OBSERVATION OF COHERENT EDGE RADIATION Emitted BY A 100 FEMTOSECOND COMPRESSED ELECTRON BEAM

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A chicane compressor developed by UCLA for the production of ultra-short, 60 MeV electron beams at the Brookhaven National Laboratory Accelerator Test Facility has been commissioned, and initial beam physics experiments have been performed. These measurements have established the compression of electron beams to the 100 femtosecond (1 kA peak current) regime, via coherent transition radiation (CTR) based measurements. Investigations of coherent edge radiation (CER) include signatures that differentiate it from coherent synchrotron radiation (CSR), such as polarization and far-field angular distribution. Additionally, the radiation wavelength spectrum is determined from autocorrelation measurements. Radiation properties are compared to detailed start-to-end simulations derived from PARMELA and QUINDI (a Lienard-Wiechert code developed at UCLA). Plans for future experiments which further explore the observed wavelength spectra are presented.
1. Introduction

The chicane compressor developed by the UCLA Particle Beam Physics Laboratory (PBPL) was designed with numerous goals in mind. The compressor would be used to enhance the peak current of the electron beam needed to drive the existing free-electron laser (FEL) to saturation\(^1\). Moreover, the compressor was built to extend the capabilities of the Accelerator Test Facility (ATF) at Brookhaven National Laboratory (BNL).

The chicane compressor has been commissioned and fundamental beam physics experiments have been performed. In previous applications, the compressed beam was used for initial plasma wakefield acceleration experiments. In this paper, we report the basic beam physics experiments performed with the compressed beam as well as analytic studies on the consequent radiative processes. These compression experiments have focused on the creation of very short electron beam pulses, as short as 30 \(\mu\)m (or 100 femtoseconds rms), measurement of the longitudinal phase space characteristics of the bunches produced, and the subsequent initial measurement of coherent edge radiation (CER) emitted from such short beams.

Parametric studies of the bunch properties as a function of RF phase have been carried out. The ultra-short bunch longitudinal profile is measured using coherent transition radiation (CTR) interferometry, and analyzed by both time-domain fitting, and Kramers-Kronig-based reconstruction of the profile itself. The particular geometry of the vacuum vessel of the UCLA-ATF chicane, in which a radiation port allows direct viewing of the beam path as it leaves the third and enters the fourth magnet (Fig. 1), gives an ideal scenario for observing CER, in which radiation from the two adjacent edges add constructively.

The emitted CER power has been examined for its dependence on degree of compression, and its spectrum for its unique signatures in polarization, far-field distribution. The wavelength distribution, concentrated in the THz region, was examined using auto-correlation, and temporal reconstructions of the radiation pulse developed. These attributes of the radiation are benchmarked against start-to-end simulations of the beam dynamics and electromagnetic radiation with striking agreement. Based upon the comparison of experimental and simulation results, the application of CER for a non-destructive bunch length monitor are mentioned.
2. Experiment Description

2.1. Chicane Compressor

The chicane compressor was conceived of, designed and fabricated by the PBPL group at UCLA in close collaboration with the engineering staff of the ATF. The chicane compressor is installed in the high-energy beam line (H-line) of the ATF. The compressor consists of four dipole magnets oriented in a chicane layout (Fig. 1). Each magnet has a field of 2 kGauss and a gap of 2.1 cm. The design bend angle is 20 degrees.

The strong natural vertical-focusing of the magnets that would lead to excessive charge density in the chicane is compensated by the addition of initial and final horizontally focusing edge angles. The simulation tool, AMPERES, a fully 3D magnetostatic code, was used to model the chicane magnets. The field quality was rigorously bench tested and documented at UCLA. Each dipole magnet has fine trim coils that are used to correct beam trajectories that arise from remnant magnetic fields when the chicane is powered off.

