BNL -65842

The VISA FEL Undulator

Roger Carr , Max Cornacchia, Paul Emma, Heinz-Dieter Nuhn, Robert Ruland,
Stanford Linear Accelerator Center

Erik Johnson, George Rakowsky,
Brookhaven National Laboratory

Steve Lidia,
Lawrence Berkeley Laboratory

Lou Bertolini , Marcus Libkind,
Lawrence Livermore National Laboratory

Pedro Frigola, Claudio Pellegrini, James Rosenzweig
University of California at Los Angeles

August 1998

National Synchrotron Light Source

Brookhaven National Laboratory
Operated by
Brookhaven Science Associates
Upton, NY 11973

Under Contract with the United States Department of Energy
Contract Number DE-AC02-98CH10886

DISCLAIMER

The VISA FEL Undulator

Roger Carr, Max Cornacchia, Paul Emma, Heinz-Dieter Nuhn, Robert Ruland,
Stanford Linear Accelerator Center

Erik Johnson, George Rakowsky,
Brookhaven National Laboratory

Steve Lidia,
Lawrence Berkeley Laboratory

Lou Bertolini, Marcus Libkind,
Lawrence Livermore National Laboratory

Pedro Frigola, Claudio Pellegrini, James Rosenzweig
University of California at Los Angeles

Abstract The Visible-Infrared SASE Amplifier (VISA) FEL is an experimental device designed to show Self Amplified Spontaneous Emission (SASE) to saturation in the visible light energy range. It will generate a resonant wavelength output from 800 - 600 nm, so that silicon detectors may be used to characterize the optical properties of the FEL radiation. VISA is the first SASE FEL designed to reach saturation, and its diagnostics will provide important checks of theory. This paper includes a description of the VISA undulator, the magnet measuring and shimming system, and the alignment strategy.

VISA will have a 4 m pure permanent magnet undulator comprising four 99 cm segments, each with 55 periods of 18 mm length. The undulator has distributed focusing built into it, to reduce the average beta function of the 70-85 MeV electron beam to about 30 cm. There are four FODO cells per segment. The permanent magnet focusing lattice consists of blocks mounted on either side of the electron beam, in the undulator gap. The most important undulator error parameter for a free electron laser is the trajectory walkoff, or lack of overlap of the photon and electron beams. Using pulsed wire magnet measurements and magnet shimming, we expect to be able to control trajectory walkoff to less than ±50 μm per field gain length.

Introduction

It is our long range goal to design and build an x-ray free electron laser based on a linac electron source and a single pass undulator that will generate FEL radiation starting from noise. The single pass design is required for a mirrorless x-ray FEL, and it must amplify noise because we have no coherent seed at x-ray wavelengths. Therefore, it is essential to understand the physics of Self Amplified Spontaneous Emission (SASE), saturation and cleanup in these devices [1]. SASE gain has been demonstrated from startup at a 15 μm wavelength, but the 2m, 100 period undulator was not long enough to reach saturation. [2] Also, at that wavelength, detectors are not suitable to investigate the detailed structure of the gain mechanism. A preferable wavelength range would be in the visible or near-infrared, where silicon detectors can be used and where Fourier transform methods are available to analyze the time structure of the FEL radiation. It was for this reason that we are building the VISA FEL. It is designed to be placed on the Accelerator Test Facility (ATF) linac at Brookhaven National Laboratory, which is being upgraded to an energy range of 70-85 MeV. The ATF has a laser photocathode gun capable of delivering 1.5 psec, 200 A electron pulses with a normalized emittance of 2π mm-mrad. Experiments are scheduled for January, 1999.

