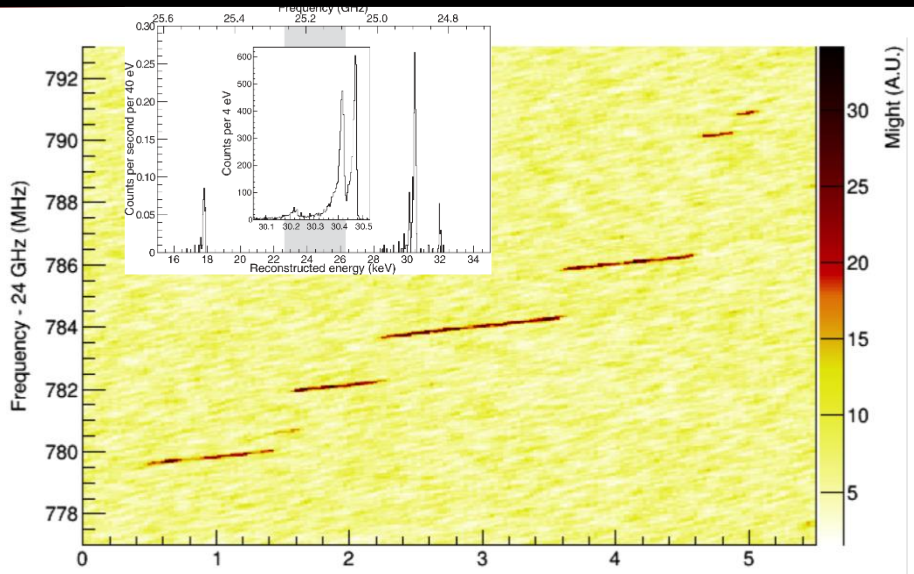
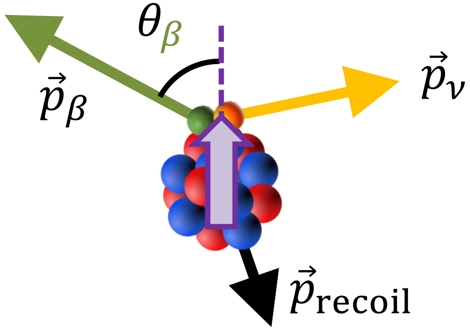
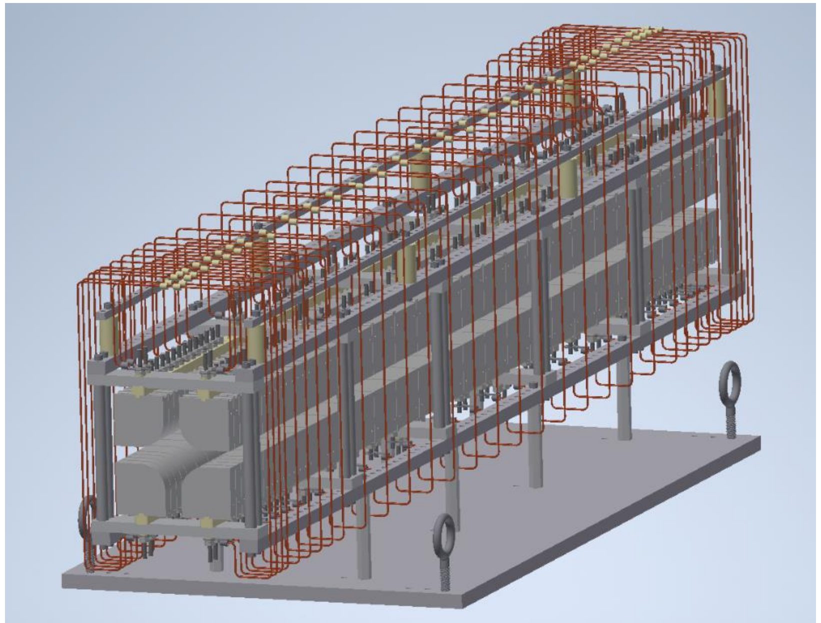
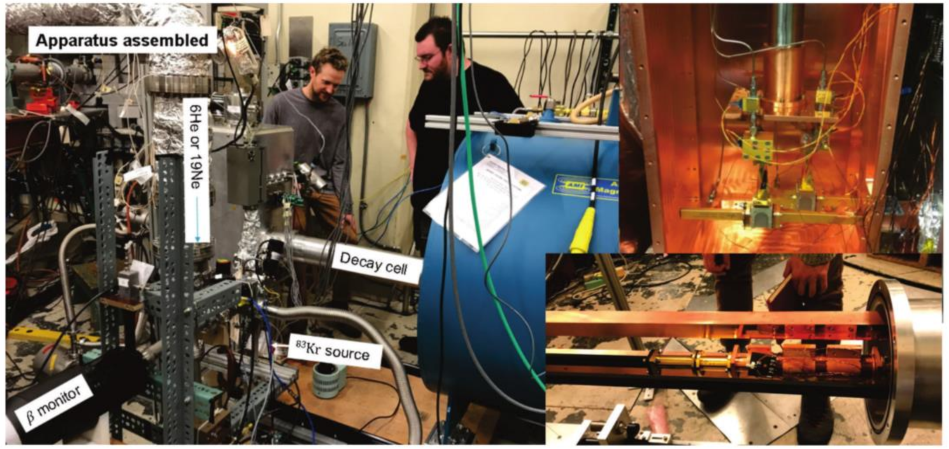
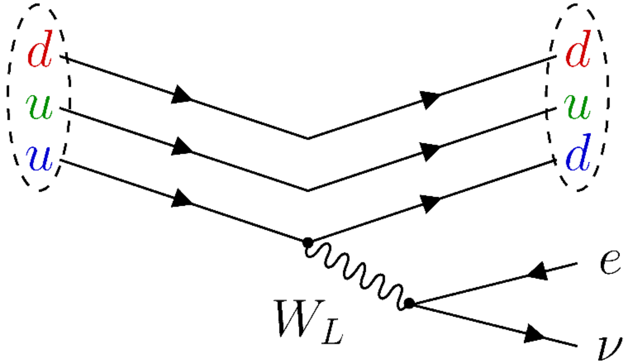
Towards measuring the Fierz interference parameter in ^{6}He β decay from a Penning trap using the CRES technique

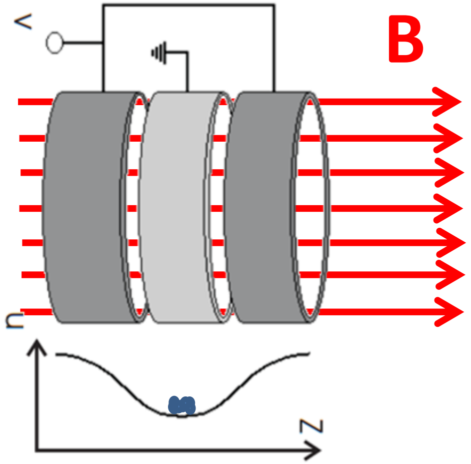






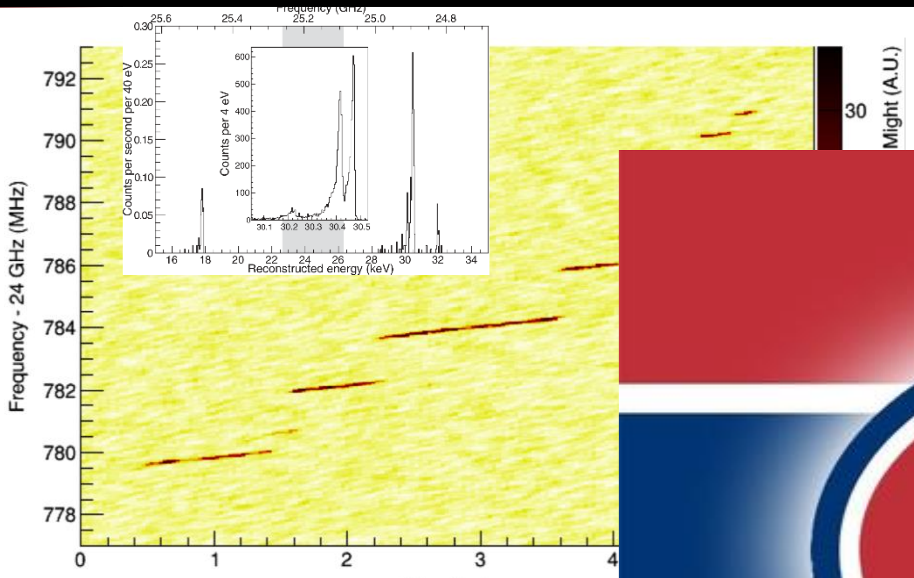


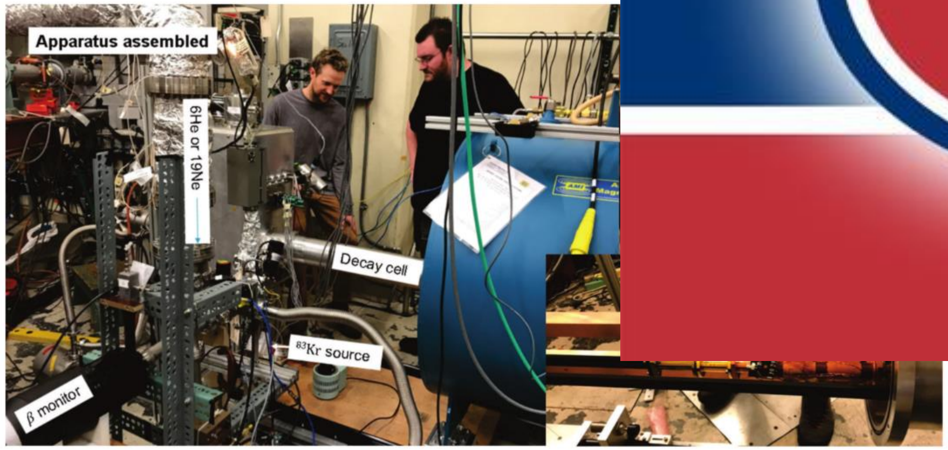


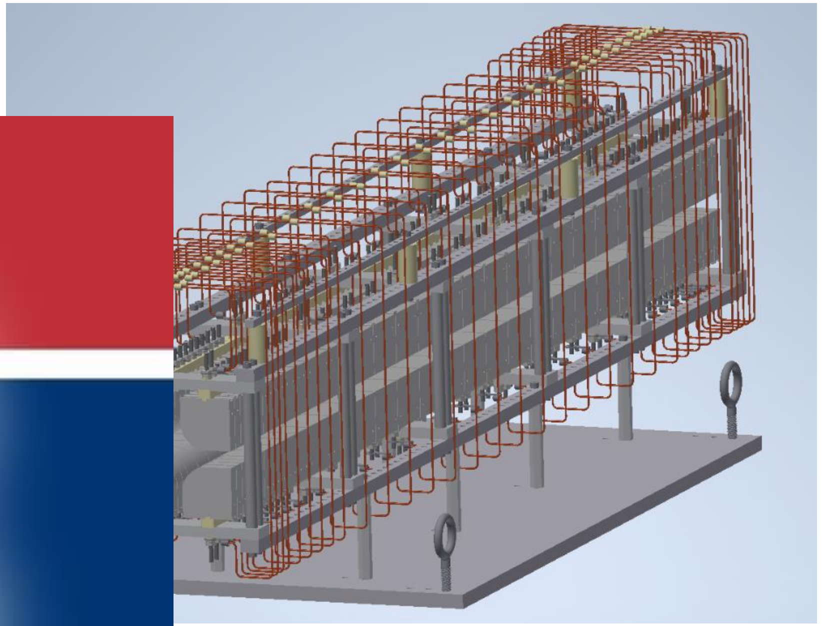


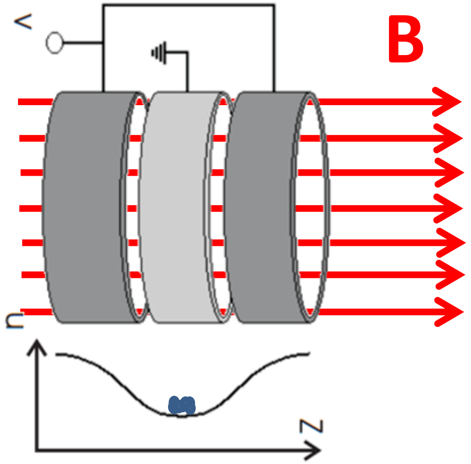
Dan Melconian – CAP Congress, June 2021

Towards measuring the Fierz interference parameter in ^{6}He β decay from a Penning trap using the CRES technique









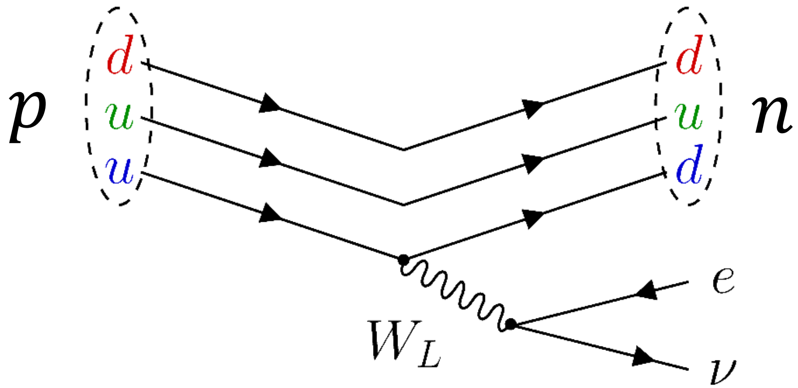
Dan Melconian – CAP Congress, June 2021

Outline

- **Introduction**
  - Testing the standard model via the precision frontier
  - The Fierz interference parameter
- **The CRES technique**
  - Great idea, Project-8!
  - Cyclotron radiation emission spectroscopy offers unbelievable precision
- **Current status and recent accomplishments**
  - Set up at CENPA/UW
  - Source measurements with $^{83m}\mathrm{Kr}$
- **Looking forward: upgrading to a Penning trap**
  - Why? To avoid wall effects: $\Delta b = 10^{-3} \rightarrow 10^{-4}$
  - Cooler/buncher design

The standard model and beyond

- This is the standard model:



pure $V - A$ interaction

$$H_\beta = \bar{p}\gamma_\mu n(C_V \bar{e}\gamma^\mu \nu + C_V' \bar{e}\gamma^\mu \gamma_5 \nu) - \bar{p}\gamma_\mu\gamma_5 n(C_A \bar{e}\gamma^\mu\gamma_5 \nu + C_A' \bar{e}\gamma^\mu \nu)$$

