Tunable subpicosecond electron bunch train generation using a transverse-to-longitudinal phase space exchange technique

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We report on the experimental generation of a train of subpicosecond electron bunches. The bunch train generation is accomplished using a beamline capable of exchanging the coordinates between the horizontal and longitudinal degrees of freedom. An initial beam consisting of a set of horizontally-separated beamlets is converted into a train of bunches temporally separated with tunable bunch duration and separation. The experiment reported in this Letter unambiguously demonstrates the conversion process and its versatility.

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Recent applications of electron accelerators have spurred the demand for precise phase-space control schemes. In particular, electron bunches with a well-defined temporal distribution are often desired. An interesting class of temporal distribution consists of trains of bunches with subpicosecond duration and separation. Applications of such trains include the generation of super-radiant radiation1–3 and the resonant excitation of wakefields in novel beam-driven acceleration methods4–6. To date there are very few methods capable of providing this class of beams reliably.7,8 We have recently explored an alternative technique based on the use of a transverse-to-longitudinal phase space exchange method.9,10 The method consists of shaping the beam’s transverse density to produce the desired horizontal profile, the horizontal profile is then mapped onto the longitudinal profile by a beamline capable of exchanging the phase spaces between the horizontal and longitudinal momenta,11,12,13,14 where

\[
\begin{align*}
\eta & = \frac{L}{\eta} \left( \frac{z}{\eta} - \frac{\xi}{\eta} x_{0} \right), \\
\delta & = -\frac{1}{\eta} x_{0} - \frac{\xi}{\eta} x_{0}',
\end{align*}
\]

(1)

where \( L \) is the distance between the dogleg’s dipoles, and \( \eta \) and \( \xi \) are respectively the horizontal and longitudinal dispersions generated by one dogleg. Here the deflecting cavity is operated at the zero-crossing phase, i.e., the center of the bunch is not affected while the head and tail are horizontally deflected in opposite directions. The deflecting strength of the cavity \( \kappa \equiv 2 \pi |e| V_{z} / (\lambda c \langle p_{z} \rangle) \) where \( e \) is the electron charge, \( \lambda \) is the wavelength of the TM_{110} mode, and \( V_{z} \) is the integrated maximum deflecting voltage, is chosen as \( \kappa = -1/\eta \). The coupling described by Eq. (1) can be used to arbitrarily shape the current or energy profile of an electron beam14.

The experiment reported in this Letter uses the \( \sim 14 \) MeV electron bunches produced by a radiofrequency (rf) photoemission electron source and accelerated in an rf superconducting cavity at Fermilab’s A0 Photoinjector.15 Downstream of the cavity, the beamline includes a set of quadrupole and steering dipole magnets, and beam diagnostics stations before splitting into two beamlines as shown in Fig. 1.

The “straight ahead” beamline incorporates a horizontally-bending spectrometer equipped with a Cerium-doped Yttrium Aluminum Garnet (Ce:YAG) scintillating screen (labeled as XS3 in Fig. 1) to measure...
are emittance exchange. The Courant-Snyder (C-S) parameters at the XS3 location is 317 mm. The horizontal dispersion of the bunch temporal distribution provided $\sigma_z \ll \gamma \sigma_{\perp}$ where $\sigma_z$ and $\sigma_{\perp}$ are respectively the rms bunch length and transverse size at the CTR radiator location (the beam is assumed to be cylindrically symmetric at this location). In the present experiment the beam was focused to an rms spot size of $\sigma_{\perp} \approx 400 \mu m$ at X24. Imperfections due to the frequency-dependent transmissions of the THz beamline components alter the spectrum of the detected CTR and limit the resolution to $\sim 200$ fs.

