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Initial Gain Measurements of a 800nm SASE FEL, VISA

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Abstract

The VISA (Visible to Infrared SASE Amplifier) FEL is designed to obtain high gain at a radiation wavelength of 800nm. The FEL uses the high brightness electron beam of the Accelerator Test Facility (ATF), with energy of 72MeV. VISA uses a novel, 4 m long, strong focussing undulator with a gap of 6mm and a period of 1.8cm. To obtain large gain the beam and undulator axis have to be aligned to better than 50μm. Results from initial measurements on the alignment, gain, and spectrum will be presented and compared to theoretical calculations and simulations.

1. INTRODUCTION

Recent SASE FEL research has aimed at developing shorter wavelength devices [1,2] and a current proposal [3] to generate high power, coherent x-rays at 1.5 Å has already received initial funding-LCLS (Linac Coherent Light Source). During the last few years, SASE FELs have demonstrated very high gain [2] and have agreed well with simulations in the far infrared. VISA, while R&D for the LCLS, will continue this study into the visible and harmonic UV wavelengths. In addition, VISA employs the use of a novel small gap 4m long strong focusing undulator which not only makes the intra-undulator diagnostics challenging, but the alignment of the undulator to be very critical on FEL performance as will be shown below. These challenges are unique to VISA and an understanding of them is needed in order to build the next generation SASE FEL devices.

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2. EXPERIMENTAL SETUP

VISA has been commissioned and initial results have been obtained at the ATF [4] in BNL. The electron source is a 1.6 cell S-band photoinjector with an emittance compensating solenoid. A separate klystron powers two 3m traveling wave linac sections after which the electron beam has an energy greater than 70MeV. Added to the VISA beamline, is a matching section including a focusing quadrupole triplet and beam position and profile monitors providing the proper electron beam matching conditions (Table 1) to the undulator.

The VISA undulator [5] is a strong focusing 4m planar permanent magnet Hallbach array design; the parameters are given in Table 1 and an endview of the undulator is shown in Fig.1. Dipole magnets with vertically oriented fields are put on either side of the gap providing strong quadrupole focusing [6]. These quadrupoles are arranged along the undulator in a FODO lattice design with a period of 24.75 cm giving four FODO cells per 1m undulator section and an average beta-function of 30cm. According to simulations [7], implementation of the strong focusing decreases the gain length by up to 40% compared to a natural focusing scheme.

Simulations [9] have also shown that the electron beam and co-propagating SASE FEL radiation must remain within an rms beam diameter, 60 μm, of each other throughout the undulator in order for VISA to achieve high gain. This puts very rigid requirements on the measurements and alignment of the undulator. We have set the requirement on aligning the four 1m sections to be within 30μm. To do this, a laser interferometric alignment system [8] has been developed in which these strict alignment tolerances can be reached.

Eight steering magnets and diagnostic pop-in ports are evenly spaced (by 50cm) down the length of the undulator. The steering might be necessary to help propagate the electron beam through the 4m and prevent electron beam walk-off. Each actuated diagnostic port serves to make electron beam measurements using OTR and also to extract FEL light [9]. This setup gives VISA the ability to make accurate electron beam profile and SASE radiation measurements versus distance along the undulator.

3. Experimental Measurements

In order to study gain, the gun phase was set to compress the electron beam to about 2ps FWHM and increase the peak current to about 130A with an emittance about 3.5mm-mrad. It will be discussed further below that the undulator sections were not aligned to the specified tolerances given above and for a strong focusing system like VISA, a >100μm misalignment is very detrimental to SASE FEL performance [7].

A factory calibrated Molectron Joulemeter is used to collect undulator radiation and is placed about 2m from the exit of the undulator and has an acceptance angle of 10mrad. A faraday cup at the beamline end is used for charge measurements. Once SASE signal was seen, the intra-undulator corrector magnets, gun focusing solenoid, and matching sections quadruples were all used to peak the signal. Figure 2 plots detector energy vs. charge. The plot is very non-linear indicating gain. Spontaneous radiation is linear with charge and for our experimental setup we calculate .68nJ of expected spontaneous energy at 240pC. Extrapolating the low charge linear portion of Figure 3 (0-.16nC) which is purely spontaneous radiation, one can see we measured about .5nJ of spontaneous energy at 240pJ.

