Observation of Anomalously Large Spectral Bandwidth in a High Gain Self-amplified Spontaneous Emission Free-Electron Laser


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Observation of ultra-wide bandwidth, up to a full width of 15%, high-gain operation of a self-amplified spontaneous emission free-electron laser (SASE FEL) is reported. This type of lasing is obtained with a strongly chirped beam ($\delta E/E \sim 1.7\%$) emitted from the accelerator. Because of non-linear pulse compression during beam transport, a short, high current pulse with strong mismatch errors is injected into the undulator, bringing about high FEL gain. Start-end simulations reproduce key features of the measured results, and provide insight into mechanisms, such as angular spread in both emitted photon and electron trajectory distributions, which yield novel features in the radiation spectrum.

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High-brightness, ultra-short duration X-ray radiation from the self-amplified spontaneous emission free-electron laser (SASE FEL) promises to be an invaluable tool for broad sections of the scientific community. Coherent light sources which extend into the X-ray regime will allow investigations at the time and length scales of atomic processes. For example, such a source will enable biological sampling (single molecule diffraction) [1] and atomic structural dynamics studies. Current proposals [2, 3] to construct single-pass high gain X-ray SASE FELs will generate Angstrom wavelength radiation, providing the spatial resolution desired for scientific applications. However, these source are designed to operate at hundreds of femtosecond pulse lengths [4], with a clear demand to push to shorter time scales, down to the few fs regime.

A scheme to obtain such ultra-short pulses by creating and manipulating frequency chirped FEL output has been proposed [5]. In the first stage of the scenario, an energy-chirped electron beam injected into the undulator produces a frequency-chirped output. This light is then monochromatized and thus shortened to the desired pulse length. It is then injected into a second stage, where only a short section of the electron beam overlaps with the seeding pulse, amplifying the pulse to saturation. In order to test aspects of this scheme, the VISA II experiment has been designed to operate with the highest chirp allowable at the Brookhaven National Laboratory Accelerator Test Facility (BNL ATF). In this experiment, the aim is to produce and measure strongly chirped SASE FEL radiation based on electron beam chirping.

To understand the present measurements, we first review some results of the VISA (Visible to Infrared SASE Amplification) FEL experiment. In 2001, VISA successfully demonstrated a high gain SASE FEL, and saturation within the 4-m undulator at 840 nm [6]. An atypical electron bunch compression mechanism was responsible for creating beam conditions which produced high-gain lasing. The large second order longitudinal time dispersion, $T_{566}$ [7], yielded longitudinal compression, giving 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-end simulation suite of codes that models the electron beam and its interactions from its inception at a photocathode to the FEL undulator exit. The electron beam dynamics in the gun and linac sections are modeled with PARMELA [8], the electron beam transport calculations are analyzed with ELEGANT [9], and the evolution of the beam and FEL radiation in the undulator is computed with GENESIS 1.3 [10]. The reproduction of important features of the FEL radiation, as well as the identification of the bunch compression mechanism, were significant achievements of the simulations. The benchmarking of the start-end simulations against the experimental knowledge of the beam production and transport in VISA allows reliance on the same modeling process to analyze microscopic aspects of the present measurements.

Although the original bunch compression mechanism facilitated high-gain lasing, it restricted the management and manipulation of the electron beam properties prior to injection into the undulator. The VISA II experiment seeks to preserve the electron beam chirp linearization of the longitudinal compression process, through the use of sextupole magnets at high horizontal dispersion points in the dogleg transport. This method has been shown to mitigate second order effects in energy-momentum, particularly by reducing $T_{566}$ to a negligible value [11]. The initial, nearly linear, electron beam chirp applied at the linac, can then be preserved, and even modestly enhanced (to increase the peak current) before injection into the undulator.

As a prelude to the implementation of transport lin-
earization, a set of experiments performed without sextupoles have been made on the existing VISA facilities at the ATF. These measurements employ a highly-chirped, post-linac pulse, which through nonlinear longitudinal compression, achieves conditions, which while not having a linear chirp, generate robust FEL amplification.

This transitional experiment indeed demonstrates unanticipated and previously unobserved phenomena. In particular, an extremely large relative bandwidth of the FEL radiation, up to 15% FW, at high gain is observed, as illustrated by Fig. 1. The large spectral width is accompanied by an anomalously wide far-field angular radiation pattern, similar to that observed in Ref. [6], but even more pronounced in angle. In this Letter, we present these results, as well as simulations that reproduce the most striking aspects of the radiation measurements.

![Simulated electron beam longitudinal phase space at (A) linac exit (PARMELA output, ELEGANT input), and (B) at undulator injection (ELEGANT output). Pulse compression, from 10 ps to 4 ps, and clipping at the slits is evident.](image)

**FIG. 2:** Simulated electron beam longitudinal phase space at (A) linac exit (PARMELA output, ELEGANT input), and (B) at undulator injection (ELEGANT output). Pulse compression, from 10 ps to 4 ps, and clipping at the slits is evident.