Undulator Structure

The VISA undulator has a resonant wavelength of 800 nm (600 nm) at 72.6 MeV (83.8 MeV). The corresponding saturation length is calculated numerically to be 3.4 m (3.8 m), for an ideal undulator with 18 mm period, and a maximum magnetic field of 0.75 T. Therefore, we decided to build an undulator 4 m long. The period length and field strength are optimized from numerical calculations of FEL performance. These parameters can be achieved with a pure Halbach permanent magnet approach with no permeable materials, NdFeB magnets with Br = 1.25 T, and a fixed gap of 6 mm. [3] The magnet blocks are 10 mm high and 4.5 mm thick; the extra height gives 23% more field than square cross section blocks would yield. Figure 1 shows the magnetic scheme for the VISA undulator.

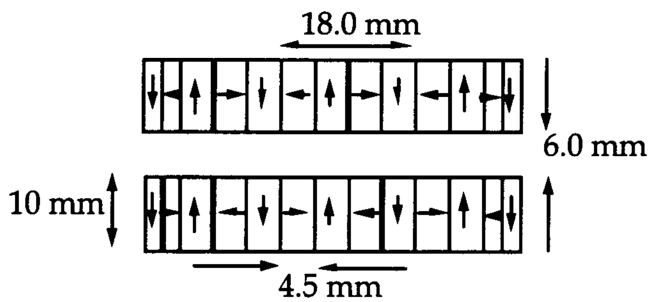

Figure 1: Schematic side view of two periods of the VISA undulator structure, showing a symmetric two-half-block termination scheme. Arrows within the magnet blocks indicate the direction of magnetization.

The symmetric two-half-block termination scheme results in negligible trajectory displacement, as shown in figure 2:

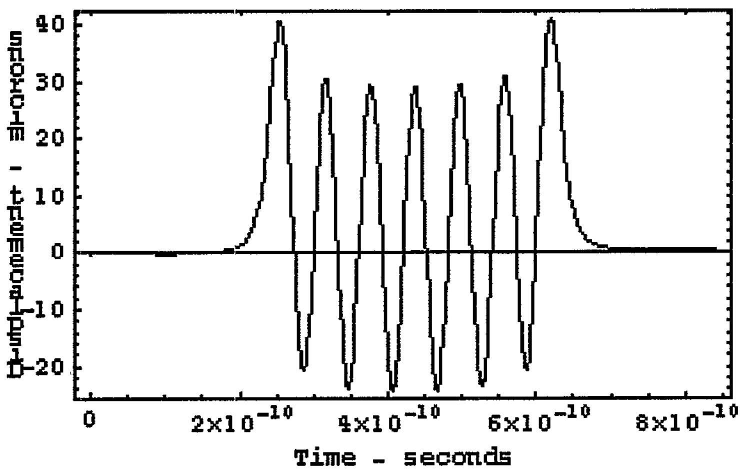

Figure 2: Numerical trajectory calculation for 6 periods of VISA undulator, with symmetric two-half-block termination. The displacement amplitude, peak-to-peak, is about half the beam diameter.

The 4 m VISA undulator is built from the beginning as part of a subsequent experiment at the Source Development Laboratory at Brookhaven National Laboratory which calls for a 6 m undulator with the same period length and gap. Therefore, we modularized the magnetic structure into 99 cm segments. Four of these 55 period segments will comprise VISA, and they will be butted together. If one-wavelength drift spaces, 32.3 mm long, were allowed between segments, the short Rayleigh length (30-38 mm) of this FEL would allow unacceptable diffraction losses. There may be gaps of a fraction of a millimeter between segments, which cause a trajectory phase error, but should not seriously harm the FEL gain. Figure 3 shows the entire 4m undulator.

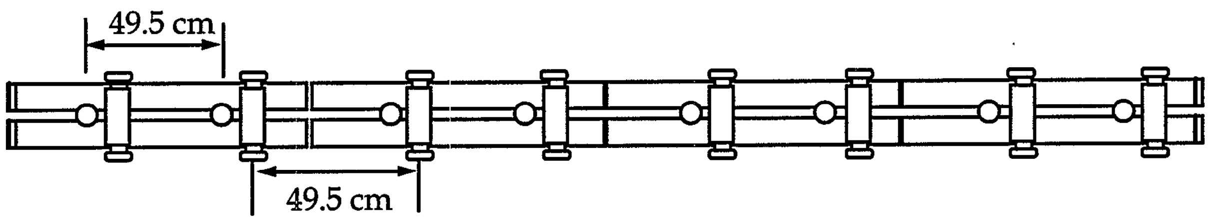

Figure 3: Schematic side view of the VISA undulator, with end terminating magnets on both ends, pop-in diagnostic ports (circles) and steering trim coils (vertical oblong shapes).

