WIEN-FILTER SPIN ROTATOR WITH INTEGRATED ION PUMP *

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Workshop on Polarized Sources Targets and Polarimetry 2022

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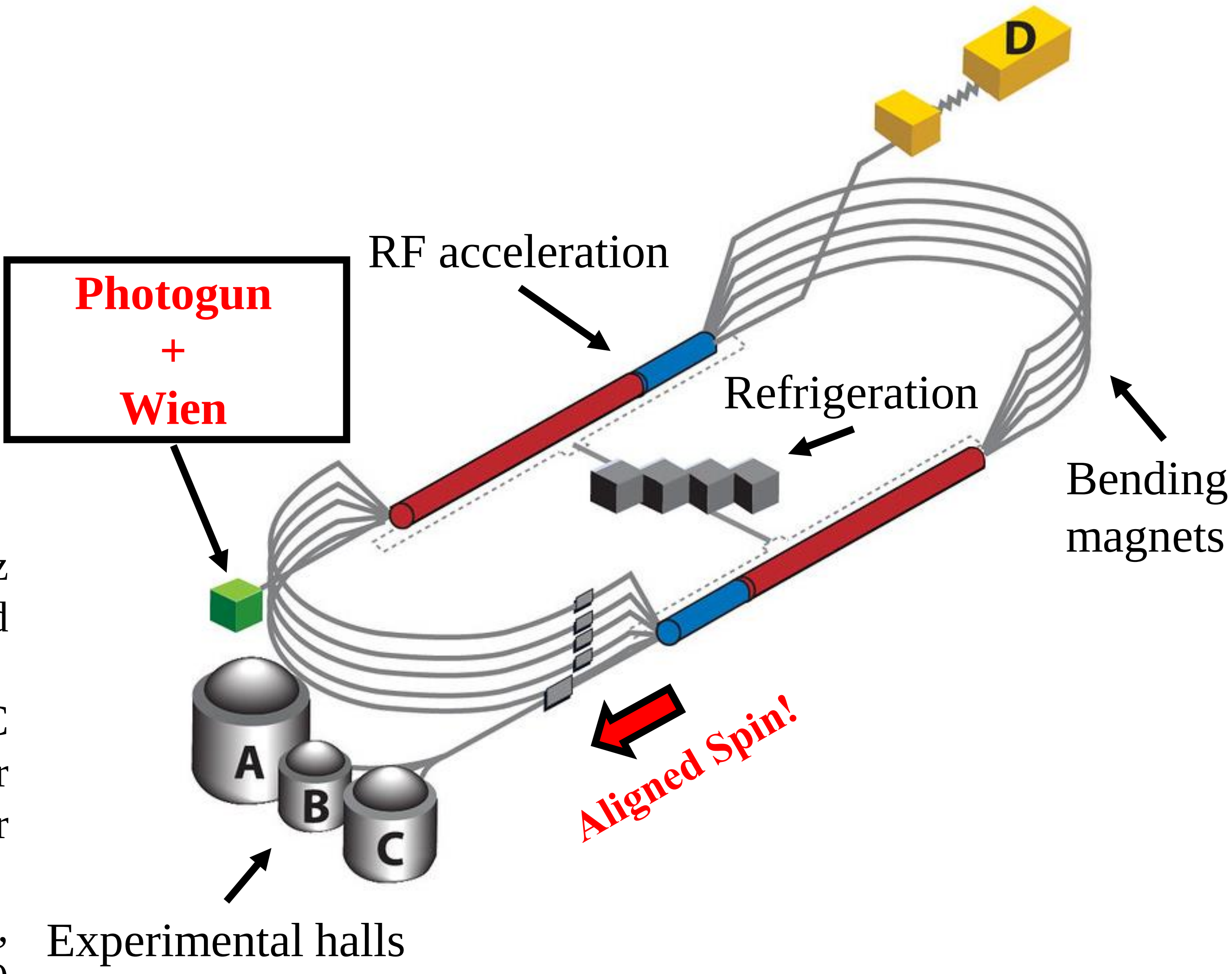
Abstract

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 ("Willy") Wien invented the device and measured cathode rays q/m ratio.
- Almost 80 years later C. K. Sinclair *et al* at SLAC designed and implemented a compact Wien filter to obtain transverse polarization from their polarized electron source.
- Great design replicated at the MIT-Bates, CEBAF, MAMI, and S-DALINAC for operation at 100 keV beam energy.

Thomas Jefferson Nation Accelerator Facility (2019)



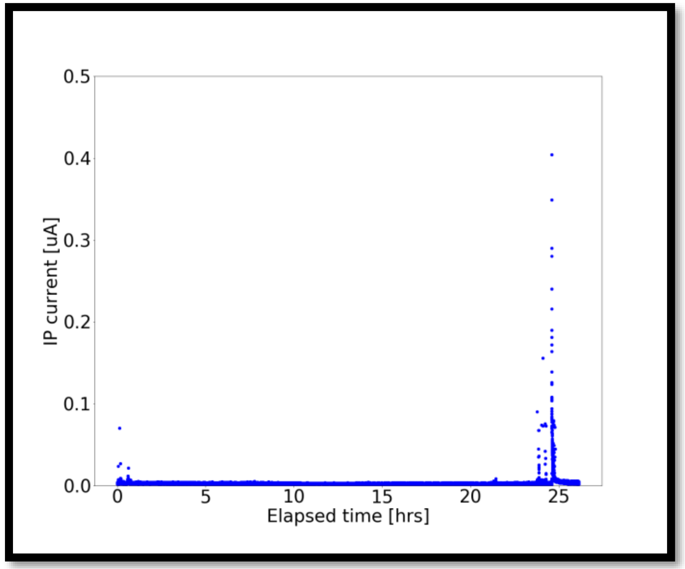
Continuous Electron Beam Accelerator Facility **(CEBAF)**

