WIEN-FILTER SPIN ROTATOR WITH INTEGRATED ION PUMP*

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Abstract

Nuclear physics experiments performed at the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Laboratory (JLab) require highly polarized electron beams, produced from strained super-lattice GaAs/GaAsP photocathodes. To prolong the photocathode operational lifetime, the photogun and adjoining beamline should be maintained at the lowest possible pressure. This document describes a Wien-filter spin manipulator with Penning traps incorporated along the length of the high voltage electrodes. For some spin settings, the Wien filter acts as an ion pump. Although the Wien filters at CEBAF are relatively far from the photocathode, a Wien-filter spin manipulator with distributed pumping could serve to improve photocathode operating lifetime.

INTRODUCTION

In 1898 Wilhelm Carl Werner Otto Fritz Franz Wien or "Willy" Wien invented the device that carries his name, in which orthogonal and independent electric and magnetic fields allowed him to measure the electron charge to mass ratio of electrons in cathode rays. As described in the *tour de force* document by Tsuno and Ioanoviciu [1], the simple, yet robust device found applications as energy analyzer and monochromator in electron microscopy, and later as a velocity selector at Brookhaven National Laboratory (BNL) [2]. Almost eighty years later, C. K. Sinclair and his collaborators at the Stanford Linear Accelerator (SLAC) designed and implemented a compact Wien filter to obtain transverse polarization from their polarized electron source [3]. Their elegant and compact design was favored by the accelerator community, being replicated at the Massachusetts Institute of Technology-Bates Research and Engineering Center (MIT-Bates), the Continuous Electron Beam Accelerator Facility (CEBAF), the Mainz Microtron (MAMI), and the Superconducting Darmstadt Electron Linear Accelerator (S-DALINAC) for operation at 100 keV beam energy. More recently, the design robustness was further demonstrated by operating a modified version at Jefferson Lab with a 180 keV beam [4].

The delicate strained super-lattice GaAs/GaAsP photocathodes used at Jefferson Lab (JLab) to produce polarized electron beams requires ultra-high vacuum conditions (10^{-12} Torr) in the photogun for two main reasons: to aid in preventing field emission from the stainless steel cathode electrode, and to reduce ion-back bombardment that diminishes the photocathode lifetime [5]. In addition, the projected and current nuclear physics experiments at CEBAF require the implementation of Wien-filter spin rotator pairs to rotate the electron beam spin up to ±π/2 rad [6]. While upgrading the existing JLab Wien filters, our team had the serendipitous realization that a Wien filter could be used to rotate the spin of an electron beam while simultaneously providing differential pumping by introducing Penning traps within the electrodes, and getter plates on the chamber walls, resembling commonly used ion pumps. In this document, we describe the development and initial testing of this device, referred to hereafter as a *Wien pump*.

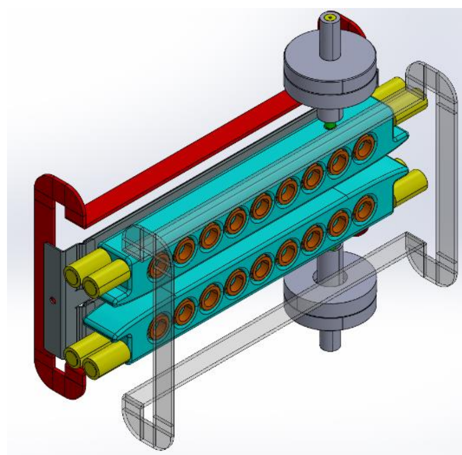

Figure 1: Modified Wien filter 3D model isometric view showing the Penning traps in both the electrodes.

OPERATION PRINCIPLE

In a Wien filter, the velocity vector of the electrons in a spin-polarized beam, traveling along the device central axis, interacts with homogeneous and independent electric and magnetic fields, such that they form a mutually orthogonal system. The dynamics in these conditions are described by the Thomas-Bargmann-Michel-Telegdi (Thomas-BMT) equation, from which it is possible to obtain the magnitudes of the fields given a fixed beam energy and a desired spin rotation angle, as noted by Eqns. (2) and (3) in [7]. In practice at JLab, two highly polished stainless steel electrodes are biased inside a vacuum chamber to produce the homogeneous electric field between them, and a current is established through a set of window frame coils surrounding the vacuum enclosure to induce the homogeneous magnetic field [8].

