SLAC-PUB-9583
November 2002

Characterization of an 800 nm SASE FEL at Saturation*

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Abstract

VISA (Visible to Infrared SASE Amplifier) is an FEL (Free Electron Laser) designed to saturate at a radiation wavelength of 800 nm within a 4-m long, strong focusing undulator. Large gain is achieved by driving the FEL with the 72 MeV, high brightness beam of BNL's Accelerator Test Facility (ATF). We present measurements that demonstrate saturation in addition to the frequency spectrum of the FEL radiation. Energy, gain length and spectral characteristics are compared and shown to agree with simulation and theoretical predictions.

SASE, FEL, Saturation, Strong focusing, undulator
PACS # 41.60C

1. Introduction

Several FEL schemes are used to generate coherent, high power radiation: oscillators, seeded and single pass devices. Because hard X-ray mirrors and seed sources are currently unavailable, the SASE FEL is the most promising configuration for obtaining coherent, X-ray radiation. The proposal for a SASE FEL to generate hard X-rays was made several years ago [1], and recently experiments have confirmed high gain, short wavelength SASE FEL theory [2,3,4,5,6]. X-ray SASE FEL devices have been proposed [7,8], and recent experimental success shows the feasibility of building such facilities.

In this paper, we describe a visible SASE FEL, VISA [5,6] that is R&D for the Linac Coherent Light Source (LCLS) X-ray facility and lases at a fundamental wavelength of 840 nm. The electron beam source and matching beamline optics upstream of the undulator are reviewed. Since the electron beam quality is important to the

Presented at 23rd International Free Electron Laser Conference
And The 8th FEL Users Workshop, 20-24 Aug 2001, Darmstadt, Germany

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

performance of VISA, a detailed analysis of the transport line and beam parameters is given. The strong focusing undulator and the high beam quality allow VISA to saturate in only 3.6 m with a power gain length of 18.7 cm. These experimental results in addition to the frequency spectrum are described and compared to simulation and theory.

2. Experimental Setup

In this section, we give a description of the electron source, beam transport, and undulator. The electron beam is derived from a 1.6 cell S-band photo-injector system after which the beam is accelerated by two SLAC type linacs to a final energy of 72 MeV. Detailed measurements immediately after the 2nd linac confirm that a high brightness beam with an emittance of .8mm-mrad and current of 60 A [9] can be generated by the ATF photoinjector.

The electron beam then passes through a double bend consisting of two 20 degree deflecting dipole magnets and quadrupoles. When the electron bunch energy is chirped in the linac, the double bend longitudinally compresses the electron bunch, thus increasing its peak current. Consequently, the transverse emittance is increased through this section as we will further discuss in the next section. After the dispersion section, a quadrupole triplet is used for final matching of the electron beam into the undulator.

The VISA 4-m long, strong focusing undulator [10] has a 6 mm gap and a 1.8 cm period. The undulator is made up of four 1 m sections and the strong focusing quadrupole field requires alignment to within 30 μm. A laser interferometric system specifically designed for VISA [11] aligns the undulator to this tolerance. If this alignment tolerance is not met, then VISA high gain is reduced [12]. Dipole magnets placed on either side of the propagation axis with opposite polarity introduce strong focusing [13] in the undulator. Simulations confirm [11] that the enhanced electron beam density reduces the saturation length by 40%. Eight steering magnets spaced by 50 cm are situated along the undulator and used to keep the electron beam and SASE radiation co-linear.

Eight diagnostic pop-in ports (spaced by 50 cm with the last port 25 cm from the end of the undulator) are situated along the length of the undulator [14]. Both SASE and electron beam parameters vs. distance measurements use these pop-ins. A faraday cup downstream of the undulator and an electronic BPM upstream of the undulator are both used for charge measurements.

3. Experimental Measurements

Electron beam parameters were measured immediately after the 2nd linac, before the 2-dipole dispersion section. Here, the beam had a charge of 250 pC and a 60 A peak current. Quad-scans of the projected emittance in the linac section gave an emittance of 0.8 mm-mrad [9]. To longitudinally compress the beam in the double bend line, and increase the peak current, an energy chirp (measured after the linac section) of .15-.2% rms is needed.

