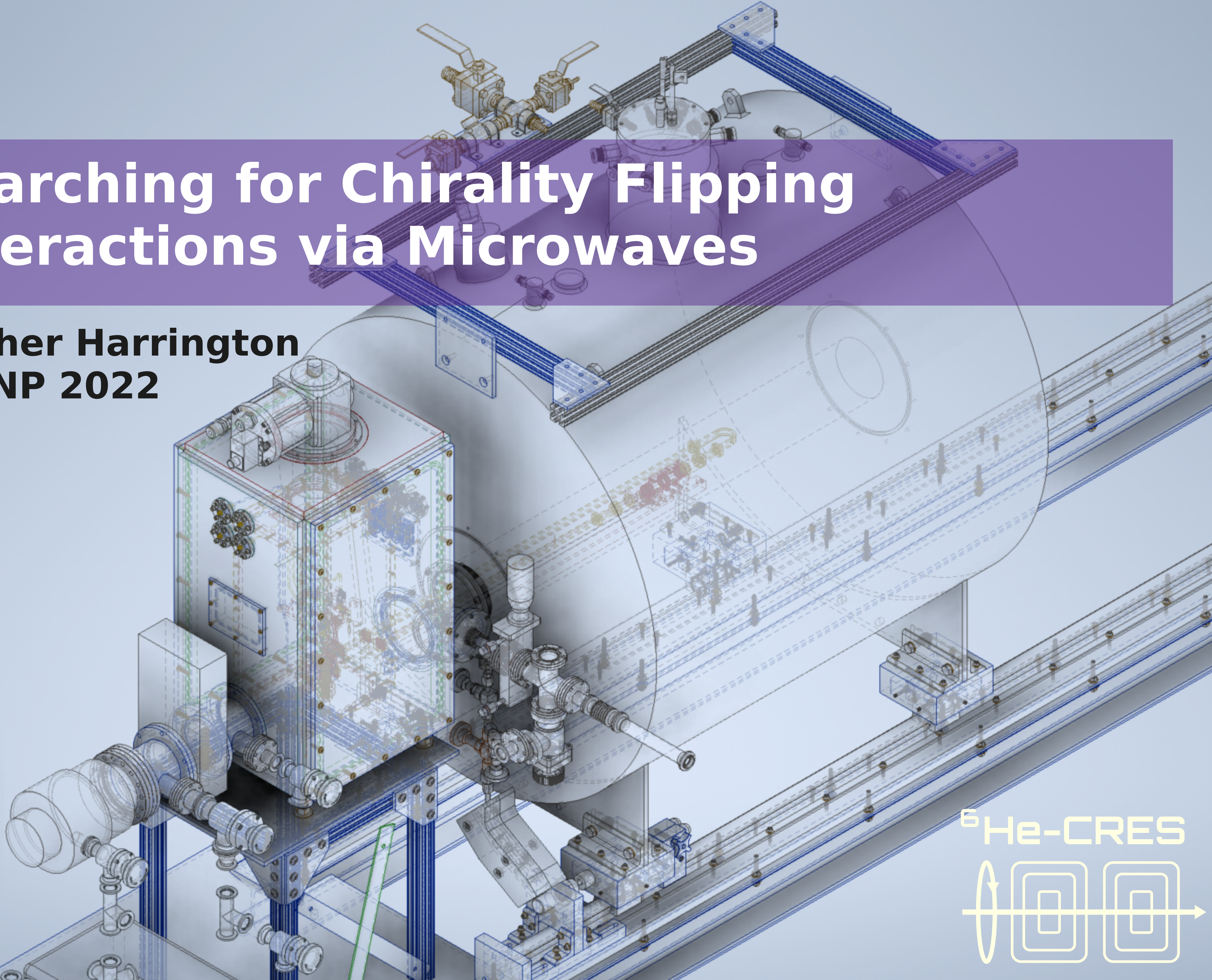
Searching for Chirality Flipping Interactions via Microwaves

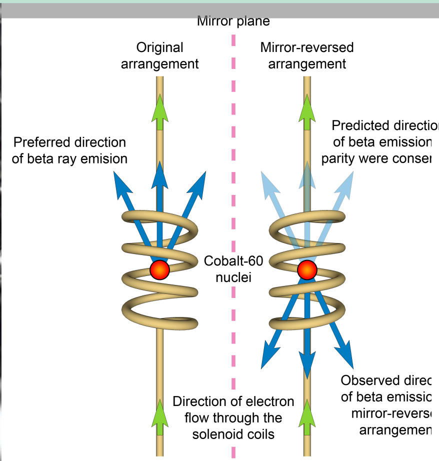
Heather Harrington
CIPANP 2022

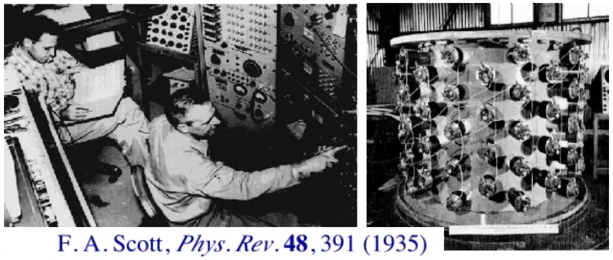


^{6}He-CRES

Beta decay as a window to new physics

1956 Parity violation – Wu Experiment





F. A. Scott, *Phys. Rev.* **48**, 391 (1935)

Discovery of neutrinos (1935)

