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Title: STREAK CAMERA ENHANCED QUADRUPOLE SCAN
TECHNIQUE

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STREAK CAMERA ENHANCED QUADRUPOLE SCAN TECHNIQUE

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A streak camera is used in combination with the quadrupole scan technique to characterize the temporal dependence of the trace-space distribution of a bunched electron beam. The quadrupole scan procedure is used to determine the ellipse that represents the beam on the two-dimensional trace space (the xx' plane), and the streak camera diagnostic shows how electrons in axial slices at different locations within a single, average bunch contribute to the trace-space distribution and emittance of the full bunch. For purposes of analysis, the 15–20 ps FWHM electron bunch is partitioned into seven contiguous 4-ps slices. The quadrupole scans are performed over a range of focusing strengths in the solenoid lens that is wrapped around the photocathode cell of an 11-cell 1300 MHz rf photoinjector. The radial focusing of the solenoid is intended to reverse a space-charge-driven emittance blow-up that occurs in the low-energy end of the photoinjector and that is correlated with the axially nonuniform transverse space-charge field. In the parameter space investigated in this experiment, the solenoid does not appear to perform that function. Simulations of the experiment with the particle code PARMELA indicate that by keeping the transverse dimension of the beam small, the focusing does circumvent an rf-driven emittance growth, but otherwise does little to reverse the emittance blow-up that occurs in the first few cells.

1 Introduction and Motivation

A bunched electron beam has axial correlations in its trace-space distribution that arise from time-dependent applied forces and from axially-nonuniform space-charge fields within the bunch. These forces introduce an axial dependence into the particle flows. An ordinary example is given in Fig. 1, where an electron bunch is shown partitioned into axial slices and the trace-space ellipses representing particles in each slice are displayed. If the beam were free of correlations each slice ellipse would overlap precisely all the other ones, and were a particle to be chosen at random from the distribution there would be no way of knowing from which slice it came. The distribution shown here is quite different than that description: particles in the end slices occupy the nearly vertical ellipses and particles near the center of the bunch are in the horizontal ellipses. In this case the vivid display of correlation results from a solenoid lens that has *overfocused* particles at the ends of the bunch where the space-charge force is weakest; particles near the ends cross through the beam axis and follow trace-space flows distinct from the laminar flow experi-

Figure 1. On the left, a "snapshot" of an electron bunch moving along the z axis partitioned into distinct axial slices; the curve represents a projected Gaussian density. On the right, trace-space ellipses associated with individual slices. Each ellipse characterizes the spread in particle coordinates $(x_i(z_0), x'_i(z_0))$ of the $i = 1, 2, \dots, N$ particles in that slice as the bunch sweeps past an axial location z_0 . The coordinate x is transverse to the propagation axis z , and $x' \equiv dx/dz$ defines a small angle. The location z_0 referenced in the right-hand plot is 98 cm beyond the exit of the AFEL linac, 220 cm from the photocathode and the solenoid lens that has focused the beam (Fig. 2). The ellipses shown here were determined by the particle-pushing code PARMELA, using beam and configuration parameters measured in the laboratory. Particles in the end slices occupy the nearly vertical ellipses, and those near the center of the bunch are in the more horizontal ellipses. Correlations elevate the emittance of the full bunch, represented by the solid curve.

enced by particles near the center of the bunch, where the space-charge force is greater. In a laminar flow convergence of a focused beam is reversed by space-charge repulsion, and the beam envelope re-expands without particles having crossed through the axis.

A problem with a correlated distribution is that not all slice ellipses can be matched to a given application or beamline component. A common strategy is to match for the full-bunch rms ellipse, represented above by a solid curve. The larger emittance ($\propto$ area) of this ellipse relative to the slice ellipses reflects the diminished effectiveness of the full bunch—a consequence of the beam correlations.

Based on the results of multiparticle simulation, emittances of photoinjector beams are said to be dominated by correlations originating in the axial-dependence of the transverse space-charge field. The dominant effect is an emittance blow-up that occurs in the low-energy stage of acceleration. Pho-

toinjector design studies^{1,2} dating back to the late 1980s have indicated, however, that a solenoid lens positioned near the cathode provides an effective means for reversing the initial emittance blow-up. This technique has since become known in the literature as "emittance compensation." More recently, an analytic account³ of this process has emerged.