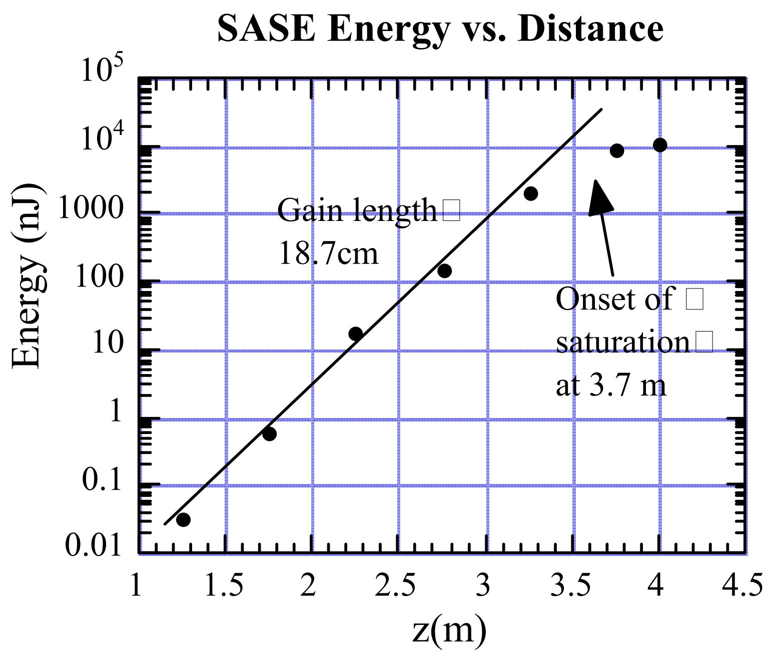


Figure 1. SASE Energy vs. Distance. Deviation of last two points from the line fit of the previous five is evidence that the system is in saturation.

The diagnostic pop-ins are used for SASE energy vs. distance measurements along the undulator and Fig.1 shows this result. The deviation of the last two points from the linear fit for the previous five shows that the system has reached saturation after 3.6 m of undulator. The slope of the line produces a power gain length of $L_g = 18.7$ cm. Defining gain as

$$G = \frac{E}{E_0} \tag{1}$$

where E_0 is the spontaneous energy inside the coherency cone and bandwidth within the first field gain length and E is the energy measured at the exit of the undulator, we obtain a value $G = 2 \times 10^7$.

A spectrum at saturation is shown in Fig. 2 with a central wavelength at 840 nm. The wavelength for an FEL is given by the equation,

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \tag{2}$$

where λ_u is the undulator period, γ is the electron beam energy, and *K=1.26* is the undulator parameter. For our parameters, Eq. 2 predicts a fundamental SASE radiation wavelength of 840 nm, thus confirming the measurement in Fig. 2.

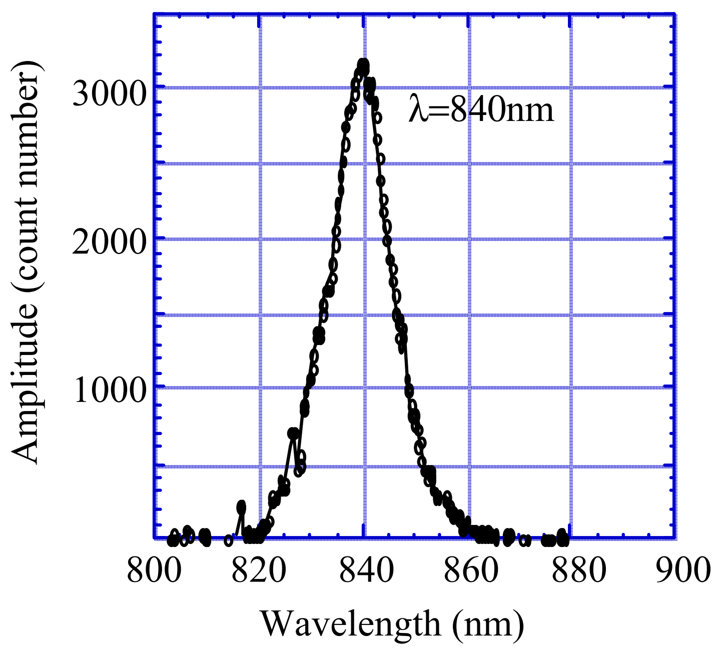


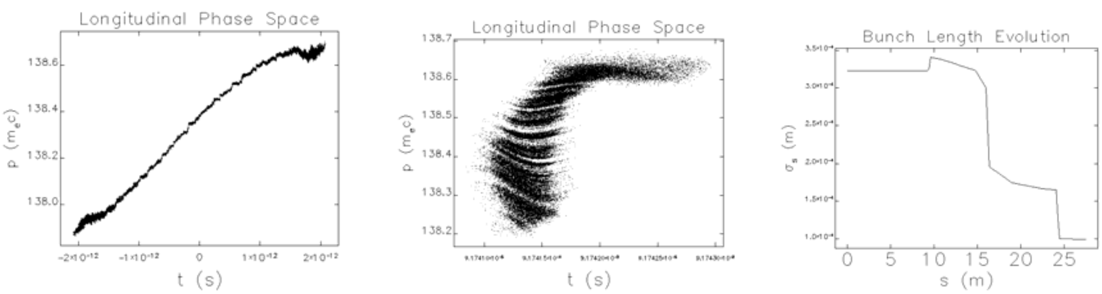
Figure 2. VISA single shot spectrum at saturation. The central wavelength is 840 nm, and the one spike indicates a bunch length of the order of the cooperation length.

