Fierz Term ^{6}He Decay Measurement via Cyclotron Radiation Emission Spectroscopy

Brent Graner for the He6CRES Collab.

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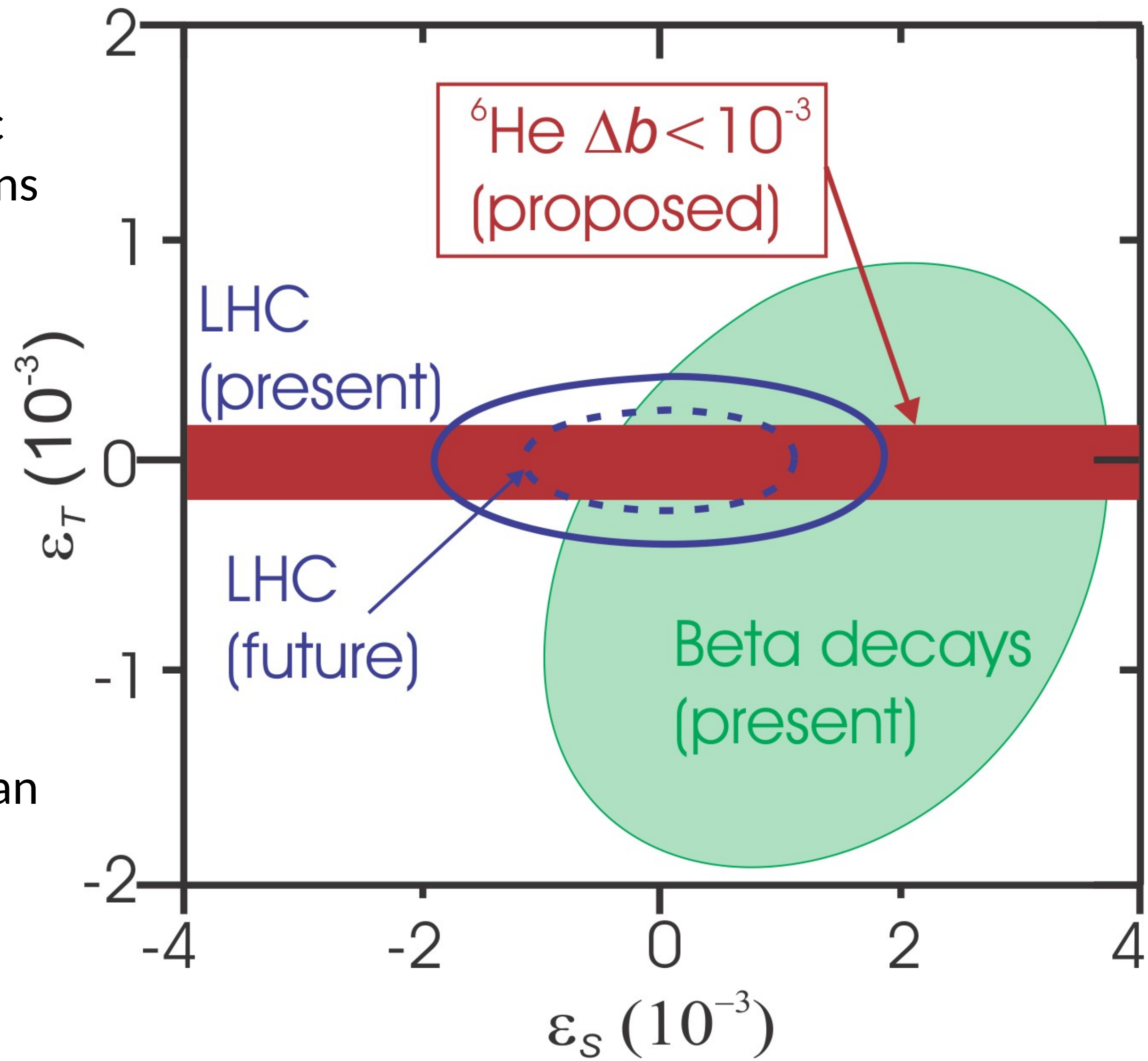
Introduction/Caveats

- We are building a new cyclotron radiation spectroscopy (CRES) experiment
- The CRES technique was developed by the Project8 collab. for neutrino masses in ^{3}H
- Our setup will work for ^{6}He, ^{19}Ne sources at CENPA
- I’m an experimentalist; won’t go into fundamental physics/ EFT energy scales
- I don’t know the future

New Physics Potential in ^{6}He Decay

- LHC currently searching for exotic (BSM) chirality-flipping interactions in weak sector
- High-precision beta-decay measurements are potentially competitive
- ^{6}He is primarily sensitive to BSM tensor interactions
- We believe the CRES technique can constrain b to within 10^{-4}