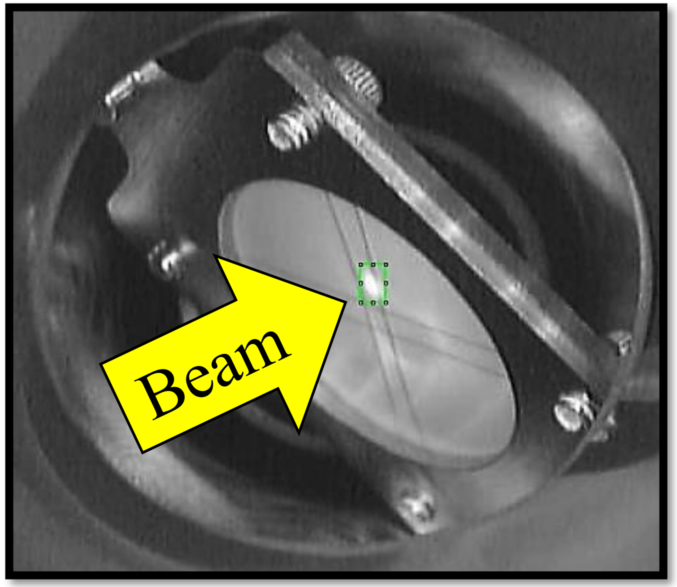
Jefferson Lab

INTRODUCTION

- More recently, the design robustness was further demonstrated by operating a modified version at Jefferson Lab with a 180 keV beam.
- The mutually orthogonal independent electric and magnetic fields configuration can be exploited to allow a Wien filter spin rotator to simultaneously act as an ion pump by adding Penning traps to the electrodes.

Vacuum during operation

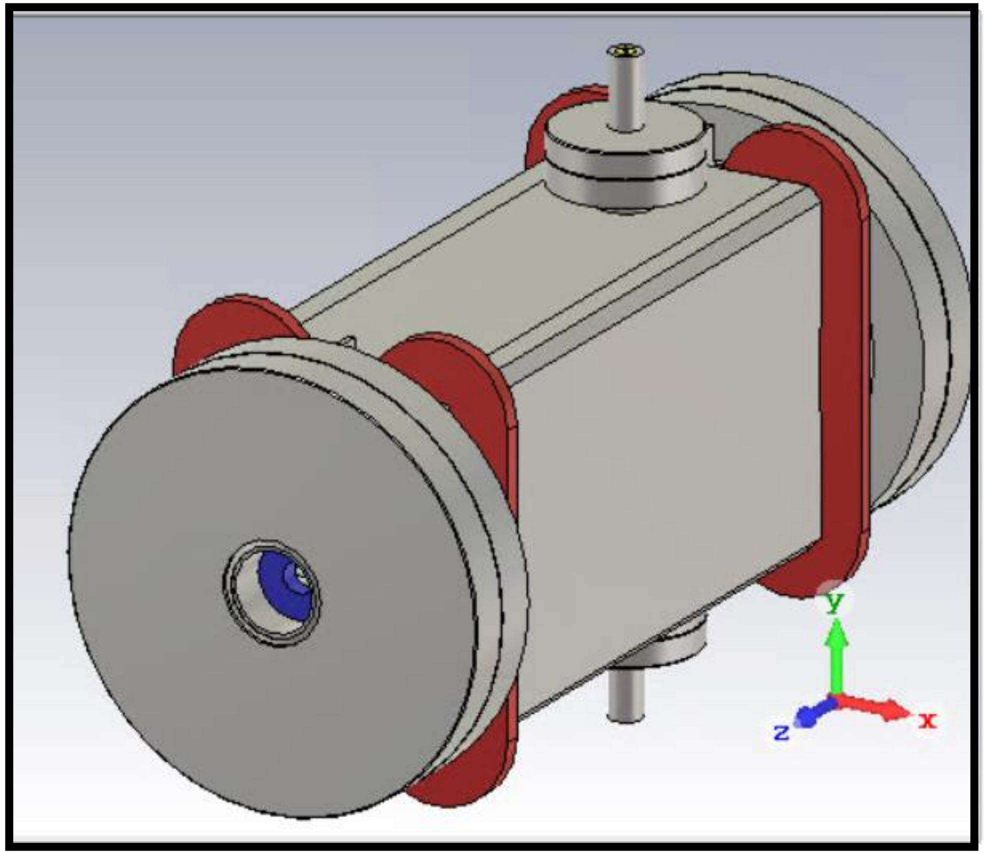




180 keV beam on fluorescent screen

- **3D Solidworks Model**
  - The Wien filter is composed of
    - HV electrode plates with mounting tabs and Rogowski profile
    - HV spring guide contacts with spring coils
    - HV electrical feedthroughs with alumina insulators
    - MACOR mounting insulators
    - Vacuum chamber with electrode mounting springs
    - Magnet coils
    - Endplates, steel shell

Isometric view of 3D model of the existing CEBAF 100 keV Wien filter based on SLAC's original design.



