Velocity bunching has been recently proposed as a tool for compressing electron beam pulses in modern high brightness photoinjector sources. This tool is familiar from earlier schemes implemented for bunching dc electron sources, but presents peculiar challenges when applied to high current, low emittance beams from photoinjectors. The main difficulty foreseen is control of emittance oscillations in the beam in this scheme, which can be naturally considered as an extension of the emittance compensation process at moderate energies. This paper presents two scenarios in which velocity bunching, combined with emittance control, is to play a role in nascent projects. The first is termed ballistic bunching, where the changing of relative particle velocities and positions occur in distinct regions, a short high gradient linac, and a h. This scenario is discussed in the context of the proposed ORION photoinjector. Simulations are used to explore the relationship between the degree of bunching, and the emittance compensation process. Experimental measurements performed at the UCLA Neptune Laboratory of the surprisingly robust bunching process, and accompanying deleterious transverse effects, are presented. The second scenario may be designated as phase space rotation, and corresponds closely to the recent proposal of Ferrario and Serafini. Its implementation for the compression of the electron beam pulse length in the PLEIADES inverse Compton scattering (ICS) experiment at LLNL is discussed. It is shown in simulations that optimum compression may be obtained by manipulation of the phases in low gradient traveling wave accelerator sections. Measurements of the bunching achieved in such an implementation at PLEIADES, as well as aspects of the use of velocity-bunched beam directly in ICS experiments, are presented.
1. Introduction

Recently, the demand for applications of high brightness — low emittance, high current, with sub-ps pulse length — electron beams has increased dramatically. Such applications are found in advanced accelerators; for example, the source injection requirements for short wavelength, high gradient accelerators, demand ultra-short pulses of very low emittance. Alternatively, relatively high charge, sub-ps electron beams are required for driving plasma wake-field accelerators. In the 4th generation synchrotron light source community, high brightness beams are demanded for application to short wavelength self-amplified spontaneous emission free-electron lasers (SASE FEL), as well as for inverse-Compton-scattering (ICS) generation of short X-ray pulses.

Recent designs of systems capable of delivering high brightness very short electron beams have included the use of conventional photoinjectors in conjunction with magnetic compressors. While the magnetic compression scheme has proven successful in increasing the beam current, the impact on the transverse phase space has been shown not to be benign. When performing the compression at low energy, both velocity-field and centrifugal space charge forces are not strongly suppressed by the relativistic cancellation of electric and magnetic fields and their emittance-damaging effect becomes significant especially in bending trajectories. In the case of compression at higher energy, one has to deal with the deleterious effects on the longitudinal as well as the transverse phase space of coherent synchrotron radiation (CSR). Both longitudinal and transverse phase space filamentation and associated emittance growth are effects that run counter the goal of achieving the desired high brightness that motivates the compression process to begin with.

An alternative scheme which may preserve the transverse phase space quality while compressing the beam to sub-ps bunch length has been proposed by Serafini and Ferrario (SF). This scheme, commonly known as “velocity bunching” — as opposed to the path-length dependence of magnetic compression systems — is an elaboration of the commonly employed technique of RF rectilinear compression, typically used at kinetic energies in the 100’s of keV range, to the RF photoinjector system, with the bunching occurring at energies above 4 MeV. As trajectory bending is not needed in this system, one may avoid the deleterious effects observed in magnetic compression experiments on photoinjector-derived beams. With the compression occurring at low energy, where the transverse beam dynamics are space-charge dominated, special care must be taken to preserve the transverse emittance compensation. This process is based upon precise control of the transverse beam (plasma) oscillations, allowing nearly cancel the space-charge derived emittance growth. The simultaneous action of velocity bunching and emittance compensation has been initially studied by SF; it is examined in further detail using simulations and experiments in two different scenarios in this paper.

It should be emphasized that velocity bunching allows for the compression to occur early in the acceleration process, and at concomitant lower energy than magnetic compression. This attribute plays a strong motivating role for the implementation of velocity bunching in the two applications discussed in the following sections. In the first application, to the ORION
photoinjector, we examine the use of velocity bunching to compress bunches emitted from an S-band (2.856 MHz) RF gun, using a high gradient, short S-band linac section as a buncher. This scheme, which operates in a ballistic bunching regime where the compression occurs mainly in a drift, is needed to shorten the bunch length from one characteristic of the S-band gun, to one scaled appropriately in length to the X-band linacs which give the major portion of the total acceleration in the ORION photoinjector. Thus one may control the phase spread of the beam at the lowest possible energy (near 5 MeV), thus mitigating the beam’s final energy spread. This scenario, which is critical to the ORION facility mission, will be elaborated upon further below.

The other experimental scheme we present here is the use of velocity bunching at the PLEIADES (Picosecond Laser Electron Inter-Action for Dynamic Evaluation of Structures) ICS experiment located at LLNL. In this experiment, one simultaneously strives for short bunches, in order to achieve shorter pulse X-rays through electron pulse compression, and low energy spread, to obtain smaller — not as severely chromatic aberration-limited — electron beam spot sizes in the beam’s final focus system. The photoinjection system in this case is an S-band RF gun that is nearly identical to the ORION gun, followed by four S-band traveling wave linear accelerator (linac) sections. This layout is similar in most respects to the original SF proposal, with some notable exceptions that are discussed below in the context of simulations. As the velocity-based compression occurs not within a drift, but inside of a linac, we term this variant of velocity bunching “phase space rotation”, in which the synchrotron motion is mediated by continuous application of RF acceleration forces.

In order to place the present work in correct context, one must review the previous experiments in which velocity bunching has been employed in high brightness RF photoinjectors. At ATF, bunching been observed in a 1.6 cell S-band RF gun when the electron beam is launched from the cathode at phases far off crest\textsuperscript{12}, in standard RF gun phase convention, far below 90°. This effect has been shown to produce modest compression of beams, and is based on both phase space rotation within the gun, and ballistic bunching after the gun. Furthermore, it is consistent with achieving good emittance behavior. The use of this type of velocity bunching is limited, however, by the constraints simultaneously placed on the photo-emission, acceleration, focusing, and space-charge handling aspects of the system. The SF proposal allows more flexibility in velocity bunching, by moving the compression process to begin at the entrance to the first linac section, after the initial compensation of the emittance, and thus separating the functions of producing an initially optimized beam, and its subsequent compression. Further, in order to preserve the emittance during velocity bunching, the SF scheme proposes use of external focusing solenoids around the linac sections. This allows for tuning of the beam sizes and associated emittance oscillations during velocity bunching and post-acceleration.

Recently, a set of experiments have been performed\textsuperscript{13} at the BNL SDL laboratory, in a layout in which one may approximate, from the viewpoint of longitudinal dynamics, the low energy component (first two 3-m linac sections) of the SF scheme. In these measurements, agreement was obtained between simulation and experimental determination of the bunch length, with minimum observed rms pulse length of 0.6 ps. Because no solenoid focusing was available at the
SDL linacs, however, the issues of transverse beam size and emittance control was not addressed experimentally. In the LLNL experiments discussed here, solenoids are used to optimize the transverse emittance. Further, the compressed beams, which have rms pulse lengths as short as 0.3 psec, are used in ICS experiments in a demonstration of the utility of velocity bunching.

To motivate the experiments at Neptune Laboratory and at the LLNL PLEIADES photoinjector, we will review two design studies. The ORION velocity-bunching scheme will form the background of the Neptune experiments, while the PLEIADES design study is directly relevant to the experiment itself. These studies are presented in the following sections.

2. Ballistic bunching at the ORION photoinjector

The ORION photoinjector\textsuperscript{14}, which is now under construction as a joint SLAC/UCLA project, has at its core, 1.6 cell S-band (2.856 MHz) RF gun, which is to be operated at high gradient, 120-140 MV/m peak on-axis field. The emittance compensation process proceeds as in the now-standard LCLS design\textsuperscript{15}, with a beam being focused by a solenoid directly after the gun, through a 1.4 m drift, to the initial linac. Unlike the LCLS case, however, the linacs, which run at moderately high acceleration gradient (33 MeV/m average), are X-band devices. Nevertheless, these 11.424 GHz linac sections are equipped with a series of independently powered solenoid coils, and thus one may choose a solenoid field which allows operation on the invariant envelope, which optimizes emittance compensation\textsuperscript{16}. Thus excellent emittance performance is expected in this scenario, about 0.3 mm-mrad at the nominal design charge of 0.25 nC.

