# EXPERIMENTAL INVESTIGATION OF THE LONGITUDINAL BEAM DYNAMICS IN A PHOTOINJECTOR USING A TWO-MACROPARTICLE BUNCH

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## *Abstract*

We have developed a two-macroparticle bunch to explore the longitudinal beam dynamics through various component of the Fermilab/NICADD photoinjector laboratory. Such a two-macroparticle bunch is generated by splitting the photocathode drive laser impinging the photocathode. The presented method allows the exploration of rf-induced compression in the 1+1/2 cell rf-gun and in the 9-cell TESLA cavity. It also allows a direct measurement of the magnetic chicane bunch compressor parameters such as its momentum compaction.

## INTRODUCTION

Linear accelerators designed to drive FEL-based light sources or advanced accelerator physics R&D experiments (e.g. plasma wakefield accelerators) need to provide small emittance high peak current electron bunches. In order to achieve such high-brightness beams, the bunch, after generation, is generally manipulated both in the transverse (e.g. emittance compensation in photo-injector) and longitudinal (e.g. bunch compression) phase spaces. The beam dynamics associated with such beams is intricate since both external and space charge forces play an important role in the dynamics. It is, therefore, difficult to set-up or optimize the beam manipulation process by simply measuring the bunch properties. Instead, it is first necessary to make sure the lattice is set in a proper way, e.g. as devised by numerical simulations. Directly measuring the lattice properties is generally an easy task in the transverse phase space. However, it is not such an easy matter as far as the longitudinal phase space is concerned. In the present paper we propose a simple method based on generating a bunch that consists of two macroparticles. There are two main advantages of the two-macroparticle method. Firstly, measuring the change of the separation between two macroparticles is much easier than measuring the change of the bunch size. On the other hand the space charge force is negligible for the two-macroparticle case and the evolution of their relative separation is truly a measurement of the longitudinal focussing properties.

## EXPERIMENTAL SET-UP

The experimental tests of the two-macroparticle method were performed at the Fermilab/NICADD photoinjector laboratory (FNPL). The bunch length measurement can be performed by a streak camera that streaks optical transition radiation (OTR) pulses emitted as the bunch strikes an Al-coated mirror. An alternative frequency-domain bunch length diagnostics based on Martin-Puplett interferometry of coherent transition radiation is also available. For measurements reported hereafter, only the total power of the CTR emission was detected using a pyroelectric detector. The CTR signal only provide a way to monitor and minimize the bunch length (by maximizing the CTR emission). Downstream of the beamline, the electron beam can be horizontally bent in a dispersive section, to measure the beam energy distribution using a fluorescent screen located downstream at a (horizontal) dispersion of $|\eta_x| = 317$ mm.

The double-beam optical set-up used to create a two-macroparticle bunch was initially developed for the witness probe/plasma wake-field experiment. The photoinjector laser beam is split into two and then recombined in such a way that a time-delay is introduced between the two pulses. The delay can be remotely varied from $\sim$7 to $\sim$35 ps. A calibrated potentiometer provide a read-out for the delay between the two pulses. When such double-pulse impinges the photocathode it creates two electron bunches with a time separation much smaller than the rf period (769 ps). Hence both macroparticles fall into the same rf bucket and can be treated as a single bunch. This bunch is henceforth

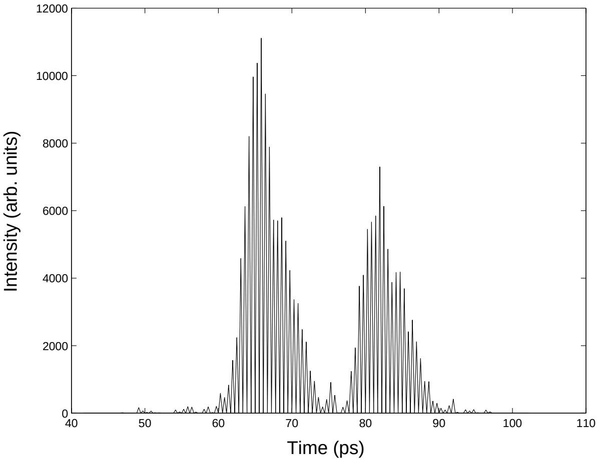

Figure 1: Example of two optical pulse streak camera measurement. The two pulses do not have exactly the same intensity in this measurement.

refer to as two-macroparticle bunch. The macroparticle which is delayed is refered to as a witness pulse (or witness macroparticle) in the following. The witness macroparticle can be "turned off" by the means of a mechanical shutter located in the delayed path. An example of two-pulse profile obtained via streak camera measurement is presented in Fig. 1.

