

Advanced Photon Source Low-Energy Undulator Test Line

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1. INTRODUCTION

The injector system of the Advanced Photon Source (APS) consists of a linac capable of producing 450-MeV positrons or > 650 -MeV electrons, a positron accumulator ring (PAR), and a booster synchrotron designed to accelerate particles to 7 GeV. There are long periods of time when these machines are not required for filling the main storage ring and instead can be used for synchrotron radiation research. We describe here an extension of the linac beam transport called the Low-Energy Undulator Test Line (LEUTL).

The LEUTL will have a twofold purpose. The first is to fully characterize innovative, future generation undulators, some of which may prove difficult or impossible to measure by traditional techniques. These might include small-gap and superconducting undulators, very long undulators, undulators with designed-in internal focusing, and helical undulators. This technique also holds the promise of extending the magnetic measurement sensitivity beyond that presently attainable. This line will provide the capability to directly test undulators before their possible insertion into operating storage rings. A second use for the test line will be to investigate the generation of coherent radiation at wavelengths down to a few tens of nanometers.

Basic undulator characterization will be performed by observing two effects. First, the trajectory variations of the beam as it passes through the undulator field will be measured. In this manner, the beam will be used to directly observe the effect of undulator magnetic field errors on the beam. Second, the use of a very low-emittance, low-energy-spread beam will also generate near or completely diffraction-limited radiation. In this diffraction-limited regime, the emitted light intensity and spectrum are nearly independent of the properties of the beam. Measurement of this light can then reveal the quality of the undulator. Using these complimentary means, the undulator's capabilities can be anticipated before installation in a storage ring.

Perhaps the most intriguing and exciting use of the LEUTL, however, will be in the planned investigation and generation of coherent radiation at wavelengths below 100 nm. This is due to the use of the high quality electron beam generated from a thermionic microwave gun. A further increase in electron beam brightness is also expected after the planned installation of a photocathode rf gun source. Coupled with > 650 MV of accelerating potential and a full suite of suitable beam diagnostics,¹ these high quality sources naturally lend themselves well to the study of how such a beam might interact with its own radiation fields produced when passing through the undulator being tested. Success in this endeavor will require perseverance and great care to preserve the beam emittance, bunch length, and small energy spread during the acceleration and transport process.

Control of the beam is essential; therefore, in support of the above-mentioned measurements, the LEUTL will also serve as a test bed to characterize present diagnostics and to develop new beam measurement and synchrotron radiation detection techniques.

2. DESCRIPTIONS

Initially, four modifications to the APS injection system are envisioned:

- Installation of a thermionic microwave electron gun
- Addition of the positron accumulator ring (PAR) bypass and booster synchrotron bypass lines
- Construction of the undulator test line itself
- Extension of the booster vault into the new LEUTL building

2.1 High Quality Electron Gun System

The microwave electron gun system, with alpha magnet bunch compression,² was installed at the head of the linac (Figure 1) and is presently undergoing commissioning. Performance of the gun and transport system up to the entrance point of the first APS linac section is shown in Table 1. The electron beam from this gun,

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after further acceleration to as high as 700 MeV, makes an ideal initial source for performing a direct evaluation of undulator quality without the added complexity of a photocathode rf gun system. An upgrade to a photocathode rf gun is planned should further reduction in the normalized emittance and increase in the peak current become necessary.