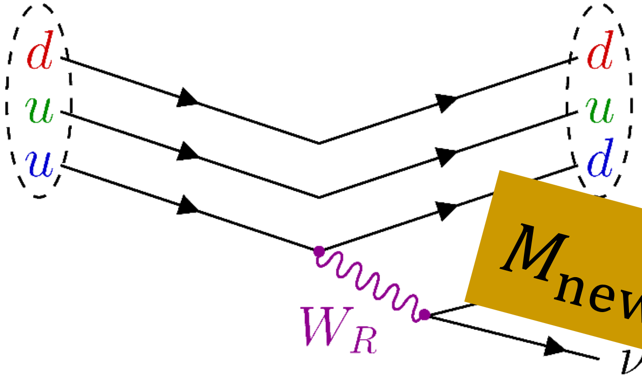
$$C_V = C_V' = 1$$

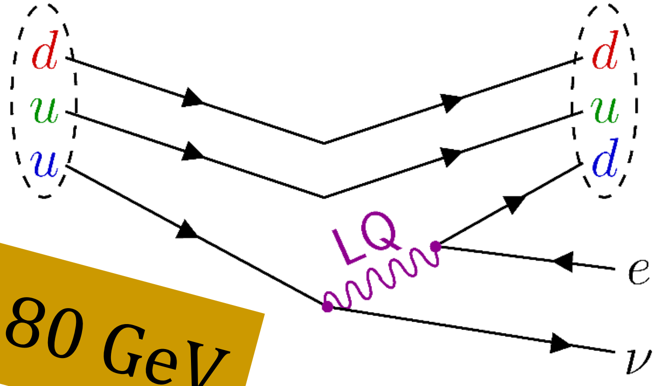
$$C_A = C_A' \approx 1.27$$

$$M_W = 80.385 \text{ GeV}$$

- These are not:

Right-handed bosons, or scalar/tensor leptoquarks, or SUSY, or…





$M_{new} \gg 80$ GeV

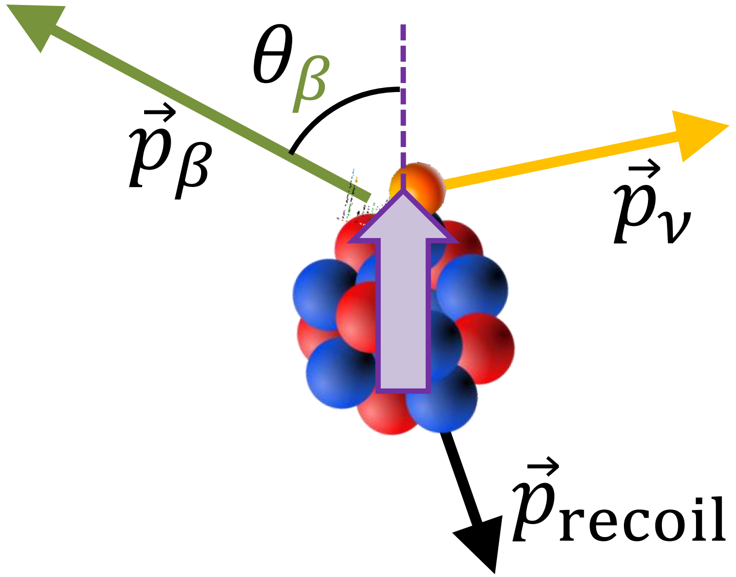
$C_i \neq C_i'$

$C_S, C_T \neq 0$

- Profumo, Ramsey-Musolf, Tulin, Phys. Rev. D **75**, 075017 (2007)
- Vos, Wilschut, Timmermans, Rev. Mod. Phys. **87**, 1483 (2015)
- Bhattacharya *et al.*, Phys. Rev. D **94**, 054508 (2016)

The precision frontier

- Goal:
  - To complement high-energy experiments by pushing the precision frontier
  - Angular distributions of β decay: values sensitive to new physics



- Global gameplan:
  - Measure parameters of β-decay
  - Compare to SM predictions
  - Look for deviations ⇔ new physics
  - Precision of $\leq \mathbf{0.1\%}$ needed to complement other searches (LHC)

Naviliat-Cuncic and Gonzalez-Alonso, Ann Phys **525**, 600 (2013)
Cirigliano, Gonzalez-Alonso and Graesser, JHEP **1302**, 046 (2013)
Vos, Wilschut and Timmermans, RMP **87**, 1483 (2015)
González-Alonso, Naviliat-Čunčić and Severijns, Prog. Part. Nucl Phys **104**, 165 (2019)

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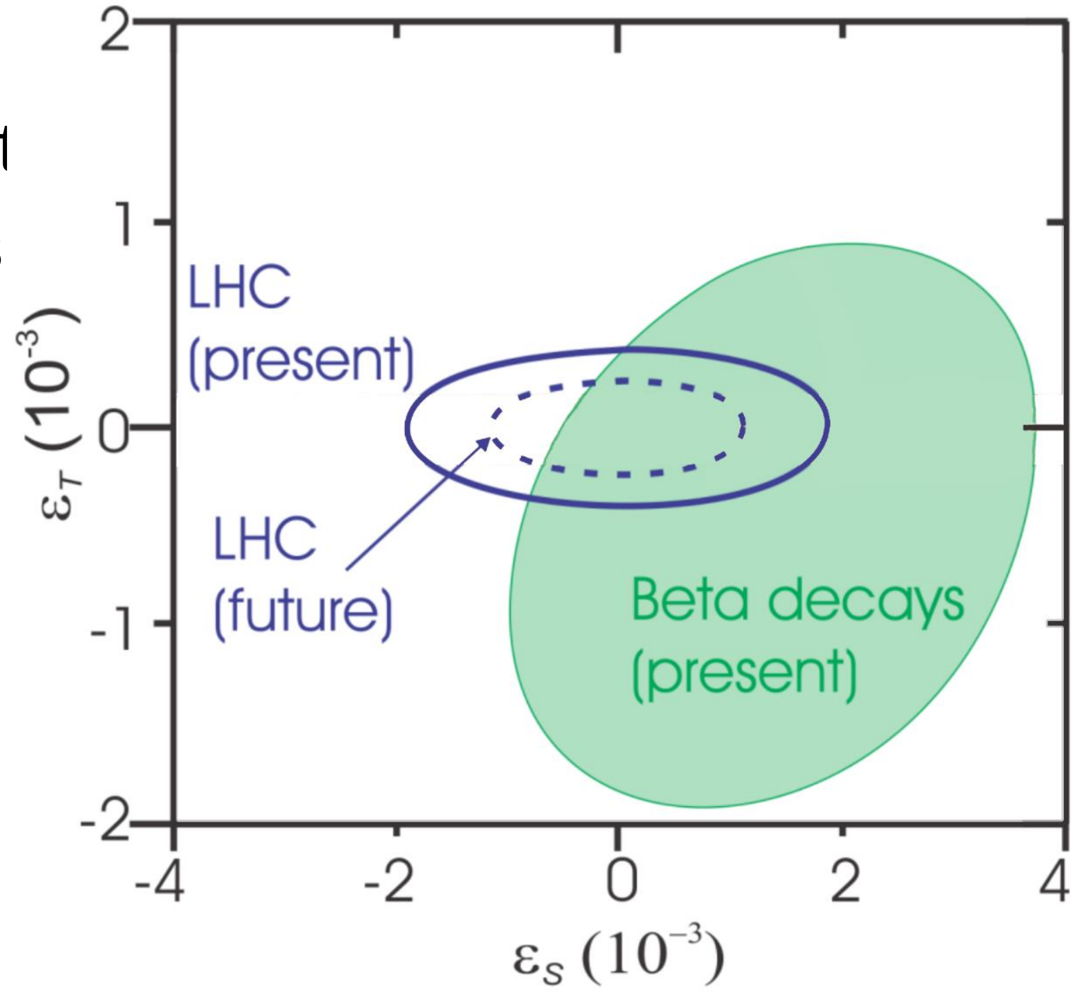

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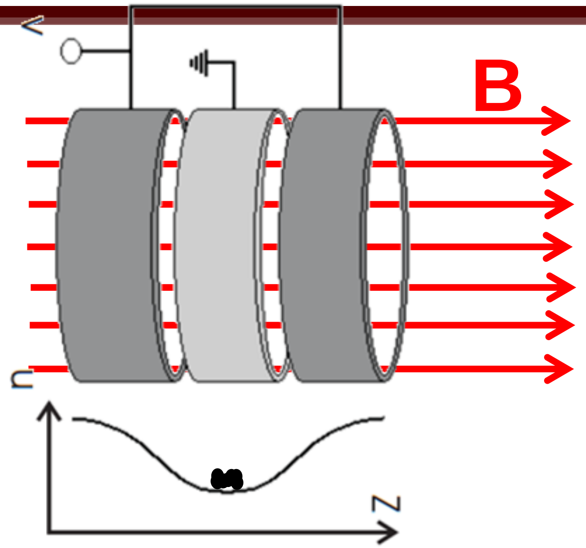
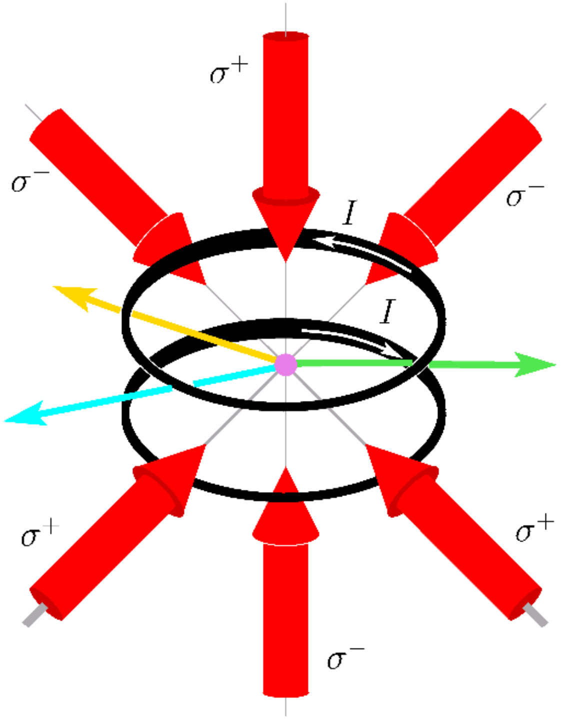
0.1% is a tall order…how to reach that precision?

- Ion traps
  - Can trap any ion; well-known for mass measurements (CPT, ISOLTRAP, JYFLTRAP, LEBIT, TITAN,…)
  - Beta-Decay Paul Trap @ ANL
    - β-ν correlation of ^{8}Li to 1%; poised to reach 0.1% precision
  - No other correlation experiments completed yet, but a number planned:
    - TAMUTRAP @ Texas A&M (^{20}Mg, ^{24}Si, ^{28}S, ^{32}Ar; ^{36}Ca, ^{40}Ti)
    - LPCTrap @ GANIL (^{6}He)
    - EIBT @ Weizmann Institute → SARAF (^{6}He to start)
    - NSLTrap @ Notre Dame (^{11}C, ^{13}N, ^{15}O, ^{17}F)
    - ^{6}He CRES @ CENPA/UW



- Magneto-optical traps
  - Atoms are cold and confined to a small volume
  - TRINAT @ TRIUMF (K isotopes)
  - ^{6}He @ CENPA/UW
  - NeAT @ SARAF (Ne isotopes)



^{6}He at UW

- Decay rate is: $dw = dw_0 \left[1 + a_{\beta\nu}\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\,\frac{\Gamma m_e}{E_e}\right]$
  - Most sensitive probe of new physics is the Fierz interference parameter
- ^{6}He is a great case!
  - Large endpoint (3.5 MeV)
  - 100% $0^+ \rightarrow 1^+\ \beta^-$ transition
  - Nuclear structure under control
  - Sensitive to tensor interactions

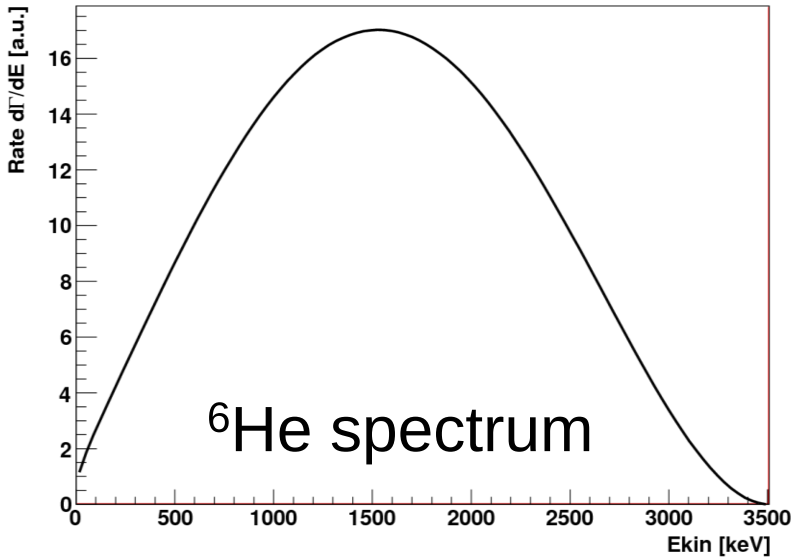
$$a_{\beta\nu} \approx -\frac{1}{3}\left(1 - \frac{C_T^2 + C'^2_T}{2C_A^2}\right)$$

