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DESIGN FEATURES OF A PLANAR HYBRID/PERMANENT MAGNET STRONG-FOCUSING UNDULATOR FOR FREE ELECTRON LASER (FEL) AND SYNCHROTRON RADIATION (SR) APPLICATIONS*

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Abstract

Insertion devices for Ångstrom-wavelength Free Electron Laser (FEL) amplifiers driven by multi-GeV electron beams generally require distributed focusing substantially stronger than their own natural focusing fields. Over the last several years a wide variety of focusing schemes and configurations have been proposed for undulators of this class, ranging from conventional current-driven quadrupoles external to the undulator magnets to permanent magnet (PM) lattices inserted into the insertion device gap. In this paper we present design studies of a flexible high-field hybrid/PM undulator with strong superimposed planar PM focusing proposed for a 1.5 Angstrom Linac Coherent Light Source (LCLS) driven by an electron beam with a 1 mm-mr normalized emittance. Attainable field parameters, tuning modes, and potential applications of the proposed structure are discussed.

I. INTRODUCTION

Å-wavelength LCLS undulators driven by multi-Gev elecron beams generally require superimposed focusing [1,2]. Since it is typically optimal to induce 1 full betatron oscillation over the length of the undulator, the required strength of the focusing field (for a fixed undulator K and fundamental output wavelength) varies inversely with the required undulator length. But since the undulator length required to attain saturation varies roughly inversely with e-beam emittance, the required focusing gradient for, say, a FODO lattice of given period and quadrupole length, also varies inversely with the minimum attainable emittance. This dependency is illustrated by the LCLS design study recently undertaken at SLAC [3], which projects a net emittance of approximately 1.5 mm-mr at the undulator entrance. The LCLS parameters from this study are contrasted in Table 1 with those from an earlier study [4], which presupposed a net attainable emittance of 1 mm-mr.

The focusing strength (viz., gradient Q) that can be attained in a FODO lattice superimposed on the undulator field inside the gap is highly dependent on the technique employed. For Q≤45 T/m, for example, external quadrupoles can be employed in pure-permanent magnet (PM) designs [5], and pole wedging, staggering, and canting can be employed with hybrid/permanent magnet (hybrid/PM) technology [6]. If the details associated with shimming are disregarded, the latter technology has the advantage of utilizing a minimal number of elements per period. For Q≥45 T/m, alternative techniques need to be employed [7-10]. In this paper, the planar-PM multipole technology proposed in recent years [7,8] is explored as a basis for a strong-focusing LCLS undulator field design [4,11]. The r&d associated with this work anticipates the eventual development of photocathode (pc) rf guns and linac-based compressor/transport systems that will deliver emittances of 1 mm-mr or less to the LCLS insertion device.

Table 1. LCLS Parameters.

	Earlier study	Current Study
Radiation wavelength [Å]	1.5	1.5
Norm. emitt. $\gamma\varepsilon$ [mm-mrad]	1	1.5
Bunch Charge (initial) [nC]	0.94	0.94
Peak current I_p [kA]	5	3.4
Electron beam energy E [GeV]	14.55	14.35
σ_E / E [%]	0.02	0.02
Pulse duration $\sqrt{2\pi}\sigma_\tau$ [fs]	260	250
Repetition rate [Hz]	120	120
Undulator period λ_u [cm]	3.0	3.0
Peak field B_u [T]	1.3	1.3
Saturation length[a] L_u [m]	60	100
Focusing beta [m/rad]	10	18
Peak spontaneous power [GW]	66	81
Peak coherent power* [GW]	50	9.3
Average coherent power [W]	0.64	0.09
Energy/pulse [mJ]	5	0.75
Coherent photons/pulse (x10^{12})	12.2	1.4
Approx. Bandwidth (BW) [%]	0.1	0.1
Peak brightness** (x10^{31})	5.1	61.7
Average brightness** (x10^{21})	1.7	20.6
Transverse size [m, FWHM]***	30	30
Diverg. angle [mrad, FWHM]***	10	5

[a] Sufficiently small field errors assumed;
*Output fully transversely coherent;
**Photons/s/mm2/mrad2/0.1%BW;
***At exit of undulator

II. A HIGH-FIELD LCLS UNDULATOR DESIGN WITH STRONG PLANAR-PM FOCUSING

The basic undulator construction, schematized in Fig. 1, is seen to consist entirely of PM and permeable pole pieces with rectangular cross sections. The easy axes of all the PM pieces are, in each piece, perpendicular to two

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opposed faces. This not only optimizes the ease and accuracy of component fabrication and undulator construction, but provides a left-right symmetry in the undulator's dipole field structure that can be exploited for shimming and tuning purposes. In addition, the geometrical symmetry allows the axially magnetized PM material to be brought as close as possible to the undulator axis, allowing for the utmost maximization of the on-axis field strength.