These considerations motivated the development of an experimental technique for observing correlations in bunched electron beams. The technique relies on the usual quadrupole scan method for determining the beam ellipse, and is augmented by the use of a streak camera for determining slice ellipses. This paper describes that technique, presents experimental results, and compares the latter with simulation. It turns out that the parameter space sampled here is *not* one in which emittance compensation occurs. Although measurements and simulation are in agreement on this point, laboratory observations indicate that simulations are insensitive to space-charge effects that occur when the photoinjector is operated too close to the space-charge-limit on emission. Experimental results suggest that space-charge may then be responsible for a degradation of the beam emittance that occurs over the length of the bunch.

2 Experimental Arrangement and Apparatus

2.1 AFEL Photoinjector System

The Advanced Free-Electron Laser (AFEL) photoinjector⁴ at Los Alamos National Laboratory is an eleven cell, rf linear accelerator with a photocathode plug aligned flush with the flat end-wall in the first cell (see Fig. 2). The rf frequency is 1.3 GHz. A single rf feed at the middle cell energizes the accelerator. The field strength during emission is about 10 MV/m, the on-crest field is about 25 MV/m, and electron energy at the accelerator exit is about 17 MeV. A solenoid lens wrapped around the photocathode cell provides focusing for the high-charge bunch, and is also meant to control the correlated emittance growth.

The cathode is a thin film of cesium telluride (Cs_2Te) deposited on a molybdenum plug. It emits every twelfth rf cycle (over a 5–20 μs macropulse), driven by a mode-locked Nd:YLF oscillator. Output from the oscillator is temporally compressed in a fiber/grating arrangement, amplified in a pair of lasing rods, and then frequency quadrupled in a pair of doubling crystals (Cs_2Te emission threshold energy $E_T = 3.5 \text{ eV}$). During transport the laser spot overfills an iris, and a lens downstream makes an image of the iris on the photocathode. The overfilled iris allows a round spot with a relatively

Figure 2. Schematic diagram of experimental arrangement (not to scale). The drive-laser system is shown in abbreviated form. The quad scan uses only the downstream element of the quadrupole doublet; this lens focuses the beam along an axis perpendicular to the plane of the page and defocuses it along an axis in that plane. A dipole magnet (not shown) accomplishes the 30° bend of the electron beam after the TR foil. The streak camera image, which shows the intensity of the electron beam as it crosses the TR foil, is captured by a CCD camera. This image gives the temporal dependence of the beam intensity along the one-dimensional axis where the TR foil intersects the front focal plane of the optical-transport system.

flat intensity profile at the cathode, and the lens damps at its image spot-hopping that occurs on the iris so that the position of the laser spot at the cathode is stable. For the experiment reported here the laser pulse has a Gaussian temporal profile with a 17 ps FWHM, the laser spot at the cathode has a 2.6 mm radius, and the photoemitted electron bunch charge Q_b is about 1.1 nC.

2.2 Emittance Diagnostic

The emittance diagnostic (Fig. 2) includes a quadrupole lens for focusing the electron beam, a thin foil screen for imaging it, an optical transport system with bandpass filter, the streak camera, and a charge-coupled device (CCD) controlled by a personal computer (PC) for recording and displaying streak-tube output. A streak camera is an electronic device for imaging and measuring short optical pulses. The essential component in the camera is the streak tube, an electron tube with a photoemissive surface at the input end and a luminescent phosphor screen at the output end. The input signal is a short optical pulse delivered to the photocathode, and the output is luminescence produced by photoelectron bombardment at the phosphor screen. The streak tube converts the incident optical pulse to an electron pulse directed toward the phosphor screen; enroute, the electron pulse acquires a transverse velocity chirp as it passes between a pair of deflection plates sweeping a linearly time-dependent electric field. After an extended drift electrons arrive at the luminescent screen with a vertical displacement that is proportional to their axial position within the bunch.

The experimental technique requires measuring the photoinjector beamwidth at the imaging screen. The beamwidth is measured along the one-dimensional axis-of-intersection of the foil screen with the front focal plane of the optical transport system. An image of this axis is made at a slit at the entrance to the streak camera; the gap across this slit is only 20 μm wide, but it has a long axis of 5 mm that contains the image from the foil. Optics internal to the streak camera reimage the slit onto the streak tube photocathode. Optical transition radiation (TR) produced when the electron bunch crosses the foil boundary is prompt, so the intensity in the emitted optical pulse has a temporal structure the same as that of the incident electron pulse. Streak tube output is a two-dimensional display that gives the temporal dependence of the electron bunch intensity along the one-dimensional spatial axis at the TR foil.