## STUDY OF VELOCITY BUNCHING

### *Theoretical Background*

We briefly elaborate how bunching in an rf-structure occurs. A more detailed discussion is given in Reference [2, 3, 4]. An electron in an rf standing wave accelerating structure experiences the longitudinal electric field: $E_z(z,t) = E_o \cos(kz)\sin(\omega t - \psi_o)$, where $E_o$ is the peak field, $k = \omega/c$ and the rf wavenumber and $\psi_o$ the injection phase of the electron with respect to the rf wave. Let $\psi(z,t) = \omega t - kz + \psi_o$ be the relative phase of the electron w.r.t the wave. The evolution of $\psi(t,z)$ can be expressed as a function of $z$ solely:

$$\frac{d\psi}{dz} = \omega\frac{dt}{dz} - k = \frac{\omega}{\beta c} - k = k\left(\frac{\gamma}{\sqrt{\gamma^2-1}} - 1\right). \quad (1)$$

Introducing the parameter $\alpha \doteq \frac{eE_o}{kmc^2}$, we write for the energy gradient [2]:

$$\frac{d\gamma}{dz} = \alpha k\left(\sin(\psi) + \sin(\psi + 2kz)\right). \quad (2)$$

The system of coupled differential equations (1) and (2) with the initial conditions $\gamma(z=0) = \gamma_0$ and $\psi(z=0) = \psi_0$ describes the longitudinal motion of an electron in the rf structure. In structure, where an incoming low-energy beam (e.g. in a rf-gun $\gamma_0 = 1$) is injected, the there is a relative longitudinal motion of the particle within the bunch: this can lead to bunch compression/decompression.

### *Experiment*

The nominal rf-gun phase is set to $45°$ w.r.t. to the zero-crossing. The booster cavity phase was adjusted to obtained the maximum energy gain. The double-pulse set-up was set to have a 20 ps optical path difference between the two laser pulses and the charge was approximately 1.5 nC per macroparticle. In a first experiment the rf-gun phase was varied while keeping the booster cavity phase "on-crest". For each rf-gun phase the separation between the two macroparticles within the electron bunch was measured and then computed a compression ratio by normalizing the measured time separation on the electron beam by the laser time separation: $\Delta\tau_f/\Delta\tau_{cath}$. The results are compared with numerical simulations performed with the program ASTRA [6] in Fig.2. In a second set of experiment, the booster cavity phase was varied while keeping the rf-gun phase at its nominal value of $45°$. Streak camera measurements of the macroparticle time separation versus the phase. The results are shown in Fig.3. The compression ratio is calculated by normalizing the macroparticle time separation to the time separation when the cavity is operated on crest. Similarly to the previous measurement, numerical simulations performed with ASTRA agree with the experimental measurement within the error bars. Unfortunately during this experiment we were limited to phases $\phi \in [-40°, +40°]$ off-crest, trying to go further off-crest resulted in large transverse envelope (due to rf-induced defocussing and chromatic aberrations) difficult to transport up to the streak camera, we could not measure the on-set the simulation predict at $\sim \pm 70°$.

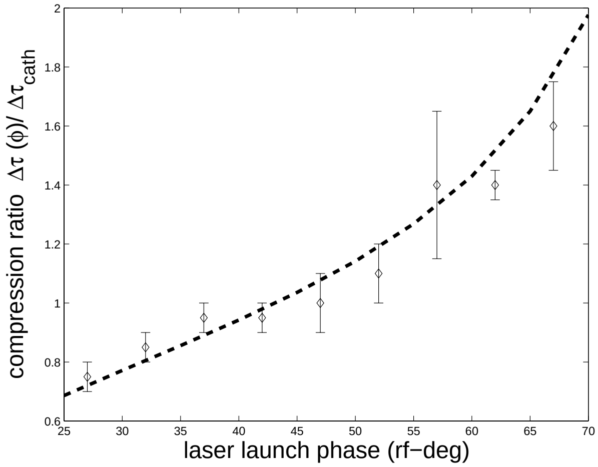

Figure 2: Velocity bunching in the rf-gun cavity. Diamonds are experimental measurements and dashed line corresponds to numerical simulations.

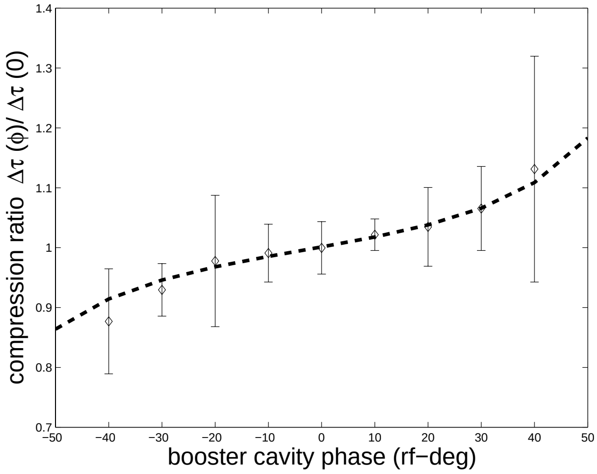

Figure 3: Velocity bunching in the booster cavity. Diamonds are experimental measurements and dashed line correspond to numerical simulations.

