FUTURE FEL STUDIES AT THE VISA EXPERIMENT IN THE SASE AND SEEDED MODES*

G. Andonian, M. Dunning, A. Murokh, C. Pellegrini, S. Reiche, J. Rosenzweig,
UCLA, Los Angeles, CA 90095, USA
M. Babzien, I. Ben-Zvi, V. Yakimenko, BNL, Upton, NY 11973, USA.

Abstract

The VISA (Visible to Infrared SASE Amplifier) experiment at BNL (Brookhaven National Laboratory) has previously demonstrated saturation at 840 nm in 2001. Further SASE studies, in 2003, have demonstrated an anomalously large bandwidth spread of the FEL spectrum due to off-angle emissions. This paper disseminates the current and future program of the VISA experiments at BNL. This includes a study of a seeded FEL, using a 1 micron YAG laser as a seed, and the accompanying diagnostics to characterize the radiation. Diagnostics include the double differential spectrometer, a mode converter to investigate the orbital angular momentum of light in the FEL, and an optical pepper-pot for coherence measurements. Start-to-end simulations, which are reliably used for experimental modeling, are presented.

INTRODUCTION

The advent of the X-ray free electron laser (FEL) is on the horizon [1, 2]. The creation and diagnosis of ultra-short pulses is of great importance to the FEL community. The generation of femtosecond long, Ångstrom wavelength radiation will open doors to a myriad of scientific endeavors at ultra-short time scales [3].

The VISA program was developed to investigate properties of a high gain self amplified spontaneous emission (SASE) free electron laser. A proposal to obtain ultra-short pulses [4], by manipulating frequency chirped FEL output, is the inspiration for the VISA II experiment. The frequency chirped radiation produced from an undulator is monochromatized and is used to seed a second undulator. The ultimate goal of the VISA II project is to operate the high gain SASE FEL with a large electron beam chirp.

The current mode of operations expands on this goal by utilizing the optimized capabilities of the facilities employed. Under these conditions, the VISA FEL operates in the seeded mode, using a 1 micron YAG laser as the seed. The experimental mission of the seeded FEL is to investigate high gain radiation properties with studies focusing on the far-field angular distribution and coherence of the radiation.

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THE VISA EXPERIMENTAL PROGRAM

VISA I

The VISA project is hosted by the Accelerator Test Facility (ATF) of Brookhaven National Laboratory (BNL). The experimental layout is described in detail in Ref. [5] (Fig. 1 shows a schematic). The VISA I project successfully demonstrated saturation of a SASE FEL within a 4 meter undulator at 840 nm. The high peak current, a result of nonlinear electron bunch compressoin along the dispersive line of the transport, was ultimately responsible for the observed high gain lasing. A start-to-end simulation suite of codes, PARMELA [6], ELEGANT [7], and GENESIS 1.3 [8], modeled the beam dynamics in the gun, transport and undulator, respectively. SASE FEL properties, such as pulse energy, profile, and angular distribution were computed with GENESIS. The complete characterization of the SASE FEL properties included gain lengths, spectra, energies, angular distributions and observation of nonlinear harmonics, and was successfully benchmarked against the simulation suite [9].

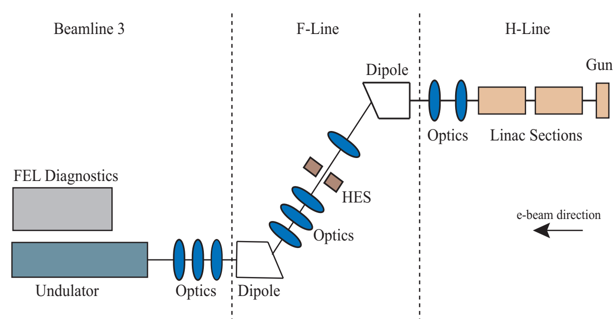

Figure 1: Layout of the ATF beam transport (not to scale). The VISA undulator is located along Beamline 3 after the 20 degree dogleg.

VISA IB

Subsequent measurements at VISA, informally referred to as VISA IB, also took place at the ATF in 2003. An anomolously large bandwidth, up to 15% full width, was observed at high gain (Fig. 2), accompanied by atypical far-field angular radiation patterns.

