Setting and Measuring the Longitudinal Optics in CEBAF Injector*

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Abstract

The CEBAF injector is designed to produce three cw polarized beams to be simultaneously accelerated and delivered to three experimental halls. These beams have independent current controls that can be as low as few hundred pico-amperes or as high as 200 microamperes. The beams are created in a photocathode gun using 3 separate rf gain switched lasers each operating at 499 MHz which together make up 1497 MHz, the CEBAF fundamental frequency. At the gun, the beams have the same time structure as the lasers with about 55 pico-seconds bunch length at 499 MHz. Through the injector, this bunch length is then adiabatically reduced to less than 1 pico-seconds. The main requirement is that the beams have short stable bunch lengths at the end of the injector. In this paper we discuss the longitudinal bunching process for the JLAB injector. We also describe how the bunch length is measured at various places along the injector and how the measurement results are used to set relative phases of the three lasers and the phases and amplitudes of various rf cavities with high precision.

1 INTRODUCTION

The injector provides beam to the main accelerator, which consists of two re-circulating super conducting linacs operating at 1497 MHz fundamental frequency. The beam re-circulates up to 5 times through the two linacs. The beam bunches are received at each of the 3 experimental halls at 499 MHz, one third of the linac frequency. This allows simultaneous operation of the three halls. Three beams are produced in the injector gun each at 499 MHz with 120 degrees phase separation.

Table 1: Injector specifications

Parameter	required	Measured
Energy	22.5 to 67.5 MeV	22.5 to 67.5 MeV
Current per bunch train	1 μA to 100 μA	<100 pA to 150 μA
Bunch length	<2.2 ps	<1 ps
$\Delta E/E$	10^{-3}	$<10^{-3}$

To maintain the restrict beam quality in the main machine and the experimental halls, the beam at the exit of the injector must satisfy tight requirements listed in Table 1. The challenges from the beam dynamics point of view is to first have a configuration which produces such a small bunch length at different currents and energies without too much degradation of transmission or energy spread. The second challenge is to measure and maintain the bunch length and energy spread through the injector.

In the next sections we will describe the main elements of the injector relevant to the longitudinal beam dynamics, describe different bunch length measurement methods and give the results of such measurements.

2 BASIC DESCRIPTION

2.1 General Layout

A block diagram of the injector layout is given in Figure 1. It lists only the beam elements influencing the beam dynamics. The elements are: the 100 kV photo-cathode guns where the beams are created, the pre-buncher cavity where some bunching is provided when the current is high, the chopper system, the buncher cavity where the main bunching starts, the capture cavity which accelerates the beam to 500 keV, the first two super-conducting cavities (SRF) where some more bunching is done and the beam is accelerated to 5 MeV, and finally the two rf modules each containing 8 SRF cavities which together accelerate the beam to final injector energy.

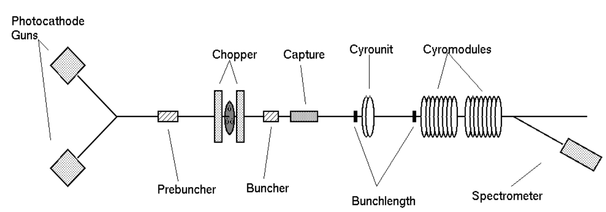

Figure 1: The injector layout

During the operation, only one gun is on. The 3 beams are produced at the same spot on the cathode using 3 independent laser beams. The time structure of the beam at the gun is the same as the time structure of the laser light. The laser micro pulses are at 499 MHz which is in synch with the rest of the injector rf. These pulses are about 55 ps long (FWHM). The phase requirement for the 3 lasers is to be exactly 120 degree of 499 MHz apart. The distance between the gun and the chopping system is about 6.5 meters. At high currents (much above 30 μA)

