SLAC-PUB-7651
October 1997

Design of an X-ray Free Electron Laser Undulator

Roger Carr

Stanford Synchrotron Radiation Laboratory
Stanford Linear Accelerator Center
Stanford, CA 94309 USA

Abstract. An undulator designed to be used for an x-ray free electron laser has to meet a set of stringent requirements. With no optical cavity, an x-ray FEL operates in the single pass Self Amplfied Spontaneous Emission (SASE) mode; an electron macropulse is microbunched by an undulator and the radiation it creates. The microbunched pulse emits spontaneous radiation and coherent FEL radiation, whose power may reach saturation in a sufficiently long and perfect undulator. The pulse must have low emittance and high current, and its trajectory in the undulator must keep the radiation and the pulse together with a very high degree of overlap. We shall consider the case of the Linear Coherent Light Source (LCLS) FEL project at SLAC, which is intended to create 1.5 Å x-rays using an electron beam with 15 GeV energy, 1.5π mm-mrad normalized emittance, 3400 A peak current, and 280 fsec FWHM bunch duration. We find that this 65 μm rms diameter beam must overlap its radiation with a walkoff of no more than 5 μm for efficient gain. This places severe limitations on the magnetic field errors and other mechanical tolerances. The following is a discussion of the undulator design, specifications, alignment, engineering, and beam position monitoring we plan to implement for the LCLS X-ray FEL.

INTRODUCTION

In a single pass free electron laser operating in the Self Amplified Spontaneous Emission (SASE) mode, exponential gain of coherent radiation intensity is predicted by theory, and power saturation is achieved in about 10 field gain lengths, assuming no tapering of the undulator. [1] It is desirable to build an FEL undulator to a full saturation length, so that the output is more stable than it would be on the exponential part of the gain growth curve. Given the desired output radiation wavelength and the energy of the available electron beam, saturation implies a certain output power, desired or not. If one reduces the beam current or enlarges the emittance in order to lower the output power, saturation will not be achieved.

At SLAC, we are studying the design of a 1.5 Å x-ray FEL based on a laser photocathode electron gun capable of generating a 1 mm-mrad electron pulse with 8 psec duration. [2] The bunch is accelerated in the last kilometer of the SLAC linac to E_e = 15 GeV, and passes through two bunch compressors that reduce the bunch duration to 280 fsec FWHM and raise the peak current to 3400 A. The expected normalized emittance is $\varepsilon_n = \gamma\, \varepsilon$ = 1.5π mm-mrad at the entrance to the undulator, with a bunch diameter of $2\sigma_r$ = 65 mm rms. The energy spread of the beam is σ_E = 0.0002 E_e, and the field gain length is 11.7 m. We shall discuss x-ray FEL undulators with this example in mind. The task of the undulator design is to achieve saturation with an undulator that is not excessively longer than the saturation length based on ideal undulator parameters. In the case of the LCLS, a perfect undulator is predicted to saturate in 94 m, based on both GINGER simulations [3] and semi-analytic models [4]. We hope that building a 100-110 meter device will allow for imperfections and reach saturation.

CHOICE OF UNDULATOR TYPE

After studying several undulator options, we chose a plane polarizing design using hybrid permanent magnet technology. We examined harmonic generation strategies where longer period bunching would feed radiation to successive shorter period devices, but no overall length savings were predicted [5] We looked at putting optical klystron style dispersive sections in the undulator to allow the energy modulated bunch to become spatially modulated, but found that energy spread ruled out this approach. [6] We also considered superconducting bifilar helix and other helical devices, but chose the planar hybrid on grounds of simplicity of construction, focusing, and correction strategy.

*Work supported by Department of Energy Contract DE-AC03-76SF00515.

Simulations of the LCLS show that strong focusing must be added to the undulator lattice in order to maintain a small beam size. Natural focusing would give a beta function length of more than 50 m, but optimal focusing occurs with a beta function of less than 20 m. We intend to operate the LCLS from 5 GeV to 15 GeV, and if we choose an optimum beta function for the 15 GeV limit, we are not far off optimum at 5 GeV. Our models do not presently consider the decrease in energy of the electron beam due to emission of spontaneous radiation; we do not expect this to necessitate tapering the undulator when it is accounted for.