![Figure 1. HOMDYN simulation of the rms bunch length and relative momentum spread for a 10 pC case, optimized for laser acceleration experiments at the ORION photoinjector.](image-url)
Because of scaling of beam size inherent in the S-band gun, however, the energy spread due to the phase spread in the X-band may be too large for certain experiments. The most relevant example is laser acceleration, in which the needed energy resolution is very small, on the level of 100 keV. In order to achieve ultra-small energy resolution with a velocity-bunching scheme in the ORION injector, we have studied the inclusion of a short 0.42 m bunching section placed at the same initial position, 1.5 m downstream of the cathode, as the first X-band linac in the nominal design [14]. This positioning guarantees that the initial emittance oscillation is identical to that in the optimized LCLS-type design. The bunching linac is taken in the simulations to be an S-band PWT linac of the type installed at the Neptune Lab\textsuperscript{17}. The two X-band linac sections are moved downstream 1 m, allowing for the ballistic bunching of the beam in a 0.6 m drift after the PWT, as shown schematically in Fig. 1. In this figure, the results of a HOMDYN slice-envelope simulation[14], showing the evolution of the rms bunch length and relative momentum spread for a 10 pC beam case are shown. It can be seen that the longitudinal dynamics in this case are well-optimized for laser acceleration experiments at the ORION photoinjector, with a final state of 20 micron rms bunch length, and less than 0.2% residual rms energy spread (<100 keV). The transverse dynamics are not well-modeled by HOMDYN in this case, and are discussed further below in the context of multi-particle simulations.

This scenario is but one of many where velocity bunching should be considered at the ORION photoinjector. Another is the case where one desires very high peak currents, for studying plasma wakefield excitation. This mode of operation has been studied using UCLA PARMELA, in order to explore the issue of emittance compensation during the compression process illustrated in Fig.1. As PARMELA is a multi-particle, instead of a slice-envelope, code, it is capable of modeling the transverse phase space evolution of the beam in detail.

The results of this study are shown in Figs. 2-7, which displays the case of a 1 nC beam. Figures 2 and 3 indicate the overall parameters that control the evolution of the longitudinal and transverse dynamics, respectively. In Fig. 2, we display the normalized mean energy $\gamma$ of the beam as a function of distance along the beamline $z$; note that the PWT bunching linac is run ten degrees ahead of the zero crossing, and the beam is actually decelerated on average. This is necessary because of the strong dependence of the bunching process on average energy, and on space-charge forces. To quantify the dependence, we note that the drift one must use to remove a chirp $d(\delta p/p)/d\xi$ (where $\xi = z - vt$ is longitudinal distance measured in the beam frame), is

$$L_d = \gamma^3 \frac{d(\delta p/p)}{d\xi}$$

(1)

The chirp after the bunching linac is related to that before it, $d(\delta p/p)/d\xi$, by

$$\frac{d(\delta p/p)}{d\xi} = \frac{d(\delta p/p)}{d\xi} \bigg|_0 + k_{RF} \Delta p_m \frac{\sin\phi}{p_0} \left[ \frac{N_{ph}}{p_0^2} \cos\phi \right]$$

(2)

where $p_0$ is the beam momentum after the gun, $\Delta p_m$ is the maximum momentum gain available in the linac, the RF wavenumber is defined as $k_{RF} = 2\pi / \lambda_{RF}$, and the RF phase $\phi = k_{RF}(z - vt) + \phi_0$ has the opposite sign convention of the gun phase mentioned above.
With the longitudinal dynamics established, the transverse beam dynamics then are controlled by adjusting the solenoid amplitude and spatial profile. As the ORION photoinjector X-band traveling wave linacs inherit the NLCTA injector focusing solenoids overlayed upon the acceleration region, one may use these existing magnets to achieve a fine tailoring of the longitudinal magnetic field profile. The optimized field profile which produces good emittance compensation at the exit of the first X-band linac section is shown in Fig. 3.

**Figure 2.** The evolution of the normalized beam energy for 1 nC beam in the ORION photoinjector, velocity-bunching case, from PARMELA simulation.

**Figure 3.** The z-dependence of the longitudinal magnetic field used in the PARMELA simulation of the ORION photoinjector.
For the parameters of the ORION design \( (p_0 = 7 \text{ MeV/c}, \Delta p_m = 14 \text{ MeV/c}, d(\delta p/p)/d{\xi}_0 = 14 \text{ m}^{-1}) \), the drift from the bunching linac to longitudinal focus is predicted to be approximately 0.8 m. In fact, it is a bit longer than this, as can be seen in Figs. 2 and 4, because of the defocusing effects of longitudinal space-charge forces. It can be seen in Fig. 4 that the longitudinal focusing is arrested by acceleration in the X-band linac after bunching from 800 µm rms down to 150 µm. The compressed bunch length is limited from below by both nonlinearities in the (sinusoidal) rf accelerating waveform, and by space-charge forces. Explicit manifestations of these collective forces are displayed in the longitudinal phase space shown in Fig. 6.

![Graph](image)

**Figure 4.** Evolution of the rms bunch length for 1 nC beam in the ORION photoinjector, velocity bunching case, from PARMELA simulation.

The \( z \)-dependences of the beam’s transverse rms size and emittance, as predicted by PARMELA, are shown in Fig. 5. It can be seen that the increase in the beam current (to above 1 kA) associated with the bunch compression causes the control of the beam emittance oscillations to become much more difficult. These oscillations show characteristic increased frequency as the beam-plasma frequency grows with higher current, and also display a secular trend upward. This secular behavior could have been anticipated from previous theoretical work on phase space evolution in near-equilibrium situations, in which wave-breaking of the phase space distribution and associated emittance growth occurs\(^{18,19}\). It should be noted also that the case shown in Figs. 2-5 is one in which the beam does not undergo wave-breaking (cross-over) in longitudinal phase space, as can be seen in the PARMELA simulation results displayed in Fig. 6. Under cross-over conditions, different longitudinal “slices” of the original beam are allowed to overlap. This results, as in the case of magnetic compression, in strong emittance growth due to the enhanced amplitude and nonlinearity of the transverse space-charge fields [6].
Figure 5. Evolution of the rms transverse beam size and emittance for 1 nC beam in the ORION photoinjector, velocity bunching case, from PARMELA simulation.

Figure 6. Final state longitudinal phase space of the 1 nC beam in the ORION photoinjector, velocity-bunching case, from PARMELA simulation.
Even in the absence of longitudinal cross-over, the secular transverse emittance growth over the series of emittance oscillations is non-negligible, and leads to development of a halo of large amplitude particles. This halo may be dealt with by cutting the distribution, which upon removal of only 17% of the particles using horizontal collimation, gives a reduction of the normalized emittance from 1.7 mm-mrad to 1.0 mm-mrad.

From this discussion, we see that there are numerous experimental questions concerning this ballistic bunching scheme, with most arising from the effects of space-charge forces. From the viewpoint of longitudinal space-charge, one may search for a signature of minimum achievable bunch length and accompanying momentum spread, if not a complete characterization of the longitudinal phase space. With respect to transverse forces, one should study the effects of space-charge in the various regions: ballistic drift, accelerator and/or solenoid. With these studies in hand, one may more confidently address the full process of maintaining emittance compensation during velocity bunching.

It will be seen that not all of these goals could be addressed in the test bed we have used to explore the ballistic regime. Our available experimental configuration is that of the Neptune photoinjector at UCLA, which contains a 1.6 cell gun and a PWT standing wave linac; these are the same first two RF devices in the ORION ballistic bunching system. This system has no post-acceleration or solenoid focusing after the PWT buncher, thus limiting the range of experimental questions that can be addressed. Nevertheless, significant experimental progress in understanding the ballistic bunching scheme was accomplished.

In the following sections we review the experimental scheme employed, give experimental results, and compare the results to computational models. The investigations that could be undertaken at Neptune were mainly centered on measurement of the bunch length using the
coherent transition radiation (CTR) interferometry. Parametric studies of linac electric field amplitude in the bunching linac were performed, allowing determination of the best compressing phase for different acceleration gradients. A partial investigation of transverse dynamics relevant to the ORION scheme was undertaken. The presence of strong chirping of the beam means that one may use a dispersing dipole to select a portion of the beam with a relatively small energy spread, thus allowing longitudinal slice measurements of the beam. In this way, the emittance of the central slice of the electron beam was studied via quad scan techniques. As the phase of the RF accelerating wave in the PWT approached the optimum compression conditions, emittance growth was observed. We present three-dimensional simulations that agree well with the experimental results. The interpretation of this experimental scenario has some subtlety, however, and a curious effect that can introduce an unanticipated emittance growth in the bend is thus discussed.

**Figure 7.** Schematic layout of the Neptune ballistic bunching experiment.

3. Neptune experimental layout

The Neptune facility at UCLA is operated both as an injector for an advanced accelerator experiments such as plasma beat-wave acceleration\(^{21}\), and as a test bed for high brightness beam dynamics studies. These studies have included emittance growth in bends \(^{5}\) and negative \(R_{56}\) compressors\(^{22}\) for production of shaped beams that may be employed as optimum plasma wake-field drivers. The Neptune photoinjector\(^{23}\) and associated laboratory measurement capabilities\(^{24}\) are thus readily available for ballistic compression studies.

