HIGH VOLTAGE DESIGN AND EVALUATION OF WIEN FILTERS FOR THE CEBAF 200 keV INJECTOR UPGRADE*

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Abstract

Our contribution describes design, fabrication and testing of the high voltage system to upgrade the Wien spin rotator to be compatible with the 200 keV electron beam. This required Solidworks modeling, CST and Opera electro- and magnetostatic simulations, upgrading HV vacuum feedthroughs, and assembly techniques for improving electrode alignment. The electric and magnetic fields required by the Wien condition and the successful HV characterization under vacuum conditions are also presented.

INTRODUCTION

High-energy nuclear physics experiments at the Jefferson Lab Continuous Electron Beam Accelerator Facility (CEBAF) require highly spin-polarized electron beams, produced from strained super-lattice GaAs photocathodes, activated to negative electron affinity in a photogun operating at 130 kV direct current (dc). A pair of Wien filter spin rotators in the injector defines the orientation of the electron beam polarization at the end station target. An upgrade of the CEBAF injector to better support the upcoming MOLLER experiment [1] requires increasing the electron beam energy from 130 keV to 200 keV (and thus the Wien filter design), to reduce helicity correlated intensity and position systematics and provide precise control of the polarization orientation.

THEORETICAL FOUNDATION

The Thomas Bargmann-Michel-Telegdi (BMT) equation is used to describe the rotation of the spin of a single particle in its rest frame with respect to the particle velocity vector v [2]. The rotation in a Wien filter, a consequence of the interaction of the particle's magnetic moment with the external mutually orthogonal electric and magnetic fields E and B, can be simplified to [3]

$$\theta = \frac{eL}{m_0 c \beta \gamma^2}\left[\frac{E_y}{v_z}\right], \qquad (1)$$

where θ is the spin rotation angle, L is the effective field length, e is the electron charge, E_y is the electric field magnitude perpendicular to the particle velocity $\beta = \frac{v_z}{c}$, the particle rest mass is m_o, and γ is the Lorentz factor.

For the Wien filter to operate as a spin rotator it is important to maintain the trajectory of the particles that traverse the device. In the single-particle model, this is achieved by ensuring that the contributions of the electric and magnetic fields to the total force is zero, thus fulfilling the so-called "Wien condition" [4]:

$$E_y = v_z\left(-B_x\right). \qquad (2)$$

Using this mathematical framework, the electric and magnetic field magnitudes corresponding to the desired spin rotation angle useful for operations, between -100 and +100 deg for a 200 keV electron, are calculated to be 2.7 MV/m, and 13 mT respectively. In practice, the electric and magnetic forces cannot be perfectly balanced at the ends of the Wien filter, resulting in the deviation of the electron beam trajectory due to unequal contributions of the fields to the total force. This has been observed in previous experiments [3, 5], and even though it has been demonstrated to have negligible effects at CEBAF [6], the energy upgrade motivated the further studies described in this work.
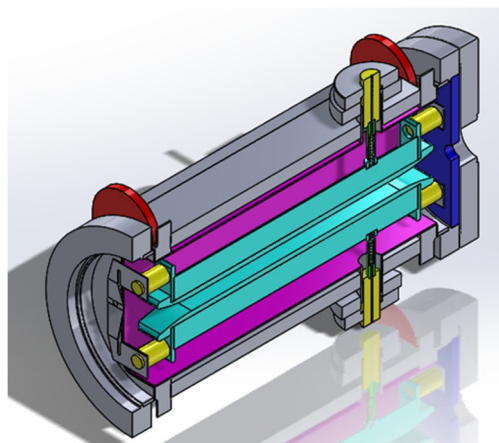

Figure 1: Isometric view of the 3D model of the Jefferson Lab Wien filter with a lateral cross section cut showing

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MC6: Beam Instrumentation, Controls, Feedback and Operational Aspects

T03 Beam Diagnostics and Instrumentation

high voltage plates (teal), insulator standoffs (yellow), vacuum chamber enclosure (pink), magnetic coils (red), and endplates (blue).

WIEN FILTER DESIGN

An isometric lateral cross section of the Solidworks [7] 3D model of the Wien filter design used at CEBAF for operation with a 200 keV electron beam, and based on the original from SLAC [3, 5], was produced and it is shown in Fig. 1.

