devices are: (a) the copper wire temperature at the end of a pulse limits the pulse length, (b) the cooling capability limits the rep-rate, and (c) the tensile

strength of the copper wire limits the current. A 2.7-cm-period, 0.86 cm bore bifilar device operating at 5 kA achieved a $K_{rms} = 1$ for a maximum 100 μs pulse length. Maximum rep rates of 1 per minute for solid copper wire and 1 per second for internally cooled copper tubing are achievable. A 0.85-cm-period, 0.8-mm-bore device likewise achieves a $K_{rms} = 1$.

3 Iron-core Superconducting Undulator Technology

An elegantly-simple, iron-core superconducting undulator technology has been developed at Brookhaven [4]. The design features a superconducting wire wound continuously along the device length around a soft iron mandrel or magnetic yoke which has fins restraining the superconductor while simultaneously serving as poles of the linear undulator. It is capable of providing a tunable, highly-stable, good-quality DC field, with adjustable taperability. Demands on the superconductor are minimal, as the field there is small, < 3 T. The major drawbacks are the presence of the cryogenics and the lack of accessibility to the undulator and ensuing alignment difficulties.

Two devices using this technology have been built at Brookhaven: a 0.88-cm-period, 0.44-cm-gap, 0.6-meter-long device with a peak field $B_0 = 0.47$ T for a 470 nm oscillator experiment and a 1.8-cm-period, 0.80-cm-gap, 1.5-meter-long device with a peak field $B_0 = 0.58$ T for a harmonic generation experiment. Two more such devices are part of Brookhaven's DUV proposal: a 3.9-cm-period, 0.6-cm-gap, 2-meter-long modulating undulator with a peak field $B_0 = 0.77$ and a 2.2-cm-period, 0.6-cm-gap, 7-meter-long radiating undulator with a peak field $B_0 = 0.75$ T. (See the four points labeled "B" on Fig. 1).

Typically it is the saturation in the pole, rather than the quench limit of the superconductor that limits the attainable field in the regime where this technology outperforms hybrid technology, i.e., $0.25 < g/\lambda_w < 0.55$ and $0.5 \leq \lambda_w \leq 2.5$ cm. This indeed was the case for the Brookhaven devices. Two modifications that could increase on-axis field in such devices are [9]: (1) increasing the pole thickness as one moves away from the gap and (2) increasing the pole x-direction dimension as one moves away from the gap. Real estate in the x-direction is inexpensive.

The harmonic generation device and the DUV FEL utilize parabolic pole tips [10] to provide equal plane natural focusing. However, strong focusing in these iron dominated devices is possible, just as is the case with hybrid devices.

For LCLS's larger K, and thus optimal device period range of 2.7-4.0 cm, the superconducting device performance advantage is increasingly diminished. Incorporating the large gradient into a higher K device, yet keeping the period, thereby device length, as short as possible is the challenge. Several promising undulator options are being pursued.

4 Strong Focusing Hybrid Undulator

One LCLS possibility is a hybrid device, featuring vanadium permendur poles excited by NdFeB 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. (See Fig. 2). For example, such a device with a 4 cm period, a 0.6 cm gap on-center, a 1.0 cm pole thickness on center, a ± 5.7 degree tilt, and a ± 7.1 degree wedge could provide a 34 T/m gradient and an on-axis field strength of 1.04 T, $\Longrightarrow K = 4$.

Minimum/maximum gap at transverse position $x = \pm 1$ cm would be 0.40/0.80 cm. Pole thickness at $x = \pm 1$ cm is 1.0 ± 0.25 cm. The iron pole pieces shape the field, perhaps affording better field quality than is possible with a pure permanent magnet device at this small gap.

Alternating gradient focusing in a hybrid undulator. The choice of simultaneous pole tilt with respect to the midplane and variable 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 in our ideal strong focusing undulator. Define complex variables $w \equiv Z + iy$ and $z \equiv x + iy$. The desired wiggle field and focusing field are, repectively,

$$B^*_{wig}(w) = iB_0 \cos(kw); \quad \texttt{where } k = 2pi/\lambda \quad \texttt{and} \tag{1}$$

$$B^*_{foc}(z) = i2az; \Longrightarrow dB_{foc}/dz = i2a, \quad \texttt{the gradient.} \tag{2}$$

The magnetic scalar potential, V, where $\vec{B} = -\nabla V$, in the region is

$$V_{3D} = V_{wig}(w) + V_{foc}(z) = (B_0/k) \sinh ky \cos kZ + 2axy \tag{3}$$

A contour along which V is constant is an equi-scalar potential surface to which the magnetic field is orthogonal. For our strong focusing undulator, choosing the boundary of the vanadium permendur pole, whose permeability is effectively infinite, to lie along a constant $V_{wig} + V_{foc}$ contour specified by $V = f(B_0, 2a, \lambda, h)$, where h is the half-gap, gives rise to the combination wiggle and focusing fields described above.

