A PARMELA MODEL OF THE CEBAF INJECTOR VALID OVER A WIDE RANGE OF PARAMETERS *

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Abstract

An earlier PARMELA model of the Jefferson Lab CEBAF photoinjector was recently revised. The initial phase space distribution of an electron bunch was determined by measuring spot size and pulselength of the driver laser and by beam emittance measurements. The improved model has been used for simulations of the simultaneous delivery of the Hall A beam required for a hypernuclear experiment, and the Hall C beam required for the G0 parity violation experiment. The Hall C beam requires a factor of 6 higher bunch charge than the Hall A beam, with significant space charge effects, while the Hall A beam has an exceedingly stringent energy spread requirement of $3x10^{-5}$ rms. Measurements of beam properties at 100 keV and several values of bunch charge were performed using the standard quad-wire scanner technique. Comparisons of simulated transmission rate, longitudinal beam size and transverse emittances against experimental data yield reasonably good agreement. The model is being used for optimization of the CEBAF injector.

INTRODUCTION

One important feature of the Jefferson Lab CEBAF facility is the capability to deliver polarized electron beams of different specifications to three experiment halls simultaneously. While this unique feature enhances productivity of physics program, it imposes significant challenges to operation of the accelerator facility in general and the photoinjector in particular. A recent parity violation experiment in Hall C required a 40 μA average beam current at 31 MHz repetition rate, which corresponds to a single bunch charge that is 6 times the original design specification. As a consequence, the space charge effect becomes a critical issue in the low energy (100 keV) section of the injector. At the same time, a hypernuclear experiment in Hall A received a CW beam of a relatively smaller bunch charge (100 μA at 499 MHz) with energy spread less than $3x10^{-5}$ rms [1], an exceedingly stringent requirement. Searching for injector settings to satisfy both requirements was a nontrivial undertaking [2] and benefited from computer modeling of the injector.

Modeling of the CEBAF injector using PARMELA has a long and successful history that dates back before commissioning of the CEBAF facility [3]. The original injector model was based on an earlier version of the LANL PARMELA software [4]. The software has since been extensively customized for many unique CEBAF injector components such as the chopper and Wien filter. Detailed studies, such as the impact of macroparticle size on space charge calculations [5], had been done to improve the model, which was benchmarked against the experiment data. This model was used for injector optimization [6], hardware reconfiguration studies [7], and other base operation support. A PARMELA deck based on a similar model also has been established for the high current photoinjector for the JLab free electron laser program. [8]

The work reported here is a continuation and expansion of the CEBAF injector modeling activities. We started with verification of the existing PARMELA deck by conducting a hardware survey to accurately determine component locations. We verified the driving laser information: spot size and pulselength. We measured transmission of beam through the 100 keV section of the injector and in addition we measured 100 keV emittance by quad-wire scanner. We then extended this deck [9] to the whole injector, from existing 5 MeV up to 65 MeV, the entering point to the main CEBAF Linac. The new deck was then used for simulations of the CEBAF injector under a new setting that was empirically tuned for meeting new and much harder beam specifications [2]. We will present comparisons between the model and the experimental measurements. We confine this paper to the 100 keV section since that part of the injector is most critical to the beam transport through apertures and chopper slit. Simulations of the downstream section will be reported later.

MODEL

The CEBAF injector uses a DC photo emission gun to produce polarized electrons and acceleration to 100 keV. The injector employs a two stage bunching mechanism (prebuncher and buncher) [9] and a three-slit chopper [10] to regulate three CW beams. Four apertures with hole size from 4 to 6 mm are placed along the beamline for transverse emittance control. A Wien filter is used to manipulate spin direction in the halls. A 15-degree bend dipole is placed near the cathode to accommodate two photoguns for alternate use. The beam is then accelerated

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to 0.5 MeV with a capture RF cavity, and then to 5 MeV with two SRF cavities and finally to energies from 30 to 68 MeV with 16 SRF cavities. There are 11 solenoids and 20 quads in the injector beamline for transverse focusing. These are the elements incorporated into the injector PARMELA model, while other inactive elements such as correctors and various beam monitor devices are treated as drift spaces. The 15-degree bend dipole is modeled by a straight drift space plus a solenoid for the focusing effect of the dipole.