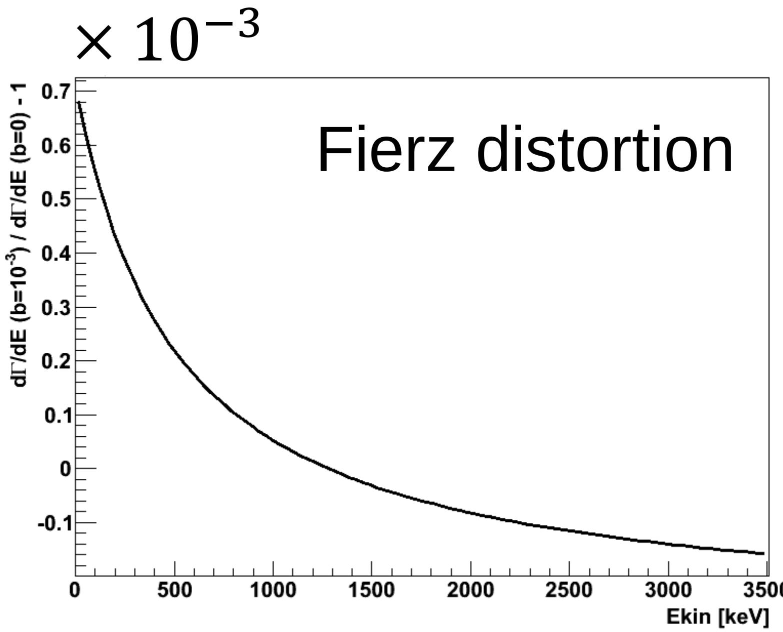
$\beta - \nu$ correlation

$$b \approx \pm\frac{(C_T + C_T')}{C_A}$$

Fierz interference

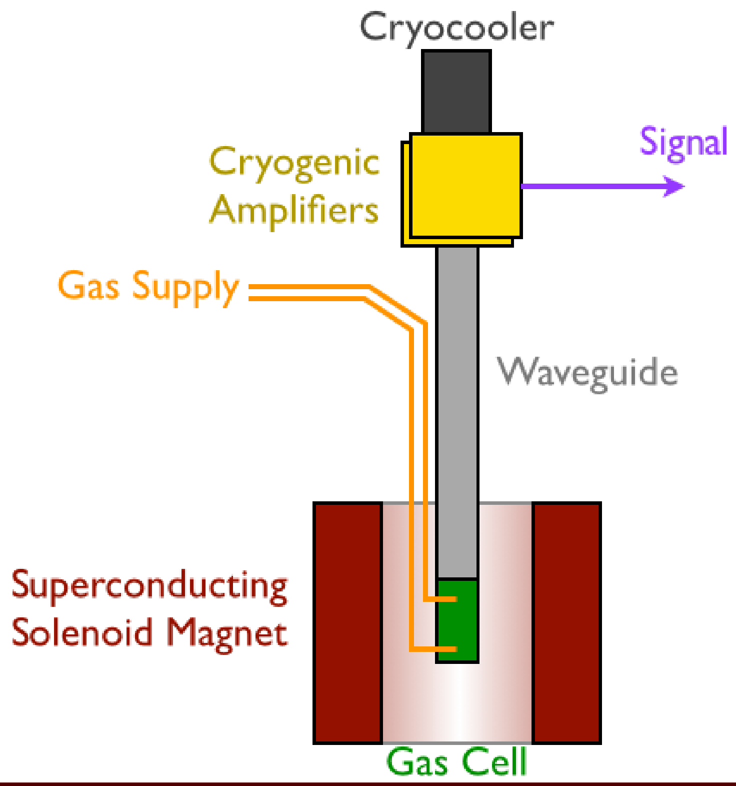
- Check signature by measuring ^{14}O and ^{19}Ne





^{6}He at UW – CRES technique

- New idea: use the Cyclotron Radiation Emission Spectroscopy (CRES) technique
  - Project 8 collaboration gets $\frac{\text{FWHM}}{E} \approx 10^{-3}$ resolution for conversion electrons of 18 – 32 keV

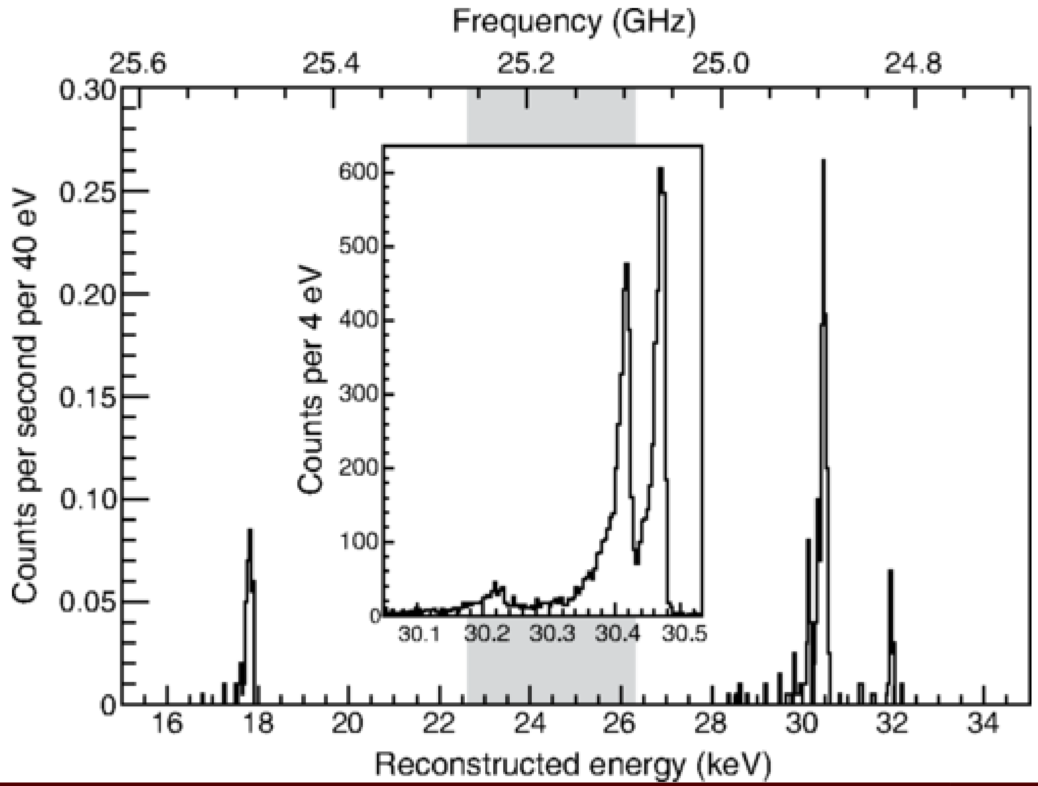


Selected for a Viewpoint in Physics
PRL 114, 162501 (2015) PHYSICAL REVIEW LETTERS week ending 24 APRIL 2015

Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

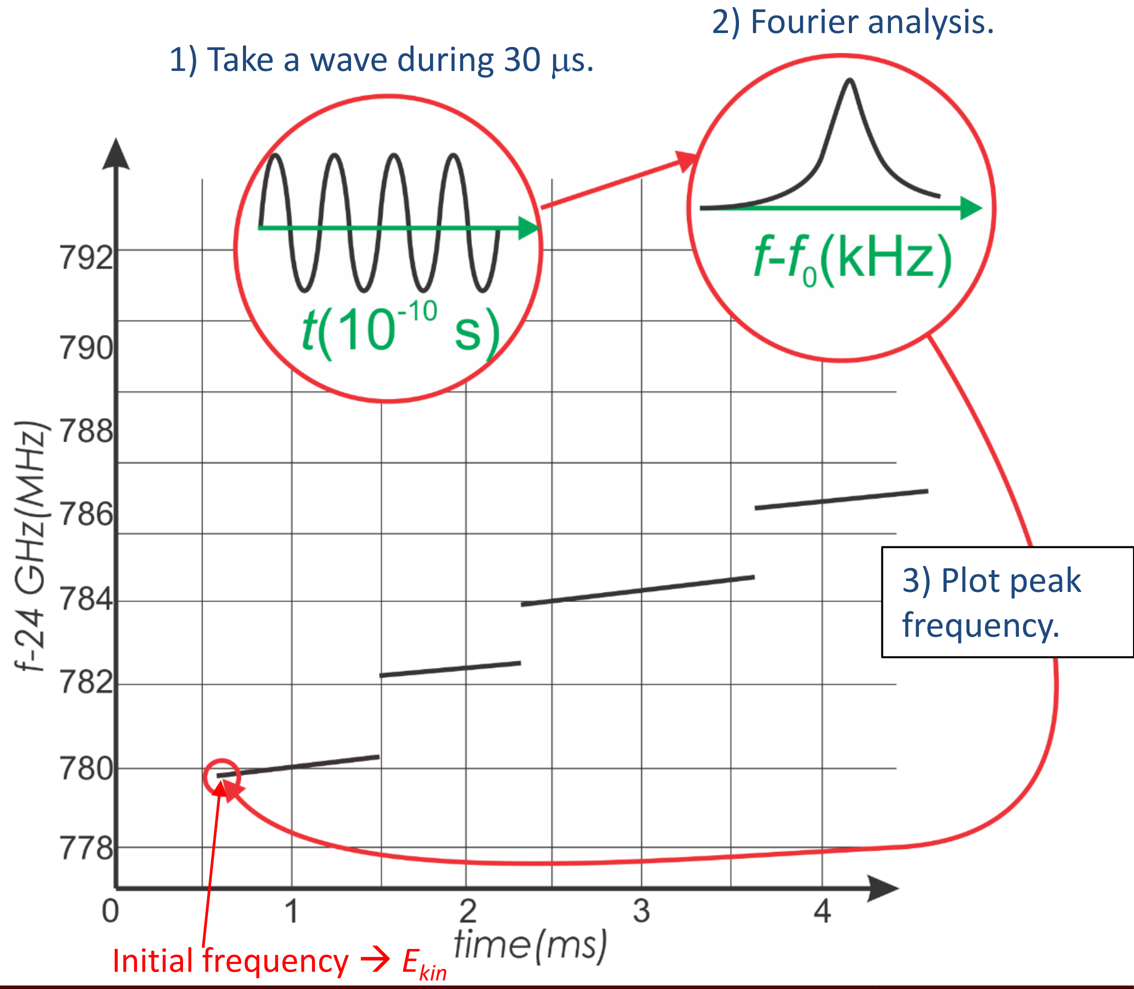
D. M. Asner,[1] R. F. Bradley,[2] L. de Viveiros,[3] P. J. Doe,[4] J. L. Fernandes,[1] M. Fertl,[4] E. C. Finn,[1] J. A. Formaggio,[5] D. Furse,[5] A. M. Jones,[1] J. N. Kofron,[4] B. H. LaRoque,[3] M. Leber,[3] E. L. McBride,[4] M. L. Miller,[4] P. Mohanmurthy,[5] B. Monreal,[3] N. S. Oblath,[5] R. G. H. Robertson,[4] L. J Rosenberg,[4] G. Rybka,[4] D. Rysewyk,[5] M. G. Sternberg,[4] J. R. Tedeschi,[1] T. Thümmler,[6] B. A. VanDevender,[1] and N. L. Woods[4]

(Project 8 Collaboration)



^{6}He at UW – CRES technique

- Why CRES for ^{6}He?
  - Measures β energy at creation, before complicated energy-loss mechanisms
  - High resolution allows debugging of systematic uncertainties
  - No background from photon or e scattering
  - ^{6}He in gaseous form works well with the technique
  - ^{6}He ion trap allows sensitivity higher than any other proposed
  - Counts needed not a big demand on running time