Using the hybrid curve in Fig. 1 as a guide, we attempt to attain a desired on-axis field $B_0 = 1$ T and desired gradient $2a = 33$ T/m, in a 4-cm-period, 0.6-cm-gap strong focusing undulator. The equi-scalar potential contour along the ideal pole surface passes through the point $(x, y, Z) = (0, h, 0)$:

$$V_{3D}(0, h, 0) = (B_0/k) \sinh kh = B_0 h(\sinh kh/kh) \tag{4}$$

Defining $g \equiv B_0/2a$, the ideal pole contour (see Fig. 3) is given by

$$1 = \cos kZ \left(\frac{\sinh ky}{\sinh kh}\right) + \left(\frac{y}{h}\right)\left(\frac{x}{g}\right)\left(\frac{kh}{\sinh kh}\right). \tag{5}$$

The complicated three-dimensionally-curved pole shape, Eq. (5), 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 permanent magnet material laced between poles remains a simple cuboid. Of course, our designed pole shape only approximates the curved surface of the ideal pole, and thus harmonics will be present, and x and y plane strong focusing are not equivalent locally, (though integrated over a wiggle period they are equal in magnitude since in a 3-D structure with coordinates (x, y, Z), the integrated field $B^*(z) \equiv \int_{Z_1}^{Z_2} B^*(z)dZ$ is analytic with respect to z if for all z, $B^*(z)|_{Z_1} = B^*(z)|_{Z_2}$ [11]).

The 3-D TOSCA computer result ($B_0/2a = 1.04/34.0 = 0.0306$) using the canted, wedged, flat surfaced pole achieves very nearly the performance attained in the analytical curved model. Computer runs of analogous designs with poles wedged but not canted and with poles canted but not wedged give gradients of one-third and two-thirds of that when both are employed, assuming

the same wiggle field magnitude in all cases. Thus, for maximum performance and field quality both pole canting and wedging are needed.

Hybrid technology is proven, and the PM sizes for LCLS are small and manageable, with no large forces. Modular construction of a $\sim$ 40 meter device is convenient. PM cost for 1000 periods, each consisting of four 1 cm x 3 cm x 3 cm arrays at \$4/cm^3 is only \$144,000. Figure 4 shows the layout over a focusing section, followed by a "drift" section and a defocusing section. The wiggle field is matched throughout the sections.

Regarding ultimate performace limitations and the maximum achievable gradient: if we attempt to increase the gradient by increasing the pole cant and/or wedge, the pole tip will eventually saturate. The $\mu = \infty$ assumption for the vanadium permendur pole tip is then no longer valid, so the pole contour is no longer an iso-scalar potential surface and the and the gradient will cease to increase.

It should be noted that a superconducting undulator of the design of the previous section is amenable to the strong focusing produced by pole cants and wedges as described above. The same equations can be used to guide the choice of the magnitudes for a practical, yet effective, optimal pole tip shape. Tradeoffs are the relative ease in tunability, construction and transportability, reliability, radiation resistance, and of course magnetic performance capability.

5 Small Bore Helical Superconducting Undulator

An alternative LCLS design being considered [12] that offers the additional desirable feature of producing circularly polarized light is a bifilar superconducting

undulator. Such a device with a 4-cm period, a 0.5-cm-radius magnetic bore, a 0.7-cm-coil outer radius, with a superconducting wire current density times packing factor of $\sim$ 3000 A/mm^2 $\times$ 0.44 could produce a rotating on-axis transverse field of $\sim$ 1.1 T. A 50 T/m coaxial superconducting quadrupole of the style of the SSC ring quadrupoles positioned just outside of the undulator windings could easily provide the requisite beam focusing.