OPERATION PRINCIPLE

- The Thomas Bargmann-Michel-Telegdi (BMT) equation describes the rotation of the electron spin 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**, and can be simplified to:

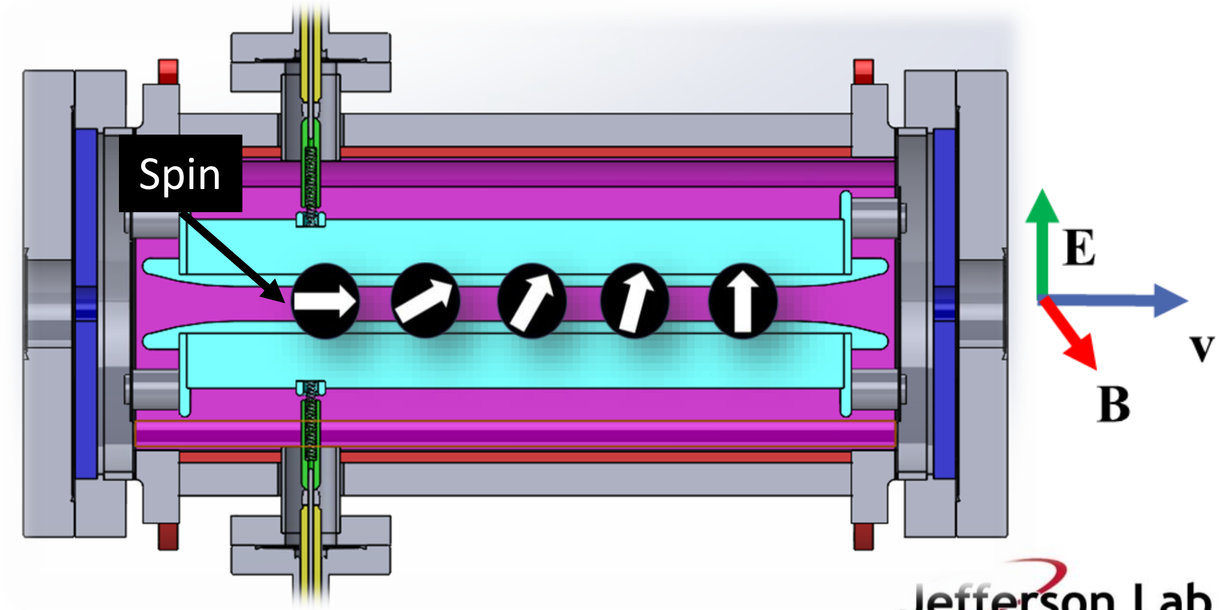
$$\theta = \frac{eL}{m_0 c\beta\gamma^2}\left[\frac{E_y}{v_z}\right]$$

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

- It is important to maintain the trajectory of the particles that traverse the device, this is achieved by ensuring that the contributions of the electric and magnetic fields to the total force is zero, thus fulfilling the "Wien condition" :

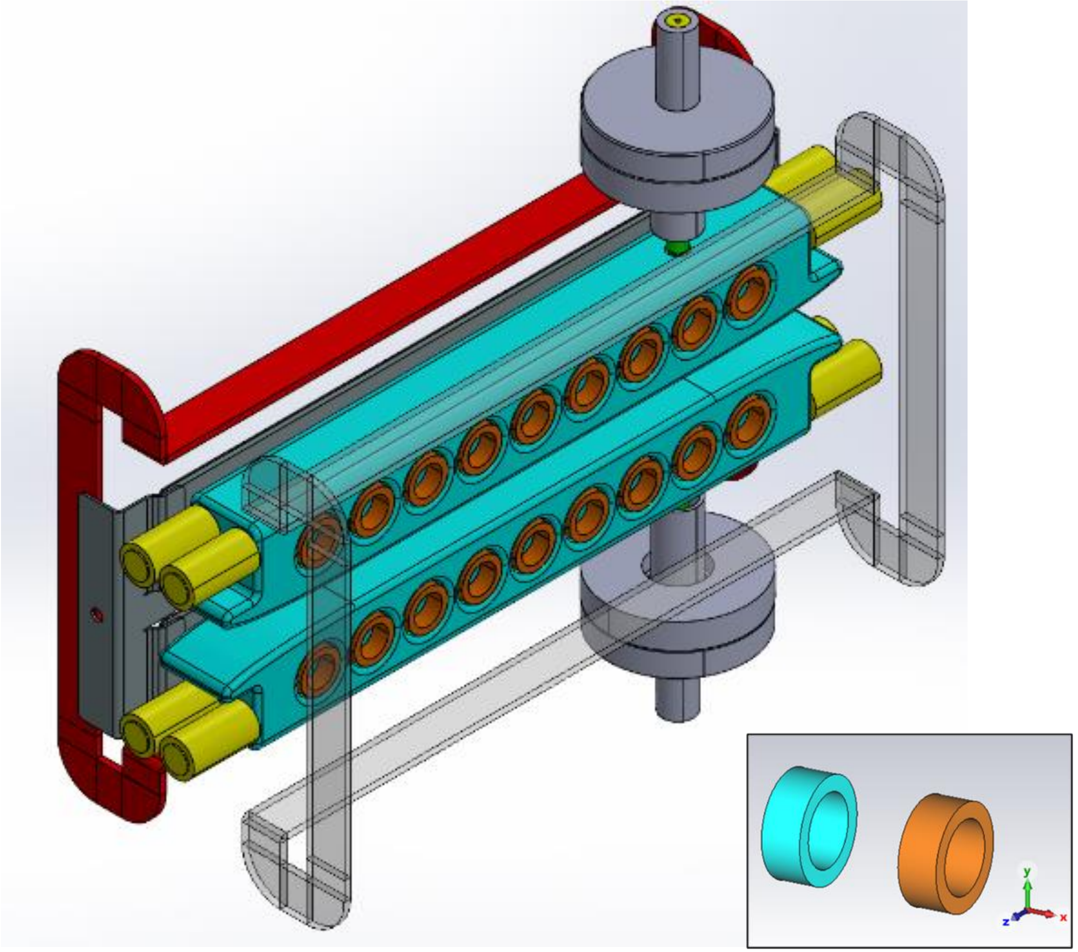
$$E_y = v_z B_x$$

- In ion pumps, Penning traps are used to create a quadrupole electrostatic field, which in combination with a homogeneous axial magnetic field, are capable of confining electrons inside the trap. 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.