The photoinjector beam in these experiments is created initially by a 266 nm wavelength, 6 ps rms long laser pulse impinging on a single crystal copper cathode inside of a 1.6 cell RF gun. The photoelectrons generated are then accelerated by the RF fields of peak on-axis amplitude \(\sim 80\) MV/m, and are transversely focused into the PWT linac entrance using the emittance compensation solenoid. At this point the beam can be energy-chirped for ballistic bunching inside the 8-cell, 42 cm long, S-band PWT RF cavity that is run forward of crest (maximum acceleration). There is independent control and measurement the phases of the two accelerating structures, as one needs for testing the ballistic bunching scheme. Downstream of the linac there
is an insertable aluminum foil to generate coherent transition radiation, which is collected by a parabolic mirror and reflected to a Martin-Puplett autocorrelator which is used as a pulse length diagnostic. There are also 4 dipoles along the beamline; all of them are used in chicane mode (magnetic compression, which is not of direct use in these experiment, while if only the final two of are used to bend in the same direction, a 45 degree total bend, normally used for momentum spectroscopy, is created. For the ballistic bunching experiments, a quadrupole lens and a Ce:YAG screen are employed after the 45 degree bend, for “slice”-emittance measurements employing quad scanning.

4. **Longitudinal dynamics in the ballistic bunching experiment**

The ballistic bunching in the Neptune experiments is described well by the approximate relations given in Eqs. 1 and 2. Because one compresses with ballistic bunching by running the PWT far from crest (+70 degrees), and near the zero-crossing, the final bunch length is not as strongly limited by RF nonlinearity as in magnetic compression [2] or phase space rotation, where the beam manipulations require application of RF fields having strong longitudinal curvature near to the wave crest. Additionally, since the beam is not well-focused transversely after the PWT, the effects of longitudinal space charge are not as notable at Neptune as in the ORION case. As shown below, very short beams can be created by use of this scheme.

![Figure 8](image-url)

**Figure 8.** Autocorrelation of optimally compressed beam in Neptune ballistic bunching experiment, with time-domain fit analysis.
4.1. Measurements

The pulse length in these measurements is determined by use of coherent transition radiation (CTR) interferometry using a polarizing Martin-Puplett interferometer with two Golay cell detectors. The resolution of the interferometer is limited by the spectral response of the two wire grid polarizers. The wire grid does not efficiently reflect wavelengths shorter than the wire separation distance of 100 µm. As for long wavelengths, the analysis of the interferometer data must take into account the loss of such components in the CTR spectrum due to: inefficient creation of the CTR due to finite target size, subsequent the diffraction of long wavelengths, and poor vacuum window transmission. These effects are all dealt with in analysis using a frequency filtering algorithm that is fit to the time-domain data. We note that since the CTR measurement is performed on a moderately relativistic beam, the radiation divergence (≈1/γ) cone of the radiation is quite large. Because the Martin-Puplett is a polarizing interferometer, and because the polarization of transition radiation depends on the direction of propagation, much care in must be taken to mitigate the effects of misalignment and resultant losses in the collection of the divergent cone, as they can result in systematic errors in the measurement.

![Graph](image)

**Figure 9.** Maximum bunching phase in PWT vs. PWT accelerating gradient, theory and measurement.

For a case with approximately \( Q \approx 250 \) pC of charge and 70 degrees off crest in the PWT cavity (optimal compression), scanning the moving arm of the interferometer, we obtain the interferogram shown in Fig. 8. The time-domain filtered fit to the data gives an rms pulse length 0.39 psec. It is worth noting the compressed beam is shorter than that achieved, over 0.6 psec, using magnetic compression at Neptune [6] with comparable beam charge and slightly shorter initial bunch length. This observation strongly confirms the role of the linearity of the RF wave, which is generally the limiting factor in the final achievable pulse length [2]. It is also interesting to see that the beam at Neptune case was compressed to a length 35% shorter than achieved in
the BNL velocity bunching experiments [13]; further, the compression factor (12-15) is much larger than in the BNL measurements (approximately 3).

The predictions from the linear approximation for optimum bunching conditions given in Eqs. 1 and 2 have been experimentally tested by measuring the phase $\phi$ of best compression, while changing the energy gradient in the PWT. The RF-cavity phase can be measured precisely by mixing the RF fields inside the structure with a reference RF-clock, while the phase for maximum compression is easily determined by maximizing the CTR energy on the Golay-cell bolometer detectors. Maximizing the CTR minimizes the bunch length, since the coherent energy scales with the inverse bunch length\[^2\] $E_{CTR} \propto Q^2/\sigma_t$. A comparison between the measured data and the analytical approximation is within the experimental uncertainties, as seen in Fig. 9. The higher uncertainties in the measurement for higher gradient indicate that the system is increasingly sensitive to RF phase noise when higher gradients are used for bunching.

With the calibration of RF, beam charge and launch dimensions known, one may also compare aspects of the measurements with more complete models of the beam dynamics. Figure 10 shows the results of a HOMDYN simulation of the conditions of the Neptune experiment, for the calibrated RF linac phase of 70 degrees, $\sigma_{z,min} = 128 \, \mu$m. The minimum achieved rms bunch length deduced from the CTR measurement is 117 microns, in quite good agreement. Note that the simulation indicates a compression of the beam by one order of magnitude, as does the comparison of measured photocathode laser pulse length with the measured electron beam $\sigma_{z,min}$.

\[ \text{Figure 10. Evolution of rms bunch length in Neptune ballistic bunching experiment, showing minimum of } \sigma_{z,min} = 128 \, \mu m \text{ near CTR measurement screen location for experimental conditions.} \]

5. **Transverse dynamics in the ballistic bunching experiment**

The results of the previous section confirm that ballistic bunching can be an efficient and compact way of increasing the peak current of the beam, which was raised from roughly 17 A to
over 250 A in the experiment. The remaining question of course is if this increase in beam current corresponds to a relative increase in brightness; what is the damage to the emittance during this compression process, which has no downstream beam focusing or post-acceleration?

As the initial energy of the beam upon entrance to the PWT buncher is low, 4.2 MeV, it is not necessary to run forward of the RF zero-crossing; for optimal compression the beam runs through the high gradient structure 70° off crest, still in the roughly linearly changing part of the RF wave. Under these conditions, the energy spread at the exit of the PWT is large. For example, in the case in which the focus of the longitudinal lens is 3 m downstream on the beam-line, and the RF phase set 70° off crest, the resulting a energy spectrum extends from 5 MeV to 9 MeV. This would not be an inherent problem in a system where the beam energy can be boosted up by additional accelerating cavities to quickly remove the relative energy spread, but at the Neptune photoinjector there is no such capability. This limits the determination of the transverse projected emittance, because the energy spread will appear, in trace space quad scan measurements, as unphysical transverse emittance arising from severe chromatic aberrations.

On the other hand, the energy is correlated with the longitudinal position within the beam. If a small window in energy is accepted in a given measurement, a longitudinal slice of the beam can be selected. Experimentally, a 45° bend dipole was employed to horizontally disperse the beam momenta, and then a beam slice was selected over which a vertical quad scan emittance measurement was performed. We have studied the vertical phase space with this method of the longitudinal core of the electron beam, scanning the phase of the linac to understand the transverse dynamics of the beam as it was undergoing compression.

5.1. Slicing the beam with the 45° dispersive dipole

Changing the linac phase, which is the variable that controls the compression, also causes changes in the energy spectrum of the beam. On the other hand, it is important to ensure that the same longitudinal slice of the beam impinges on the quad scan detection screen. The screen subtends several degrees of bending angle corresponding to ~2% of energy spread. In order to be able to set the dipole current to keep the same portion of the beam at the 45° bend angle as the overall beam energy changes, we first measure the full spectrum of the beam as the linac phase is changed, then select one reference slice. In our case this chosen as is the central (maximum current, as determined as the maximum of the Faraday cup detection of transmitted charge) slice, and the dipole current is thus stay to keep in the slice analysis window.

In Fig. 11, one can see the energy change of this central reference slice, of the beam as the linac phase is varied. This curve also allows an independent determination of the RF cavities’ accelerating gradients. We deduce from fitting this RF phase scan data that the energy gain in the 1.6 cell gun is 4.2 MeV corresponding to a peak on-axis gradient of 80 MV/m, and the gain in the PWT is 8.4 MeV, corresponding to a peak on-axis 40 MV/m accelerating gradient.
**Figure 11.** Energy of central slice, measured vs. the phase of the linac, as determined by maximum Faraday cup signal. Energy fit to data has assumed functional form $E = E_{\text{gun}} + E_{\text{PWT}} \sin(\phi + \phi_0)$.

