SIMULATIONS, DIAGNOSTICS AND RECENT RESULTS OF THE VISA II EXPERIMENT

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Abstract

The VISA II experiment entails the use of a chirped electron beam to drive a high gain SASE FEL. Sextupoles are implemented to correct the longitudinal aberrations affecting the high energy spread chirped beam during transport to the undulator. The output radiation is diagnosed with a modified frequency resolved optical gating (FROG) technique. The double differential energy spectrum is measured with a pair of slits and a set of gratings. In this paper, we report on start-to-end simulations, radiation diagnostics, as well as intial experimental results. Technical considerations for future experimental methods are also addressed.

INTRODUCTION

As the promise of X-ray free electron lasers (FEL) comes close to realization [1, 2], the creation and diagnosis of ultra-short pulses is of great relevance to the FEL community. Femtosecond long, Ångstrom wavelength radiation will provide the spatial resolution desired for scientific investigations at the time scales of atomic process, such as biological sampling (single molecule imaging) [3]. Such sources are designed to operate at hundred femtosecond pulse lengths with a clear demand, from the scientific community, to push to even shorter time scales.

A proposal to obtain such ultra-short pulses [4], by manipulating frequency chirped FEL output, serves as the inspiration for the VISA II experiment. In the proposal, the notion of a two-stage undulator is described. The frequency chirped radiation produced from the first undulator is monochromatized and serves as the seed for the second undulator. The aim of the VISA II project is to operate the high gain SASE (Self Amplified Spontaneous Amplification) FEL with the largest electron beam chirp allowable at the upgraded systems of the Accelerator Test Facility (ATF) located in Brookhaven National Laboratory (BNL). The production, and subsequent measurement, of strongly chirped SASE FEL radiation based on electron beam chirping is the objective of this multi-institutional collaborative effort.

EXPERIMENT DESCRIPTION

Summary of Prior Results

The VISA experiment layout is described in detail in Ref. [5]. The VISA project succesfully demonstrated saturation of a SASE FEL within a 4 meter undulator at 840 nm. An electron bunch compression mechanism, exploiting the nonlinear properties of transport along the dispersive line of the ATF, was discovered to increase the peak current from 55 A to 240 A. This compression was ultimately responsible for the observed high gain lasing. Electron beam dynamics in the gun, transport, and undulator were modeled with the simulation codes PARMELA [6], ELEGANT [7], and GENESIS 1.3 [8] respectively. SASE FEL properties, such as pulse energy, profile, and angular distribution were computed with GENESIS. The harvest of the start-end suite of codes was accurately benchmarked against experimental findings. The complete characterization of the SASE FEL properties included gain lengths, spectra, energies, angular distributions and observation of nonlinear harmonics [9].

More Results and Analysis

Follow-up measurements at VISA took place with the employ of a highly chirped electron pulse, with longitudinal compression, and subsequent FEL amplification. An anomolously large bandwidth, up to 15% full width, was observed at high gain (Fig. 1), accompanied by atypical far-field angular radiation patterns.

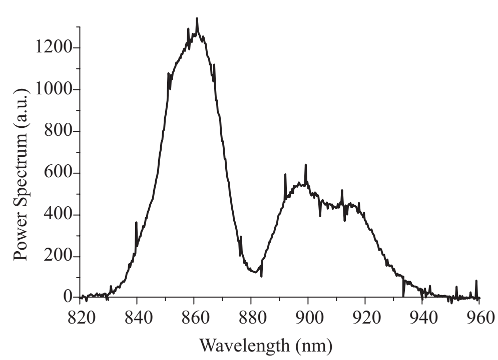

Figure 1: Sample shot of observed SASE FEL spectrum with anomalously large bandwidth.

An electron bunch, of approximately 330 pC, with 1.7% energy spread, was propogated through the undulator. Due to nonlinear compression, the peak current of the pulse reached 300 A. The compression, as well as the SASE FEL output, was extremely stable and insensitive to RF and laser timing jitter. Sextupoles were not energized during these runs, thus there was no control of electron beam chirp prior to undulator injection. The average measured SASE radiated energy was approximately 2 μJ and displayed an extraordinary wavelength distribution. The spectrum is notable for a characteristic double peak structure, accompanied by a mean bandwidth value of 12% full width (in excess of 100 nm), as seen in Fig. 1.

Start-to-end simulations were able to reproduce the unique features of the radiation and held the key for the physical understanding behind this previously unobserved FEL amplification. After transport, the electron beam displayed a highly nonlinear longitudinal phase space. Moreover, GENESIS simulations reproduced the large bandwidth and the associated double spiked structure. The secondary spike was due to the amplification of an off-axis mode. The mode was excited by the non-ideal centroid and envelope motion of the electron beam through the undulator's quadrupole focusing lattice. Mismatches of the beam's lasing core to the focusing lattice caused excursions in beam size near 30 μm in both transverse planes. Additional transverse motion causes a red-shift in the radiated wavelength and an ensuant inclination to ampify the off-axis modes [10].