The CCD detector is a two-dimensional array of imaging elements or pixels, with the time axis along the vertical and the space axis along the

horizontal. Each pixel element records the luminescent intensity imaged onto it from the phosphor screen. A single pixel represents approximately a 0.6 ps increment in the vertical direction, and a 4 μm increment at the TR foil in the horizontal direction. The 7 ps FWHM temporal resolution of the experimental apparatus as a whole is a result of several effects, including a nonzero slit width at the streak camera, timing jitter throughout the system, streak tube characteristics, and dispersion in the optical glasses that comprise the TR transport line (hence the bandpass filter). Spatial resolution is limited by the streak tube (not optical transport) and is 20–25 line pairs per millimeter. The CCD detector vastly oversamples the data, but in doing so does not compromise it. In the data analysis the entire image can be projected onto the time axis, yielding an axial profile of the full electron bunch, or it can be projected onto the space axis resulting in a transverse profile of the full bunch. The slice data is arrived at by projecting a smaller set of contiguous rows onto the space axis; a seven-row projection representing a 4.2 ps slice was used throughout the data analysis. The electron bunches at the TR foil have a 15–20 ps FWHM and are partitioned into seven nonoverlapping, contiguous slices when analyzed.

The CCD detector is operated in a low-noise, slow-readout mode. Readout noise at the 16-bit digitizer (the dominant source of noise) is minimized at the expense of a slow, eight-second readout of the full CCD array (768×512 pixels). Dark count is reduced by operating the detector at -10°C . To enhance the signal-to-noise ratio the streak camera is operated in *synchroscan mode*. In this mode all 760 electron bunches in a 7 μs rf macropulse are stacked one atop another in a single CCD image, so that the electron bunch in the image represents a macropulse average. A full quad scan in which three images are acquired at each of the 10–15 quadrupole field strengths sampled requires approximately 45 minutes for completion.

3 Quadrupole Scan Analysis

A “quad scan” is a set of observations of the beam intensity at the imaging screen as the strength of the quadrupole lens is scanned over a range of values. Analysis requires a characterization of the beamwidth at each quadrupole field strength; the widths reported here are “rms” values determined by a Gaussian fit to the image intensity. The definition of “beamwidth” does not affect the analytic formalism, but may be important in interpreting results.

The representation of the beam (or a particular slice) as a distribution bounded by an ellipse on trace space is obtained by fitting in a least-squares

Figure 3. The measured, third-slice beamwidths at the TR foil are plotted as a function of quadrupole field strength; field strength (in kilogauss) is characterized by the quadrupole gradient integrated from the quad to the TR foil. The solid curve is a least-squares fit to the data using Eq. (1) and the best fit parameters a_i . The a_i define the trace-space ellipse at the right. The values obtained here are $a_1 = 0.173 \pm 0.006 \text{ mm}^2$, $a_2 = 0.037 \pm 0.002 \text{ mm mrad}$, and $a_3 = 0.025 \pm 0.006 \text{ mrad}^2$. The normalized emittance is $\bar{\epsilon}_{nx} = 1.8 \pm 0.1 \text{ mm mrad}$. The five or six percent error bar on emittance accounts for statistical deviation in the data but does not include systematic error in the experimental procedure.

sense the measured beamwidths $\tilde{x}$ to the expression⁵

$$\tilde{x} = (a_1 f_1 + a_2 f_2 + a_3 f_3)^{1/2}. \quad (1)$$

Here the f_i are known functions of the quadrupole field strength and position (relative to the TR foil) and the beam momentum, and the a_i are constants to be determined. The best-fit a_i define the trace-space ellipse that represents the beam as it arrives at the quadrupole according to

$$a_3 x^2 - 2a_2 x x' + a_1 x'^2 = a_1 a_3 - a_2^2. \quad (2)$$

The right-hand side of this expression is the square of the geometric emittance, and the normalized emittance is

$$\bar{\epsilon}_{nx} = \gamma \beta (a_1 a_3 - a_2^2)^{1/2}, \quad (3)$$

where γ is the relativistic energy factor and β the beam velocity normalized to the speed of light. An example of data analysis is given in Fig. 3.