In a hybrid structure, one could add strong focusing with quadrupole magnets between segments of the undulator, or distribute strong focusing along the undulator lattice. To keep the beta function modulation ('sausaging') small, we would chose distributed focusing, for which we reviewed several strategies. They included putting permanent magnet quadrupole magnets between the poles of a hybrid undulator [7] a canted and wedged pole design [8], permanent magnets placed alongside the beampipe [9], transversely staggered poles, canted poles, and combined function pole pieces. We also considered a design with lumped quadrupole focusing and no quadrupole moment in the undulator segments. We chose this design because it affords much easier tolerance control, and a separated lattice is more flexible. The focusing and defocusing quadrupole magnets are moveable transversely, so they can act as trajectory correctors, with feedback from beam position monitors. Working with the Tesla-TTF group at DESY, we have determined that the resulting large beta function modulation does not have a deleterious effect on FEL performance [10]

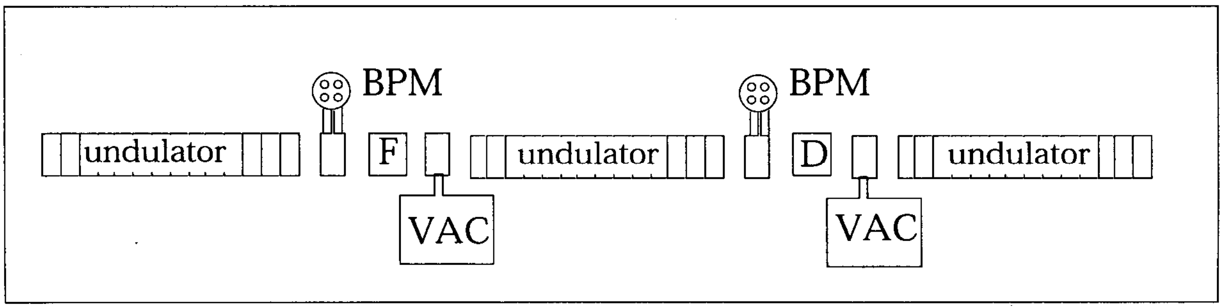

FIGURE 1. A schematic side view of the undulator structure, showing the FODO lattice with separations between 2m undulator sections for diagnostics, focusing (F and D) correctors, and vacuum ports.

The present undulator design has fifty 1.92 meter segments, mounted rigidly to high precision on aluminum girders. The undulator period is λ_u = 30 mm and the gap is 6 mm. Aluminum was chosen for its high ratio of thermal conductivity/thermal expansion. Each end of the girder will be supported by a pier, and a separation between segments of $\lambda_u(1 + K^2/2) = 23.75$ cm will be allowed between undulators, to allow the electrons to slip behind the photons by one period. The separation will be used for diagnostics, pumping, and focusing corrector magnets.

SPECIFICATIONS AND TOLERANCES

The resonance condition for the energy of the radiation first harmonic of an undulator is:

$$E_1\,(\text{eV}) = \frac{950\, E_e^2\,(\text{GeV})}{\lambda_u(\text{cm})\left(1 + K^2/2\right)} \tag{1}$$

where E_e is the energy of the electron beam, and $K = 0.934$ Bmax (T) λ_u (cm). For an NdFeB hybrid, the maximum value of the magnetic field is: [11]

$$B_{max}\,(\text{T}) = 3.44\, e^{-\,gap/\lambda_u}\,(5.08 - 1.54\, gap/\lambda_u) \tag{2}$$

An energy difference of $\sigma_E = 0.0002\, E_e$ would cause a resonance shift of 0. 0004 E_1, as would a gap change of 0.77 μm, a period change of 1.4 μm, or a change of field strength of 15 Gauss. These tolerances would be extremely severe. However, FRED-3D simulations show that FEL efficiency drops off only if random ΔBmax/Bmax is greater than 0.1%. [12] This tolerance is reached when we have a period change of 70 μm, or a gap change of 13.5 μm. These are merely tight tolerances, which we would meet with machining, assembly, and magnetic shimming techniques.

Even with precision machining, sorting of magnets, tight specifications, and precise assembly, we expect measurable field errors. A standard Hall probe can, in principle, detect fields in the Tesla range with 20 μTesla resolution. [13] It is our strategy to shim each pole, to minimize the trajectory and photon resonance errors. We have a coordinate measuring machine with 0.8 μm absolute positioning accuracy over a volume of 1.2 m x 1 m x 0.6 m; it can be fitted with a temperature compensated Hall probe (calibration drift = 80 ppm/K [14] We have modeled the effect of placing small shims on the ends of the pole pieces away from the gap as shown in figure 1. The effect is to lower the field in the gap by a few Gauss, or a few 10's of Gauss. It is possible to order magnets with $\Delta B/B_{rms} < 0.5\%$, and an angular error of 0.5° from the nominal easy axis, but 1.0%, 1° magnets are much less costly. We have found in the case of pure permanent magnet devices that we can use computerized sorting techniques to improve undulator errors by a factor of about 5 over the case of a randomly assembled undulator; we would hope to be able to do as well with a hybrid structure. [15] If we purchase magnets with 1% errors, and lower the errors to 0.2% with sorting, we are well within the range of this shimming strategy.

