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# Photoinjector improvements at CEBAF in support of parity violation experiments

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**Summary.** — Three photoinjector modifications were undertaken at CEBAF to help ensure successful completion of the PREx and $Q_{\mathrm{weak}}$ parity violation experiments: the development of a pockels cell high voltage switch that provides stable voltages at 960 Hz helicity flip rate with 60 $\mu$s rise/fall time, the installation of a two-Wien-filter spin flipper for slow spin reversal, and the installation of a new photogun with inverted insulator geometry that operates at higher bias voltage.

PACS 29.27.Hj – Polarized beams.
PACS 29.25.Bx – Electron sources.
PACS 21.10.Hw – Spin, parity, and isobaric spin.

## 1. – Introduction

The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab has proved to be an ideal facility to conduct parity violation experiments, providing reliable highly polarized electron beams with sufficiently small helicity correlated beam asymmetries that have enabled measurement of increasingly smaller physics asymmetries, as illustrated in table I (experiments listed in chronological order). Recent parity violation experiments PREx and $Q_{\mathrm{weak}}$ represent significant challenges for the accelerator division because the physics asymmetries are less than 1 ppm, which imposes tight tolerances on helicity correlated beam properties. A conscious effort was made to improve photoinjector accelerator systems to meet these demands, including the development of a pockels cell high voltage switch that can provide spin flipping at 960 Hz, the installation of a two-Wien-filter spin flipper for slow helicity reversal [1], and construction of a new photogun that operates at higher bias voltage [2]. These systems are described below.

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TABLE I. – *Parameters and beam specifications for parity violation experiments at CEBAF. The upper portion of table are experiments which have been completed with beam specifications achieved.*

| Experiment | Energy (GeV) | $I$ ($\mu$A) | $A_{pv}$ (ppb) | Charge (ppm) | Position (nm) | Angle (nrad) | Size (d$A/A$) |
|---|---|---|---|---|---|---|---|
| HAPPEx-I | 3.3 | 40 | 15050 | 200 | 12 | 12 | – |
| G0-Forward | 3.0 | 40 | 3000–40000 | $300 \pm 300$ | $7 \pm 4$ | $3 \pm 1$ | – |
| HAPPEx-II | 3.0 | 55 | 1580 | 400 | 1 | 0.2 | – |
| HAPPEx-III | 3.484 | 100 | 22100 | $200 \pm 100$ | $3 \pm 3$ | $0.5 \pm 0.1$ | $10^{-3}$ |
| PREx-I | 1.056 | 100 | $657 \pm 60$ | $100 \pm 130$ | $2 \pm 3$ | 1 | $10^{-4}$ |
| $Q_{\mathrm{weak}}$ | 1.162 | 180 | $288 \pm 5$ | $100 \pm 10$ | $2 \pm 1$ | $30 \pm 3$ | $10^{-4}$ |
| PREx-II | 1.0 | 70 | $500 \pm 15$ | $100 \pm 10$ | $1 \pm 1$ | $0.3 \pm 0.1$ | $10^{-4}$ |
| Moeller | 11.0 | 85 | $36 \pm 0.6$ | $10 \pm 10$ | $0.5 \pm 0.5$ | $0.05 \pm 0.05$ | $10^{-5}$ |

## 2. – Fast pockels cell high voltage switch

Polarized beam experiments measure the scattering asymmetry at a target by flipping the spin direction of the electron beam at a relatively fast rate. This is accomplished via an electro-optical device called a pockels cell at the photoinjector drive laser table. By applying positve or negative high voltage to the pockels cell, the helicity of the laser light and hence the electron beam, can be flipped. Prior to PREx and $Q_{\mathrm{weak}}$, all parity-violation experiments flipped polarization at 30 Hz, which served to cancel 60 Hz beam motion.

The first pockels cell high voltage switch used at CEBAF was homemade and utilized two MOSFET switches capable of driving the cell to $+/-2700$ V in less than 1 $\mu$s. Unfortunately, at each helicity transition, the voltage would oscillate—or ring— for approximately 500 $\mu$s before stabilizing. In addition, MOSFET drive circuitry requires relatively high current and this caused a voltage droop of the regulated high voltage power supplies powering the circuitry. This voltage droop introduced a long settling time-constant that was evident when using a pseudo-random helicity flip pattern. Specifically, distinct asymmetry values were observed depending on the state of the previous helicity pair (or quartet, or octet, etc.). This phenomenon was termed pockel cell memory, however in hindsight, this behavior was not related to the pockels cell as much as it was related to the non-constant voltage applied to the pockels cell. Thinking that problems were related to the homemade nature of the switch, it was replaced with a commercial system that was expected to provide much faster rise/fall times and constant voltage throughout the duration of each helicity state (according to the vendor). Surprisingly, the new switch (that also used MOSFET technology) produced nearly identical results. Furthermore, and perhaps more problematic, the commercial switch radiated helicity information that could be picked up by nearby electrical systems. These observations suggested ringing was not a drive circuit problem, but were associated with peizo-electric properties of the KD*P cell. Indeed we found that in order to get a shorter transition to a new helicity state, we had to slow the application of voltage to a critically damped rate to avoid inducing piezo-electric ringing. Whereas a 50 ns switch speed would induce ringing that made the electron beam unusable for 500 $\mu$s, a slower switch rate that carefully ramped the voltage over 50 $\mu$s provided quality electron beam within 60 $\mu$s.

