COMPRESSION OF HIGH-CHARGE ELECTRON BUNCHES*

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Abstract

The AØ Photoinjector at Fermilab can produce high charge (10-14 nC) electron bunches of low emittance (20π mm-mrad for 12 nC). We have undertaken a study of the optimal compression conditions. Off-crest acceleration in the 9-cell capture cavity induces an energy-time correlation, which is rotated by the compressor chicane (4 dipoles). The bunch length is measured using streak camera images of optical transition radiation. We present measurements under various conditions, including the effect of the laser pulse length (2 ps sigma Gaussian vs. 10 ps FWHM flat top). The best compression to date is for a 13.2 nC bunch with $\sigma_z = 0.63$ mm (1.89 ps), which corresponds to a peak current of 2.8 kA.

1 INTRODUCTION

Electron beams with short bunch lengths are desirable for high energy physics, free-electron lasers, and other applications.

In this paper we report on studies of compression at the AØ Photoinjector of Fermilab [1, 2] with a chicane of four dipoles as measured by a picosecond streak camera. The photoinjector was prototyped for the TeSLA Test Facility [3], and in that context, there are three stages of acceleration and compression, and the chicane is the first compressor. The gun is a 1.625-cell π-mode normal conducting copper structure at 1.3 GHz whose backplane accepts a molybdenum plug coated with a Cs_2Te photocathode. Solenoids for emittance compensation surround the gun. A superconducting Nb nine-cell cavity accelerates the beam to 16–18 MeV. After the dipole chicane are experimental and diagnostic beamlines.

These streak camera measurements support electro-optic sampling measurements reported in a companion paper in these proceedings. Emittance measurements are reported by J.-P. Carneiro *et al*. in these proceedings, and for 12 nC the normalized emittance is $\epsilon_n = 20\pi$ mm-mrad without compression. The issue of emittance growth during bunch compression [4–8] is under study, though preliminary studies suggest an emittance increase of approximately a factor of two.

2 EXPERIMENT

The streak camera is a Hamamatsu C5680-21S streak camera with M5676 fast sweep module[1] read out by a Pulnix progessive scan digital CCD camera. Calibration was done using a short UV laser pulse and a thick fused silica delay block. We find a calibration of 3.9 pixels/ps at the fastest sweep speed with a limiting resolution of about 1 ps. After one year, the calibration was repeated, and the high-voltage sweep of the streak tube had degraded somewhat to 3.6 pixels/ps, so we report at most a 10% systematic uncertainty in the bunch length measurements.

Optical transition radiation (OTR) light [9–11] was imaged by all-reflective optics to the slit of the streak camera. OTR is prompt, and has a characteristic opening angle of $1/\gamma$, and in our case $E = \gamma mc^2 \sim 16$ MeV, so $1/\gamma \sim 32$ mrad or 1.8°. An out-of-plane (periscope) bend rotates the image so that the vertical direction of the beam falls on the horizontal slit. This is desirable to diagnose aberrations since the chicane bends in the vertical plane.

The photocathode drive laser (built by the University of Rochester) is a lamp-pumped Nd:glass system frequency-quadrupled to the UV ($\lambda = 263$ nm) [12]. The UV laser pulse is a Gaussian with $\sigma_t = 1.9$ ps. Then, the UV pulses are temporally shaped to an approximate flat-top distribution with 10.7 ps FWHM. We have measured the bunch length with both the long and the short laser pulse.

A number of streak images was acquired at each setting. After subtracting a constant background trace from the projected image, (unsubtracted noise which varied from image to image was within ± 0.5 pixel.) each streak image trace is fit to a Gaussian. The mean value from the ensemble at each setting is reported, with error bars assigned from the statistical spread of values from this ensemble. The exception to this is in Figure 1, where each streak image is correlated with the charge measured on that shot, and the error bar is the error in the Gaussian fit.