The other beamline, referred to as the EEX beamline, implements the double-dogleg setup described above [16] and has been used to explore emittance exchange [17]. The doglegs consist of dipole magnets with $\pm 22.5^\circ$ bending angles and each generates horizontal and longitudinal dispersion of $\eta \simeq -33$ cm and $\xi \simeq -12$ cm, respectively [18]. The deflecting cavity is a liquid-Nitrogen-cooled five-cell copper cavity operating on the TM$_{110}$ $\pi$-mode at 3.9 GHz [19]. The section downstream of the EEX beamline includes three quadrupoles, beam diagnostics stations and a vertical spectrometer. The dispersion generated by the spectrometer at the X5 Ce:YAG screen is 944 mm. The temporal distribution of the electron bunch is diagnosed via the coherent transition radiation (CTR) transmitted through a single-crystal quartz window as the beam impinges an aluminum foil at X24. The CTR is sent through a Michelson autocorrelator [20] and the autocorrelation function is measured by a liquid helium-cooled bolometer which is used as the detector of the autocorrelator. The CTR spectrum is representative of the bunch temporal distribution provided $\sigma_\perp \ll \gamma \sigma_z$ where $\sigma_z$ and $\sigma_{\perp}$ are respectively the rms bunch length and

| Parameter             | Symbol | Value   | Units |
|-----------------------|--------|---------|-------|
| energy                | $E$    | 14.3 ± 0.1 | MeV   |
| charge                | $Q$    | 550 ± 30 | pC    |
| rms duration          | $\sigma_t$ | 4.0 ± 0.3 | ps    |
| horizontal emit.      | $\epsilon_z^0$ | 4.7 ± 0.3 | $\mu m$ |
| rms frac. energy spread | $\sigma_\delta$ | 0.06 ± 0.01 | %     |
| horizontal C-S param. | $(\alpha_z , \beta_z )$ | (1.2 ± 0.3, 14.3 ± 1.6) | cm     |

The multislit mask, nominally designed for single-shot transverse emittance measurements, consists of 48 $\mu m$-wide slits made out of a 3-mm-thick tungsten plate. The slits are separated by 1 mm. Less than 5 % of the incoming beam is transmitted through the mask. Up to 50 electron bunches repeated at 1 MHz were used to increase the signal-to-noise ratio.

![Image](image_url)
of the measurements.

The beam was first diagnosed in the straight-ahead line to ensure that horizontal modulations are clearly present and there are no energy modulations [Fig. 2 (a) and (b)]. It was then transported through the EEX beamline with the deflecting cavity turned off. The transverse modulation was still observable at X23 but no energy modulation was present measurement the incoming horizontal Courant-Snyder (C-S) parameters at the EEX beamline entrance were empirically tuned for energy and time modulation in the beam by setting the current of quadrupole magnets \( Q_1 \) and \( Q_2 \) to respectively 1.6 A and -0.6 A.

To characterize the expected temporal modulations we detect and analyze the CTR emitted as the beam impinges the X24 aluminum foil [21]. The total CTR energy detected within the detector bandwidth \( [\omega_l, \omega_u] \) and angular acceptance increases as the bunch duration \( \sigma_t \equiv \sigma_z/c \) decreases. In the limit \( \omega_l \ll \sigma_z^{-1} \ll \omega_u \), the total radiated energy is inversely proportional to the rms bunch duration [22]. The final longitudinal C-S parameters downstream of the EEX beamline can be varied by altering the initial horizontal C-S parameters using the quadrupole magnets \( Q_1 \) and \( Q_2 \). Figure 3 shows the detected CTR energy as a function of quadrupole magnet currents for the cases without (a) and with (b) intercepting the beam with the X3 multislit mask. The two plots illustrate the ability to control the final bunch length (as monitored by the CTR power detected at X24) using the EEX technique. The insertion of the multislit mask results in the appearance of a small island of coherent radiation at the lower right corner of Fig. 3 (b). The corresponding autocorrelation functions \( \Gamma(\tau) \) (where \( \tau \) is the optical path difference) recorded by the bolometer for the quadrupole magnets currents \( (I_{Q1}, I_{Q2}) = (1.6 \text{ A}, -0.6 \text{ A}) \) are shown in Fig. 4 (a) with and without inserting the multislit mask. When the multislit mask is inserted the autocorrelation function is multipeaked indicating a train of bunches is produced. For this particular case a train of \( N = 6 \) bunches with unequal peak intensity are produced resulting in an autocorrelation function with \( 2N-1 = 11 \) peaks. The measured separation between the bunches is \( \Delta z = 762 \pm 44 \mu \text{m} \). It should be noted that the two autocorrelations shown in Fig. 4 correspond to very different charges and longitudinal space charge effects influence the bunch dynamics and result in different final longitudinal C-S parameters. In addition, the low frequency limit of the CTR detection system prevents the accurate measurement of autocorrelation functions of bunches with rms length larger than \( \sim 500 \mu \text{m} \) [23].

