

Tomography of longitudinal phase space linearization for the generation of attosecond electron bunches

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The generation of electron bunches on the attosecond timescale is important for a multitude of accelerator-based applications. Here, we report on a tomographic measurement of the (pre)linearized longitudinal phase space of a low charge 3 MeV electron bunch generated with the 1.6 cell Pegasus photoinjector for the generation of attosecond bunches. The nonlinear correlations in the longitudinal phase space induced by space charge at the photocathode, radiofrequency field curvature of the gun, and vacuum dispersion are compensated using a compact X-band linearizer. Then, the initial and compensated phase of the picosecond electron bunch is precisely reconstructed by neural network assisted tomographic reconstruction from momentum spectra at varying buncher linac phase. Finally, we combine the measured phase space shape with particle tracking simulations to show that electron bunches as short as 941 as develop downstream the beamline.

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I. INTRODUCTION

The generation of ultrashort relativistic electron bunches on the (sub-)femtosecond timescale in linear accelerators is crucial for a wide range of applications, such as ultrafast electron diffraction [1], laser-driven dielectric laser acceleration [2,3], inverse Compton scattering sources [4], and free electron lasers [5]. In order to generate such strongly compressed bunches, however, it is imperative to accurately measure and control the longitudinal characteristics of the electron bunch.

Control of the electron beam in linear accelerators in most cases is carried out using radio-frequency (rf) fields. In particular, short bunches are obtained by accelerating rf fields that impart a momentum chirp on the beam, resulting in faster trailing particles that catch up with slower leading particles. With this so-called velocity bunching approach, sub-100 fs bunches have been generated at subrelativistic energies [6] and sub-10 fs bunches at relativistic energy [7]. Utilization of an additional decelerating rf cavity to compensate for nonlinear correlations in the longitudinal phase space has been proposed in the previous work to allow for the generation of attosecond bunching via velocity bunching [8,9].

Next to radiative approaches [10], electro-optic sampling [11], and machine learning techniques [12], the use of rf fields is also a standard tool to diagnose the longitudinal properties of the beam. For instance, the bunch length can be measured by using a transverse deflecting rf cavity, which induces time dependent deflection that can be detected on a downstream screen [7,13]. Additional to this, the longitudinal phase space can be reconstructed from a set of measured momentum spectra with varying chirp induced by an accelerator. Such tomographic reconstruction has been used in a variety of beamlines using S-band acceleration cavities [14,15]. However, in practice both of these methods have a time resolution on the order of tens of femtoseconds, orders of magnitude larger than resolution required for an attosecond electron bunch.

In this paper, we report on an indirect approach to demonstrate attosecond velocity bunching with the Pegasus beamline at UCLA. In particular, as depicted schematically in Fig. 1(a), a compact X-band accelerator prelinearizes the nonlinear time-velocity correlations induced by an upstream S-band buncher linac on a 7 ps electron bunch with 80 fC bunch charge at 3 MeV kinetic beam energy generated with an S-band rf photoinjector. The phase space compensation is verified before compression by measuring momentum spectra for varying buncher linac phase using a magnetic dipole. An example of a set of momentum spectra, also called a sinogram, is shown in Fig. 1(b). Then, from the sinogram, the longitudinal phase space, see Fig. 1(c), is accurately reconstructed using an iterative tomographic algorithm. Finally, as shown in Fig. 1(d), we use particle tracking simulations to propagate the measured

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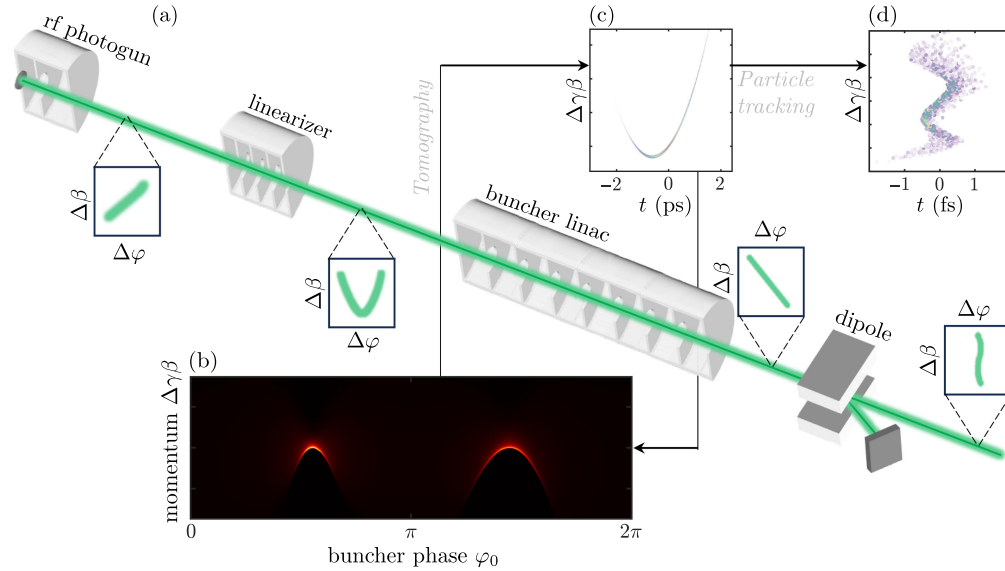