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the bunch lengthening due to the space charge becomes a problem. The function of the pre-buncher cavity is to provide enough bunching so that the bunch length at the chopper stays within the acceptance of the chopper. The pre-buncher operates at the zero-crossing phase corresponding to no energy gain or pure bunching. The amplitude of the pre-buncher has to be adjusted depending on the beam current. The three beam chopping system operates at 499 MHz, therefore it distinguish between the three beams. It has three independently variable slits, which define a phase acceptance from 0 to 110 ps for each beam. Note that 0 to 110 ps is not an rms or sigma value, since any beam outside this limit will be stopped at the chopper. The chopper system is the only element in the injector beside the lasers which operates at the one-third fundamental frequency, and it is well described in reference [1]. The only relevant chopper parameter is its phase which has to be in synch with both gun and the pre-buncher to allow the beam to pass through it. After the chopper, the main beam bunching starts at the buncher cavity. The buncher is followed by the capture cavity, which is a five-cell graded β warm rf accelerating structure. At the end of the capture cavity the beam energy is ~500 keV. The phase and amplitude of both buncher and capture cavities are very crucial to proper shaping of the beam bunch length and energy spread. After the capture, the beam is further bunched and accelerated to 5 MeV by the two SRF cavities. As was said before, the final beam energy is achieved in the two rf modules. In fact, the machine set up from the gun to 5 MeV stays the same independent of the final energy of the injector. There is no more bunching in the two modules and all 16 SRF cavities in the two modules operate on crest.

3 MEASURING THE BUNCH LENGTH

In this section, we describe the bunch length measurement at different points along the injector. Different methods are used at different locations in the injector.

3.1 Chopper Phase Scan

In this scheme the beam is set up to go through the chopper system and stop in a Faraday cup right after the chopper. The chopper slit is then adjusted to only allow small fraction of the bunch length to pass through (typically 16 ps or less). In this case the chopper selects a small fraction of longitudinal phase. 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 profile is in shown in Figure 2.

3.2 Bunch Length Cavity

This method uses a time of flight measurement from the chopping slits to signal pickup devices after the chopper; in this case 6 GHz (4th harmonic) cavities. Again, the chopper slit is set up to allow only small fraction of the phase to pass through. As this electron beam passes through the pickup cavity, the cavity resonates in phase with the electron bunches. A plot of the phase of the pickup cavity vs. the phase of the chopper reveals the phase compression between the two points. A sample of such plot is in shown in Figure 3. The "Phase IN" is the phase at the chopper.