The analysis presented above does not include the space-charge force during the drift from the quadrupole to the TR foil. Although the beams studied in this experiment are moderately space-charge dominated when they arrive at the quadrupole, a more complete analysis⁵ involving the envelope equation shows that space charge has only a small affect on beamwidths over the 24 cm drift to the TR foil. The simpler formalism of Eq. (1) was therefore used for analysis.

Figure 4. Full bunch and slice ellipses. Slice 1 is at the leading edge of the bunch. The ellipse at the lower-right, calculated as a weighted sum of the slice ellipses, is replotted throughout as a visual reference. Listed are the *normalized* emittance $\bar{\epsilon}_{nz}$ (mm mrad) and slice fractions (%).

4 Experimental Results

The results of a quad scan are presented in Fig. 4. Shown are trace-space ellipses for the full bunch, the seven slices, and an additional “weighted-sum” ellipse. The ellipse for the latter is obtained by summing over the seven slices the ellipse parameters a_i weighted by the slice fractions. The graphical

Figure 5. Slice "rms" beam parameters and the slice fractions. Full-bunch values are assigned "slice 0." Solenoid currents are distinguished by triangles (290 A), diamonds (300 A), and stars (310 A).

presentation is intended to convey a qualitative sense of beam correlations that are otherwise difficult to quantify. Listed with each ellipse are its normalized emittance and weight (fraction).

Figure 4 shows the width $\tilde{x}$ of the bunch growing rapidly over the first few slices, and then flattening out. With the exception of the first slice, the ellipses have similar orientations; the relative disorientation of slice 1 is most likely a result of particles crossing through the axis (see Sec. 1). The most striking feature seen here is that although the shape and orientation of the ellipse is evolving over the first half of the bunch, the emittance is flat at 1.8 mm mrad—and then more than doubles by the tail of the bunch.

These results correspond to a current $I_{\text{sol}} = 300$ A in the solenoid that is wrapped around the photocathode. This coil provides the focusing required for successful transport of the high-charge bunch through accelerator apertures, and is also intended to control correlated emittance growth. Two other coil currents, 290 A and 310 A, were sampled in the experiment. The effect of the solenoid on the particle distribution is summarized in Fig. 5. Rather than the confusion of ellipses, the beam distribution is characterized by the

envelope width $\tilde{x} = \sqrt{a_1}$ and slope $\tilde{x}' \equiv d\tilde{x}/dz = a_2/\sqrt{a_1}$, and the normalized emittance $\tilde{\epsilon}_{nx}$. Full-bunch values are conveniently represented as "slice 0."

The focusing effect of the solenoid is evident in the plot of the envelope width $\tilde{x}$: the full-bunch values decrease as the coil current increases. The bunch is widest at its mid-section (the location of the greater space-charge force) at the lowest coil current, but at the high coil current the beam is narrow in the middle and wide at its ends. The stronger focusing has driven particles in the end slices through the beam axis. Particularly striking in this regard is the envelope slope $\tilde{x}'$ (note the convergence of the middle slice as the ends diverge strongly at the high coil current).

The distinguishing characteristic of the emittance curves is that they all double over the latter half of the bunch. The elevated emittance at the low coil current was correlated with distortions in the current profiles.^a Similar distortions came and went over the course of the experiment, seemingly with small changes in bunch charge (< 10%). Their occurrence prompted a separate investigation in which profiles were observed over a range of charge values (quad scans were not part of this effort). It was observed that over the range $0.94 \leq Q_b \leq 1.95$ nC, the profiles were especially sensitive to charge; see Fig. 6. The distortions are thought to originate during the emission interval at the photocathode. The radius of emission is 2.6 mm, and the applied rf field at the cathode is 6.7–10.2 MV/m during the 17 ps emission interval. The space-charge-limit^b Q_* on bunch charge is near 2 nC for these conditions, and the conclusion is that the current profile is quite sensitive to charge when $Q_b/Q_* > 1/2$. The distortion in the profile at the high-charge value in Fig. 6 may be signaling the onset of sub-bunching similar to that observed by Dowell *et al.*⁸ Limited laser power precluded taking the charge to higher values.

The irregular occurrence of profile distortion over the course of the quad scan experiments was puzzling at the time. It may be the case that distortions were aggravated by nonuniform emission; patchy emission implies higher current densities off parts of the cathode to make up for weaker emission elsewhere (the total charge extracted from the circular spot being held constant). Returning to the emittance curves of Fig. 5, the question arises as to whether emittance growth over the latter half of the bunch might be related to the space-charge force that drives profile distortion during the emission interval. Here the argument is that the disturbances appear with small changes in bunch charge, and the emittance may be showing a sensitivity to these forces even when the current profiles appear normal (not distorted).

