JLAB-ACP-97-03

THE CALCULATION, SIMULATION, AND MEASUREMENT OF LONGITUDINAL BEAM DYNAMICS IN ELECTRON INJECTORS

DOE/ER/40150--1130

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CONF-970503--22

Abstract

Polarized electrons are a valuable commodity for nuclear physics research and every effort must be made to preserve them during transport. Measurements of the beam emitted from the polarized source at the Thomas Jefferson National Accelerator Facility (Jefferson Lab) have shown a considerable bunch lengthening with increasing beam current. This lengthening leads to unacceptable loss as the beam passes through the injector chopping system. We present an application of the longitudinal envelope equation to describe the bunch lengthening and compare the results to measurements and simulations using PARMELA. In addition, a possible solution to the problem by adding a low power buncher to the beamline is described and initial results are shown.

1 INTRODUCTION

Polarized electrons are a very valuable commodity for nuclear physics research, and every effort must be made to preserve them during transport through the accelerator. A typical thermionic injector discards 5/6th of the DC beam during the initial chopping process to prepare the beam for bunching and capture before injection into the main accelerator: this is clearly not the preferred method for polarized electrons. In addition, throwing away part of the charge during the chopping process will effectively lower the useful lifetime of the cathode.

To overcome this problem, the beam from the photocathode must either be prechopped at the cathode using a laser (as is done in RF guns), or adiabatically bunched with minimal beam loss (as is done for protons and ions using an RFQ). As no reliable adiabatic bunching scheme exists for electrons, and prechopping with a laser is straightforward, this is the method chosen for the polarized source at the Jefferson Lab. The present laser has a pulse width of 54 ps (FWHM) [1] which matches the 60° (110 ps) total RF phase acceptance (at 1497 MHz) used in the chopping system.

Initial measurements of the bunch length after the beam has traversed approximately 10 meters through the injector show that bunch length is much longer than the initial laser pulse width and also depends on current. In this report, the longitudinal envelope equation will be reviewed and applied to the observed bunch lengthening. In addition, a corrective action using a bun[illegible] discussed.

2 DESCRIPTION OF THE SYSTEM

In the calculation of the longitudinal properties of the beam (see section 3), the longitudinal envelope equation assumes that the beam has a constant transverse dimension. While this is certainly not the case, the mean beam size can be used as an estimate for the longitudinal calculations. Thus, the sketch below only includes the location of elements that effect the longitudinal properties of the beam, and not focusing elements such as solenoids. Details of the polarized beam transport system and the chopping system can be found elsewhere (see [2] and [3] respectively).

The beam is accelerated to 100 kV in a photocathode gun and then deflected from vertical to horizontal using a dipole (see figure 1). It then passes through a 'Z' shaped spin manipulation system consisting of two electrostatic bends plus a number of solenoids. After leaving the 'Z' the beam continues on and enters the regular thermionic injector beamline where it is chopped, bunched and accelerated before injection into the main machine.

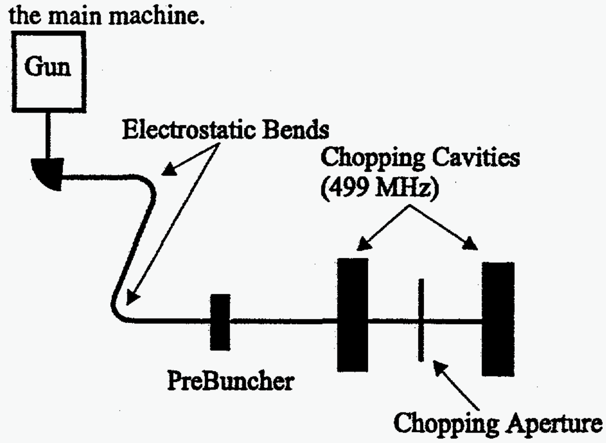

Figure 1 Schematic of the injector beamline

To measure the bunch length, the first chopping cavity deflects the beam and sweeps it into a 3 cm diameter circle at the chopping aperture. The chopping aperture is then set to transmit a 10° slice from the circle incident on it, and the transmitted current is measured as a function of the laser phase in a downstream faraday cup. A plot of the transmitted current versus the laser phase gives a direct measure (after correcting for the

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finite size of the slit) of the bunch length at the chopping aperture.

3 LONGITUDINAL ENVELOPE EQUATION

Many are familiar with the calculation of the transverse envelope behavior of a beam using the envelope equation, but not with the calculation of the longitudinal envelope properties (bunch length and energy spread). The longitudinal envelope equation [4,5] represents the ideal situation of a beam with a parabolic charge distribution with no transverse variations. The parabolic distribution leads to a self-consistent solution with linear space charge forces. It is also is correct relativistically and includes the effects of acceleration. Experimental verification of the equation at low energies using a beam with a parabolic distribution have been carried out [5].