Over years of CEBAF operation, many injector components have been replaced, repositioned or decommissioned. Our first effort of verification of the model was to update the PARMELA deck with a machine survey. We found that most injector components were very close to their original positions or off only by 0.5 to 3.5 cm. Four components were off by 6 to 8 cm [11].

The initial phase space distribution of macroparticles in the PARMELA model is assumed Gaussian in emission time, the transverse dimensions and energy spread, truncated at three times sigma value. Greater attention was devoted to measuring the pulse length and spot size of the driver laser than in the past. These values were used to specify the initial distribution of the pulse. The laser for the parity violation experiment was not perfectly symmetric, σ_x=595±47 μm and σ_y=526±38 μm. The average spot size, <σ>=560 μm, was used in the PARMELA model since it assumes a symmetric transverse distribution.

The initial energy spread, σ_E, is an empirical value in the initial phase space distribution and was determined by fitting the simulated emittances with measurements from a lens-wire scan. The previous value in the deck is 0.1 eV, but a new fit of the data suggests that we should use a smaller value of 0.01 eV.

Space charge force in the JLab version of PARMELA, which is very critical to simulate beams of large bunch charge, was based on the particle-particle direct calculation. Macroparticles were assumed to have a finite size. As a cross check, we benchmarked PARMELA against ASTRA [12], another space-charge code. It was found that simulation results from both codes converge as the number of macroparticles increases and agree very well when the marcoparticle number is greater than 5000. We found that, for pC bunches, there is a noticeable underestimation of the space charge effect by PARMELA when only 1000 macroparticles are used. With current computing capability and trade-off of computing time and simulation quality, we decided that all simulations should be done with a minimum of 5000 marcoparticles.

SIMULATIONS

PARMELA simulations were performed using CEBAF injector component settings determined empirically during the commissioning of the Hall C parity violation experiment [2]. Solenoid lens with strong focusing settings and a strong prebuncher amplitude were employed to suppress space charge effects and to achieve maximum particle transmission through apertures and the chopper slit and to maintain smallest transverse emittances. These injector settings provided a good benchmark for the new model under much harsher conditions than before.

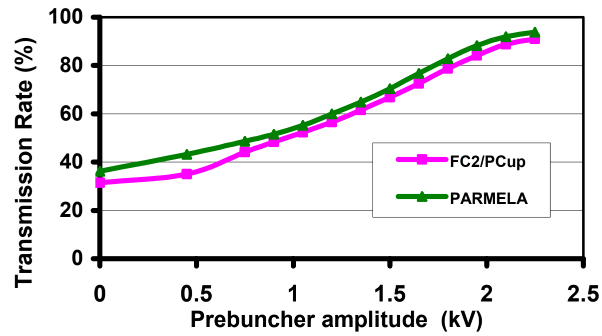

Figure 1. Particle transmission after aperture A1, A2 and chopper slit for a 45 μA CW beam of 31.5 MHz.

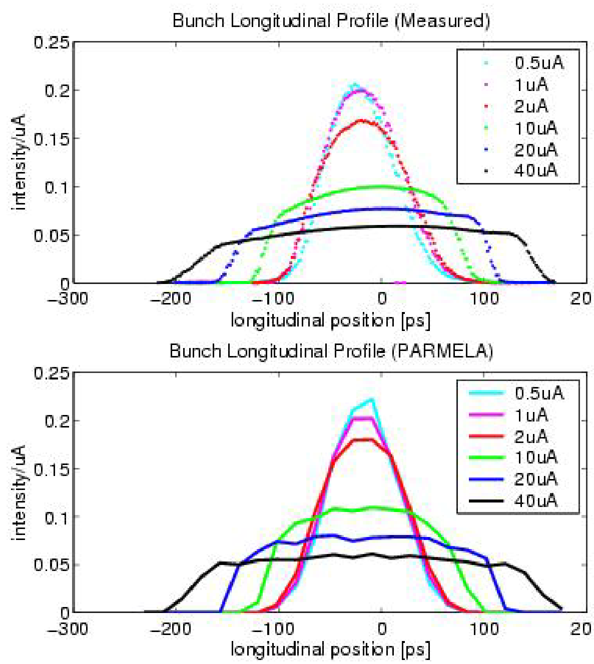

Figure 2. Longitudinal density profiles for a beam with 31 MHz repetition rate at the chopper slit. Wien filter is off. Top panel, measured. Bottom panel, simulations.