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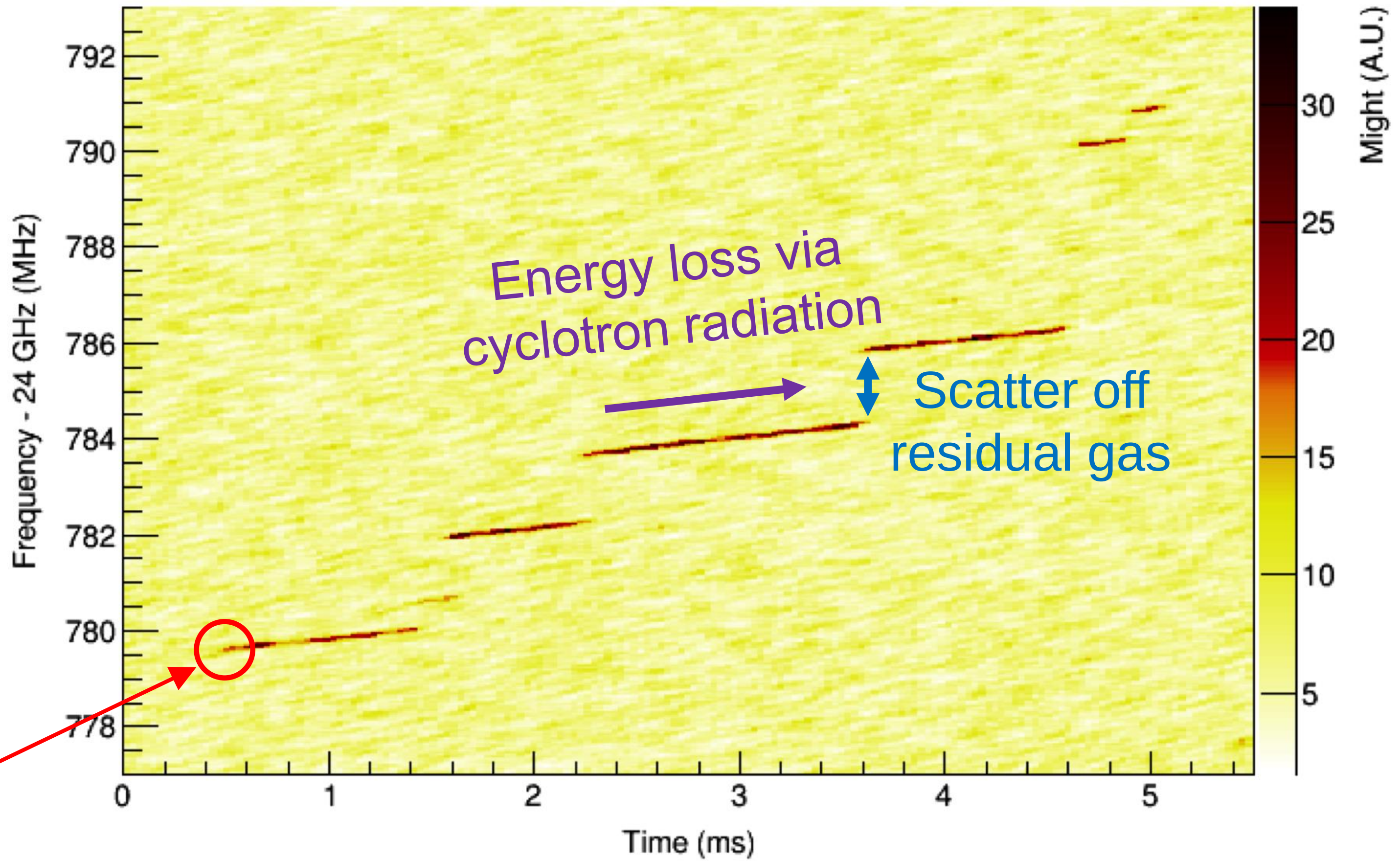
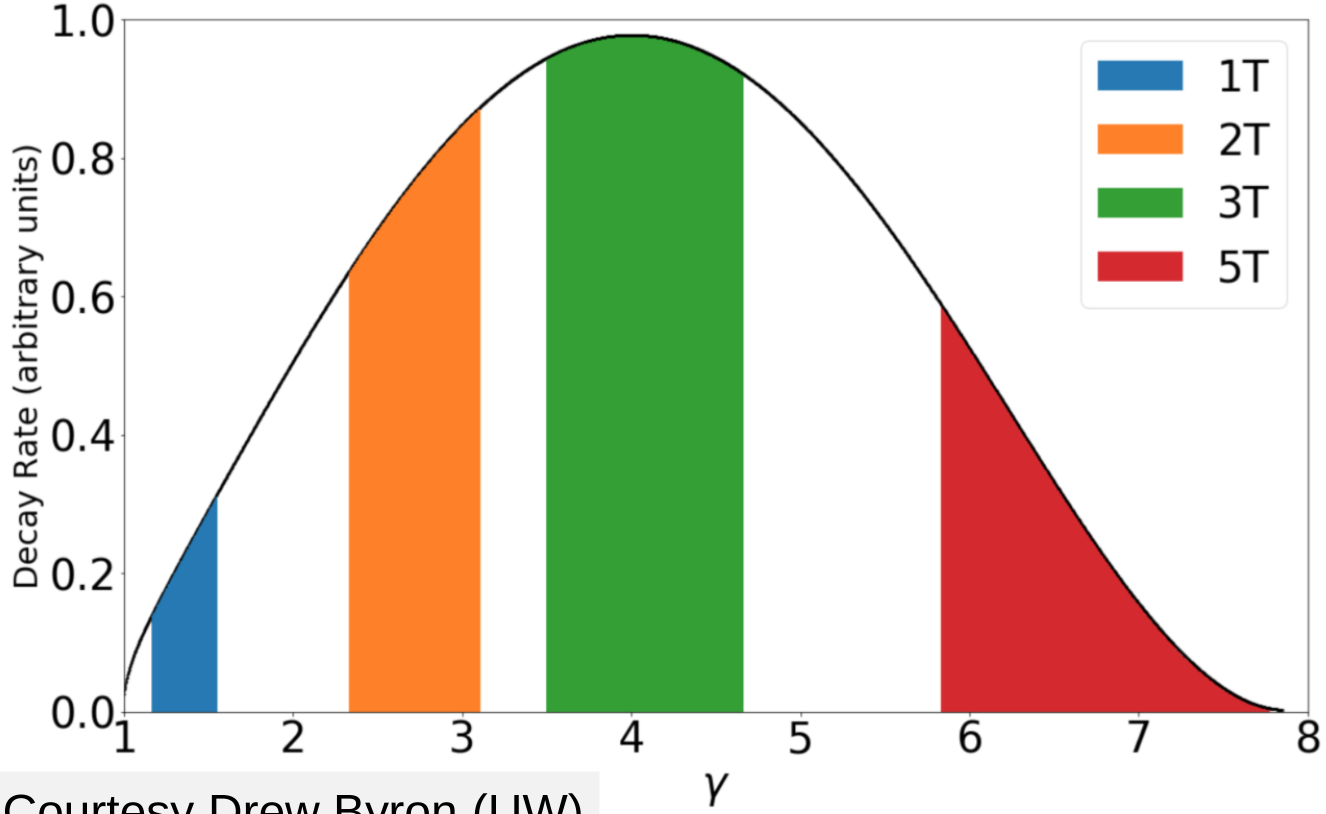
$$2\pi f = \frac{qB}{m + E_{\text{kin}}}$$

Initial frequency → E_{kin}



Bandwidth: a challenge beyond Project-8's m_ν search

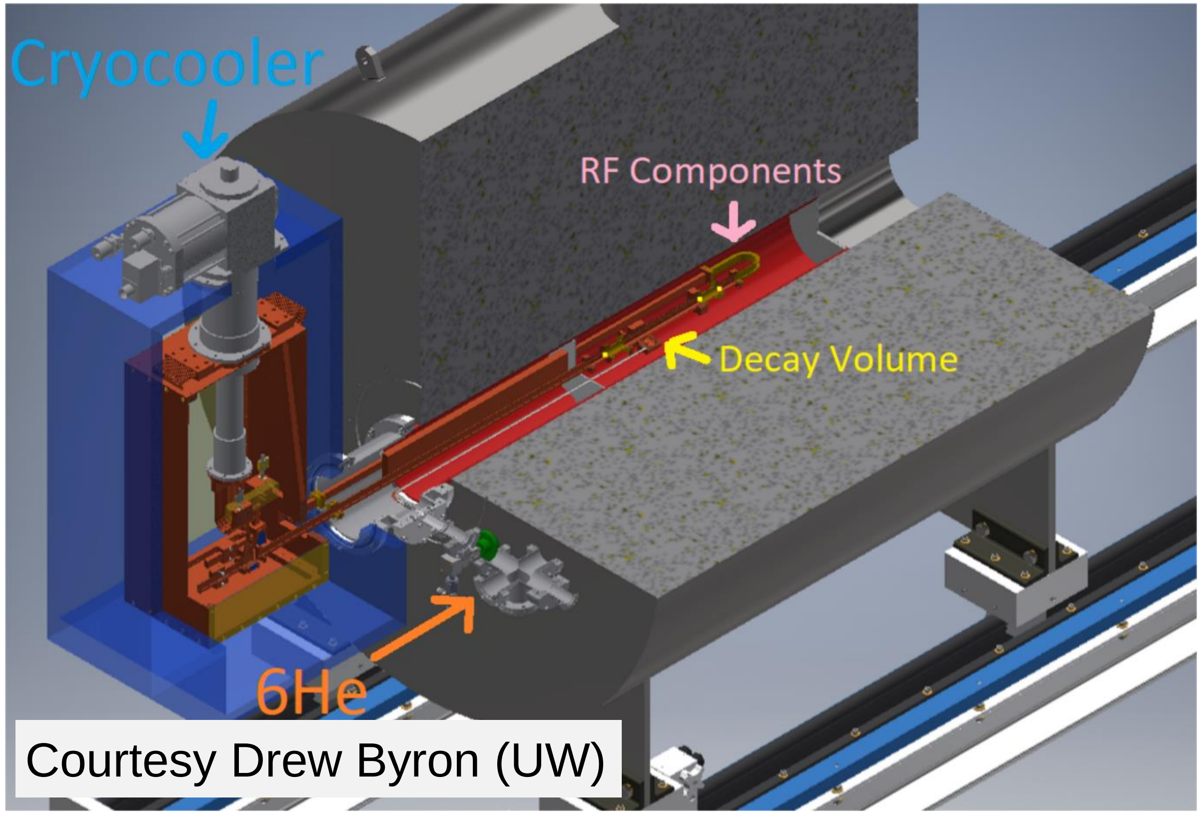
- The frequency bandwidth is limited
  - Currently have 1.2 GHz
  - Goal is 4.0 GHz
- We can set the magnet to different fields to sample different ranges in the energy spectrum:



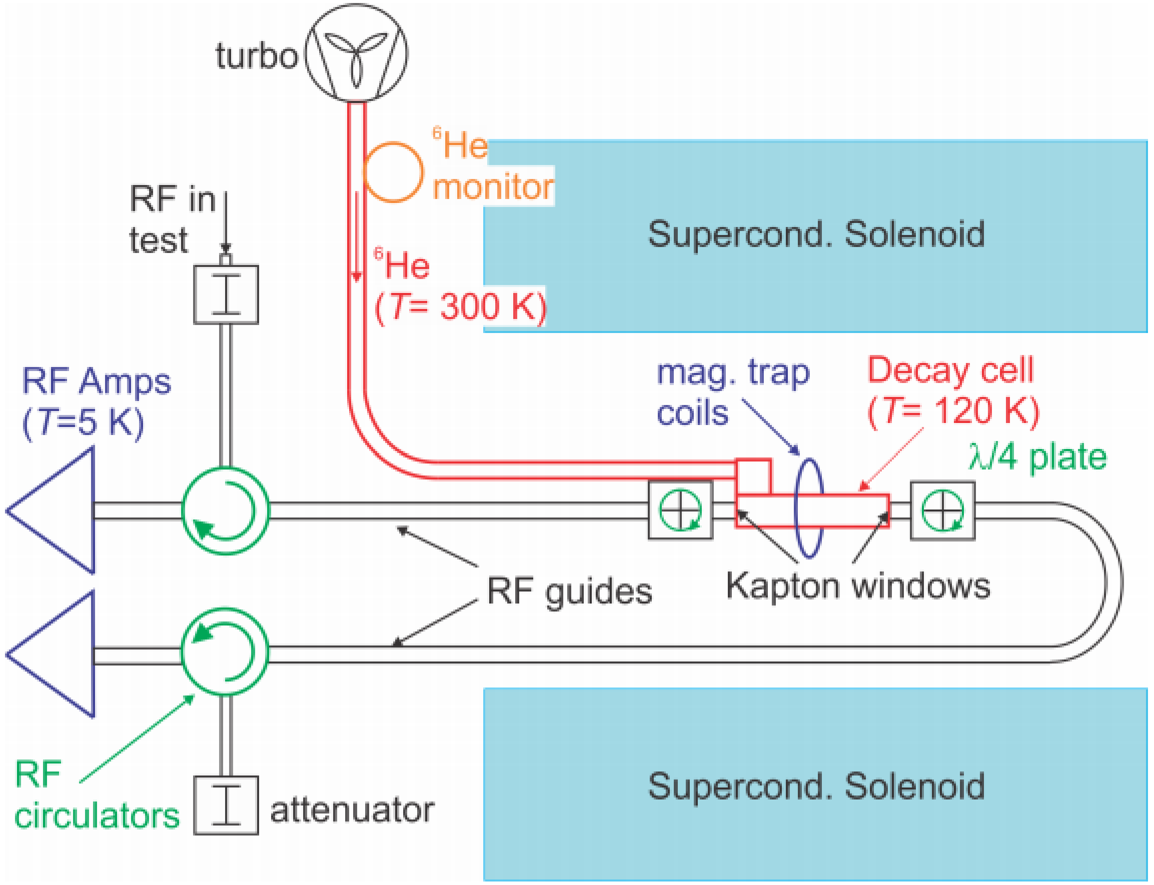
Courtesy Drew Byron (UW)

^{6}He little-*b* collaboration

- Phase I: proof of principle (present)
  - 2 GHz bandwidth
  - Show detection of cyclotron radiation from ^{6}He
  - Study power distribution

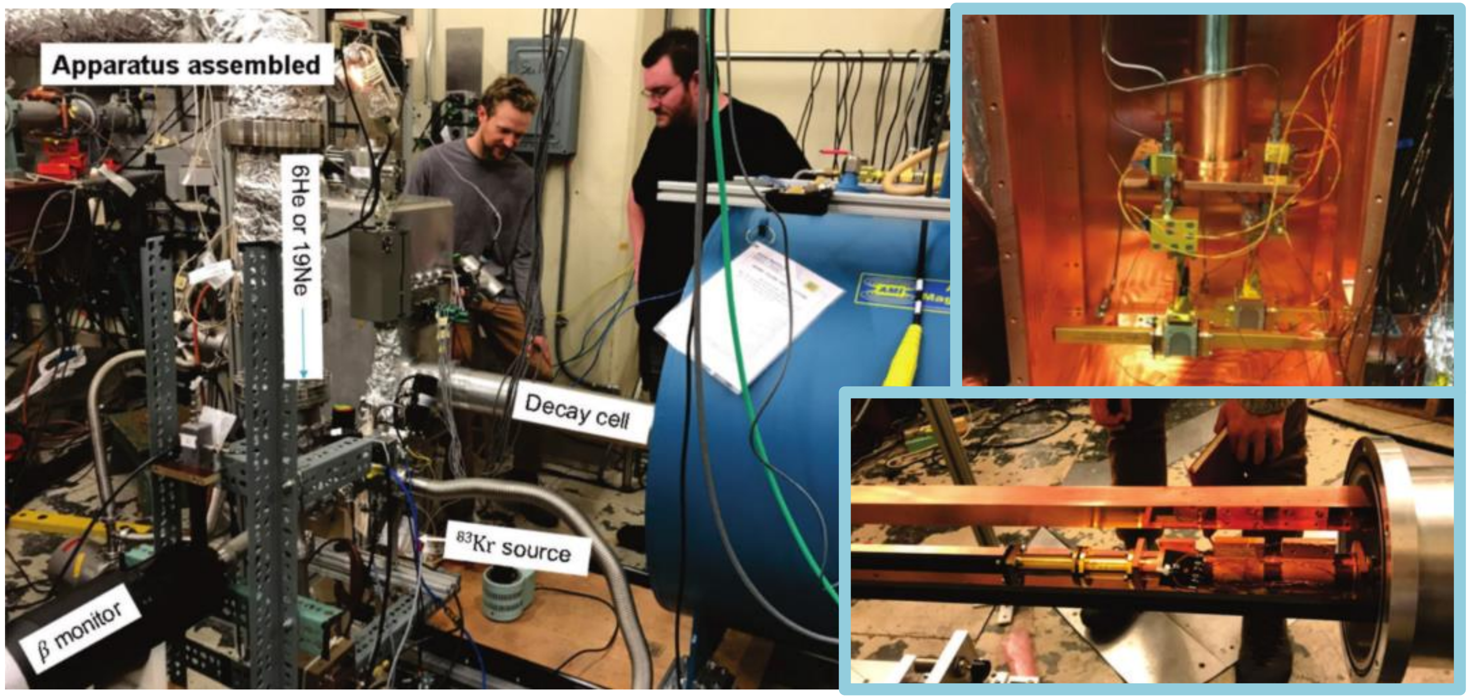


Courtesy Drew Byron (UW)