FIG. 1. (a) Schematic of the attosecond bunching scheme in the Pegasus beamline with the electron beam in green. (b) Sinogram: set of momentum distributions measured with the dipole magnet spectrometer. (c) Reconstructed longitudinal phase space from the measured sinogram. (d) Phase space of attosecond bunch after particle tracking based on reconstructed phase space in (c).

phase space to the compression point demonstrating that bunch lengths of about 941 as are attained.

The structure of this paper is as follows. First, we review the limitations on the final attainable bunch length set by the nonlinear effects in the velocity bunching scheme and how the conditions where the addition of a linearizer cavity helps. Then, we discuss the algebraic reconstruction technique that was used for the phase space reconstruction. Finally, we will present the results of the tomographic reconstruction for the UCLA Pegasus beamline and show that propagation of the retrieved phase space would result in sub-fs bunch duration at the longitudinal waist.

II. NONLINEAR EFFECTS IN RF BUNCH COMPRESSION

In the limit of negligible space charge effects, the minimum bunch length achievable with velocity bunching is limited by nonlinear effects induced by curvature of the rf fields and vacuum dispersion. In the following, these two contributions are briefly clarified using a simple analytical model for rf bunch compression, and we will show how to compensate for them in our specific case. For a more general discussion of velocity bunching, we refer to Refs. [8,9,16].

Consider an electron in an idealized rf buncher cavity with a phase φ with respect to the reference beam phase φ_0 . In this case, the change in axial momentum of the electron with respect to the reference beam momentum can be written as

$$\Delta\gamma\beta = a \cos(\varphi + \varphi_0) - a \cos \varphi_0, \quad (1)$$

where γ is the Lorentz factor, β is the velocity of an electron normalized to the speed of light, and a is the maximum normalized momentum gain determined by the field strength and length of the cavity. In many practical cases, the particle phase deviations are much smaller than unity such that the momentum change can be approximated, resulting in the following expression for compressing phase ($\varphi_0 = \pi/2$):

$$\Delta\gamma\beta \simeq -a(\varphi - \varphi^3/6). \quad (2)$$

At this phase of maximum compression, there is no net acceleration of the electron beam and the nonlinear contribution of the rf-field curvature on the momentum chirp begins only at the third order in electron phase. Note that when the compression occurs for a phase closer to the crest of the rf wave, quadratic field curvature will increasingly impact compression.

In addition to rf induced non linearities, even if only a linear momentum chirp could be imparted on the electron beam, velocity bunching is still limited due to the relativistic dispersion of electrons in vacuum. The effect of the dispersion relation becomes clear by Taylor expanding the normalized velocity deviation from the beam reference/average velocity for small momentum deviations $\Delta\gamma\beta$, which up to the third order is given by [17]

$$\Delta\beta = \frac{1}{\gamma^3} \Delta\gamma\beta - \frac{3}{2} \frac{\beta}{\gamma^4} (\Delta\gamma\beta)^2 + \frac{1}{2} \frac{4\gamma^2\beta^2 - 1}{\gamma^7} (\Delta\gamma\beta)^3. \quad (3)$$