### 5.2. Quad scan measurement

Once the central reference beam slice is found, the quad scan is performed to determine the emittance in the vertical dimension. Since the beam varies in size significantly going through the quad, an analysis that takes into account the thickness of the quadrupole lens is needed. The parameterization of the square of the measured beam size with respect to the quad strength is:

$$
\sigma^2(K) = \left[ \cos(\sqrt{K} l_q) - \sqrt{K} l_d \sin(\sqrt{K} l_q) \right]^2 \sigma_{11} + \\
2 \left[ \frac{\sin(\sqrt{K} l_q)}{\sqrt{K}} + l_d \cos(\sqrt{K} l_q) \right] \left[ \cos(\sqrt{K} l_q) - \sqrt{K} l_d \sin(\sqrt{K} l_q) \right] \sigma_{12} + \\
\left[ \frac{\sin(\sqrt{K} l_q)}{\sqrt{K}} + l_d \cos(\sqrt{K} l_q) \right]^2 \sigma_{22},
$$

where $l_{q,d}$ are the quad and drift lengths, respectively, and the quadrupole field gradient $B'$ is parameterized by the focusing strength $K = \frac{299.8B'(T)}{pc(\text{MeV})}$. With Eq. 3, one takes into account the full thick lens matrix instead, of the more common thin lens analysis in which the betatron phase advance inside the quad is negligible.
Figure 12: Example data and fit for thick lens the quad scan on central slice of velocity-bunched beam.

Figure 13. Emittance growth during compression, experimental results from quadrupole scan, and TREDI multiparticle simulations of compression and measurement system.

Figure 13 shows the observed emittance growth as a function of PWT linac RF phase. It can be seen that a sharp onset occurs as the phase approaches, but does yet reach, that which gives rise to optimum bunching. To quantify this effect, we have employed more a sophisticated tool that can model 3D multi-particle collective effects. The simulation code, TREDI\textsuperscript{27}, is a self-consistent tracking code that employs a 3D Lienard-Wiechert field calculator. It is capable of giving detailed phase space information and, allowing an understanding a measurement system that has an unexpected systematic problem arising from space-charge effects in the bend. Note that the simulation results given in Fig. 13 match the experimental data for the emittance growth well, and as will become apparent, can also aid in deducing the precise mechanism of this growth.
6. Compression of a beam with chirped energy spectrum in a bending magnet

We expected to observe emittance growth for PWT phases where the longitudinal waist of the beam occurs before the measurement screen due to the deleterious effect of a longitudinal cross-over in the transverse phase space. On the other hand, the experimental data and the simulation results shown in Fig. 13 display an increase in emittance even for phases for which the beam is not yet near to full compression within the drift between the PWT and the dispersing dipole. To explain this, a deeper look into the dynamics of a negatively energy-chirped beam going through the bending magnet that has been used as a slice selector in the measurement is required. This investigation is carried out using both a linear model for the beam configuration space evolution, and the full six-dimensional phase space model from TREDI.

6.1. Model considerations

For the vertical phase space the bending magnet is a simple drift. However, examining the beam behavior in \((x-s)\) configuration space, one may observe notable rearrangement of particle positions. These may in turn lead to a strong enhancement of the local beam density if the beam is initially chirped in energy, with particles having higher energy located in the tail of the beam. Note that a bending magnet has a negative \(R_{56} = \partial \zeta_i / \partial (\delta p / p)_i\) (defocusing for such a chirp) so that this effect cannot be ascribed to standard notions of longitudinal compression; it is therefore anomalous. The size of the projections of the beam extent onto the curvilinear longit-udinal axis \(s\) or onto the transverse dimension \(x\) and \(y\) do not diminish in the bend. On the other hand, when one examines the mechanism for density increase, and accompanying emittance growth, with greater care, it is found that the physical three-dimensional volume of the beam can indeed become smaller, go through a minimum, and finally increase again inside of a dipole magnet. This is a 3D configuration space effect that is may be important when a strong negative chirp \((d(\delta p / p) / d\zeta < 0)\) is imparted upon the beam before it traverses a simple bending magnet.

The negative effects on the beam quality of this electron density increase are dramatic, in both experiment and simulation, especially at moderately relativistic energies where space charge forces dominate the dynamics of the beam. A similar effect was observed in the Neptune magnetic compression experiment, where configuration space correlations associated with the evolution of beam in the final chicane bend magnet gave rise to large phase space distortions[6].

In the next subsection, we analyze the problem of a chirped beam traversing a bending magnet using linear matrix calculations, in order to illustrate the compression dynamics. This approach neglects space charge forces and is only a first order approximation. In the following subsection we examine the evolution of the microscopic beam distributions in configuration space predicted by fully 3D simulations using TREDI, where the electron density increase is clearly visible.
6.2. Linear analysis

A simple way to understand the physics of this process is the linear matrix-based approach to the beam dynamics. Because the vertical phase space is uncoupled in a bending magnet transport line, we need only to concentrate on the 4-dimension phase space \((x,x',s,\delta p/p)\).

Given the initial beam matrix \(\Sigma\),

\[
\Sigma = \begin{pmatrix}
\sigma_{xx} & \sigma_{xx'} & \sigma_{xs} & \sigma_{x\delta} \\
\sigma_{s'x} & \sigma_{s'x'} & \sigma_{ss} & \sigma_{s\delta} \\
\sigma_{sx} & \sigma_{sx'} & \sigma_{ss} & \sigma_{s\delta} \\
\sigma_{s\delta} & \sigma_{s\delta'} & \sigma_{s\delta} & \sigma_{s\delta}
\end{pmatrix},
\]

(4)

where the elements \(\sigma_{ij}\) are the second moment of the beam phase space distributions (for example \(\sigma_{xx} = \langle x^2 \rangle\), \(\sigma_{xx'} = \langle xx' \rangle\), etc.). This matrix evolves according to the transformation,

\[
\Sigma_f = R \cdot \Sigma_i \cdot R^T
\]

(5)

where the transport matrix \(R\) for a flat-field bending magnet is

\[
R(s) = \begin{pmatrix}
1 & s & 0 & -R \left(1 - \cos \left(\frac{s}{R}\right)\right) \\
0 & 1 & 0 & -s \sin \left(\frac{s}{R}\right) \\
\frac{s}{R} & \frac{s^2}{2R} & 1 & \frac{s}{\gamma^2} - s + R \sin \left(\frac{s}{R}\right) \\
0 & 0 & 0 & 1
\end{pmatrix}.
\]

(6)

Here \(s\) is the longitudinal coordinate along the beam path, \(R\) is the bending radius and \(\gamma\) is the Lorentz factor of the design energy.

One can then calculate the configuration space volume taking into account possible correlations between \(x\) and the longitudinal coordinate \(s\),

\[
V = \sqrt{\sigma_{xx} \sigma_{ss} - \sigma_{xs}^2 \sigma_{yy}}.
\]

(7)

The transverse emittance contribution \((\sigma_{xx'}, \sigma_{x'x'} = 0)\) may be neglected because the RF nonlinearity makes the longitudinal trace space contribution dominant to the final volume. We may also take the vertical rms beam size \(\sqrt{\sigma_{yy}}\) to be roughly constant over the region of interest, \(\sqrt{\sigma_{yy}} = \sqrt{\sigma_{yy,0}}\). With these assumption one obtains for the configuration space volume

\[
V = \sqrt{\sigma_{xx} \left(\sigma_{xx} + 2\sigma_{\delta \delta'} R^*_{56} + \sigma_{\delta \delta} \cdot R^*_{56}^2\right) + R_{16}^2 \left(\sigma_{ss} \sigma_{\delta \delta} - \sigma_{s\delta}^2\right)}} \cdot \sqrt{\sigma_{yy,0}}.
\]

(8)

where the modified longitudinal transport element \(R^*_{56}\) can be written as
\[
R_{56}^* = \frac{S}{\gamma} + R \cdot \sin \left( \frac{S}{R} \right) - s \cdot \cos \left( \frac{S}{R} \right).
\]  

Equation 9 indicates that \( R_{56}^* \) (in contrast the standard element, \( R_{56} \)) is a positive quantity and that increases quickly with distance (in the ultrarelativistic case, \( \sim s^3 \)), and \( R_{16} \) is the horizontal dispersion function, also increasing with distance. The initial rms beam configuration space volume is \( \sqrt{\sigma_{xx,0}\sigma_{ss,0}\sigma_{yy,0}} \). If the beam initially has a negative energy-position chirp, \( \sigma_{s\delta} < 0 \), so that particles in the tail are more energetic than particles in the head, this correlation can be removed by the positive \( R_{56}^* \) at the anomalous compression, or minimum volume point. The linear evolution of the configuration space volume, as well as the apparent projected configuration space volume \( \sqrt{\sigma_{xx,0}\sigma_{ss,0}\sigma_{yy,0}} \), is shown in Fig. 14. The apparent projected volume was what drove our initial assumption that space-charge and related effects would be mitigated in the bend. Examining the projected volume, one may naively conclude that the beam becomes quickly more spread out in both \( x \) and \( s \) dimensions, thus lowering its density dramatically. This, as we have just demonstrated, is not always necessarily case.