The electron beam (330 pC, 1.7% energy spread) was subjected to the same nonlinear bunch compression mechanism as in VISA I, except with a much higher degree of compression and thus a higher peak current. The SASE

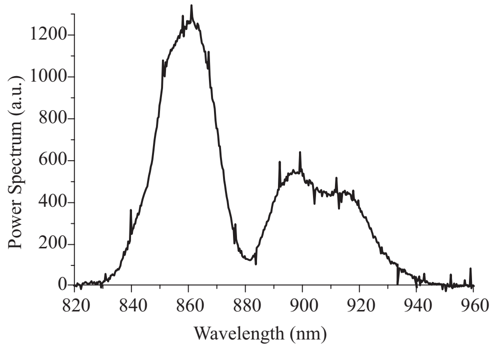

Figure 2: Sample shot of observed SASE FEL spectrum displays an anomalously large bandwidth.

FEL output (2 μJ average energy), was extremely stable and insensitive to RF and laser timing jitter. The spectrum is notable for a characteristic double peak structure, accompanied by a mean bandwidth value of 12% full width (greater than 100 nm), as seen in Fig. 2.

GENESIS simulations reproduced the features of the radiation (large bandwidth and double spiked structure). After transport, the electron beam displayed a highly nonlinear longitudinal phase space. The secondary spike was due to amplification of an off-axis mode. The mode was excited by the non-ideal centroid and envelope motion of the beam through the undulator's quadrupole focusing lattice. The lasing core of the beam was mismatched to the undulator focusing lattice yielding significant excursions in beam size in both transverse planes. Additional transverse motion causes a red-shift in the radiated wavelength and amplification of the off-axis modes [10].

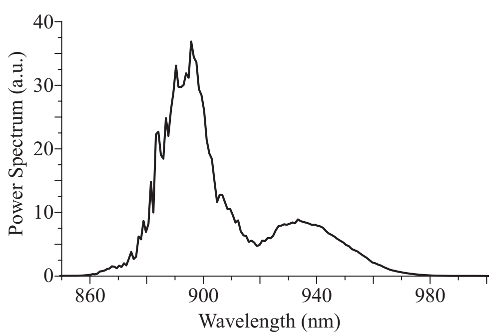

Figure 3: SASE FEL power spectrum obtained from GENESIS. The large bandwidth and the double hump feature observed in measurements were reproduced with simulations.

Double Differential Spectrometer The double differential spectrometer is diagnostic developed to unfold the relationships between frequency and angle of the FEL radiation. A slice of the FEL ouput is passed through graduated slits, then focused onto a set gratings (1200 in^{-1}). The resulting image displays the photon beam with frequency along one axis, and transverse angle along the other axis, and is a direct study of the intensity of the beam presented in the familiar form, $\frac{d^2 I}{d\omega d\theta_y}$.

Raw data from a preliminary prototype of this diagnostic is presented in Fig. 4. The overall parabolic structure of the beam, from red shifting, in (θ, ω) space is evident, with even richer multi-mode patterns also present. Upgraded GENESIS post-processing tools were used to further understand this data and indeed displayed the parabolic structures along with the presence of higher order modes.

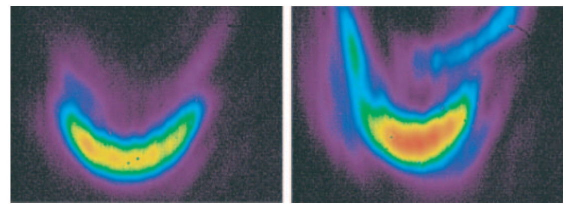

Figure 4: The parabolic structure (left) is evident in the images from the double differential spectrometer, where the angle is represented along the horizontal axis and the frequency along the vertical. Richer structures have also been observed (right).

Far-field Angular Distribution This far-field angular distribution measurement was made by propagating the output radiation, without optical focusing, to a screen located 3 m (10 Z_R) downstream. Observed patterns were hollow in nature, like previous VISA results, except more pronounced in angle (with spiral shaped patterns accompanying the hollow modes). The helicity of this patterns will be studied via a mode converter.