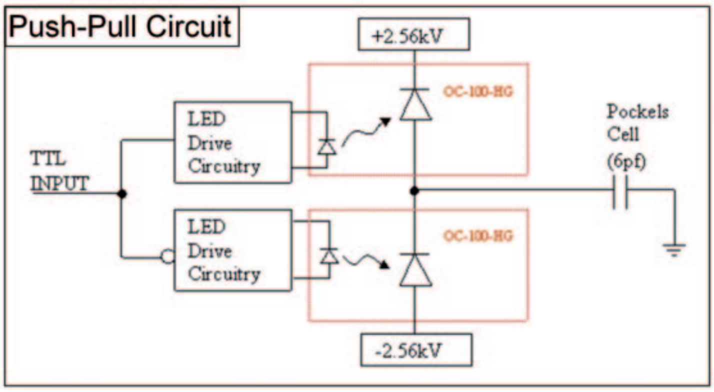


Fig. 1. – Pockels cell high voltage switch that relies on optical diodes.

Knowing that high-speed MOSFET switches were no longer necessary or desirable, a new pockels cell high voltage switch was constructed using high-voltage optical diodes that "reverse conduct" when light is applied via LEDs shining on the diode (fig. 1). A custom TTL drive circuit was designed to sequentially apply light to two optical diodes in series, and thereby flip the polarity of the voltage applied to the pockels cell. The optical diodes are suitably fast, providing 60 $\mu$s rise/fall times (1.4% deadtime for PRex at 240 Hz flip rate and 5.8% deadtime for $Q_{\mathrm{weak}}$ at 960 Hz) and the capacitance of the switch circuit is very small. Consequently, voltage stability throughout each helicity state is markedly better compared to previous switches, with "pockels cell memory" small enough as to be ignored. Finally, the simplicity of the optical diode switching gives us a vastly improved level of confidence in our ability to control parasitic currents that were previously leaking or radiating into the helicity data acquisition system. Future experiments require even faster flipping and the optical diode approach might be improved to reduce rise/fall times further.

## 3. – Two-Wien spin flipper

Helicity-correlated variations in the electron beam properties can generate false asymmetries that affect the parity-violating physics asymmetry the experiment is trying to measure. To address this problem, it is customary to reverse the helicity of the beam polarization (relative to a fixed helicity clock) on a daily basis, which serves to cancel the false-asymmetry contribution to the parity-violating asymmetry. This slow reversal also helps identify small helicity-correlated electronic pickup between accelerator electronic systems and the experiment data acquisition system which can introduce comparatively large offsets in the experimental asymmetry measurement. Prior to 2009, the only slow spin reversal available at CEBAF was provided by changing the polarity of the drive laser light by inserting an optical halfwave plate immediately upstream of the drive laser pockels cell, however, this method cancels only some of the helicity-correlated beam variations, namely those related to pockels cell residual birefringence [3]. For the PREx and $Q_{\mathrm{weak}}$ experiments, a new slow reversal method was deemed necessary to cancel-out other effects, in particular, helicity-correlated beam size variations that can be introduced via pockels cell focusing. The new slow reversal mechanism changes the polarity of the electron beam directly and is composed of two orthogonal Wien filters with intervening solenoids.