![Graph](image)

**Figure 14:** Anomalous compression analysis for a beam chirped by traversing the PWT 70 degrees off crest in the PWT. The initial beam sizes at the entrance of the dipole magnetic field are \( \sigma_x = 2.8 \) mm, \( \sigma_y = 0.6 \) mm. Shown are the linear evolution of the configuration space volume, as well as the apparent projected configuration space volume \( \sqrt{\sigma_{xx,0}\sigma_{ss,0}\sigma_{yy,0}} \). The anomalous compression point is 12 cm inside the magnet and the compression factor is 4.7.

Geometrically the minimum volume conditions roughly corresponds to a point along the beam line in which the more energetic particles in the tail of the beam overtake the less energetic ones in the direction of initial beam motion \( z \), as shown in Fig. 15.
The compression factor depends strongly on the initial transverse beam size and the longitudinal trace space emittance. It is given by

$$ B = \frac{V_i}{V_f} = \sqrt{\epsilon_s \cdot \left( \frac{\sigma_{ss}}{\sigma_{ss}} \left( R_{16}^* \right) + \left( R_{16} \right)^2 \right)^2}, \quad (9) $$

where $\epsilon_s$ is the longitudinal trace space emittance, and $R_{16}$ and $R_{56}^*$ are evaluated at the anomalous compression point.

### 6.3. TREDI Simulations

The linear analysis is useful for obtaining a conceptual understanding of what happens to the beam distribution as it traverses the dipole bend. In order to fully understand our measurement we must, however, we examine the 3D TREDI simulations. In doing so, we may observe not only the density increase of the beam that occurs at the anomalous compression point, but also extract the growth of both the vertical and horizontal emittances that accompany this density increase. The success of the comparison of the TREDI model with the quadrupole scan results shown in Fig. 13 gives confidence that the TREDI results give insight into the microscopic mechanisms behind the observed emittance growth.

Examination of the configuration space in the TREDI simulations has shown that if the chirp on the beam is not too big ($<10\%$ when the beam is accelerated 30 degrees off crest), the cross-over does not occur, because the dispersion ($R_o$) in the horizontal plane dilutes the beam before the anomalous compression point. In this case, the beam simply bends inside the dipole without strong degradation of phase space quality. On the other hand, for a beam with large energy chirp that has been accelerated far off crest in the bunching linac, a configuration space cross-over (in $z$) takes place after less than 10 cm from the entrance of the dipole, as is illustrated in Fig. 16. The
more energetic particles that are in the tail reach the less energetic ones that follow a trajectory having a larger bending angle. The accompanying density increase is also easily seen in Fig. 16. This density increase is seen in the simulations to coincide in time with significant emittance growth; thus the density increase is indeed verified to be the reason for emittance growth even at phases for which the compression in the rectilinear drift is incomplete.

Figure 16: Cartesian configuration space x-z projections for a beam accelerated 70 degrees off crest in the PWT linac at three different locations along the Neptune beam line: before the dipole (first column), at the anomalous compression point 12 cm inside the dipole (second column) and after the crossover (third column). The top line has equal scale on x and z axes. An arrow shows the beam propagation direction. The bottom pictures are zoomed versions of the top ones with expanded axes. Particles with higher energy (blue) that were in the tail of the beam overcome the lower energy particles (red) in the front.

7. Conclusions from Neptune ballistic bunching measurements

The Neptune ballistic bunching experiments have illustrated both the physics involved in the bunching process, and the limitations of the experimental techniques employed in the measurements. In terms of longitudinal dynamics, the measurement of the extent of the bunching can be viewed as an improvement on previous results from both the velocity bunching measurements at BNL [13] and the magnetic compression results obtained at Neptune [6], even though the initial bunch length was longer in the present experiments.
In both cases, part of the improvement can be attributed to the use of the linear region of the RF wave near the zero-crossing, with accompanying mitigation of the induced longitudinal emittance growth. Quantitatively, the Neptune experiments succeeded in lowering the observed pulse length from 0.6 ps in both Refs. 6 and 13, to less than 0.4 ps. This value raises the issue of the resolution of the CTR measurement. As we shall see, this question becomes more urgent in the velocity bunching measurements at LLNL, where even shorter bunch lengths are observed. Discussion of bunch length measurement resolution and its potential improvement is thus delayed until the LLNL results are presented.

The measurement of transverse phase space in the Neptune experiments definitively shows emittance growth. This is an important, albeit expected result. On the other hand, the observed emittance growth could not be fully attributed to space-charge effects due to rectilinear motion, but partially to a systematic collective effect in the measurement. This is also not surprising, as there are many analogous scenarios in high-brightness beam experimentation where collective effects tend to obscure the measurement being undertaken. In an effort to take advantage of the time-correlation in the beam energy spread, we have adopted a beam-slicing technique. While it was initially concluded from the predictions of the projected beam distribution onto the usual local Cartesian axes that the bending of the beam would cause the beam to become less dense, it was found that the opposite was true. Thus as a side effect of this investigation, a novel effect, that of anomalous density increase of energy-chirped beams in bends, has been brought to light. The importance of this general result probably lies most significantly in understanding it in precisely the scenario in which it was encountered — in a beam-slicing measurement.

While it is of interest to study the intermediate state of the beam as it undergoes velocity bunching, it has been seen to be far from straightforward to do so. In addition to collective effects, one can generally state that beams with such large energy spread as the chirped beam in the Neptune experiments will be difficult to unambiguously diagnose. We thus proceed to study beams at LLNL that have been completely velocity bunched, with the bunching arrested, and the large energy spread removed as well as possible. The experiments we present are performed in a different regime, that of phase space rotation in long linac. The physics the bunch compression in this regime are discussed within the context of the relevant experimental setup located at the Livermore ICS facility, PLEIADES. This facility allows not only the opportunity for optimized bunch compression and energy spread mitigation, but it also contains focusing solenoids that can be used to control the emittance growth that asserts itself during the compression.

8. Velocity bunching using phase space rotation

Velocity bunching, in the form initially proposed by SF, differs from the ballistic bunching technique discussed above. While in ballistic compression the RF structure is used to impart a longitudinal phase space correlation that is removed later by a drift, in the phase space rotation method, the energy/phase correlation is imparted and removed smoothly, through phase slippage
and acceleration, inside of the RF section. In this method the beam is rotated through one quarter of a phase space oscillation, as in Fig. 17.

To understand the velocity bunching mechanism in detail, we perform an analysis similar to that of SF, but using a speed-of-light phase velocity wave, as is available at the PLEIADES linac, instead of a slow wave treatment. If one follows the arguments of SF, it can be seen that a speed-of-light phase velocity may give very close to optimum compression, as deduced from a phase space mapping analysis which we will review below. The analysis of SF emphasizes the utility of slowing the wave phase velocity in the bunching system, in this case a one may obtain a quarter-rotation of the phase space occurs during acceleration. This rotation is idealized as beginning with a beam having no initial phase-energy correlation, injected at the zero-crossing of the wave, and ending with maximum energy spread and minimum phase extent.

In practice, the fact that this quarter-wave rotation from the ideal initial condition is not typically found in a speed-of-light accelerating wave is not critical, as the one may simply choose a slightly different initial RF phase to provide further rotation. Also, the tuning of the phase velocity also may be used to change the distance along the accelerator required to obtain a quarter synchrotron oscillation. This is helpful, as in the absence of such an option, one must rely on tuning of the accelerating field amplitude alone. In practice, this concern is also mitigated, since the linac sections at PLEIADES are relatively short (2.5 m), and adjustments in the phase between sections may be used to fine-tune the acceleration scheme, in a way that is functionally equivalent to changing the phase velocity. Because of these considerations, one may view the PLEIADES setup as equal in effectiveness to the ideal, slow-wave case analyzed by SF. As a final comment, we note that the minimum bunch length achievable in this system is dominated by the distortion of the final phase space by the nonlinearity of the sinusoidal forces used. This effect may be mitigated by use of higher harmonic RF cavities in addition to the fundamental.

