CEBAF INJECTOR ACHIEVED WORLD'S BEST BEAM QUALITY FOR THREE SIMULTANEOUS BEAMS WITH A WIDE RANGE OF BUNCH CHARGES *

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Abstract

The CEBAF accelerator provides interleaved 499 MHz electron beams, spanning 5 decades in beam intensity (a few nA to 200 µA), to three experimental halls simultaneously. The physics program became more challenging when the G^0 experiment was approved, requiring more than six times higher bunch charge than is routine. This experiment requires up to 8 million electrons per bunch at a reduced repetition rate of 31 MHz, while the lowest current hall simultaneously receives 100 electrons per bunch. A bunch destined for one hall may experience significant space charge forces, while the next bunch may have negligible space charge. This disparity in beam intensity must be maintained while delivering "best ever" values in rms beam quality, including relative energy spread (<2.5x10^{-5}) and normalized transverse emittance (<1 mm-mrad). Space charge difficulties emerge in the 10m long, 100 keV section of the CEBAF injector during initial bunch formation and spin manipulation. A series of changes was introduced to meet the new requirements, including adding new magnets, replacing photoinjector lasers, modifying typical laser parameters, stabilizing RF systems, and changing standard operating procedures. In this paper, we discuss these modifications in detail, including the agreement between the experimental results and detailed simulations.

INTRODUCTION

The forward angle scattering portion of the G^0 parity violation experiment was successfully completed this year at Jefferson Lab, however, it posed numerous challenges for the accelerator. It required an average beam intensity of 40 µA of highly polarized electrons with a micropulse repetition rate of 31 MHz (a factor of 16 smaller than usual). Despite the modest beam current specification, the bunch charge of 1.6 pC was large compared with the usual peak requirement of 0.2 pC for a 100 uA average beam current with 499 MHz pulse repetition rate. The beam suffered significant emittance growth in the extended 100 keV transport, which made it difficult to deliver the required beam without significant transmission losses. Successful transport through the JLab injector came as a result of numerous modifications to our usual setup, done while maintaining the beam parameters for other halls at their best values. In fact, during the G^0 run in Hall C, another challenging experiment with high demands on beam energy spread was carried out successfully in Hall A. The key modifications were in the early part of the injector where the beam is created and the bunch is formed. In the following sections we present the beam requirements set by the experimenters, explain the work we have done in the injector to meet these requirements, and show the result of beam measurements at the experimental halls.

THE REQUIREMENT

Table 1 shows recent beam requirements for Halls A, B, and C at Jefferson Lab. The numbers are generated from the experiments performed in each hall: the Hypernuclear experiment in Hall A, the g10 experiment in Hall B, and the G^0 experiment in Hall C. This table also shows that each experiment has stressed different aspects of the beam. The critical parameter in Hall A is the low energy spread. For Hall B it is the low current and low beam size, and for Hall C it is the high charge per bunch and the stringent halo limit.

Table 1: Beam Requirements

Beam Parameters	Hall A	Hall B	Hall C
Current	100µA	Few nA	40µA
Charge/bunch	0.2 pC	2e-17 C	1.3 pC
Energy	1-5 GeV	1-5 GeV	1-5 GeV
ΔE/E	2.5x10^{-5}	<10^{-4}	5.0x10^{-5}
Size at target	>100 µm <1000µm	100µm	<200 µm
Divergence	--	100µrad	100 µrad
Fractional Beam Halo	100Hz/µA @R=3mm	<10^{-3} @ >0.5mm	<10^{-6} @ R>3mm
Polarization	--	--	>70%

In addition to Table 1 is "parity quality" of the beam, an important requirement for G^0 and other parity violation experiments. "Parity quality" means that when the polarization of the electron beam is reversed, there is negligible change to the beam current (charge asymmetry) and beam position (position asymmetry) at the target. The parity quality of the beam depends on several parameters. High transmission through apertures in the machine and proper beam optics matching of different parts of the machine are important. We defer the full discussion on the parity quality of the beam to future papers.

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INJECTOR MODIFICATIONS

Background

The CEBAF injector provides beam to the main accelerator, two recirculating Linacs operating at 1497 MHz, connected by beam transport arcs. The beam is delivered to each experimental hall at 499 MHz, one third of the linac Frequency. This allows simultaneous operation of the three halls. Three beams are typically produced in the injector, each at 499 MHz with 120 degrees phase separation. The G^0 experiment was unusual in that it required a much larger inter-bunch time interval.