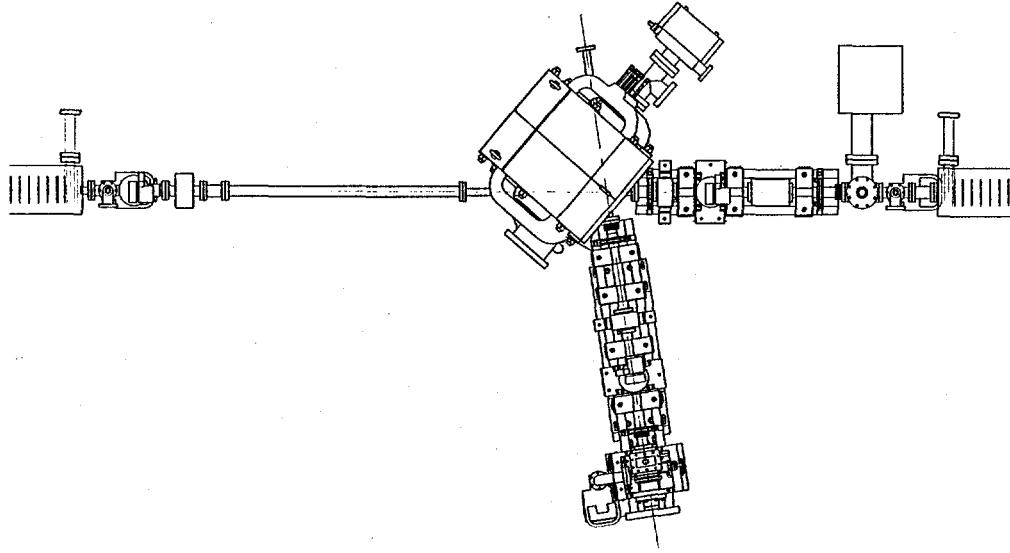


Figure 1: Thermionic microwave gun with alpha magnet pulse compression as installed in the APS linac.

Table 1: Expected Gun Performance

Energy	3 MeV
Peak current	150 A
Normalized emittance	$5 \pi \cdot \text{mm-mrad}$
Energy spread	1 %

2.2 Transfer Lines

Two additional transport lines are required to guide the beam into the LEUTL building. The first is the PAR bypass transport line (Figure 2). This line, at the end of the linac, will be equipped with the diagnostics to fully measure the beam emittance and temporal properties and to control the beam after acceleration. The PAR bypass line contains two sets of quadrupole triplets, placed as far apart as physically possible. Included between the triplets are four optical transition radiation (OTR) screens, all of which are capable of 25- μm FWHM resolution. These will be sufficient to allow determination of a normalized emittance of $\epsilon_n = 10 \pi \cdot m_e c \mu\text{m}$ to $\approx 6\%$ and a normalized emittance of $\epsilon_n = 1 \pi \cdot m_e c \mu\text{m}$ to $\approx 20\%$. A fifth OTR screen will be placed just before this region at a location which simplifies the transport of the light outside the linac enclosure. Here a streak camera with 0.6-ps resolution will be used to measure the bunch length. These screens will be the primary means of measuring the beam emittance.

The second line is the booster synchrotron bypass line. Approximately 55 m in length, it will transport the beam through the booster enclosure and out into the LEUTL building while the beam elevation is gently raised by 1 m. Using the formula^{3,4}

$$\Delta\epsilon_n \approx 0.5\alpha^2\sigma_r \frac{I}{I_A} \left(\frac{\rho}{\sigma_z} \right), \quad (1)$$

where α is the bend angle in radians, σ_r and σ_z are the rms radius and bunch length of the electron beam, respectively, I is the peak beam current, and I_A is 17,000A, the growth in emittance due to the coherent space charge force is found to be negligible for the entire beam parameter space envisioned.