3 RESULTS: LONG LASER PULSE

In Figure 1 we give the uncompressed bunch length versus charge. At low charge, the bunch length is the same as that of the UV laser pulse on the cathode, but increases dramatically at higher charges. At high charge, ($\sim$11–13 nC), the beam was compressed and measured as a function of the accelerating phases (Figure 2). We set the middle pair of dipole chicane magnets to the nominal values (current $I = +2.0$ A or 680 Gauss), and reduce the outer pair

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[1]We thank A. Hahn, FNAL Beams Division, for the loan of the streak camera.
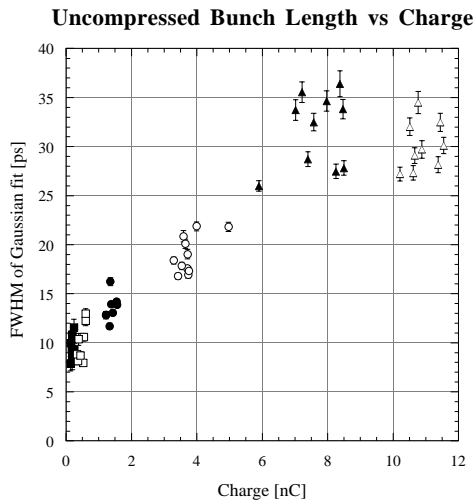
Uncompressed Bunch Length vs Charge

Figure 1: Uncompressed bunch length vs. charge for the long (10 ps FWHM) laser pulse length.

slightly for vertical steering (typically -1.9 to -1.95 A). The phases of the gun RF and 9-cell cavity RF are recorded as the "set phase" from the control system (UNIX). In addition to the set phase, we give the 9-cell phase for maximum energy (crest). The gun phase is referenced to PARMELA by the curve of charge transmission vs. gun phase.

The point of best compression (Figure 2) is not sensitive to the gun phase, however the bunch lengthens if the phase is too early. Even for high charge, the measured bunch length is easily compressed to less than 1 mm σ_z (or 3 ps), and the optimum is 0.63 mm σ_z (1.89 ps).
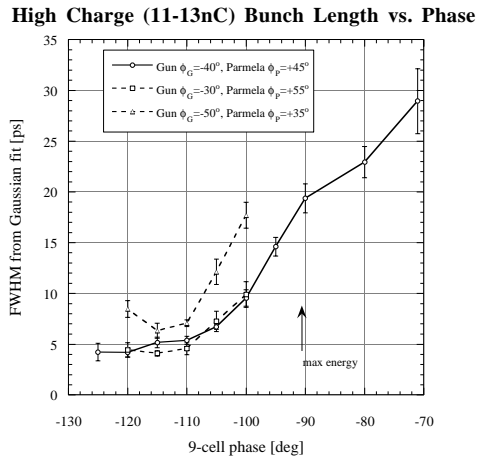
High Charge (11-13nC) Bunch Length vs. Phase

Figure 2: Compression vs. Phases of the 9-cell cavity and gun for the 10 ps laser pulse length. The width of the focus mode image was 2.77 ps FWHM, and the data were corrected assuming this broadening adds in quadrature to the real width.

Repeating this experiment as a function of charge, we find that the minimum bunch length is shorter at lower charge (Figure 3), because non-linear space charge growth is uncompensated. The phase of optimal compression is

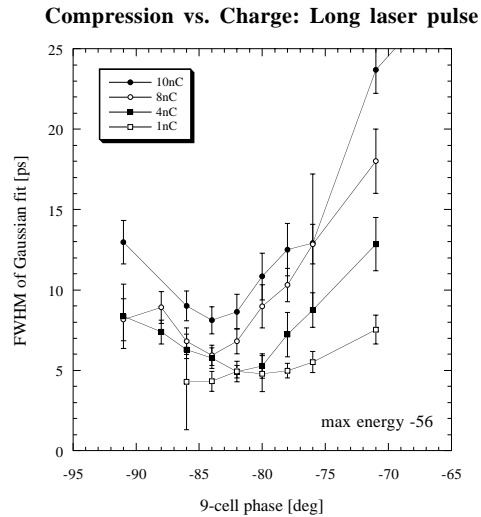only weakly dependent on the charge, shifting by $4°$ from 1 nC to 10 nC.

