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Subpicosecond Compression Experiments at Los Alamos National Laboratory*

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Abstract. We report on recent experiments using a magnetic chicane compressor at 8 MeV. Electron bunches at both low (0.1 nC) and high (1 nC) charges were compressed from 20 ps to less than 1 ps (FWHM). A transverse deflecting rf cavity was used to measure the bunch length at low charge; the bunch length at high charge was inferred from an induced energy spread of the beam. The longitudinal centrifugal-space charge force [Phys. Rev. E **51**, 1453 (1995)] is calculated using a point-to-point numerical simulation and is shown not to influence the energy-spread measurement.

INTRODUCTION

The prospect of advanced accelerator applications such as linear colliders (1,2) and short-wavelength free-electron lasers (3,4) has motivated research into developing shorter and shorter electron bunches while maintaining high brightness. Typical design goals for pending machines require compressing 1 nC into a FWHM bunch length of

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about 0.25 ps with a final emittance of 1π mm mrad. The current state-of-the-art bunch compression is from 10 ps to 0.6 ps at 37 MeV with 0.15 nC, with a transverse normalized emittance of about 25π mm mrad (5). Also of note is the compression reported using an alpha-magnet and rf gun (6), which was as low as 0.1 ps, but with charges less than 0.05 nC. These results clearly do not meet advanced accelerator requirements.

We have recently completed construction of a low energy (8 MeV) linac, the Subpicosecond, High-brightness Accelerator Facility, which is being used for magnetic compression experiments aimed at investigating fundamental limits regarding the above goals. This linac is based on the 8-MeV, 5.5-cell photoinjector standing-wave accelerator tank used in the APEX free-electron laser experiment at Los Alamos (7). Prompt electron emission from a cathode on the upstream end of the tank is triggered by an ultraviolet drive laser pulse of variable radius, length, and timing relative to the rf in the resonant cavities in the tank. The drive laser is typically timed such that the electrons are emitted very early in the rf cycle, well before the field in the first cell is peaked. This ensures that the electrons at the rear of the bunch have a higher energy after they exit the tank than those at the front. After the electrons leave the accelerator they encounter a independently phased rf cavity, called the phasing cavity. The purpose of this cavity is to allow for some modification of the beam's energy-phase distribution. In general, this cavity is phased such that the center of the bunch does not change energy (it arrives at the center of the cavity during the zero-crossing of the sinusoidal rf field), but the front of the bunch is decelerated and the rear is accelerated in order to increase the energy slew across the bunch. However, for some applications this cavity's net phase can be modified. Next, after some focusing elements, is a four dipole chicane. The chicane consists of four identical dipoles with parallel pole faces and with virtually no gap separating them. The beam box is large through the chicane, and allows transmission of the beam with no appreciable interception throughout the range of bend angles from 0 degrees to 45

degrees. A transversely deflecting rf cavity, known as the fast deflector (8), is located after the chicane. The fast deflector has a TM_{110} mode operating at the same frequency as the injector and phasing cavities. The magnetic field of this mode points vertically, and deflects the beam horizontally. If the phase of the cavity is adjusted so the field is zero when the center of the bunch is at the center of the cavity, the bunch center will not be transversely deflected. However, the front of the bunch will be deflected sideways, and the rear of the bunch will be deflected in the opposite direction. As the bunch travels further, it spreads out horizontally, and the bunch length can be measured on a downstream screen that intercepts the beam. The beam line is shown in Fig. 1 and the chicane geometry, including the dipoles and the beam box, are shown in Fig. 2.

This paper begins with a short discussion concerning the design of the chicane compressor. Because of the low energy of the linac, special care was taken to minimize the effect of space charge degrading the compression and the beam emittance. In the following section, we review the main effects of the longitudinal centrifugal space-charge force (LCSCF), and present simulations of the induced emittance growth from these effects in this chicane. In the fourth section we discuss our low and high charge results, including a description of the measurement techniques and estimated measurement accuracy. We measured a compressed FWHM bunch length of less than 0.25 ps for 0.1 nC and a compressed FWHM bunch length of about 0.70 ps for 1.1 nC. The low charge case corresponds to a pulse width compression ratio of at least 60. The paper concludes with a section describing future emittance measurements which will be used to investigate the longitudinal centrifugal space-charge force. Because the emittance for a beam produced in a photoinjector is very hard to measure, a new technique is being developed, which is discussed in some detail.