Relevant aspects of the VISA experimental set-up employed in the present measurements are discussed in detail in Ref. [6, 12]. The 70 MeV photoinjector electron source is followed by a 20° dogleg transport line which delivers beam to the undulator. The dogleg contains an adjustable collimator, termed the high energy slits (HES), at a high energy dispersion point. Measurements of electron beam size and transmitted fraction at the HES are used to determine the transmitted beam’s mean energy and energy spread. Due to the time-energy chirp imparted by the linac, the 500 pC electron beam possesses a 2.8% energy spread, as observed impinging on the HES. Of this initial charge, approximately 330 pC (1.7% energy spread) propagates through the HES to the undulator.

As in Ref. [6], the compression process in the dispersive section is monitored by measuring the coherent transition radiation (CTR) [13] intensity emitted from an insertable foil. The CTR energy is peaked when the beam’s energy-time chirp is chosen to optimize the compression in the dogleg. Measurements from the CTR pulse length monitor, along with energy and energy spread observed at the HES, allow the benchmarking of the model to experiment by simulations.

The modeling of the beam transport indicates that the peak current in the electron pulse after nonlinear compression can reach up to 300 A. GENESIS simulations show that the lasing peak contains 25-30 pC of charge and is short in duration, compared to the electron bunch length. Unlike the original VISA conditions, the compression is insensitive to injection phase fluctuations arising from either RF or photocathode laser timing jitter. This is due to the large energy spread in the initially chirped beam (Fig. 2A), which guarantees that a component of the beam is compressed, as the injection errors are much smaller than the initial bunch length of 10 ps. The electron beam after transport, but prior to undulator injection, displays a highly nonlinear longitudinal phase space as a result of the second order effects in the transport line (Fig. 2B).

The observed FEL radiation at high gain displays an extraordinary wavelength distribution. The spectrum is notable for its double peak structure, having a relative full width (FW) bandwidth mean value of 12% (relative width above noise floor). The average measured SASE radiated energy is approximately 2 µJ, which is less than an order of magnitude of the saturation energy of the initial VISA experiment. The dual-spike spectral structure indicates there are two distinct lasing modes. The FEL output is much more stable than in earlier VISA runs, due to the enhanced reproducibility of the electron beam pulse compression process.

The anomalous width of the wavelength spectrum is observed whenever high gain conditions are present. In Fig. 3 the distribution of the spectral rms width is shown for the radiation shots yielding the top ten percent of SASE energy. The peak of this distribution is at 21 nm rms width, which corresponds to 12% FW (2.3% rms relative width). Shots up to 33 nm rms width (15% FW, 3.6% rms relative width) are observed. For comparison, the relative width observed previously at VISA was 2.4%
The simulations with GENESIS provide insight into the underpinnings of the unusual FEL amplification. First and foremost, the FEL reaches the onset of saturation, consistent with the experimental comparison to previous VISA data. This lasing condition shows that the high current obtained through compression ensures high gain SASE FEL operation and outweighs any possible degradation of the slice emittance due to the large energy spread and residual dispersion.

While the electron beam as a whole is aligned to the undulator axis, the lasing core’s centroid is misaligned, undergoing ~300 \( \mu \text{m} \) oscillations. Further, the rms envelope of the lasing core is strongly mismatched to the focusing lattice, resulting in variations between 30 and 90 \( \mu \text{m} \) in \( x \) and 40 and 70 \( \mu \text{m} \) in \( y \). As seen in Fig. 5, there is a notable correlation between the oscillations in beam radius and the periodic growth in the spectral bandwidth. To aid in identifying the roles of various effects in producing the observed spectra, we refer to the FEL resonance condition,

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

Here \( \lambda_r \) is the radiation wavelength, \( \lambda_u \) is the undulator period, \( \gamma = E/m_e c^2 \) is the normalized energy of the electron beam, \( K \) is the normalized undulator field parameter, \( K_q \) accounts for effects on the resonance due to quadrupole focusing, and \( \theta \) is the observation angle of the radiation with respect to the electron beam trajectory. Energy spread has a negligible impact on the spectral bandwidth. Even when GENESIS is run with all particles set to near equal energy, there is no notable change in the simulated FEL spectrum.