The longitudinal envelope equation can be written (ignoring acceleration) as [4]

$$\frac{d^2z}{ds^2}-\frac{2gz_{init}I_{peak}}{\beta^3\gamma^5 I_0}\frac{1}{z^2}-\frac{\varepsilon_L^2}{z^3}-K(s)z=0$$

where z is the half bunch length, K is the focusing term, ε_L is longitudinal emittance, I_0 is a constant equal to 17 kA, and g is the geometry factor $1+2\ln(R/r)$, where R is the pipe radius and r is the average beam radius. For now, we will assume that the emittance is negligible and that there is no external focusing. The equation can then be written in the simplified form

$$\frac{d^2z}{ds^2}=\frac{a^2z_{init}}{2z^2} \text{ where } a^2=\frac{4gz_{init}}{\beta^3\gamma^5 I_o}.$$

This equation can be integrated to give $\eta'^2=\frac{a^2}{z_{init}^2}\left(b-\frac{1}{\eta}\right)$ with $b=1+z_{init}'^2/a^2$ and $\eta=z/z_{init}$. Integrating once more gives (for $z'_{init}>0$)

$$\frac{sab^{3/2}}{z_{init}}=\log\left(\sqrt{\eta b}+\sqrt{\eta b-1}\right)+\sqrt{\eta b}\sqrt{\eta b-1}-\log\left(\sqrt{b}+\sqrt{b-1}\right)-\sqrt{b}\sqrt{b-1}$$

and

(for $z'_{init}<0$)

$$\frac{sab^{3/2}}{z_{init}}=\pm\left[\log\left(\sqrt{\eta b}+\sqrt{\eta b-1}\right)+\sqrt{\eta b}\sqrt{\eta b-1}\right]+\log\left(\sqrt{b}+\sqrt{b-1}\right)+\sqrt{b}\sqrt{b-1}$$

where the + sign is for positions before the waist and the - sign is for positions after the waist.

4 CALCULATIONS AND RESULTS

The longitudinal envelope equation requires that the initial particle distribution be parabolic in order for the self-consistency condition to be satisfied. The laser beam profile for the polarized source is roughly Gaussian with a FWHM of 54 ps [1]. For the first step in the bunch lengthening calculations, we will assume that the initial electron distribution follows the laser beam distribution, and that the Gaussian can be approximated by a parabolic distribution with the same rms width and area. Then, assuming that the beamline is a 10.0 meter drift (s=10 m, the distance from the gun to the chopping aperture) the final bunch length can be calculated using the equations in section 3 with the initial conditions given by parameters a and b. The geometry factor 'g' is calculated using PARMELA to be 4.84 (σ_r = 0.4 mm) including all of the transverse focusing elements. Figure 2 shows the results of the calculations as a function of average current and several geometry factors (g) along with the measured bunch length. The numbers are all in terms of the parameters of the parabolic distribution (i.e. the plotted bunch length (2z) corresponds to the parabolic distribution, not the actual number). A comparison to the PARMELA simulations is also shown.

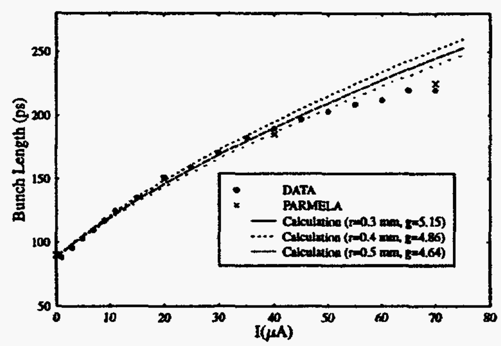

Figure 2 Bunch lengthening calculations compared to measurements and PARMELA simulations.

The calculations agree well for currents up to about 40 μA. For higher currents, beam loss occurs during the last meter of travel as the beam passes through two small emittance defining apertures. This reduces the bunch lengthening and distorts the longitudinal profile, making comparisons more difficult. The apertures, which are necessary only for operation of the thermionic gun, have since been enlarged to allow nearly complete transmission of the beam from the photocathode gun.

5 ADDITION OF A BUNCHER

A buncher located after the Z spin manipulator can provide a longitudinal kick to compensate for the debunching during transport through the injector. Instead of solving the envelope equation including the force term, the kick can be treated by matching boundary conditions at the location of the buncher. To solve the problem the slope ($z' = dz/ds$) and bunch length (z) at the entrance to the buncher are calculated, then the change in the slope at the buncher necessary to reduce the bunch length to the nominal ±30° at the chopping aperture is determined.