Thus, the signal detected above the .5nJ at 240pC is SASE and at 240pC a peak SASE signal of 1nJ was measured. We define gain as

$$g = \frac{I}{I_0} = \frac{1}{9}\exp\left(\frac{L_{und}}{L_{gain}}\right)$$

where I and I_0 are the SASE and spontaneous energy inside the coherency cone respectively, L_{und} is the undulator length and L_{gain} is the gain length. Calculations show for our setup $I_0 = 9pJ$ thus, giving a peak gain, $g = 110$, and a gain length, $L_{gain} = 58cm$. As the gain signal increases, the SASE shot to shot signal is expected to fluctuate more due to the statistical nature of the SASE FEL start-up process [10]. This is clearly the case in Figure 2 where signal fluctuations near 240pC are quite large and decrease as the charge/SASE signal lessens. At the moment there is no comparison with theory because of the uncertainty in the undulator section positions, however in the future when the alignment becomes more certain, a comparison will be more relevant.

Study of the electron beam trajectories through the undulator is necessary in order to understand and optimise the SASE FEL performance. If the four 1m sections are misaligned (which is the case shown below), orbit kicks will show up in electron beam trajectory studies.

Without the use of the corrector magnets along the length of the undulator, beam horizontal (wiggle plane) orbits were studied by changing the upstream (matching section) launch conditions into the undulator. Shown in Fig. 3 is the electron beam centroid positions at the BPM just before the undulator and inside the undulator at the eight BPM pop-in positions relative to our alignment laser where z=0 is the undulator entrance. The alignment laser gives a straight-line path reference through the undulator. Fig. 3 shows a peak to peak trajectory amplitude of nearly 3mm (pre-move orbit) and a significant kick between undulator Sections 2 & 3 before steps were taken for improvement.

After we were satisfied this was the best trajectory we could attain, we decided to do a beam-based alignment and move the undulator while under vacuum. The VISA system has the ability to horizontally (in the wiggle plane) move the undulator while under vacuum. An undulator monitoring system was implemented during installation in which the body of the undulator could be monitored to an accuracy of <15μm giving us fairly precise control of the undulator's horizontal position. Using a trajectory simulator, we were able to predict which direction and how far to move the undulator sections, do another orbit study, and move the undulator again. To the accuracy of the simulator, we needed to move only the last two sections, Sections 3 & 4. After seven iterative undulator section moves, we had reduced the peak to peak oscillation from 3mm to 500μm. Figure 3 shows only three trajectories after moving the undulator for clarity of picture. At first, Section 3 was moved until the oscillation amplitude through it was similar to the first two sections and then movement of Section 4 followed. The distance the sections needed to be moved was between 150μm and .60mm depending where the realignment was necessary. The limiting factor of this method is the fact that the trajectory model assumes only one undulator section to be misaligned which was clearly not the case. Figure 4 shows great improvement in the electron beam trajectory using this method to align our undulator.

4. CONCLUSION

For strong focusing undulator systems, alignment is very critical. We demonstrated beam-based alignment on the VISA system by a series of trajectory studies and undulator movements. This method re-aligned the undulator from a peak to peak trajectory amplitude of 3mm to 500μm. Also, a significant gain, $g = 110$, was measured with gross misalignments of the undulator sections. Currently, work is in progress to bring the alignment to the several microns level using the interferometric system. Once aligned the trajectory orbit amplitude should be reduced further along with attaining much higher gain.

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Peak Power (Saturation)	P_{Sat}	60 MW
Wavelength	λ_r	800 nm
Electron Beam Energy	E	71 MeV
Peak Current	I_P	200 A
Normalized Emittance	ε	2 mm-mrad
Bunch Length (FWHM)	τ	<10ps
Undulator Period	λ_u	1.8cm
On axis Field	B	.75T
1-D FEL parameter	ρ	.0085
Field Gain Length	L_g	.35m

Table 1. VISA experimental design parameters including output radiation, electron beam requirements, and undulator parameters.