When the bunch length, L_b, is much longer than a cooperation length, L_c, we also expect to see spikes inside the spectral line. The expected number of spikes is [15] $N_s \sim L_b / 2\pi L_c$. While we see spikes when running with a non-compressed beam, none are observed with a compressed beam, as in the case of Fig. 2. In this last case, $2\pi L_c \sim 50\,\mu\text{m}$, and an absence of spikes indicates a very short bunch length. An analysis on this electron bunch compression is presented in the next section.

Additional measurements of VISA include those on the non-linear harmonics and longitudinal electron beam microbunching. Here, we just state the general results as future publications will describe both in detail. The gain lengths for the 2nd and 3rd non-linear harmonics have been measured and confirmed to decrease with mode number, *n*, compared to that of the fundamental. In addition the spectra for the non-linear harmonics have been measured, and in a single shot the fundamental, 2nd and 3rd harmonics were captured for the first time in a SASE FEL. Also, the fundamental and 2nd harmonic longitudinal microbunching of the electron beam at the exit of the undulator has been measured. Using a microbunching CTR experimental setup, shot-to-shot measurements of microbunching for the two lowest modes vs. SASE radiation were captured. These measurements show the microbunching for both modes saturating at very high SASE radiation, another confirmation that the VISA FEL is in saturation.

4. Electron Beam Measurements and Analysis

As the compression hypothesis was situated, a need emerged to measure the current directly at the location of the undulator. A single bolometer approach was used to construct a CTR (coherent transition radiation) indicator, which would be sensitive to the changes in the beam longitudinal distribution [16]. Initial measurements of CTR energy as a function of the linac conditions indicated a strong compression, as the CTR signal peaked up sharply within a narrow sub 2° window of the linac RF phase. The measurements with and without a filter of know cut-off frequency demonstrated signal ratio of 0.68 at the SASE operating point. Such a ratio indicates a short bunch-length (less than a 100 μm rms), which differs greatly from the beam parameters measured at the linac. The test proved strong bunch compression in the dispersive section of the beam line and introduced a quantitative benchmark for the simulation studies.



a. b. c.

Figure 3. Compression through the dispersion section. 3a. Energy chirped electron beam exiting the linac section, before the dispersion section. 3b. Compressed beam after dispersion section, before the undulator. 3c. Longitudinal beam size from the linac to the undulator.

To support the experimental results with simulations, PARMELA was used to simulate ATF photo-injection line and reproduce a particle distribution similar to the one measured after linac. In the dispersive section CSR has to be taken into account and the code ELEGANT was found to be the most suitable. The control knob for a non-linear compression in the simulations was an energy offset of the electron beam with respect to the nominal tune (resembling a natural uncertainty in the experiment). The compression was varied until the output ELEGANT file matched CTR bunch length measurements, and the result was an asymmetric beam with the peak current 250 Amp, core horizontal emittance growth up to 4 mm-mrad and vertical emittance preservation. The phase space compression generated by ELEGANT is shown in Fig. 3.

