VISA IB: ULTRA-HIGH BANDWIDTH, HIGH GAIN SASE FEL

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Abstract

We report the results of a high energy spread SASE FEL experiment, the intermediary experiment linking the VISA I and VISA II projects. A highly chirped beam (1.7 %) was transported, without corrections of longitudinal aberrations in the ATF dogleg, and injected into the VISA undulator. The ouput radiation displayed an uncharacteristicly large bandwidth (12 %) with extremely stable lasing and measured energy of about 2 μJ. Start-to-end simulations reproduced key features of the experiment and provided an insight into the michanisms giving rise to such a high bandwidth. These analyses have important implications on the VISA II experiment.

INTRODUCTION

The advent of high-brightness, ultra-short duration X-ray radiation from self-amplified spontaneous emission free-election lasers (SASE FEL) promises to be an invaluable tool for the scientific community. There are current proposals [1, 2] to construct single-pass high gain free electron lasers that will generate angstrom wavelength radiation with femtosecond pulse lengths [3].

A possible scheme to obtain yet shorter pulses by creating and manipulating frequency chirped FEL output has been proposed [4]. In the first stage of the scheme, an energy chirped electron beam injected into the undulator would produce a frequency chirped output. This light is then monochromatized, and thus sliced, and injected into a second stage undulator, where only a short section of the electron beam is seeded by the shortened radiation pulse well above the shot-noise power level. This, and similar schemes, give motivation for VISA (Visible to Infrared SASE Amplifier) and VISA II, an extension of the VISA program. The ultimate goal of the VISA II experiment is to run a SASE FEL with the highest electron beam energy-time chirp allowable by the modified beam transport at the Accelerator Test Facility (ATF) in Brookhaven National Laboratory (BNL), enabling the production and measurement of strongly chirped SASE FEL radiation [5].

Summary of VISA I Results

A brief review of some results from the VISA (Visible-to-Infrared SASE Amplification) FEL experiment will place the recent measurements in context. In 2001, VISA successfully demonstrated saturation of a SASE FEL within a 4 meter undulator at 840 nm. [6]. An anomalous electron bunch compression mechanism created beam conditions allowing high-gain lasing. The large negative second order longitudinal time dispersion, T_{566} [7], yielded a longitudinal compression and an increase in peak current from 55 A to 240 A.

The nonlinear properties along the dispersive segment of the ATF transport line were studied using a start-to-end suite of simulation codes. The electron beam dynamics in the gun and linac sections were modeled with PARMELA [8], the electron beam transport matrix calculations were analyzed with ELEGANT[9], and the FEL studies were computed with GENESIS 1.3[10]. The reproduction of pulse energy, profile and angular distribution of the FEL radiation, as well as the measurements of the bunch compression process and other aspects of the beam phase space, were significant achievements of the start-to-end simulations. The benchmarking of the code suite against the experimental results at the ATF of the beam production and transport allowed reliance on the same modeling process to analyze microscopic aspects of the most recent measurements.

Motivation for VISA II

Although the original bunch compression mechanism facilitated high-gain lasing, it restricted the management and manipulation of the electron beam and its properties prior to injection. The ultimate goal of the VISA II program is to inject a linearly chirped beam into the undulator to produce frequency chirped output radiation. In the experiment, preservation of the electron beam chirp will be accomplished by elimination of the nonlinear longitudinal compression through the use of sextupole mangets at high horizontal dispersion points in the dogleg transport [11]. The sextupoles, installed along the dispersive line, mitigate second order effects, in particular diminishing T_{566} to a negligible value. The initial, nearly linear, electron beam chirp applied at the linac, can then be preserved, and even enhanced by a modest amount of linear compression during transport, before injection into the undulator.

EXPERIMENT DESCRIPTION

Before the needed improvements in the linac to undulator transport were made, a set of measurements, performed without sextupole correction, took place at the existing facilities of the ATF. These measurements explored the use of a highly chirped pulse, with nonlinear longitudinal compression, and subsequent FEL amplification, as a stepping stone to VISA II. This transitional experiment demonstrated a previously unobserved large bandwidth of the FEL radiation of $\sim$ 12%, at high gain, accompanied by an anomalously wide far-field angular radiation pattern. We present these results below, as well as start-to-end simulations that reproduce some of the more striking aspects of the radiation measurements.