A custom vacuum vessel was designed and constructed at UCLA and incorporated into the chicane design considerations. The vacuum vessel mates to pre-existing vacuum pipes at the ATF. The vessel consists of a straight through pipe used for normal (non-compressed beam) operations, and a bend pipe for compressor operations. CER and CSR measurements are made through a dedicated radiation extraction port that is incorporated into the vacuum vessel. A two-stage beam profile monitor was designed to give the availability to intercept the beam in both modes of operation.
(compression on or off). A seven meter radiation transport originating from the CER port delivers the radiation to the diagnostic station.

The chicane compressor power supplies and safety interlocks were designed by the ATF. Numerous considerations, including radiation and electrical safety, and other logistical concerns, such as installation and alignment in the high-energy line, were addressed prior to commissioning.

2.2. Diagnostics

Radiation exits the chicane compressor through a fused silica vacuum window located on the extraction port. The radiation is guided via adjustable, gold-coated mirrors through metallic pipes (50 mm diameter) to a diagnostic station located external to the radiation tunnel. The entire length of the radiation transport line is approximately 7 m. A Picarin lens is positioned one focal length (1.25 m) from the approximate radiation source (between the third and fourth dipoles) which provides a point-to-parallel transport configuration. The transport line terminates in a diagnostic station, where both a bolometer and interferometer are used to conduct measurements on the emitted radiation.

2.2.1. Silicon Bolometer

In order to observe the effects of CER, a cold bolometer is used to detect the long-wavelength photons efficiently. The bolometer is manufactured by IR Labs (Model No. HDL-5) \(^4\). It is cooled with liquid helium and has built-in filter wheel, loaded with specified filters that have cut-on wavelengths (low-pass frequencies) of 13, 27, 45, 103, and 285 \(\mu\)m. A wedged polyethylene window protects the Winston cone and detector of the bolometer.

2.2.2. Interferometer (CER Spectral Measurements)

The radiation spectrum is measured at the output of a Michelson-type interferometer as a function of bolometer voltage. The interferometer is optimized for the 15 \(\mu\)m to 1 mm wavelength range, and has a translatable mirror along one orthogonal leg with 1 \(\mu\)m spatial resolution \(^5\). The spectral measurement is described in the upcoming sections.

3. Overview of CER

Radiation exiting the chicane contains features of both synchrotron and edge radiation due to the measurement position and the magnet geome-
try. For electrons emitting under the same radiation process, the far-field intensity distribution is expressed as

\[ I(\omega) = I_0(\omega)[N_e + N_e(N_e - 1)F(\omega)] \tag{1} \]

where \( I_0(\omega) \) is the single electron intensity distribution and \( F(\omega) \) is the bunch form factor. For wavelengths longer than the bunch length (~30 \( \mu \)m), each type of radiation is coherently enhanced by a factor of \( N_e \) (~10\(^9\) for given parameters), the number of electrons in a bunch.

The edge radiation emitted from electrons entering and exiting the edges of bend magnets is expected to have greater intensity at longer wavelengths than synchrotron radiation \(^7\). The characteristics of CER also depend on the topology of the field gradient. In the zero-edge length model \(^8\), the field of the bending magnet is approximated by a step function. The resultant radiation is radially polarized, with a cylindrically symmetric spatial distribution characterized by a null on the straight section axis and maxima at \( \theta \sim 1/\gamma \), analogous to transition radiation. When the magnetic edge is considered finite, the resulting radiation is no longer cylindrically symmetric or completely radially polarized. Analytic finite edge length models result in complicated expressions, requiring numerical calculations \(^9\).
3.1. Simulations

In order to model the experiment, a start-to-end simulation suite has been developed at UCLA. The beam generation and acceleration is studied with the code PARMELA and the beam interaction through transport and compression are modeled with ELEGANT. The expected performance of the compressor, according to the simulation suite, is predicted to compress a 60 MeV, 55 A electron beam to a 1.6 kA peak. A normalized emittance growth in the bend plane from 1.5 mm-mrad to 6 mm-mrad is expected to accompany this compression.

Further, the parallel-computing code QUINDI was developed to perform the radiative studies of the compressed bunches at the ATF. The program avoids the sequential approach of a magnetic lattice, relying instead on an object-driven description of magnetic elements. Magnets with arbitrary shapes of convex polygons and user defined fringe fields are permitted. The observed radiation field is calculated on a user-defined plane based on the acceleration field of the Lienard-Wiechert potentials.