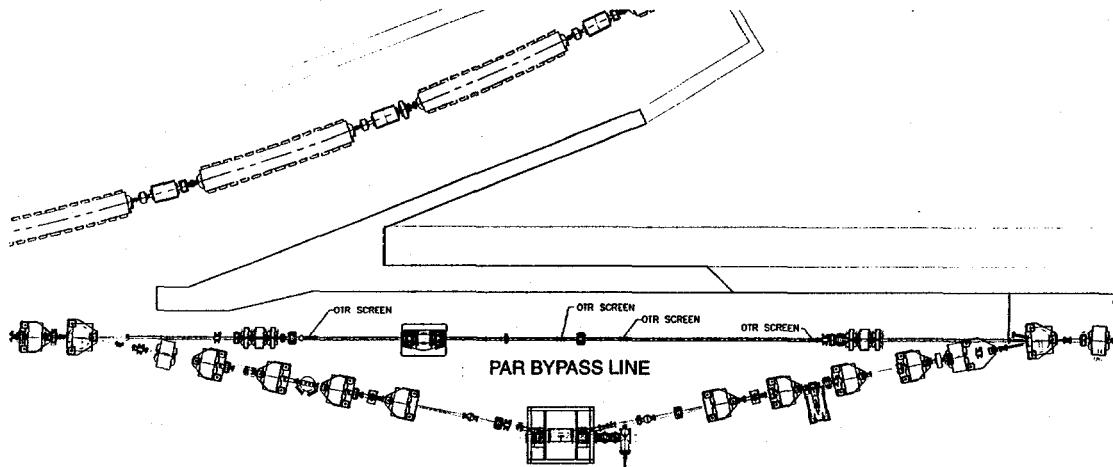


Figure 2: Layout of the PAR bypass line.

2.3 LEUTL Building

Expansion of the APS beamline enclosures is necessary in order to accommodate undulators of substantial length without the need for any major redirection, and possible emittance degradation, of the primary electron beam. The necessary expansion is shown in Figure 3.

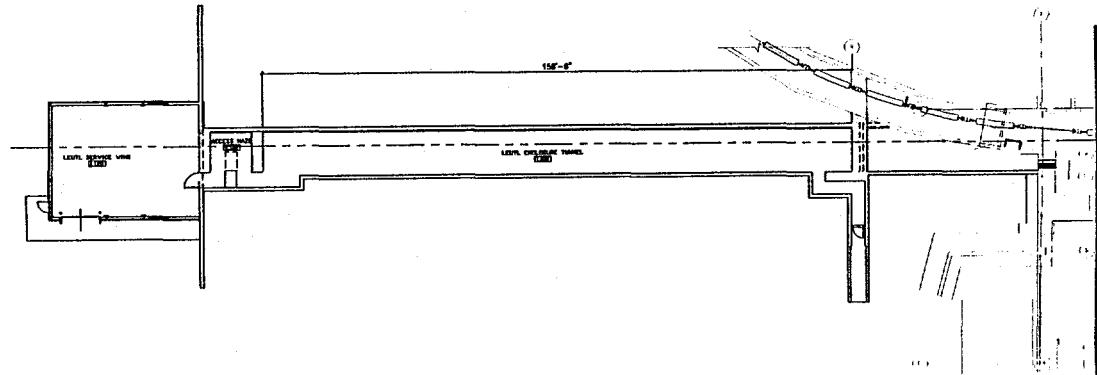


Figure 3: The LEUTL building and end station.

The new LEUTL building will have nearly 50 m of available length for beamlines, undulators, diagnostics, and the beam dump. It is also constructed wide enough to allow an additional parallel line in the future. Although the full length is not needed immediately, the building was purposely built longer than initially required in order to accommodate the testing of very long undulators. It is therefore ideally suited to house the undulators required for the experimental investigations of the self-amplified spontaneous emission (SASE) process.

The final section of beamline, the undulator test line, will be contained entirely in the LEUTL building. Its primary purpose is to accurately guide the beam into and through the undulator being tested and to measure the beam's properties both before entering and after leaving the undulator. This line will consist of a section for general matching into an undulator, the undulator section itself, a beam optics "telescope" to follow the undulator, a beam dump, and a complete set of beam diagnostics.

In addition to the primary beamline enclosure, an end station area will be built to detect the radiation generated from the undulator and to measure the degree of degradation of the emitted spectrum compared to ideal. For SASE investigations, the station will also be used to measure the properties of the very high peak brightness light source.

The entire LEUTL building, including the end station, is currently under construction and is expected to be ready for installation of the technical components by the end of spring 1998.

3. UNDULATOR TESTING

3.1 Beam-based Measurements

Following magnetic measurements, most undulators will go into the main APS storage ring where the beam energy is 7 GeV. The beam of the LEUTL is designed for 650 MeV, but has a range from 300 MeV to 710 MeV. Operation at this lower energy enhances the sensitivity to the imperfections of an undulator; however, it is important to insure that the results can be scaled to 7 GeV. The degree to which one can rely on linear scaling will be given below.