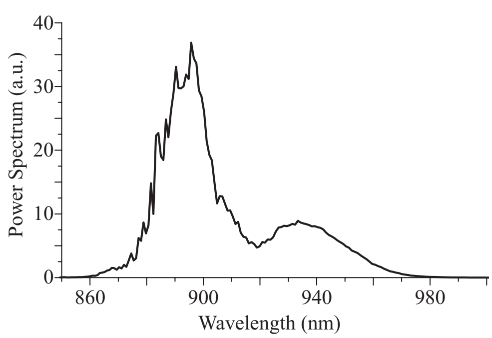

Figure 2: SASE FEL Power Spectrum obtained from GENESIS. Key facets of the spectrum, such as the large bandwidth and the double hump feature, were reproduced.

Double Differential Spectrometer

An additional diagnostic has been developed to unfold the relationship between frequency and angle of the FEL radiation. This diagnostic employs the use of an adjustible slit, two cylindrical lenses for focusing, a set of gratings, and a CCD (charge coupled device) camera. A slice of the FEL ouput is passed through the slits, then focused onto the gratings (1200 in^{-1}). The resulting raw image displays the photon beam with frequency along one axis, and transverse angle along the other axis. The double-differential spectrometer is calibrated with the spectral lines of a commercial Argon lamp. The resultant is a direct study of the intensity of the beam presented in the familiar form, $\frac{d^2 I}{d\omega d\theta_y}$, the double differential spectrum.

Some recent data of this diagnostic is shown in Fig. 3. This data was retrieved from a preliminary prototype of the double differential spectrometer that did not contain focusing lenses; the raw image on the CCD camera had adequate brightness. The overall parabolic structure of the beam, from red shifting, in (θ, ω) space is evident, with even richer multi-mode patterns also present.

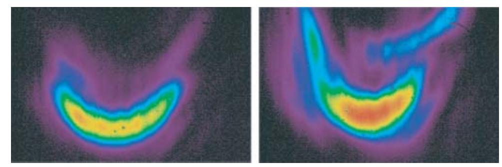

Figure 3: The overall parabolic structure (left) is clear in the images from the double differential spectrometer; here, the angle is represented along the horizontal axis and the frequency along the vertical. More exotic and richer structures have also been observed (right).

Start-to-end simulations have been carried out to examine these results further. The GENESIS post-processing unit has been upgraded to compute the double differential spectrum for the experimental parameters at VISA. Preliminary runs display the aforementioned parabolic structure and even some higher order modes are apparent, confirming the dual lasing modes observed in the previous runs (Fig. 4).

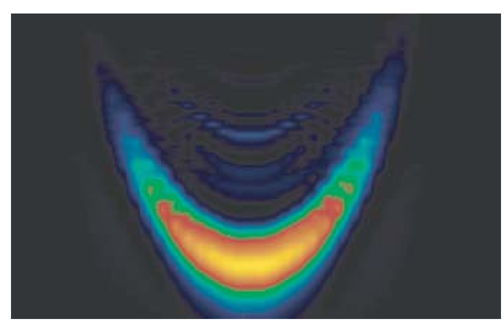

Figure 4: Output from a GENESIS simulation confirms the parabolic nature observed in VISA. Angles lie along the horizontal axis, frequencies along the vertical.

Far-field Angular Distribution

A unique ancillary component of the experiment is the observed angular distribution profile in the far-field. This measurement was made by allowing the output radiation to propogate, without focusing lenses, to a screen approximately 3 m (10 Z_R) away. The patterns observed were hollow in nature, like previous VISA results, but more pronounced in angle. Spiral shaped patterns accompanied the hollow modes. The helicity of this patterns will be studied via a mode converter, described later in this note.

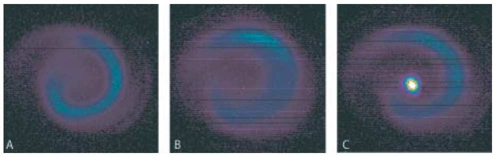

Figure 5: Far-field angular distribution profiles from VISA demonstrating the atypical spirality and helicity (A,B) and superimposed with the red diode alignment laser for reference (C).

MEASUREMENTS AT VISA II

Chirped Beam Operation

The main goal of the VISA II experiment is to inject a linearly chirped electron beam into the undulator to produce frequency chirped SASE FEL radiation. Although the bunch compression mechanism facilitates high-gain lasing, 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 lonigtudinal compression with the use of sextupole magnets placed at points of high horizontal dispersion. The sextupoles will mitigate second order effects, particularly by diminshing the T_{566} element of the transport matrix, to a negligible value [11]. Currently there are three sextupoles installed along the dispersive line at the ATF to serve this purpose.