WIEN FILTER MODIFICATION

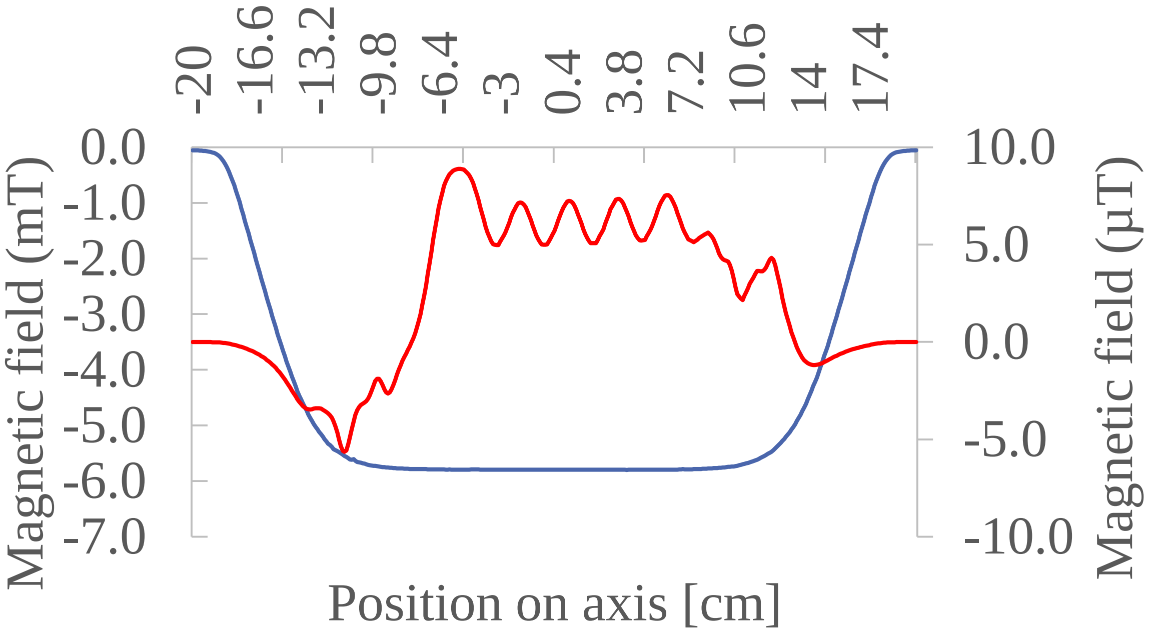
- For a 100 keV beam, 1.5 cm electrode gap, and π/2 rad spin rotation angle, our calculations yield an electric field of 1.2 MV/m and a magnetic field of 7.5 mT at the beam path.
- Mutually orthogonal static and independent electric and magnetic fields can work simultaneously for spin rotation and pumping by adding Penning traps to the electrodes.
- Each electrode thickness was increased to 3.5 cm, and nine 1 cm radius equidistant Penning traps were machined in the electrode body.
- The magnetic field produced by the window frame coils was deemed too low to produce detectable pumping in initial testing, therefore permanent ring-magnet pairs of 180 mT magnetic field were proposed.
- Two sets of titanium and tantalum plates on the chamber sides.

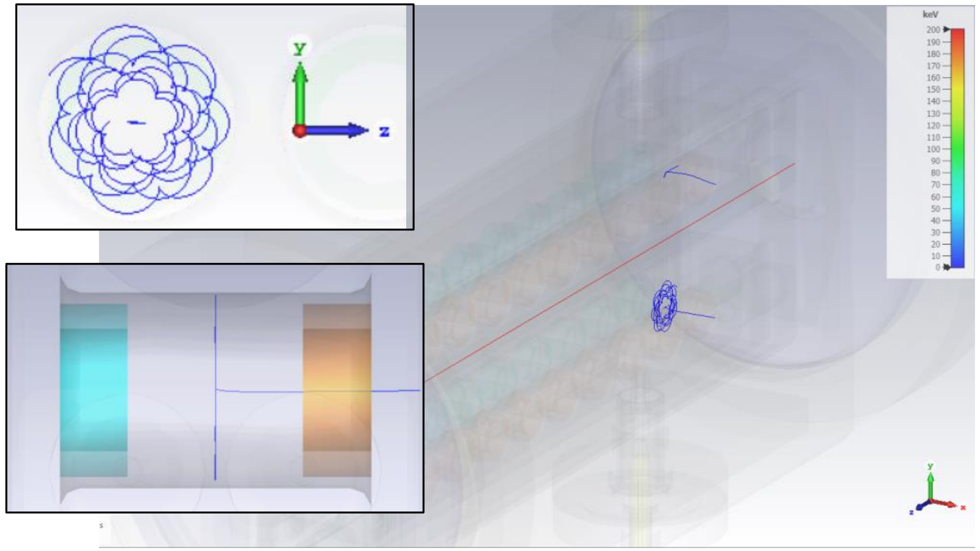


Modified Wien filter 3D model isometric view showing the Penning traps in both the electrodes.

SIMULATIONS

- It is preponderant to minimize the impact of the magnetic field induced by the permanent ring-magnets at the beam path.
- 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 -10kV (top) and +10 kV (bottom) was solved in combination with the magnetic field of the permanent magnets and dynamics of particles inside the traps.
- 0.1 cm radius ring with 25 homogeneously distributed electrons and 200 keV energy passes through the central axis.
- 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