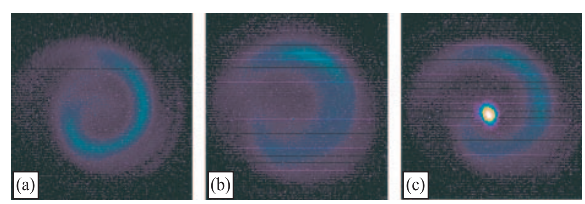

Figure 5: Far-field angular distribution profiles display an atypical spirality and helicity (a,b); superimposed with a reference alignment laser (c).

Chirped Beam FEL

The goal of the VISA II experiment is to inject a linearly chirped electron beam into the undulator to produce frequency chirped SASE FEL radiation. The bunch compression mechanism facilitates high-gain lasing, however, it restricts the management of beam properties through transport. Preservation of the electron beam chirp applied at the linac will be accomplished by the manipulation of nonlinear longitudinal compression by the addition of sextupole magnets placed at high horizontal dispersion points. The sextupoles will mitigate second order effects, particularly by diminishing the T_{566} element, of the transport matrix, to a negligible value [11]. Three sextupoles have been installed and commissioned at the ATF.

Frequency Resolved Optical Gating A frequency resolved optical gating (FROG) [12] system will be used to measure the frequency chirped, short pulse radiation. This method was successfully used elsewhere, to measure both the amplitude and phase of the radiation [13].

The frequency resolution of the FROG spectrogram is a concern at the VISA experiment. The diagnostic system is constrained by the doubling crystal and can not adequately resolve the radiation expected from the VISA II FEL. The thick lens must be replaced by a thin lens to increase the resolution; a dedicated spectrometer must be added to compensate for the loss of functionality of the thin lens. The CCD camera (several megapixel) must be able to cover a large range of wavelengths to resolve the observed bandwidth.

GENESIS outputs for the chirped beam case show a clear effect for idealized beam shapes and have been analyzed for varying degrees of chirp. Indeed, the inversion algorithm is robust enough to handle other exotic shapes and patterns which have been simulated and reconstructed via the commercial FROG software (Femtosoft) for the VISA II experiment. Fig. 6 shows an example of a spectrogram obtained from GENESIS for the running conditions of the VISA II FEL. This structure shows the complex nature of the FEL pulse, which is expected to contain several spikes. This longitudinal pulse profile was retrieved when the spectrogram was analyzed with the FROG reconstruction algorithm.

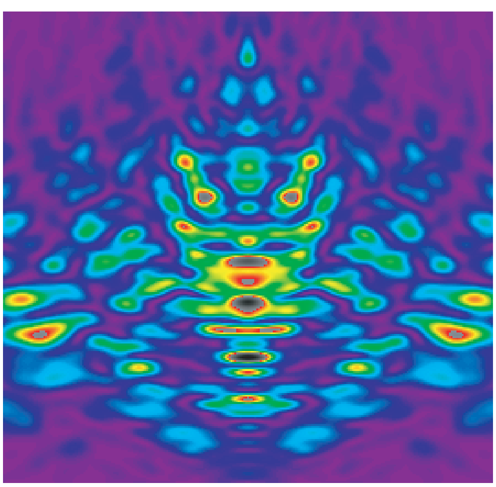

Figure 6: Spectrogram (with frequency along the vertical axis and time delay along the horizontal) of the expected radiation from the VISA II experiment. Further processing of this spectrogram has yielded the longitudinal profile of the pulse used in simulations.

Mode Converter The investigation of hollow mode and spiral shaped far-field angular radiation patterns at VISA is conducted with the introduction of a diagnostic mode converter. The mode converter is designed to transform light with planar polarization to circular polarization, and vice versa [14]. The $\pi/2$ mode converter is constructed of two cylindrical lenses, separated by a distance of $d = \sqrt{2}f$, and the resultant light will have distinct observable properties. This data will yield insight into the underpinnings of the unusual angular distribution patterns observed throughout the tenure of the VISA program. The cylindrical lenses for the mode converter have been setup and will be placed in the diagnostic station downstream of the undulator.

Polarizer The VISA project will also examine the study of coherent transition undulator radiation [15], the radiation emitted by the electron bunch as it passes through the entrance and exit of the undulator, due to the change in longitudinal velocity. Theoretically, the radiation is radially polarized, describing yet another possible explanation for the helicity of the observed far-field patterns from the planar undulator at VISA. The quantization of this effect requires minimal alteration of already existing diagnostics with the addition of grid polarizers to determine the polarization of the radiation. The effects of coherent transition radiation, from the electron beam striking a metal mirror, will have to be addressed (by the placement of a kicker magnet) before useful data is recovered from this measurement.

