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Design Considerations for a 60 Meter Pure Permanent Magnet Undulator for the SLAC Linac Coherent Light Source (LCLS)*

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Abstract

In this paper we describe design, fabrication , and measurement aspects of a pure permanent magnet (PM) insertion device designed to operate as an FEL at a 1st harmonic energy of 300 eV and an electron energy of 7 GeV in the Self-Amplified Spontaneous Emission (SASE) regime.

I. INTRODUCTION

In recent years, progress in the development of short-pulse, low emittance, laser-driven RF photocathode guns [1], and in the modulation and control of high energy particle beams [2], has made possible the consideration of linac-driven Free Electron Lasers (FELs) designed for SASE [3] operation at 1st harmonic energies extending well into the soft x-ray range. In this paper selected design considerations for an undulator optimized for operation in the water window (300-400eV) on a subsection of the Stanford Linear Accelerator Center (SLAC) 3km linac are described. Using three-dimensional SASE simulation codes reported on elsewhere [4,5], the basic undulator parameters were derived from optimization studies incorporating: 1) the effects of the undulator period λ_u, 2) the field amplitude B_0, and 3) a strong external focussing β on both the undulator's effective gain parameter, ρ_{eff}, and gain length, L_G ($=\lambda_u/4\pi\sqrt{3}\rho_{eff}$). Using the optimization goals of increasing the gain and simultaneously reducing the gain length (to avoid overly long undulator structures [6]) the following set of basic operating parameters was derived:

E (electron energy) = 7GeV	$\gamma\varepsilon$(emittance) = 3×10^{-6}r-m
λ (1st harmonic) = 40Å	I(peak current) = 2500A
λ_u(und. period) = 8 cm	β(focussing) = 8.2m
B_0(field amplitude) = 0.8T	L_G(gain length) = 2.37m

Further simulation studies investigating the effects of field errors on the SASE gain were also conducted [7], and the results were used to help assess the minimal required mechanical and field tolerances of the undulator components.

II. GENERAL DESIGN FEATURES

Given the broad base of experience acquired by the scientific community in the area of PM undulators [8], the continuing improvement of commercially available PM materials, and the advantage of relatively straightforward analytical investigations, the LCLS group decided to base its initial undulator studies on a pure PM design. Upon consideration of a number of alternatives, the focussing lattice was chosen to consist of current-driven iron quadrupoles in a FODO configuration. As shown in Fig. 1, the configuration selected for the PM undulator lattice is of the standard type [9], with 8 magnets per period.

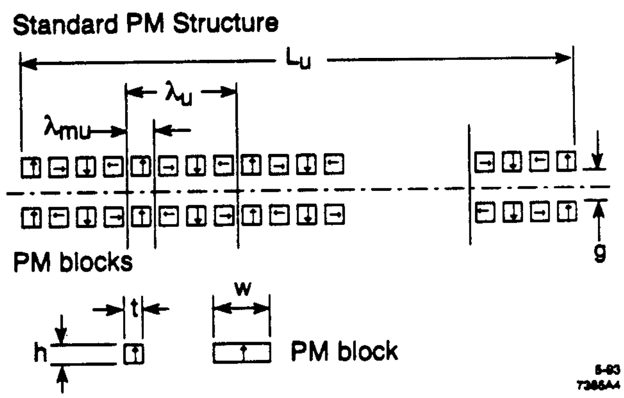

Figure 1. Standard PM configuration of the LCLS.

The PM blocks' dimensional and field parameters were arrived at by both analytical [9] and numerical field calculations. The quadrupole design follows from the computer-study identification of an optimal betatron wavelength of 51.4m, which determined the necessary focal length of the individual quads to be approximately 4.1m. The individual quad dimensions were arrived at by : 1) utilizing 50% of the longitudinal free space along the undulator to help reduce the required quad gradients, and 2) specifying a minimum quad aperture radius of 6cm to inhibit the perturbation of the PM undulator fields by the quad yoke material. The resulting basic parameters are given below.