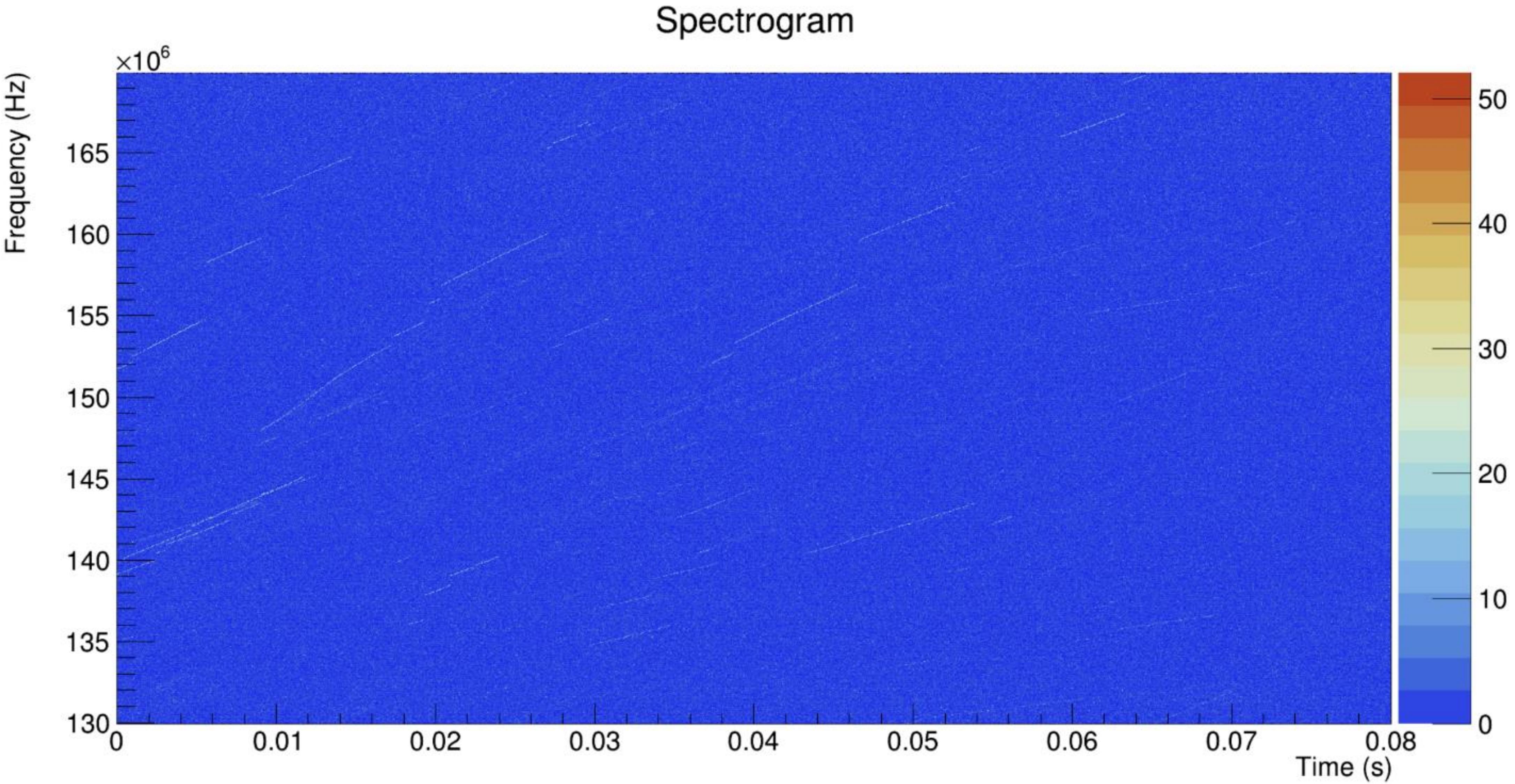
No time to describe in detail efforts to date

- Get DAQ working
- Assemble waveguide, rf readouts, cryocooler,…
- Vacuum system
- Ramping the magnet
- Test the rf; understand gain, noise and expected S/N of a 1 fW CRES signal



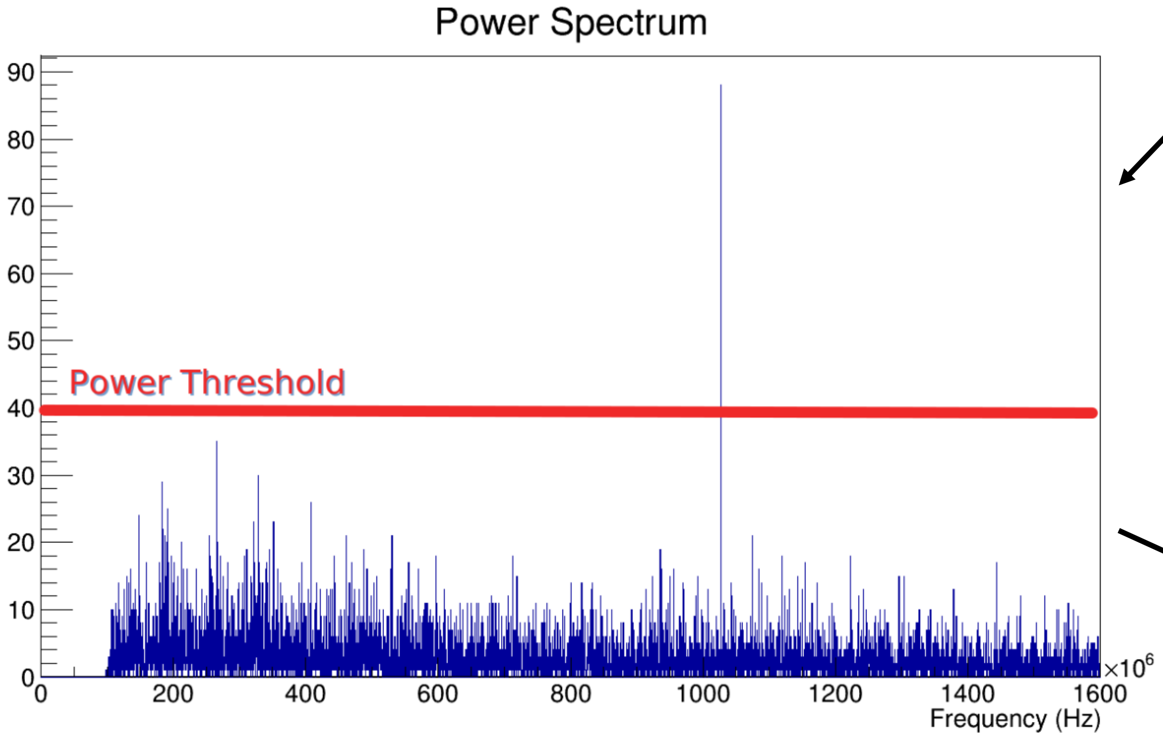
Success – just a few weeks ago!

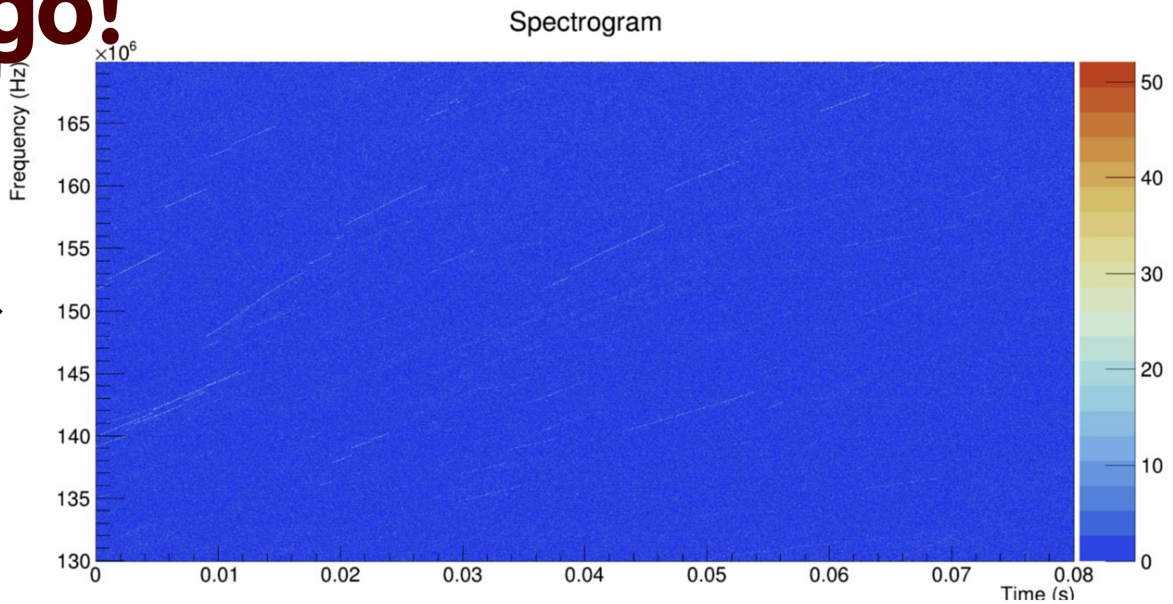
- ^{83m}Kr conversion e^-: 17.8 (*K*, 25%), 30.5 (*L*, 62%) and 31.9 keV (*M*, 10%)

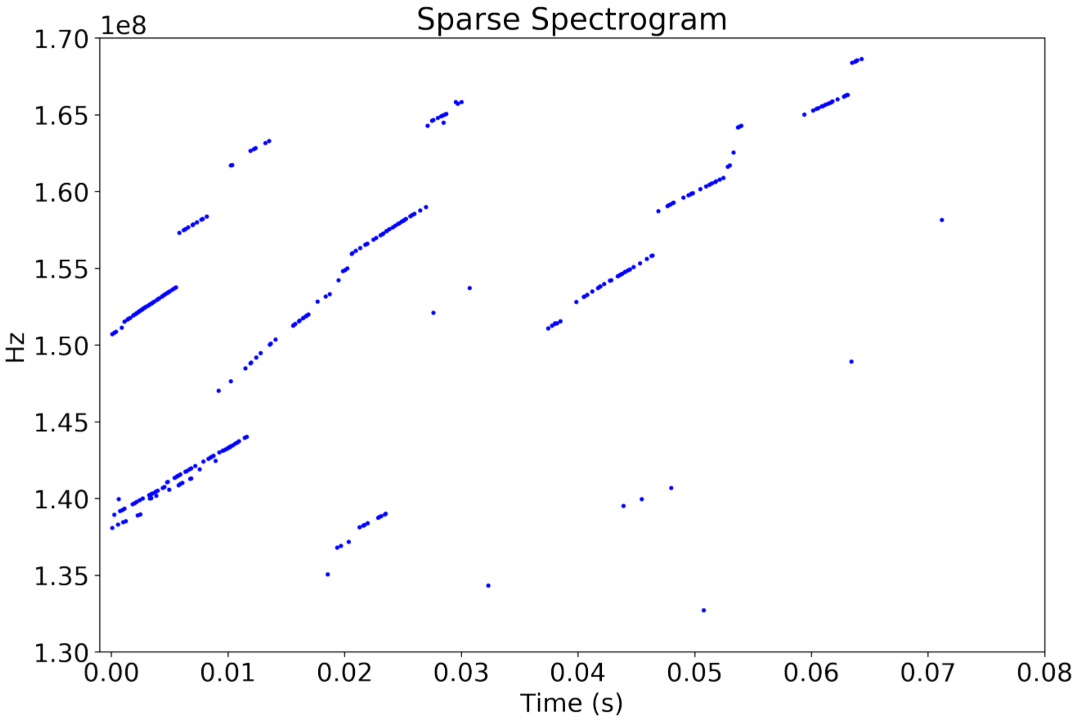


Success just a few weeks ago!