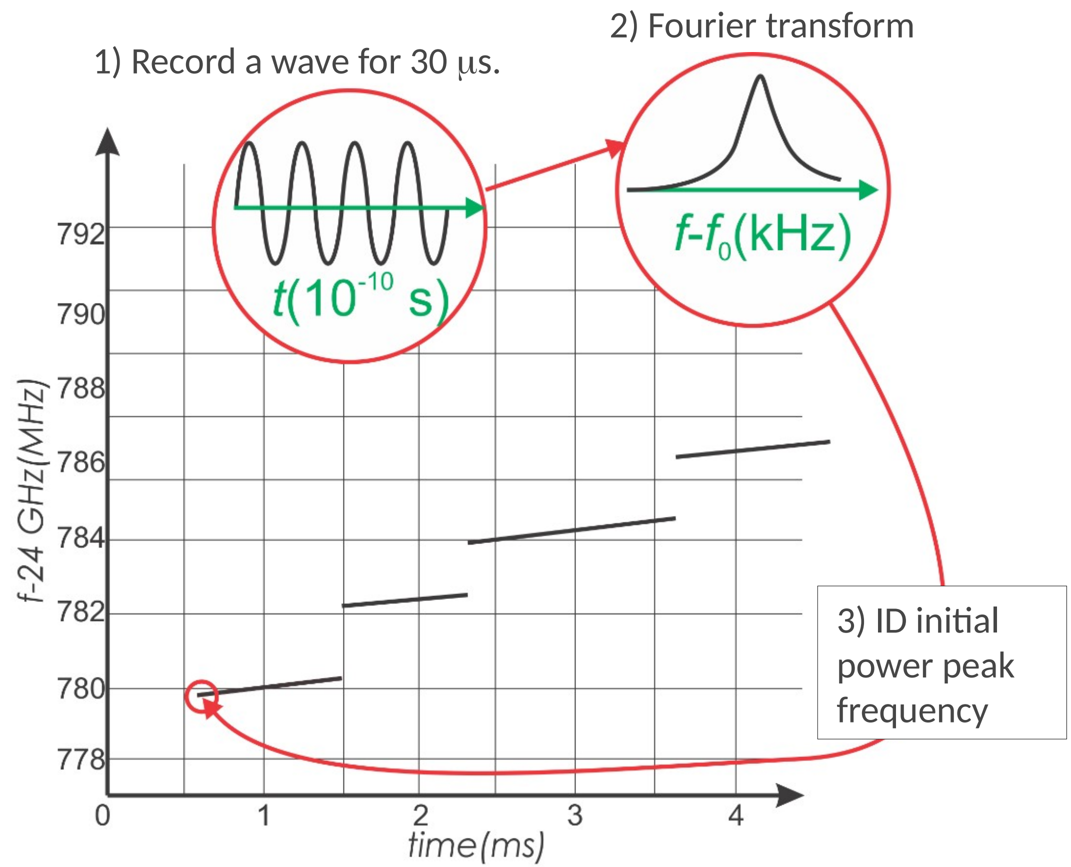


See also: M. Gonzalez-Alonso, O. Naviliat-Cuncic, and N. Severijns, *Prog. in Part. and Nuc. Phys.* 104, 165 (2019)

Overview of the CRES Technique

$$\omega_{cyclotron} = \frac{e\mathbf{B}}{\gamma m_e} = \frac{e\mathbf{B}}{m_e(1 + K/m_e c^2)}$$

- Measures beta energy at creation
- Avoids complicated energy-loss mechanisms
- Frequency-based measurement gives high-resolution
- **Magnetic trapping efficiency is energy independent**



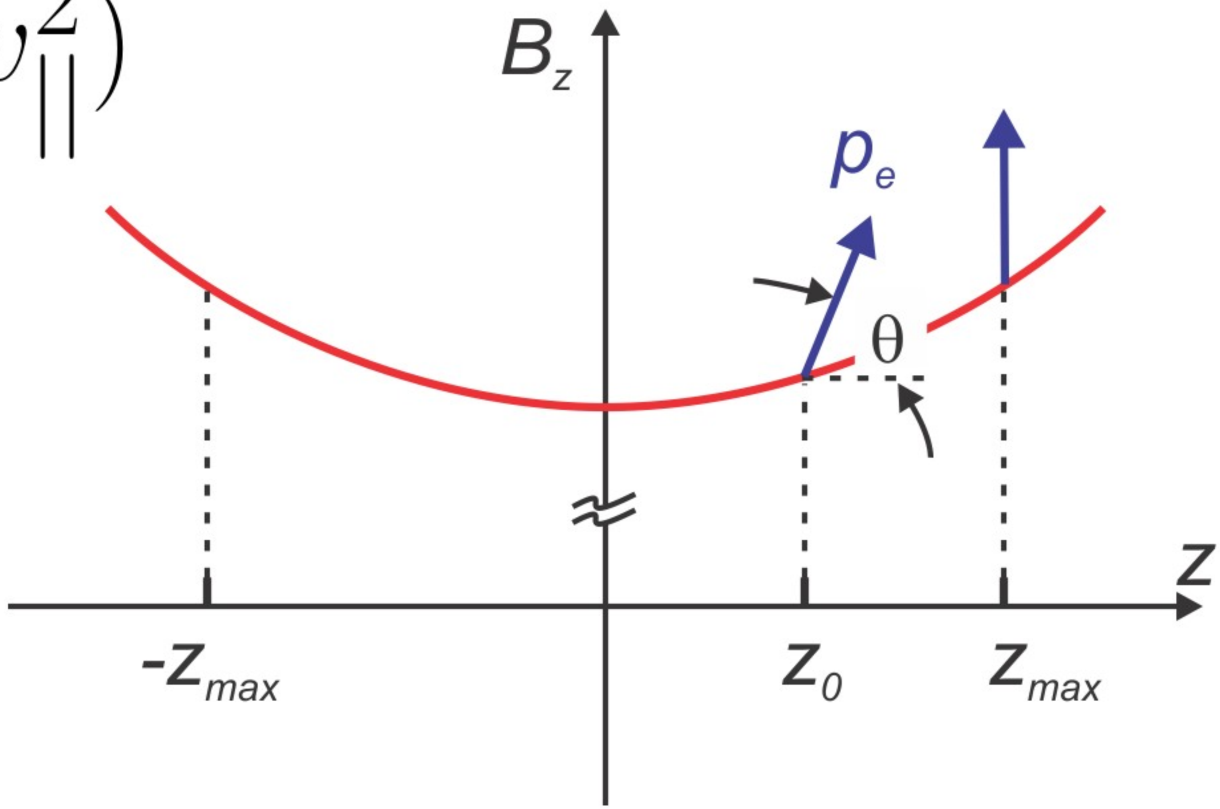
"Never measure anything but **frequency**!"