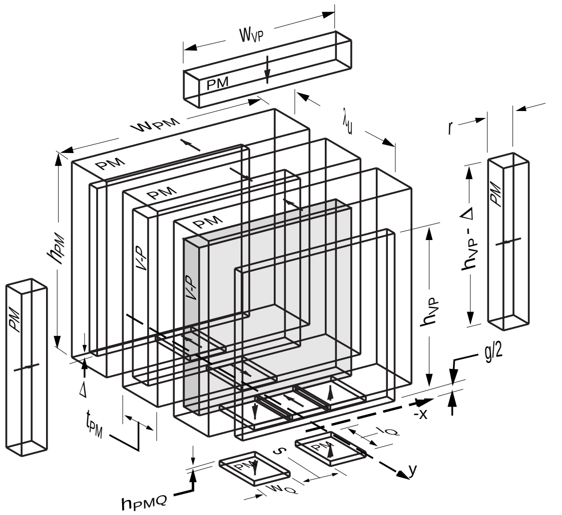

Figure 1. Undulator components and design options (structure mirror-symmetric with respect to the x-y plane; top half shown). To maximize or shim the on-axis field, each pole piece can have one top and two side bias pieces appended to it. Bevels on pole surface edges not shown. For the recessed PMQs, l_Q=t_{PM} and s=w_{smin}.

The proposed structure is seen to be of the "separated-function" type, allowing the quadrupole focusing to be implemented basically independently of the dipole field structure [11]. There are a number of possible implementations; for some of these the axially-magnetized PM material immediately above the axis can: 1) be excluded. 2) comprise individual PM pieces (as depicted in Fig. 1), or 3) comprise continuous extensions of the large axial PM magnet blocks. First, the axial PM blocks can be recessed back from the plane of the permeable pole faces by a distance Δ (>h_{PMQ}), leaving room for the insertion and full variation of the PMQ's lateral gap parameter s ($\geq$0). Second, if s can be bounded by some minimum value w_{smin}, the axial PM blocks can be cut with lateral indents allowing for both the lateral insertion of the PMQ pieces and the extension of the axial PM block material down toward the plane of the pole faces. Third, the PMQ pieces can be made with l_Q>t_{PM} and extended (below the pole faces) along distances of several periods. Here, s$\geq$$w_{smin}$, and the PMQ pieces could be either affixed to the vacuum duct and tuned with linear wire currents [4], or moved into the gap laterally with high-precision mechanical movers. Finally, the dipole structure could be implemented with periodic drift spaces [12], and the PMQ pieces could be installed thereinto, again with mechanical or wire-current tuning of their gradients.

In view of their large spontaneous power output, LCLSs of the class being considered here can induce energy chirps in the electron bunch substantially larger than the the natural linewidth of the FEL (see Table 1). In this case, it could be advantageous to be able to induce a compensating chirp in the undulator field strength. As shown in Fig. 2, this can be accomplished with the proposed design by moving two planar shunt bars into locations at equal distances above and below the undulator structure.

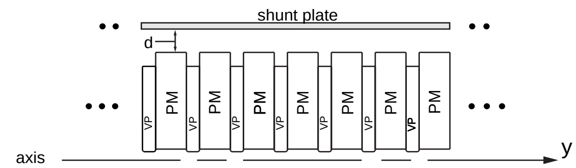

Figure 2. Scheme for tailoring the field profile of the strong-focusing LCLS undulator using two monolithic field shunts (top half of full structure shown). The shunt can be segmented and each segment can be canted along the entire FEL. It can also be segmented, with each segment placed parallel to each gain length (as depicted) at an incrementally varying distance. PMQ pieces not shown.

