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BUNCH LENGTH MEASUREMENTS AT THE CEBAF INJECTOR AT 130 kV *

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Abstract

In this work, we investigated the evolution in bunch length of beams through the CEBAF injector for 8–770 fC charge per bunch. Using the software General Particle Tracer (GPT), we have simulated beams through the beamline of the CEBAF injector to predict bunch lengths at the location of a beam chopper for comparison with measurements and to validate the model. We performed these simulations with the existing injector using a 130 kV gun voltage. The measurements have been done using chopper phase scanning technique for two injector laser drive frequencies 499 MHz and 249.5 MHz.

INTRODUCTION

The Continuous Electron Beam Accelerator Facility (CEBAF) injector at Jefferson Lab provides beams to the main accelerator, two recirculating linacs operating at 1497 MHz, connected by beam transport arcs. The beams are delivered to the experimental halls at either 499 MHz or 249.5 MHz. The CEBAF polarized electron source creates a spin-polarized electrons beams using a DC high-voltage photo-gun. The electron beam itself is composed of four interleaved electron beams created using four lasers, allowing four experimental halls to simultaneously receive electron beams [1]. This paper describes the main elements of the injector relevant to the longitudinal beam dynamics, and bunch length measurement methods and gives the results of such measurements.

BASIC DESCRIPTION

General Layout

Figure 1 is a schematic representation of the general layout of the CEBAF injector, showing the elements related to bunching and timing of the beam. The elements are the 130 kV photo-cathode gun where the beams are created, a 1497 MHz pre-buncher cavity where some bunching is provided when the current is high, a 499 MHz chopper system, a 1497 MHz buncher cavity where the main bunching starts, a 1497 MHz capture cavity, which accelerates the beam to 500 keV, and two 1497 MHz superconducting cavities (SRF) where some bunching is performed and the beams are accelerated to 5 MeV. Finally two 1497 MHz cryomodules accelerate the beams to a final energy of 123 MeV before injection to the first linac.

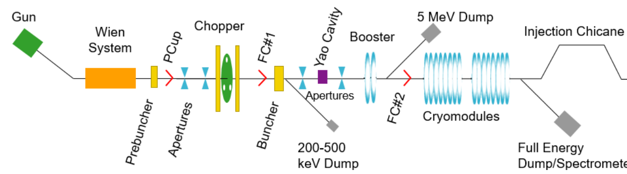

Figure 1: A schematic representation of the CEBAF injector at Jefferson Lab.

CEBAF RF Chopper and Faraday Cup

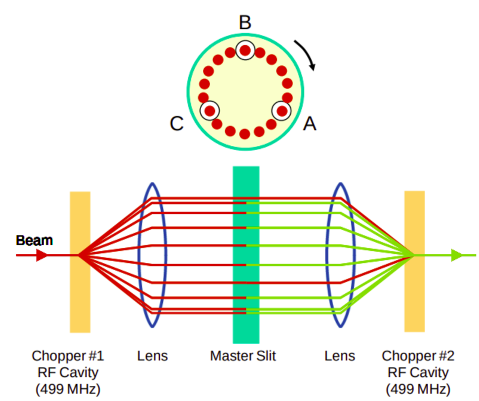

Figure 2: Schematic of the CEBAF three beam chopping systems containing two 499 MHz RF chopper cavities, two solenoid lenses, and a master slit [2].

The four beams are produced at the same spot on the cathode using four independent laser beams. The time structure of the beams originating from the gun is the same as the time structure of the laser light. Each laser micro-pulse frequency is either 499 MHz or 249 5 MHz, ~ 50 ps full width at half maximum (FWHM), however the lower rep rate of the gain- switched laser is somewhat longer. Figure 2 shows a schematic of the three beam chopping system showing possible trajectories of an electron beam. The beams from the 130 kV photo-cathode pass through two 499 MHz RF Chopper cavities with two solenoid lenses and a master slit in between is shown in Fig. 2 [2]. The distance between the gun and the chopping system is about 7.6 meters. The beam enters the first RF chopper cavity and is deflected by transverse magnetic fields along a cone whose apex is at

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the center of the cavity. The deflection axis depends on the phase of the cavity at entry. The beam passes through a solenoid lens to make the beam parallel to the central axis before passing through a master slit. The master slit contains three fixed apertures each 110 ps "wide" each with an additional variable aperture which can further reduce the bunch length, corresponding to a different experimental hall. By adjusting the aperture size, one can select the beam current going to each hall. The beam is re-centered with the beamline axis after passing through a second solenoid and Chopper cavity [2, 3].