The electron beam in VISA has an rms diameter of 120 μm, and numerical simulations show that saturation length is adversely affected if the trajectory walks off a straight line by more than 50 μm per field gain length of 34 cm (38 cm) at 72 MeV (83 MeV). Note that the saturation lengths are almost exactly 10 gain lengths. A magnetic field with rms errors of less than 0.4% is required in order to achieve this trajectory walkoff tolerance.

Natural focusing is too weak for a 4 m undulator to saturate at these wavelengths, and we are constrained by the ATF lab layout to this length. Therefore we had to add strong focusing to the undulator. To achieve an average beta function of 27-30 cm between 72 and 83 MeV, distributed focusing is preferred to lumped focusing, so we decided to put a FODO lattice with four cells per segment into the undulator. This will be done by placing rows of paired magnets alongside the beam, as shown in Figure 4:[4]

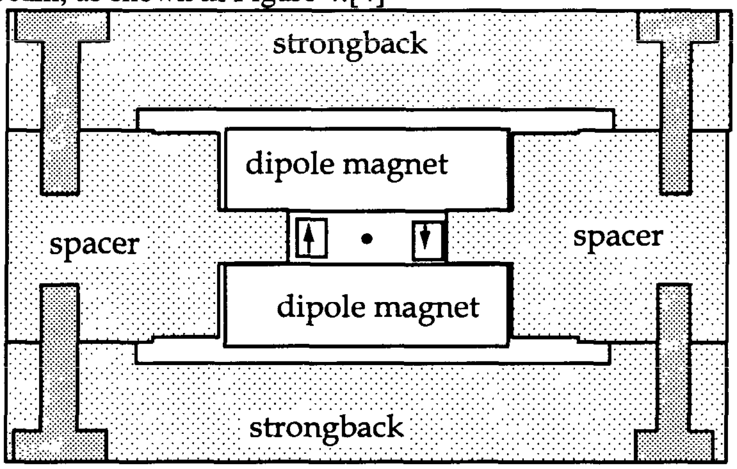

Figure 4: Schematic end view of the VISA undulator. The spacers assure a precise gap between the dipole magnets. Focusing magnets are shown as rectangles on either side of the central beam. For a beam coming out of the page, the arrows indicating the easy axis of magnetization correspond to a horizontally focusing, vertically defocusing (F) quadrupole. Reversing the magnetization gives a horizontally defocusing, vertically focusing (D) quadrupole. The superposition of focusing fields has the desirable effect of suppressing walkoff, in addition to its role in maintaining beam size.

The focusing magnets blocks are 30 mm long x 4 mm wide horizontally x 4.5 mm high, arranged in assemblies of three on each side of the beam axis. There are four FODO cells per undulator segment, and thus 16 F or D assemblies. The assemblies are 100 mm long (because there are spaces between blocks), there is a gap of about 10.25 mm between them, and with a remenance of Br = 1.25 T, they generate gradient of 33 T/m on-axis. All permanent magnets have Hci > 20 kOe, so that they resist demagnetization in this geometry.

The focusing assemblies comprise magnet blocks sandwiched between aluminum bars, so that the horizontal aperture for the beam is about 7 mm. The surfaces of the undulator magnets above and below the aperture are covered by a 25 μm Ni foil that provides a smooth, high conductivity surface to reduce resistive wall wakefields, and wakefield effects caused by the narrow gaps between magnets.