The VISA experimental schematic used in the present experiments is discussed in detail in Ref. [6]. The post-injector 20^{o} dogleg transport line that delivers beam to the VISA undulator contains an adjustable collimator located near the begining of the dispersive line, the high energy slit (HES). The measurements of beam size and transmitted fraction at the HES are used to determine the beam energy and energy spread at this point, which are important benchmarks for the simulations. The electron beam (500 pC) at the HES is observed to have a 2.8 % energy spread due to a correlation between energy and longitudinal position (chirp) after the linac exit. Approximately 330 pC propagates through the fully open HES, collimating the beam to a 1.7 % energy spread. Electron beam charge is measured by a Faraday cups located after the gun exit and after the undulator exit. The compression process in the dispersive section is monitored by a Golay cell, installed in front of the undulator, which measures the coherent transition radiation (CTR) intensity emitted from an insertable metallic foil. The CTR energy is peaked when the beam central momentum is chosen to optimize the compression in the dogleg.

The measured FEL radiation displayed an unusual spectrum. The spectrum contained a characteristic double peak structure with a full width bandwidth as high as 12 percent (Figure 1). An average SASE radiation energy of approximately 2 μJ was recorded; which is within an order of magnitude of the saturation energy of the initial VISA experiment. The dual spiked spectral structure indicates there are 2 distinct lasing modes. The lasing FEL output radiation was also unusually stable in energy, a result of the collimation at the HES, ensuring that the same energy portion of the beam was being transported on each shot. The FEL output was far less sensitive to rf fluctuations and laser and beam centroid jitter, as compared to earlier VISA runs.

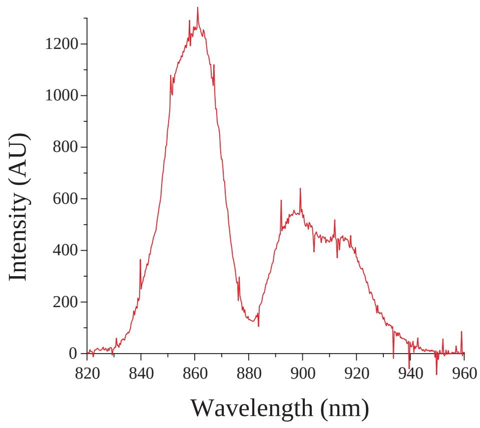

Figure 1: Sample shot of the ultra-wide bandwidth observed during the VISA IB runs (Ocean Optics USB2000 Spectrometer).

Simulations and Analysis

The PARMELA-ELEGANT components of the start-to-end simulations reproduced the compression process as observed by the combined slit and Golay cell measurements. The simulations show that the bunch peak current after nonlinear compression can reach up to 300 A. This peak is very short in duration ($\sim$200 fs FWHM), containing only 25-30 pC of charge. Unlike the original VISA conditions, however, in the present experiment the compression was insensitive to injection phase fluctuations arising from either RF or photocathode laser timing errors. This is due to the

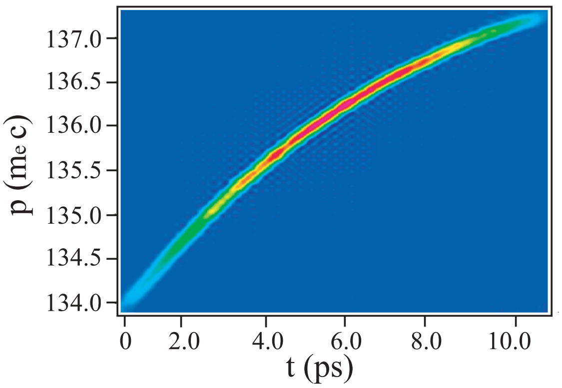

Figure 2: Longitudinal phase space of a linearly chirped electron beam at linac exit.

large energy spread in the initially chirped beam (Figure

2), which guarantees that a component of the beam will be compressed, and thus have proper conditions for lasing, because the laser injection and rf phase errors are much smaller than the initial bunch length of 10 ps. The electron beam, prior to injection into the undulator, displays a highly nonlinear longitudinal phase space as a result of the second order dispersion effects of the transport line (Figure 3). Because of these effects, the beam distribution at the undulator entrance also has a highly distorted distribution in $x - t$ configuration space. As seen in Fig.4, the highly compressed lasing core of the beam lies off axis.