DESIGN CONSIDERATIONS

The fundamental idea behind magnetic compression is that although each particle travels essentially at the speed of light, they can have different path lengths from one point to another, and thus their longitudinal distribution is not fixed. In a four-dipole chicane this is done by having the magnetic field in the dipoles oriented in a $+-+-$ or $-+-+$ order. In Fig. 3 we see the path taken by both a high and a low energy electron, and note that the path length is longer for the lower energy particle. Thus, if the particles at the rear of the bunch have higher energy than those at the front, at the end of the chicane they will have caught up somewhat. Ideally, the dispersion of the magnetic compressor and the energy-phase correlation of the bunch are both linear, and the bunch can be compressed to extremely short lengths. In practice, both the dispersion and the energy-phase correlation are nonlinear, and in addition, the longitudinal emittance is nonzero, leading to a nonzero energy spread at all longitudinal positions within the bunch. Some combination of the nonlinearities of the dispersion and energy-phase correlation and the instantaneous nonzero energy spread lead to the minimum possible bunch length. Both of the recent experiments referenced above (5,6) used compressors with large nonlinear dispersions, and typically a sizable fraction of the bunch was not compressed well.

In this experiment, we wanted to have as linear a dispersion as possible, in order to investigate compression limits. The magnetic chicane is well-known for its relatively linear dispersion (9,10,11), and its use would allow us (1) to investigate how linear we could massage the bunch's energy-phase correlation with various drive laser and phasing cavity phasings, and with various drive laser pulse lengths, and (2) to try to compress down to the limit imposed by the instantaneous energy spread. In addition, the low emittance of the photoinjector (as low as 2.5π mm mrad per nC of charge) would allow

investigation into the proposed emittance growth mechanism of the short-bunch longitudinal centrifugal space-charge force (12).

Let us examine the optics of the chicane (dipoles and beam-box), shown in Fig. 2, in a little more detail. The first and last dipole deflect the beam upwards (in the figure) and the middle two dipoles defect the beam downwards. By adjusting the phasing cavity, the energy slew from the front of the bunch to the rear can be adjusted. When the slew is relatively small for a given dipole field strength, the particles at the end of the bunch only catch up partway to the ones at the front of the bunch (this condition is called under compression), and when the slew is relatively large, they overtake and lead the particles initially at the front of the bunch (this condition is called over compression). Maximum compression occurs at the energy slew with which the particles initially at the rear of the bunch end up after the chicane essentially at the same axial position as those initially at the front. Note that for a given energy slew, the conditions of under compression, maximum compression, and over compression can be achieved by varying the magnetic field strength in the chicane dipoles. The beam box used is wide at the center of the chicane where the dispersion is greatest. Thus the current driving the field in the dipoles can be gradually increased, changing the bending angle in each of the dipoles in the chicane from the condition of no compression to the condition of maximum compression, with full beam transmission for all cases. The major design consideration for the chicane was to keep it as short as possible in order to eliminate excessive drift distances. As the beam drifts, the longitudinal space charge force accelerates the front of the bunch and decelerates the rear. This change in energy can degrade the compression if it occurs within the chicane. In addition to eliminating drifts between the dipoles, the optics were designed to keep the beam as large as possible in the final dipole in order to minimize the longitudinal space-charge force. The danger in keeping the beam large in the final dipole is that a large beam radius acerbates any emittance growth; however the primary purpose of this experiment is to demonstrate high compression ratios and as small as possible

final bunch lengths. An ancillary requirement in removing the drifts between the dipoles is to minimize the fringe fields from the dipoles. This was done by using H-magnets and using a vertical 10-turn stack, only a single loop thick, for the current driving the electromagnets (Fig. 4). This geometry provides for the maximum pole face area, and eliminates much of the fringing fields. A useful quantitative figure of merit for the extent of how far the fields fringe is the k_1 value, defined in (13):

$$k_1 = \int_{-\infty}^{\infty} B_y(s) \frac{B_o - B_y(s)}{gB_o^2} ds \quad (1)$$

where s is the path length variable for the beam in the bend, g is the magnet gap, $B_y(s)$ is the dipole field as a function of path position, and B_o is the asymptotic dipole field in the center of the magnet. Note from this definition, if the dipole field is truly "hard-edged" (uniform through the dipole and zero outside), k_1 vanishes. Typical values of k_1 vary from 0.45 to unity, depending on the exact design and characteristics of the magnet (C-magnet yoke, permanent magnet, and so on). The k_1 value for the fringe fields between the central magnets for this design is 0.045, the k_1 value for the fringe fields between the dipoles of opposite polarity is 0.12, and the k_1 value for the end fringe fields is 0.22.