GEOPHYSICAL, THERMAL, AND MECHANICAL DESIGN

The LCLS undulator will be placed in the existing Final Focus Test Beam (FFTB) facility at SLAC. The first third of the tunnel for the unduator is underground; the last two thirds are in an above-ground heavily shielded concrete structure. The substrate throughout is miocene sandstone. We propose to place the undulator on piers made of a proprietary sand and expoxy material [16], which is much more damping than metal piers, and much more stable against water related swelling and shrinking than ordinary concrete. In the range below 100 Hz, there is cultural and ocean generated vibration, but at the top of existing sand/epoxy FFTB piers, the measured amplitude of these vibrations is less than 50 nm.

Diurnal thermal distortions of the tunnel outside the hilliside can be as much as 100 μm /day, but they can be reduced by isolating the tunnel with trenches cut into the substrate alongside it. The slow diffusive ground motion can separate points 100 m apart by about 100 μm /year. [17] These measurements indicate that our feedback system needs to have a dynamic range of some fraction of a millimeter. Presently the tunnel air temperature is stable to about 1K, but we plan to stabilize the undulator structure with flowing water that can be stabilized to 0.1K.

We propose to detect and correct diurnal, thermal, and ground motions with a system that was successfully implemented on the FFTB. [18] Two wires will be suspended inside hollow chambers that run the length of the undulator. The chambers are fixed to the magnets, and one end of the wire runs over a pulley and is tensioned by a fixed hanging weight. The exact shape of the curve described by the wire is not a catenary, but is distorted by imperfections in the wire at the micron level. However, a wire suspended this way is very stable. We will monitor the position of the wire with optical LED and split photodiode position sensors that are capable of resolving motions of the wire with submicron resolution.

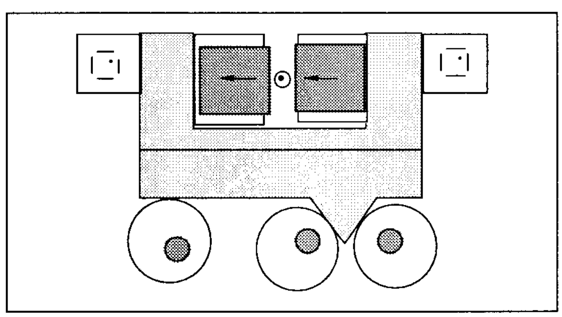

FIGURE 2. End view of the undulator magnet, showing three of the cams on one end of the girder (there are two on the other end) and the wire position monitors (upper left and right). The beampipe is 6 mm OD stainless steel tube.

The undulator magnets will be mounted on 5 eccentric cams, which are driven by stepping motors and harmonic drive gear reduction units. [19] The stepping motors might have 200 steps/turn, the harmonic drives might have 100:1 gear ratios, and the cam might have an eccentricity of 1 mm, for a net resolution of 10 steps/μm. In the

FFTB, these units have been shown to have submicron resolution and repeatability, which matches that of the wire position monitoring system. Rotation of the 5 cams controls pitch, yaw, roll, x, and y motion; an kinematic algorithm is used to control the motors; all 5 may have to move to correct an error in any of these 5 degrees of freedom. It is our intention to energize the stepping motors only when they move, so as not to create unwanted heat. Each motor dissipates about 10 W and only while it is in motion.

ALIGNMENT, STABILIZATION, AND BEAM POSITION MONITORING

Once the undulator is aligned, the wire position monitoring and cam system should be able to maintain its alignment at the micron level, with a response time on the order of seconds. However, the initial alignment of the undulator is a major challenge. The basic specification for alignment is that the beam trajectory must be straight to within about 5 μm over each 10 m field gain length. High performance laser tracker survey instruments could be used to position absolute beam position monitors (such as carbon wires) to within about 50 μm over this distance, perhaps somewhat less with great care and thermal stability. A hydrostatic level is capable of absolute micron tolerances, but only in the vertical. [20] Simulations show us that with the 50 μm tolerances over 10 meters that we expect from conventional surveying, we should achieve SASE laser action at 5 GeV, but not necessarily at 15 GeV.

We used trajectory modeling codes to find out how to monitor and correct the beam position. We find that beam position monitors and correctors with micron resolution should be placed at 4-5 meter intervals for optimum correction. If such correctors are installed, we calculated that initial trajectory errors of 100-200 μm could be reduced to 5 μm. Motions less than 200 μm are required of the quadrupole movers.