CRES Signal Attributes

$$\text{Trapping condition:} \frac{v_\perp}{v} = \sin(\theta_{min}) \geq \frac{B_{min}}{B_{max}}$$

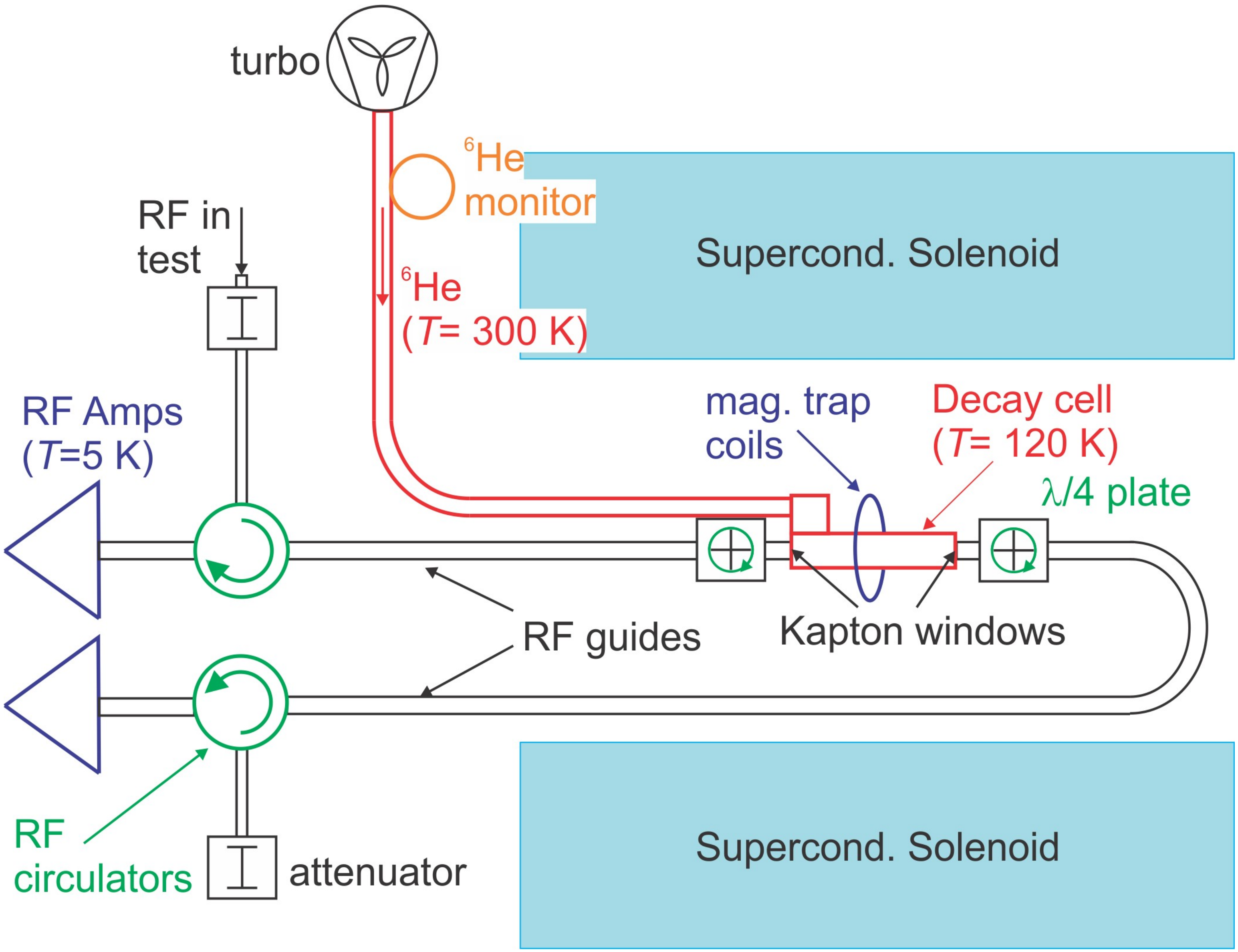
$$E = \frac{m_e}{2}(v_\perp^2 + v_{||}^2)$$