Further enhancements to the overall accuracy of the measurements are possible and will be exploited. For example, beam position measurements are essentially complete in a single pass. To increase the accuracy of these measurements, averaging over many shots will be performed. A second method which will be employed is the use of a beam optics telescope. Here the transport matrix is adjusted according to

$$\begin{aligned} R_{12} &= R_{21} = R_{34} = R_{43} = 0 \\ R_{11} &= 1/R_{22} \quad R_{33} = 1/R_{44} \end{aligned} \quad (2)$$

for point-to-point imaging and

$$\begin{aligned} R_{11} &= R_{22} = R_{33} = R_{44} = 0 \\ R_{12} &= 1/R_{21} \quad R_{34} = 1/R_{43} \end{aligned} \quad (3)$$

for parallel-to-point imaging. As an example, an arrangement proposed by M. Borland is shown in Figure 4. Here the point-to-point magnification in the horizontal plane is -13.5. A similar magnification of 8.8 m/rad was obtained in the parallel-to-point mode of operation.

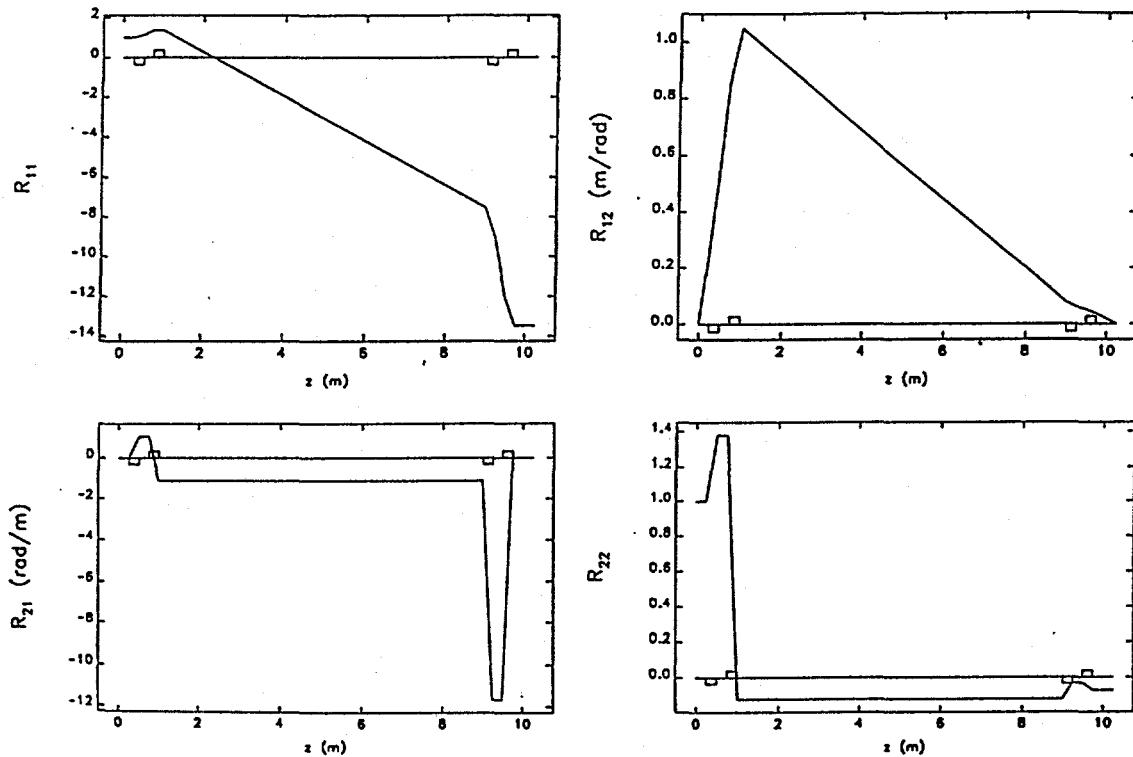


Figure 4: The beam telescope transport matrix values for point-to-point imaging.