By substituting Eq. (2) into Eq. (3), we find that any linear momentum chirp leads to nonlinear correlations in time-velocity space, i.e., longitudinal trace space. These correlations are undesired since they induce nonlinear drift

dynamics during velocity bunching that significantly limit the shortest bunch length attainable. For example, consider an electron beam with a Gaussian temporal distribution with rms spread σ_{t_0} in the cold beam limit, i.e., without initial momentum spread. Furthermore, assume the beam is short enough such that the buncher will induce a linear momentum chirp and it is relativistic with $\gamma \gg 1$ such that the quadratic term in Eq. (3) is dominant. In this case, where the effect of vacuum dispersion is isolated, the shortest attainable bunch at the longitudinal focus $L = c\beta\gamma^3/(a\omega)$ with ω the angular frequency of the buncher cavity and c the speed of light, is given by $\sigma_t = 3a\beta\omega\sigma_{t_0}^2/(\sqrt{2}\gamma)$ [9]. For a 2 ps electron beam with 3 MeV kinetic energy having a moderate chirp with $a = 3$ induced by a 2.856 GHz S-band buncher cavity, the final bunch length is $\sigma_t = 65$ fs. The expression for σ_t suggests that a shorter initial bunch length strongly minimizes the focus. However, a shorter electron bunch goes hand in hand with a larger uncorrelated momentum spread and larger space charge forces at the photocathode, which would then limit the bunch length for linear compression.

It is clear from the previous example that, in order to reach the attosecond regime, it is favorable to mitigate higher order trace space curvature. Since the nonlinear terms induced by the compression field have the same sign, an additional linearizing device is required. To this end, a correction cavity operating in a decelerating phase can be used, as proposed in earlier work in the context of rf compression and in FEL beamlines [8]. The axial momentum change due to this additional cavity is given by rewriting Eq. (1) with the following substitutions: $\varphi \rightarrow \varphi'$ and $a \rightarrow a'$, where $\varphi' = \varphi\omega'/\omega$ with ω' is the angular frequency of the compensating cavity. In decelerating phase ($\varphi'_0 = \pi$), the momentum change for small phases is given by

$$\Delta\gamma\beta' \simeq a' \left(\frac{\omega'}{\omega} \right)^2 \frac{\varphi^2}{2}. \quad (4)$$

This expression describes the induced quadratic correlation in the phase space. Assuming that the phase drift between the compensation cavity and buncher linac is negligible, we insert the sum of the phase dependent terms in Eqs. (2), and (4) into Eq. (3) to find the velocity deviation. Using the resulting expression, it is now straightforward to show that the velocity deviation becomes linear in phase if the amplitude of compensation cavity if following condition is satisfied:

$$a' = 3 \frac{a^2\beta}{\gamma} \left(\frac{\omega}{\omega'} \right)^2. \quad (5)$$

This expression shows that the higher the frequency of the compensation cavity with respect to the buncher frequency is, the smaller the deceleration required for compensation of the nonlinear vacuum dispersion is. If the condition (5) is

satisfied, the bunch is limited by uncorrelated energy spread and space charge effects (see Sec. IV).

III. TOMOGRAPHIC RECONSTRUCTION

In practice, several effects can modify the required compensation, which are not taken into account in the simple analytical model discussed in the previous section. For example, the drift section between the linearizer and buncher linac changes the compensated phase space distribution at the entrance of the buncher. Another example is the longitudinal phase space correlations from space charge at the photocathode and gun rf field curvature, which in general are nonzero. Numerical simulations can be used to fine tune the phase and amplitudes of the compensating and bunching cavities to minimize the final bunch length. For the same reason, in order to tune the system precisely it would be extremely useful to have direct access to the beam longitudinal phase space at the various stages of the compression. This can be obtained by tomographic reconstruction from the measured momentum spectra for varying buncher phase.

Various numerical methods have been developed to retrieve a two-dimensional phase space distribution from a set of one-dimensional angular projections, i.e., sinogram. A commonly used algorithm is the algebraic reconstruction technique (ART) [18]. ART exploits how the discretized contents of the sinogram are redistributed over the unknown distribution using backpropagation. The weights of the backpropagated bins are determined by the difference between the measured and the reconstructed sinogram, which consequently are adjusted each iteration until a convergence criterion is reached.

In conventional ART, the backpropagation is based on straight-line backprojection, assuming angular rotation of the sample under investigation. However, in our case, the sample phase space is only skewed in momentum space by the chirp imposed by the buncher. To this end, instead of straight-line projections, the phase space can be regarded as an array of weighted particles, which are mapped to each projection by forward particle tracking. The calculation of the weight coefficients is determined by the sum of the number particles weights in each sinogram bin. Thus, a hybrid algorithm that combines particle tracking with ART allows for tomographic reconstruction using noncircular transformations [19].