$$\mu = \frac{m_e v_\perp^2}{2B}$$

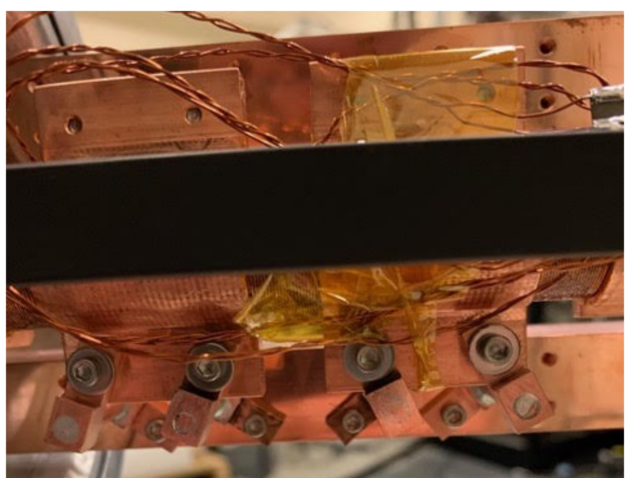


- The **pitch angle** is between the momentum and B_0 at the bottom of the trap

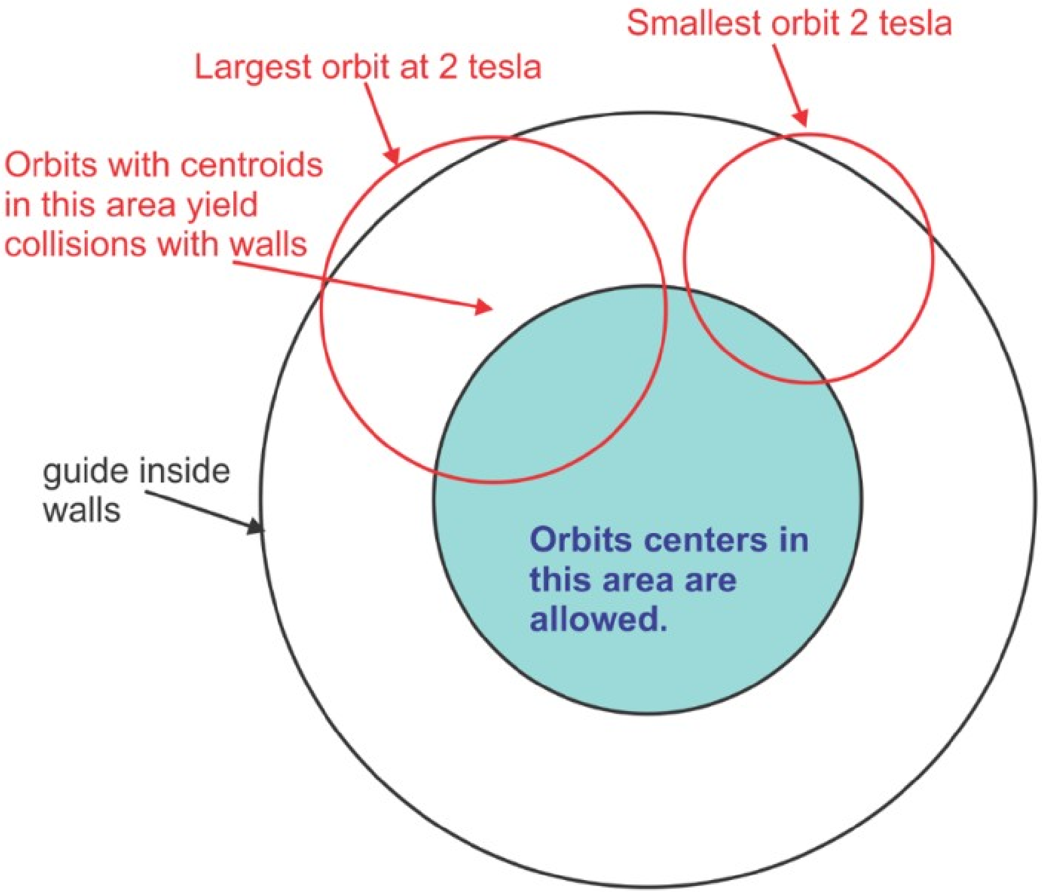
Outline of CRES Measurement



CRES Waveguide Apparatus



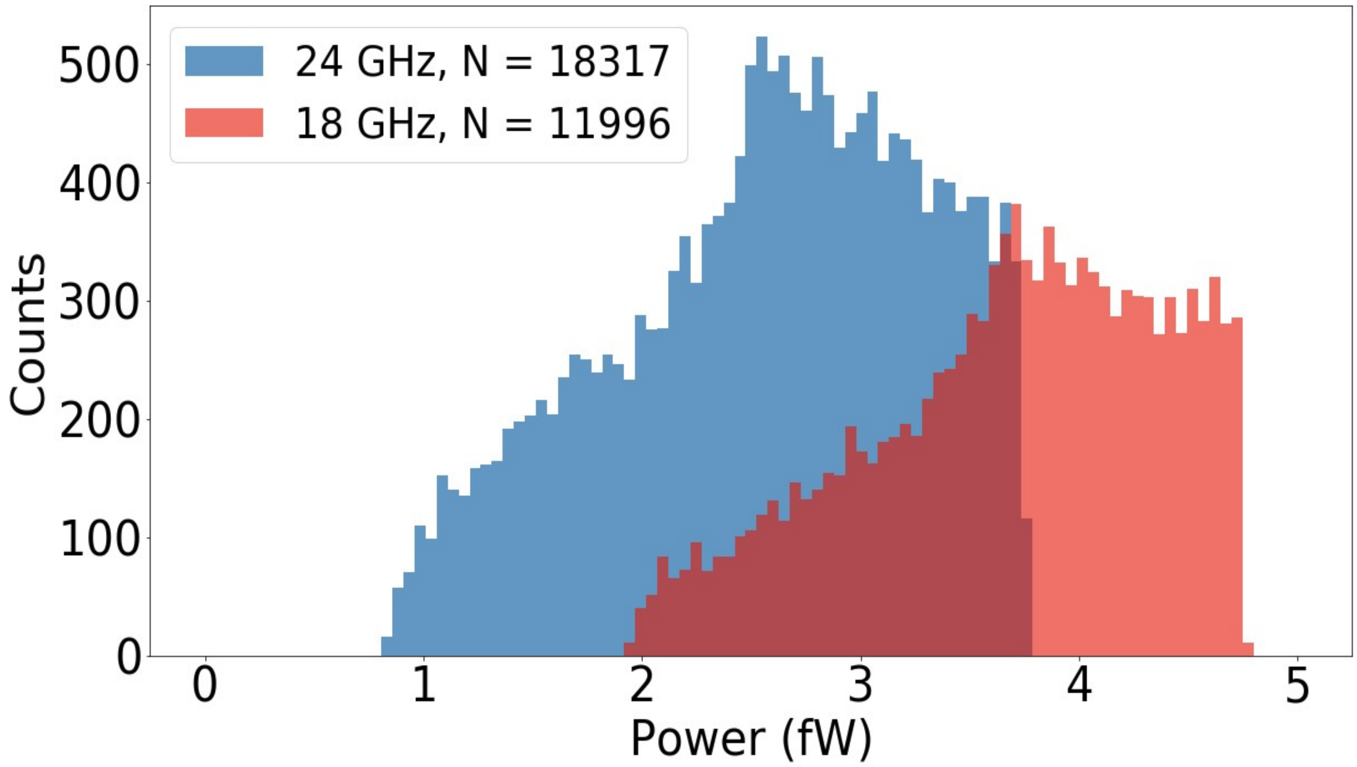
He6 CRES Signals and Trapping Efficiency