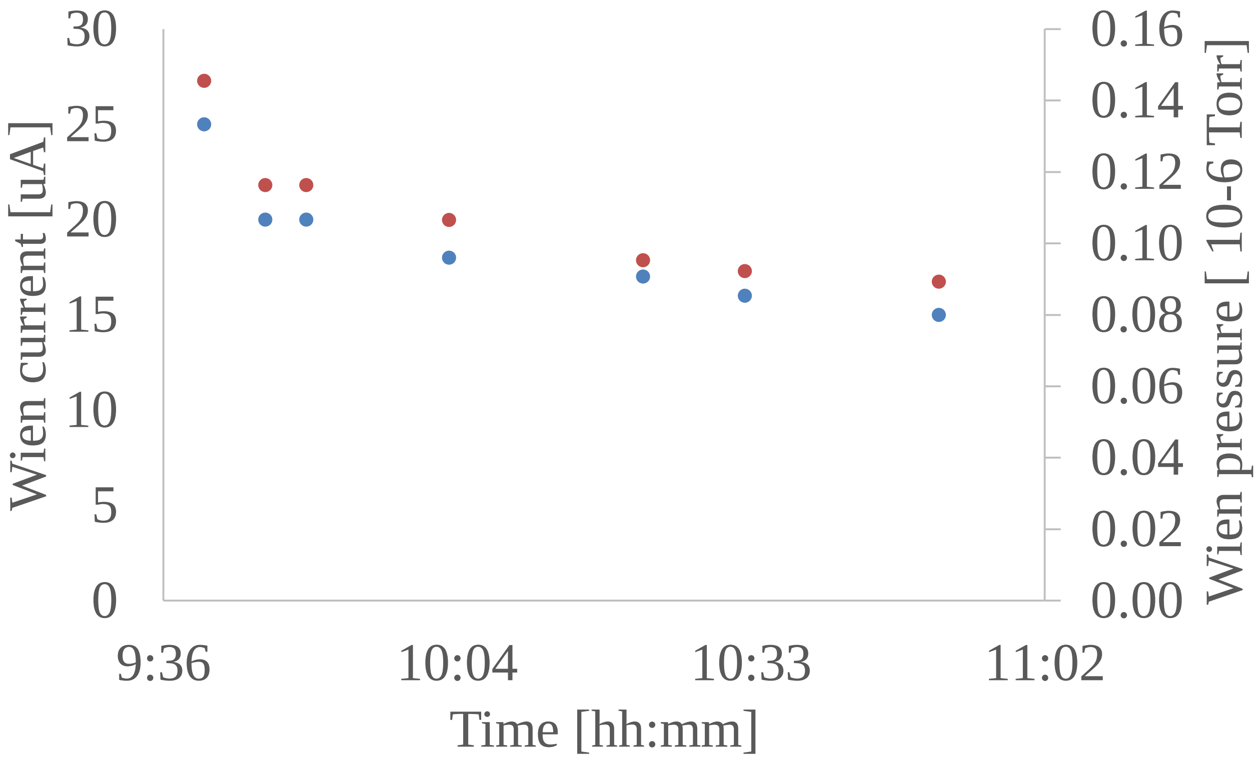




CST particle tracking simulation

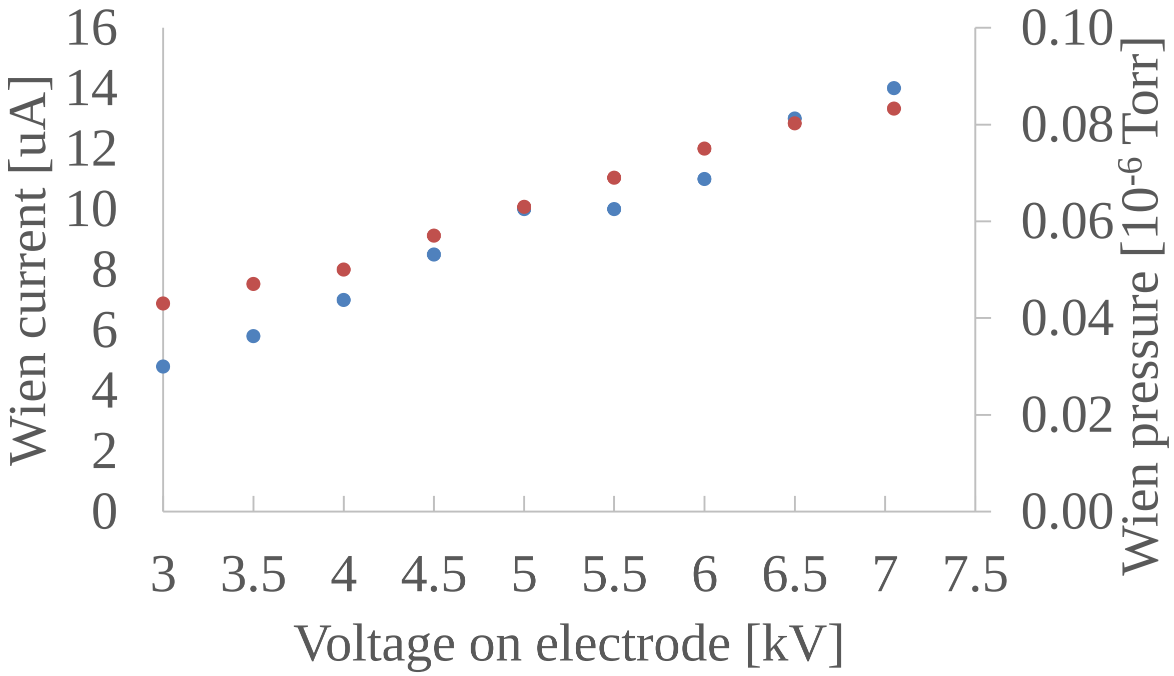
EXPERIMENT

- A Wien filter test setup was assembled.
- Two 316/316L highly polished stainless steel electrodes including the penning traps was used.
- 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.
- 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.
- Only on the positive electrode was biased 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 (180 mT) permanent magnets were placed on either side of the positively biased electrode.