The red-shifting of the radiation arises mainly from the last two terms in Eq. 1. The first of these terms indicates the degradation of the longitudinal velocity due to transverse motion, which has two sources in this experiment. The first component of this term is quantified by the undulator parameter; \( K = 2\pi e B_u/m_e \lambda_u c = 1.26 \), as the peak magnetic field \( B_u = 0.72 \text{T} \) for the VISA undulator. Because of the large excursions in the undulator focusing lattice, additional transverse motion causes a red-shift in the radiated wavelength. The bend in the electron trajectory due to the quadrupole fields, which have a square-wave form, yields an effective quadrupole focusing parameter of \( K_q \approx e B' \Delta x L_q / \sqrt{2}\pi m_e c \), where \( B' \) is the quadrupole gradient, \( \Delta x \) is the amplitude of oscillation, and \( L_q \) is the focusing period. For VISA parameters, \( K_q \approx 0.16 \), corresponding to a maximum trajectory angle of 1.2 mrad. The maximum predicted fractional red-shifting of the resonant wavelength due to this effect is a notable 1.5%, corresponding to an rms spectral spread of 0.38%, when averaged over a betatron period.
Large amplitude betatron motion and its associated horizontal angles give not only this novel, direct source of radiation red-shift, but also allow greater coupling to off-axis (higher spatial order) emission modes. In turn, this off-axis emission provides the dominant source of red-shifting in the radiation spectrum. As in previous VISA results [6], the far-field angular spectrum is typically hollow, but has maximum intensity at much larger angle, in excess of 2 mrad. The red-shifting associated with this maximum-intensity angle is ~4.2%, corresponding to the relative shift of the long wavelength peak compared to the short wavelength (on-axis) peak (Fig. 1). The relative shift in wavelength for a given off-axis observation angle deduced from Eq. 1 is \[ \Delta \lambda / \lambda_r \simeq (\gamma^2 \theta^2) / \left(1 + \frac{K^2}{2} \right). \] Given the simulation distribution data, the rms wavelength spread is calculated to be 2.0%. Accounting for all sources of spectral spread, we obtain a total rms spread of 2.2%, in good agreement with observations.

The production of the anomalous aspects of the measured bandwidth through off-axis emission is correlated to oscillations in rms beam size. A bi-Gaussian transverse distribution of electron radiators with rms widths \( \sigma_{x,c} \) and \( \sigma_{y,c} \) may emit coherently into angles as large as

\[
\theta_c = \left( \frac{\lambda_r}{4\pi} \right) \sqrt{\frac{\sigma_{x,c}^2}{\sigma_{x,c}^2 + \sigma_{y,c}^2}}.
\]

For the beam sizes indicated in Fig. 5, this prediction, which is limited by the assumption of a bi-Gaussian distribution, yields \( \theta_c \) in the range of 1.7-2.5 mrad, consistent with the observed emission angles. On the other hand, Fig. 5 shows that when the transverse beam size is smallest the bandwidth rapidly decreases. This behavior is accompanied in simulations by a notable increase in the gain. The connection between these phenomena is that the gain of the off-axis, short wavelength mode is strongly enhanced by the increase in beam density when the transverse beam size is small, undergoing stronger “gain guiding” [14]. However, the gain of the red-shifted mode is not as strongly enhanced, due to its wider angular emission, and the radiation bandwidth is diminished. As the FEL enters the onset of saturation, and gain guiding is no longer effective, the contrast ratio of on-axis radiation to that of higher order modes is reduced. The FEL enters a final, pronounced period of bandwidth growth, yielding the observed state of large spectral spread.

Further work is ongoing to obtain a more complete understanding of the physics of large-angle coherent emission in an FEL. Initial follow-on experiments have yielded even richer off-axis mode structures, including not only hollow ring mode profiles, but spiral shapes as well. In order to explore the angular emission effects in a high gain FEL, a radiation diagnostic is being developed to image the far-field intensity along a slit. The wavelength spectrum is dispersed in the direction normal to the slit by gratings to produce a double-differential energy spectrum, \( d^2I / d\omega d\theta \); this allows direct comparison to the form of common approaches to analysis of radiative processes [15]. Initial data show the existence of several modes, and verify the overall parabolic shape of the radiation intensity in \((\theta, \omega)-space\).

The results presented here have general implications for the possible observable emission spectra in FELs. Indeed, ultra-high bandwidth emission while not desirable from the viewpoint of absolute brightness, or for VISA II, may be beneficial for selected applications. In particular, for material absorption studies, this operating regime limits the sensitivity of a narrow absorption-line experiment to the inherent fluctuations of the FEL central frequency; alternatively, one may scan a range of absorption wavelengths with a single pulse. The high bandwidth also allows for more flexibility in use of the radiation pulse, as it may be manipulated (via, e.g. monochromators) without changing the running parameters of the linac. This option would be attractive for a multiple-user facility.

Generation of an unusually wide angular distribution may also be desirable in an X-ray FEL [2, 3], where the natural divergence of the on-axis FEL radiation is so small, and the intensities are so large, that the generated pulse requires a very long drift [2] before it can be manipulated with X-ray optics. Purposeful coupling of the FEL emission into off-axis modes, through mechanisms uncovered in the present work, may be a useful maneuver for reducing the length and complexity of the X-ray transport line.

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