Ultimately these measurements must be compared to the magnetic tolerance requirements and to the capabilities of the traditional magnetic measurement techniques. Perhaps the best undulator measurement system in the world is here at the APS.⁵ First and second field integral specifications for the APS are < 100 G-cm and < 10⁵ G-cm², respectively. Typically a 2.5-m-long APS type-A undulator can be measured with repeatability to < 1 G-cm and absolute accuracy of 10 G-cm in the first field integral and with repeatability to < 100 G-cm² and absolute accuracy of 1000 G-cm² in the second field integral. However, there are limits to this system. For one, these numbers are for the plane perpendicular to the plane of oscillation. Furthermore, the maximum length undulator which can be measured is 5 m; measurements at longer lengths suffer in the accuracy and precision of the measurements as stated above. Also, the minimum gap size which can be measured is approximately 4 to 5 mm. One final problem which can arise is related to how the measurement probe is inserted into the undulator. Limited access to the field region, such as in some helical and variable polarization undulator designs, could make measurement very difficult or impossible.

By comparison, the LEUTL should be able to significantly improve on the accuracy and precision of such measurements without suffering from the limitations of length, gap size, plane of measurement, and peculiarities of entry into the gap. With the LEUTL system accuracy is dependent primarily on the stability of the beam and the beam position monitoring capabilities. As an example, consider the measurement of the first and second field integrals

$$\int_1 = \frac{\delta x(B\rho)}{M_\theta A} \quad \int_2 = \frac{\delta x(B\rho)}{M_x A}, \quad (4)$$

where δx is the single-pass measurement accuracy, M_θ and M_x are the parallel-to-point (in units of m/rad) and point-to-point magnifications, respectively, and A is the improvement due to averaging. Assume

$$B\rho = 2 \text{ T} \cdot \text{m}; \quad \delta x = 10 \mu\text{m}; \quad M_\theta A [\text{m/rad}] = M_x A = 100, \quad (5)$$

then

$$\int_1 = 0.2 \text{ G} \cdot \text{cm} \quad \int_2 = 20 \text{ G} \cdot \text{cm}^2. \quad (6)$$

This is a significant improvement over the more common methods. Of course, these results improve further if the beam position monitor (BPM) accuracy is improved and/or the magnification or averaging enhancement factors increase. Ultimately, we hope to achieve better than 1-μm resolution on a single pass (see, for example, the SLC⁶ and JLC⁷ designs) so that the sensitivity will be further increased by an order of magnitude.

Implicit to all that has been said is that the effect of the magnet errors scales linearly with the energy. This is not entirely true, but at the energies at which the LEUTL will be run, this error is not large enough to be of much concern. As a simple example consider analysis of a single horizontal field strength error present at the middle of a 2.5-m-long planar APS type-A undulator with oscillatory plane in the horizontal direction. Two corrector magnets, one at the entrance to the undulator and the other at the exit, will be used to correct the error at this lower energy. Upon scaling the error and corrector strengths by the energy, i.e., from 700 MeV up to 7 GeV, the residual positional and angular deviations are noted. Results from two models and two simulations all indicate deviations of < 4% for this example. Shown in Figure 5 is the result of using the "thick lens" model of the undulator.

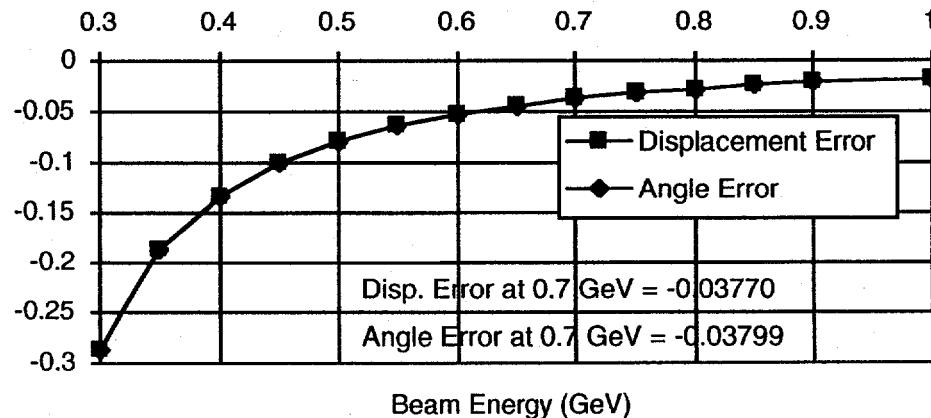


Figure 5: Induced errors with respect to 7 GeV for the "thick lens" model.