We begin our analysis by considering the (averaged over the fast fluctuations of the field occurring in a single cell of the linac) interaction of an electron with the sinusoidal longitudinal electric field component of the RF wave in a traveling wave structure,

\[ E_z = E_0 \sin(\phi), \]

where \( \phi = kz - \omega t + \phi_0 \) is, as in our discussion of the ballistic buncher, the electron phase with respect to the wave, and \( k = \omega / c \) for the speed-of-light wave. Our phase convention is such that peak acceleration occurs when \( \phi = -\pi / 4 \). With this electric field, the electron motion obeys a time-independent Hamiltonian (which is thus a constant of the motion) of the form:

\[ H = \gamma - \sqrt{\gamma^2 - 1} - \alpha \cos(\phi), \]

where \( \alpha = \frac{eE_0}{mc^2k} \) is the dimensionless vector potential amplitude of the wave. The electron trajectories can be tracked and plotted in \((\phi, \gamma)\) phase space using the electron equations of motion:

\[ \frac{d\gamma}{dz} = -\alpha k \sin \phi, \]

\[ \]
\[
\frac{d\phi}{dz} = k\left[1 - \frac{\gamma}{\sqrt{\gamma^2 - 1}}\right].
\] (13)

Examples of these phase space trajectories, which follow curves of constant Hamiltonian, is shown in Figure 17. In this case, trajectories are plotted for typical RF parameters at the LLNL 100 MeV linac, \( k = 59.8 \, \text{m}^{-1} \), \( \alpha = 0.3 \) and with a minimum \( \gamma \) between 2 and 10.

![Figure 17: Longitudinal phase space particle trajectories in a traveling wave linac section modeled by a sinusoidal accelerating field. The RF parameters used in the plot are typical values for the LLNL 100 MeV linac. The plot illustrates the phase space rotation compression mechanism for a bunch injected near the RF zero crossing.](image)

As the plot shows, particles injected at or near \( \phi_0 = 0 \) will begin to slip into an accelerating phase. As the particles accelerate to ultra-relativistic velocity, the phase slippage slows, and is eventually arrested. This can be seen by using \( \gamma >> 1 \) in Eq. 13, giving 
\[
\frac{d\phi}{dz} \approx -\frac{k}{2\gamma^2},
\]
which goes to zero sufficiently quickly for \( \phi \) to approach a finite asymptote. The asymptotic phase limit can be found from Eq. 11 to occur when 
\[
H = -\alpha \cos \phi.
\]
In terms of the initial conditions \( \phi_0 \) and \( \gamma_0 \), the phase as \( \gamma \to \infty \) is:
\[
H = -\alpha \cos \phi_\infty = \gamma_0 - \sqrt{\gamma_0^2 - 1} - \alpha \cos \phi_0, \quad \text{or} \quad (14)
\]
\[
\phi_\infty \approx \cos^{-1}\left[\cos \phi_0 - \frac{1}{2\alpha \gamma_0}\right], \quad (15)
\]
where, as above, the approximation \( 1 - \beta = 1/2\gamma^2 \) has been used.

The phase space rotation occurs as a result of the varying orientation of the phase contour lines. If two particles are injected at \( \phi_0 = 0 \) with a difference in phase but no spread in energy, such that they align parallel to a phase contour, then they will remain parallel to that contour as they slip in phase and accelerate. As the particles approach \( \phi_\infty \), their orientation becomes nearly parallel to the \( \gamma \) axis, having rotated by nearly 90 degrees. To evaluate the phase compression
that occurs for a beam with non-zero initial phase and energy spreads, \( \Delta \phi_0 \) and \( \Delta \gamma_0 \) respectively, one can assume for simplicity that the extraction phase is \( \phi_\infty \). In that case, expanding Eq. (15) to first order in the initial energy spread and second order in the initial phase spread gives

\[
\Delta \phi_\infty = \frac{\sin \phi_0}{\sin \phi_\infty} \Delta \phi_0 + \frac{1}{2 \alpha \gamma_0^2 \sin \phi_\infty} \Delta \gamma_0 + \frac{1}{2} \left[ \frac{\cos \phi_0}{\sin \phi_\infty} - \frac{\cos \phi_\infty \sin^2 \phi_0}{\sin^3 \phi_\infty} \right] (\Delta \phi_0)^2. \tag{16}
\]

Using \( \Delta \gamma_0 / \gamma_0 = 10^{-3} \), \( \Delta \phi_0 = 4^\circ \), \( \gamma_0 = 8 \), \( \alpha = 0.3 \), and \( \phi_0 = 0 \) results in a final phase spread of \( \Delta \phi_\infty = 0.2^\circ \), and a compression ratio of roughly 20.

![Figure 18](image)

**Figure 18:** (a) Phase contours (solid lines) intersecting an ellipse (dashed line) representing the injected beam distribution. (b) Phase contours (solid lines) and extracted beam phase space (dashed line) obtained by integrating Eqs. (12) and (13) for points on the injected beam ellipse.

It is important to note that for this example, the \( (\Delta \phi_0)^2 \) term in Eq. (16) is an order of magnitude larger than the \( \Delta \gamma_0 \) term, thus explaining our dropping of the term proportional to \( (\Delta \gamma_0)^2 \). The fact that the phase spread of the injected beam limits the minimum final bunch length is a result of nonlinear RF forces increasing the longitudinal emittance of the beam. This can be understood by examining the constant Hamiltonian lines at the injection and extraction points. At \( \phi_0 = 0 \) the phase contours, \( \gamma(\phi,H) \), have a curvature that does not follow the outline of the injected beam ellipse (using the same parameters as above). As the beam transforms under the influence of acceleration and slippage these contours “straighten out” near the asymptotic phase, forcing the initial ellipse to distort, gaining a nonlinear correlation and therefore, an increased emittance. This process is illustrated in Figure 18, which shows the phase contours intersecting the initial beam ellipse in (a) and the same contours in (b) as the phase approaches \( \phi_\infty \) with the resulting distorted beam shape.
9. Velocity bunching at PLEIADES

The PLEIADES facility at LLNL produces picosecond pulses of hard X-rays (10-200 keV) by colliding an ultra-relativistic electron beam (20-100 MeV) with a high intensity, 50 fs, 800 nm laser pulse. This X-ray source is designed to enable pump-probe experiments used to temporally resolve material structural dynamics on atomic time scales [4]. The duration of the X-ray pulse generated though this scattering process is determined by the duration of the overlap of the electron and laser beams. Thus, to produce sub-picosecond X-ray pulses desirable for pump-probe experiments, one may choose a 90º interaction geometry, in which the laser samples only part of the highly focused electron beam, or a 180º geometry, where the laser interacts with the entire electron bunch, which must be compressed to sub-picosecond length.

![Figure 19: HOMDYN simulation of the bunch length and relative energy spread in the velocity bunching scheme implemented at PLEIADES. The bunch charge in this case is 250 pC.](image)

Bunch compression is therefore, an attractive option for the facility, but since the brightness of the X-ray source depends critically on the electron beam spot size \( B \propto \sigma^{-4} \), the bunching method used must be evaluated to determine if negative effects on the emittance or energy spread of the beam will reduce X-ray brightness to an unacceptable level. Velocity bunching is an obvious choice for this application, because the compression effectively occurs at low (gun exit) energy, and thus one may remove much of the energy spread that can cause unacceptable chromatic aberrations in the ICS final focus. The PLEIADES experiments thus also afford us the ability to examine effect of velocity bunching on the ICS source.

The PLEIADES photoinjector and linac consist of a 1.6 cell photo-cathode RF gun followed by four SLAC style 2.5 meter, S-band traveling wave sections. While the linac is capable of producing 100 MeV electrons, it is typically run using only the first two or three sections for X-ray production, resulting in an energy between 20 and 70 MeV. The gun and each linac section are powered by separate klystrons, making power and phase control independent for each
accelerator section. We simulated the velocity bunching process in this system using HOMDYN and PARMELA, as in the ORION study above. In this case, however, experimental values of the accelerating gradients in the different accelerators were used in the simulations.

In Fig. 19 the pulse length and relative momentum spread evolution are simulated using HOMDYN. The gun field gradient used in this simulation was 75 MV/m (limited by RF breakdown at the time of the measurements) and the charge was 0.25 nC. As the figure shows, these parameters result in significant bunch lengthening and increased energy spread after the gun. At the entrance to the compressor section, the beam correlation in longitudinal phase space is the opposite of that required for compression. It is clear from the evolution of the energy spread in Fig. 19 that this correlation is quickly reversed in the compressor, but the presence of this correlation requires a larger amount of phase space rotation in order to fully compress the beam. Consequently, it was found in these simulations that the injection phase that gives the shortest output bunches was $-17^\circ$ (i.e. ahead of the zero crossing). It is interesting to note that the optimal injection phase even for an idealized, uncorrelated beam was found to be about $2^\circ$ forward of zero crossing. This is because the average exit phase of the beam is not $\phi_\infty$, since the RF section has a finite length. The phase contours at the beam exit point have a finite slope, and injecting slightly ahead of $\phi = 0$ compensates for this slope.