4. Performance Studies

Many compressor measurements have been performed at the ATF since 2002. The initial measurements concentrated on quadrupole-based transverse phase space tomography, which showed phase space bifurcation at 60 MeV. The transverse bifurcation was accompanied by dramatic breakup in the momentum spectrum, a direct effect of the collective fields (Fig. 4).

4.1. Bunch Length Measurement

In order to benchmark CER measurements to other measurements as well as the start-to-end model, a reliable measurement of the pulse length was conducted. The pulse length is measured with the use of a coherent transition radiation (CTR) interferometer. Performed in tandem with energy and spectral measurements, the interferograms characterize the longitudinal phase space of the compressed beam in great detail. The CTR interferometer is a simple, compact design using thin partially reflective beam splitters, which has a greater resolution than the standard polarizing scheme. A focusing parabolic mirror is used to direct the CTR emitted from a retractable foil downstream of the chicane compressor. Golay cells are used to detect the CTR signals.
Figure 3. The reconstructed longitudinal beam profiles using the Kramers-Kronig analysis of CTR interferograms with optimum compression (left) and over compression (right).

The results of the CTR interferometry suggest that the beam is compressed to a bunch length of \( \sim 30 \mu m \). The Kramers-Kronig analysis is used to reconstruct the time-domain bunch profile (Fig. 3). A characteristic one-sided distribution is seen at optimal compression. The beam displays distinct splitting in the time domain profile with over-compression.

4.2. Momentum Spectrum

Commissioning studies of the compressor included the observation of the momentum spectrum of the compressed electron beam. Initial coherent transition radiation (CTR) interferograms confirm that the electron bunch length was shortened to 30 \( \mu m \) RMS. The momentum spectrum of the ultrashort beam was observed on a diagnostic screen located just after a 20° bend dipole (spectrometer). Indeed, the beam exhibited bifurcation; longitudinal beam break up is a footprint of strong beam compression (Fig. 4).

5. Coherent Edge Radiation Measurements

5.1. Frequency Spectrum

Spectral measurements of the emitted chicane radiation were conducted at the ATF. Interferograms were obtained from scans with the Michelson-type interferometer to provide information about the spectral content. This data was then used to reconstruct the longitudinal charge distribution of the beam.
Figure 4. Electron beam images in the ATF spectrometer - the bend plane is horizontal. The un compressed beam (left) at near minimum energy spread and 9 degrees forward of RF crest, and the beam at maximum compression (right), 19 degrees forward of crest. Bifurcation is evident in the compressed beam case.

Interferometer signal amplitudes from the output of the silicon bolometer were recorded for $N$ shots per mirror position. An averaged, normalized interferogram with the corresponding measured electron beam charge is shown in Fig. 5a. Each point on the interferogram records the mean value and the error bars depict the standard deviation.

![Figure 5](image)

(a) Normalized, averaged signal amplitudes from interferometer scans of chicane radiation. (b) Apodized signal via Hamming function.

For an accurate spectral reconstruction with a discrete inverse Fourier transform (DIFT), the non-zero offset of the interferogram is removed and the signal is multiplied by an apodization function. Fig. 5b shows the results of apodization by a Hamming function $HM(x) = 0.54 + 0.46 \cos(\frac{\pi x}{a})$, where $2a = 4 \text{ mm}$ is the length of the interferometer scan centered on the maximum peak. This standard procedure removes artificial low-frequency components and corrects for the spurious tails that arise from the finite
sum in the DIFT\textsuperscript{12},
\[ \tilde{I}_k = \frac{1}{n} \text{Re} \sum_{j=1}^{n} I_j e^{2\pi i (k-1)(j-1)/n}, \quad (2) \]

where \( n \) is the number of equally spaced interferometer mirror positions recorded over a finite distance \([ct_{\text{min}}, ct_{\text{max}}]\). This yields \( n/2 \) non-repeating intensity values, \( I_k \), up to the maximum frequency, \( f_{\text{max}} = n/[2(t_{\text{max}} - t_{\text{min}})] \) where \( I_j \) is the \( j^{th} \) intensity point in the modified interferogram.