- Clean up spectrogram requiring a signal above the background







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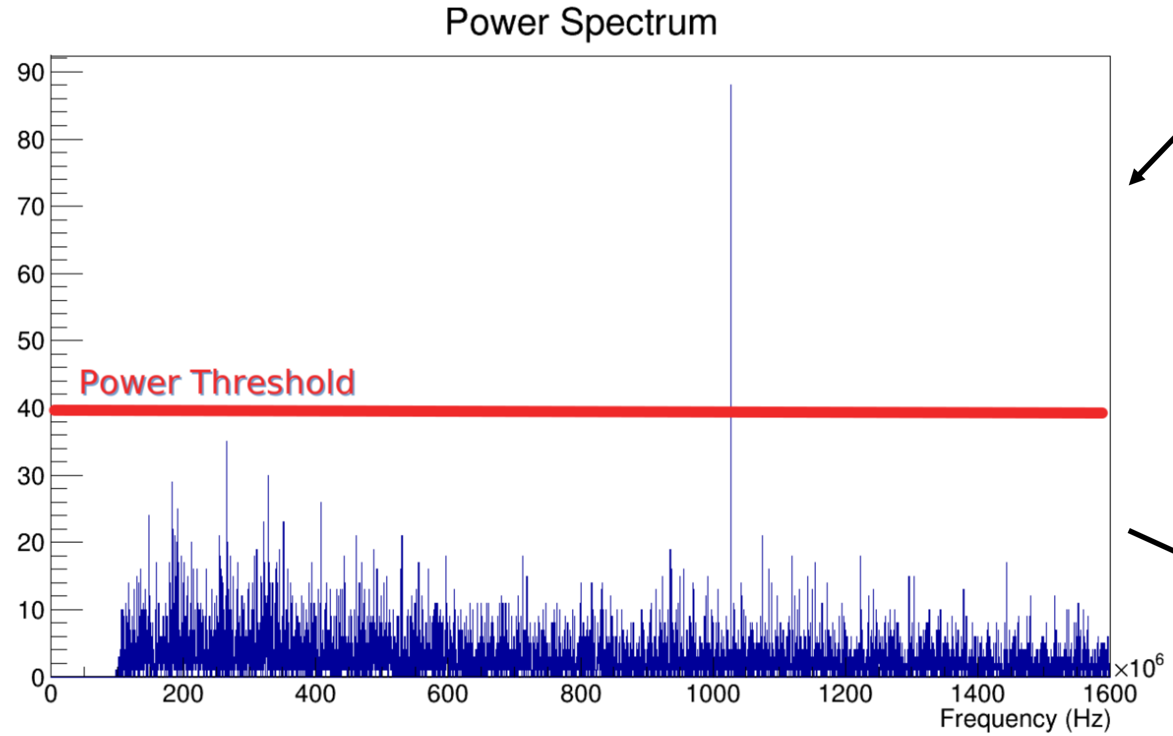
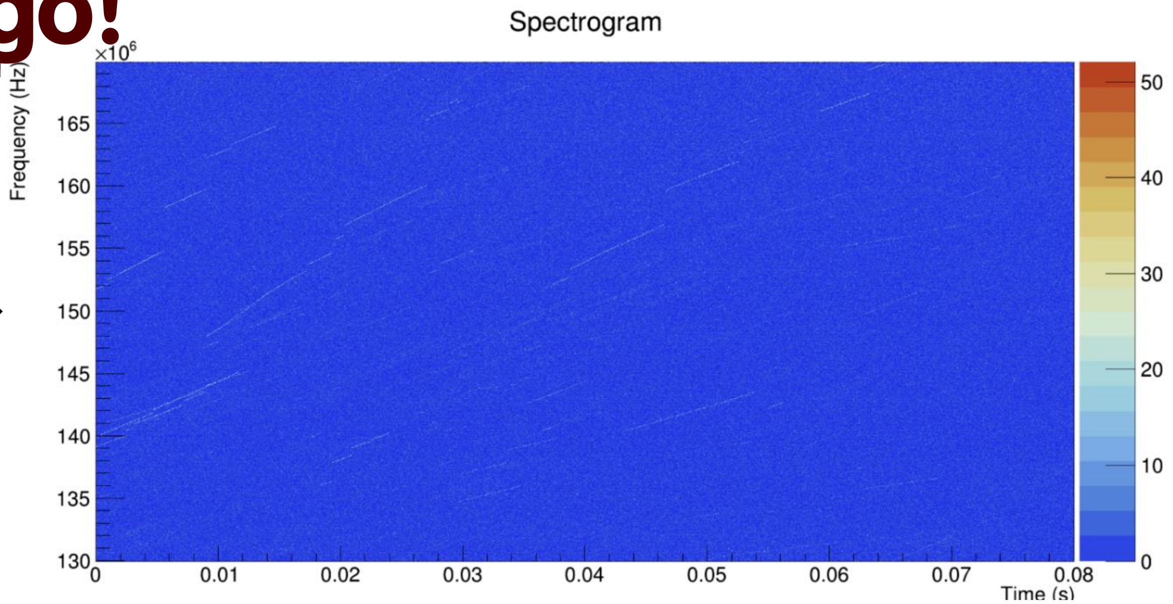
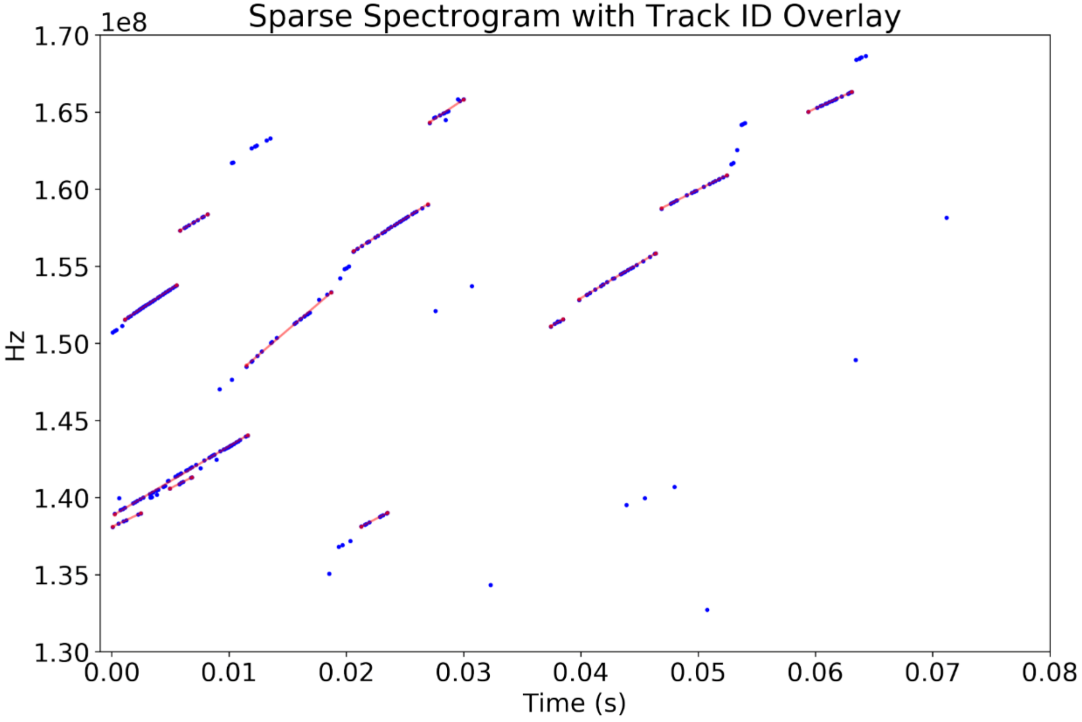


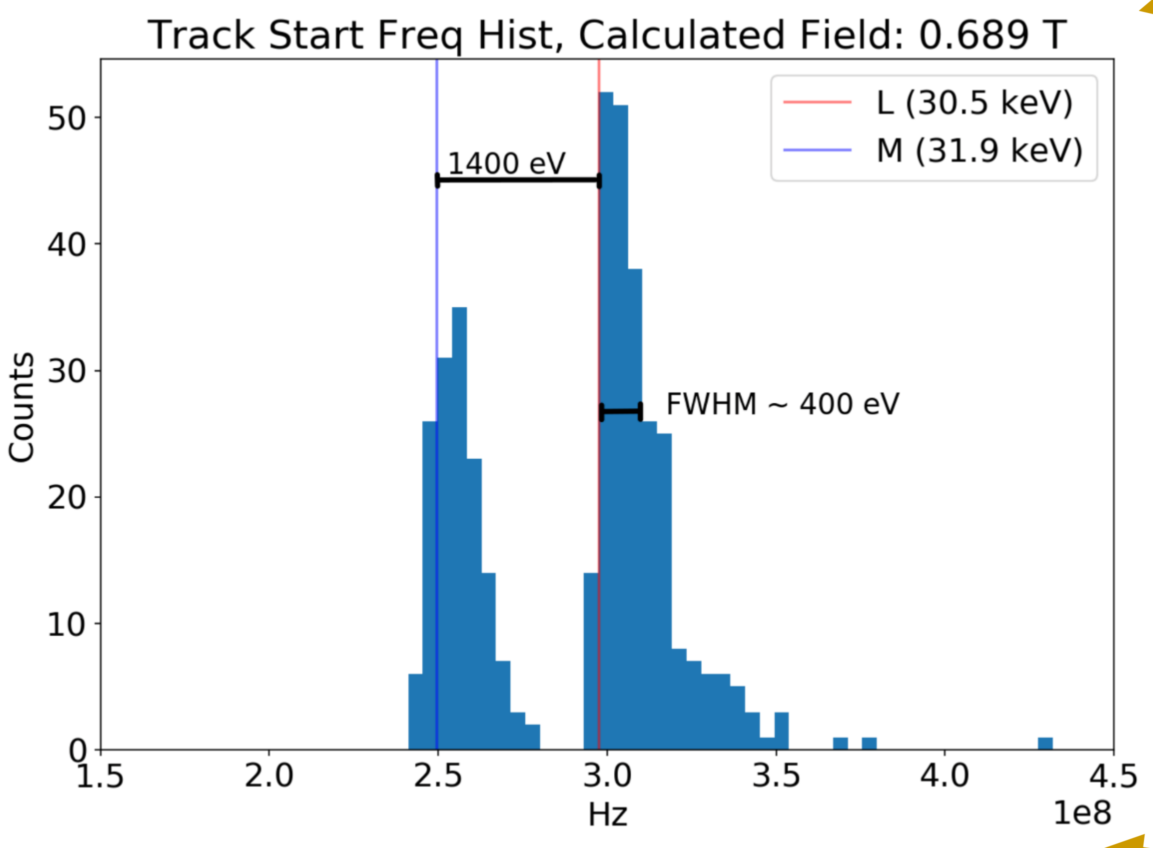


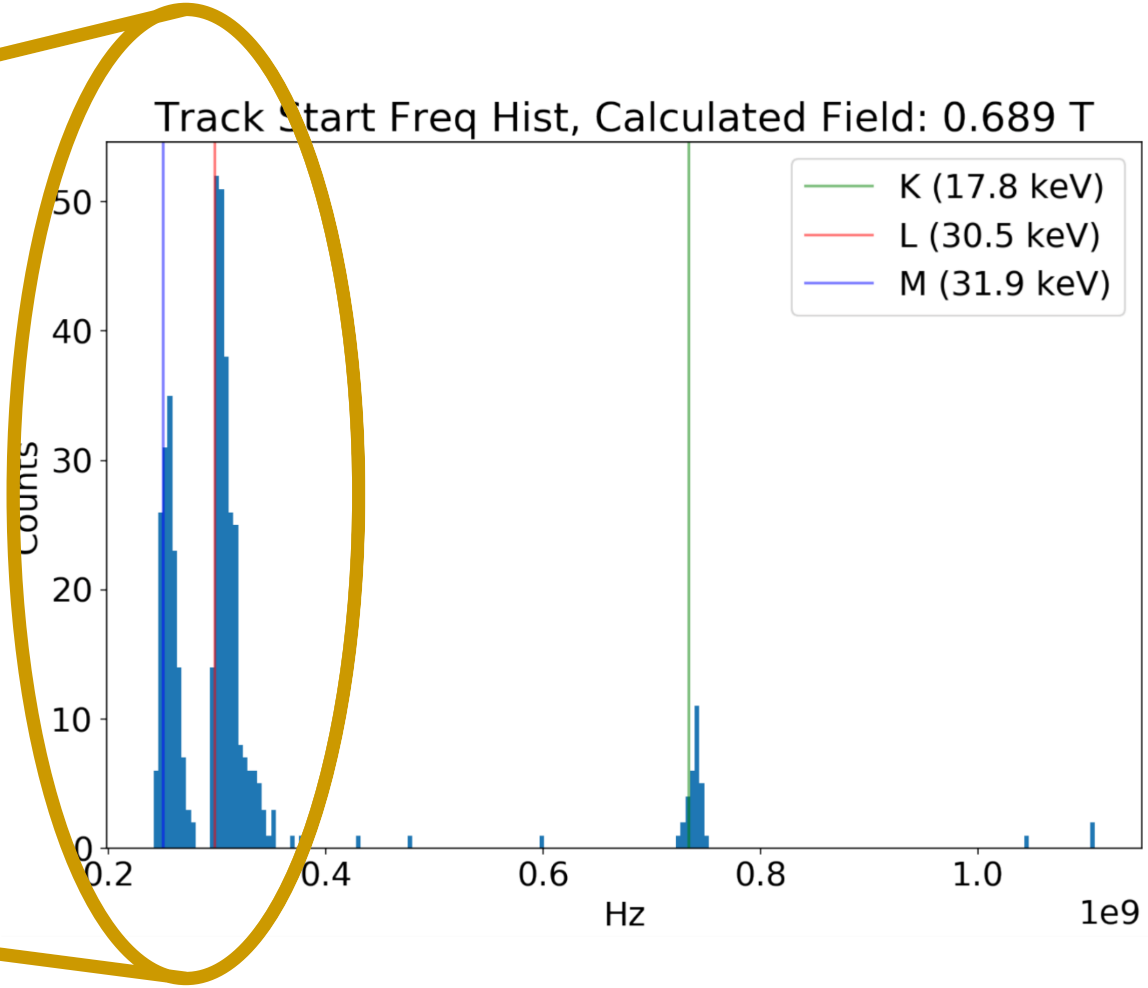


- Fit the slope, deduce initial E_{kin}

Conversion electron energy spectrum of ^{83m}Kr

- Quick estimate of unoptimized energy resolution: 400 eV @ 30 keV ⇒ 1.3%. We have a way to go to reach Project 8's precision of 0.1%, but now we have a signal!





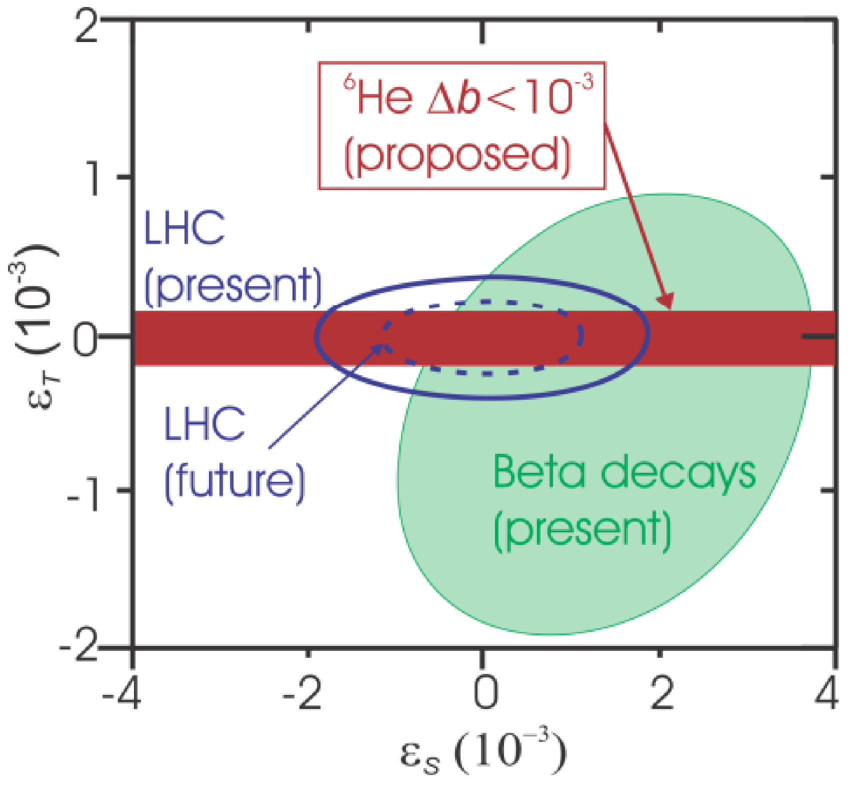
Courtesy Drew Byron (UW)

Near-term goal

- Phase I: proof of principle (present)
  - 2 GHz bandwidth
  - Show detection of cyclotron radiation from ^{6}He
  - Study power distribution

Effect	Δb	
	No trap	Ion trap
Magnetic field uncertainties	10^{-4}	$< 10^{-4}$
Wall effect uncertainties	10^{-3}	
RF pickup uncertainties	10^{-4}	10^{-5}
Misidentification of events	10^{-4}	5×10^{-5}