Figure 1 shows the particle transmission through apertures A1 and A2 and the chopper slit for a 45 μA CW beam with 31 MHz repetition rate under various prebuncher amplitudes. The Wien filter was turned off. The experimental data was obtained using two Faraday cups, one near the photocathode and the other further downstream. The second curve, which is above the experimental data, is PARMELA simulations under the same prebuncher amplitudes. Not only does overall transmission agree between experiment and simulations, but also the particle losses at each aperture and at the chopper slit are consistent.

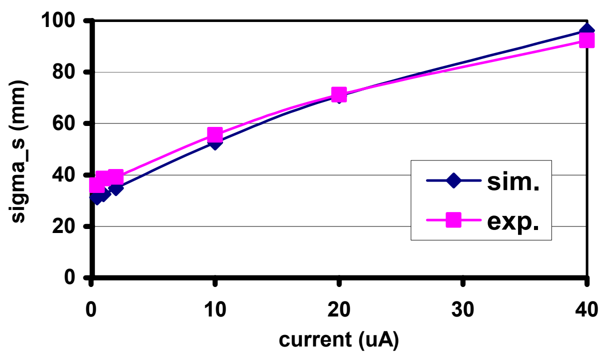

Figure 3. Bunch length for a 31 MHz repetition rate high charge bunch charge.

More information can be obtained by examining the longitudinal density profile, or bench length and shape, of the high bunch charge G0 beam. Bunch profile is measured by reducing the chopper slit size (to 18 ps) and adjusting bunch arrival time at the chopper slit by changing the phase of the optical pulse train. Figure 2 shows such bunch profiles for various beam currents at the chopper slit. The Wien filter was turned off. Figure 2 indicates that the PARMELA simulations (Panel 2) and experimental data (Panel 1) agree very well. The bunch length for each current shown in Figure 2 is plotted in Figure 3.

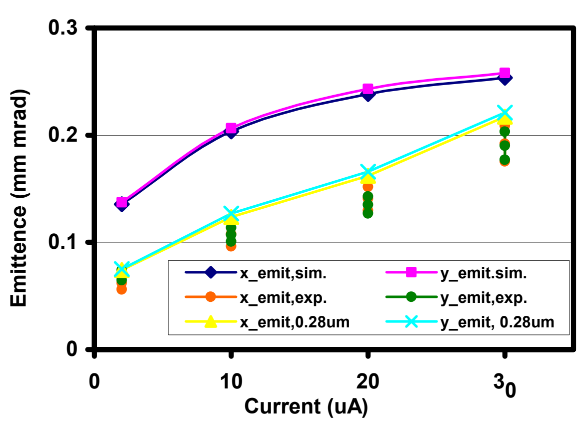

Figure 4. Measured horizontal and vertical emittances for a 31 MHz beam (points). The top curves show PARMELA simulations. The bottom curves are for simulations of the same PARMELA deck but with the initial bunch spot sized reduced by half (<σ>=280 μm).

In the transverse dimensions, the horizontal and vertical emittances can be measured by the standard quad-wire scan. Emittance values for 4 different G0 current are shown in Figure 4. Simulations results shown on the same figure are noticeably higher than the measurements. A third curve, which is in better agreement with the experimental data, is from PARMELA simulations where the initial beam spot size had been reduced by half of that we measured. From this we conclude that the new PARMELA deck needs to be further verified and improved in the transverse directions.

CONCLUSION

An effort to verify, extend and improve an existing PARMELA model for the CEBAF photoinjector has been presented. The new model was used for simulating the CEBAF injector for a wide range of parameters. We found that the model has excellent agreement with experiments in the longitudinal direction in the 100 keV section. We are able to predict the particle transmission rates to a very high degree of accuracy. The longitudinal density profiles and bunch lengths also agree very well with measurements. We have used this model to determine optimal injector settings for maximum particle transmission with lowest possible prebuncher amplitude. A comparison on the transverse emittances shows noticeable discrepancy between experiments and simulations, which indicates the current injector model needs further verification and improvement.

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