Fig. 6(a) displays the resulting spectrum of the apodized signal. The peak at \( f_{\text{peak}} \approx 0.5 \) THz coincides with the dominant frequency given by results from QUINDI simulations, which show the simulated spectral distribution is dominated by frequencies \( 0.2 \) THz \( \leq f \leq 1.5 \) THz.

5.1.1. Time-domain Profile Reconstruction

The forward far-field radiation intensity spectrum produced by the bunch is given by Eq. 1, where the longitudinal form factor \( F(\omega) \) is
\[ F(\omega) = \left| \int \tilde{\rho}(z)e^{i\omega z/c} dz \right|^2, \quad (3) \]

with \( \tilde{\rho}(z) = \rho(z)/N_e q \), the normalized longitudinal charge density. Following a minimal-phase reconstruction technique, a discretized Kramers-Kronig relation is used to extract \( \hat{\rho}(z) \textsuperscript{14} \). The minimal phase \( \psi(\omega_i) \) from \( \int_0^\infty \tilde{\rho}(z)e^{-i\omega_i z/c} dz = \xi(\omega_i)e^{i\psi(\omega_i)} \) is
\[ \psi(\omega_i) = \frac{2\omega_i}{\pi} \sum_{j \neq i}^{N_{\text{max}}} \frac{\ln[\xi(\omega_j)/\xi(\omega_i)]}{\omega_j^2 - \omega_i^2} \Delta \omega, \quad (4) \]

with \( \xi^2(\omega_i) = F(\omega_i) \) and \( \Delta \omega \) is the resolution from the spectrum. The normalized profile \( \tilde{\rho}(z) \) has the form
\[ \tilde{\rho}(z) = \frac{1}{\pi c} \sum_{i=0}^{N_{\text{max}}} \xi(\omega_i) \cos \left[ \psi(\omega_i) - \frac{\omega_i z}{c} \right] \Delta \omega. \quad (5) \]

The bunch distribution is calculated from the form factor, determined by fitting well-behaved asymptotes to the measured normalized spectrum, normalized by \( I_0(\omega) \). In principle \( N_{\text{max}} \geq n/2 \) since \( F(\omega) \) vanishes for \( \omega \to \infty \). From this expression it is clear that a reconstruction of the longitudinal profile proceeds from the structure of the form factor, which is given by fitting appropriate asymptotes to the modified spectrum such that
$F(\omega \to \infty) = 0$ and $F(\omega \to 0) = 1$. Since the high frequency asymptotic behavior of the form factor goes like an inverse power-law\(^{14}\) for high frequencies such that $F(\omega \to \infty) = 0$, and because the dominant contribution to Eqn(4) is for $\omega_i \leq 2\pi f_{\text{max}}$, the high frequency contributions to Eqn(5) for $\omega_i \gg 2\pi f_{\text{max}}$ are negligible. As a result, the upper limit $N_{\text{max}}$ can be much larger that $n/2$. In practice, this high frequency limit is set by the condition that the phase is changed only negligibly for increased values of $N_{\text{max}}$ and it’s implementation is supported by expectations from theory, simulation (Fig. 6(a) – dashed curve) and from the experimental limitation that the spectrum is attenuated for high frequencies (discussed below). Results of this reconstruction are shown in Fig. 6(b). As expected from simulation and theory for the chicane compressor, the bifurcated longitudinal bunch profile exhibits a shortened head of length $\sim 30 \ \mu m$ at FWHM. The values for current are scaled such that the integral over the entire bunch length yields to the average measured charge of $N_e q \approx 330 \ \text{pC}$. Due to experimental limitations (discussed below) and numerical fitting of the form factor, this reconstruction technique is useful as an approximation of the true bunch distribution. Nevertheless, the reconstructed profile shows general agreement with predictions from PARMELA simulations in the overall structure of the asymmetric bunch and the compressed head of $\sim 30 \ \mu m$ FWHM.