^aA current profile is a full-bunch projection onto the time axis in the CCD image.

^bThe emitted charge Q_* that produces at the cathode a surface-charge density $Q_*/\pi R_c^2$ that cancels locally the applied accelerating field. R_c is the radius of emission.

Figure 6. Electron bunch lengths $T_b \equiv 2.355 T_{rms}$ (upper left) and representative current profiles. The value T_{rms} is *not* derived from a Gaussian fit. Unfilled stars indicate the laser pulse length T_L . The laser has a Gaussian temporal profile (not shown) in all cases. Current profiles display bunch intensity (arbitrary units) over time (ps). Curves are the best Gaussian-fit. Listed with each profile is the bunch charge Q_b .

5 Comparison with Simulation

5.1 Experiment vs Simulation

Computer simulations of electron beam transport from the photocathode to the quadrupole diagnostic were performed using the particle-pushing code PARMELA⁶ and field solver POISSON SUPERFISH.⁷ The quad scans themselves were not simulated. The output from PARMELA was binned into axial slices, and the trace-space ellipses at the quadrupole were computed for comparison with those determined experimentally. The simulations were performed at the three solenoid currents $I_{\text{sol}} = 290, 300,$ and 310 A.

A general comment is that the the envelope parameters $\tilde{x}$, $\tilde{x}'$, and $\tilde{\epsilon}_{nx}$ seen in the simulations are quite symmetric with respect to the center of the bunch—much more so than what is observed in the laboratory. Quantitatively, the rms beamwidths predicted by simulation are a factor of two or more larger than the measured ones. Although they could be made smaller by increasing the solenoid current (assuming a miscalibration between laboratory current and simulation), such an adjustment appears unwarranted from the standpoint of the envelope slopes $\tilde{x}'$. The simulations show the full bunch evolving from slightly divergent at the low current $I_{\text{sol}} = 290$ A to slightly convergent at the high current $I_{\text{sol}} = 310$ A, and the degree to which particles at the ends of the bunch cross through the axis is in rough, qualitative agreement with laboratory observation. In short, stronger solenoid focusing in the simulations would produce an overfocused bunch compared with the observed slopes. The discrepancy between measured and simulated rms beamwidths is more likely explained—in part at least—by a diffuse radial wing in the distribution that is under-represented both in terms of detector sensitivity, and in terms of an inadequate characterization of the rms width by a Gaussian fit in the data analysis. In order to test this assertion a more detailed examination of PARMELA output is required (but has not been done).

According to simulation, the solenoid field strength has no effect on the slice or full-bunch emittance. For each slice or full bunch, changes in the focusing coil current manifest as area-preserving, linear transformations of the beam ellipse. That is, the strength of the focusing solenoid is not an effective agent for manipulating the trace-space distribution of one slice relative to another in the parameter space sampled. Unlike the laboratory observations, the simulated slice-emittance shows an increase from the center to the *front* of the bunch equal to that from the center to the tail. Also, the full-bunch emittance derived from simulation is about a factor of two greater than the largest slice value, indicating a much greater degree of axial correlation than

Figure 7. Comparison of experiment with simulation, including the effect of limited temporal resolution. The case presented here is for 300 A current in the focusing solenoid. Experimental data are plotted with solid diamonds, simulated data with unfilled diamonds. Exact simulation results follow dashed curves. A convolution of exact results with a Gaussian spread function yields the dotted curves. The width of the spread function is 7 ps FWHM, which is the estimated temporal resolution of the streak camera system. The convolution is performed with a finely sliced bunch (27 or 45 slices), after which the bunch is rebinned into 9 slices. Convolution smears particles into slices beyond the temporal bounds of the original bunch; 98% of the particles are accounted for in the 8 slices shown here. Slice values for the bunch width $\tilde{x}$ and emittance $\tilde{\epsilon}_{nz}$ are plotted as functions of time t . Full-bunch values are listed at $t = 0$, and are not affected by convolution.

what was observed in the laboratory, where the full-bunch emittance was mostly an *average* of slice values. The shape of the slice emittance curve seen in the simulations—elevated at the ends and minimized at the center—can be explained entirely in terms of axial correlations. In fact, the trace-space ellipses presented previously in Fig. 1 are simulation results for the case $I_{sol} = 300$ A for a beam launched from the cathode with zero thermal emittance.