Compression vs. Charge: Long laser pulse

Figure 3: Compression vs. charge for the 10 ps laser pulse length.

4 RESULTS: SHORT LASER PULSE

The compression experiments were repeated with a short Gaussian laser pulse ($\sigma_t = 2$ ps) on the cathode, with the expectation that the space charge growth of the bunch length would be more severe.

With the chicane dipole magnets off and degaussed, we measured the uncompressed bunch length with a streak camera looking at OTR radiation as before (Figure 4) from 1 nC to 5 nC. Even at low charge, the bunch length is more than a factor of two longer than the initial laser pulse length on the cathode, and increases linearly with charge. The compressed bunch length for the short laser pulse is shown in Figure 5, and the minimum is slightly larger, and at a larger angle off-crest.

5 PEAK CURRENT

One figure of merit for (sub)picosecond electron bunches is the peak current, which depends on both the charge and the bunch length. If the beam is Gaussian in time,

$$I(t) = \frac{Q}{\sqrt{2\pi}\,\sigma_t}\,\exp\left(-t^2/(2\sigma_t^2)\right) \qquad (1)$$

Then the peak current is by definition the peak value of the current profile:

$$I_p = \frac{Q}{\sqrt{2\pi}\,\sigma_t} = \frac{2\sqrt{2\ln 2}\,Q}{\sqrt{2\pi}\,\tau} \qquad (2)$$

for the rms bunch length σ_z or the full width at half maximum (FWHM) τ.

We know of two other facilities which report peak current at or above 2 kA which are 1.97 kA at the AWA [13]
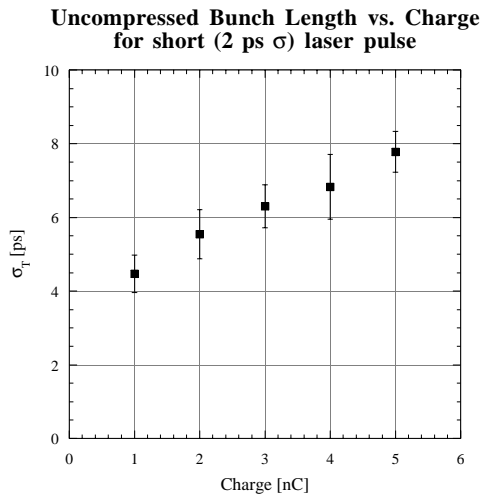
**Uncompressed Bunch Length vs. Charge
for short (2 ps σ) laser pulse**

Figure 4: Uncompressed bunch length vs. charge for the 2 ps laser pulse length.

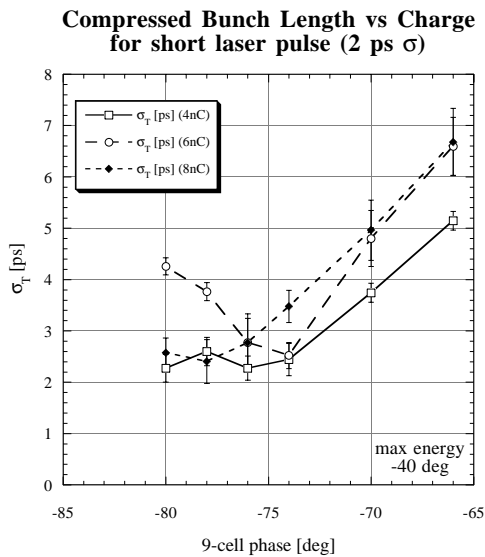**Compressed Bunch Length vs Charge
for short laser pulse (2 ps σ)**

Figure 5: Compressed bunch length vs. charge for the 2 ps laser pulse length.

and 2.3 kA at the CLIC Test Facility (CTF-II) at CERN [8]. Our reported best peak current of 2.8 kA is a significant improvement.

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