Magnetic Measurements and Error Minimization

The magnetic field errors of a pure permanent magnet undulator can be controlled in several ways. First, magnet material is chosen within a certain tolerance band on its net magnetic moment and the direction of its magnetization. We specified NdFeB material with Br = 1.25 T, moment errors of no more than 1.5% of Br in each of the three principal axes of the rectangular blocks, and direction errors of no more than 1.5°. After Helmholtz coil measurements are made of all the blocks, a sorting algorithm is executed on the data. We employ a technique called threshhold acceptance, which is similar to simulated annealing [5]. Model calculations show that the errors in a randomly assembled undulator using blocks with the specifications given start at 1.5%, and are reduced to 0.4% by the action of the algorithm, as required.

After sorting and assembly, the undulator assemblies will have magnetic errors from magnet block measurements and mechanical imperfections, so we employ magnetic shimming to improve the trajectory in each segment. This work will be done by the magnetic measurements group of the NSLS at BNL, using the pulsed wire technique. This technique is well established for simple undulators, [6] but it is more complicated in our case where quadrupole focusing fields are superposed over the undulator dipole fields.

First, we find the axis of the quadrupole focusing field. A short current pulse is put into the wire (to observe the first integral of the field), and the resulting mechanical vibrations are detected by a an optical pickup. We translate the wire transversely to seek a null in the 24.75 cm period signal from the FODO lattice. To enhance this signal, we suppress the larger 1.8 cm signal from the dipole magnet fields by low pass filtering, or by Fourier transform techniques. From tests on a prototype VISA magnet, we have demonstrated that we can locate the quadrupole axis to ±20μm. The undulator sections are designed to be rotated 90 degrees, so that separate x- and y- measurements can be made in the horizontal plane, to eliminate the effect of wire sag.

Having found the quadrupole axis, we measure its positon mechanically with a precise wire finder that is referenced to tooling balls attached to each end of the undulator segment. Micrometers mounted on the finder are moved so that they make electrical contact with the wire. We find this is repeatable to about ±5 μm. The positions of the tooling balls relative to each other will have been found on a coordinate measuring machine. Also, the wire finder will have been calibrated to determine the micrometer readings of the nominal centerline. The best axis wire positions and the calibration offsets will then be used to align the undulators when they are installed in the vacuum vessel.

After we find the quadrupole axis, we observe the second integral of the field (i.e. the trajectory), using a current step (in practice, a very long, square pulse). We can then add shim magnets outboard from the dipole array to correct errors in the trajectory from dipole or quadrupole sources. The shim magnets are small 3 mm x 3 mm x 2 mm blocks of NdFeB that are used in fours, as shown in figure 5. The blocks are mounted in pairs on movers that extend into wells machined through the strongbacks shown in Figure 5.

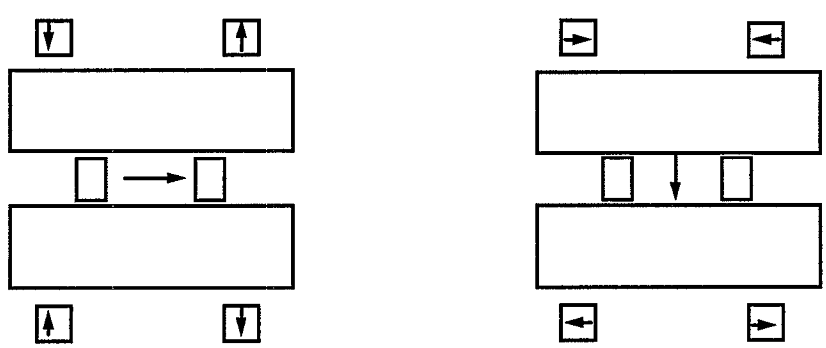

Figure 5: Schematic end view of VISA undulator, showing placement of shim magnets in groups of four. With magnetizations arranged as at left, the shim magnets create a net horizontal field on axis, and on the right they create vertical field. By varying the vertical positions of these magnets, we obtain a tuning range of about 3-35 Gauss-cm.

The BNL pulsed wire system is capable of measuring a two meter undulator. After shimming individual 1 m segments, we will set up pairs of segments, butted together, and shim the trajectory across the joint, to minimize trajectory errors.