Another important feature of this design is that the dipole pole faces are made parallel in order to ensure that the chicane is very nearly achromatic in the absence of space charge. Note that with parallel pole faces any transverse or angular displacement of the beam does not lead to an emittance growth. The coils for the dipoles in this experiment are connected electrically in series to simplify their operation. The slight field differences (about 3%) between the outer and inner dipoles due to the small difference in the k_1 values is eliminated by driving the center two dipoles with a small power supply in parallel to the main one.

Special care was also taken for the design of the chicane beam box to prevent the generation of any longitudinal wakefield. Any perturbation in the beam box can lead to significant wakefields, which then change the energy of the bunch within the chicane, destroy the chicane's achromaticity, and can lead to a large emittance growth (14,15). At the start of the beam box, the initially round beam pipe opens into an elliptical pipe, with a 3 to 1 ratio (the wider side is in the bend plane), shown in Fig. 5. This elliptical geometry concentrates the beam's wall currents above and below the beam, and any protrusion or discontinuity along the horizontal ends does not produce significant wake fields (16). This also eliminates any significant wakefields as the beam is bent in the dipole field and as the horizontal gap is widened further to allow for both straight through passage and large chicane bend angles. At the downstream exit of the beam box, a round beam pipe with the same dimension as the preceding round beam pipe protrudes into the elliptical pipe. The radial electric space-charge field lines extending from the bunch to the elliptical beam pipe walls are neatly sliced off as the bunch reaches the entrance of the round pipe, and no significant longitudinal wakefields are produced there either.

In addition to the chicane itself, care was taken to minimize the wakefields produced by the electron bunch throughout the beam line. The intercepting diagnostic screens (based on transition radiation as the beam passes through them) are "self-healing", and when the screen are retracted they are replaced by a smooth round section of beam pipe, in electrical contact with the rest of the beam line. Bellows used in the beam line for alignment have smooth round tubes shielding the beam from the metal folds. It should be noted that the energy spread induced by the longitudinal wakefields are virtually the same preceding and after compression; however, the longitudinal wakefields could harmfully distort the bunch's energy-phase correlation before the chicane, leading to poor compression. Also, emittance growth from transverse wakefields after compression are minimal because of the short electron bunch size. Thus, extraordinary care to eliminate wakefields was only performed up to and through the

chicane. The few wakefield-inducing components after the chicane (spectrometer box and beam pipe size mismatches around the fast deflector) lead to minor adjustments in interpreting energy spread measurements in the spectrometer (about 1/2%). Of course, there are substantial longitudinal wakefields produced in the accelerator cavities and phasing cavity; these wakefields are an important contribution to linearizing the bunch's energy-phase correlation. Without the wakefields, the correlation is always nonlinear from the sinusoidal dependence of the rf field. In order to compress a beam with a nonlinear correlation significantly, a large bend angle must be used in the dipoles in order to introduce a nonlinearity in the chicane's dispersion that can cancel the nonlinearity in the beam's longitudinal phase space. This is relatively hard to experimentally optimize, and not always possible. However, as longitudinal wakefields are produced, the energy-phase correlation becomes more linear (because the instantaneous current is peaked at the center of the bunch). This allows operation with a smaller bend angle and more linear dispersion.

THE LONGITUDINAL CENTRIFUGAL SPACE-CHARGE FORCE

The short-bunch longitudinal centrifugal space-charge force may lead to a fundamental limit for compression. If an electron beam is not accelerating, it is easy to show that both the transverse and longitudinal space-charge forces scale inversely with the square of the relativistic mass factor. Because of this fact, designs for advanced accelerators which include bunch compression have the bunch compression occurring when the beam is at a relatively high energy (often greater than a GeV). However, an energy-independent component of the longitudinal space-charge field is introduced if the beam is bent in a dipole field. Particles within the beam gain and lose differing amounts of energy as the beam travels in the dipole field, which lead to a potentially large and unacceptable emittance growth. This effect is easily seen if one first considers a short,

relativistic line of charge being bent in a circle by a dipole field, Fig. 6. The electric field along the direction of motion is given by