In some cases, the particle mapping can be done with an analytical model of the beamline elements used to perturb the phase space. For example, Eq. (1) can be used to model the phase space propagation through a short rf cavity. In other cases, one has to resort to integrating the equations of motion in realistic electromagnetic field maps using an additional particle tracking code. Relying on such particle tracking simulations for each reconstruction step is, however, computationally intensive. To circumvent slow particle tracking during tomographic reconstruction, the

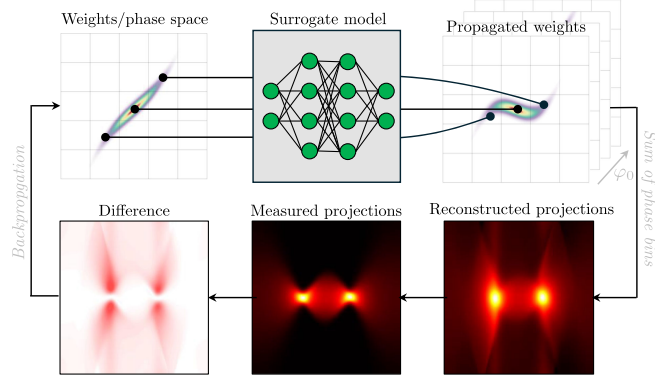


FIG. 2. Schematic description of the tomographic reconstruction algorithm. First, the reconstructed phase space (starting with a guess, which is typically an empty two-dimensional array) is propagated using a fast-executing surrogate model for each buncher phase. Then, the propagated phase space is summed into the momentum bins of the measured sinogram. Finally, the difference between the reconstructed sinogram and the measured sinogram serve as weights to the reconstructed phase space after backpropagation of the bins to the reconstructed phase space.

complex nonlinear mapping may be precalculated. Especially for a large amount of time-varying accelerator parameters, precalculation can be still time-consuming and rely on building large libraries that have to be stored in memory. Here, we significantly speed up simulations by using a fast-executing machine learning model that learns the nonlinear mapping of the accelerator as depicted schematically in Fig. 2.

The surrogate model used for the particle tracking is a feed-forward neural network consisting of two hidden layers of eight nodes each that have a hyperbolic tangent activation function. It is trained with the results of 10,000 particle tracking simulations using the general particle tracer code [20]. In the simulations, a field map of the buncher linac was used. We have assumed that space charge forces in the drift section from the buncher to the spectrometer screen are negligible. The neural network is thus a longitudinal phase space propagation model of the linac, and the nonlinear dispersion in the dipole is taken into account later in the conversion from pixel position to momentum.

In summary, the reconstruction method described here uses a feed-forward neural network model to improve the backprojection of conventional ART. For simple beam transfer, such as acceleration close to crest or propagation through a short linac, an analytic model could also represent the backpropagation instead of the neural network. However, for more complex systems such as the inclusion of collective effects such as space charge or even wakefields, the use of a surrogate model is necessary.

The reconstruction method in this work is different from generative phase space reconstruction [12], which combines generative machine learning models and differentiable beam dynamics simulations to efficiently reconstruct high

dimensional phase space distributions [21,22]. The main advantage of our model over generative phase space reconstruction is that it does not require a differentiable simulation model and, at least for two dimensional distributions, still retains computational efficiency as, after training has been completed, a reconstruction can be obtained in less than 1 min running on a normal laptop. Furthermore, although collective effects are not accounted for at present, this could be included to the neural network model in the future.

A. Resolution of ART

The spectrometer parameters and electron beam itself determine the resolution of ART. The spectrometer dispersion, pixel size, and point spread function of the detector determine the momentum resolution. The smallest measured momentum spread resolvable in the measurement is then given by

$$\Delta\gamma\beta_{\min} = \sqrt{\sigma_{\gamma\beta}^2 + \sigma_d^2}, \quad (6)$$

where $\sigma_{\gamma\beta}$ is the real momentum spread of the beam and σ_d is the resolution of the detector due to the point spread function and dispersion of the spectrometer.