Alignment

When trajectory errors are reduced to satisfactory levels and successive pairs of segments are shimmed across their joints, the segments are mounted into a 4 m aluminum vacuum box with a cross section of about 20 x 20 cm. It was decided that the entire undulator should be surrounded by a vacuum vessel, rather than trying to make a vacuum pipe small enough to fit in the gap. The vacuum need only be 10^{-6} Torr. This requires that the undulator be mounted through bellows to an external beam so it can be aligned in air, and not experience any stresses when the vessel is evacuated. The vacuum box has a lid on the top, that will be removed during alignment, and sealed with an 'O' ring when we pump down. Each undulator segment is mounted on x-z tables that allow transverse and longitudinal position and yaw to be controlled. We have no roll control, since we are not that sensitive to roll, and pitch may be adjusted by means of separate feedthrus on the vacuum vessel.

The segments will be surveyed into rough alignment, using the tooling balls mounted on each of the segments. Rough alignment should bring the axis to straightness within about 200 μm. A fixture with slits, referenced to the tooling balls and previously calibrated to the magnetic axis, will be used to align the entrance and exit of the undulator to a beamline reference laser, which will also be used to calibrate the diagnostic pop-ins. Two laser straightness interferometers, also aligned parallel to the beamline reference laser, will then be used to achieve about 20 μm alignment of the magnetic axes. One interferometer can be moved on a path level with the axis horizontally, and the other is vertically above the axis. A rod with invariant length is used to transfer the distance between the tooling ball and the interferometer, and the interferometer optic may be moved over the entire 4 m length.

Runtime Diagnostics and Trajectory Controls

We elected to use Eu:YAG crystals as beam position monitors. When the electron beam strikes a 0.5 mm thick Eu:YAG crystal, it causes the crystal to fluoresce with negligible blooming. [7] The fluorescent light reflects from two 45 degree mirrors into a CCD camera, as shown in figure 6:

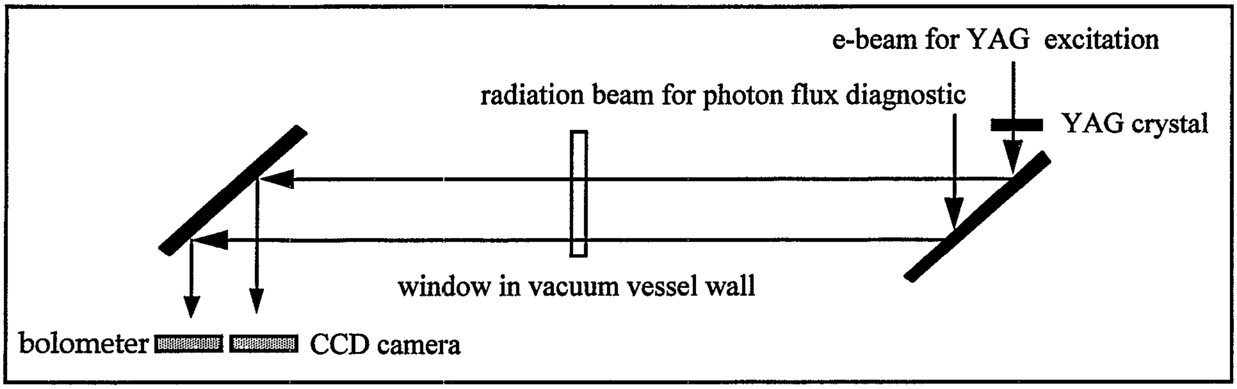

Figure 6: Schematic view of pop-in diagnostic. The mirrors and YAG crystal are translated into two positions that intercept the combined photon and electron beams. The diagram reflects two positions of the periscope; the beams are in the same place with respect to the undulator.

The diagnostic pop-ins are mounted on the vessel, but they are just periscopes that bring light out to CCD cameras. The cameras are mounted on the same beam as the undulator, so that exact position repeatability for the pop-in is unnecessary. The resolution of the BPM's should be about 20 μm.

