

DESIGN, COMMISSIONING, AND OPERATION OF THE UPGRADED CEBAF INJECTOR\*

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Abstract

The CEBAF injector has undergone a major upgrade. In the new injector, the existing thermionic gun has been moved perpendicular to the beam line to allow the addition of a polarized gun. A new chopping system allows independent control of the current delivered to three experimental halls. Increase in the expected final CEBAF energy from 4 GeV to 6 GeV necessitated the replacement of the previous superconducting accelerating modules with ones of higher  $Q$  and higher gradient, raising the maximum injector operating energy from 45 MeV to 67.5 MeV. Two chicanes have been added. One is placed before the accelerating modules to allow simultaneous acceleration of a future high current beam along with the nuclear physics beam. The other chicane is at the end of the injector to merge the injected beam with the higher pass beams. Finally, the injector has been simulated in detail, with the goal of enhancing its predictability, operability, and reliability.

Introduction

Precommissioning of the injector and north linac of the CEBAF accelerator took place in the spring of 1993. After this was completed, the injector underwent a major upgrade to support full CEBAF design specifications and to enhance its operability. This upgrade has been completed and results of both experiment and numerical modeling are presented.

The CEBAF injector provides beam to the main accelerator, which consists of two recirculating superconducting linacs operating at 1497 MHz fundamental frequency. The beam recirculates 5 times through the two linacs. When fully operational, beam bunches will be received at each of the 3 experimental endstations at 499 MHz. In addition, the pulse train for each hall can be extracted after any of the 5 passes. The CEBAF design requirements for both the injector and main accelerator are summarized in Table 1.

In the upgraded injector, the 100 keV beam is generated by the gun and passes through two circular apertures that define the normalized rms emittance to be  $0.19\pi$  mm-mrad. This DC beam is chopped into bunches of  $60^\circ$  or less. The bunching and initial acceleration processes then occur in a buncher cavity, a graded beta cavity and two superconducting cavities. At this point, the bunch length is  $< 1^\circ$  and the energy is 5 MeV. The beam passes through a chicane that bypasses the possible location of a future source. The final energy is provided by 16 superconducting cavities which are housed in two cryomodules. The beam then enters a chicane which merges the injected beam with the recirculated beams.

Because of the sensitivity and operational difficulties associated with the setup of the first chicane, this portion of beam pipe has been replaced by a straight section.

TABLE 1  
CEBAF and Injector Specifications

Parameter	CEBAF Specifications	Injector Specifications
Energy	0.5–4 GeV 6 GeV desired	22.5–67.5 MeV
Total beam current	1–200 $\mu$ A CW	1–200 $\mu$ A CW
Current per bunch train	100 $\mu$ A	100 $\mu$ A
Normalized, rms emittance	$1 \pi$ mm-mrad	$0.5 \pi$ mm-mrad
$\Delta E/E$	$10^{-4}$	$10^{-3}$

The upgrades to the injector took place from April to November of 1993 and include repositioning of the gun, construction and installation of a three-beam chopping system, replacement of all superconducting cavities with ones of higher maximum accelerating gradient and higher  $Q$ , and the addition of the two chicanes described earlier. Injector commissioning took place in December 1993 and subsequent operation has occurred since January of 1994. During this time, extensive procedures have been developed to set up the injector and optimize its operation. The upgrades and operational results are discussed in detail in the next sections. The layout of the injector and the locations of the upgrades are shown in Fig. 1.

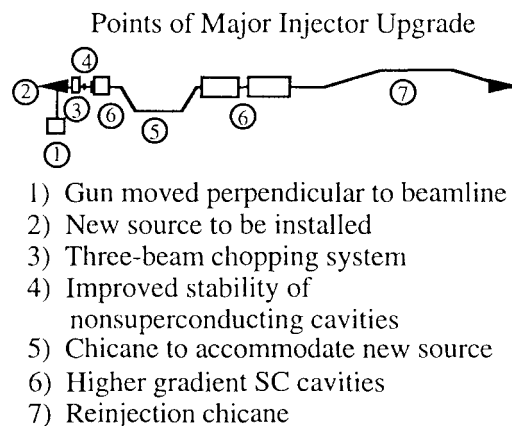


Figure 1 Summary of the major upgrades in the injector

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### Repositioning of the Gun

Since many of the nuclear physics experiments to be performed at CEBAF require polarized electron beams, a polarized electron source will be installed in the injector in the near future. To make room for this source, the existing thermionic gun was moved 90 deg to the main beam line as shown in Fig. 1. Such an arrangement allows one to easily switch from polarized to unpolarized operation by changing the magnetic field of the dipole. The dipole is a parallel face magnet 15 cm long, canted at 45° to the main beam line. Various options, such as wedge magnets and alpha magnets, were considered, but given the small energy spread emerging from the gun, this arrangement was simplest to construct. The optics up to and through the dipole has been set to preserve the symmetry of the beam downstream of the bend. Also, all solenoids in the injector have been converted to counter-wound types so that the beam polarization will be preserved during transport.