$$E_{\theta} = -\frac{\partial A_{\theta}}{\partial t} - \frac{1}{r} \frac{\partial \phi}{\partial \theta} \quad (2)$$

where the vector potential $\bar{A}$ is given to a very good approximation by $\bar{A} = \left(0, \frac{\beta}{c} \phi, 0\right)$ for typical advanced compressor designs, and where ϕ is the scalar potential. If the beam length is extremely short this expression fails, but otherwise the error introduced by this approximation is of higher order and can be neglected (12). Now let us assume a harmonic decomposition of the line of charge and field components in terms of the revolution frequency in the dipole. Equation (2) now holds where the field and potential components are replaced by $E_{\theta,n}$, $A_{\theta,n}$ and ϕ_n , and where the components have an $e^{jn(\omega t - \theta)}$ dependence and $A_{\theta,n} = \frac{\beta}{c} \phi_n$. Equation (2) becomes

$$E_{\theta,n} = j \frac{n \phi_n}{R} \left(\frac{1}{\gamma^2} - \frac{x}{R} \right) \quad (3)$$

Because we know that the first term leads to the "usual" longitudinal space-charge field (which scales as the inverse of the relativistic mass factor squared), the harmonic summation is trivial and the total azimuthal field from a line of charge is

$$E_{\theta} = E_{usual} \left(1 - \gamma^2 \frac{x}{R} \right) \quad (4)$$

The second term represents the contribution from the longitudinal centrifugal space-charge force. It has been estimated earlier (12) that emittance growth from the second term can be as large as $200 \pi \text{ mm mrad}$ for a 1-nC, 1-mm-radius bunch compressed to 1

ps in a 1-radian bend. A better estimate is made by including this effect directly into a particle pushing code. A custom space-charge routine was written (17) for the particle-pushing code PARMELA (18) in which the space-charge forces were calculated for point-by-point interactions between source lines of charge and observation points. The additional force from the LCSCF can be easily included in this type of space-charge routine by just multiplying the contribution from the source line of charge by the $\left(1 - \gamma^2 \frac{x}{R}\right)$ factor, where x is the separation between the line of charge and the observer point in the direction of the bend curvature and R is the bend radius for that source line. Care must be taken to ensure that causality is not violated in the simulation, in which case the longitudinal field contribution from that source line of charge vanishes. Simulations including this effect demonstrate that the emittance can be severely degraded during compression, but the induced energy spread is itself negligible and does not degrade the bunching.

Two useful numerical examples of the LCSCF for this compressor system are for (1) 1 nC at 7.5 MeV, and (2) 3 nC at 8.2 MeV, shown in Table I. The relatively large pre-compressor emittances are mostly due to the large rf-induced emittance growth associated with the long (20 ps) initial electron bunch length. In both cases, the emittance growth from the LCSCF easily dominates the rf-induced emittance growth and the compression is not affected.

LOW AND HIGH CHARGE COMPRESSION RESULTS

The Subpicosecond, High-brightness Accelerator Facility was designed to compress a 3-nC bunch from 20 ps to 0.65 ps (19) at 8.2 MeV. Initial experiments were carried out at 5.5 MeV, where only low charge bunching was feasible. Low charge (about 0.1 nC) experiments were performed, setting the chicane deflection angle to about

40 degrees, and then varying either the phase of the drive laser relative to the rf or, more commonly, changing the field strength in the phasing cavity while it was phased for no energy gain of the bunch center. Snapshots of the beam as it intercepts a screen 1 meter downstream from the fast deflector for a typical case are shown in Fig. 7. The deflection is calibrated by monitoring the spot shift on the screen as the phase of the fast deflector is changed slightly, and for the focusing in this case the deflection is 0.065 ps/pixel. Shown are images on the final screen for the cases: (1) fast deflector off (spot size FWHM 0.78 +/- 0.05 ps), (2) fast deflector on, phasing cavity on partially (field gradient 10 MV/m) (spot size FWHM 4.8 +/- 0.5 ps), and (3) fast deflector on, phasing cavity on full (field gradient 26 MV/m) (spot size FWHM 1.19 +/- 0.12 ps). After deconvolving the resolution limit (the focus size with the fast deflector off), the minimum FWHM bunch size for this case is 0.90 ps with an uncertainty of 0.15 ps. The horizontal profile of the spot for the compressed case (the image is integrated vertically) is shown in Fig. 8.