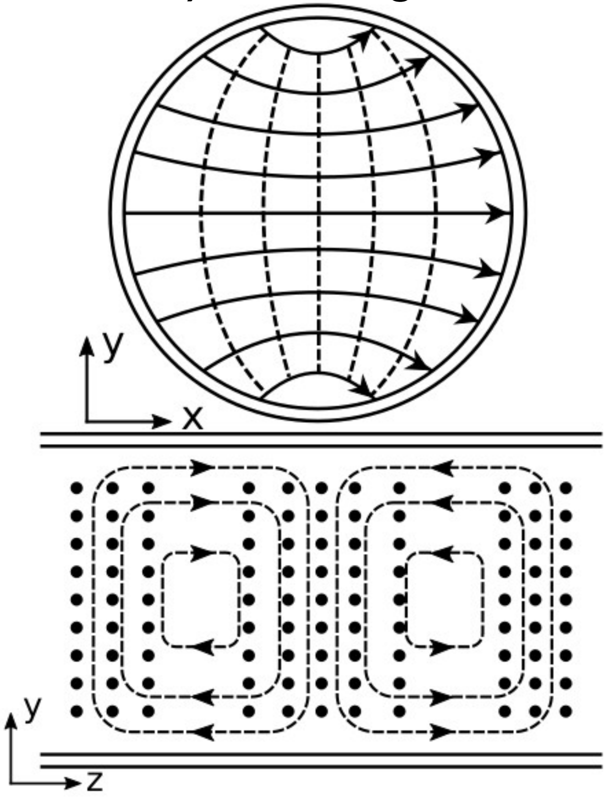
- Cyclotron radius is energy-dependent
- Electrons hitting the guide walls are instantly lost
- **If the guide radius is not well known, the distribution of trapped electrons will deviate from expectations**
- Trapping helium ions in the guide center would remove this uncertainty

He6 CRES Signal Power and Detection Efficiency

Distribution of simulated power in a 1.16 cm diameter cylindrical guide (B = 2 T)



