Investigation of Voltage Configuration and Radial Dependence of Transmission Curves in PTOLEMY

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Abstract

Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield (PTOLEMY) aims to directly detect relic neutrinos. This is achieved by measuring the energies of electrons produced from neutrino capture by tritium, which would lie just above the endpoint of tritium beta decay. The Magnetic Adiabatic Collimation combined with an Electrostatic filter (MAC-E filter) is a spectrometer that allows for the transmission and detection of these high-energy signal electrons while filtering the background beta electrons. Characterizing the process by which the MAC-E filter utilizes electric and magnetic fields helps determine the desired properties of the filter's configuration. The electric field is generated by nine electrode rings of adjustable voltages. A mathematical method incorporating the superposition principle is used as a guide to estimate the voltages that achieve the most favorable transmission curve. Once these values are determined, the different cut-off potentials of electrons due to magnetic field expansion are calculated. By manipulating the voltages on the electron source, the transmission curve for different source radii can be aligned. This overall process approaches the accuracy that the MAC-E filter demands in order to limit the flux of electrons on the calorimeter to those with energies that could indicate a relic neutrino signal.

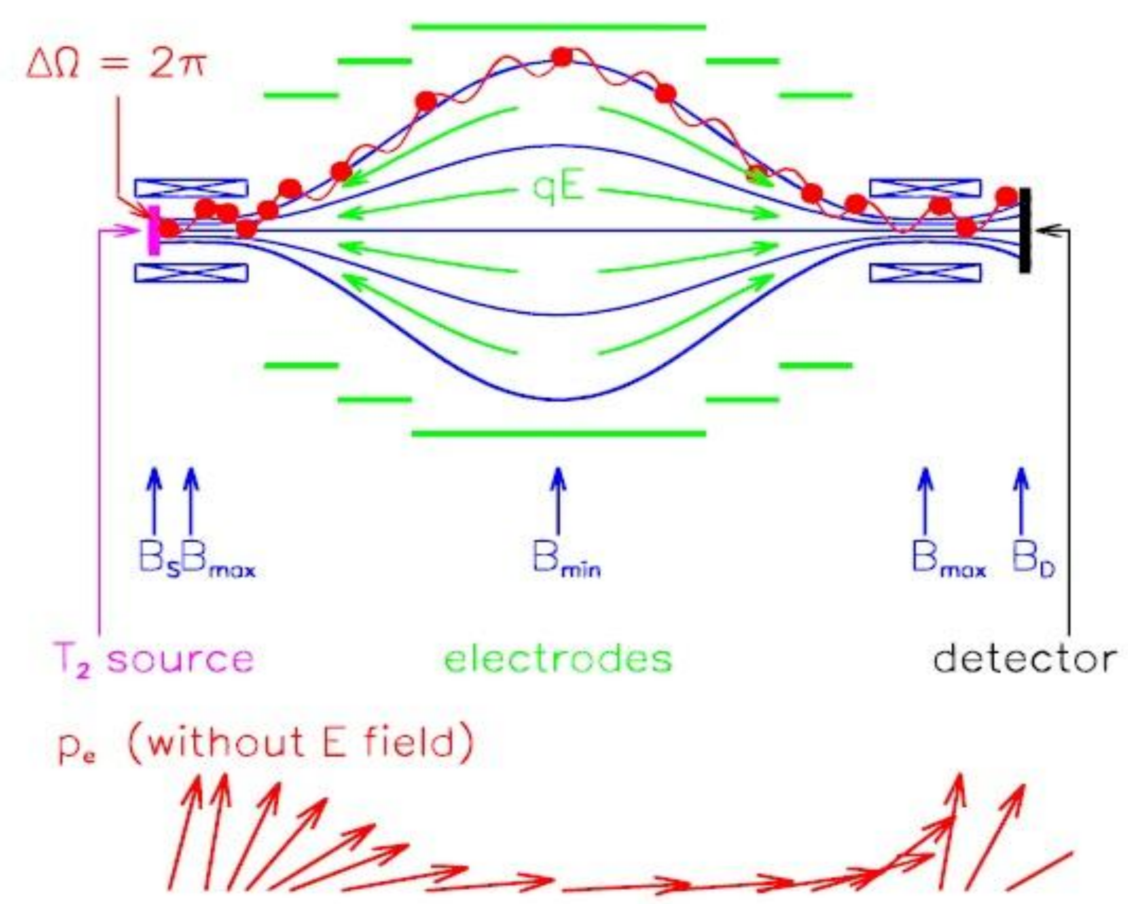


Figure 1: Trajectory of an electron through the MAC-E filter, reproduced from KATRIN