The average phase resolution of the reconstructed phase space depends on the momentum resolution and on the maximum chirp $a \sin \varphi_0$ applied by the buncher linac. The phase resolution can be estimated as [14]

$$\Delta\varphi_{\min} = \frac{\Delta\gamma\beta_{\min}}{a \sin \varphi_0}. \quad (7)$$

The temporal resolution, therefore, increases for a stronger modulation amplitude a and better spectrometer resolution.

IV. EXPERIMENTAL RESULTS

The following experiment was carried out at the UCLA Pegasus photoinjector laboratory, which is schematically shown in Fig. 1(a). The Pegasus electron source is a 1.6 cell photoinjector operating in the S-band radio-frequency range (2.856 GHz). The drive for the photoinjector is a frequency-tripled Ti:sapphire laser system, which provides 266 nm pulses to a high quantum efficiency NaSKb cathode [23]. In order to generate a 7 ps long beam, we used three α -BBO crystals of 4.375, 2.1875, and 1.094 mm thickness, respectively, to split a single 100 fs (FWHM) laser pulse into eighth pulses separated by approximately 1 ps. The pulse train then is stretched by a long fused silica crystal for increased overlap. At gun phase of 25° and an acceleration gradient of 65 MV/m, the electron bunch is accelerated in the gun to a kinetic energy of 3 MeV. The photoinjector is immediately followed by a focusing solenoid.

Centered at 1.1 m downstream is a 7-cell X-band acceleration cavity with a total length of 10.9 cm. The cavity frequency of 9.6 GHz simplifies the synchronization with the S-band since it allows a frequency converted

S-band signal to be used as a seed for the X-band klystron. The klystron provides up to 40 kW rf power, which, given the shunt impedance of 93 M Ω /m, results in a maximum achievable on-axis field strength of about 10 MV/m. The cavity is used to (pre)compensate higher order correlations of the gun or downstream linac to generate very low energy spread or, such as described in this paper, very short electron bunches.

An 11-cell S-band linac [24] with a total length of 58 cm is centered at 1.72 m downstream the photocathode. The spectrograms discussed later on are generated at a gradient of 18 MV/m around accelerating phase ($\varphi_0 = 0$). The large beam energy at accelerating phase together with the low bunch charge of about 80 fC ensures that space charge effects are negligible between the buncher and the spectrometer screen.

After the linac, a dipole magnet with a radius of curvature of 67 cm bends the electron beam in an angle of 45° with respect to the initial beam. The transversely dispersed beam, with linear and second-order dispersion of $R_{16} = 19.6$ cm and $T_{166} = -16.8$ cm, is detected on a screen 27 cm downstream the bend axis. The second-order dispersion is taken into account in the recording of the momentum spectrum. For each linac phase, a momentum spectrum is recorded, which then together form the sinogram.

A. Comparison ART with matrix model-based reconstruction

Before demonstrating the phase space compensation with the X-band cavity, we use the setup to verify the

tomographic reconstruction from the ART algorithm. The short X-band section can in fact be considered as idealized acceleration cavity, allowing for the use of thin lens approximation for phase space propagation. Additionally, the analytical thin lens model can be used to reconstruct the phases and first moments of separate beamlets to self-consistently verify the ART algorithm. To this end, the 1.094 mm α -BBO and the stretcher rod are taken out of the UV line to intentionally generate a temporally modulated electron beam. Furthermore, we additionally add chirp on the beam by increasing the gun phase to 35° in order to generate clearly distinguishable beamlets in momentum.

The X-band accelerator, operating at a gradient of 280 kV/m, induces a momentum modulation to the beam with an amplitude of $a = 0.055$. Operation at this low gradient ensures that the beamlets remain separable in momentum and stay within the field of view of the spectrometer screen for all X-band phases as is visible from the resulting sinogram shown in Fig. 3(a). Using the ART algorithm, the longitudinal phase space of the beamlets is reconstructed. In Figs. 3(b) and 3(c), the reconstructed sinogram and phase space of the beamlets at the entrance of the X-band are shown, respectively, after 25 iterations. The total length of the beam is about 8 ps with about 2 ps of separation between the beamlets in agreement with the measured length induced by the birefringent crystals used on the UV line.