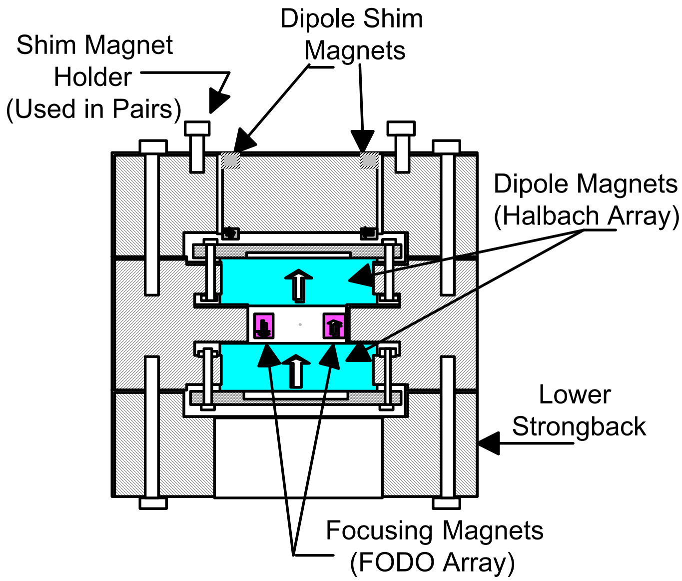

Figure 1. Endview of the VISA undulator. Shown are the dipole magnets along with the quadrupole magnet array (FODO) which provides strong focusing. The electron beam comes out of the page.

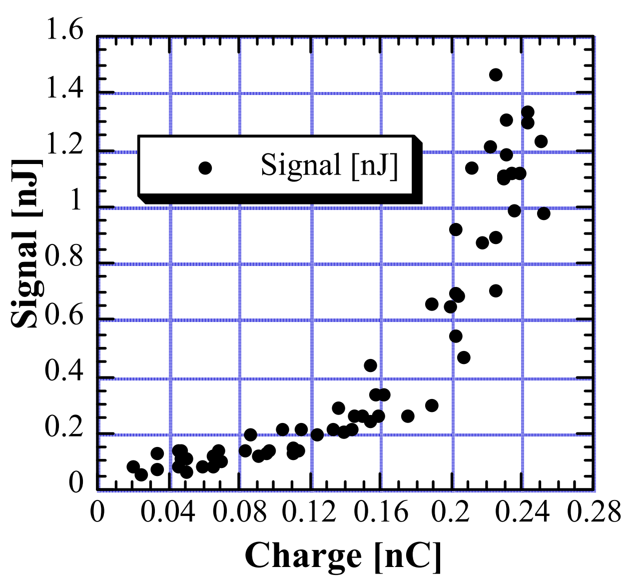

Figure 2. Detector signal vs. charge at the down stream Joulemerter about m past the exit of the undulator. The graph is highly non-linear indicating gain, which we calculate to be ~110.

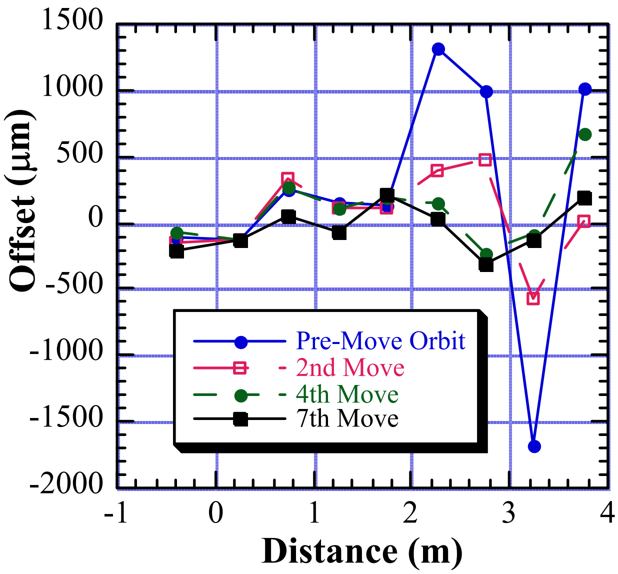

Figure 3. Beam-based alignment of undulator. Before undulator is moved, the electron orbit has 3mm amplitude. Trajectory model fitting and multiple movements of undulator sections reduced trajectory amplitude to 500µm. z=0 is the undulator entrance.