III. FIELD SIMULATIONS

Comprehensive field design studies were conducted with the AMPERES [13] modeling package. Here we present results for a selected number of configuration cases (see Table 2), with λ_u=3cm, t_{PM}=10.5mm, h_{PM}=34mm, w_{PM}=4cm, t_{VP}(=(λ_u-2t_{PM})/2)=4.5mm, h_{VP}=3cm, w_{VP}=3cm, r=5mm, w_Q=7mm, l_Q(=t_{PM})=10.5mm, h_{PMQ}=0.95mm, Δ=1mm, and g/2=3mm. The model consists exactly of the configuration shown in Fig. 1, extended by symmetry reflections in the x-y and x-z planes. The pole material is Vanadium Permendur and B_r=1.25T (H_c~11900 Oersted) for the PM (Nd/Fe/B).

Table 2. Four configurations modeled with AMPERES.

	Lateral PM Bias Blocks	s $\geq$ w_s (Axial PM Near Axis)	Shunt Plate	PMQs recessed
Case I	Yes	Yes	No	Yes
Case II	No	Yes	No	Yes
Case III	No	No	Yes	Yes
Case IV	No	No	No	Yes

In Fig. 3 Cases I, II, and IV are plotted to show the corresponding range of attainable on-axis fields. A harmonic analysis of the curves confirms a field amplitude in the fundamental of 1.3 T or more for Cases I and II. In Fig. 4, B_z is plotted vs. x between the middlemost poles of the symmetry-extended structure. Both curves show homogeneous central field regions of >2mm extent, fully adequate for the given LCLS beam. In Fig. 5, B_z is plotted vs. x directly under the axial center of a recessed PMQ (Case I) for spacings s of 5mm and 2mm. The curves reveal gradients of 19T/m and 55T/m, respectively, to be contrasted with a maximum value, for s=0, of ~62T/m. With h_{PMQ} increased to 3mm, this maximum could be increased to ~200T/m. Finally, in Fig. 6 the effects of parallel shunt plates (Case III) on the on-axis field amplitude is plotted for three different spacings d (see. Fig. 2). A reasonable sensitivity to field control over the 10^{-1}-10^{-4} range, adequate for strong tapering through low-level chirp correction, is indicated.

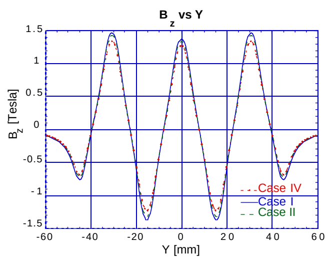

Figure 3. Modeled on-axis dipole field $B_z(y)$.

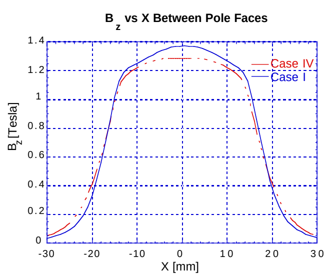

Figure 4. Modeled transverse field $B_z(x)$ under central pole face.

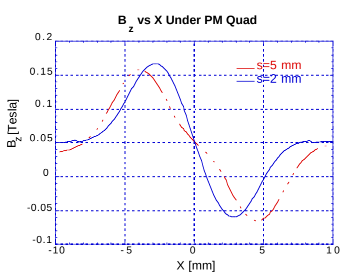

Figure 5. Transverse field $B_z(x)$ under the axial center of a PMQ.

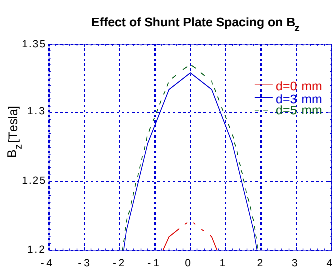

Figure 6. $B_z(y)$ about the undulator's central peak field for 3 different shunt plate spacings.

IV. CONCLUSIONS

We have described selected structural and field features of a simple high-field, strong-focusing LCLS undulator design developed at SSRL over the 1993-1996 period. These were motivated by the requirements for minimizing the length and cost while maximizing the field strength and quality of the structure. The proposed technology and design are also of interest for the development of long (viz., >>β), short-period, small-gap insertion devices for storage ring straights, a recognized direction for attaining 4th generation increases in brightness over conventional 3rd generation storage rings [14]. Future work will include further design refinement, including the simulation of wire-current quad field correction, planar-PM sextupole focusing, and the development of small prototypes.

V. REFERENCES

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