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Design considerations for the magnetic system of a prototype x-ray free electron laser

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ABSTRACT

The design of the magnetic system for the high gain soft x-ray free electron laser is described.

Keywords: undulators, free electron lasers

INTRODUCTION

A number of difficult technical challenges need to be solved in the fields of accelerator and free-electron laser (FEL) technologies in order to build an x-ray FEL. One of the tasks well suited to the Advanced Photon Source Low Energy Undulator Test Line (LEUTL)[1] is to take the intermediate step of solving some of the problems of single-pass FEL operation in the ultraviolet range.

CHOICE OF UNDULATOR PARAMETERS

The existing Advanced Photon Source (APS) linac, in addition to its role of supplying positrons for the APS storage ring, will also be used to generate the particle beam for the LEUTL. The linac was not originally designed with a high brightness source, but, due to an upgrade of the source to a thermionic RF gun, the following beam parameters can reasonably be assumed when considering how to best optimize an undulator for FEL operation using the LEUTL system:

Table 1. The input parameters for the optimization choices.

Peak Current, A	150
Normalized Emittance, $\pi\cdot$mm mrad	5
Energy Dispersion, keV	300
Radiation Wavelength, nm	120

For initial operation, a wavelength of 120 nm was chosen to make the optical diagnostics easier and to relax the positioning and emittance requirements.

The goal in optimizing the undulator parameters is to minimize the gain length, as calculated using the formulae from Refs. 2 and 3. Several issues must be considered when choosing the minimum undulator gap. A smaller gap gives a higher peak magnetic field. The gap cannot be too small, however, or magnetic field measurement probes will not fit. Also, a small gap increases the induced current in the vacuum chamber wall and its interaction with the beam. The current induced by the head of the beam reduces the energy in the beam's tail due to the finite wall conductivity, thereby increasing the beam energy spread. This will be mitigated by the use of a Cu vacuum chamber. The available peak current for the beam is not so high as to make this the limiting factor, however. Instead we chose a minimum gap of 5 mm in the undulator to allow space for existing magnetic field probes, so that precise magnetic field measurements are not hampered. The LEUTL itself will also be used to further improve these measurements. The dependence of the undulator field on the period and gap was taken from the Halbach formula,[4] with modifications for the particular design. A minimum gain length of about 1.5 m was found at an undulator period of 30 mm and undulator beta functions of 2 m. The values chosen for undulator period and radiation wavelength for initial operations require an electron energy of about 400 MeV. The linac is, however, capable of producing electron beams of up to 700 MeV. For later operations with higher-energy electron beams, the FEL would produce wavelengths down to 40 nm. Also, because of the planned upgrade to a photocathode RF gun system, the electron beam for these future operations would have higher peak current and lower emittance. In order to have a shorter gain length for these future operations, the undulator period was chosen to be 27 mm. This period length and gap, with the use of Nd-Fe-B magnets and iron poles, results in a magnetic field strength of 1.2 T and requires 400 MeV beam energy for initial operations.

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CONSIDERATION OF BEAM FOCUSING

An undulator that causes the electron beam to wiggle in the x (horizontal) direction has an intrinsic focusing effect on the electron beam in the vertical (y) direction. If, in addition, the pole tips of the undulator are concave, i.e., shaped to increase the field strength at positions displaced laterally (in x) from the center ('sextupole focusing'), then the undulator will also focus in the x direction. This focusing by the undulator may be characterized by the focusing strengths k_x and k_y. They are related to the matched (i.e., a beam injected into the undulator with this beta function will have a constant beta function through the undulator) beta function β_u for a planar undulator with an x-independent magnetic field strength H by:

$$\beta_u = \frac{\sqrt{2}\,E}{eH} = \frac{1}{\sqrt{k_x + k_y}}\ , \qquad (1)$$

where e and E are the electron charge and energy, respectively. Substituting our design parameters into Eq. 1 gives β_u=1.6 m. If the focusing is distributed equally in the x and y directions, this results in 2.2 m beta functions, which are very close to the value that minimizes the gain length, as seen earlier. The focusing in both directions can be achieved in a variety of ways. Sextupole focusing, as mentioned above, can be built into the undulator by using concave pole tips. Quadrupole focusing can be built into the undulator by tilting its pole tips so that the gap between opposing poles varies linearly with x. Another option, and the one we are pursuing, is to separate a planar flat-pole undulator into longitudinal sections and then insert horizontally focusing quadrupole magnets between the sections. This scheme is technically more direct and convenient because it allows for the installation of quadrupole magnets, beam diagnostics and vacuum pumping between the undulator sections.