In the Wien spin rotator, the maximum ±100 deg spin rotation angle is achieved by producing orthogonal electric and magnetic fields that ideally should be homogeneous across the length of the device. To produce the electric field, a voltage potential (typically equal and opposite) is applied across two parallel electrode plates separated by a 1.5 cm gap. The Rogowski profile on the tip of the plates was designed to produce an electric field profile that coincides with that of the magnetic field, looking to reduce the deviation of the beam trajectory [8]. The plates are supported using insulators secured to flexible Inconel grounded frames that attach to either end of the vacuum chamber. The top of each plate is in mechanical contact with a non-magnetic spring coil pinned inside a 304 SS hollow cylinder referred as HV spring guide, thus providing a force to ensure electrical contact. The spring guides mate with HV feedthroughs mounted on 2-¾ CF flanges. HV cables connect the feedthroughs to two independent opposite-polarity direct current (DC) power supplies.

A magnet dipole (see Fig. 2) consisting of a pair of window frame coils, nickel endplates, and a steel shell is mounted around the vacuum chamber and connected to an independent power supply. The external magnetic field is generated by applying current through the coils, and the field profile particular to the Wien design is defined by a combination of steel yokes that surround the coils, and by two nickel endplates (magnetic mirrors) located at the entry and exit flanges.

There is no alignment for the electrodes (something that can be improved), their position is set by interlocking components machined to high tolerance. Metrology measurements showed 1.49 cm +/- 0.01 cm gap parallelism with <0.1 deg pitch and roll.
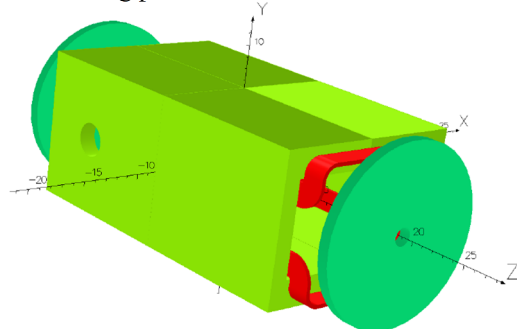

Figure 2: Wien filter magnet dipole array showing window frame coils (red), steel shell (light green), and nickel endplates (dark green) [9].

MODELING AND ELECTROSTATIC SIMULATIONS

For the previous CEBAF 130 keV Wien spin rotator design, the field magnitudes were 1.6 MV/m and 9.1 mT. As the beam energy increased to 200 keV, and to produce the desired spin rotation, the required engineering parameters were recalculated using Eqs. (1) and (2), yielding 2.7 MV/m and 13 mT.

The objective of this work is to upgrade the existing design to fulfill these field requirements, nevertheless the modifications were constrained: alterations to the electrode plates and separation between them, to the vacuum chamber, and to the magnetic shield structure were to be avoided. Therefore, to produce the necessary electric field the bias voltage has to increase from 12 kV to 20 kV per electrode, requiring 40 kV-rated feedthroughs, modified HV contacts, and longer mounting insulators. Similarly, the current through the window frame coils had to increase from 10 to 15 A [9]. The existing coil made with 28 turns of #16 round wire was substituted with a new, 26 turns of #13 square wire coil increasing conductor section a factor of 2.5.

3D models for the existing 130 keV and the 200 keV upgraded Wien filters were produced using Solidworks. Each part was modeled separately with great attention to minute details, and assembled using mating properties. The 40 kV-rated voltage feedthroughs were modeled using dimensions provided by the vendor. The HV spring guide design was adapted to be compatible with the feedthrough and its outer diameter adjusted to minimize the electric field strength. Longer versions of the mounting insulators (3.07 cm length) were modeled to increase the distance between the electrode plate's Rogowski profile tip and the grounded mounting frame, intended to reduce the electric field in that region. The assembly model was then imported to CST EM studio [10] for electrostatic simulations to qualify the modifications. An iterative process was carried out in which the simulation results were used to correct and improve the 3D models.

For the upgraded design, the transverse vertical component of the electric field E_y was obtained using CST EM studio post processing tools and plotted as a function of position along the device' central axis shown in Fig. 3 as the blue trace. In this plot, the magnetic field B_x is shown as a red trace, and was generated using Opera software [9]. Both fields are normalized to show the inherent mismatch at the fringe regions.

ASSEMBLY AND HIGH VOLTAGE EVALUATION

A spare 130 keV Wien filter setup [6] was upgraded with 40 kV rated CeramTec feedthroughs. The electrodes and modified high voltage spring guides were polished in a tumbler barrel filled with dry corn-cob media for ~1 hour [11]. New insulators, 0.42 cm longer than those used in the Wien 130 keV version were machined out from Macor.
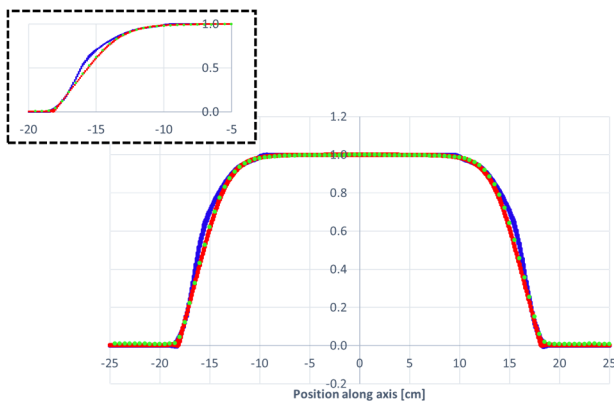
Figure 3: Simulated electric (blue) and magnetic (red) fields. The experimentally measured magnetic field (green) is also shown. All fields are normalized. The inset shows a close-up of the left side fringe region.