MAC-E Filter

- The MAC-E filter allows for the transmission of the high-energy electrons released by neutrino capture from tritium decay

$$^{A}_{Z}\mathrm{N} + \nu_e \rightarrow {}_{Z+1}^{A}\mathrm{N}' + \mathrm{e}^-$$

- As electrons travel from high to low magnetic field regions, their cyclotron momentum is transformed into longitudinal momentum
- Electrostatic retarding potential V is imposed by the analyzing plane
- Only electrons with minimum energy parallel to the field lines can pass

$$E^{\parallel} > qV$$

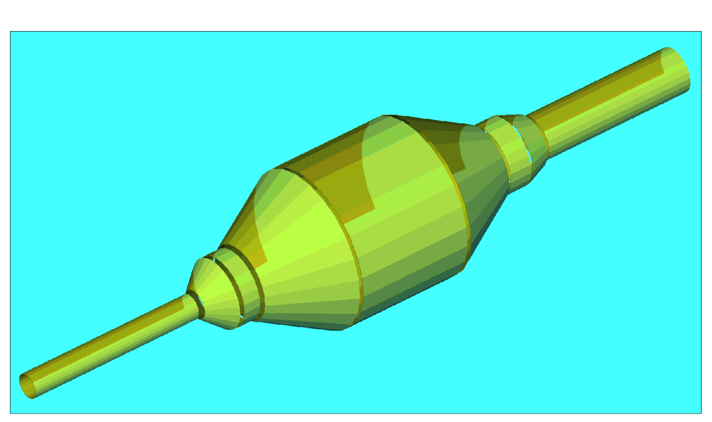


Figure 2: The electrode rings generating electric field,

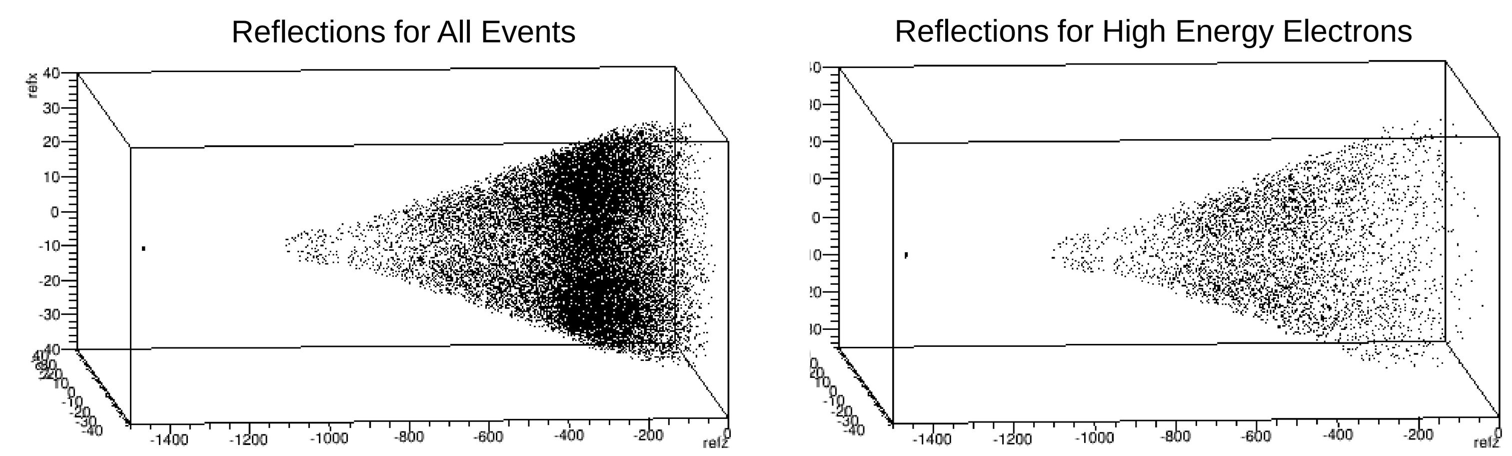
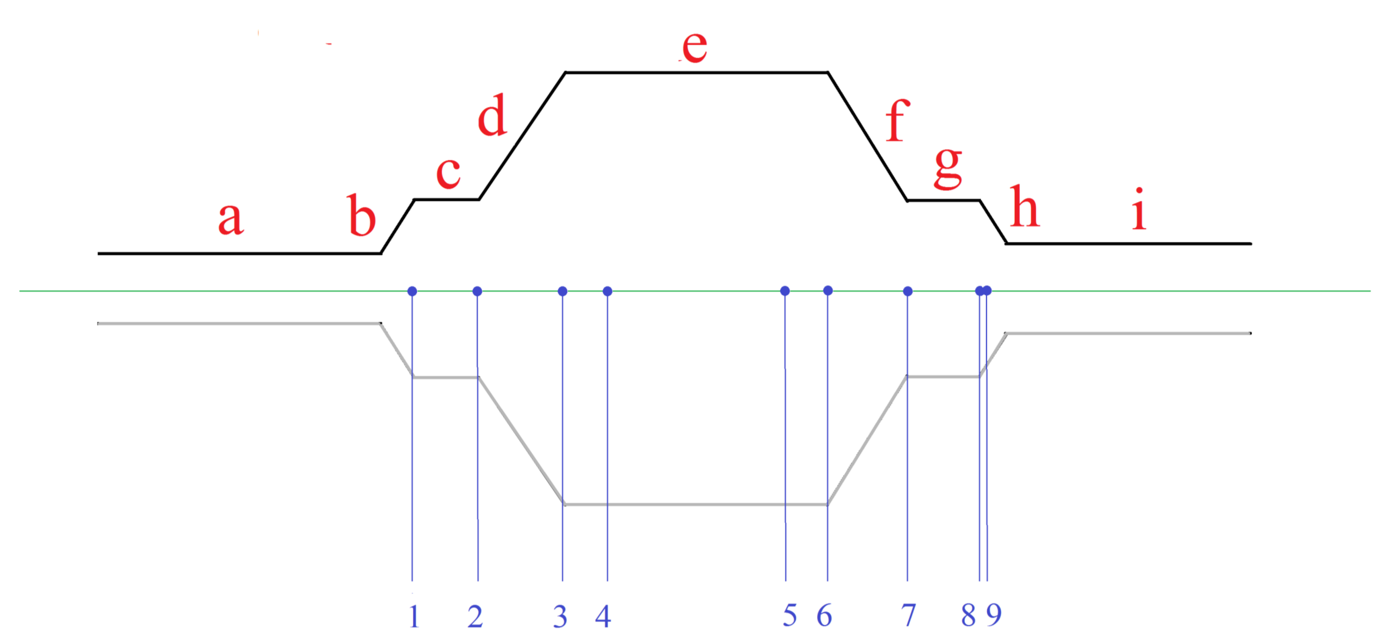


Figure 3 and 4: The Cartesian coordinates in the MAC-E filter of all reflected events and the reflected events with a source energy >18.5keV, respectively

What was the issue?

- A small percentage of electrons with a source energy > 18.5keV are reflected, many without reaching the analyzing plane
- Not all of electrons with a source energy < 18.3keV are reflected, so the flux of the electrons on the calorimeter is not limited
- Constraints imposed by magnetic field and electric field both contribute to the unfavorable transmission curve



$$\begin{array}{c} \\ \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \\ E_6 \\ E_7 \\ E_8 \\ E_9 \end{bmatrix} \end{array} = \begin{array}{cc} & a \ b \ c \ d \ e \ f \ g \ h \ i \\ \begin{matrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \\ 8 \\ 9 \end{matrix} & \begin{bmatrix} & & & & & & & & \\ & & & & & & & & \\ & & & & & & & & \\ & & & & & & & & \\ & & & & & & & & \\ & & & & & & & & \\ & & & & & & & & \\ & & & & & & & & \\ & & & & & & & & \end{bmatrix} \end{array} \begin{array}{c} \\ \begin{bmatrix} V_a \\ V_b \\ V_c \\ V_d \\ V_e \\ V_f \\ V_g \\ V_h \\ V_i \end{bmatrix} \end{array}$$

$$E = AV$$

Figure 5: A is a 9 x 9 matrix determined by performing 9 computation experiments in which all but one ring voltage is set to zero. Each row of A multiplied by matrix V finds the electric field component at a specific point.