The minimum bunch length was found to occur when the drive laser was phased to emit the center of the electron bunch at 20 degrees past the zero-crossing of the rf in the first cavity and a relatively large chicane bend angle of over 40 degrees was used. For that case the resolution spot size FWHM (fast deflector off) was 0.92 +/- 0.10 ps, and the spot size with the fast deflector on was 0.80 +/- 0.20 ps, with a fast deflector calibration of 0.065 ps/pixel. The FWHM bunch length is less than the resolution limit of the fast deflector, 0.20 ps for this case. In Fig. 9 we show the PARMELA simulation for this case. We see that the predicted bunch length is 0.22 ps, which is consistent with the measurement. In the simulation, the minimum bunch length is determined by the energy spread across the radial dimension of the bunch, which is dominated by the different total acceleration of different electron at different radial positions in the beam. If the beam size is reduced in the accelerator, probably the compressed bunch length could be reduced, although it would be beyond our experimental resolution. PARMELA simulations indicate that the electron bunch length is compressed slightly in the

accelerator tank due to rf longitudinal focusing to 15 ps, but this measurement still indicates a compression ratio of at least 60 to 1, surpassing previous results.

After modification to our rf system, we next accelerated the beam to 8.0 MeV in the photoinjector tank, sufficient for compressing up to 1.5 nC to less than 1 ps. However, at the higher charges, the emittance of the beam became sufficiently large such that the minimum spot size on the diagnostic screen with the fast deflector off was large, limiting the resolution to 2-3 ps. For this case we used the induced energy spread on the beam as it drifts after compression to infer the peak current of the bunch.

If the beam is sufficiently relativistic so that its length is large compared to its radius in its own frame of reference, the axial electric field for a beam with a uniform radial profile as it drifts is given by

$$E_z = \frac{\partial I}{\partial z} \frac{1}{2\pi\epsilon\beta\gamma^2 ca^2} \left(\frac{a^2 - r^2}{2} + a^2 \ln \frac{b}{a} \right) \quad (5)$$

where the beam current I is a function of both axial position away from the chicane and relative axial position within the bunch, a is the beam radius and b is the beam pipe radius. If the radial profile is not uniform there are some changes to the form of the field, but in all cases it linearly depends on $\frac{\partial I}{\partial z}$, which scales as I^2 / Q where Q is the bunch charge or Q / τ^2 , where τ is the bunch length. Thus the energy spread induced as the beam drifts can be expected to be

$$\frac{\Delta\gamma}{\gamma} = c_1 \frac{I^2}{Q\gamma^3} = c_2 \frac{Q}{\tau^2\gamma^3} \quad (6)$$

where c_1 and c_2 are some constants that can be found from solving Equation (5) or from simulations. This empirical expression can be confirmed with PARMELA simulations. In Fig. 10 we see the induced energy spread as a bunch drifts 170 cm for various charges,

for a fixed initial bunch FWHM length of 1 ps. The drift length corresponds roughly to the drift length in the beam line from the end of the chicane to the spectrometer. The deviation in Fig. 10 from a linear dependence on bunch charge arises because the bunch undergoes differing amounts of axial expansion for different charges; the induced energy spread appears to depend on the charge to the 0.8 power, in fair agreement with Equation (6).

We would expect that a large energy spread is induced by the beam as it drifts to the spectrometer after significant compression. We would also expect a slight decrease in the energy spread as the bunch is compressed somewhat, but not fully. This occurs because in a chicane the leading particles have lower energy. If the bunch is partially compressed to a couple of picoseconds, the low energy particles are still in the front. However, as the beam drifts to the spectrometer the axial electric field accelerates them, increasing their energy and reducing the FWHM energy spread. As the bunch is compressed a little more, this field increases and the energy spread is decreased somewhat further. This dip in the energy spread does not occur if the bunch is over compressed to a few picoseconds, because in that case the particles have switched from front to rear and the new particles in the front have higher energy than the rest.

In order to use this technique to infer the peak current from the induced energy spread, we will keep the energy slew along the bunch constant and vary the field in the chicane dipoles in order to change the level of compression. This is done because the magnetic field itself cannot modify the energy distribution of the particles - any change in the energy spread of the particles as they reach the spectrometer has to arise from changes in their space-charge fields, as indicated in Equation (6).