![Image](image.png)

Figure 6. (a) Spectra from apodized interferogram and from simulation. Prominent water absorption frequencies are shown as vertical dotted lines. (b) Minimal phase Kramers-Kronig bunch reconstruction for the measured spectrum.
5.1.2. *Experimental Limitations on Spectral Analysis*

The simulated and measured spectra show that the radiation is dominated by frequencies below 1.5 THz, however, several experimental factors contribute to spectral filtering which affect the measured frequency distribution and the longitudinal bunch reconstruction. The primary experimental artifact near the dominant frequency band is the selective filtering from water absorption (due to high levels of humidity encountered through the radiation transport on the dates of data acquisition). This effect is exemplified by strong absorption troughs located near $f = 0.57$ and 0.75 THz. Significant absorption frequencies are plotted in Fig. 6(a) for a 7 m travel path\(^{15}\). The spectrum is also affected by the radiation transport line, which acts as a high pass filter due to its inherent finite apertures and acceptance angles. Further, the fused silica vacuum port window maintains a transmission coefficient that slowly decreases for frequencies greater than 0.3 THz, but rapidly approaches zero for frequencies greater than 6 THz. Consequently, the observed spectrum suffers from attenuation that increases steadily with frequency up to 3 THz, where-after the window becomes largely opaque near these frequencies.

### 5.2. *Polarization*

The transverse radiation profile and polarization were measured in an effort to observe the distinctions between CER and CSR. Fig. 7 shows the measured intensity (normalized to maximum) as a function of polarizer angle. The wire grid polarizer was mounted at the end of the transport and rotated in 15° increments. The focused signal intensity was measured with the bolometer. The linearly polarized component of radiation (sinusoidal) is consistent with that expected from synchrotron radiation. The non-linearly polarized component, which introduces a vertical offset, is a clear signature of edge radiation. Analytic studies show that pure synchrotron radiation would give a ratio of approximately 7:1 between the maximum and minimum signal\(^{16}\), while the observed ratio is approximately 4:1. QUINDI results are consistent with the measured data (Fig. 7).

### 5.3. *Transverse Spatial Distribution*

The transverse far-field spatial intensity distribution of the emitted radiation was measured by scanning a small iris (3 mm diameter) in a 19 mm $\times$ 23 mm rectangular array of discrete points ($\Delta d = 3.8$ mm). The
iridescently scanned across the transport tube exit and the signal was focused into the bolometer with the parabolic mirror. Iris scans were performed for varying radiation polarizations with the aforementioned wire-grid polarizer (Fig. 8).

The results of the iris scan measurement were compared to a similar study performed with the start-to-end simulation suite. In fact, QUINDI results (Fig. 9) show striking similarities with the experimental data. The overall presence of strong intensity peaks (\(\sigma\)-polarization) due to in-bend-plane radiation is complemented by the existence of out-of-bend-plane radiation (\(\pi\)-polarization) as evidenced by multiple, lower-intensity, peaks as a function of polarization angle.
6. Conclusions

The unique geometry of the compressor, in which adjacent magnet edges constructively interfere in producing edge radiation, has further allowed exploration of a new phenomena – short wavelength coherent edge radiation. The chicane radiation measurements conducted at the ATF display striking signatures of CER. The transverse spatial distributions show patterns consistent with QUINDI simulations, notably strong intensity peaks shifting into multiple peaks for varying degrees of polarization with identifiable nulls in the distribution on-axis. The non linearly polarized component of radiation observed as on offset to the sinusoidal in the overall polarization curve is a clear indication of prominent edge radiation.

Future plans to improve the measurements include radiation transport modifications such as replacement of the fused silica chicane radiation port window with a diamond or z-cut crystalline quartz window; this will greatly improve the spectral range of the measurements. In addition, enclosing and flushing the transport line with dry nitrogen will mitigate the effects of water absorption lines in the measured spectrum.

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References