### Three-Beam Chopping System

The 499 MHz third subharmonic three-beam chopping system, shown schematically in Fig. 2, consists of two rectangular cavities, two counter-wound solenoids, and the chopping aperture assembly.

Built to specification by the Haimson Corporation, the 1500 lb, 29.25" x 29.25" x 17" chopper cavities operate in the TM210 and TM120 modes at 499 MHz with better than 26 dB of mode isolation. The operating temperature of the cavities is regulated to 43.5±0.1°C via heated water. The RF control system maintains the field gradient stable to 2×10<sup>-4</sup> and the phase stable to < 0.1°.

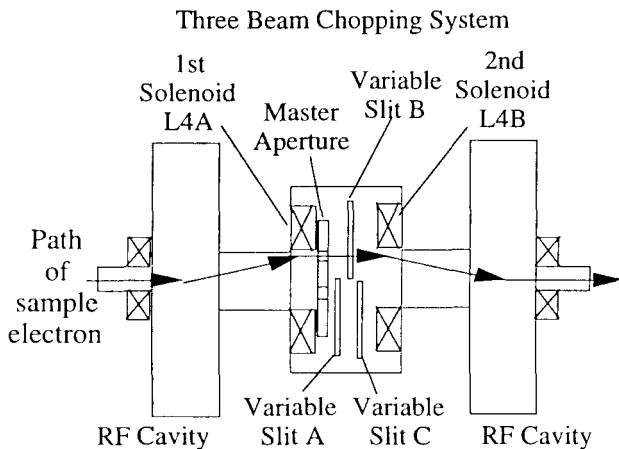


Fig. 2 Schematic of the three-beam chopping system showing the trajectory of a sample electron.

As the DC electron beam passes through the first chopping cavity, it is deflected radially via the action of the orthogonal TM modes, causing the beam to trace a cone whose apex is

located at the center of the cavity. The first counter-wound solenoid then transforms the beam from a cone to a 3 cm diameter cylinder which then strikes the chopping apertures. A schematic of the apertures is shown in Fig. 3. The majority of the beam is intercepted by the Master Aperture that has circular holes located 120° apart, corresponding to 360° at 1497 MHz. Behind each hole is a moveable triangular aperture. The aperture width determines the initial bunch length, and hence the pulse train charge. After going through the variable apertures, the second counter-wound solenoid powered in series with the first focuses the beam to the center of the second chopper cavity, which is adjusted to cancel out the effects of the first cavity, resulting in 3 consecutive bunch trains with independently settable currents that will be delivered to each of the endstations.

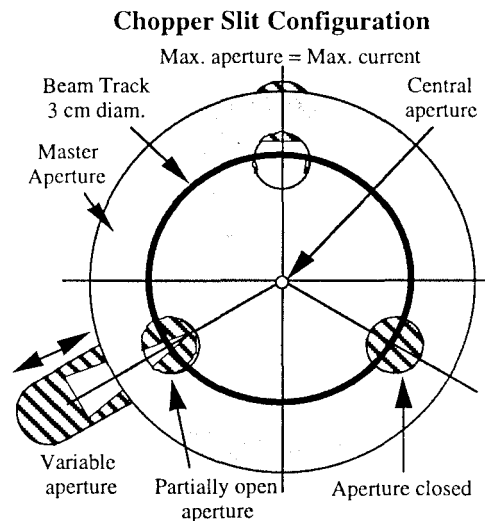


Fig. 3 Schematic of the three-beam chopping apertures. The width of the triangular slit at the location the beam passes over it defines the bunch charge.

In an ideal chopping system, a DC beam is chopped axially, leaving the longitudinal and transverse phase space densities intact. A measure of this is the growth in emittance and energy spread caused by the chopping system. A major area of concern was whether the beam energy spreads induced by the two chopping cavities cancel each other. The cancellation is physically governed by properly powering and phasing each mode of the two chopping cavities and by properly powering the lens pair L4A/L4B. Theory and simulation predict that the beam energy spreads induced by the two chopping cavities do in fact cancel [1]. However, due to lens aberrations, there is a minimum of 20% emittance growth and a relative energy spread increase from 10<sup>-4</sup> to 2.5×10<sup>-4</sup> predicted by simulation that cannot be undone with the completion of the chopping process. The numerical simulations of the three beam chopping system were performed using a modified PARMELA code. PARMELA was modified so that it uses: (1) the real chopping cavity model (verified by MAFIA)

in place of zero length transform; and (2) the POISSON calculated magnetic fields for solenoids in place of hard-edge field profiles.