Mode fields for cylindrical guide



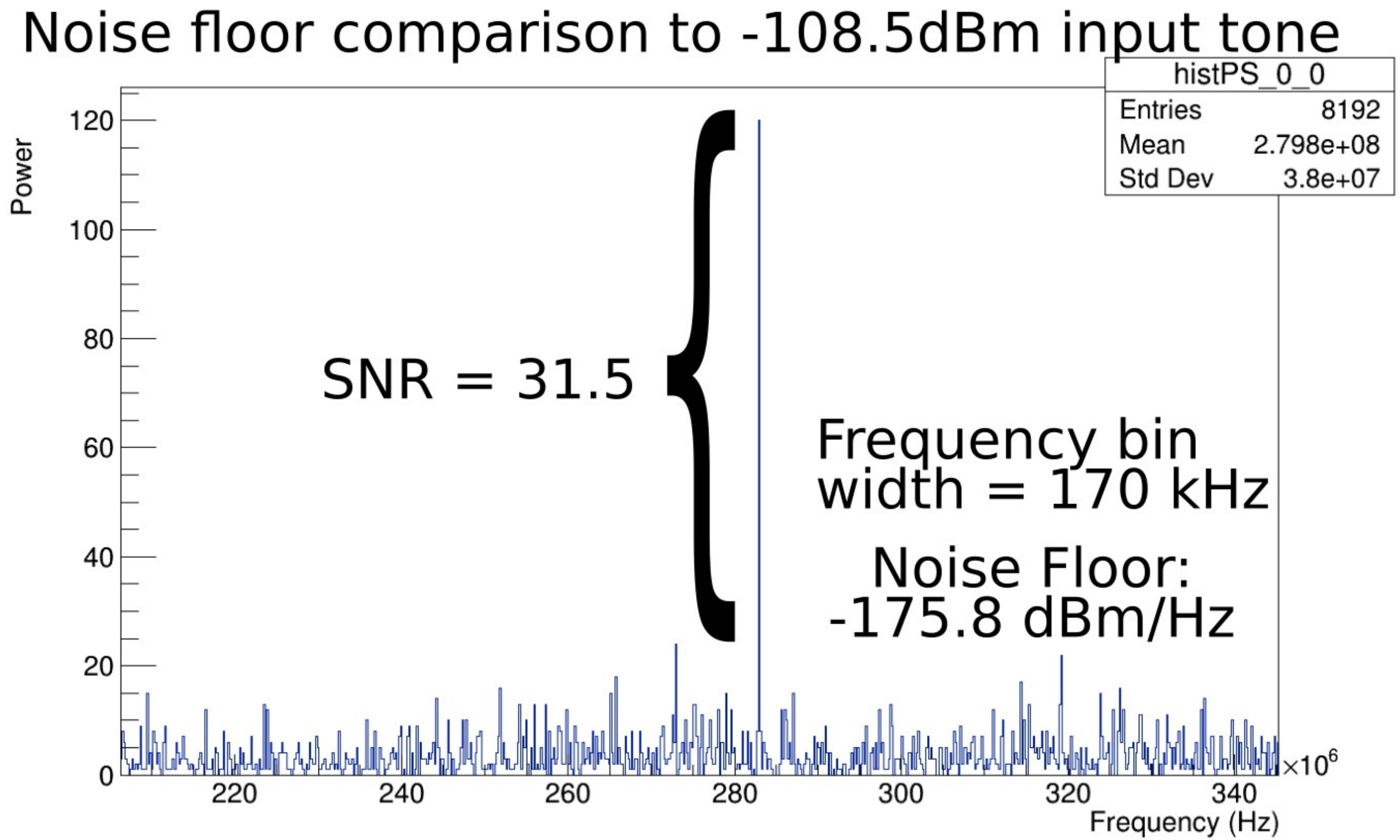
He6 CRES Noise Power

$$T_{cascade} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 \times G_2} + \cdots$$

Noise power/temp is highly dependent on temperature of first-stage amplifiers

Parameter	Value
Cryogenic first stage gain	32.0 dB
Second stage gain	52.4 dB
Estimated Source Power	1 fW = -120.0 dBm
Receiver Noise Temperature	39.1 K
Thermal Noise Power Density	-182.7 dBm/Hz
ADC Input Noise Power to 250 kHz FFT Channel	-45.4 dBm
ADC Input Signal Power	-35.6 dBm
SNR for Thermal Noise	9.6 dB
SNR for DAQ Quantization Noise (LSB = 2 mV)	14.6 dB

He6 CRES Noise Power



cf. -183 dBm/Hz noise target

=> SNR = 10 for 1 fW (-120 dBm) sig.

Data Acquisition (DAQ) System

- Based on ROACH2 system created by CASPER radio astronomy collaboration
- 2 x High-speed (5Gs/sec) analog-digital converters
  - 8-bit samples
  - 500 mV input range
  - => -50 dBm quant. Noise
- Vertex-6 FPGA capable of 10 GB/sec throughput
- Output power spectrum in 48 us, write to disk at ~250 MB/sec