Also, we need confidence in PARMELA's ability to faithfully calculate the longitudinal space-charge force. Fortunately, we have used this version of PARMELA to simulate the bunch length expansion of 1-5 nC bunches, initially at 10 ps, for various drive laser phases, and it has shown excellent agreement with streak-camera

measurements (20,21). The longitudinal space-charge force tries to expand the bunch length whereas the rf acceleration tends to compress the bunch length, and these two effects cancel to a large fraction. The final bunch length after acceleration is thus a strong function of the longitudinal space-charge force, and any significant error in the simulated longitudinal space-charge force would have been apparent in the comparison.

In Fig. 11 we show a typical FWHM energy spread experimental measurement as the chicane angle is changed for a typical 2/3 nC case, where the unbunched energy spread is about 2.5% at the spectrometer (and about 3.5% at the entrance to the chicane). Note both the prominent energy spread decrease and the subsequent peak as the chicane bend angle is increased, as expected. The error bars shown indicate the accuracy of each measurement, averaged over several individual measurements, and do not include any systematic errors. In Fig. 12 we show results from corresponding PARMELA simulations, with as similar initial conditions as possible. The initial bunch was constrained to have a hypergaussian shape (with more pronounced tails than a pure Gaussian distribution), a 20-ps FWHM initial bunch length at the cathode, and a 2.5% energy spread at the spectrometer in the absence of magnetic field in the chicane. These constraints were met in the simulation by superimposing a 12-ps FWHM bunch-length Gaussian distribution and a 35-ps FWHM bunch-length Gaussian distribution, each of equal total charge, at the cathode. This superimposed distribution is in agreement with streak camera measurements of the drive laser temporal distribution. In Fig. 12(a) we plot the predicted energy spread in the spectrometer as a function of chicane bend angle. In Fig. 12(b) we plot the predicted compressed FWHM bunch length as a function of chicane bend angle. Overall, there is good quantitative agreement between the predicted energy spread plot and the experimental data shown in Fig. 11 - the dip and the peak are very close to the same size. Note that there is an apparent discrepancy in the measured and experimental induced energy spreads after the peak energy spread was reached (the experimental curve shows a sharp drop-off, but the predicted curve remains fairly flat).

However, this occurs because the energy spread has a relatively Gaussian distribution for chicane angles less than 30 degrees, but becomes a hollowed-out flat top distribution for chicane angles greater than 30 degrees. The FWHM of the hollowed-out distribution is hard to measure - does the FWHM include the upper energy peak, the lower energy peak, or both? In the simulation, the FWHM enclosed both peaks; typically, though, in the experiment only the higher energy peak was included in the measurement because the large background from the scattered electrons pushed the half-maximum point up above the level of the hollowed-out part. The minimum bunch length in the PARMELA simulations is about 0.4 ps, with a peak current of about 1.1 kA. This result is in reasonable agreement with simply using Equation (6), calibrating c_2 from Fig. 10. From Equation (6) we would expect a minimum peak current of 1.0 kA. Thus we infer from this comparison that the bunch was compressed to a peak current of about 1.0 kA.

We have also measured induced energy spreads of 9.0% for a bunch charge of 1.1 nC at a chicane bend angle of 29 degrees. In Fig. 13 we plot (a) induced energy spread versus chicane angle, (b) compressed FWHM bunch length versus chicane angle, and (c) induced energy spread versus compressed bunch length, for a series of 1.1 nC PARMELA simulations, again using the spectrometer measurements to reconstruct the initial beam distribution. Note in Fig. 13(c) that the induced energy spread scales very closely to the inverse square of the compressed bunch length, in agreement with Equation (6). The PARMELA simulations indicate that the minimum bunch length should be 0.4 ps, which corresponds to an induced energy spread of about 16% (Fig. 13(c)). This energy spread was not measured in the experiment, implying that the bunch length never reached 0.4 ps. This might be due to an unaccountable excessive instantaneous energy spread, or distortions in the energy-phase correlation perhaps resulting from additional wakefields not included in the simulation. However, because the peak induced energy spread is directly related to the minimum bunch length, we can use Fig. 13(c) to infer the

minimum bunch length in the experiment - for an induced energy spread of 9.0%, this implies a minimum bunch length of about 0.7 ps (and a peak current of 1.4 kA).