3.2 Light Output Measurements

Measurement of the light generated from the beam as it passes through the undulator is also a means of extracting information about the quality of the undulator field. As an example, simulation of the light output from a typical APS type-A undulator was performed by R. DeJus using the program UR⁸ for a number of different scenarios ranging from the case of an ideal beam and ideal undulator to a real undulator and real beam conditions. Table 2 lists the properties of the assumed beam and actual undulator simulated. Figure 6 shows the results of the simulation at the ninth harmonic of the undulator radiation for the different test cases. Most significant was the impact of the beam energy spread on the light output as well as the overall errors within the undulator. As 0.1% energy spread was overly conservative, it is anticipated that the distinction between broadening caused by the beam and broadening attributed to the undulator will become more significant with the comparison being more similar to that between cases 2a and 4a.

Table 2: Parameters Used for Simulation

Beam Properties	
Central energy	650 MeV
Energy spread	0.1%
Charge/bunch	350 pC
Bunch length	2 ps
Emittance (H/V)	4×10^{-9} m-rad
Optics	
β_0 (H/V)	5 m @ center
η	0 m
Undulator Properties	
λ	3.3 cm
K	2,464
Gap	11.5 mm
N	72
L	2.37 m
1st field integral	28 G - cm
2nd field integral	35,000 G - cm ²
rms field error	0.5%
rms phase error	3.3°

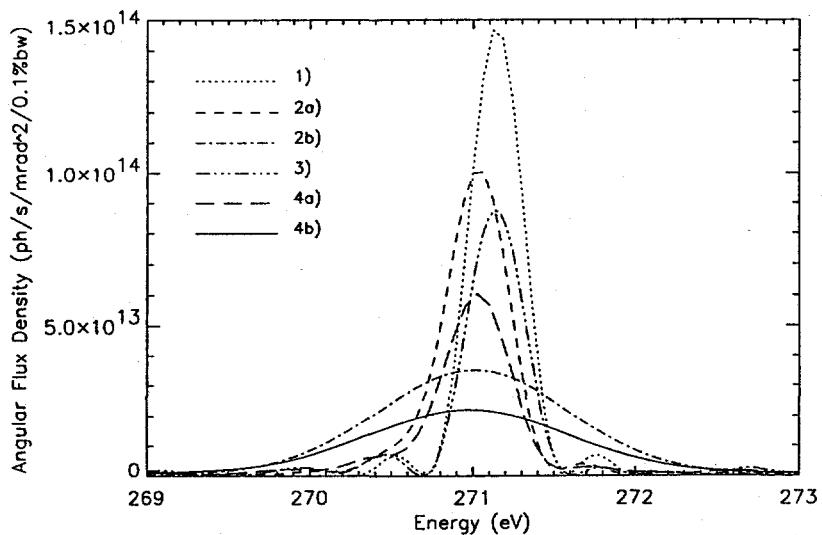


Figure 6: Simulated light output for the following cases: 1) Ideal undulator and ideal beam; 2a) Ideal undulator and beam with emittance (no energy spread); 2b) Ideal undulator and real beam; 3) Real undulator and ideal beam; 4a) Real undulator and beam with emittance (no energy spread); 4b) Real undulator and real beam.