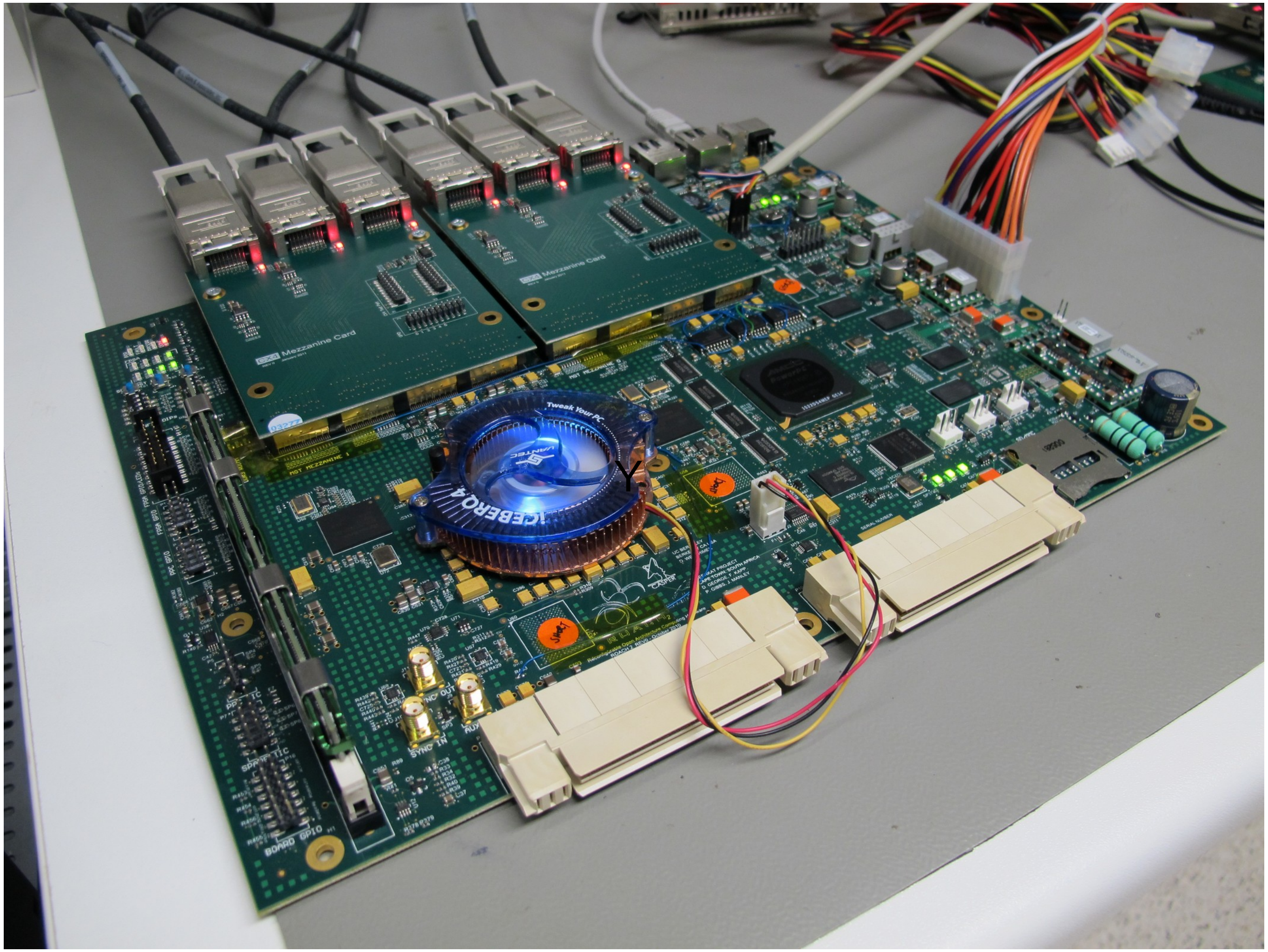
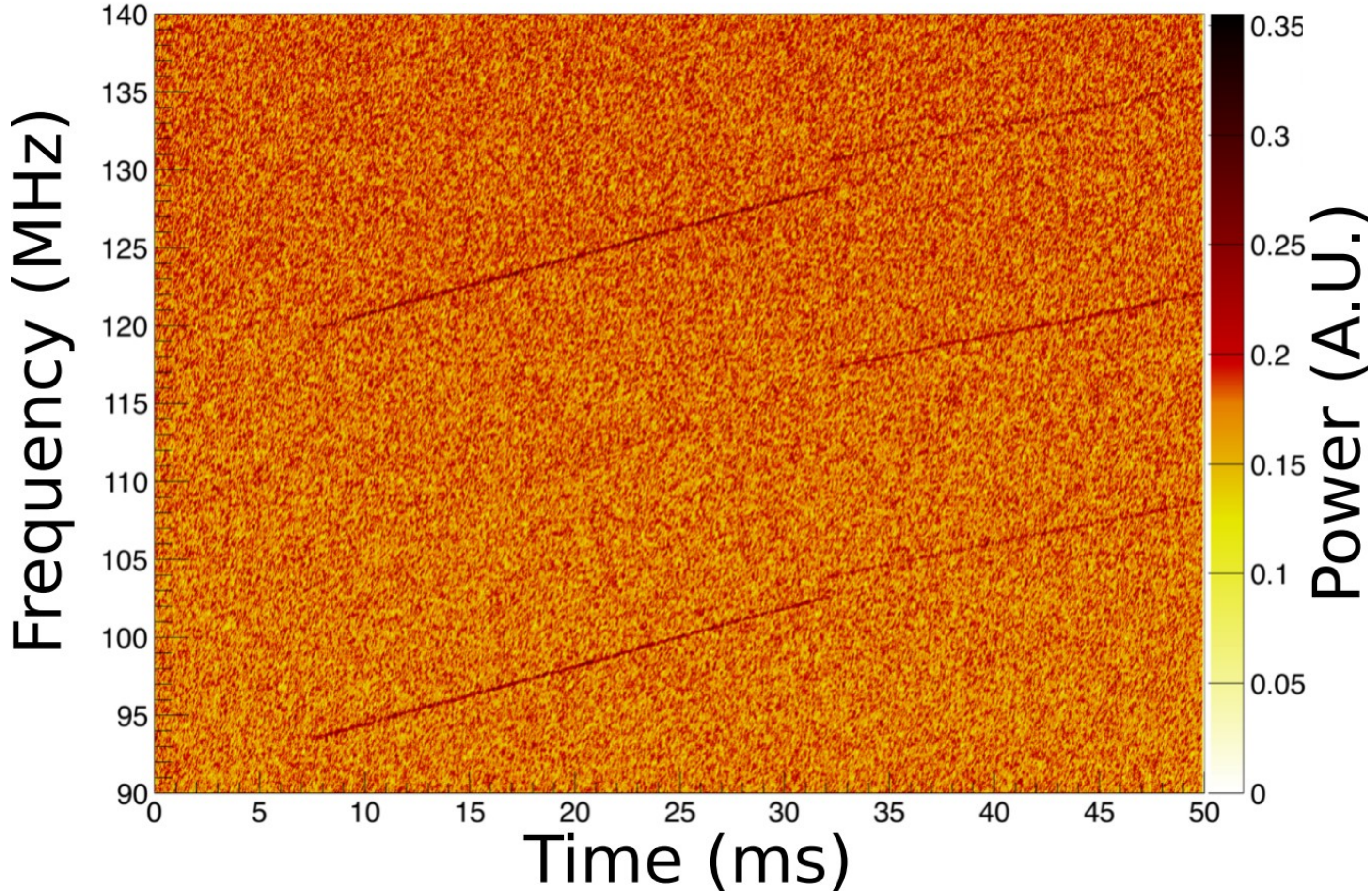


Image credit: CASPER collaboration
www.casper.berkeley.edu

Doppler Effect in CRES Signals

- Doppler sidebands siphon power from carriers, impacting detection efficiency
- Sidebands can also be misidentified as distinct events
- Gas scattering from high to low modulation index can bias identified events towards lower energy

$$\cos\left(2\pi f_c t + K\sin 2\pi f_a t\right) = \sum_{n=-\infty}^{n=\infty} J_n(K)\cos\left(2\pi\left(f_c + n f_a\right)t\right)$$