## MAGNETIC BUNCH COMPRESSION

### Theoretical Background

In magnetic-based bunch compressor an energy-dependent path length is introduced via a series of dipole forming a chicane. The incoming, to be compressed, bunch is first passed through an accelerating section operated off-crest so to introduced a time-energy correlation along the bunch (a chirp). The correlation is so that the bunch head has a lower energy than the tail. When such a bunch propagate though the magnetic chicane it gets compressed. Under a single-particle approach and using the TRANSPORT formalism, an electron with coordinate $(t_i, \delta_i)$ in the longitudinal phase space within the bunch is mapped downstream of the bunch compressor following:

$$ct_f = ct_i + R_{56}\delta_i - \frac{3}{2}R_{56}\delta_i^2, \text{ and,} \quad (3)$$

$$\delta_f = \delta_i. \quad (4)$$

$R_{56}$ is the so-called first order momentum compaction for the bunch compressor, $c$ is the velocity of light [1]. The coordinate of the electron in the longitudinal phase space is time $t_i$ and fraction energy spread $\delta_i \doteq (\mathcal{E}_i - \langle\mathcal{E}\rangle)/\langle\mathcal{E}\rangle$. Note that minimum bunch length is achieved (i.e. $t_f = 0$ under single-particle linear dynamics) provided the incoming chirp, $d\delta_i/dt_i$ and momentum verify:

$$\frac{d\delta_i}{dt_i} = \frac{c}{R_{56}}, \quad (5)$$

Finally we note that in the case of two macropaticles, the evolution of the macropaticle separation downstream of the bunch compressor is given by:

$$\Delta\tau_f = \Delta\tau_i + \frac{R_{56}}{c}\frac{\Delta\mathcal{E}}{\mathcal{E}}\left[1 - \frac{3}{2}\frac{\Delta\mathcal{E}}{\mathcal{E}}\right], \quad (6)$$

where $\Delta\mathcal{E}$ is the macroparticle energy difference and $\tau_{i,f}$ their initial and final time separations. Thus a measurement of the separation and energy difference between the two macroparticle provide a way to infer the momentum compaction of the chicane.

### Experiment

The booster cavity phase was operated "on-crest", i.e. to the phase corresponding to the maximum energy gain (henceforth refer to $\phi = 0°$); the corresponding beam energy was 16.06 MeV. The charge was set to $\sim$ 2 nC per macroparticle and the double-beam tuned to obtained a 16 ps time separation between the two pulses. The dipoles of magnetic chicane were excited to their nominal value (corresponding to a bending angle of 22.5 deg). The CTR signal was used to find the phase corresponding to the best compression for each macroparticle; the results are: $-42°$ and $-34°$ for the reference and witness beam (macroparticle) respectively; the corresponding phase difference is $\Delta\phi = 8°$. The next step was to go back to the uncompressed scenario (i.e. magnetic chicane dipoles unexcited and degaussed) and take the energy and time measurements. The energy was measured to be 13.07 MeV and the macroparticle fraction energy spread was $\Delta\mathcal{E}/\mathcal{E} = 9\%$. The time separation between the two macroparticles was measured with the streak camera: $\Delta t_i = 16.3$ ps. From Eq.6 this yields the value $R_{56} = 6.3$ cm. We can cross-check our direct results with corresponding phase measurements. The time between the macroparticles of 16.3 ps correlates well with their phase difference of $8°$ which corresponds to 17.1 ps. The energy drop from the "on-crest" position (16.06 MeV) to the "best-compression" position (13.07 MeV) corresponds to the $41.4°$ off-crest (4 MeV rf-gun energy was assumed). The measured phase values for each particle ($-42°$ and $-34°$) yield 8.6% energy difference. The momentum compaction experimentally measured is 30% lower than what we expect from numerical simulation ($R_{56}^{simu} = 8.3$ cm), this discrepancy is not yet understood.

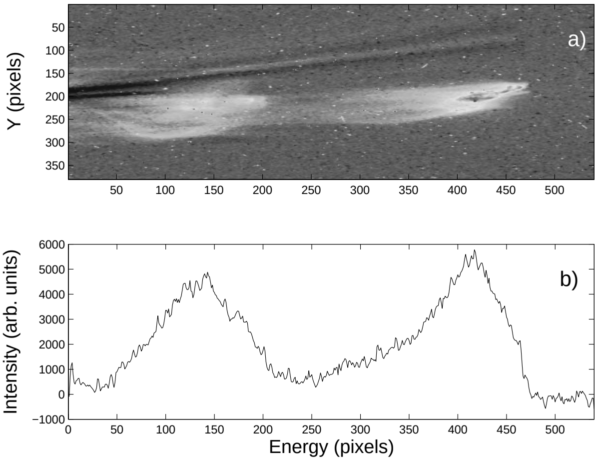

Figure 4: Example of data set for measurement of energy separation between the two macroparticles. **a)**: beam density on dispersive viewer, **b)**: corresponding projection.

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