The pop-ins have three positions, controlled by air cylinders. In the 'out' position, the pop-in should leave as little gap in the beam aperture wall as possible, to minimize wakefield effects on the beam. In the 'BPM' position, the electron beam strikes the YAG crystal, and in the 'flux' position, the radiation beam is deflected into a bolometer. It is possible that some correction of the trajectory might be obtained by trying sequentially to optimize the flux at each diagnostic. The main purpose of the flux measurements is to generate a plot of the gain curve, for comparison with theory. It is intended that the pop-in target positions be calibrated, using a HeNe laser beam aligned with the axis as determined by the pulsed wire measurements.

There are approximately two betatron oscillation periods in the length of the VISA undulator, and the diagnostics and steering trim coils are placed at intervals of roughly $\pi/2$ phase advance. The trim coils are iron-core picture-frame electromagnets mounted outside the aluminum vacuum vessel. A separate power supply is provided for each pair of coils. Simulations have been performed to anlayze the effect of runtime corrections. We find that errors as large as 200 μm can be reduced to 50 μm, but can require kicks up to 1 mrad. The coils are 5 cm long, axially, so a 1 mrad kick 85 MeV requires a field of about 57 Gauss.

The power supplies are controlled by a computer that also reads the positions of the beam on the CCD cameras. The pop-ins are inserted sequentially, the beam positions are acquired, and then a computer algorithm determines the required changes in steering trim currents. This process may be iterated, but it will be a soft-constraints approach that does not require the beam to pass through the center of each BPM, but only requires the best overall straightness. Launch positions and angles will be monitored by button-type electron BPM's, so that run-time corrections can be made. However, the diagnostics will be used infrequently to align the electron beam in the FEL, so we rely on thermal and mechanical stability in the intervals between re-correction of the steering currents.

Downstream from the undulator is a beam dump for the electrons, and photon diagnostics for the FEL radiation. It is of particular importance to use Fourier transform techniques, such as Fourier Resolved Optical Gating (FROG). [8] This should help us generate a picture of the superradiant spikes we expect from the SASE process, to investigate the cleanup process.

Summary

The VISA FEL is expected to emit 800-600 nm light from the SASE process. A 4m undulator should be adequate to reach saturation at these wavelengths, providing that tolerances on magnetic field errors and alignment can be maintained. The most stringent requirement is that trajectory walkoff be held to less than about 50 microns/gain length. By specifying tight tolerances on the permanent magnets, sorting them, assembling them precisely and shimming errors in each 1 meter segment, we expect to hold this tolerance within the segment. By shimming across segment joints, and accurately aligning the segments with straightness interferometers, we expect to minimize errors over the entire device. Finally, by beam position monitoring and steering trims, any remaining trajectory errors can be corrected.

Acknowledgements:

This work was supported by the United States Department of Energy, Office of Basic Energy Sciences under contract No. DE-AC03-76SF00515. The authors are pleased to acknowledge valuable contributions from Lorraine Solomon, John Skaritka, Jeff Aspenleiter, and Michael Lehecka, all of Brookhaven National Laboratory.

References:

1 R. Bonifacio, C. Pellegrini, and L.M. Narducci, Opt. Commun. 50, (1984) p. 373

2 M. Hogan, et. al. submitted to Phys. Rev. Lett.

3 K. Halbach, Nucl. Inst. & Methods 187 (1981) p. 109

4 A.A. Varfolomeev and A.H. Hairetdinov, Nucl. Inst. & Methods A341 (1994) p. 462

5 S. Lidia and R. Carr, Rev. Sci. Inst. 66 (1995) p. 1865

6 R. Warren and C. Fortgang, Nucl. Inst. & Methods A341 (1994) p. 444

7 E. D. Johnson, W. S. Graves, K.E. Robinson, Proceedings of the 8th Beam Instrumentation Workshop (1998)

8 R. Trebino, et. al. Rev. Sci. Inst. 68 (1997) p. 3277