Figure 20: PARMELA simulation of the longitudinal phase space (a) before the compressing RF section and (b) after the section. A clear de-bunching correlation is present and must be removed at the beginning of the bunching section.

Figure 20 shows the longitudinal phase space plots in PARMELA simulations for the injected and extracted electron bunches. The strong debunching phase space correlation of the injected beam is clearly evident. The simulated rms bunch duration reaches a minimum value of approximately 200 femtoseconds, and does not change significantly after the compressor. The rms relative energy spread at the end of the compressing section is 3%. In the two accelerator sections after the compressor, the beam is injected at $\phi = -\pi/2$ for maximum acceleration. Immediate acceleration of the beam is important, as it arrests the bunching process, decreases the
relative energy spread, and mitigates the extremely strong transverse space-charge forces on the bunch, which at this point has 500 amps peak current and low energy ($\gamma = 16$).

The final beam energy predicted by simulation was 50 MeV. The final rms energy spread, as shown in Fig. (19) is 0.5%. The energy spread produced by simulating all three sections on crest is 0.2%, in agreement with beam measurements. This increase in energy spread is potentially problematic, since it can limit the minimum spot size achievable in ICS X-ray generation. It will be shown below however, that emittance is the dominant factor for our experiments so that emittance growth and not energy spread is the larger concern for X-ray production.

![Figure 21](image)

**Figure 21**: PARMELA simulation of the rms spot size (solid line) and normalized emittance (dashed line). In (a) the solenoid strengths are chosen to keep the beam size constant in the compressing and accelerating sections. The beam is mismatched in (b), resulting in emittance growth.

As was done in the ORION simulations, control of the transverse dynamics is accomplished with the solenoids that are placed around each of the traveling wave sections. Emittance growth is avoided by choosing the focusing strength of the solenoids to match the defocusing space-charge forces on the beam. This process is illustrated in Fig. 21, which shows the evolution of the horizontal spot size and normalized emittance of the beam as it compresses. The gun solenoid strength is set to match the beam into the compressor section in the manner prescribed by emittance compensation. From the compressing section the solenoid strengths are set to minimized beam size oscillations through the system. The emittance oscillations, as in the ORION simulations, increase in frequency as the bunch compresses and subsequently slow as the beam accelerates. This is a sensitive process; the plot in Fig. 21(b) shows emittance growth caused by mismatching one of the section solenoids.

In addition to this matching sensitivity, it was also observed in the simulations that emittance growth was a very sensitive function of compression. When the beam compresses to the point of longitudinal phase space wave-breaking, the emittance compensation (or more aptly, control of oscillation) process no longer works well.
9.1. *Experimental Measurements*

The phase space rotation method has been used in the PLEIADES system as described in the previous section. The beam and accelerator parameters were measured and used to generate the simulations shown above. Specifically, a 250 pC, 3.5 MeV bunch was generated with the 1.6 cell gun and compressed in the first of three traveling wave sections used in the experiment. The accelerating gradients of the first to last sections were 5, 10, and 10 MeV/m, respectively, with the low gradient in the first section due to low available klystron power.

![Figure 22](image-url)

*Figure 22:* Model calculation of the phase slippage in the compressor as a function of injection phase. The injected phase is relative to the phase for best acceleration, 20° ahead of crest.

![Figure 23](image-url)

*Figure 23:* Autocorrelation data for the optimally compressed bunch at PLEIADES.

As in the Neptune measurements, CTR interferometry was used to measure the sub-picosecond pulses we produced. The experimental procedure used to compress the beam was complicated slightly by the fact that the amount of phase slippage in the compressor section
varies significantly with injection phase. As a result, it is insufficient to change only the phase of the compressor and ignore the phases of the following sections. A model calculation of the dependence of phase slippage on injection phase is shown in Fig. 22; it indicates that the amount of phase slippage increase from the best acceleration phase to the best compression phase is more than 30º. Phasing the following sections appropriately must be done to properly accelerate on crest, thereby arresting the phase space rotation and minimizing the relative energy spread.

The electron bunch was compressed by initially tuning the linac for highest energy. The phase of the compressor section was then set and the phases of the accelerating sections were also set using the calculation in Fig. 22 and fine tuned by maximizing the CTR detector signal.

![Figure 24](image)

Figure 24: (a) Image of the compressed beam at the spectrometer. (b) Lineout of the image in (a). The relative, rms energy spread is roughly 0.5%.

The interferometer data obtained for the shortest bunch length achieved is given in Fig. 23. The data analysis was performed using the same method as with the Neptune case. The fit gives a 300 fs rms minimum bunch length. The 100 µm wire spacing in the interferometer polarizers sets an upper limit for frequencies transmitted to the Golay cell detectors and therefore a lower limit on the detectable pulse length. This effect is clearly important for bunch lengths of 300 fs or shorter. The measurement therefore may give an upper bound to the bunch length, which is a bit longer than given in simulations (~200 fs) as seen in Fig. 19. Note also that this measurement produced even shorter beams, at approximately the same charge, as the Neptune measurements. This is most likely due to the shorter initial pulse length (2.5 psec rms) in the PLEIADIES case. The minimum rms bunch length obtained at PLEIADIES is also a factor of 2 shorter than that observed in previous velocity bunching experiments at BNL [13].

The compressor phase for strongest compression was measured at 85º ahead of the best acceleration phase, which, because of the amount of slippage through the section, is about 20º ahead of crest. This agrees well with simulations. The energy spread was measured at the end of the linac using a spectrometer magnet and found to be roughly 0.5%, as shown in Fig. 24.
9.2. ICS X-ray Generation

While compression of electron beam to ultra-short length using velocity bunching is of high interest, application of this beam is perhaps more compelling. The compressed electron bunch was used in ICS experiments to generate sub-picosecond, 78 keV X-rays at PLEIADES. A schematic of the PLEIADES beamline is given in Fig. 25. The electron beamline consists of a two triplets of quadrupole magnets, the first used to measure the Twiss parameters of the beam exiting the accelerator and match into the second set, which serve as the final focus optics before the laser-electron interaction. In addition, there are pop-in diagnostic cubes, one used to generate CTR for the bunch length diagnostic and the other to image the beam. The FALCON
Ti:Sapphire based laser system delivers a 500 mJ, 50 fs (FWHM) pulse of 800 nm light to the interaction area. The laser is focused by a 1.5 m focal length off-axis parabolic lens and directed by a final turning mirror into the 180° interaction geometry displayed in Fig 25. The X-rays generated at the interaction point propagate in the direction of the electron beam, pass through the final laser mirror and are detected by a CsI scintillator fiber coupled to a 16-bit CCD camera.

Two of the technical requirements of the ICS experiment are the ability to overlap the two beams spatially and temporally at the interaction point, and to achieve the highest beam densities possible at that point. These issues are addressed with a diagnostic inserted at the interaction point. A 0.76 cm, polished aluminum cube, mounted on a 3-axis translation stage, is placed in the beam path as illustrated in Fig. 26. In one position the cube reflects the (highly attenuated for measurement purposes) laser and the optical transition radiation (OTR), generated by the electron beam passing through the cube surface, out of the vacuum chamber to a CCD video camera. When the cube is translated horizontally, the beams hit adjacent sides of the cube and are redirected out the opposite vacuum port to a streak camera.

For both the compressed and uncompressed electron beams, the emittance was measured using quadrupole scanning. The best emittance achieved in the uncompressed case was considerably poorer than that predicted by PARMELA. This is most likely due to the poor spatial profile of the photoinjector drive laser, and the observed misalignments of the section solenoid magnets. The emittance was observed to be asymmetric in the $x$ and $y$ dimensions, and the best rms normalized emittances obtained were 5 mm-mrad horizontal by 12 mm-mrad vertical. These problems made the study of emittance of the compressed beam more difficult to interpret. Since, for the present experiment, we are interested in emittance growth in so far as it affects the focusability of the electrons, the details of this study have been left for future investigation. Note however, that the emittance was found to be very sensitive to the strength of the compressor solenoid, as was also observed in simulations. The minimum emittances of the fully compressed beam grew from those of the uncompressed case to 12 by 12 mm-mrad.

Typical optimized focused electron beam spots at the interaction point are shown for both the uncompressed and compressed cases in Fig. 27. The bunch charge in both cases was 250 pC. The compressed beam was measured to be roughly 50% larger than the uncompressed. The rms dimensions of both beams are given in Table 1.