PM Lattice parameters	FODO lattice parameters
λ_u = 8cm	Quad aperture radius = 6cm
λ_{mu} = 2cm	Quad outside diameter=20cm
h = 1.9cm	Quad length =40cm
t = 1.9cm	Quad gradient =15T/m
w = 4cm	FODO period =1.6m
g = 1.5cm	Phase advance per cell=11.5°
B_r = 1.08T	Total Pwr. Budget ~300kW

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III. MECHANICAL DESIGN

As depicted in Fig. 2, the basic approach to the mechanical design of the LCLS undulator is modular. Two basic reasons for this are: 1) simplification and statistical control of the fabrication and field measurement processes; and 2) facilitation of the installation and alignment of the undulatorin the SLAC FFTB tunnel [10] prior to operation.

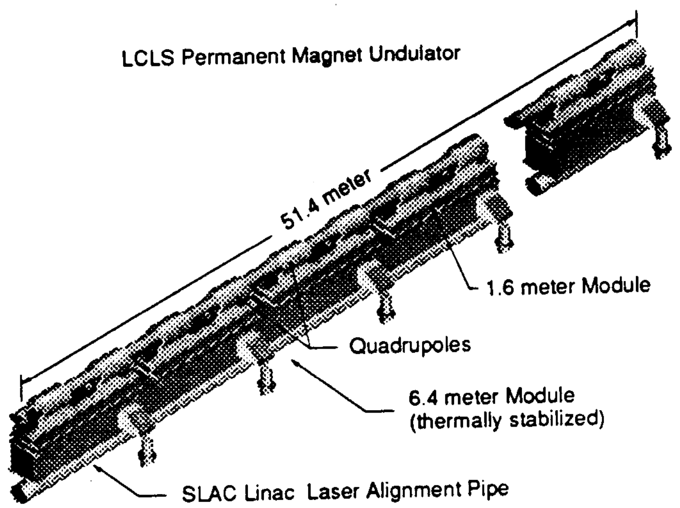

Figure 2. LCLS undulator layout showing modular sections.

Given the possibility of tuning the 1st FEL harmonic by varying E, the conventional use of undulator jaw motion was determined to be dispensable, making possible the design of a relatively simple support system for the PM and quadrupole lattices. At the same time, the small gap necessary for the attainment of the required B_0 introduced troublesome design obstacles to the incorporation of the necessary system components. In Fig. 3, the basic modular unit of the LCLS, a 1.6 meter PM lattice section integrated with one period of the FODO lattice, is shown with a minimal repeating set of system components. For clarity, a schematized and enlarged cross section of the LCLS undulator is shown in Fig. 4.

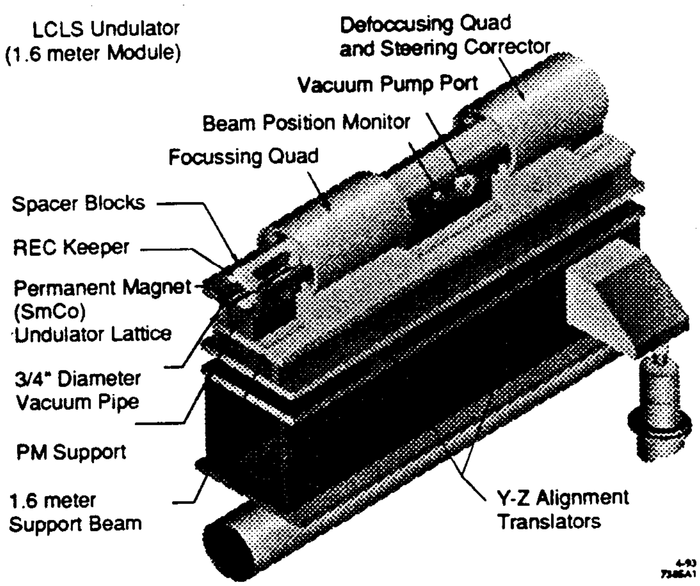

Figure 3. Selected mechanical and electrical details of a 1.6m LCLS module.