SEEDED FEL MEASUREMENTS

The results of the far-field angular distribution patterns at the VISA experiment have motivated further studies of the FEL in the seeded regime. The seeding pulse (a 1 micron YAG laser) will establish transverse and longitudinal coherence of the FEL (low bandwidth, high brightness). Such a radiation source will provide a short Rayleigh length FEL beam.

Further motivation for seeded FEL studies arises from controlling and managing the high power FEL in the far-field. Increasing the emission angles will decrease the intensity in the far-field (hollow modes) which will be technically useful in delivering high power radiation with minimal damage to sensitive optical elements.

The proposed experiment involves the VISA undulator with the ATF YAG laser as a seed. The YAG laser (1064 nm) serves as the drive laser for the photoelectron beam at the ATF and some its energy is transported to the experimental hall for deposition into the VISA undulator. A longitudinal delay line is currently being used to ensure adequate timing overlap with the electron beam and seed laser. The electron beam energy for the seeded FEL operations is lowered to 61 MeV to account for the higher wavelength operations

The experiments that will be carried out revolve around the detuning parameter of the FEL. Start-to-end simulations have been conducted for ideal and virtual particle sets. The results of the far-field angular distribution patters are presented in Fig. 7. It is apparent that detuning the electron beam indeed changes the angles and produces hollow modes in the far-field. The power gain curves derived from GENESIS simulations (Fig. 8) have also been studied.

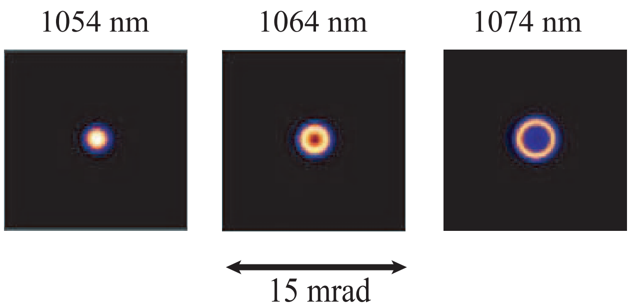

Figure 7: GENESIS simulation of the far-field angular distribution patterns of the seeded FEL for different values of detuning (1064 nm is the nominal wavelength).

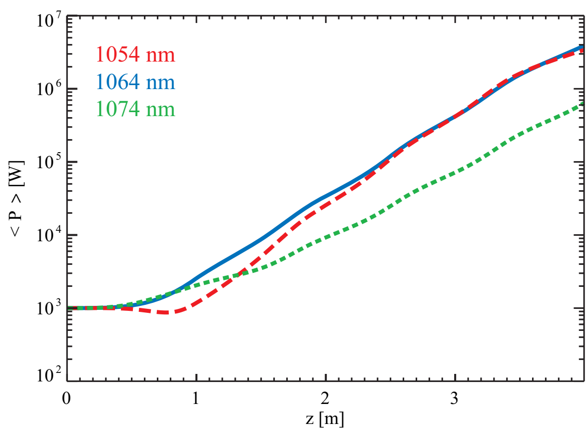

Figure 8: Power gain curves (GENESIS simulations) for varying detuning parameters.

Transverse Coherence

Transverse, or spatial coherence is an important figure of merit of any FEL. The transverse coherence for the seeded FEL will be verified with an arrangement of slits, by performing variations on the classical Young double-slit experiment. The FEL radiation diffracts at the slits, and the transverse coherence is calculated by measuring the ratio of the sum and difference of the maximum and minimum observed intensities [16]. Since the transverse coherence is a function of longitudinal position, it is measured at different positions downstream of the undulator exit. Several variations of slits have been fabricated for the transverse coherence study, including double-slits of various widths and spacings, crossed-slits, circular apertures of differing diameter, and a pepper-pot pattern of circular apertures. The use of these slits will be expanded after the seeded FEL experiment to also encompass SASE coherence measurements. The pepper-pot pattern is of particular interest because the emitted radiation from the uncorrected chirped-beam FEL experiments yielded intensity distributions with radial (helical) characteristics that provoke further investigation.

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