In order to achieve gain in the FEL, the microbunching of the beam is essential. Effects that increase the width in the distribution of the longitudinal velocity components of particles within the beam and thus smear out the micro-bunches are undesirable. To compare the different focusing schemes, we consider the correction to the longitudinal velocity of the electrons that arises from the lateral velocity components:

$$\Delta\beta_{\|} = \frac{x'^2 + y'^2 + k_x x^2 + k_y y^2}{2}, \qquad (2)$$

where x, y, x', y' are the transverse coordinates and angles, averaged over one undulator period. If a Gaussian distribution in transverse phase space is assumed, the longitudinal velocity dispersion can be expressed in terms of the emittances $\varepsilon_{x,y}$ and Twiss parameters $\beta_{x,y}$ and $\gamma_{x,y}$:

$$\sqrt{\left\langle\left(\beta_{\|} - \langle\beta_{\|}\rangle\right)^2\right\rangle} = \sqrt{\varepsilon_x^2\left[\frac{\left(\gamma_x + k_x\beta_x\right)^2}{2} - k_x\right] + \varepsilon_y^2\left[\frac{\left(\gamma_y + k_y\beta_y\right)^2}{2} - k_y\right]}\ . \qquad (3)$$

For the undivided undulator with sextupole focusing provided by shaped pole tips, substituting

$$\beta_x = \frac{1}{\gamma_x} = \frac{1}{\sqrt{k_x}} \quad \text{and} \quad \beta_y = \frac{1}{\gamma_y} = \frac{1}{\sqrt{k_y}} \qquad (4)$$

in Eq. (3) and setting the x and y emittances to both be equal to ε gives:

$$\sqrt{\left\langle\left(\beta_{\|} - \langle\beta_{\|}\rangle\right)^2\right\rangle} = \frac{\varepsilon}{\beta_u}\ . \qquad (5)$$

For the case of a planar undulator with flat pole tips so that the magnetic field is independent of x, we have $k_x = 0$. If the x and y emittances are both set equal to ε, and the Twiss parameters α_x and α_y are both equal to zero at some point inside the undulator, then one can express the velocity dispersion at that point in terms of the beta functions at that point:

$$\sqrt{\left\langle\left(\beta_{\|} - \langle\beta_{\|}\rangle\right)^2\right\rangle} = \frac{\varepsilon}{\sqrt{2}}\sqrt{\frac{1}{\beta_x^2} + \frac{1}{\beta_y^2} + \frac{\beta_y^2}{\beta_u^4}}\ . \qquad (6)$$

If the weak quadrupoles are used to equalize the horizontal and vertical focusing, $\beta_x \cong \beta_y \cong \beta_u\sqrt{2}$ and Eq. 6 becomes

$$\sqrt{\left\langle\left(\beta_{\|} - \langle\beta_{\|}\rangle\right)^2\right\rangle} = \frac{\varepsilon}{\beta_u}\sqrt{\frac{3}{2}}\ . \qquad (7)$$

This is 20% greater than for the undulator with built-in sextupole focusing (see Eq. 5). It is due to the more rapid variation of the magnetic field strength with y in the undulator with flat pole tips. This difference can be reduced, however, by reducing the quadrupole strength below the equal-focusing value:

$$\frac{1}{F} < \frac{L}{2\beta_u^2} , \qquad (8)$$

where L is the length of one undulator section. The beta functions vary through the undulator sections and through the spaces between them. To keep this variation in the size of the electron beam small, the length of one undulator section must be kept short:

$$L < \beta_u \frac{\pi}{2} \qquad (9)$$

Making the length of an undulator section too short, however, reduces the fraction of the overall length that is occupied by photon-producing undulator structure (see Refs. 5 and 6). Therefore, the optimum undulator section length is very close to $\beta_u \cdot \pi / 2$.