Measuring the T_{566} term directly presents a challenge as compression is required for high gain lasing in VISA II. The actual value that can be quantified is the T_{166} element. This value is measured by comparing the effect of incremental changes in the magnetic fields of all magneto-optic elements along the beamline to the change in position of the electron beam centroid at a point of non-zero dispersion. The correlation between the T_{166} and T_{566} terms is used to quantify the effects of the sextupoles.

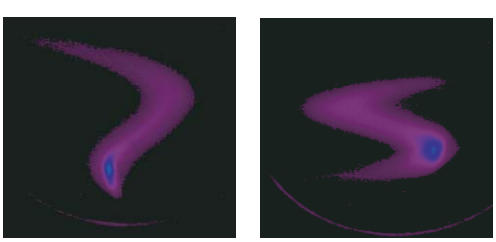

Figure 6: Two transverse profiles of the electron beam in the dispersive section of the transport with sextupole magnets energized. To create such extreme beam profiles the settings of the sextupoles were exaggerated from the design values computed using simulations.

Modified Frequency Resolved Optical Gating

Once electron beam chirp is preserved for injection into the undulator, and subsequent SASE FEL lasing at high gain is achieved, the resulting radiation will be frequency chirped. Measuring the properties of this radiation requires state-of-the-art diagnostics. A standard method of measuring the structure of short pulse, frequency chirped light is frequency resolved optical gating (FROG) [12]. This method has been used successfully, previously at the Low-Energy Undulator Test Line (LEUTL) at the Advanced Photon Source, to measure both the amplitude and phase of FEL radiation [13]. For the expected parameters of the VISA II SASE FEL, a modified version of FROG is the most viable candidate.

One aspect of FROG, or GRENOUILLE [12] (a close relative of the FROG family of detectors designed to simplifiy alignment issues by employing fewer, multi-purpose optical elements), that is a concern for the proposed measurement is the frequency resolution of the spectrogram. For the radiated profile presented in previous results and properties studied in GENESIS simulations, namely the anomalously large spectral width and the hollow mode angular distribution pattern, the FROG technique requires modification to efficiently serve as a reliable diagnostic. The proposed modifications revolve around the GRENOUILLE detector. The GRENOUILLE employs the use of a thick crystal which has the dual purpose of recombining the incoming and the delayed signal and dispersing of the split signal. However, for our purposes, this system is too constrained by the doubling crystal to properly 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 that comes with the replaced lens. In addition, a larger (several megapixel) CCD must replace the camera that is used in the commercial version of this diagnostic. The camera must be able to cover a large range of wavelenghts to resolve the wide bandwidths observed previously.

Simulations concerning the feasibility of this measurement have been conducted. GENESIS outputs for the chirped beam case show a clear effect for idealized beam shapes. These results 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. Figure 7 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. Indeed, this longitudinal pulse profile was retrieved when the spectrogram was analyzed with the FROG reconstruction algorithm.

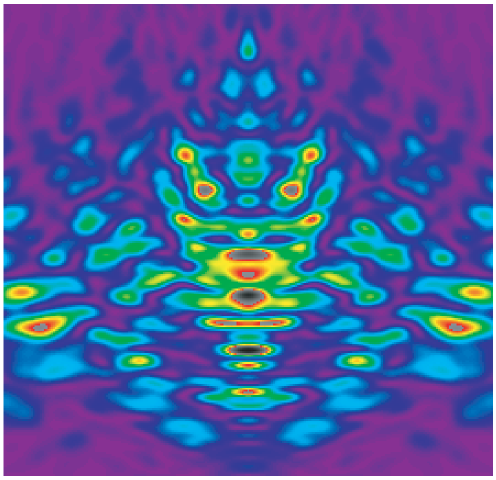

Figure 7: Spectrogram (with frequency along the vertical axis and time delay along the horizontal) of the expected radiation from the VISA II experiment. Further processing of this spectrogram has yielded the longitudinal profile of the pulse used in simulations.

Mode Converter and Polarizer

The investigation of hollow mode and spiral shaped far-field angular radiation patterns at VISA continues via a diagnostic mode converter. The mode converter is designed to transform light with planar polarization to circular polarization, and vice versa; the transfer of orbital angular momentum is the observable [14]. The $\pi/2$ mode converter is constructed of two cyldrical lenses, separated by a distance of $d = \sqrt{2}f$, and the resultant light will have distinct observable properties. This data will hopefully yield insight into the underpinnings of the unusual angular distribution patterns observed at VISA.

The VISA project will also examine the study of Coherent Transistion Undulator Radiation (CTUR) [15], the radiation emitted by the electron bunch as it passes through the entrance and exit of the undulator, due to its change in longitudinal velocity. In fact, this radiation is thought to be 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.

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