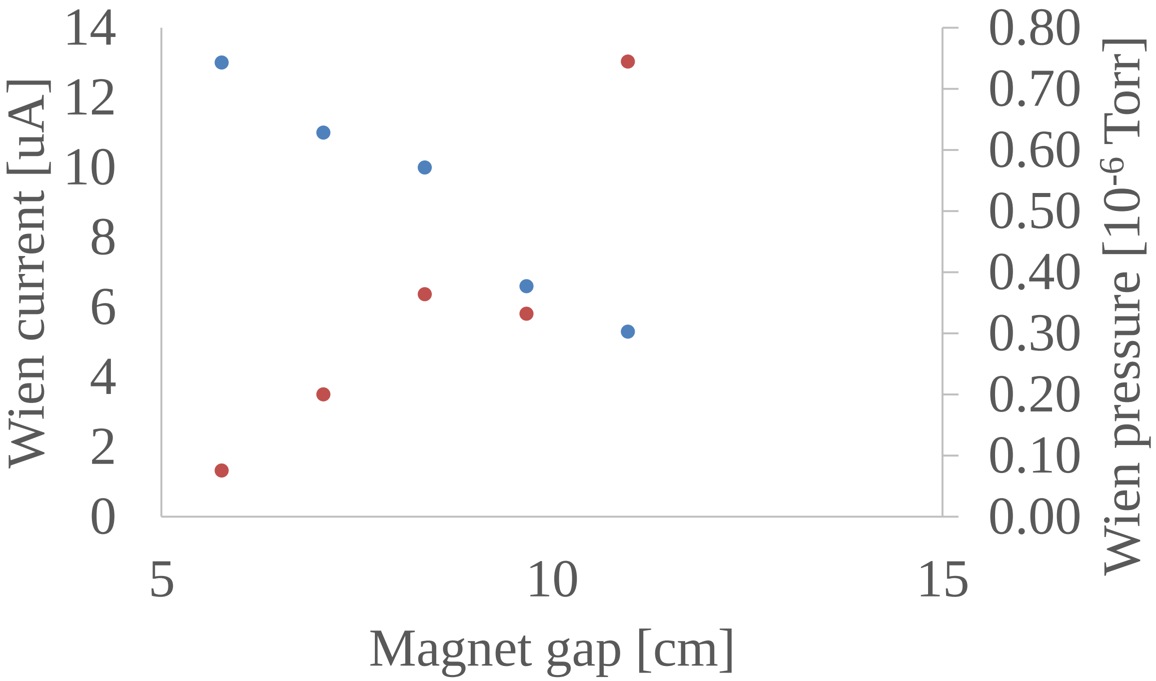


Wien pump current (blue) and pressure (red) as a function of elapsed time.

EXPERIMENT



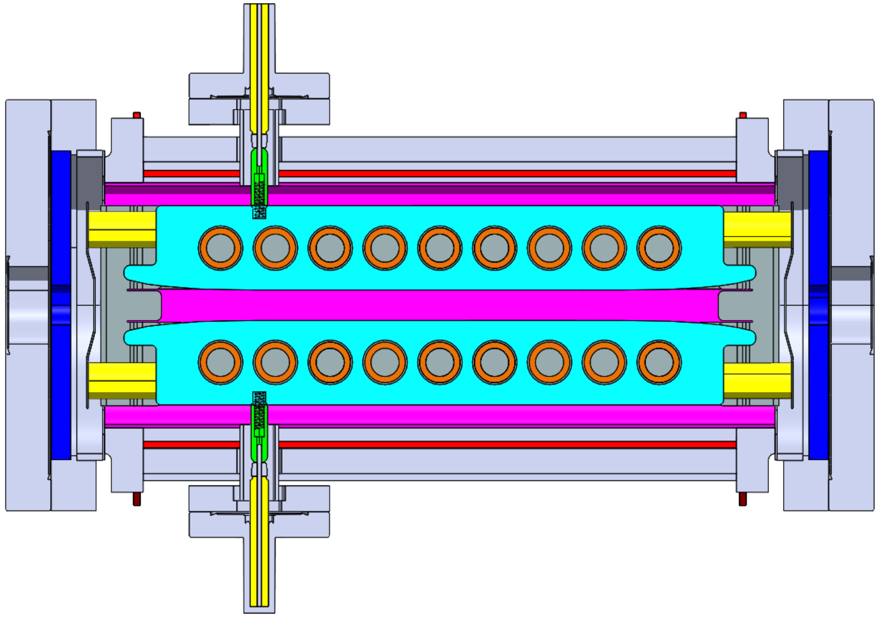
Wien pump current (blue) and pressure (red) as a function of positive electrode voltage.



Wien pump current (blue) and pressure (red) 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 ±π/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 mag-nets, 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 para-mount in nuclear physics experiments at JLab and planned accelerator projects around the world as the Electron Ion Collider and the International Linear Collider.



ACKNOWLEDGMENTS

The authors wish to thank Bubba Bullard, K. Harding, P. Adderley, J. Benesch, M. Stutzman, and the JLab Injector Group.