![Figure 27](image-url): CCD images of the (a) uncompressed and (b) compressed electron-beam spots at the interaction point.
Table 1: RMS sizes of the compressed and uncompressed electron beams at the interaction point.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Compressed Beam</th>
<th>Uncompressed Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>50 µm</td>
<td>30 µm</td>
</tr>
<tr>
<td>Y</td>
<td>35 µm</td>
<td>25 µm</td>
</tr>
<tr>
<td>Z</td>
<td>0.1 mm</td>
<td>1.0 mm</td>
</tr>
</tbody>
</table>

Temporal overlap was accomplished by streaking the two beams at the interaction point. Streaking also allowed us to examine the timing jitter and drift of the beams. Picosecond level timing jitter is obtained at PLEIADES by using a single laser oscillator as the source that seeds both the Compton scattering laser and the photo-cathode drive laser. The low level RF is also generated by frequency multiplying a photodiode signal from the same oscillator. With the RF and laser pulses synchronized in this way, the timing jitter at the interaction point has been measured to be 2 ps rms, which is at the resolution limit of the streak camera that was used.

![Figure 28](image_url)

**Figure 28:** Laser to electron beam timing jitter measurements taken at three different times. The shot-to-shot jitter is 2-4 psec while the total drift from the two extreme data sets is 35 psec.

The process of bunch compression suppresses differences in injection phase, as measured with respect to the RF clock, demagnifying the initial laser-to-rf jitter by approximately the compression ratio. Thus because the FALCON and photoinjector drive laser are nominally locked, the tendency of the photoelectron beam to be locked to the RF clock by compression should increase the electron beam/FALCON laser jitter. The compressed bunch was streaked at the interaction point in order to measure this effect. An analysis of three different sets of streak camera images, each set taken a few minutes apart, was performed and the result is shown in Fig. 28. The shot-to-shot jitter was found to be 2-4 psec, rms, which was slightly higher than that obtained with the uncompressed beam. More impressively, the laser and electron beam timing drifted noticeably over time, an effect not seen with uncompressed electrons. This drift was observed to be as large as 35 psec, and occurred on a time scale of several minutes. The phase of
the gun and each of the TW sections in the linac are measured and feedback loops are in place to prevent phase drift on a time scale longer than a second. The observed time-of-flight drift may be due to slow drifts in the klystron power output feeding the compressor section, which is not controlled by a feedback loop. This drift affects X-ray production in the uncompressed case as well since it alters the beam energy, thereby affecting the steering and focusing of the electrons at the interaction point.

Figure 29: Single shot, false-color X-ray beam images measured by the CCD for the (a) uncompressed and (b) compressed electron beams. The color scale has yellow as most intense, with violet as lowest non-negligible intensity observed.

To produce X-rays, the energy of the compressed electron beam was increased to 58 MeV by increasing the amount of RF power in the final TW section. This was done to match the energy obtained under normal conditions, and therefore produce the same X-ray wavelength. Doing this makes the comparison of X-ray data simpler since it removes the energy dependence of the laser turning mirror attenuation and the calibration of the X-ray CCD (see Fig. 25). The bunch length and emittance dynamics are not affected significantly by increasing the energy in this way.

The ICS X-rays were measured with the X-ray CCD camera for both the compressed and uncompressed beams. Figure 29 shows single shot X-ray beam data in these two cases. The number of X-ray photons can be derived from the CCD images and in the uncompressed case this number is $5 \times 10^6 \gamma$/pulse. For the compressed beam, a factor of 4-5 fewer photons were observed, yielding approximately $10^6 \gamma$/pulse. When the CCD camera is integrated over many shots the ratio of normal/compressed X-rays increases. This is most likely a result of the timing drift discussed above.

The degradation of X-ray photon yield with velocity-bunched beam is due to the loss of electron beam focusability, which arises because of both emittance growth, and final focus chromatic aberrations that increase in importance with the enhanced energy spread of a velocity-bunched beam. At the present time, the electron beam final focus has been upgraded to an extremely short focal length, permanent magnet quadrupole-based system\textsuperscript{31}. This improvement allows the mitigation of the chromatic aberrations while lowering the minimum $\beta$-function at
focus, thus giving the potential to obtain much smaller spots. Much smaller spot sizes have been obtained with this system, but not yet with velocity bunching deployed.

10. Conclusions

We have presented here two scenarios for velocity bunching, one employing ballistic bunching, and the other based on phase space rotation. The ballistic bunching scenario was introduced in the context of the ORION injector, and the physical issues surrounding its use were discussed using illustrative simulations. These simulations included the envelope code HOMDYN, which was used to identify the overall experimental parameters, and macroscopic envelope performance. In order to understand microscopic issues such as emittance evolution, it was necessary to use of multi-particle simulation. It was shown that the bunch may be shortened by an order of magnitude in length using a short, high gradient linac section, followed by a drift to compress the beam. The compression is arrested in post-acceleration, longer linacs, which are embedded in magnetic solenoids with a tailored, increasing profile in $z$. These solenoids provide transverse focusing that serves to control the emittance oscillations that arise from the raising of the beam current during compression. This control is predicted to work well provided that a longitudinal “cross-over” is avoided, a scenario already known to give emittance growth from low-energy chicane compression experiments.

Experimental investigations of the ballistic bunching scheme, carried out at the UCLA Neptune laboratory photoinjector, allowed examination of the bunching stage of the scheme, but not post-acceleration or emittance control. Excellent bunching performance, with over an order of magnitude compression factor, has been observed. This bunching effectiveness exceeded those seen in both Neptune chicane compression and BNL velocity bunching experiments. In addition, measurement of the transverse emittance growth as a function of bunching was attempted. The interpretation of these “slice” experiments was obscured somewhat by the presence of a previously unanticipated anomalous compression expression in the dispersive dipole. This effect leads, according to three-dimensional Lienard-Wiechert code simulations, to emittance growth in addition to that occuring during the rectilinear propagation of the beam.

The concept of phase space rotation-based velocity bunching has been discussed in the context of the PLEIADES injector, which is employed in inverse Compton scattering experiments at LLNL. This system is part of an integrated beam handling philosophy which cThis system is similar to the original proposal of Serafini and Ferrario, with the exception of the use of speed-of-light phase velocity. It was shown, through Hamiltonian analysis and HOMDYN simulations, that the slow-wave linacs emphasized by SF are not critically necessary, especially for the relatively short (2.5 m) low gradient linac sections. The PLEIADES injector system is outfitted with independently-powered solenoids, allowing emittance control, which was shown to be both imperfect in effectiveness and sensitive to envelope injection mismatch. The multi-particle PARMELA simulations we employed have shown that the emittance control is nonetheless relatively robust until one encounters longitudinal cross-over effects.
In experiments at PLEIADES, an even shorter rms pulse length, $\sigma_p = 0.3$ psec, was achieved than that found at Neptune, and a factor of 2 shorter than that observed in a similar scenario at BNL SDL[13]. The PLEIADES measurement is near the minimum resolvable pulse length of the CTR interferometer used, and is thus consistent with the predictions of simulation and instrument resolution. Achieving this pulse length is accompanied by moderate emittance growth, which, along with chromatic aberrations, produce an increase in final spot size. Nevertheless, we have shown the utility of the velocity bunching process for producing a decrease in X-ray pulse length, and an increase in photon brightness from the PLEIADES ICS. This spot size increase causes the yield to decline by a factor of 4, while the peak current rises by at least a factor of ten. The performance of the system was limited by poor initial emittance in the beam after the gun, by misalignment of the focusing solenoids, and by drifts in the RF system. Efforts are underway to improve all of these experimental characteristics, in order to achieve velocity-bunched beam spots as small as 10 $\mu$m rms using the new permanent-magnet quadrupole final focus system.

One of the most compelling improvements in velocity bunching experiments would be to run the rf gun at much higher gradient, in order to improve the emittance performance, and move to higher beam charge cases. Such a system, the SPARC photoinjector$^{32}$, is now under construction in Frascati. The SPARC experiment, which is intended to demonstrate beam brightness that is consistent with driving of a very short wavelength FEL, will devote much of its agenda to optimized velocity bunching studies, with precisely aligned solenoids, slow-wave bunching linacs, and an array of advanced beam diagnostics. The bunch length diagnostics will include a new, higher resolution CTR interferometer based on amplitude splitting, not polarization$^{33}$, as well as an RF deflector which should provide sub-100 micron resolution. Additionally, plans are underway to install a 4th harmonic rf cavity, allowing a much more linear compression, and shorter bunch final lengths. The SPARC experiment promises to provide more definitive tests of the usefulness of velocity bunching for high brightness electron beam production.

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12. References

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