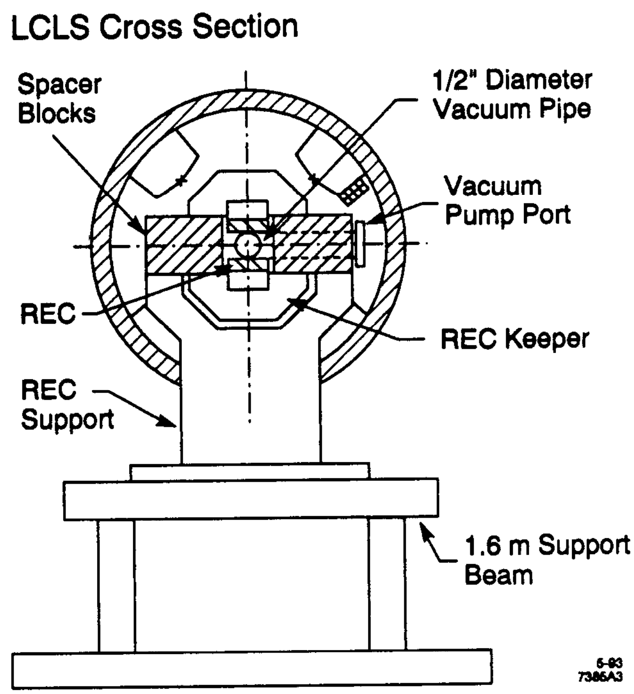

Figure 4. Selected component details of the LCLS insertion device in cross section.

The field gap is set by spacer blocks with optional provisions for limited PM adjustment designed into the keepers. The computed force/period on each linear PM array for the given parameters is approximately 90lbs, necessitating careful attention to the mechanical and compositional details of the keeper assemblies. To allow for longitudinal phasing control and attitude alignment, precision translators are indicated for y-z alignment of each 1.6 meter module. Not explicitly shown are: 1) short magnet block assemblies for continuing the PM lattice in proper phase from one module to the next, 2) coarse y-adjustment provisions for each 6.4m module, 3) a water-based thermal stabilization system for suppressing temperature deviations in excess of ±0.5°C along the entire length of the LCLS insertion device, and 4) in-vacuum Beam Position Monitors (BPMs).

IV. TOLERANCES

The assessment of the effects of random field errors and their correction on the SASE gain process was based primarily on comprehensive 3-D simulations [7]. These simulations, which yield the expected degradation of SASE in the LCLS as a function of random magnetic errors and the precision of compensating orbit corrections, indicate a reduced sensitivity of the FEL gain to field errors, especially in the high gain regime. The results of these studies suggest that dimensional and field tolerances typical of the best currently available "3rd generation [8]" magnets should result in passable performance of the LCLS provided: 1) the magnets are optimally sorted; 2) sufficiently precise orbit detection is achieved; and 3) equally precise orbit correction is implemented every 3m or less. In practical terms, typical magnet field strength tolerances of 0.1%-0.2% and easy axis orientation errors of < 5 mr would be required. Typical positional tolerance on the, say, vertically oriented magnets in Fig. 1 lie in the <15μ range. Using these figures, typical field vs. temperature coefficients (e.g., -0.03%/°K for Sm_2Co_5) lead to the above-cited requirement of a $\leq \pm 0.5$°C temperature variation along the undulator's PM lattice. A number of closely related tolerance parameters, such as, e.g., the accuracy of the BPMs, are expected to be difficult to attain under the design constraints of the LCLS, and directed development is likely to be required to attain the design goals.

V. FIELD MEASUREMENT ISSUES

An important procedure for attaining an undulator field of the requisite quality consists of accurately measuring and sorting the magnets to reduce the field irregularities that adversely influence gain [11,12]. An important advantage of the modular configuration of the LCLS undulator is that this procedure can be applied to sections whose length is typical of 1st-3rd generation insertion devices, and can consequently be expected to attain the necessary field quality without unexpected difficulties. However, the total length of the LCLS insertion device represents an order of magnitude increase over conventional structures, and the problem of measuring its entire field following assembly appears difficult to resolve. Evidently, this raises the issue of the final alignment of the device prior to operation. If no suitable method of alignment based on the full field measurement is developed, it may prove necessary to turn the FEL on and attempt to align it by using the emitted radiation and suitable detector arrays. To this end, it will be important for the field quality over a single gain length to be high enough to produce the required (i.e., observable) gain. A backup strategy that has been considered is to further reduce the field and fabrication tolerances by a factor of 2-3 beyond the above-cited minimums to minimize the number of controls required for successful operation. In either case, the complete fields of at least the (16) 3.2m subsections of the 6.4m modules will evidently need to be characterized with exceptional accuracy. To this end, the development of existing or novel techniques capable of rapid and accurate field measurement [13] is expected to play an important role in the successful implementation of the LCLS.

At present, we are continuing our research activities in a number of the directions described in this note. A short prototype section is in the process of being prepared to help resolve selected tolerance and field measurement issues raised by our analytical and numerical studies.

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