The phase space can also be reconstructed by fitting the momentum centroids of the measured data to Eq. (1) and the rms momentum spread to the corresponding linear transport as given by

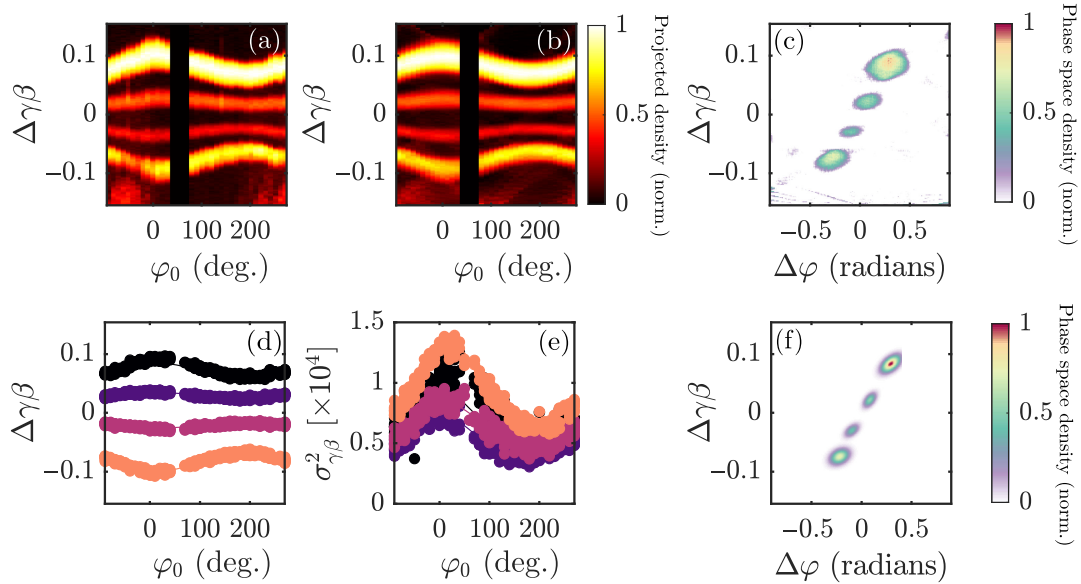


FIG. 3. (a) Measured sinogram with X-band accelerator. (b) Reconstructed sinogram using ART. (c) Reconstructed longitudinal phase space at entrance of X-band accelerator. (d) Centroids of the momentum distribution of the beamlets. Each color corresponds to a separate beamlet. (e) Momentum spread (squared) of the beamlets. (f) Reconstructed longitudinal phase space at entrance of the X-band accelerator using analytical propagation of the second-order moments of each beamlet.

$$\sigma_{\gamma\beta}^2 = a^2 \sigma_{\varphi,i}^2 \sin^2 \varphi_0 - 2a \sigma_{\gamma\beta\varphi,i} \sin \varphi_0 + \sigma_{\gamma\beta,i}^2, \quad (8)$$

where $\sigma_{\varphi,i}$ is the initial rms bunch length in radians of accelerator phase, $\sigma_{\gamma\beta,i}$ the initial normalized momentum spread, and $\sigma_{\gamma\beta\varphi,i}$ the initial linear correlation between momentum and phase. The beamlet centroid and rms momentum spread oscillations are shown in Figs. 3(d) and 3(e), respectively. From the fits, we find the central phases, rms spreads, and linear correlations for each beamlet. In Fig. 3(f), the resulting ellipsoidal phase space distributions of the individual beamlets with corresponding moments are plotted with an amplitude that is normalized to the respective spectrometer counts.

Although there are slight mismatches between Figs. 3(c) and 3(f), the main properties such as the average phase and momenta of the beamlets match well with the reconstructed distribution using ART. The minor differences, mainly in the temporal spread of the beamlets, can be attributed to the small modulation amplitude resulting in a relatively poor phase resolution of $\Delta\varphi_{\min} = 0.15$ estimated with Eq. (7). Using the ART method, however, arbitrary, nonlinear longitudinal phase space distributions can in principle be resolved, making it the preferred method for the measurement of the precompensation. Furthermore, ART does not require splitting of the phase space distribution in separable points in momentum space for reconstruction of the phase space.

These results indicate sensitivity to the temporal response of the photoemission process at the cathode and, therefore, can be used for future time-response measurements. Inferring the response time is especially important for shaping or manipulation of the bunch charge

distribution at the photocathode and applications requiring ultrashort bunches, such as ultrafast electron diffraction or free electron lasers.