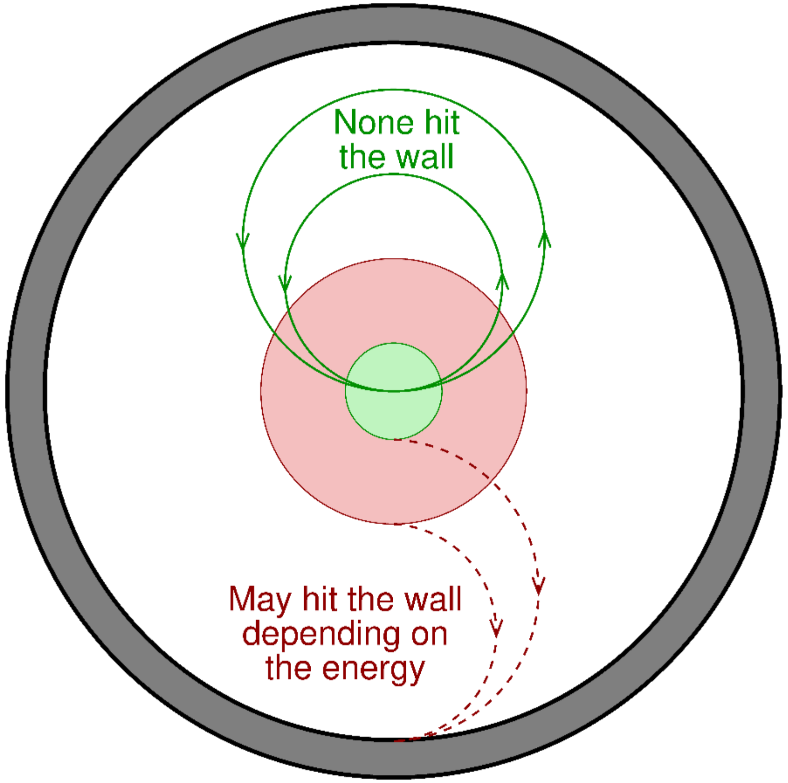
- Phase II: first measurement ($b < 10^{-3}$)
  - 6 GHz bandwidth
  - ^{6}He and ^{19}Ne measurements



Looking forward (to crushing the LHC)

- Phase I: proof of pri
  - 2 GHz bandwidth
  - Show detection of c
  - Study power distrib

Largest and smallest electron orbits at 2 T



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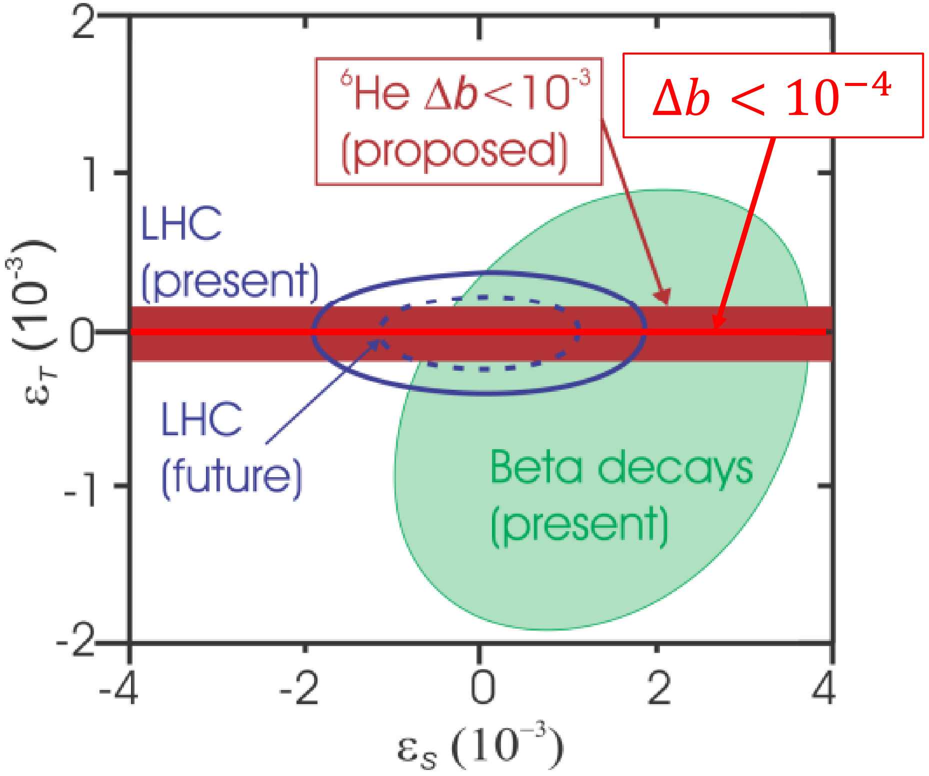
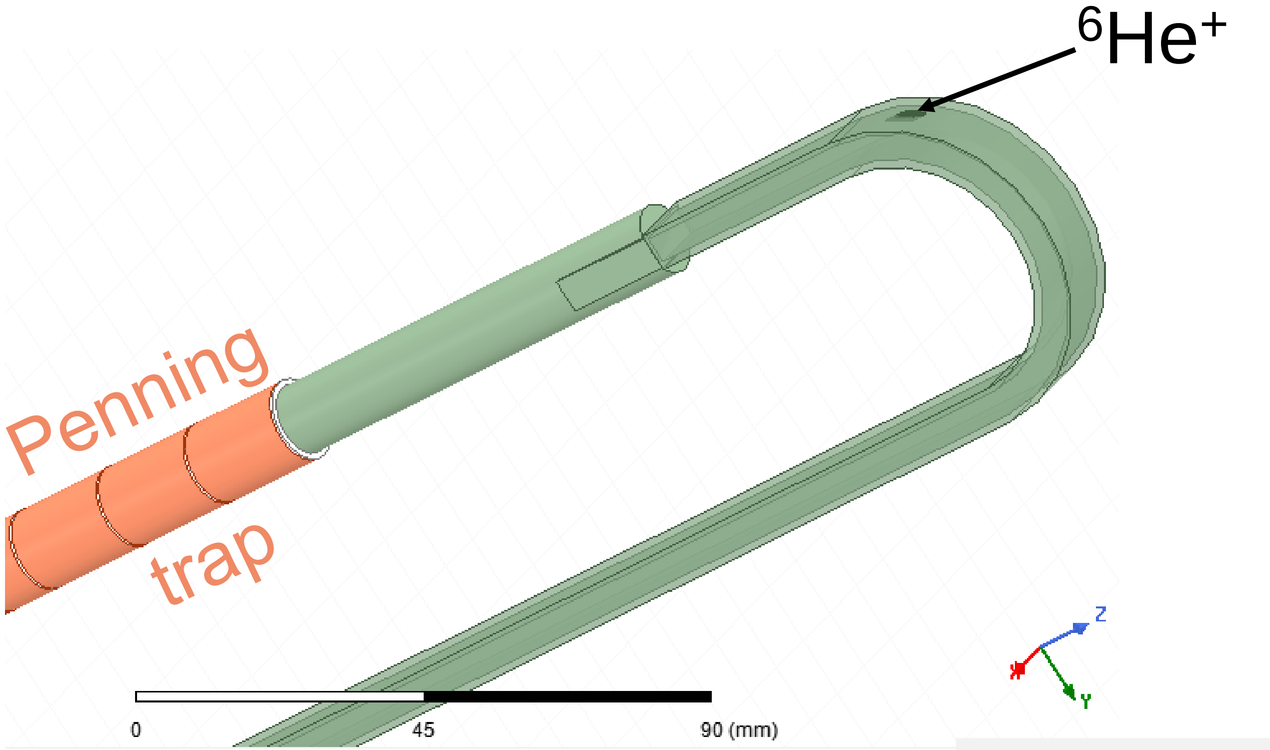


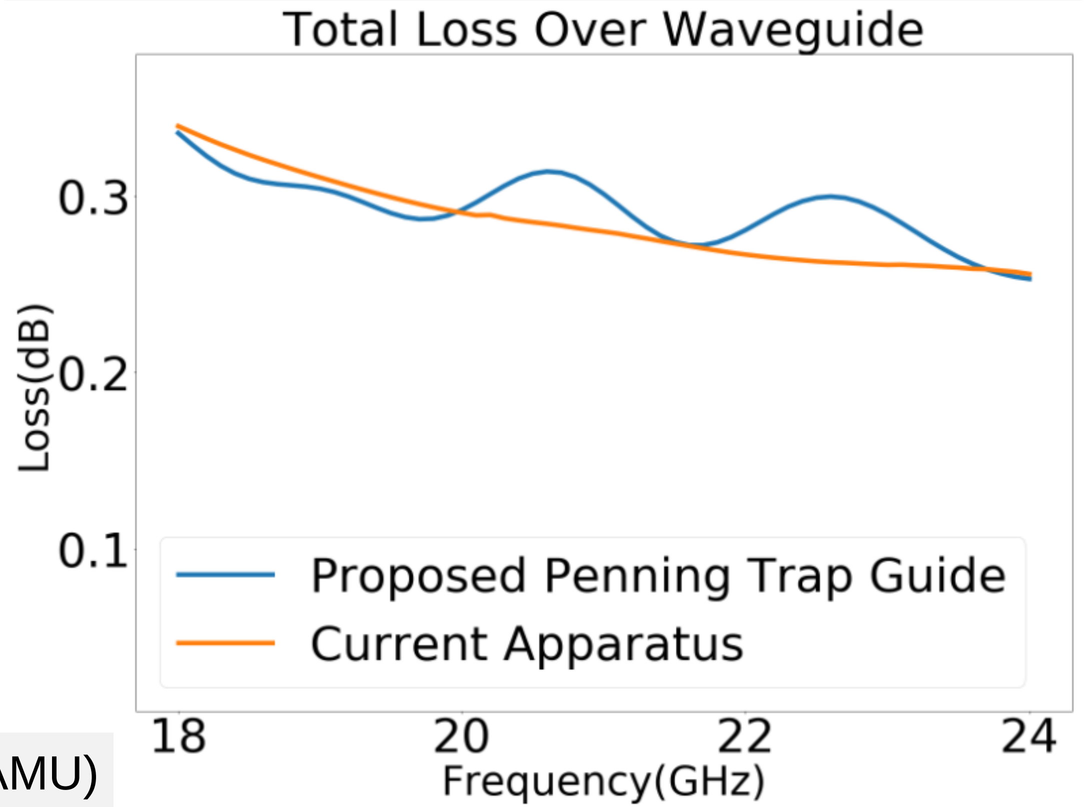
- Phase III: ultimate measurement ($b < 10^{-4}$)
  - Ion trap for no limitation from geometric effect

CRES from a trap: TAMU's contribution is starting

- Along with ANL collaborators (Savard, Mueller), mapping out upgrades necessary for Phase III
- Potential show-stopper: need a hole in the waveguide to inject $^6He^+$ ions
  - HFSS ⇒ signal degradation is essentially no worse than present geometry



David McClain (TAMU)



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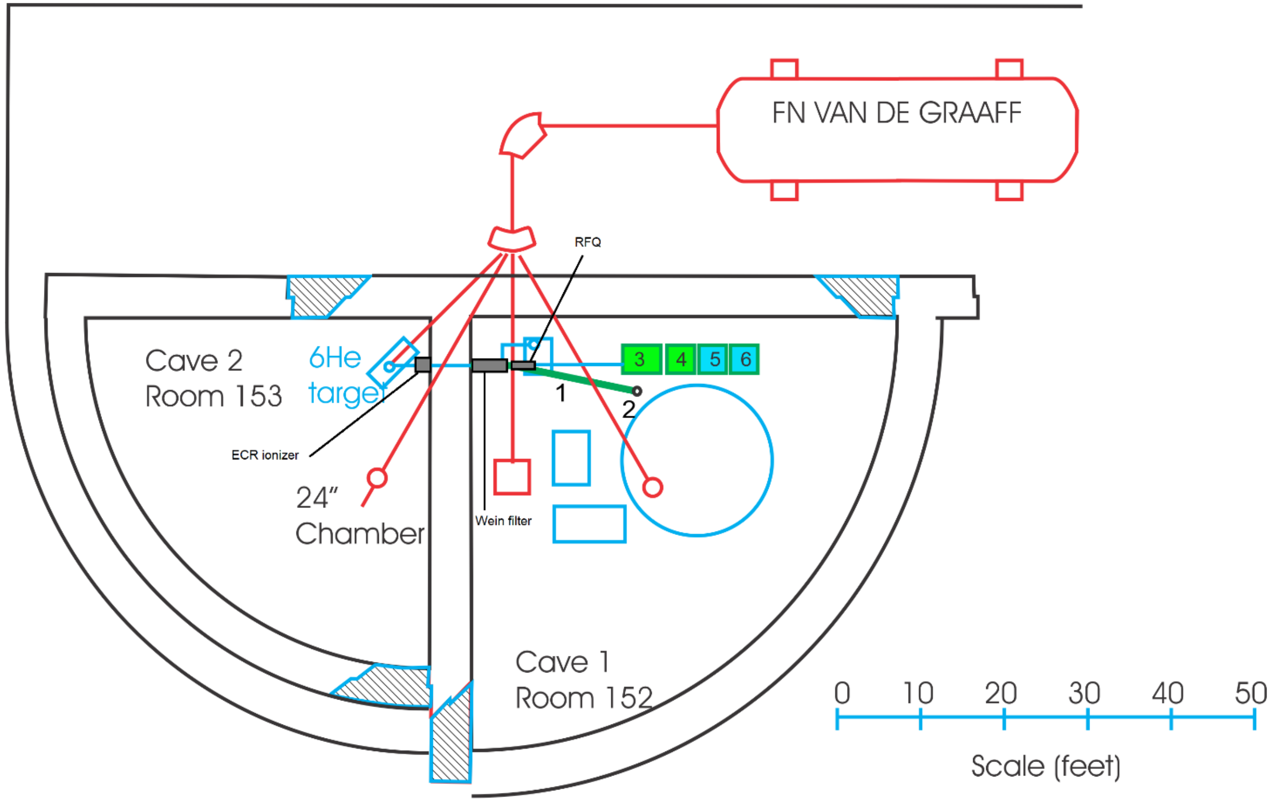