In addition to the energy spread cancellation, various kinds of aberrations can substantially affect the performance of the system. Because of the tight schedule for commissioning, we have not yet quantitatively evaluated the effects of the aberrations on the chopping process.

The current in pulsed mode from each slit has been measured by Faraday cup to be variable from 0 to 110  $\mu\text{A}$  with 330  $\mu\text{A}$  maximum total current. Setup of the second chopper RF cavity has been successfully performed by adjusting cavity phase and amplitude such that all three beam spots appear as a single spot on 3 fluorescent viewers downstream of the chopping region. Though this is a strong indication that dechopping has been successfully achieved, further tests are required for complete verification.

### Overall Results Of Injector Operation

Extensive operations of the injector have been ongoing since December of 1993. During this time, operability has improved dramatically as a result of procedure development and hardware improvement. A summary of operational results and specifications for energy, beam current, emittance, energy spread, and bunch length is given in Table 2. These results are discussed in more detail below.

During the 4 week April 1994 commissioning run of the accelerator north linac, the injector was responsible for 40-50% of the downtime of the machine. The primary problem was found to be wide ambient temperature swings in the buildings that housed the RF control modules and the master oscillator that synchronizes the various parts of the machine. When this problem was corrected, the availability of the injector increased dramatically, reaching 90% during a 2 week run in July 1994. Essentially the only adjustments required in the injector are adjustments in the phases of the chopper cavities with respect to the rest of the machine RF. This adjustment is performed roughly every 8-12 hours and is under investigation.

**TABLE 2**  
**Injector Specifications and Operational Results**

Parameter	Specifications	Operational Results
Energy	22.5-67.5 MeV	45 MeV
Total beam current	1-200 $\mu\text{A}$ CW	95 $\mu\text{A}$ CW (1 slit)
Maximum current per aperture	100 $\mu\text{A}$	110 $\mu\text{A}$ , pulsed
Normalized, rms emittance	0.5 $\pi$ mm-mrad	0.3 $\pi$ mm-mrad
$\Delta E/E$	$10^{-3}$	$10^{-3}$
Bunch length	$<1.2^\circ$	$0.6^\circ$

The bunch length measurement system [2,3] makes a time of flight measurement from the chopping slits to signal pickup devices, in this case 6 GHz (4th harmonic) cavities, located at three different points in the beamline. The first and second cavities are located immediately before and after the first two

superconducting cavities. The third cavity is located immediately prior to the next superconducting cavities. At this point, the bunching process is complete and the bunch length should remain constant throughout the machine. The  $4\sigma$  bunch lengths were measured at these locations to be  $5^\circ$ ,  $1^\circ$ , and  $0.6^\circ$ , which are in excellent agreement with simulation. Injector specifications require the final bunch length to be  $\leq 1.2^\circ$ .

For the measurements discussed below, the injector was in the machine commissioning configuration. This corresponds to macropulse width set to 100  $\mu\text{sec}$ , a repetition rate of 60 Hz, two chopping slits closed, the third slit set to produce 12  $\mu\text{A}$  of beam current (variable aperture produces an initial bunch length of  $10^\circ$  at 1497 MHz), and 45 MeV beam energy.

Vertical and horizontal emittance measurements were performed using an upstream quadrupole and a profile scanner in the 45 MeV region immediately prior to the reinjection chicane. The measurements give a normalized rms emittance of 0.31  $\pi$  mm-mrad for the x-dimension and 0.22  $\pi$  mm-mrad for the y-dimension. This corresponds to a  $\approx 60\%$  growth in x and  $\approx 20\%$  growth in y above that defined by the emittance filter before the chopping system. It is suspected that the larger growth in x-dimension is due to incomplete dispersion suppression in the first chicane. Further measurements of the maximum current beam from multiple slits are planned.

The  $4\sigma$  energy spread  $\Delta E/E$  was measured at a high dispersion region ( $\eta = 3.5$  m) of the reinjection chicane using a profile scanner and found to be  $10^{-3}$ .

### Conclusion

The CEBAF injector upgrade has been completed and subsequent operation has revealed that specifications for beam energy, current, emittance, and energy spread have been achieved. Agreement of experiment with simulation has been good. Three-beam chopping has been achieved but requires further testing for full verification. Extensive procedures for machine setup have been developed and optimized based on operational experience.

### Acknowledgments

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### References

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