To find the relationship between the change in slope and the buncher amplitude, note that $z' = \Delta\beta/\beta$ where the difference is between the center of the bunch and the head (or tail) of the bunch. The energy gain is $\Delta E = mc^2\Delta\gamma = eV\sin\varphi$ where φ is the phase of the electron with respect to the center of the bunch. Using the relation $\beta\,\Delta\beta = \Delta\gamma/\gamma^3$, this can be rearranged to find the peak buncher voltage for an ideal, zero-length buncher (see figure 3)

$$eV = \frac{mc^2\beta\Delta\beta\gamma^3}{\sin\varphi} = \frac{z'mc^2\beta^2\gamma^3}{\sin\varphi}$$

Making the small angle approximation and substituting $\varphi = \omega z/\beta c = \omega\eta z_{init}/\beta c$ gives

$$eV = \frac{\gamma\beta c(\gamma^2 - 1)z'mc^2}{\omega\eta z_{init}}.$$

A low power buncher has been constructed and installed in the beamline. Figure 4 shows pictures of a viewer at the chopping aperture. The upper left picture shows the nominal beam (no buncher): three beams are present as the choppers operate at 499 MHz while the gun fills every bucket at 1497 MHz. The upper right picture displays the beam with the buncher on and at zero crossing phase. A buncher power of 1.5 W is sufficient to compress the 30 µA (average current) beam to pass through the chopping system loss-free.

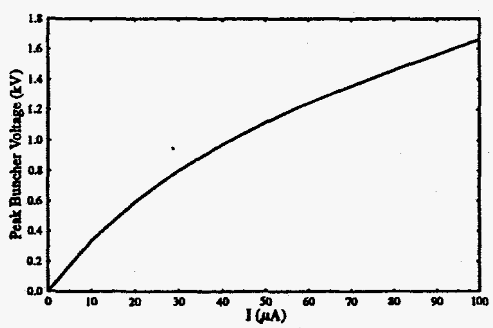

Figure 3 Calculated buncher voltage as a function of current (for an ideal, zero-length buncher).

4 CONCLUSION

Polarized electrons are a very valuable commodity for nuclear physics research, and every effort must be made to preserve them during transport through the accelerator. Initial measurements of the bunch length of the beam emitted from the polarized source have shown that the beam cannot pass loss free through the injector chopping system. We present an application of the longitudinal envelope equation to describe the measured bunch lengthening and find very good agreement between the prediction and the measurements. A solution to the problem of bunch lengthening using a buncher cavity has also been demonstrated.

5 ACKNOWLEDGEMENTS

This work was supported by the U.S. DOE under contract number DE-AC05-84ER40150. Thanks to M. Poelker for helping to obtain the data and to C. Sinclair for motivating this work. Also, thanks to C. Piller and C. Hovater for quickly designing and building the prebuncher.

REFERENCES

[1] M. Poelker, private communication.
[2] D. Engwall., B. Dunham, L.S. Cardman, D.P. Heddle and C.K. Sinclair, Nucl. Instr. Methods **A324**, 409 (1993).
[3] M.G. Tiefenback and G.A. Krafft, 1993 Part. Accel. Conf, 426 (1993).
[4] D. Neuffer, IEEE Trans. Nucl. Sci., **26**, 3031 (1979).
[5] D.X. Wang, J.G. Wang, D. Kehne, and M. Reiser, Appl. Phys. Lett. **95** (25), 3232 (1993).

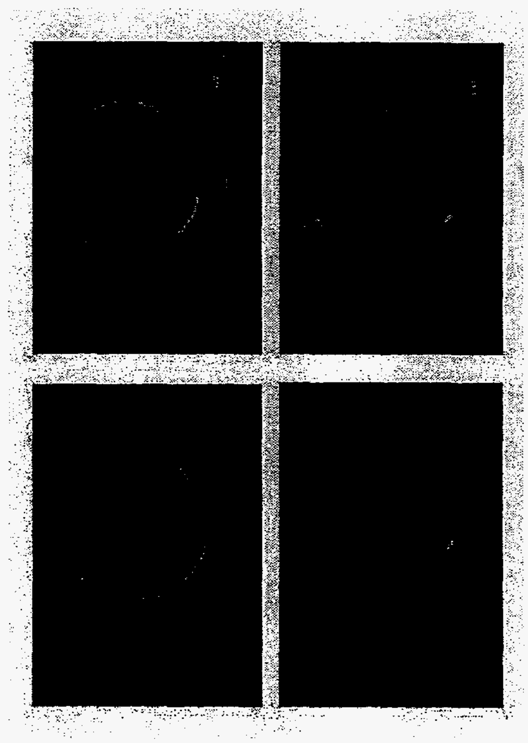

Figure 4 Clockwise from upper left: 1) buncher off with 30 µA of average current; 2) buncher on at zero crossing; 3) buncher on 30° off zero crossing; and 4) buncher on with the phase set to the wrong zero crossing.