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FIG. 3: Total normalized CTR energy detected at X24 as a function of quadrupole magnets currents \( I_{Q1} \) and \( I_{Q2} \) with X3 slits out (a) and in (b) the beamline. The bolometer signal is representative of the inverse of the bunch duration \( \sigma_t \). The white dots in (b) indicate loci where more detailed measurements were performed; see Fig. 4.

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FIG. 4: (a) Normalized autocorrelation function \( \Gamma(\tau)/\Gamma(0) \) of the CTR signal (a) recorded with (solid) and without (dashed) the X3 slits inserted as a function of the optical path difference \( \tau \). The corresponding beam transverse densities at XS4 appear in (b) and (c). The vertical axis on the bottom image is proportional to the beam’s fractional momentum spread \( \delta \). The nominal bunch charge is \( 550 \pm 30 \text{ pC} \) and reduces to \( \sim 15 \pm 3 \text{ pC} \) when the slits are inserted.

In addition, varying the settings of the quadrupole magnets provide control over the final longitudinal phase space time-energy correlation. The correlation can be measured as the ratio of the peak separation along the longitudinal coordinate and the energy \( \mathcal{C} = \langle z \delta \rangle \langle z^2 \rangle \approx \Delta \delta / \Delta t \). These measurements are presented in Fig. 5 for different quadrupole magnet settings. As shown in Fig. 5 the technique can provide a tunable bunch spacing ranging from \( \sim 350 \) to \( 760 \mu \text{m} \) given an initial slit spacing of 1 mm by adjusting one quadrupole magnet strength \( (Q1) \) only. For \( \Delta z \approx 350 \mu \text{m} \) (corresponding to \( \Delta t = \Delta z/c \approx 1.2 \text{ ps} \)), the autocorrelation has a 100%
FIG. 5: Fractional momentum spread separation $\Delta \delta$ versus time separation $\Delta t$ between the bunches within the train for different initial beam conditions. The different data points are obtained from the autocorrelation functions recorded for settings $I_{Q1} = 1.0, 1.2, 1.4, 1.6, \text{and} 1.8 \text{A}$ (from left to right) shown as white dots in Fig. 3. The current $I_{Q2}$ is kept constant at $-0.6 \text{A}$.

modulation implying that the bunches within the train are fully separated. Assuming the bunches follow a Gaussian distribution, their estimated rms duration is $< 300 \text{fs}$ (this estimate includes the finite resolution of our diagnostics). Variation of both $Q1$ and $Q2$ quadrupole magnet strengths can generate even shorter bunch separations, however our current measurement system has limited sensitivity in the shorter wavelength region, resulting in less than 100% modulation in the autocorrelation curve.

In summary we have experimentally demonstrated that an incoming phase space modulation in the horizontal coordinate can be converted into the longitudinal phase space using an EEX beamline. The method was shown to produce energy- and time-modulated bunches arranged as a train of subpicosecond bunches with variable spacing. This proof-of-principle experiment also provides an unambiguous demonstration of the main property of the EEX beamline to exchange the phase space coordinates between the horizontal and longitudinal degrees of freedom. The technique experimentally demonstrated in this Letter can be used to tailor the current and energy profile of electron beams and could have applications in novel beam-driven acceleration techniques, compact short-wavelength accelerator-based light sources, and ultra-fast electron diffraction.

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