A. A. Esfahani, PhD Thesis, 2020

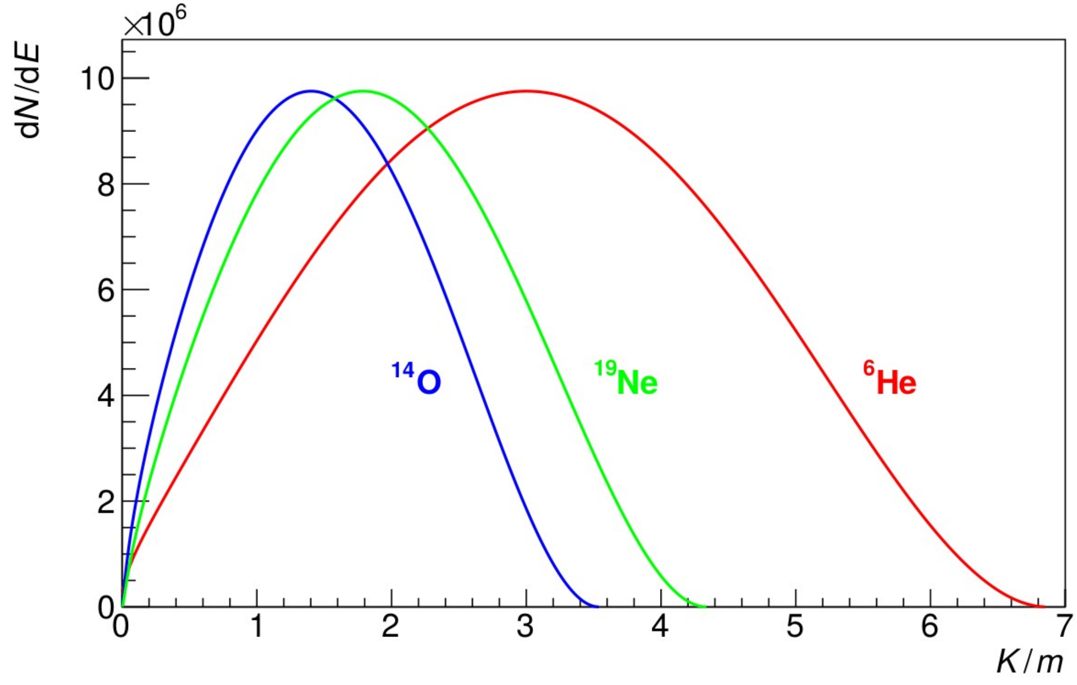
Doppler Effect: Signal Convolution

- Multiplying signals before FFTing introduces components at sum and diff frequencies

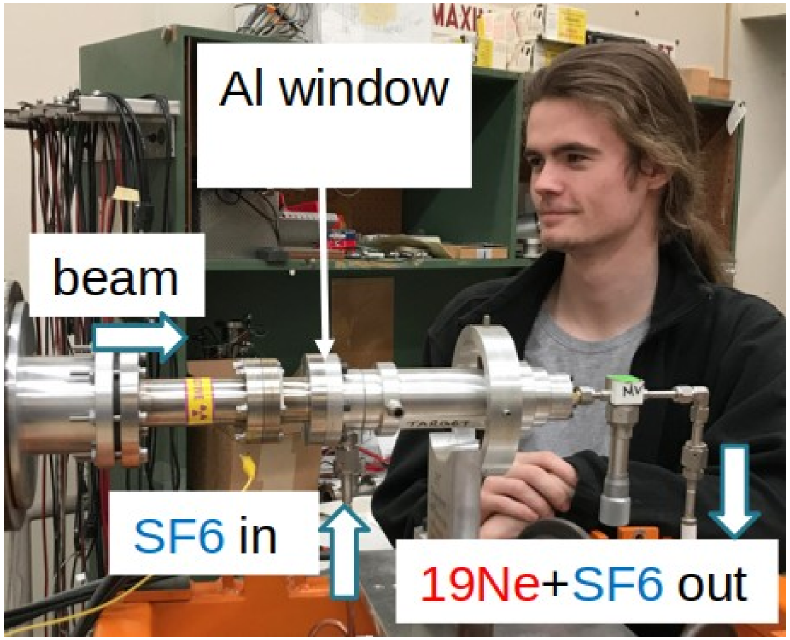
$$\cos(\omega_c+\Delta\omega)\cos(\omega_c-\Delta\omega) = \frac{1}{2}[\cos(2\omega_c)+\cos(2\Delta\omega)]$$

- Gets rid of sidebands
- Works across all carrier frequencies
- Not clear if the signal power cut is affordable

Future Directions



- Low-energy atomic exchange effects
- Reactor neutrino anomaly
- Neon 19 source
- Oxygen 14 scalar component sensitivity



Conclusions

- ^6He is a useful system to look for BSM physics/tensor couplings in the weak sector
- Magnetic trapping + frequency based detection used in CRES technique offers unprecedented precision in individual event energy reconstruction
- We have developed a receiver chain + DAQ system capable of taking RF signals at -120 dBm from 18-20 GHz and computing 2GHz FFT in real-time
- Taking data in the frequency domain helps maximize bandwidth without introducing data rate problems
- Averaging frequency-domain data helps improve SNR
- Doppler shift of particle in harmonic potential is a substantial problem; can be overcome at the cost of reduced SNR

He6CRES Collaboration

University of Washington CENPA: W. Byron, A. Garcia, G. Garvey, B. Graner, H. Harrington, M. Higgins, N. Hoppis, K. Knutsen, R.G.H. Robertson, G. Rybka, H.E. Swanson, R. Zite

Argonne National Lab: P. Mueller, G. Savard

North Carolina State University: A. Allen, D. Combs, L. Hayen, D. Stancil, R.J. Taylor, A. Young

Pacific Northwest National Laboratory: N. Oblath, J. Tedeschi, B.A. Vandevender, X. Huyan

Tulane University: F. Wietfeldt

Johannes Gutenberg-Universität Mainz: M. Fertl

Texas A&M University: D. McClain, D. Melconian