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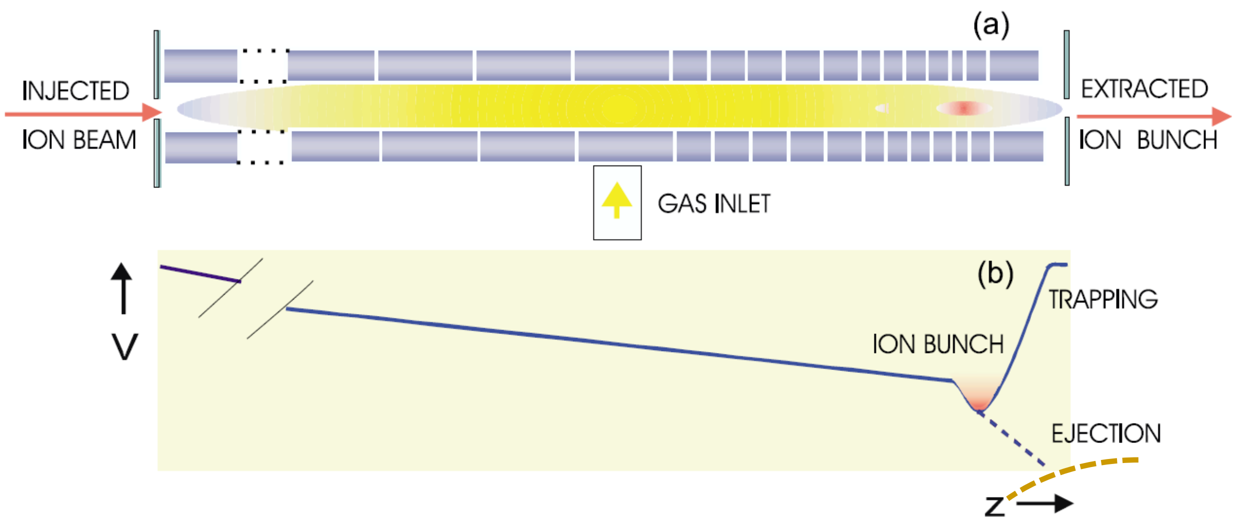
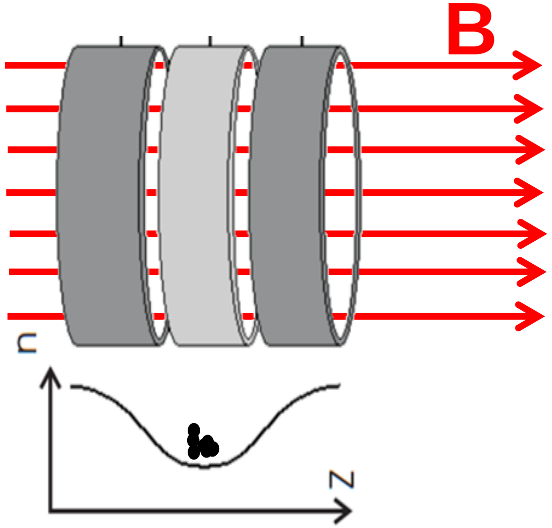
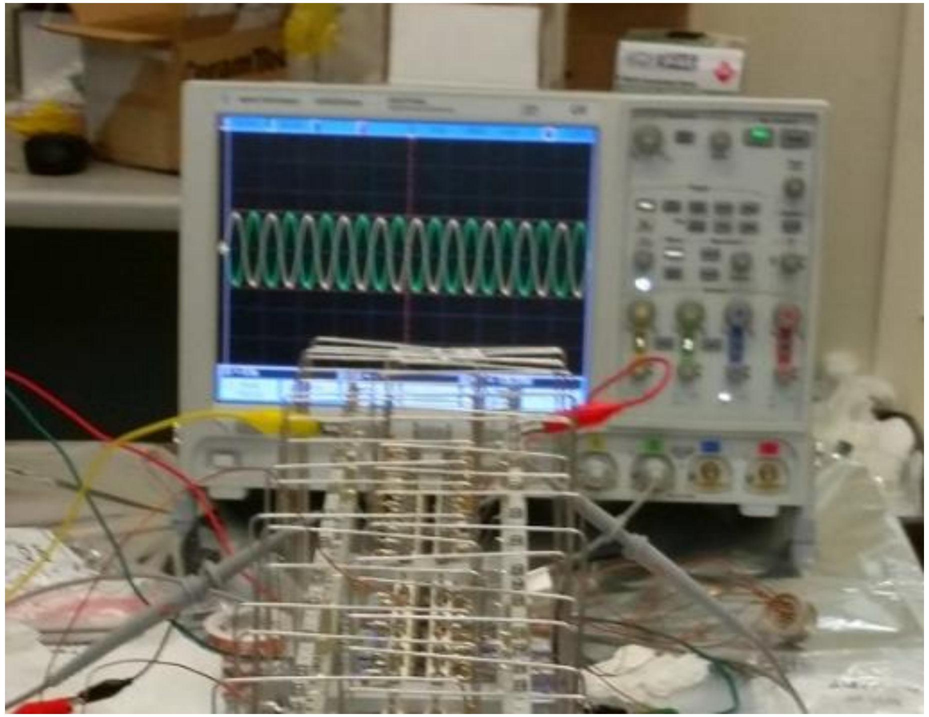
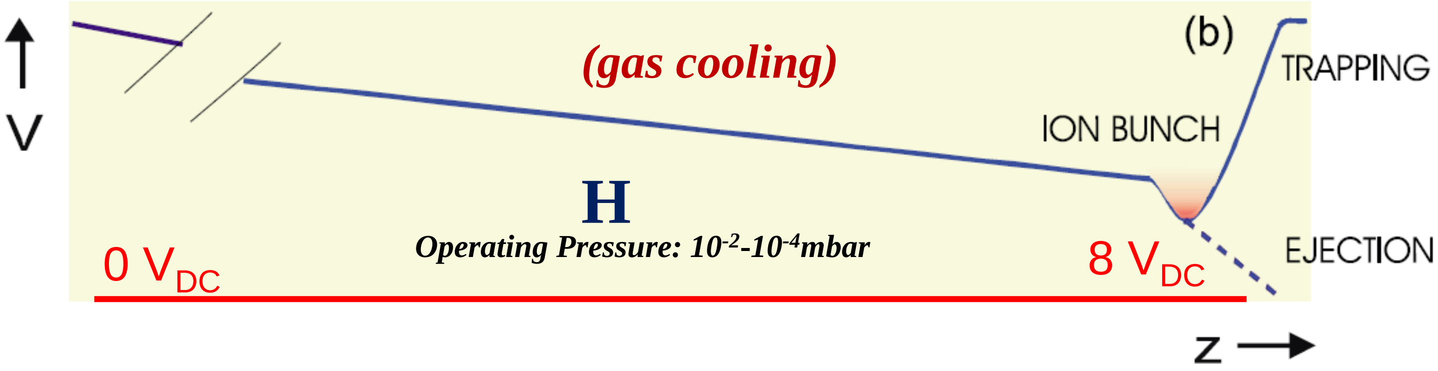
  - HFSS ⇒ signal degradation is essentially no worse than present geometry
- Need to convert ^{6}He atoms to ions
  - Need an ECR and Wein filter (being led by ANL)
- To fill the trap, need a low-energy, low-emittance, bunched beam
  - Radiofrequency quadrupole (RFQ) Paul trap cooler and buncher





The RFQ cooler/buncher – based on TAMUTRAP's

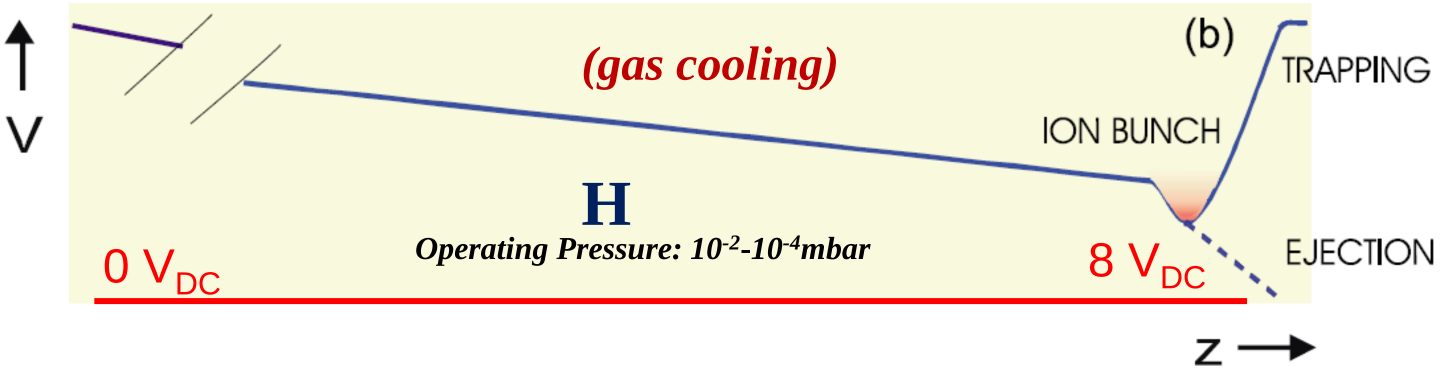


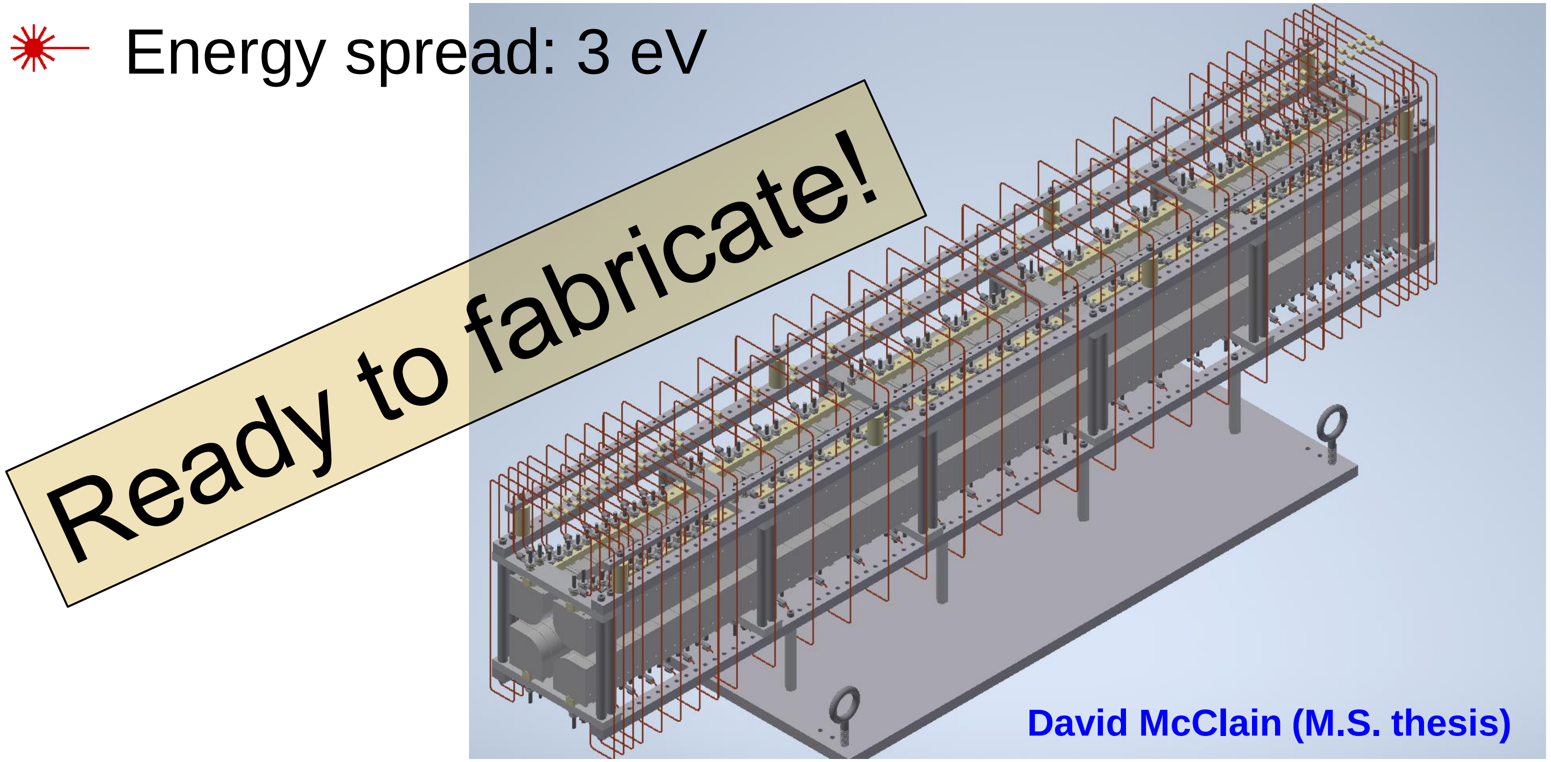


David McClain (M.S. thesis)

The RFQ cooler/buncher – based on TAMUTRAP's

- Design parameters:
  - $r_0 = 15$ mm
  - $V_{pp} = 400$ V
  - $f = 0.75 - 1.5$ MHz (He, O, Ne)
  - Time spread: 0.8 μs
  - Energy spread: 3 eV





Next steps

- Submit RFQ design for fabrication
- Set up Hydrogen buffer gas system
- Test RFQ at the Cyclotron Institute (Fall 2021)
- Send RFQ to CENPA (Spring 2022)

- Rough characteristics of the cylindrical Penning trap are designed
- Produce technical drawings, and beamline connecting RFQ to Penning trap (Fall 2021)
- Construct beamline, Penning trap and amended waveguide (Summer 2022?)

- Submit proposal with ANL to fund the Penning trap upgrade (Fall 2021)

Summary

- The CRES technique promises unparalled precision for β detection
  - Project 8 m_ν
  - Fierz interference parameter
- ^{6}He CRES collaboration is making progress
  - System assembled
  - Components tested (cryocooler, rf, …)
  - **First CRES signal seen!** ^{83m}Kr conversion electrons
  - ^{6}He and ^{19}Ne measurements in the next year
- Phase III will utilize a Penning trap to obviate wall effects
  - RFQ design completed, fabrication about to begin
  - Test at TAMU and send to UW by early next year
  - Rough Penning trap design – final version soon

Collaborators and thanks

^{6}He-CRES

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