Beam based alignment is generally preferred to external mechanical methods. Our primary beam based alignment approach is to use the sensitivity of beam dispersion to quadrupole misalignment. We can run the LCLS from 5 to 15 GeV, with a corresponding FEL fundamental wavelength of 15 to 1.5 Å. With moveable quadrupole magnet corrections, we should be able to find a trajectory that does not change with energy, and such a trajectory must be a straight line. The concept here is that we do not measure straightness directly, which is hard, but subtsitute a measurement of a change in position with energy, which is much easier.

Another strategy for beam based alignment is to use a beam position monitor that is sensitive both to photons and electrons. We considered allowing the beam to strike a 30 μm carbon wire, as shown in figure 3. Experience at the SLC shows that such a wire can survive indefinitely when struck by 1 nC, 15 GeV electron pulses, and damage by x-radiation is less than that from electrons. [21] When the wire is struck by the electron beam, it will yield bremsstrahlung in a flat power spectrum from 15-0 GeV. Sweeping a 30 μm wire through a 65 μm rms diameter electron beam should allow us to locate the center of the electron beam to a few microns, using a downstream detector.

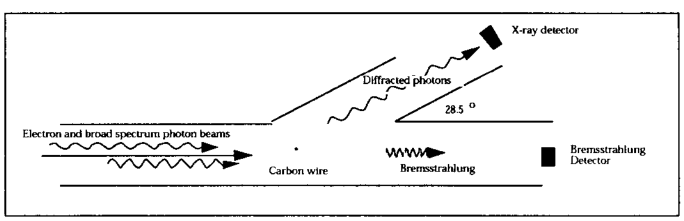

FIGURE 3. The combined photon and electron beam position monitor system. The x-ray detector could be a solid state photodiode; the bremsstrahlung detector is a radiation length of lead that converts bremsstrahlung into electron positron pairs, followed by a block of silica in which the pairs emit Cerenkov radiation that is detected by a photomultiplier tube.

We have examined the x-ray diffraction pattern from 7 μm carbon wires, and saw a peak at an angle of about 28 degrees with a FWHM of about 5 degrees, and sufficient intensity for BPM use. The spontaneous radiation at the 1.5 Å fundamental diverges by $\sigma_{r'} = \sqrt{\lambda_{rad}/L_u} = 1.2$ μrad, or 120 μm at 100 meters. The coherent FEL beam diverges by $\varepsilon / \sigma_r = 0.74$ μrad, or 74 μm at 100 meters. Therefore, we should be able to detect spontaneous radiation in the two-thirds of the undulator, where it is stronger than the FEL radiation, and use FEL radiation downstream.

After the initial alignment, we propose to turn on a feedback system to stabilize the trajectory. Electron beam position monitors will sense changes in the beam position, and correctors will null those changes. We examined many beam position monitor technolgies, including intercepting carbon wires, Compton scattering from laser 'wires', striplines and wall current monitors, diffraction radiation monitors, RF cavity monitors, fluorescent materials such as YAG crystals, and transition radiation monitors. We required simplicity, stability, low drift, low impedence, high resolution. and fabricability. The candidate technologies we are presently entertaining are carbon wires for initial beam finding, and striplines or RF cavity monitors for feedback control. We have advanced the design of a stripline for this particular application with MAFIA modeling, and feel that RF cavity technology and carbon wire technology are in hand at SLAC and CERN. [22]

RADIATION EFFECTS AND WAKEFIELDS

Our electron beam is calculated not to endanger the beampipe, but a single electron beam strike in the magnet material could fracture it, so we will protect the undulator with collimators, which will also scrape the halo off the beam. We calculate that 2-3 radiation lengths of Ti, followed by 20-30 radiation lengths of Cu is an appropriate collimator, with a possible sacrificial stopper at the entry to the undulator, for safety. [23] Radiation induced demagnetization is also a problem; it is modeled like a thermal demagnetization process, and thermal stabilization is apparently a defense against radiation induced demagnetization. [24] High coercivity NdFeB [25] used in the KEK in-vacuum undulator has been exposed to circulating beam for 7 years at a 12 mm gap with no apparent demagnetization. [26] The material was thermally stabilized to 125C, with a loss of about 2% of B_r. If NdFeB is not robust enough against radiation damage, we could use Sm_2Co_{17}.