After the chopping system, an insertable Faraday Cup measures the beam current. The Faraday Cup can be used in conjunction with the chopping system to measure the bunch length of an electron bunch. Chopper phase scanning technique was used for measuring the bunch length. In this scheme of bunch length measurement, the beam is set up to go through the chopper system and stops in the Faraday cup right after the Chopper. An individual aperture at the master slit is then adjusted to define a small fraction of the bunch length to pass through. Here, the chopper selects a small fraction of the longitudinal phase of each bunch of the beam arriving at the aperture. By recording the Faraday cup current as the chopper phase is scanned, a longitudinal profile of the bunch at the chopper is found. A sample of such a profile is shown in Fig. 3. The frequency of the chopper used is 499 MHz, therefore, the pulse length of the beam is 5.57 ps per degree of chopper cavity phase.

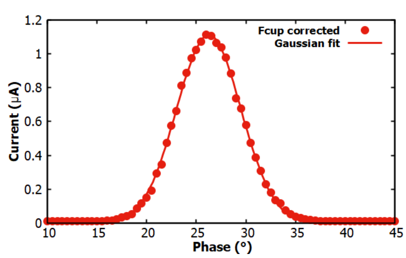

Figure 3: Chopper phase scan for 4 μA beam at 499 MHz with prebuncher OFF.

Simulation Details

We performed simulations using the commercial software General Particle Tracer (GPT) [4]. For the particle distribution at the cathode in simulation, the beam is assumed to have a Gaussian distribution in time (t), horizontal (x), vertical (y), horizontal momentum (p_x) and vertical momentum (p_y) co-ordinates following the profile of the laser. The transverse beam sizes which were previously measured for both laser drive frequencies, 249.5 MHz and 499 MHz, are $4\sigma_x = 2.237$ mm, and $4\sigma_y = 2.093$ mm, the transverse emittance is 0.061 mmmrad. The longitudinal beam size was obtained from the measurement results. The longitudinal shape was measured once for each drive frequency set by sending a near-zero charge beam (10 fC) through the injector. Because there is very little growth from space charge, the temporal profile remains nearly constant throughout the simulation. The laser pulses are 41.6 ps long (FWHM) for 499 MHz and 62.5 ps long (FWHM) for 249.5 MHz. The beam current is varied from 2.5 μA to 200 μA for 249.5 MHz laser frequency and from 4 μA to 118 μA for 499 MHz laser frequency. Thus, the bunch charge is calculated using the relation: $q = I \times f$. For the high bunch charge, the space charge effect is incorporated using the space charge3Dmesh algorithm [5]. The applied macroparticle number in the simulation is 10^4.

RESULTS

Using the simulation and measurement techniques described above, bunch lengths of the electron beams were predicted and measured at the location of chopper.

Measurements at Low Charge and High Bunch Charges

At low charges up to 80 fC, the longitudinal profile of the bunch at chopper is Gaussian, given by the following formula:

$$f(x) = \frac{A}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) \tag{1}$$

where A is the amplitude, σ is the rms value of the distributions, and μ is the mean of the distributions. For 10 fC bunch charge for two different drive laser frequencies, the longitudinal profile is shown in Fig. 4. This shows that the different modes of drive frequency have beams of different pulse lengths for low charge.

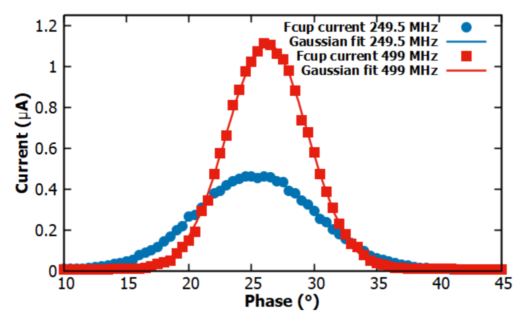

Figure 4: Chopper phase scans for two laser frequencies with prebuncher OFF. The length of the bunch is about 42.50 ± 0.22 ps FWHM for 499 MHz drive frequency and about 63.83 ± 0.27 ps FWHM for 249.5 MHz drive frequency.

However, above 80 fC bunch charge, the longitudinal profile of the bunch at chopper is a super gaussian function that describes a more rectangular distribution by the following formula [6]:

$$g(x) = \frac{A}{\sigma_0\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma_0^2}\right) \quad \text{with} \quad \sigma = \sigma_0 \left(\frac{\pi}{2}\right)^{2/N-1} \tag{2}$$

σ_0 is the rms value of the Super Gaussian distributions, and N is the exponent of the Super Gaussian and will give a

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Gaussian distribution for N = 2. For large N, the function will describe a more rectangular distribution, while for small N, it fits to a distribution with long tails on both ends. The measurement data and corresponding super gaussian fits for pulse lengths at various charges for different drive frequencies of the laser are shown in Fig. 5.