In ion pumps, Penning traps are used to create a quadrupole electrostatic field, which in combination with a homo-

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geneous axial magnetic field, are capable of confining electrons inside the trap [9]. Moreover, residual gas can be ionized by these electrons, generating positive ions that then get expelled from the trap and strike the anode walls. Using a getter material on the walls allows the positive ions to be adsorbed, subsequently reducing the pressure inside the vacuum enclosure [10].

WIEN FILTER MODIFICATION

For a 100 keV beam, 1.5 cm electrode gap, and π/2 rad spin rotation angle, our calculations yield an electric field of 1.2 MV/m and a magnetic field of 7.5 mT at the beam path. The similarities between the Wien filter and ion pump were identified, namely the mutually orthogonal static and independent electric and magnetic fields, which could work simultaneously in the Wien filter design described in our previous contribution [11], by adding Penning traps to the electrodes. The magnetic field produced by the window frame coils (Fig. 1 in red) of 7.5 mT was deemed too low to produce detectable pumping in initial testing, therefore the permanent ring-magnet pairs were selected to produce a 180 mT magnetic field at their surface. It was noticed that by adding permanent ring-magnet pairs (Fig. 1 in orange) to confine electrons in the Penning traps, and two sets of titanium and tantalum plates on the chamber sides (Fig.1 in gray behind the electrodes), the electrode would act as an ion pump. Each electrode (Fig. 1 in turquoise) thickness was increased to 3.5 cm, and nine 1 cm radius equidistant Penning traps were machined in the electrode body. This would establish the necessary electrostatic quadrupole field when the corresponding electrode is biased positively to produce the Wien homogeneous field at the beam path. In order to test these parameters before their implementation, simulations were performed.

SIMULATIONS

For the proper operation of a Wien filter, it is preponderant to minimize the impact of the magnetic field induced by the permanent ring-magnets at the beam path. Therefore CST [12] solvers were used to obtain particle dynamics generated by the full geometry of the device. The magnetic field produced by the constant cross-sectional area coils was simulated in the magnetostatics (Ms) module and imported to the particle tracking (Tr) module, in which the electrostatic field produced by the electrodes, biased at -9.3 kV (top) and +9.3 kV (bottom) was solved in combination with the magnetic field of the permanent magnets and dynamics of particles inside the traps. Following the AS-TRIZ [13] method, all ring-magnet pair polarities were flipped in the bottom electrode, in order to compensate their contribution along the beam path. As shown in Fig. 2, an electron gets trapped in an orbit at the positive (bottom) electrode, forming a flower-like blue trace near the image center. In the path of this orbit, a positive ion (Fig. 2 inset) with double the mass of a proton is repelled to the wall at the positive x-axis, and a 0.1 cm radius ring with 25 homogeneously distributed electrons and 200 keV energy passes through the central axis of the device in the z-direction. For this simulation the bias per plate was 9.3 kV (with opposite polarities) and the maximum magnetic field at the beam path was reduced to 5.8 mT to restore the single electron trajectory through the central axis. The complete analysis of particle dynamics will be further investigated and reported in a future contribution. In a post-processing step, the magnetic field was obtained along the beam path and as shown in Fig. 3, the contribution from the permanent magnets (red trace, right axis) is three orders of magnitude lower than the contribution from the window frame coil field (blue trace, left axis). These results were encouraging and a prototype was built to test its pumping capabilities, described below.

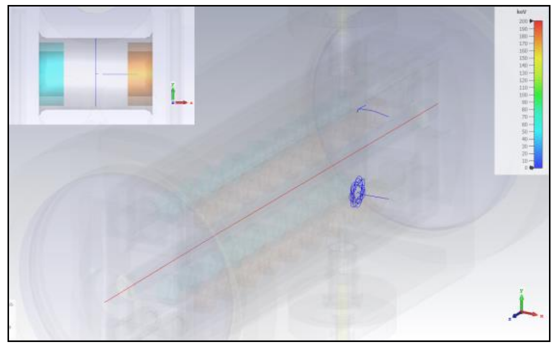

Figure 2: CST particle tracking simulation.