4. COHERENT LIGHT POSSIBILITIES

The possibility of achieving coherent light generation in a single pass of an undulator at wavelengths less than those ever achieved exists with the LEUTL system. Studies are being carried out to determine precisely the requirements of an undulator system which would be used to study the SASE process at these wavelengths.⁹ As an initial conservative test, the beam from the thermionic microwave gun source is assumed. The undulator design was optimized with an initial wavelength goal of 120 nm using a 400-MeV electron beam. To further simplify the design, a simple planar undulator with separated function external focusing and a fixed gap was chosen. This will be built up in 2.5-m-long cells with 2 m of undulator and 0.5 m available for external quadrupolar focusing plus diagnostics (Figure 7). The results of calculations and simulations indicate a gain length of 1.5 m. Again being conservative, full saturation should occur after passage of the beam through 15 undulator cells. The principle parameters are shown in Table 3.

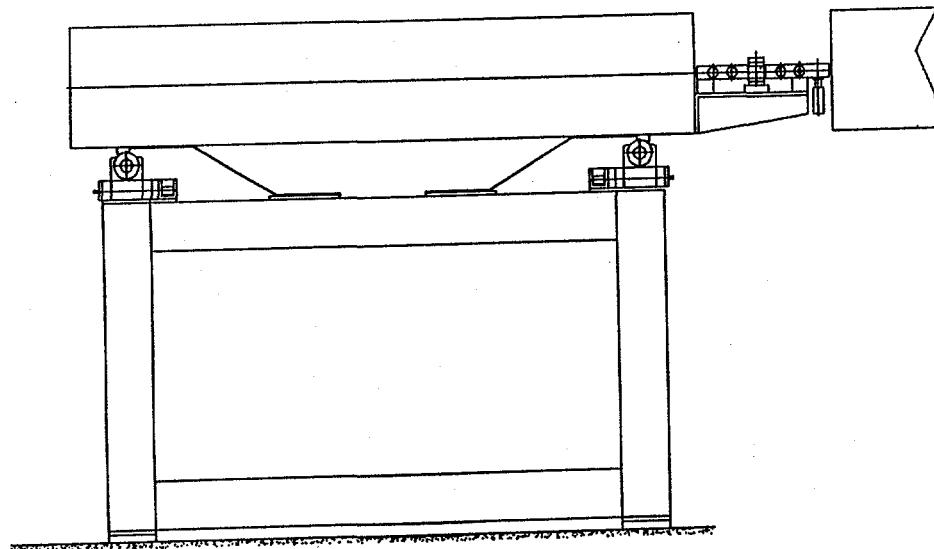


Figure 7: A single cell of the optimized undulator design.

Table 3: Optimized FEL Undulator Design

Wavelength	120 nm
Electron energy	400 MeV
Normalized emittance	$5 \pi \text{ mm-mrad}$
Energy spread	0.1%
Peak current	150 A
Undulator period	27 mm
Magnetic field	1.2 T
Undulator gap	5 mm (fixed)
Focusing	separated quadrupoles
Gain length	1.5 m
Undulator length	15 \times 2.5 m

The LEUTL beam energy can be raised to 700 MeV with a commensurate reduction in the light output of the undulator. This and the use of a photocathode rf gun electron source were both considered during the optimization process of the undulator. This system should be capable, during future operation, of achieving full saturation down to a wavelength of 40 nm.

5. INITIAL PLANS AND SCHEDULE

Our initial plans for the LEUTL are to commission the gun, the beamlines, and the diagnostics in a staged manner. The thermionic microwave gun and its associated transport system are currently being commissioned. The PAR bypass line will be commissioned next with most systems operational by mid to late summer of 1997. Beam will then be transported into the booster bypass line and on into the LEUTL enclosure itself. This is expected to occur by early 1998. First testing of actual undulators is expected shortly thereafter.

6. SUMMARY

In summary, the APS LEUTL will be able to provide a new means, and in some cases possibly the only means, of measuring new and existing undulators, and it will be able to do this to a level of sensitivity better than presently achievable. The same beam properties which make this feasible will also allow for the study of high-brightness, undulator-generated, diffraction-limited light. Furthermore, if a long optimized undulator is placed in this facility, the LEUTL should be capable of investigating SASE phenomena at wavelengths significantly below 100 nm.

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