Single Electron Detection and Spectroscopy

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The Search for New Physics

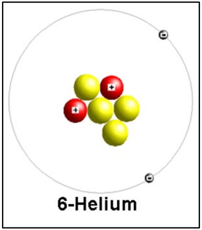
Helium-6

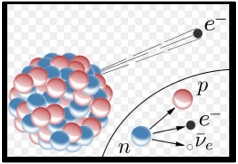
- Experiment investigating weak interactions in nuclei

Project 8

- Neutrino mass experiment

Need: Energy spectra of β-decay electrons

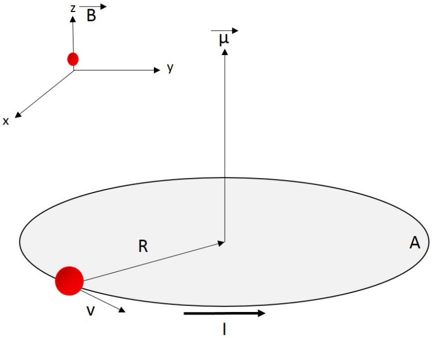




What is Project 8?

- Measures energies of trapped electrons via understanding of their motion
- Made the first measurement of single-electron cyclotron radiation

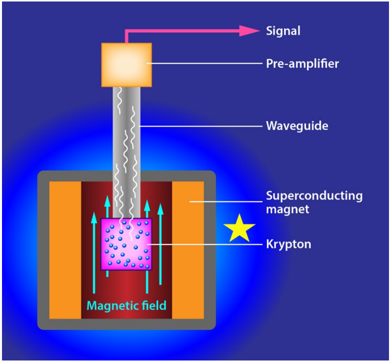
Cyclotron Frequency



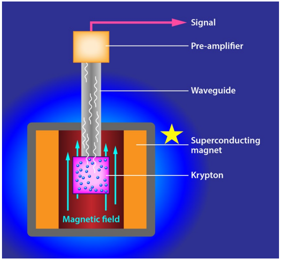
$$f_\gamma = \frac{qB}{2\pi\gamma m}$$

$$\gamma = \left(1 + \frac{K}{m_e c^2}\right)$$

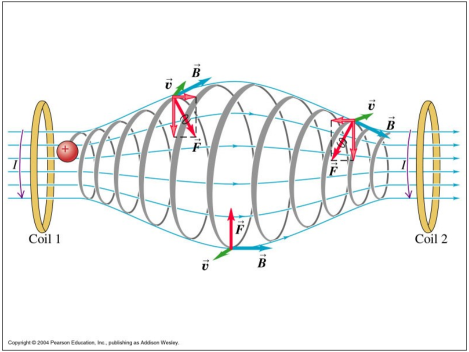
Apparatus: The Cell



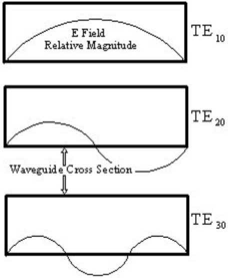
Apparatus: The Magnetic Field

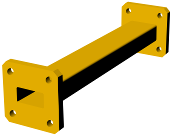


$$\vec{F} = -\nabla\left(\vec{\mu} \cdot \vec{B}\right)$$



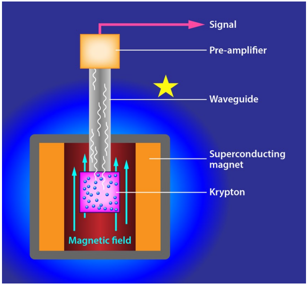
Apparatus: The Waveguide and Radiated Power





- Larmor Power:

$$P(\gamma,\theta) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{e^4}{m_e^2 c}B^2(\gamma^2-1)\sin^2\theta.$$