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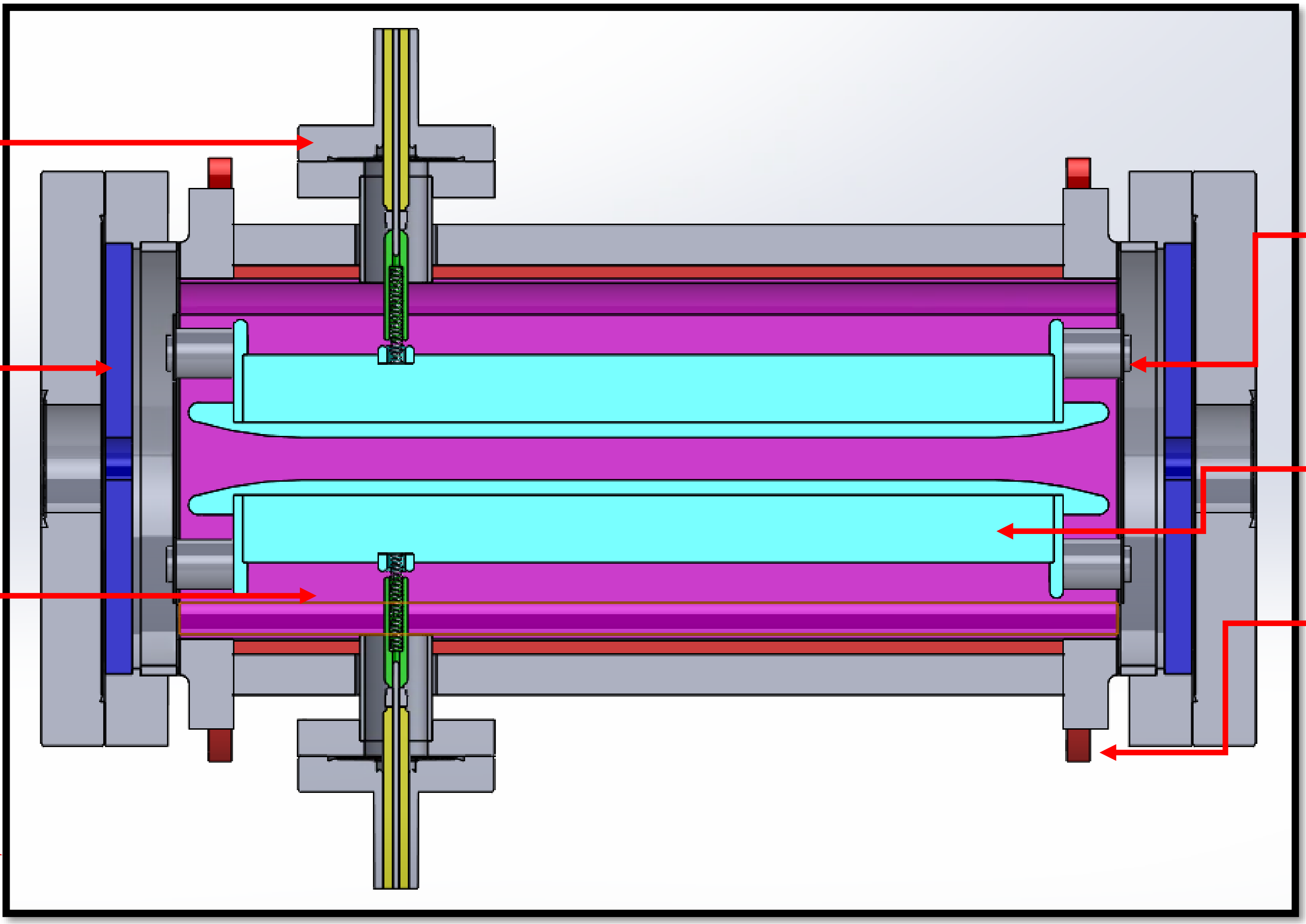
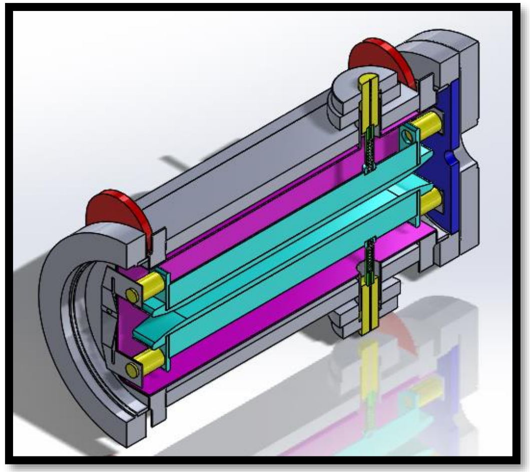
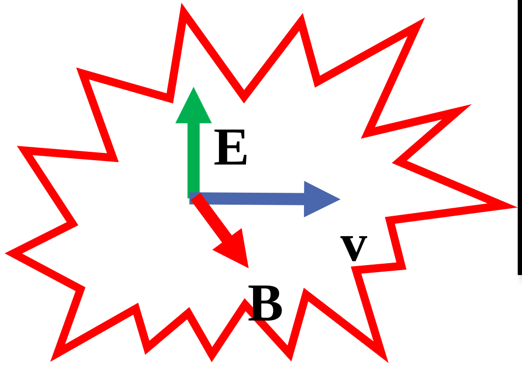
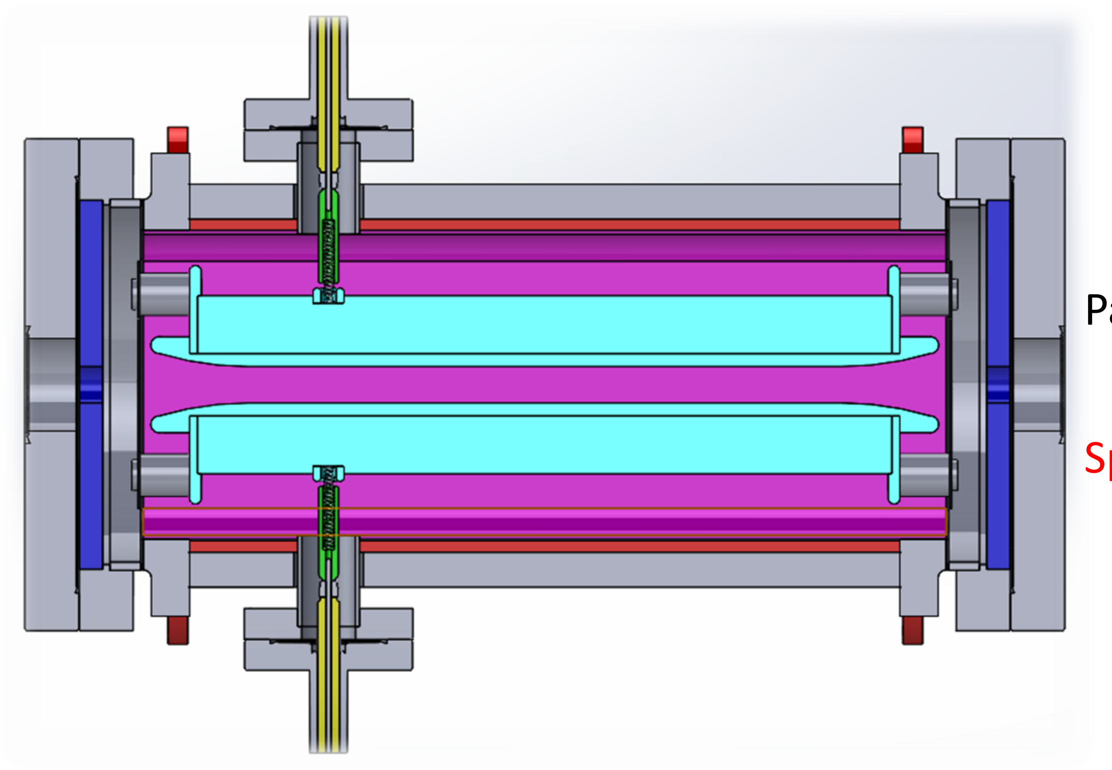
FIN