Figure 1 shows the general layout of the injector, showing the elements related to bunching and timing of the beam. It starts with 100 keV photo-cathodes. Only one gun is in use at any given time, the other gun being a hot spare.

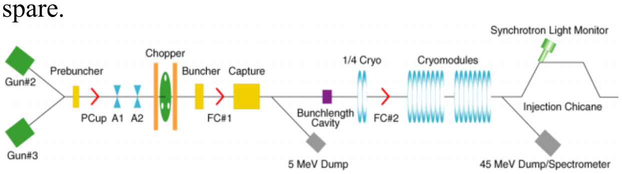

Figure 1: Layout of the CEBAF Injector

The next element is the pre-buncher cavity, to be explained shortly, followed by emittance limiting apertures A1 and A2. The three-beam chopper system assures initial timing and longitudinal structure of the beam. This system operates at 499 MHz with three independently variable slits to define a phase acceptance from 0 to 110 ps for each beam. This is the 100% acceptance aperture and not an rms or sigma value. Any beam outside this window would not go correctly through the bunching and acceleration process, and therefore is stopped at the choppers. The chopper is the only sub-harmonic system in the injector aside from the lasers, and is described in reference [1]. The buncher comes next and starts the main bunching of the beams. The capture section, a graded-β five-cell cavity, provides acceleration of the beams to 500 keV. The phase and amplitude of buncher and capture cavities are crucial to the beam bunch length and energy spread. A pillbox cavity after the capture section is part of a diagnostic system used to tune the beam bunch length by measuring the beam timing. Its function is described in reference [2]. Next are the first two superconducting (SRF) cavities where the beams are further bunched and accelerated to 5 MeV. Finally, there are two accelerating modules, each containing 8 SRF cavities, which accelerate the beams to a final energy, typically 23 to 68 MeV. At the end, the beam passes through a chicane before joining the re-circulated beams in the main machine. There are 3 Faraday cups in the injector to measure the beam current at different stages. The machine setup from gun to 5 MeV is independent of the final energy of the injector. The magnetic elements in the injector provide transverse focusing and steering of the beam. They are used to control the beam size through several apertures in the injector.

Previous measurements with typical beam currents have shown a final bunch length of less than 1 ps and fractional energy spread of less than 10^{-3}, both well within the requirements of the main accelerator [2].

Beam Dynamics Modifications

The three beams are produced at the same spot on the cathode using three independent laser beams. Therefore all three beams will go through the same injector elements. They are only separated within the chopper system. The three beam bunches at the cathode are typically 55 ps (FWHM) long, matching the acceptance of the choppers. As the bunch charge increases (above 30 μA or 0.06 pC per bunch) bunch lengthening due to space charge forces becomes a problem over the 6.5 m distance between the cathode and the chopper. The pre-buncher cavity (see Figure 1) compensates for this by rebunching the beam so that its length at the chopper remains within the longitudinal acceptance. This space charge problem becomes increasingly difficult as the charge per bunch increases. The G^0 experiment requires 1.6 pC bunches at the gun (to retain 1.3 pC with 80% transmission), which is equivalent to 770 μA of average current at 499 MHz!

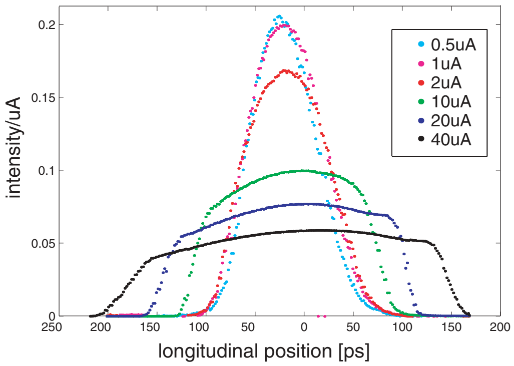

Figure 2: Measured Bunch Length at Choppers

We have studied this growth of the bunch length due to space charge in detail. Figure 2 shows the bunch length at the choppers for different gun currents when the pre-buncher cavity is turned off. It shows how the bunch grows as the function of G^0 current (the equivalent currents at 499 MHz are 16 times higher). Changing the prebuncher amplitude to preserve the high-charge bunch is necessary, but is not by itself sufficient, because it spoils the bunching process for the low-charge bunches. To keep the G^0 beam bunch within the chopper acceptance and without degrading the beam quality for the other two halls required changes in focusing and laser spot size to reduce space charge density. Also, fine changes were required in the phase and amplitude of the pre-buncher and buncher and of phases of other injector cavities. Figure 3 shows the measured transmission through the chopper system vs. PARMELA simulations as a function of prebuncher amplitude [3]. It also shows the operating point that was chosen to give 80% transmission.