Alternatively, a device with a 2.7-cm period, a 0.325-cm-radius magnetic bore, a 0.475-cm-coil outer radius, with a superconducting wire current density of $\sim$ 4000 A/mm^2 could produce 1.7 T on-axis. As dimensions scale down, the incremental field at the superconductor due to the external quadrupole decreases and thus fortunately, current density in the superconducter can be higher. With the introduction of superconductors with artificial pinning centers [13], J_c is markedly increased at these relatively low fields, making these short-period, small-bore devices magnetically attractive.

The multi-laboratory LCLS collaboration is actively pursuing the hybrid and superconducting undulator options and is planning short proof-of principle prototype devices.

6 Acknowledgments

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Figure 2. Half-period of a strong focusing hybrid undulator.

Figure 3. Ideal pole contour of a strong focusing iron-dominated undulator.

Figure 4. Focusing, drift, and defocusing sections of a stong focusing hybrid undulator.

Fig. 1

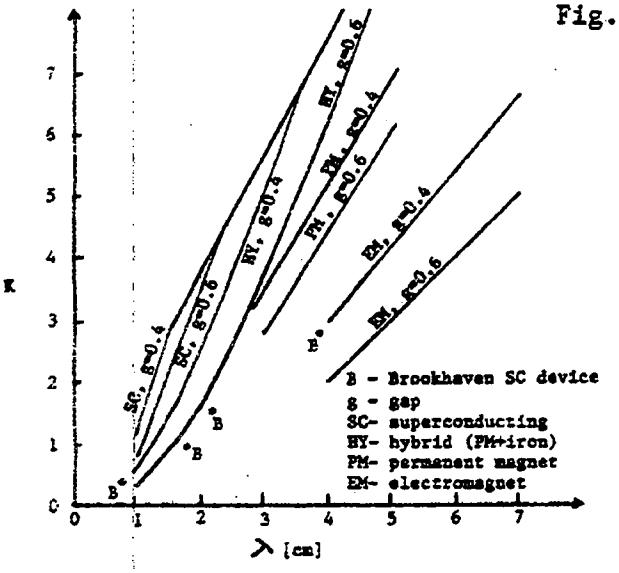


Fig. 3

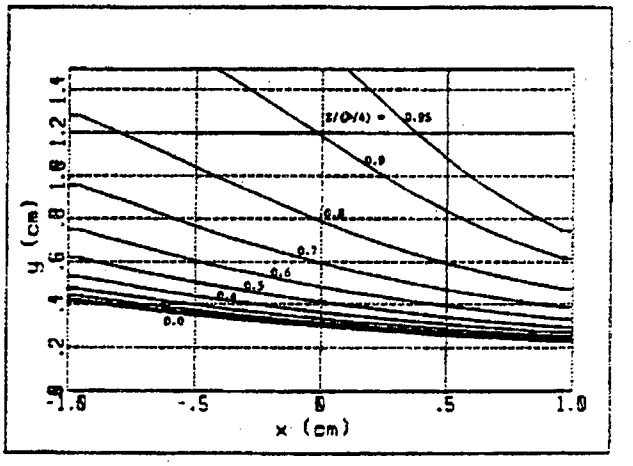


Fig. 2

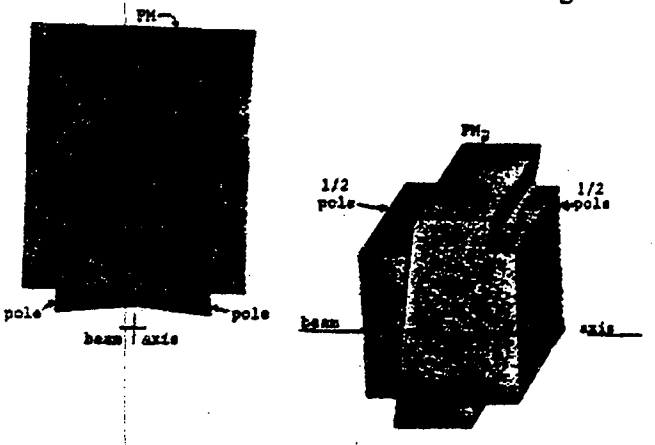
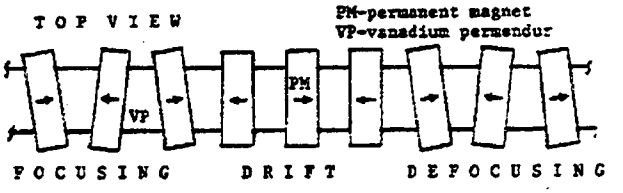


Fig. 4



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