The electrodes and all new internal components were cleaned in an ultrasonic bath of concentrated degreaser diluted in distilled, deionized water for ~1 hour and then thoroughly rinsed in distilled, deionized water. The Wien filter test setup was assembled in a cleanroom class 1000. First the Macor insulators were secured to the electrodes mounting tab holes using spring stainless steel washers, ceramic washers and ceramic screws. The electrode gap was set by using 1.5 cm +/- 0.01 cm thick Teflon spacers. Next, the Inconel frame was attached to each side and secured to the opposite end of the Macor insulators. The electrode assembly outside the vacuum chamber is shown in Fig. 4. This process ensures locking in the insulators and frames to the electrodes. Inserting the electrode assembly into the vacuum chamber required removing one of the Inconel frames. The electrode assembly was then slid into the chamber and the end frame re-attached to the electrode assembly, then the frames were bolted to the vacuum chamber. The HV feedthrough subassemblies with their connector spring and spring guide were finally inserted into the electrode's connector recess and the CF flange bolted to the vacuum chamber.
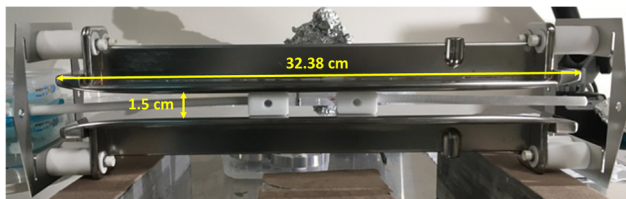

Figure 4: Photograph of the HV electrode plate assembly with white cylindrical insulators and thin Inconel frames.

Two 11 l/s ion pumps were attached to each end by means of vacuum crosses fitted with borosilicate viewports. One of the crosses was connected to a turbo pumping station. The assembled setup was baked at 200 °C for ~36 hrs, reaching ~10^{-9} Torr after cooling off to room temperature.

One of the high voltage feedthroughs was connected to a positive 30kV DC, 1 mA power supply while the opposite feedthrough was connected to a similar power supply but with negative bias.

The magnetic coil was made of 26 turns of #13 square wire and enclosed between the vacuum chamber and the steel shell. The coil was powered with a variable +/- 15 A DC power supply. Additionally, two Geiger-Mueller LM712 tube radiation detectors from LND, Inc. were placed on each end of the Wien filter setup on the external side of the borosilicate viewports.

High voltage conditioning was performed by closely monitoring the vacuum conditions (ion pump current) while increasing the bias voltage in 1 kV steps one electrode at a time to 20 kV, as the opposite electrode was held at zero bias. Then the bias polarity was inverted and the process repeated. The ion pump current increased by ~0.6% from background.

Similar behavior was observed when both electrodes were biased simultaneously, one biased negative and one positive, as shown in Fig. 5. It is noticeable that after the ±20 kV target was reached, the ion pump current decreased slightly and stabilized after the device was held at that voltage for 15 hrs.
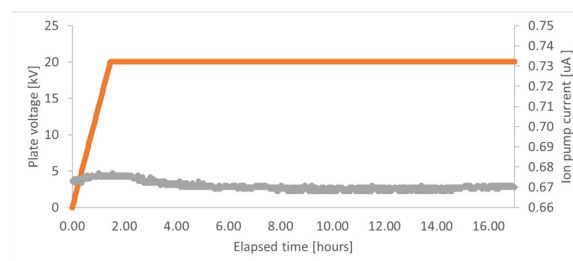

Figure 5: Ion pump current (gray) response as a function of time when voltage (orange) is applied to both electrode plates simultaneously.

CONCLUSIONS

The electrostatic simulation results lead to the implementation of the proposed changes to upgrade the existing CEBAF Wien filter to be compatible with a 200 keV energy electron beam without major modifications to the original design. In situ HV qualification tests shown in this work proved that these modifications allow the device to operate reliably at the required voltage and it was deemed satisfactory for installation at the CEBAF upgraded injector for the upcoming experimental run. Beam dynamics simulation results are being prepared for forthcoming publication to provide insight into the design of future Wien filter spin rotators compatible with even higher energy beams.

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