EXPERIMENT

A Wien filter test setup was assembled following the same procedure as in our previous contribution [11]. For this test a set of two 316/316L highly polished stainless steel electrodes including the penning traps was used. A set of four (two for each side) 28.7×3.6×0.3 cm getter titanium and tantalum plates were attached to the vacuum chamber lateral walls using custom non-magnetic holders, and were therefore grounded. A vacuum level of ~10^{-6} Torr was achieved using a turbo pump connected to one end of the Wien filter, while the other end was connected to a cross with a broad-range cold-cathode/Pirani vacuum gauge and an 11 L/s ion pump. For this initial test, a bias was established only on the positive electrode, using a Gamma vacuum SPCe ion pump power supply, limited to a maximum of 7050 V. The window frame coils were removed and a pair of 7.5×20×5.5 cm permanent magnets were placed on either side of the positively biased electrode, outside of the vacuum chamber. The permanent magnets provided 180 mT at their surface and ~ 140 mT at the location of the Penning traps center. Initially, +7 kV was applied to the electrode and the pressure inside the vacuum enclosure was left to stabilize. Subsequently the Wien was isolated from the turbo pump through a right angle valve, and the 11 L/s ion pump was turned off. At this point the current between the electrodes and grounded walls, and the pressure inside the vacuum chamber were measured versus time over 1.5 hrs as shown in Fig. 4. The blue dots represent the Wien current, and the red dots the pressure reported by the nearby vacuum gauge, showing that the device indeed was actively pumping.

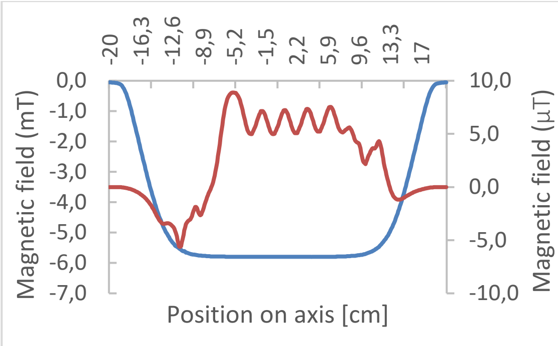

Figure 3: Coil (blue) and permanent magnets (red) magnetic field plot along beam path. Notice that the permanent magnet field is three orders of magnitude smaller than the coil field.

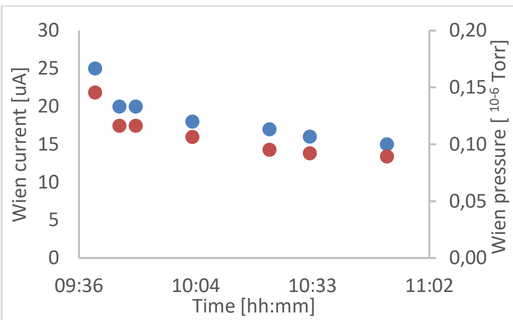

Figure 4: Wien pump current and pressure as a function of elapsed time.

A second test was performed by lowering the voltage starting from +7 kV and recording again the Wien current and pressure, as shown in Fig. 5, were the blue trace denotes the Wien current. Notice how in this pressure range, the pressure and current decrease as the voltage is reduced, coinciding with the reported results in [10]. The lower achievable bias in that power supply was +3 kV.

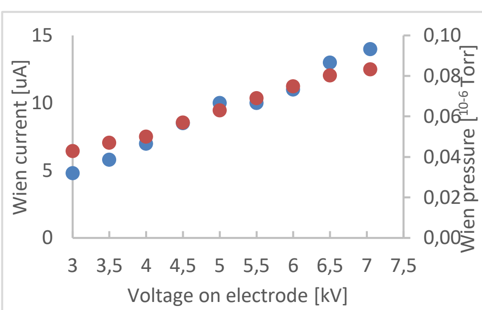

Figure 5: Wien pump current and pressure as a function of positive electrode voltage.

The results of a third test are shown in Fig. 6, in which the gap between the permanent magnet pair was increased, again keeping track of the Wien pump current and pressure. The initial separation between the chamber walls was measured at 5.7 cm. Naturally, the current (blue trace) decreases as the gap increases, and the pressure (red trace) increases. This test provides more evidence that the Wien electrode plate is indeed behaving as an ion pump.