Electric Field Approximation

- Superposition principle is applied by finding the electric fields generated by individual electrodes at 9 points
- Will be applied to the software generating transmission rates to reduce run time
- By placing the 9 points on the edge of electrodes, it is seen how individual electrodes affect the change in electric field

$$Reference\ Voltage = [18.4 \quad 10.4 \quad 8.4 \quad 0.2 \quad 0 \quad 0.2 \quad 8.4 \quad 12.4 \quad 14.4]$$
$$Electric\ Field\ Components = [26.87 \quad 31.75 \quad 1.41 \quad 0.75 \quad -0.78 \quad -1.54 \quad -34.01 \quad -29.77 \quad -29.33]$$

Magnetic Field Constraints

- Initial location of the electron on the source influences its cutoff potential because it determines its trajectory along the magnetic field
- The further the electron is from the center of the source, the higher the halfway point on its transmission curve will be
- Voltage could be added to different rings along the source to align their electrons' transmission curve

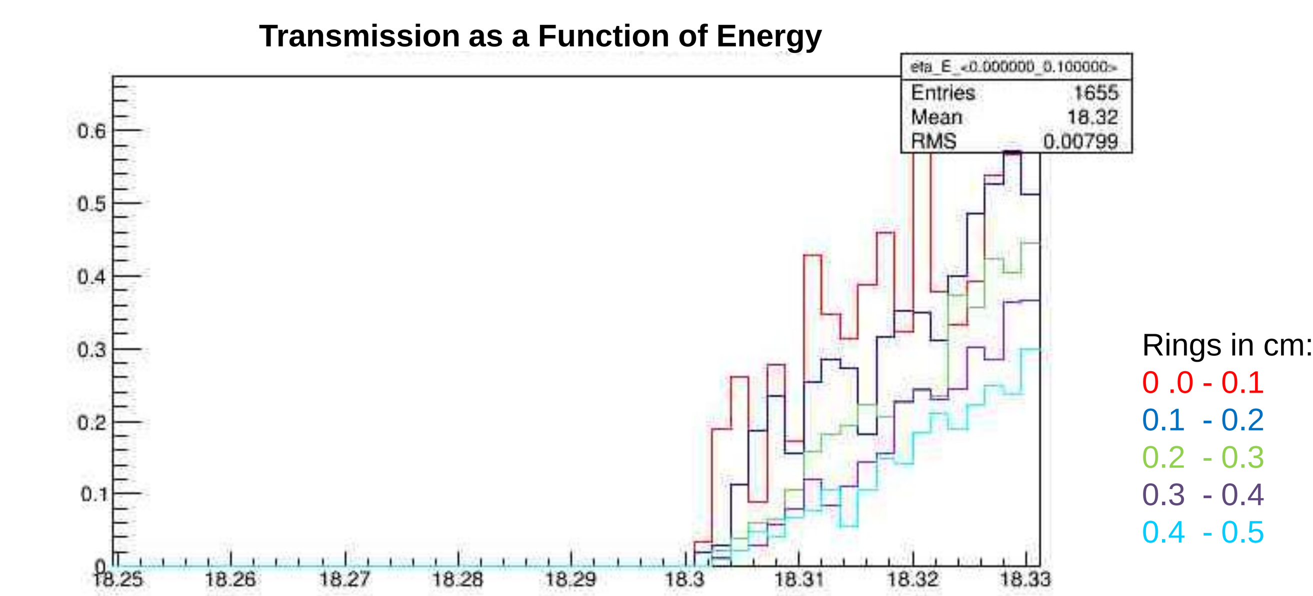


Figure 6 : The transmission curves of the electrons of different rings along the source