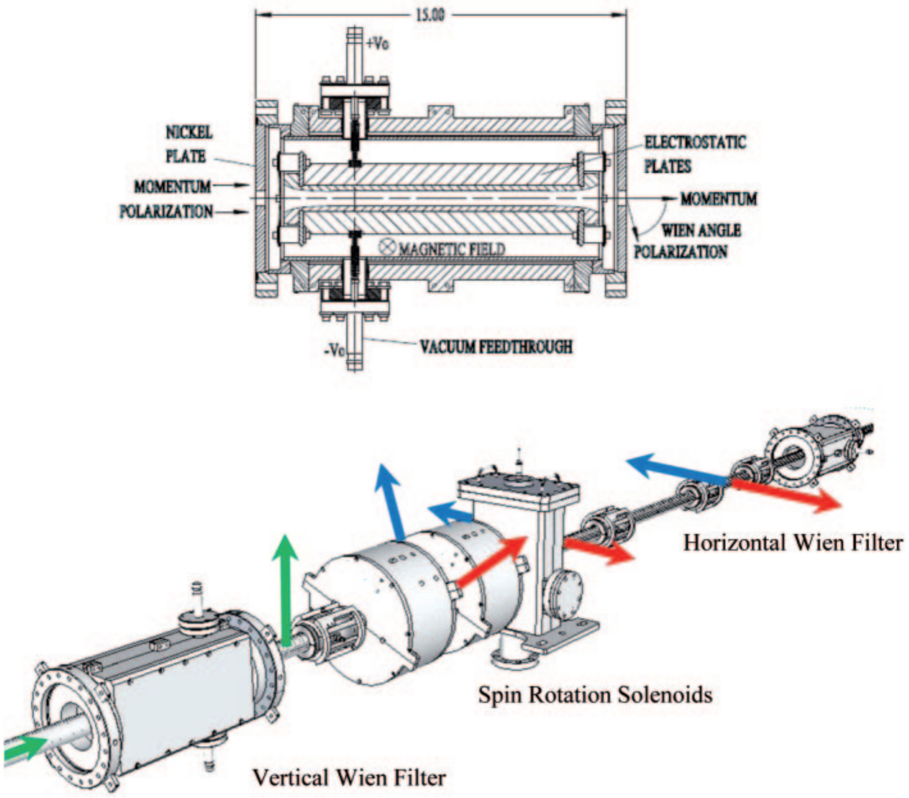


Fig. 2. – Top: The Wien filter spin manipulator used a CEBAF (magnet not shown in the cutaway view). Bottom: schematic of the two-Wien-spin flipper composed of vertical Wien filter, spin rotating solenoids, and horizontal Wien filter. Beam travels left to right, both diagrams.

A Wien filter is a device with static electric and magnetic fields perpendicular to each other and to the velocity of charged particles passing through it (fig. 2, top). Unit charged particles with a velocity of $\beta c = \frac{E}{B}$ remain undeflected in passing through the Wien filter, while the spin is rotated in the plane of the electric field. A Wien filter has been used at CEBAF [4] for years to orient the spin direction of the beam at the injector by an amount (modulo $2\pi$) equal but opposite to the spin precession introduced as the beam passes through the arcs and transport lines to the halls. This sets the spin direction of the beam longitudinal to the direction of beam motion at the target. The CEBAF Wien filter can provide $\pm\frac{\pi}{2}$ rotation at beam energies up to 140 keV. At large spin angles, a Wien filter introduces astigmatic focusing of the beam that can be corrected using quadrupole magnets.

A solenoid magnet provides effective focusing of a low momentum (0.1–1 MeV/$c$) electron beam, where the focal length is inversely proportional to the integral of the square of the magnetic field, given in the paraxial approximation by $1/f \sim \int B_z^2 \mathrm{d}z$ [5]. A solenoid is similarly well suited to rotate the spin of a low energy electron beam by an amount proportional to $\int B_z \mathrm{d}z$, with spin rotated about the longitudinal magnetic field. It is common to use two solenoids in series to simultaneously set both the optical focusing and spin rotation.

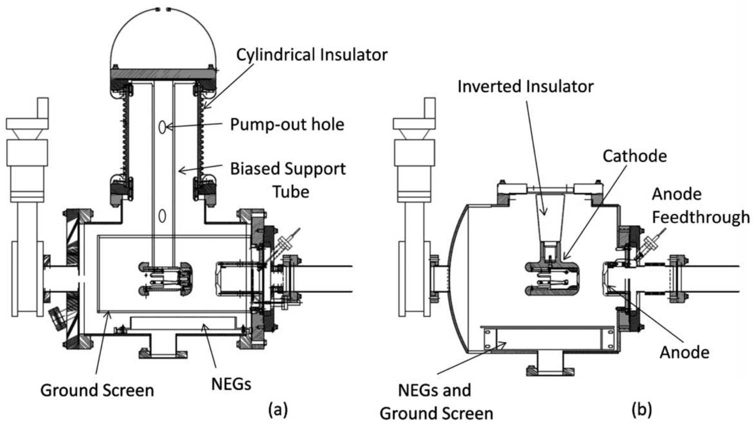


Fig. 3. – Diagrams of the two recent gun designs: (a) conventional large-bore cylindrical insulator and (b) inverted gun with compact tapered insulator that extends into the gun vacuum vessel. Both drawings have same scale with top flanges 10 diameter. The cathode/anode gap is 6.3 cm for both designs.