CEBAF’s 100 keV Wien filter









Equilibrium condition:

$$e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) = 0$$

$$\frac{E_y}{B_x} = v_z$$

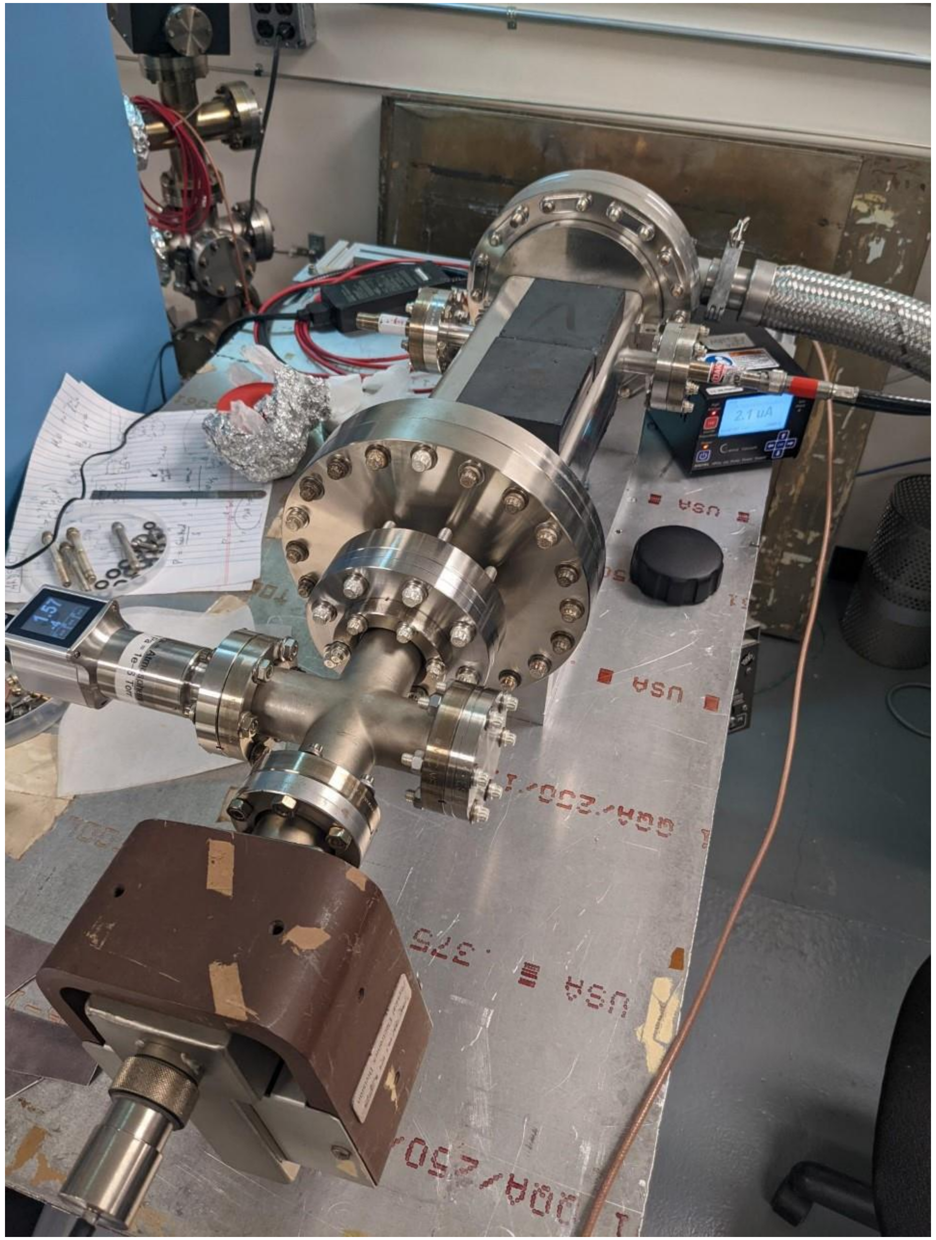
Spin rotation:

$$\frac{d\theta}{dt} = \frac{e}{m_0 c}\left[aB_x + \left(\frac{(1+a)\beta^2 - 1}{\beta}\right)E_y\right]$$

$$\theta = \frac{eL}{m_0 c \beta \gamma^2} B_x$$

E: electric field magnitude
B: magnetic field magnitude
v: particle velocity
e : electron charge
m_0: electron rest mass

c: speed of light
a: electron magnetic moment anomaly
β: normalized velocity
γ: Lorentz factor
L: effective length
θ: spin rotation angle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1.57