B. X-band compensation

With the nominal parameters as described earlier, we now use buncher linac to reconstruct the phase space. Although the frequency of the S-band linac is less than a third of the X-band accelerator frequency, the maximum momentum gain $a \simeq 10$ is significantly higher, leading to a better temporal resolution as indicated by Eq. (7). Furthermore, using the S-band linac to vary the angle of the tomographic projections, allows us to measure the phase space with and without phase space compensation by the X-band.

In Fig. 4(a), the measured sinogram without X-band on is shown. The limited field of view of the spectrometer screen restricts the range of linac phases to about 20° centered around crest. Using the ART algorithm in conjunction with the neural network assisted beam propagation, the reconstructed sinogram and phase space after 25 iteration are shown in Figs. 4(b) and 4(c), respectively. In Fig. 4(c), a fit of the phase space curvature to second order, given by $\Delta\gamma\beta = c_1\varphi + c_2\varphi^2$, is also shown. The first- and second-order coefficients, respectively, are $c_1 = 0.73 \pm 0.01$ and $c_2 = -2.12 \pm 0.20$. The nonzero quadratic term correlation imparted by the gun affects the required compensation, stressing the need for phase space reconstruction. The curvature of the bunch matches well with the expected curvature from particle tracking simulations using GPT as is shown in Fig. 4(d), where the solid curve is the same as in Fig. 4(c). The measured bunch length

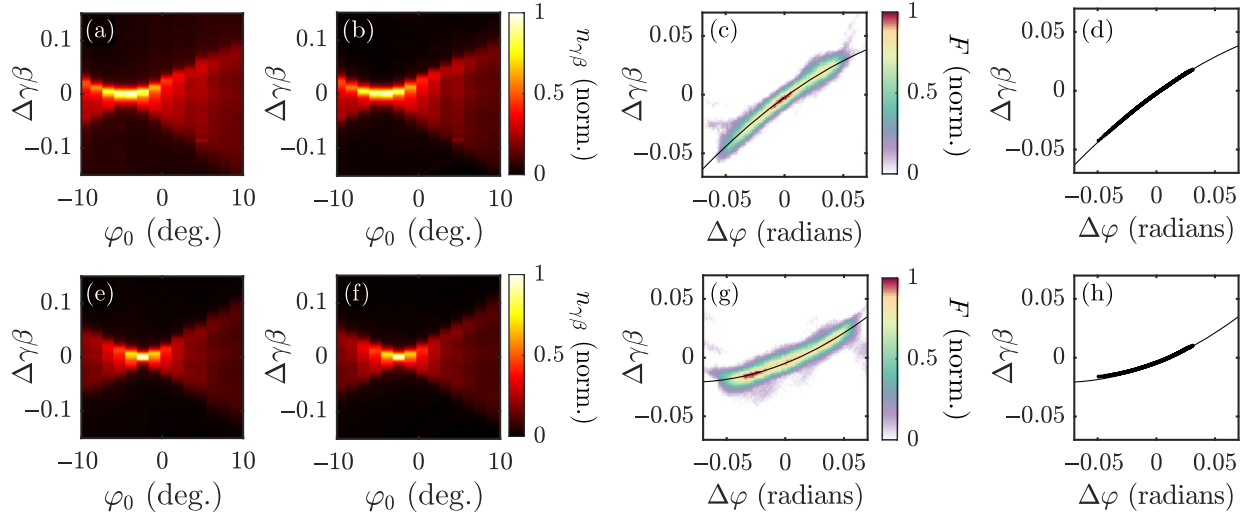


FIG. 4. (a) Measured sinogram for X-band off. (b) Reconstructed sinogram for X-band off. (c) Reconstructed longitudinal phase space at entrance of buncher linac with X-band off and fitted phase space curvature (black curve). (d) Simulated longitudinal phase space for X-band off. (e) Measured sinogram for X-band on. (f) Reconstructed sinogram with X-band on. (g) Reconstructed longitudinal phase space at entrance of buncher linac with X-band on and (black curve) fitted phase space curvature. (h) Simulated longitudinal phase space for X-band on.

is about 7 ps in agreements with the length of the stacked laser pulses on the cathode. Compared to the simulations, the measured bunch is longer by a ps, emphasizing the demand for characterization of the temporal response of the photo-emission process at the cathode. The rms slice energy spread is about 3 keV, which is about two orders of magnitude larger than expected from simulations. This is caused by the finite resolution of the spectrometer screen as indicated in Eq. (6) and the nonzero transverse dispersion from the exit of the buncher linac. The finite energy resolution together with the known gradient and phase of the linac gives a temporal resolution of approximately 194 fs.