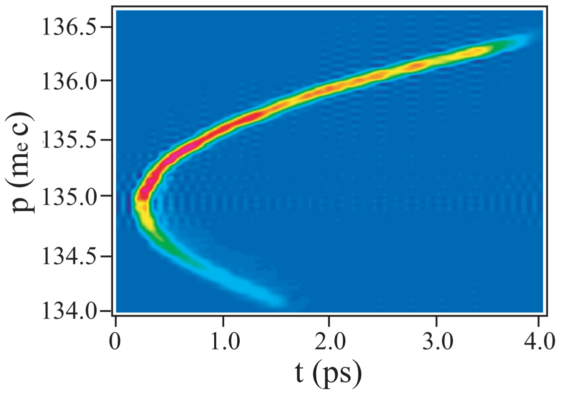

Figure 3: Longitudinal phase space of electron beam at undulator injection (Elegant Simulation).

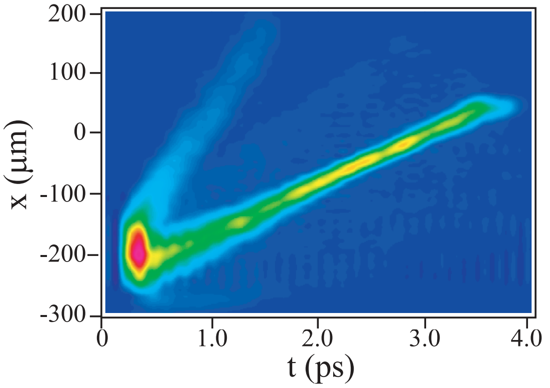

Figure 4: The time-position correlation of the electron beam prior to undulator injection (Elegant simulation).

The GENESIS module of the start-to-end simulation suite provided some insight into the basis of the observed FEL spectrum. In terms of general system performance, simulations showed that the FEL had reached near saturation, with gain comparable to that achieved in prior VISA runs. Simulations also reproduced some key facets of the observed spectrum, namely the large bandwidth and double spiked structure (Figure 5). Simulations also showed that the slice-emittance degradation, due to the large energy spread, compression, and residual dispersion, was not a crucial concern. The overall beam quality, in particular the high current, was sufficient for stable, sustained, high-gain lasing, close to saturation. The shorter wavelength spike in the spectrum of Fig. 1 is similar to that observed in VISA. The second, long wavelength spike is attributed to the amplification of a parasitic mode that is excited when the beam is off-axis in the undulator. Measurements indicate that the beam is slightly mismatched in centroid and envelope to the undulator quadrupole focusing lattice, which was incorporated into the simulations. This mismatch caused the lasing core of the beam to undergo betatron oscillations with as high as 300 μm secular amplitude. As seen in Figure 6, there is a strong correlation between the maxima in this core offset and the maxima of the observed spectral bandwidth. The relationship between the off-axis betatron motion and the spectrum has a number of components to it. The additional transverse undulation of the lasing electrons' trajectories due to the periodic application of alternating gradient quadrupoles (strong focusing) causes the FEL resonant condition to change when the beam core is off-axis. One may view this scenario as a bi-periodic undulator, with the long wavelength component of the trajectory due to the off-axis alternating, with no drift in between, quadrupole forces, which have a square-wave "FD" form, yielding an effective undulator parameter of $K_q = eB'\Delta x L_q/2\pi m_e c$, where Δx is the average offset, B' is the quadrupole gradient, and L_q is the period

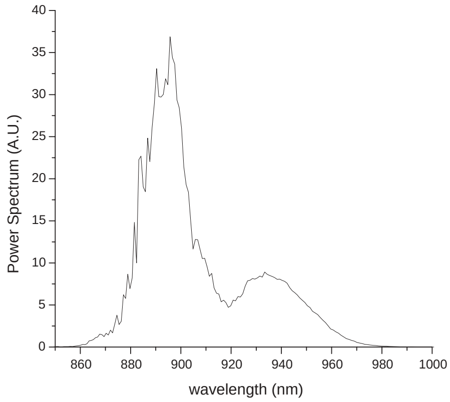

Figure 5: Wide FEL bandwidth (10%) and "double hump" structure are numerically reproduced (GENESIS Simulation).