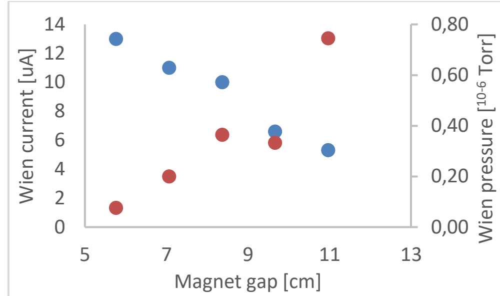

Figure 6: Wien pump current and pressure as a function of gap between external permanent magnets.

CONCLUSIONS

A Wien filter spin rotator with integrated ion pump was modeled and preliminary CST simulations including electric and magnetic fields, and particle tracking show that it is capable of performing as an ion pump and a Wien filter simultaneously, capable of rotating the spin angle of a 100 keV electron beam by $\pm\pi/2$ rad. A prototype device was built and initial experimental results show that it maintains a 1×10^{-7} Torr vacuum level with the use of external 180 mT permanent magnets, which in simulations have been substituted by permanent ring-magnet pairs that have a ± 10 µT contribution at the beam path region. These are encouraging results and more sophisticated beam dynamics simulations will be further investigated and presented in a future document. Such device could be useful to accelerator physics technology, by providing spin rotation and differential pumping, thus aiding in the preservation of photocathode life time, which is paramount in nuclear physics experiments at JLab and planned accelerator projects around the world as the Electron Ion Collider and the International Linear Collider.

ACKNOWLEDGMENTS

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REFERENCES

[1] K. Tsuno & D. Ioanoviciu. Advances in Imaging and Electron Physics 176. Academic Press (2013). ISBN: 978-0-12-408142-0.

[2] M. Salomaa, H.A. Enge. "Velocity selector for heavy-ion separation," Nuclear Instruments and Methods, Volume 145, Issue 2, Pages 279-282, (1977). ISSN 0029-554X.

[3] C. K. Sinclair, E. L. Garwin, R. H. Miller, and C. Y. Prescott. "A high intensity polarized electron source for the Stanford Linear Accelerator," AIP Conference Proceedings 35, 424 (1976).

[4] G. Palacios Serrano, P.A. Adderley, J.M. Grames, C. Hernandez-Garcia, M. Poelker. "High-Gradient Wien Spin Rotators at Jefferson Lab", NAPAC 2022 Conf. Proc., Pre-Press Status August, (2022).

[5] Wei Liu, Shukui Zhang, Marcy Stutzman, and Matt Poelker. "Effects of ion bombardment on bulk GaAs photocathodes with different surface-cleave planes", Phys. Rev. Accel. Beams 19, 103402 (2016).

[6] Juliette Mammei (for the MOLLER Collaboration), "The MOLLER Experiment", in arXiv preprint arXiv: 1208.1260, 2012. https://doi.org/10.48550/arXiv.1208.1260

[7] V. Tioukine and K. Aulenbacher, "Operation of the MAMI accelerator with a Wien filter based spin rotation system", in *Nucl. Instrum. Methods. Phys. Res. B NUCL INSTRUM METH A*, ol. 568, no. 2, pp. 537–542, Dec 2006. doi:10.1016/j.nima.2006.08.022

[8] J. M. Grames *et al.*, "Unique electron polarimeter analysing power comparison and precision spin-based energy measurement", in *Phys. Rev. ST Accel. Beams*, vol. 7, 2004.

[9] K. Blauma, Yu.N. Novikovb and G. Werthc. "Penning traps as a versatile tool for precise experiments in fundamental physics". Contemp. Phys. Vol. 51, Issue 2, (2010).

[10] © Agilent Technologies, Inc. "Agilent Sputter Ion Pumps a 60 year history". (2017).

[11] G. Palacios-Serrano *et al.*, "High Voltage Design and Evaluation of Wien Filters for the CEBAF 200 keV Injector Upgrade", in *12th Int. Particle Acc. Conf.*, 2021. doi: 10.18429/JACoW-IPAC2021-MOPAB324

[12] CST Microwave Studio, http://www.cst.com.

[13] Andrei Seryi, "Unifying Physics of Accelerators, Lasers and Plasma", CRC Press, July, (2015).