Potential errors (and a short discussion evaluating the relative error, basing the quantitative analysis on Equation (6)) in inferring the peak current using this method are: (1) error in measuring the energy spread - the energy spread is easy to measure and is good to at least 5 per cent (the error bars on the data in Fig. 11 are due to relative phase shifts between the drive laser and the rf), leading to an error in the peak current of a couple of per cent; (2) error in measuring the beam energy - this is also easy to do correctly, and is probably accurate to a few percent (we calibrated this spectrometer by measuring free-electron laser radiation (21)), leading to about a 5 per cent error in the peak current; (3) error in measuring the total bunch charge - the charge is calibrated by a Faraday cup at the end of the accelerator, but is known at best to 30%, leading to about a 15% error in the peak current; and (4) error in determining the constants $c_{1,2}$ - $c_{1,2}$ is somewhat dependent on the radial beam distribution and possible errors in the longitudinal space charge force in the simulations, both of which could possibly lead to errors of $c_{1,2}$ of about 10%, and together lead to an uncertainty of up to 20%, leading to about a 10% error in the peak current. Thus the peak current (and thereby FWHM bunch lengths) are known to only about 30% using this induced-energy spread technique. Even with the maximum allowable uncertainty, these measurements demonstrate FWHM bunch lengths less than 1 ps, and rms bunch lengths less than 0.5 ps.

FUTURE EXPERIMENTS

The next set of experiments on this injector will measure the normalized rms beam emittance as a function of compression and beam parameters, in order to verify the large potential emittance growth from the LCSCF. Previous scaling arguments (12) indicated that the emittance growth should scale as the square of the beam radius and

bend angle, and inversely as the square of the compressed bunch length, but be independent of beam energy. This scaling should be relatively straight forward to confirm.

The major technological difficulty in this next experiment is determining the rms beam emittance. The quadrupole scan technique, in common practice (22,23) systematically underestimates the emittance for beams from photoinjectors. The error in the measurement is introduced because the quadrupole scan is typically insensitive to the large emittance tails of the bunch. A new emittance measurement technique is being developed at Los Alamos (24) which should not have the same limitation. This technique was first proposed by Miller, et al, in 1983 (25), but has not been implemented previously. The idea is to difference the four signals from a beam position monitor where the signals are picked up 90 degrees apart around the beam line at the same axial position. If the pickups are located at the top (T), bottom (B), right (R) and left (L) sides of the beam pipe, the signals are:

$$\begin{aligned}
 T &= \chi \left(1 + 2 \frac{\bar{y}}{b} - 2 \left[\frac{\sigma_x^2 - \sigma_y^2}{b^2} + \frac{\bar{x}^2 - \bar{y}^2}{b^2} \right] \right) \\
 B &= \chi \left(1 - 2 \frac{\bar{y}}{b} - 2 \left[\frac{\sigma_x^2 - \sigma_y^2}{b^2} + \frac{\bar{x}^2 - \bar{y}^2}{b^2} \right] \right) \\
 L &= \chi \left(1 + 2 \frac{\bar{y}}{b} + 2 \left[\frac{\sigma_x^2 - \sigma_y^2}{b^2} + \frac{\bar{x}^2 - \bar{y}^2}{b^2} \right] \right) \\
 R &= \chi \left(1 - 2 \frac{\bar{y}}{b} + 2 \left[\frac{\sigma_x^2 - \sigma_y^2}{b^2} + \frac{\bar{x}^2 - \bar{y}^2}{b^2} \right] \right)
 \end{aligned} \tag{7}$$

where σ_x and σ_y are the rms horizontal and vertical beam sizes, respectively, and where the constant χ depends on the bunch charge, the beam-pipe radius and several constants. By manipulation of the signals it is easy to find $\sigma_x^2 - \sigma_y^2$. The initial six beam rms

parameters $\left\langle x^2 \right\rangle, \left\langle x \frac{dx}{dz} \right\rangle, \left\langle \left(\frac{dx}{dz} \right)^2 \right\rangle, \left\langle y^2 \right\rangle, \left\langle y \frac{dy}{dz} \right\rangle, \left\langle \left(\frac{dy}{dz} \right)^2 \right\rangle$ can be found at a location previous to a series of quadrupoles by calculating $\sigma_x^2 - \sigma_y^2$ for six different focusing set ups of the quadrupoles. The initial rms parameters are found by inverting the matrix equation

$$\bar{\bar{A}} \cdot \bar{\sigma} = \bar{\Omega} \quad (8)$$

where $\bar{\bar{A}}$ is easily found from the beam optics,

$$\bar{\sigma}^T = \left\langle x^2 \right\rangle, \left\langle x \frac{dx}{dz} \right\rangle, \left\langle \left(\frac{dx}{dz} \right)^2 \right\rangle, \left\langle y^2 \right\rangle, \left\langle y \frac{dy}{dz} \right\rangle, \left\langle \left(\frac{dy}{dz} \right)^2 \right\rangle \quad (9)$$