THE FEL MAGNETIC SYSTEM DESIGN

The cross section of the undulator is shown in Fig. 1. The iron poles are part of a rigid comb-like structure, with each of the four 'combs' machined from a solid iron piece (see Fig. 2). By precisely machining the pole faces and by further defining the gap by means of a spacer bar, we hope to minimize field errors caused by mechanical vertical misalignment of the poles. Relative misalignment of adjacent poles is especially to be avoided due to its effect on overall beam steering. Also, mechanical assembly is expected to be simpler and faster than for a design with separate pole pieces. This comb-structure design is similar to Halbach's "floating potential" design.[7] It is hoped that the comb structure's role as a scalar magnetic potential bus will reduce magnetic field errors due to variations in strength of the magnets themselves. Further tuning of individual pole strengths will be accomplished using tuning pins that extend from one scalar potential bus towards the side of a pole that is connected to the opposite potential bus.

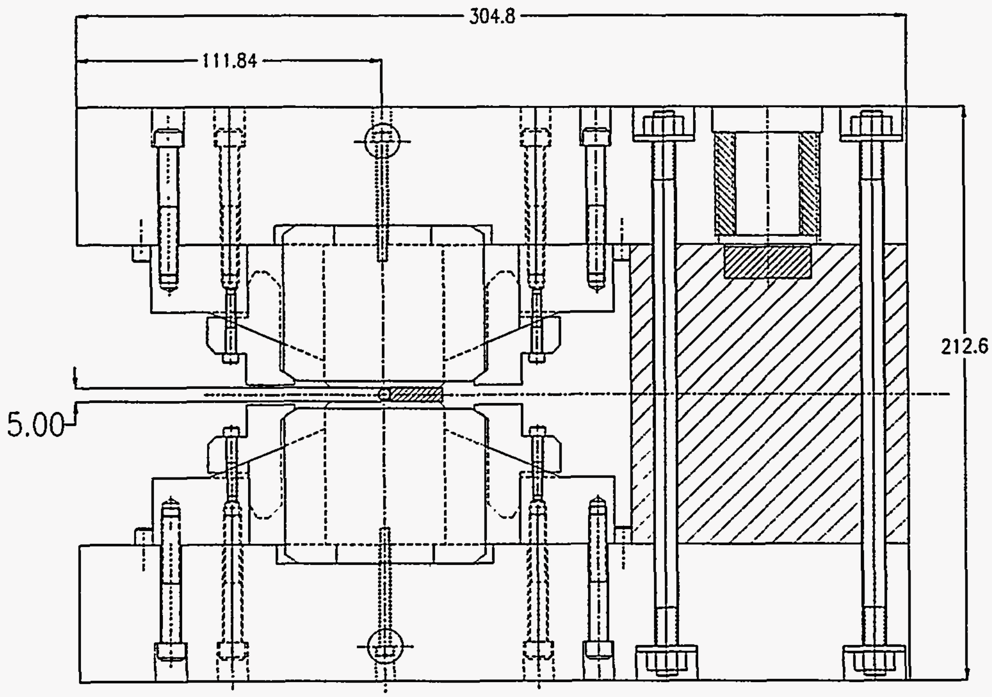

Fig. 1. The cross section of the undulator.

The length of the individual undulators was chosen to be 2 m, and the length of a cell (one undulator plus one set of the quadrupole, diagnostics, and pumping between sections) will be 2.5 m. This choice satisfies equation 9. The focal length of the horizontally focusing quadrupoles was chosen to be 2.6 m, in accordance with equation 8. The whole undulator will consist of 15 cells.

The overall alignment of the undulator is not critical in the horizontal direction, because its magnetic field is slowly varying in that direction. The overall alignment of the quadrupoles and the vertical alignment of the undulator are more critical and must be accurate to 0.1 mm. It is sufficient, however, that this requirement be met for the relative alignment of each element and its immediately adjacent upstream and downstream neighbors.