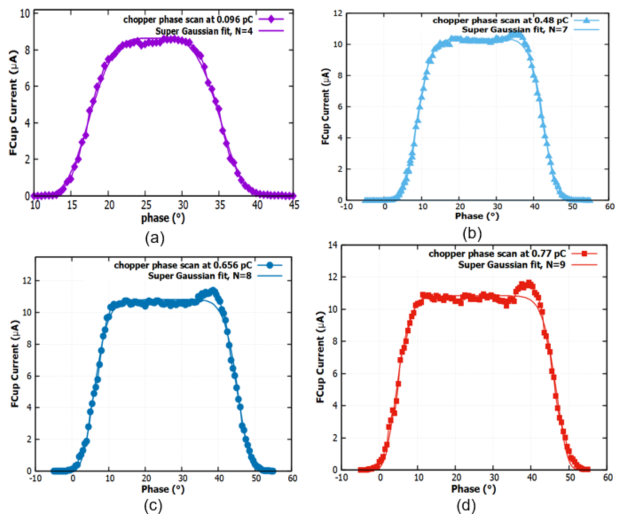

Figure 5: Longitudinal bunch profile measurements at the chopper for (a) 0.096 pC at 499 MHz, (b) 0.48 pC at 249.5 MHz, (c) 0.656 pC at 249.5 MHz, and (d) 0.77 pC at 249.5 MHz.

For the same charge per bunch electron beams for two different drive frequencies, the longitudinal bunch profile and hence the bunch lengths at the location of the chopper are equal, as shown in Fig. 6.

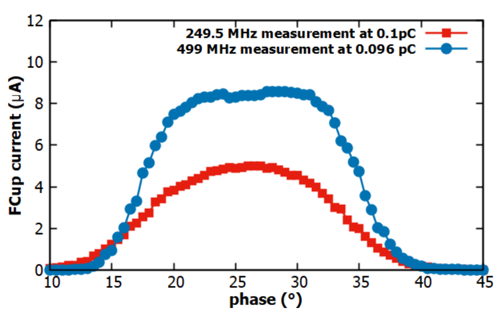

Figure 6: Longitudinal bunch profile measurements at the chopper for different drive frequencies about 0.1 pC bunch charge.

Comparison Measurements and Simulations

Figures 7 and 8 compare measurements using the chopper phase scanning technique and GPT simulations for various bunch charges studied for 499 MHz and 249.5 MHz frequencies. There is excellent agreement between them for low and high charges with prebuncher ON. But, for ALL charges with prebuncher OFF, the results deviate more from each other. This may be because the boundary in the simulations is not well defined. We can see from these Figs. 7 and 8 that for the same bunch charge, the measured data show almost equal bunch length at the chopper for two different frequencies. This is expected that the bunch lengthening due to space charge depends on the amount of charge in the bunch, for the same charge the expansion is the same. Also, compared to the pulse length at low beam current/bunch charge in the simulations and the measurements, the electron bunch length is much longer for higher currents, as shown in Figs. 7 and 8.

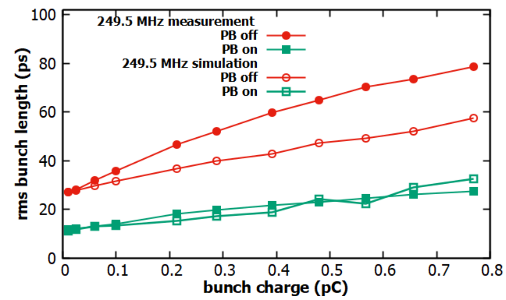

Figure 7: Bunch length at the Chopper for 249.5 MHz laser drive frequency.

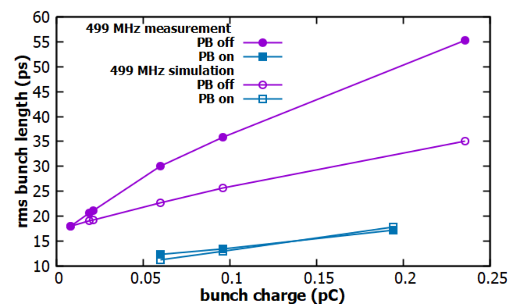

Figure 8: Bunch length at the chopper for 499 MHz laser drive frequency.

OUTLOOK

We have simulated the CEBAF injector model using General Particle Tracer (GPT) to investigate the evolution in bunch length of beams through the CEBAF injector and analyzed the beam to get the bunch lengths at the location of the Chopper with the existing 130 kV electron gun. We performed chopper phase scanning measurements to validate our model. With the prebuncher OFF the profile is gaussian at low (< 40 fC) charge but super gaussian at higher (> 90 fC) charge. With the prebuncher ON the bunch profile at the location of chopper is gaussian for both low and high charges. There is good agreement between measurements and the corresponding simulations when the prebuncher is ON, but not when it is OFF.

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