We designed and built a $4\pi$ spin manipulator using two orthogonal Wien filters and two intervening solenoid magnets, as shown in fig. 2, bottom. The first Wien filter provides a $\frac{\pi}{2}$ spin rotation into the vertical plane. The intervening solenoids provide the proper focusing and rotate the polarization into the horizontal plane, in either direction, by simply changing the direction of the current through each solenoid. The second Wien filter orients the polarization in the horizontal plane to cancel the spin precession in the accelerator, as described above. The main advantage of this scheme is that the Wien filter settings are not changed to enact a spin flip, only the direction of the current through the solenoid magnets is changed. This is appealing because, in principle, the electron-beam optics are identical in both configurations. In practice, it takes about one hour to change the direction of the spin, with time devoted to steering adjustments to regain the injector beam orbit.

## 4. – Inverted gun operating at 130 kV bias voltage

The $Q_{\text{weak}}$ experiment demands very high current from the photogun ($\sim 180\,\mu$A), roughly a factor of two greater than typical high current experiments at CEBAF. It is critical that the electron beam passes through photoinjector apertures with minimal interception (apertures that set the spatial and longitudinal acceptance of the accelerator) because aperture loss introduces fluctuations in beam current and position. These fluctuations increase the width of the charge and position asymmetry distributions, thereby reducing the accuracy of these measurements. At nominal CEBAF gun voltage 100 kV, the beamloss at injector apertures is significant ($> 30\%$) when delivering $180\,\mu$A to a single hall. This beamloss stems from space charge induced emittance growth and can only be reduced by operating the photogun at higher bias voltage. Increasing the bias voltage on the first CEBAF load locked gun (fig. 3a) was not an option, because it already suffered low level field emission that degraded the vacuum near the photocathode which resulted in very poor photocathode lifetime. To address this problem, a new photogun was built that employed a compact, tapered ceramic insulator that extends into the vacuum chamber (fig. 3b). This gun geometry

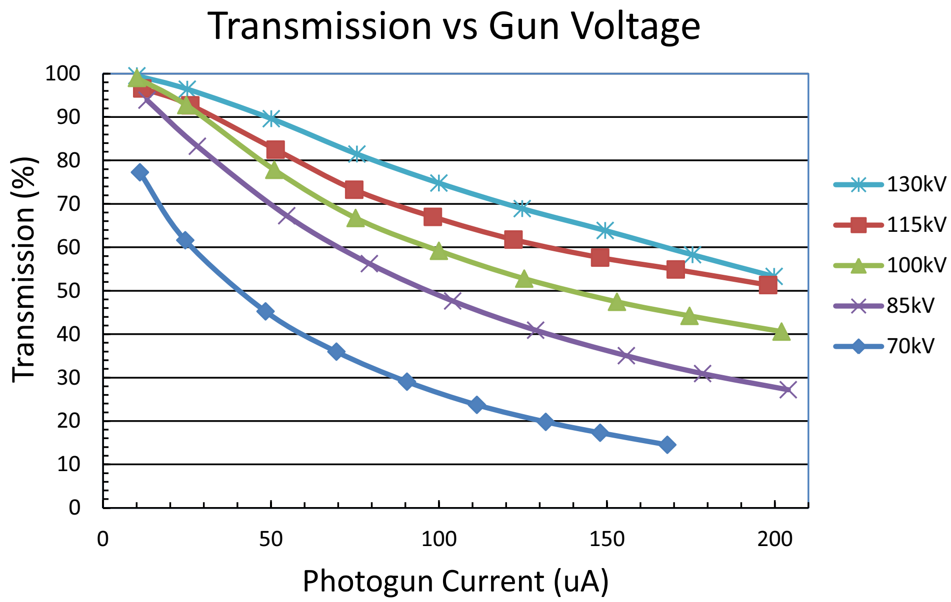


Fig. 4. – Transmission through photoinjector apertures *versus* photogun beam current and bias voltage. Significantly improved transmission is obtained at 130 kV compared to nominal 100 kV of previous photogun designs. (Note that the RF buncher was de-energized during these measurements.)

is commonly referred to as an inverted gun design, a reference to the first such implementation by M. Breidenbach *et al.*, at SLAC [6]. The inverted insulator design helped to eliminate field emission because it provided a means to increase the distance between biased and grounded parts of the photogun not related to beam delivery and more importantly, the design significantly reduced the amount of metal biased at high voltage, so there was less metal to generate field emission. The new inverted photogun was installed during the summer shutdown of 2009 and biased to 150 kV without incident. It operates reliably at 130 kV without measureable field emission for the $Q_{\mathrm{weak}}$ experiment. Transmission measurements were made *versus* beam current for different bias voltages. Figure 4 illustrates significantly improved transmission through injector apertures compared to operation at lower voltages. These measurements were obtained with an RF buncher cavity de-energized. With this buncher cavity energized, and the gun bias voltage 130 kV, transmission at $Q_{\mathrm{weak}}$ beam current 180 $\mu$A approaches 90%.

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