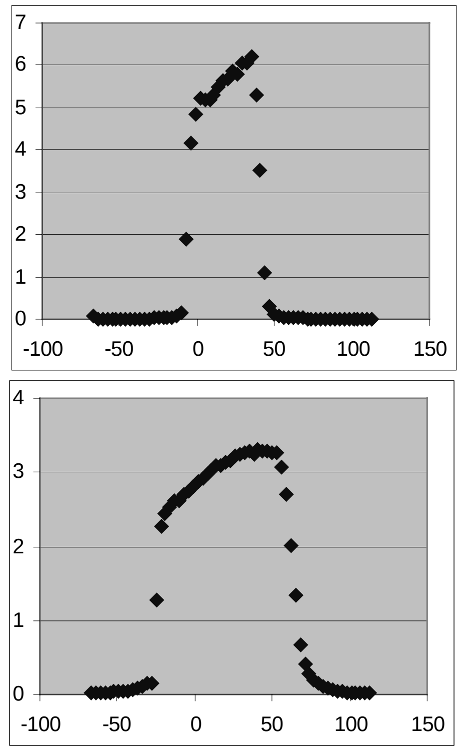


Figure 2: chopper scan for 120 μA Beam with/without prebuncher on

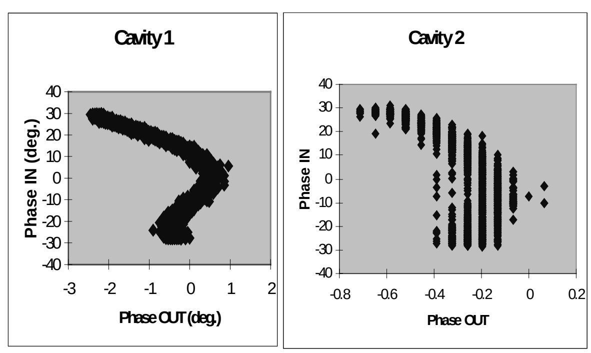


Figure 3a,b: Phase compression at 1st and 2nd bunch length cavities

3.2 RF Zero-Phasing Technique

The zero-phasing measurement uses several SRF accelerating cavities of the second rf module, a spectrometer, and a horizontal profile-measuring device. Usually we use the last 4 accelerating cavities. The phase of these cavities is set to the zero-crossing phase. As a beam bunch passes through these cavities the average energy of the bunch does not change; however, the cavities introduce a tilt in energy between the head and the tail of the bunch. The beam is then sent to a spectrometer, which translates the head tail energy difference to position difference. From a beam profile measurement after the spectrometer and dispersion of the spectrometer, one can determine the energy difference between the head and the tail, which, combined with the knowledge of the amplitude of the rf cavities, determines the beam bunch length. By performing this measurement at both zero crossing phases, plus and minus 90 degrees from the crest phase, one can even eliminate any effect from the initial energy tilt on the bunch [2]. The results of this method give a direct measurement of the final injector bunch length.

4 MEASUREMENT RESULTS

Using the methods described above a measurement of the bunch length was performed at different points along the injector. These measurements were done for the beam currents of 5, 30, 60, 100 and 120 µA from one of the 499 MHz beams.

4.1 At Chopper

This measurement shows the value of the bunch length at the chopper. It also shows how the bunch length increases as beam current is increased and it shows how the pre-buncher is effective in keeping the bunch length within the acceptance of the chopper. Figure 4 graphs the results of the measurement. Figure 2 shows the scans for a 120 µA beam. The x axis in Figure 2 is the 1497 MHz rf phase in degrees. Note that the full acceptance of the chopper slit is 60 degrees or 110 ps.

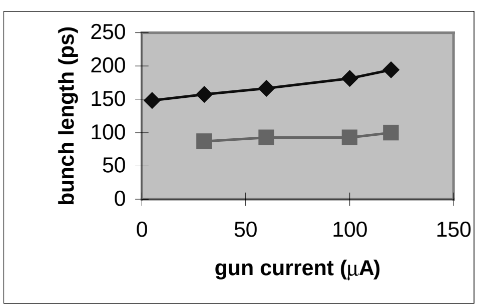


Figure 4: chopper scan.
Prebuncher on/off (bottom/top)

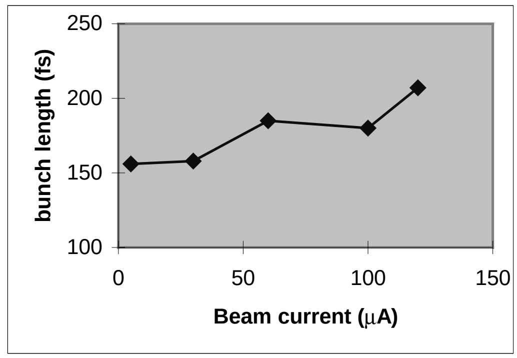
4.2 At Two Bunch length Cavities

There are three pickup cavities in the injector; however only two were used for this test. The first cavity is before the first two SRF cavities and shows the phase compression due to the buncher and the capture cavities (Figure 3a). The second cavity is located before the rf modules and shows the final phase compression (Figure 3b). Since this method only measures the phase compression from the chopper to the pickup cavity, it is independent of beam current.

4.2 RF Zero-Phasing

This measurement was performed in the spectrometer after the two rf modules. An Optical Transition Radiation (OTR) monitor [3] was used to measure the width of the beam in the spectrometer. The results are shown in Fig. 5.

Figure 5: Bunch length at the



end of the injector

5 CONCLUSION

The bunch length size at the beginning of the injector is about 50 picosecond rms; by the time it arrives at the end of the injector, it is only few hundred femtoseconds. We have been able to measure it at different points along the injector. Based on these measurements we fine-tune the rf phase and amplitude of injector elements. For example the chopper phase scan is used to phase the pre-buncher. The shape and the size of the phase compression at the first bunch length cavity reveals if the buncher or the capture cavities have a correct phase. More importantly the PARMELA simulations give the same shape and size for the bunch length as measured using the experimental methods.

6 REFERENCES

[1] R. Abbott, et al, Proceedings of the 1994 International LINAC Conf. Volume 2, p. 777

[2] D. X. Wang, et al, "Measurement of femtosecond electron bunches using a rf zero-phasing method", Phys. Rev. E 1998, Volume 57, Number 2, p.2283

[3] J.-C. Denard, et. al., “High Power Beam Profile Monitor with Optical Transition Radiation” Proceedings of the 1997 Particle Accelerator Conference, Vancouver, BC.