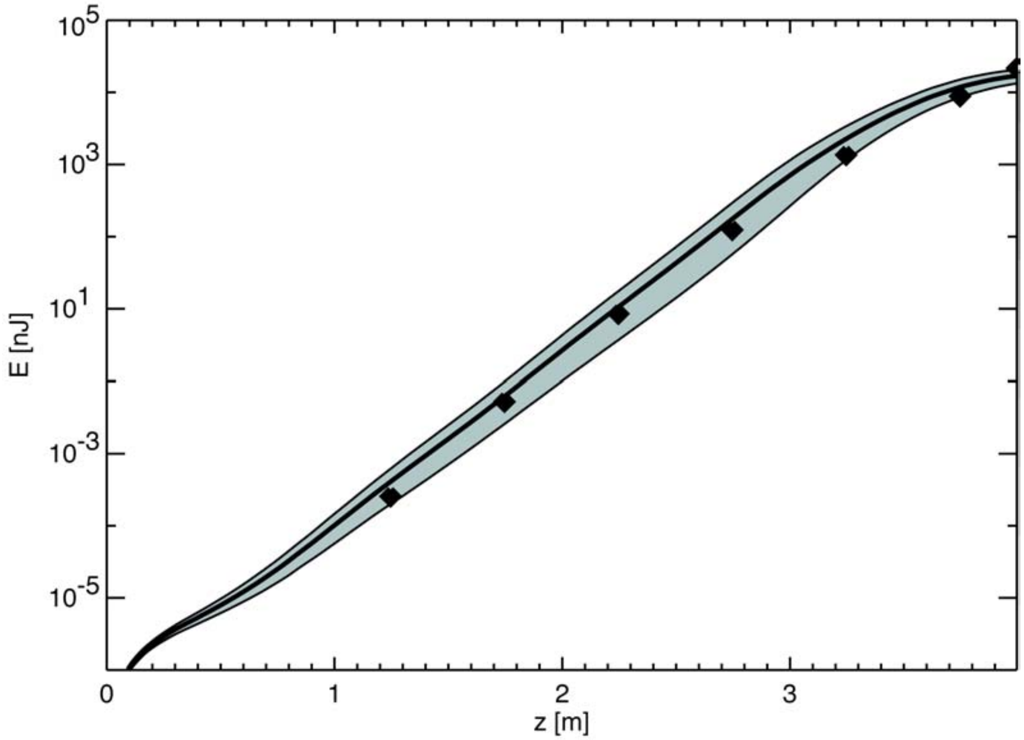


Figure 4. Energy vs. Distance. GENESIS simulation compared to measured data different that in Fig. 1. Gray area indicates a one sigma shot noise fluctuations due to different seedings in GENESIS.

The ELEGANT output distribution was roughly matched to the focusing lattice of the undulator and imported into GENESIS for FEL simulations. Figure 4 shows the comparison of the GENESIS output for several shot noise seeds with the measured data, different from those measured in Fig. 1. The data points lie in the shot noise fluctuations of the simulations and the resulting gain length of 19.2 cm agrees closely with the measured 18.7 cm gain length.

5. Conclusion

VISA, the visible to infrared SASE FEL, saturated in 3.6 m with a gain length of only 18.7 cm. Spectral measurements from the SASE radiation indicated that the bunch length at the undulator was shorter than that measured in the linac section. CTR measurements at the undulator confirmed this hypothesis. Simulations generated the beam parameters after the dispersion section and using these parameters, FEL simulations showed good agreement with the experimental measurements.

We would like to thank everybody from BNL, LLNL, SLAC and UCLA who made this experiment a success.

6. References

[1] C. Pellegrini, A 4 to 0.1 nm FEL Based on the SLAC Linac (Workshop of Fourth Generation Light Sources, Stanford Synchrotron Radiation Laboratory, Stanford, CA, 1992).

[2] M.J. Hogan *et al*., Phys. Rev. Lett. 81, 4867 (1998).

[3] J. Rossbach

[4] S. Milton *et al*., Science, 292 (2001) 2037-2041.

[5] A. Murokh *et al*., Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL.

[6] A. Tremaine *et al*., Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL.

[7] M. Cornacchia *et al*., Linac Coherent Light Source (LCLS) Design Study Report, Report SLAC-R-521 (Stanford Linear Accelerator Center, Stanford, CA, revised 1998).

[8] R. Brinkmann, G. Materlik, J. Rossbach, A. Wagner, Eds., Conceptual Design of a 500 GeV e+ e- Linear Collider with Integrated X-Ray Laser Facility, DESY Report DESY97-048 (Deutsches Elektronen-Synchrotron, Hamburg, 1997).

[9] V. Yakimenko, Proceedings of the 2001 Particle Accelerator Conference, Chicago, IL.

[10] R. Carr *et al*., Submitted to Phys. Rev. ST Accel. and Beams

[11] R. Ruland *et al*., Proceedings 1999 Particle Accelerator Conference, New York, New York, 1999.

[12] P. Emma *et al*., Proceedings of the 20th International FEL Conference (FEL98), Williamsburg, Va., USA, 1198, SLAC-PB-7913.

[13] A.A. Varvolomeev and A.H. Hairetdinov, Nucl. Inst. & Methods A341, 1994.

[14] A. Murokh *et al*., Proceedings for the 2000 International Free Electron Laser Conference, Durham, N.C., 2000.

[15] Bonifacio *et al*, Phys. Rev. Lett., 73, 70 (1994).

[16] A. Murokh *et al.,* Nucl. Instrum. and Meth. in Phys. Res A, 410 (1998) 452-460.

[17] S. Reiche, Nucl. Instr. & Meth. A429(1999) 243.