The temporal resolution of experimental apparatus compromises an ability to differentiate the trace-space flows of the various slices. Temporal smearing that occurs in the CCD images cannot be removed from the data, as the signal-to-noise ratio is not sufficient for effective deconvolution.⁹ Instead, a more direct comparison between experiment and simulation may be had by convolving simulation results with a Gaussian spread function. That comparison is made in Fig. 7 for the case $I_{sol} = 300$ A; shown are the envelope width and the normalized emittance. As expected, convolution results in a smoothing (a flattening and broadening) of the curve $\tilde{x}(t)$ representing the beamwidth. In contrast, the convolved emittance curve $\tilde{\epsilon}_{nz}(t)$ becomes somewhat sharper, but mostly it is *elevated*. The elevated slice emittance is a result of mixing axially-correlated slices, just as the full-bunch emittance is elevated

in Fig. 1. Mixing moves the slice emittance closer to that of the full bunch; as the width of the spread function is increased (> 20 ps) the emittance curve gradually smooths and flattens out at the full-bunch value. The spread function used for convolution in Fig. 7 has a 7 ps FWHM, the best estimate of the resolution of the experimental apparatus. It is emphasized that a spread function with a 14 ps FWHM produces an emittance curve with considerable curvature, implying that temporal resolution does not account for the flatter experimental curve. Thermal emittance, neglected in the simulations, will flatten somewhat the simulated curve. The thermal emittance of electrons emitted from Cs_2Te has been estimated¹⁰ to be less than 1.1 mm mrad (adjusted for an emission radius of 2.6 mm).

Summarizing, the simulations predict rms beamwidths and emittances roughly twice as large as those observed. A question yet to be investigated is the extent to which particles in the radial wings of the distribution—particles not seen by the detector or not accounted for by a Gaussian characterization of the beamwidth—contribute to the rms width seen in the simulations. The wings of a distribution may affect an rms quantity in a manner disproportionate to their fractional significance. Likewise, emittance measurements are sensitive to the exact set of particles accounted for in the measurement. For example, the central axial section spanning slices 3–6 of the simulated beam in Fig. 7 represents 72% of the bunch but has an emittance only one-third that of the full bunch. It may also be the case that particles in the radial wings of the bunch not represented in laboratory measurements contribute disproportionately to higher emittance values seen in simulation.

On the other hand, the streak camera observations show the axial structure of the bunch to be especially sensitive to charge. Current profile distortions appeared throughout the course of the experiment according to small changes in bunch charge when operating at about one-half the space-charge limit. The gross effect of profile distortion is difficult to achieve in simulation, and it appears that PARMELA will allow an unrealistic amount of charge to be pulled from the cathode. The process of photoemission is exceedingly difficult to model when the magnitude of self-fields approach those of applied fields. An interesting question raised by the observations is whether emittance growth seen over the last half of the bunch might be linked to processes that manifest also as profile distortion. Additional experimentation is required to sort through the issues.

5.2 Emittance Compensation

Emittance values derived from simulation were insensitive to solenoid focusing. Additional simulations were then performed to determine what effect, if any, the lens might have on emittance. Simulations were performed with the focusing coil turned off. Two cases were considered, one with essentially zero bunch charge and the other with $Q_b = 1.1 \text{ nC}$ (in the latter case, 1.8% of the beam was lost at apertures near the end of the accelerator, and the beam pipe that follows had to be enlarged to prevent further losses). All other parameters were unchanged from previous analysis. It was found that by keeping the transverse dimension of the bunch small, solenoid focusing circumvented rf-driven emittance growth,¹¹ but otherwise did little to reverse the space-charge-driven emittance blow-up that occurs in the first few cells.

6 Concluding Remarks

The streak camera quadrupole scan technique is viable, as indicated by its ability to resolve geometric features such as the axial dependence of the bunch beamwidth. Beam crossover is readily observable with three percent changes in focusing coil strength. Measured beamwidths and emittances differ from PARMELA by factors of two or three. Probably the first place to look in this regard is a detailed analysis of which particles in the simulation are most responsible for the discrepancies. More generally, observations indicate that space-charge effects not included in simulation may be important in determining beam quality. The parameter space investigated in this experiment is not one in which emittance compensation occurs.

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