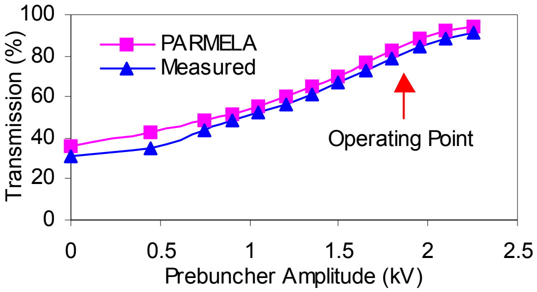

Figure 3: Transmission V

Laser Modifications

Aside from overcoming space charge driven beam dynamics issues, other difficulties had to be addressed. These included development of a laser capable of providing a 31 MHz optical pulse repetition rate at the correct laser wavelength suitable for optical pumping of strained layer GaAs without populating the adjacent 499 MHz RF buckets. A vendor was identified that provided a highly reliable laser, which could be modified to meet the requirements. In addition, optical elements were added to the laser table to provide active feedback to minimize helicity correlated position and beam current asymmetries at the target. Lastly, the G^0 laser spot was enlarged to increase the electron beam size at the cathode and in turn lower the space charge effects.

Rf Stabilization

In order to maintain the highest beam quality, RF system drifts had to be minimized. Vector voltmeters were installed to monitor the phases of RF elements in the injector. PID control loops were used to keep these phases constant over time. Other feed back loops were also used to stabilize the laser RF phase and amplitude.

Transverse Optics

Low loss transmission through injector apertures, essential to minimize helicity correlated beam loss, required nearly round beams to match the round apertures. Focusing in the injector is done with counter-wound solenoid magnets that are highly sensitive to beam position. It was essential to be centered through these solenoids to limit focusing aberrations. These aberrations became especially more important for the oversized G^0 beam. To accommodate simultaneous centering of the beam in the solenoids and apertures, we added weak magnetic coils around the beam lines to compensate the Earth's magnetic field (~0.5 G). At 100 keV the steering due to Earth's magnetic field can cause significant beam displacement.

MEASUREMENT RESULTS

The ultimate test for how successful we have been is the quality of the beam at the experimental halls and how well we have met the requirements of Table 1. For the Hall A Hypernuclear experiment, the main focus was the energy spread. This was measured from the beam size at a high dispersion point in the Hall A beam line using different devices: A wire scan, an OTR (Optical Transition Radiation), and SLI (Synchrotron Light Interferometer) [4]. Figure 4 shows the measured Hall A beam energy spread vs. beam current.

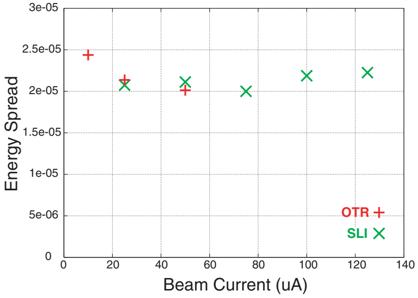

Figure 4: Hall A Energy Spread vs. Beam Current

For Hall B the important parameter was the small round beam at very low currents. We were able to deliver currents of few picoAmps to few nanoAmps with beam sigmas of about 50 micron to 70 micron.

The main parameters for G^0 experiment in Hall C were current of 40 µA at 31 MHz , parity quality, and halo. A total of 103 coulombs in 744 hours was delivered with beam currents slightly above 40 µA at 31 MHz (1.6 pC at the Gun) and the charge and position asymmetries well within requirements. Table 2 shows the results[5].

Table 2: Beam quality during the G^0 run

Beam parameter	Achieved	Specs
Current	More than 40 µA	40 µA
Charge Asymmetry	-0.28 ± 0.28 ppm	1 ppm
Position Asy(x and y)	6 ± 4nm and 8 ± 4nm	20 nm
Energy Asymmetry	58 ± 4 eV	75 eV

CONCLUSION

Over the last year, the CEBAF injector successfully provided high quality beam simultaneously to three different experiments with challenging beam quality requirements. The injector delivered high charge bunch beam to the G^0 experiment and low charge bunch beam to the g10 experiment while maintaining an energy spread below $2.5\text{x}10^{-5}$ for the Hypernuclear experiment. This was possible because the beam quality at the end of the injector, including the bunch length and energy spread, was exceptional.

REFERENCES

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