Creating a Frequency Spectrum

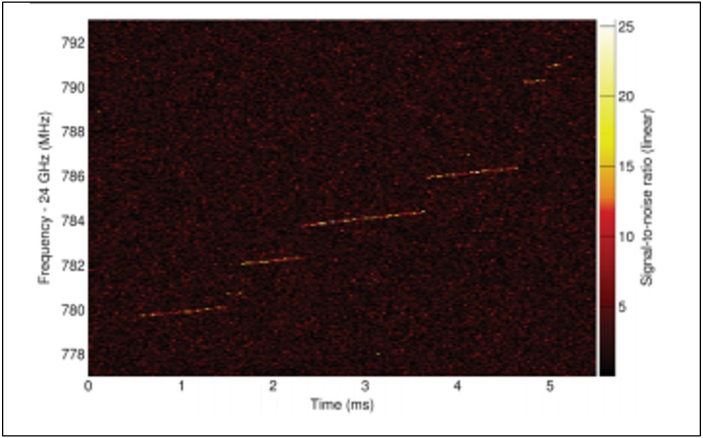


Figure: Example of Frequency Spectrum

Creating an Energy Spectrum

$$f_\gamma = \frac{qB}{2\pi\gamma m}$$

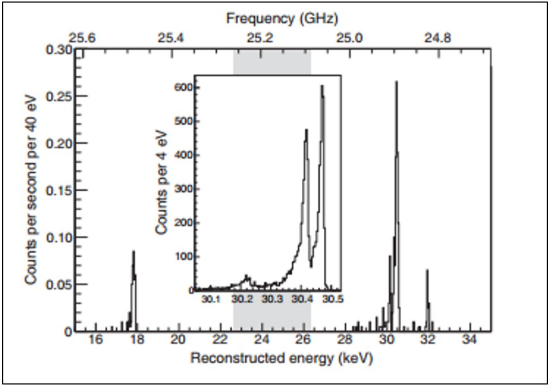


Figure: Example of Energy Spectrum

Goal and Advantages

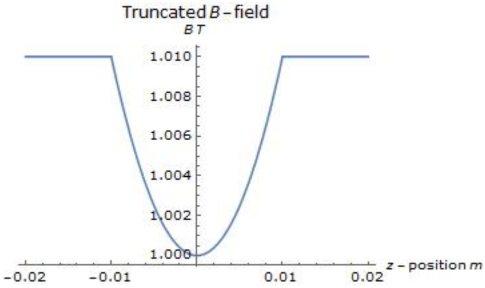
- **Task**: Distribution of average magnetic fields $\bar{B}$

$$f_\gamma = \frac{qB}{2\pi\gamma m}$$

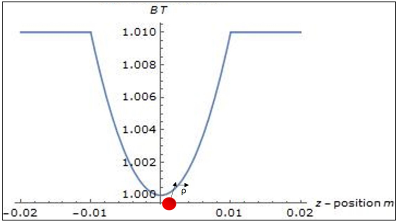
- **Goal**: Energy spectra for trapped electrons

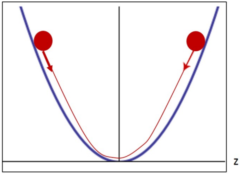
Field Configuration

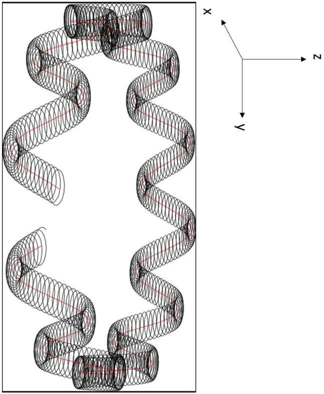
$$\vec{B} = B_0 \left(1 + \frac{z^2}{L^2}\right) \hat{z}.$$



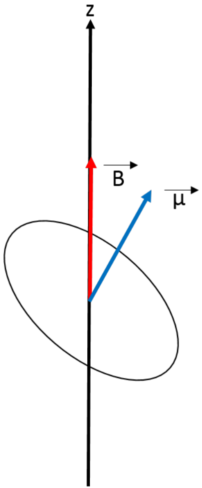
Motion of the Trapped Electron







Motion of the Trapped Electron (Contd.)



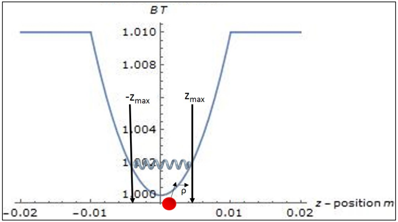
- Force: directed along $\hat{z}$.
- z-motion: $\vec{z} = z_{\text{max}} \sin \omega t \; \hat{z}$.
- z_{max}: maximum z-position attainable by a trapped particle with initial z and ϕ.

Maximum Displacement for a Trapped Particle

$$\frac{\sin^2 \phi}{\sin^2 \phi_{max}} = \frac{B(z)}{B(z_{max})}$$

$$\sin^2 \phi = \frac{B_0(1 + \frac{z^2}{L^2})}{B_0(1 + \frac{z_{max}^2}{L^2})}$$

$$z_{max} = \sqrt{\csc^2 \phi (L^2 + z^2) - L^2}$$



Time-Averaged Magnetic Field

- We need z_{max} in order to find the $\bar{B}$ experienced by a given trapped electron.
- After the integration dust settles, we have

$$\bar{B} = B_0 \left[1 + \frac{z_{\text{max}}^2}{2L^2} \right] \hat{z}.$$

Constructing the Probability Density Function

constant

Solve:

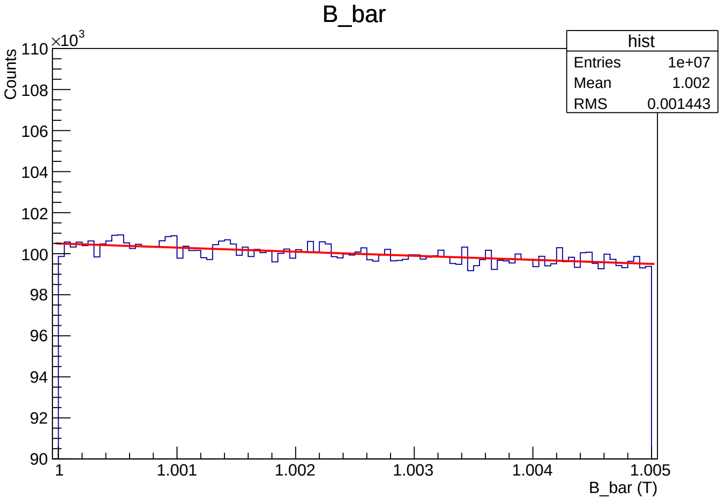
$$\frac{dN}{d\cos\phi} = \frac{dN}{d\bar{B}} \frac{d\bar{B}}{d\cos\phi}$$

Want:

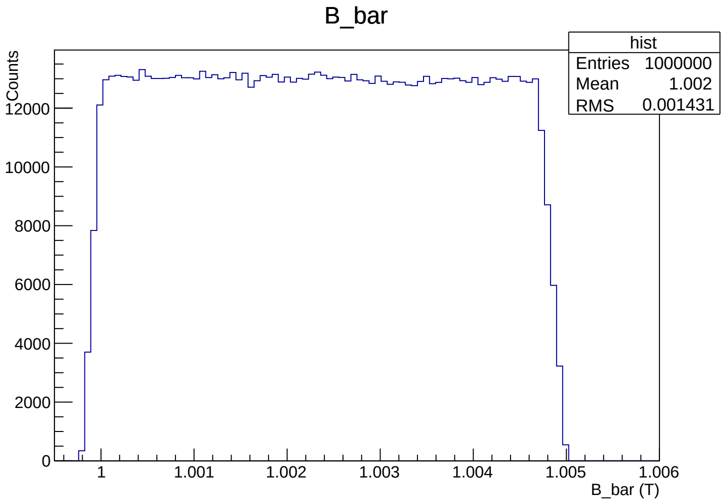
Constructing the Monte Carlo Simulation

- Populate z uniformly with electrons.
- Give each electron some pitch angle ϕ.
- Check to see if the electron is trapped.
- Calculate $\bar{B}$ and create $\bar{B}$ histogram.

Monte Carlo Simulation and Analytical Solution



Off-axis Monte Carlo Simulation



References

"Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation." DOI: 10.1103/PhysRevLett.114.162501.

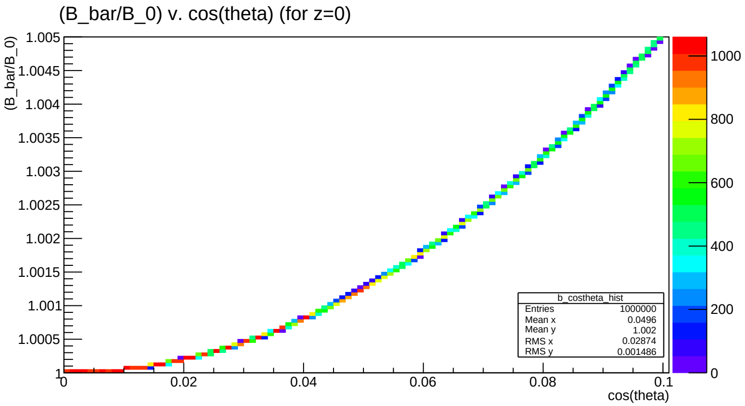
M. Leber, G. Rybka, and B. Monreal. "Project8 Average Power spectra." 2012. Print.

BACK-UP 1

Range of Trapped Angles and $\bar{B}$ Values:

- Electrons with ϕ in a particular range remain trapped.
- Maximum $\bar{B}$: determined by truncated quadratic.
- Minimum $\bar{B}$: dependent on the particle's initial z for $\phi = 90°$.

BACK-UP 2


(B_bar/B_0) v. cos(theta) (for z=0)
(B_bar/B_0)
1.005
1.0045
1.004
1.0035
1.003
1.0025
1.002
1.0015
1.001
1.0005
1
0
0.02
0.04
0.06
0.08
0.1
cos(theta)
1000
800
600
400
200
0
b_costheta_hist
Entries 1000000
Mean x 0.0496
Mean y 1.002
RMS x 0.02874
RMS y 0.001486