Moreover, as expected, the beam at the exit of the gun has a quadratic curvature with the incorrect sign for compensation of vacuum dispersion, indicating the need for the additional compensation using the X-band cavity. To this end, we operate the linearizer at a gradient of 4.5 MV/m at the decelerating phase, resulting a reduction of beam energy of about 450 keV corresponding to a modulation amplitude of $a' = 0.87$ and perform another tomographic reconstruction of the resulting phase space. The measured and reconstructed sinogram and reconstructed and simulated phase space are shown in Figs. 4(e)–4(h), respectively. The measured bunch length is again about 7 ps with an rms slice energy spread of 3 keV. The quadratic term of the phase space curvature, however, as shown in 4(g), is increased significantly. The first- and second-order coefficients, respectively, are $c_1 = 0.40 \pm 0.01$ and $c_2 = 2.45 \pm 0.15$. The increase in the nonlinear coefficient is 4.57 ± 0.25 , which is very close to what is predicted from theory discussed in the previous section: $a'(\omega'/\omega)^2/2 = 4.91$ and close to the numerical particle tracking simulations. The small deviation from theory is caused in part by the operation of the linearizer 6.5° off absolute deceleration phase as indicated by the decline in linear momentum chirp c_1 .

V. ATTOSECOND BUNCH GENERATION

The reconstructed shape of the phase space distribution is used to sample a discrete particle distribution that is tracked through the linac and following drift section including space charge forces using GPT. For this simulation, the waist size of the electron beam at the entrance of the linac is assumed to be 150 μm and the slice energy spread of the bunch is 26 eV according to detailed particle tracking simulations of the beamline. In the following simulations, 10^4 macroparticles have been used and the bunch charge is 80 fC. Transverse focusing is not considered in this study in order to avoid taking into account the additional nonlinearities coming from space charge forces or transverse to longitudinal phase space coupling. However, as was shown in Ref. [9], these additional correlations could also be at least partially compensated for comparable electron bunch parameters. In Figs. 5(a) and 5(b), the longitudinal phase space distribution of the tracked particles

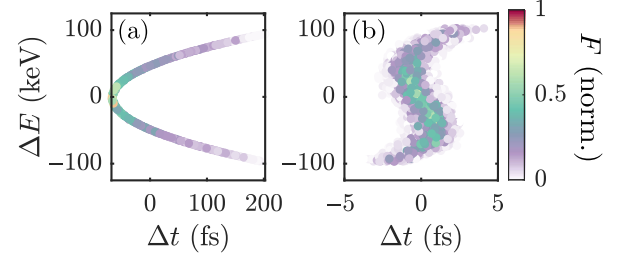


FIG. 5. Longitudinal phase space of (a) uncompensated and (b) compensated electron bunch at longitudinal focus downstream the buncher linac.

for a buncher linac gradient of 7.3 MV/m at compressing phase of $\varphi_0 = 97^\circ$ with and without X-band compensation is shown, respectively.

In the former case, without compensation, the shortest attainable rms bunch length is severely limited by the parabolic shape of the longitudinal phase space distribution. The parabolic shape is imposed by a combination of vacuum dispersion and initial phase space curvature induced by the rf field in the gun. The rms bunch length is 68 fs at the longitudinal focus.

In the precompensated case, on the other hand, the rms pulse length is 941 as almost two orders of magnitude smaller than the previous case and more than three orders of magnitude smaller than the initial bunch length. The focal length is $L = 1.3$ m, which is somewhat shorter than the previous case as a result of the lower beam energy from the X-band accelerator. The s-shaped phase space distribution of the attosecond bunch is a small third-order correlation induced by the electrons in the long initial bunch probing higher order rf-field curvature. Interestingly, given the relativistic beam energy, the corresponding spatial rms bunch length is 280 nm allowing for superradiance in a variety of emission processes [25–27].

VI. CONCLUSION

In this work, we have shown longitudinal phase space precompensation by a short X-band accelerator using tomographic reconstruction. The tomographic reconstruction was sped up with a fast feed-forward neural network model, which allows for accurate simulation of the propagation through the linac. Furthermore, through particle tracking simulations, we have shown that the compensation permits the generation of attosecond MeV-electron bunches. These findings can have great impact on a range of applications requiring ultrafast electron beams.

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