We need not have very good vacuum in the LCLS beampipe; 100 nTorr should be adequate. The main disadvantage of higher pressure is the creation of gas bremsstahlung. However, we did need to examine the 5 mm ID beampipe for the effects of wakefields. For stainless steel, resistive wall losses would generate an energy spread in the electron beam of $\Delta E/E = 0.0016$ and an emittance growth of $\Delta\ \varepsilon/\varepsilon = 100\%$, which is unacceptable, but it is simple enough to plate the inner wall with a skin depth of copper, which reduces $\Delta E/E$ to 0.0003 and $\Delta\varepsilon/\varepsilon$ to 3%. [27] The total heat generated by resistive wall losses is on the order of a watt for 120 Hz operation, so heat dissipation will not be a problem. We have also calculated the expected effects of pumping ports, flange joints, etc and find them to be much smaller than the wall effects. Beampipe roughness may lead to longitudinal wakefield effects, so a highly polished beampipe is desirable.

SUMMARY

We have briefly described above some of the problems that we addressed in studying the design of an x-ray FEL at SLAC. Among the problems that any such design must address are: 1) tight mechanical tolerances, 2) geophysical and thermal environmental problems 3) beam position monitoring 4) initial alignment strategy 5) stability of alignmnent 6) radiation dose managment and 7) wakefield effects. Of these, we consider the initial alignment the most challenging, because we have no precedent for it. The other issues have been addressed in existing SLC and FFTB machines at SLAC, and in work at other laboratories.

ACKNOWLEDGEMENTS

The author is pleased to thank the many contributors to the LCLS undulator design study, including Heinz-Dieter Nuhn, Max Cornacchia, Robert Hettel, Don Martin, Roman Tatchyn, John Arthur, Jim Sebek, Richard Boyce, Jeff Corbett, (SSRL), Gordon Bowden, Dieter Walz, Robert Ruland, Clive Field, Cho Ng, Karl Bane, John Sheppard, Paul Emma, Vinod Bharadwaj, Pantaleo Raimondi, Vaclav Vylet, Alberto Fasso, Sayed Rokni, (SLAC), Klaus Halbach, Ross Schlueter, Steve Lidia, Kwang-je Kim, Ming Xie (LBNL), Lou Bertolini, Marcus Libkind, Lee Griffith (LLNL), Ilan Ben-Zvi (BNL), and Claudio Pellegrini (UCLA). This work was supported by the US Department of Energy, Office of Basic Energy Sciences under contract number DE-AC03-76SF00515.

REFERENCES

1 R. Bonifacio, C. Pellegrini, L.M. Narducci, *Opt. Commun.* 50 (1985)
2 H. Winick, et. al. *Nucl. Inst & Methods* A347 (1994) p. 199
3 H-D Nuhn, to be published
4 M. Xie, Proceedings of the US Particle Accelerator Conference 1995
5 H-D Nuhn, private communication
6 H-D Nuhn and C. Pellegrini, to be published
7 Yu.M. Nikiyina and J. Pflueger, *Nucl. Inst. & Methods* A375 (1996) p. 325
8 R. Schlueter, *Nucl. Inst. & Methods* A358 (1995) p. 44
9 A.A. Varfolomeev, et. al. *Nucl. Inst. & Methods* A341 (1994) p. 341
10 B. Faatz, K. Floettmann, private communication
11 K. Halbach, *Nucl. Inst. & Methods* 187 (1981) p. 109
12 H-D Nuhn, to be published
13 Group 3 Technology Ltd. model DTM 130 Teslameter
14 Leitz Enhanced Accuracy Model PMM 12-10-6 Coordinate Measuring Machine
15 S. Lidia and R. Carr, *Rev. Sci. Inst.* 66 (1995) p. 1865
16 Anocast Division of Anorad Corportation, Chagrin Falls, Ohio
17 Zero Order Design Report for the Next Linear Collider, Appendix C. SLAC report 474
18 R. Ruland - private communication
19 G. Bowden, P. Holik, S.R. Wagner, G. Heimlinger, R. Settles *Nucl. Instr.&Methods* A368 (1996)p. 579
20 Fogale Nanotech 190 Parc Georges Besse, 30000 Nimes, France
21 C. Field, *Nucl. Instr.& Methods.* A 360 (1995) 467.
22 W. Schnell, J.P.H. Sladen, I Wilson, and W. Wuensch, CLIC note 170, CERN SL/92-33
23 D. Walz, private communication
24 O.P. Kahkonen, M. Talvitie, E. Kauutto and M. Mannigen, *Phys. Rev.* B49 (1994) p. 6052
25 Sumitomo Special Metals Co. Neomax 28SH NdFeB material (1993)
26 S. Yamamoto, private communication
27 K. Bane, private communication