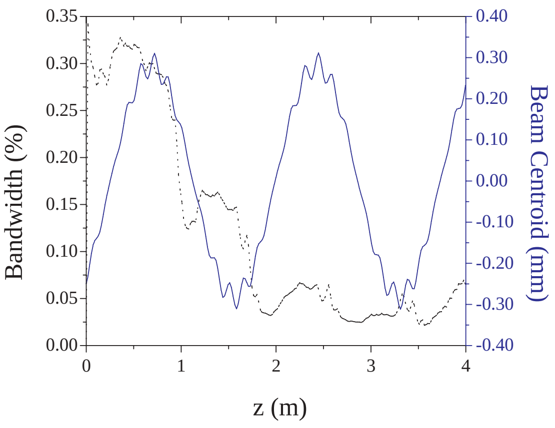

Figure 6: Simulations show a strong correlation between the beam centroid position and the FEL bandwidth (GENESIS Simulation).

of the quadrupole lattice. For the VISA parameters with $\Delta x = 300\mu$m, we have $K_q \simeq 0.23$. When one adds the effects of this additional oscillation in the central trajectory on the FEL resonance condition, the relation

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

is obtained, with the on-axis undulator parameter $K = 1.26$. The maximum redshifting of the resonant wavelength due to this effect in our experiment is predicted to be about 1.5 %. Another significant redshifting of the radiation is due to radiation into off-axis angles. As in VISA, the far-field angular spectrum is hollow, and has a maximum at an even larger angle of 2.1 mrad. For our present energies ($\gamma = 137$), the redshifting due to this effect is 4.1 %. This obviously important effect is also related to the off-axis motion, as when the beam moves off-axis, it more readily couples to higher order transverse modes having off-axis peaks. The gain in these higher order modes utilizes the bunching attained at by the gain at shorter wavelength in the near-axis lasing, and is therefore considered parasitic.

These two off-axis related effects produce nearly all of the observed redshifting in the long wavelength peak, which is about 5 % increased at its peak from the on-axis peak. One may have expected that the redshifting arises from the energy spread in the system. This is not so because the energy spread within the lasing core is quite small. In fact, when the energy spread of the beam is set to a near-zero value in the GENESIS simulations, leaving all other aspects of the phase space unchanged, the SASE output spectrum obtained is similar to that shown in Fig. 5.

CONCLUSION

The effects of bandwidth growth from off-axis radiation would be deleterious in the VISA II experiment, where the goal is to have the spread in measured frequencies be predominately due to time-correlated energy spread (chirp). In the case of VISA II, the total energy spread is expected to be 2 %, and thus the bandwidth due to this spread does not exceed 4 %. Thus the correction of second order distortions in the beam's transverse and longitudinal dynamics, through use of sextupoles, is mandatory, in order to avoid the effects observed in the present experiments.

It may also be of interest to purposefully use the mechanisms for exciting very large bandwidth radiation in a SASE FEL, for applications where spectral width is advantageous. This may be introduced at the end of a VISA-style undulator by simply introducing a mis-steering of the beam over the last few gain lengths. The coupling to large-angle radiation is limited, however, by the coherence angle of the system. In our case the lasing core of the beam was very narrow in the horizontal dimension, $\sigma_x \simeq 20\mu m$, as seen in Fig. 4, and the beam may radiate coherenty up to very large angles, $\theta \simeq 2\pi\sigma_x\lambda_r$. It is therefore easier to employ this mechanism for obtaining bandwidth increase with longer wavelength FELs.

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