and

$$\bar{\Omega}^T = (\sigma_{x,1}^2 - \sigma_{y,1}^2, \sigma_{x,2}^2 - \sigma_{y,2}^2, \sigma_{x,3}^2 - \sigma_{y,3}^2, \dots) \quad (10)$$

where the indices refer to the measurements with focusing set up number 1, then with set up number 2, and so on. Additional measurements can be made and the initial beam rms parameters can be found with a least squares fit.

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FIGURE CAPTIONS

FIGURE 1. Subpicosecond, High-brightness Accelerator Facility layout, showing location of photoinjector, phasing cavity, chicane, fast deflector and spectrometer. The overall length of the accelerator is about 16 feet.

FIGURE 2. Top view of the chicane showing dipoles and the curved beam box. The beam enters from the left and exits to the right.

FIGURE 3. High and low energy particles in a chicane. The high energy particle has a longer path length.

FIGURE 4. Dipole design showing the H geometry and the narrow indentation of the pole piece for the current coils.

FIGURE 5. Beam pipe and dipole looking along the axial direction. The small circle is the beam pipe size leading into the dipole; the beam box expands to the high aspect-ratio ellipse in the middle of the chicane.

FIGURE 6. Line of charge of length δ in a bend of radius R . The line of charge is traveling in the θ direction and we are considering the field due to the line at a transverse position offset x from the line's orbit.

FIGURE 7. (a) Fast deflector off; focusing resolution on screen is about 0.8 ps. (b) Fast deflector on; electron bunch streaked on screen with phasing cavity turn partly on (bunch length

4.8 ps). (c) Fast deflector on; electron bunch streaked on screen with phasing cavity adjusted for maximum compression (bunch length 0.9 ps).

FIGURE 8. Horizontal profile of the streaked image in Fig. 7(c).

FIGURE 9. PARMELA simulation of the compressed bunch longitudinal phase space for the 0.1 nC measurement. Horizontal units are in degrees of phase at 1.3 GHz. Note the relatively large curvature in the energy phase correlation due to the low bunch charge.

FIGURE 10. PARMELA simulations of induced energy spread versus charge, for an 8-MeV electron bunch with an initial 1-ps FWHM bunch length. The observed induced energy spread roughly agrees with the scaling in Equation (6).

FIGURE 11. Measured energy spread at the spectrometer for a 2/3 nC bunch, as a function of chicane angle.

FIGURE 12. PARMELA simulations for a 2/3 nC bunch - (a) Induced energy spread as a function of chicane angle. Note this curve has essentially the same features as the curve shown in Fig. 11. (b) Compressed bunch length as a function of chicane angle.

FIGURE 13. PARMELA simulations for a 1.1 nC bunch - (a) Induced energy spread as a function of chicane angle. (b) Compressed bunch length as a function of chicane angle. (c) Induced energy spread as a function of compressed bunch length.

TABLE 1: Effect of the longitudinal centrifugal space-charge force

Charge	initial emittance	initial bunch length	without LCSCF emittance	without LCSCF length	with LCSCF emittance	with LCSCF length
1	8π	20	12π	0.79	21π	0.79
3	14π	20	21π	0.65	62π	0.65

Subpicosecond, High-Brightness Accelerator Facility Beamline

Fig 1

R 5.18/4

R 5.7874

Fig 2

Bunching Occurs Because of Path Length Differences

Fig 3

H-Type Magnets Required to Reduce Fringe Fields

Fig 4

Fig 5

Fig 6

Fast deflector
off

(a)

(b)

(c)

Fig 7

$\psi = 180^\circ$, FD on 140mV
Chicane on 115A (picture pg 64)

0.65 p/pixel
1.1 ps au

Fig 8

E-ES VS. PHI-PHIS

ES= 6.057, PS= 204.23, Z= 262.3

270A

→ 234

0.1nC

0.22ps

Fig 9

Energy Spread versus Charge (PARMELA)

Fig 10

(800A)

~~Fig 12~~ Fig 11

2/3 nC PARMELA simulation

Fig 12 (a)

2/3 nC PARMELA simulation

Fig 12(0)

Fig 13(a)

Fig 13(b)

Fig 13 (c)