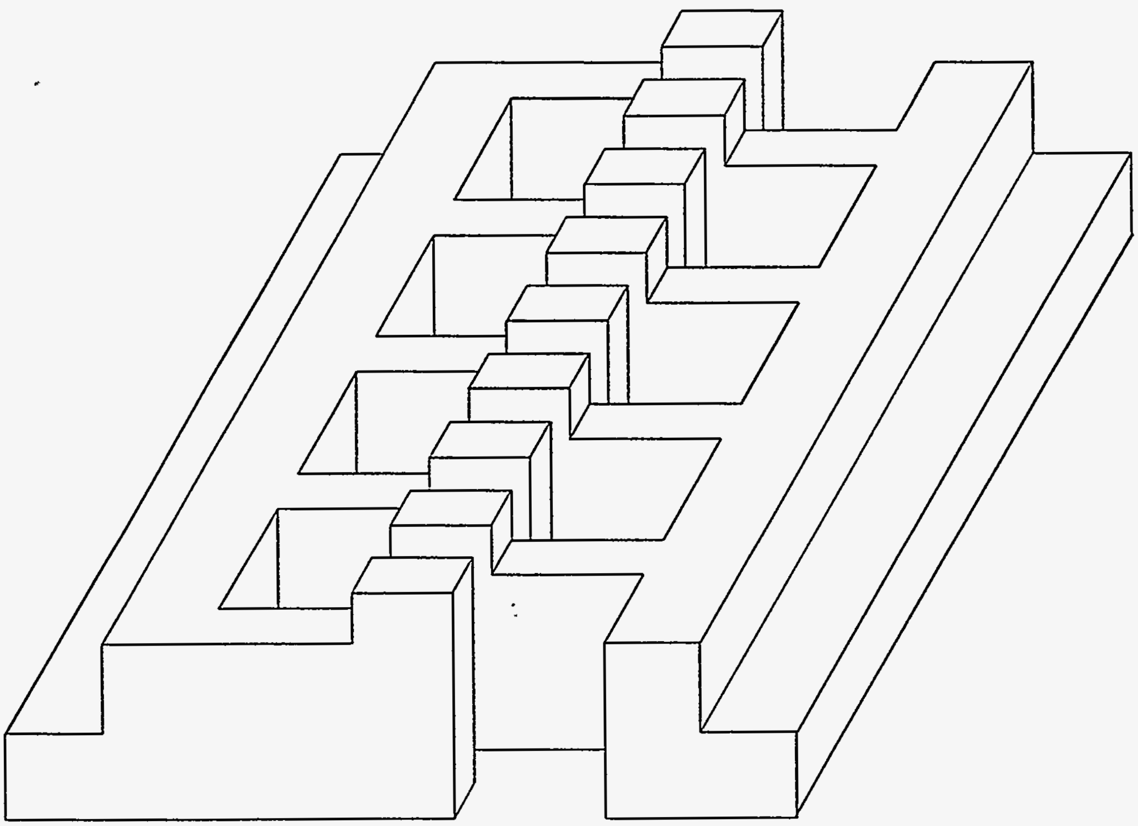

Fig.2. The layout of the lower iron poles of the undulators.

The intervals between the undulators will allow space for beam diagnostics equipment, as well as for the quadrupole magnets. Secondary emission monitors will be used to ensure precise beam trajectory alignment. The mean-square beam size will be less than 0.15 mm. This allows the use of nonretractable monitors if the spacing between their wires is chosen to be as large as 1 mm. Measurements of the beam position and transverse size will be made by scanning the beam over the monitor, using the upstream steering coils. The use of nonretractable monitors allows for measurements with good absolute precision. The possibility of using these same monitors for the radiation as well is attractive but will require further careful examination. Other diagnostics equipment that will be installed in these intervals includes retractable mirrors and luminescent screens. The planned 0.5 m length for the intervals will be enough to accommodate the quadrupoles and diagnostics.

CONCLUSION

Calculations have been carried out of the amplification per cell expected from this FEL design.[8] We find that the amplification will be approximately the same as for a 2-meter-long section of the undulator with concave pole tips, i.e., that the amplification per meter of undulator structure will be the same for either design. The overall length of the design with separated undulator sections will be longer due to the intervals between undulator sections, but these intervals were not found to have a significant adverse effect on the overall amplification.

The requirements for all aspects of this preliminary design are achievable with current technology, and most of the technical approaches will also be directly applicable to shorter-wavelength FELs. The implementation of this project will therefore be a valuable intermediate step towards x-ray FELs.

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