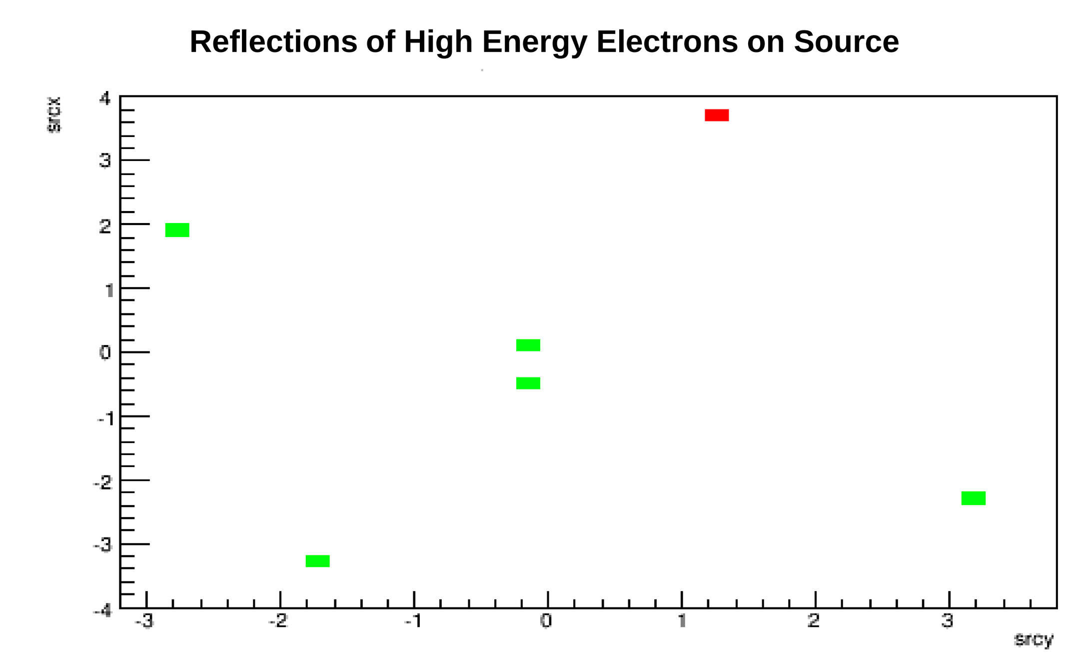


Figure 7: Once the energy loss was removed, a few high energy reflections still occurred mostly around the edge of the source

Conclusion

- A favorable transmission curve is achieved once energy loss in the source is removed
- The constraints imposed by the magnetic field could be overcome by manipulating the voltage on the electron source
- Method of electric field approximations could be applied when material other than tritium is used, such as Carbon 14

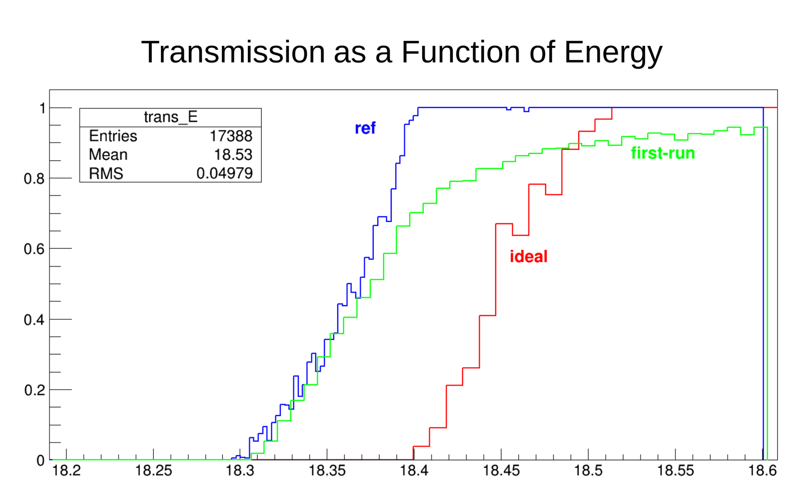


Figure 8: Transmission curve after energy loss is removed

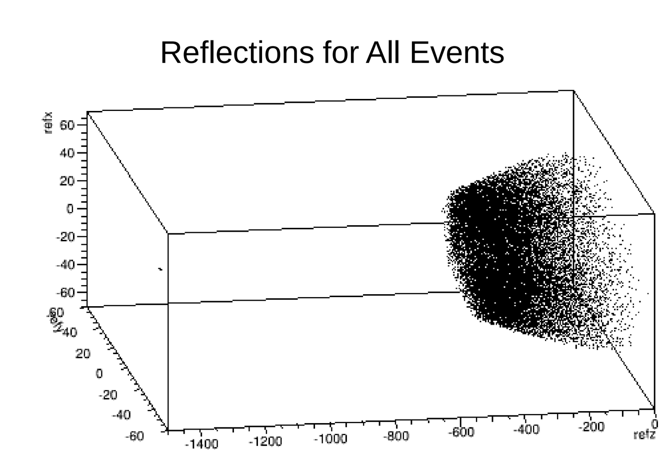


Figure 9: The Cartesian coordinates in the MAC-E filter of all reflected events after energy loss is removed

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