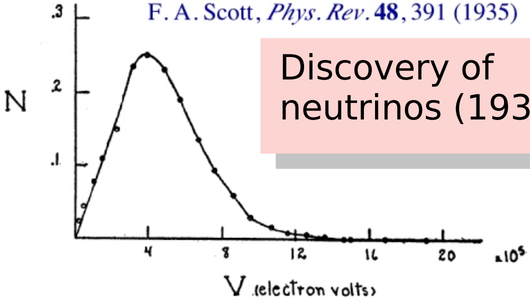


FIG. 5. Energy distribution curve of the beta-rays.

Neutrinoless double-beta decay searches (ongoing)

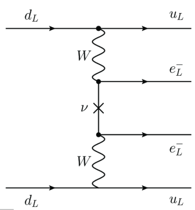
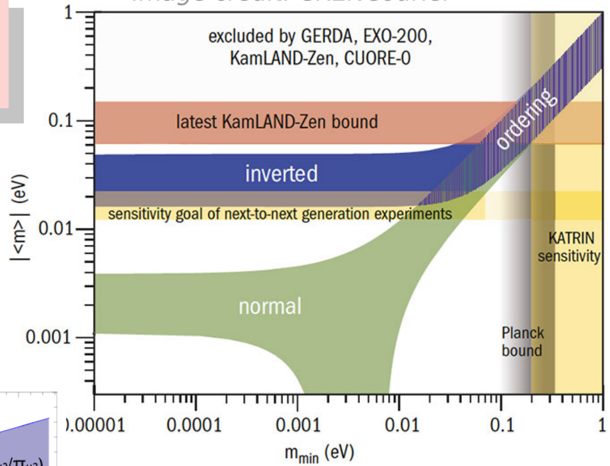
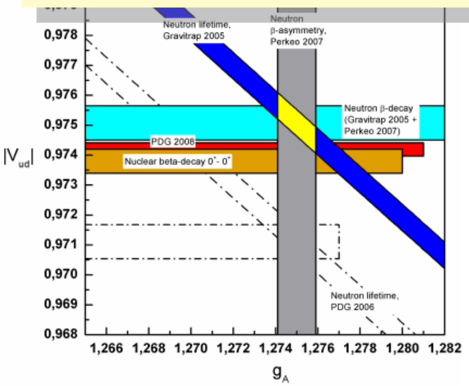
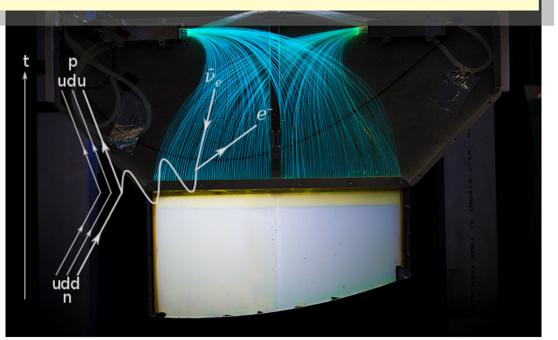


Image credit: CRENCourier

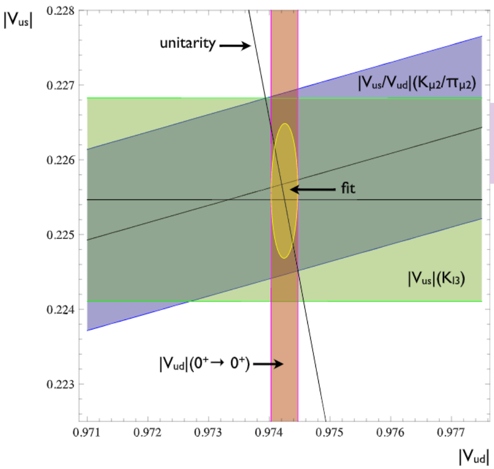


Neutron lifetime disagreement and extraction of V_{ud}





Plot credit: Faber, et. al.PHYS REV C. 80. (2009) *Picture: UCNτ Experiment*



Cabibbo universality

$$\Delta_{\mathrm{CKM}} \equiv |\overline{V}_{ud}|^2 + |\overline{V}_{us}|^2 + |\overline{V}_{ub}|^2 - 1$$

V. Cirigliano et al. Progress in Particle and Nuclear Physics 71 (2013)

Beta decay correlations (alphabet soup) and scale of new physics.

Jackson, Treiman and Wyld (Phys. Rev. 106 and Nucl. Phys. 4, 1957)

$$\frac{d\Gamma}{d\Omega_e d\Omega_\nu dE_e} = \overbrace{\frac{G_F^2|V_{ud}|^2}{(2\pi)^5} p_e E_e (E_o - E_e)^2 \xi}^{\text{basic decay rate}} \left[1 + \overbrace{a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu}}^{\beta-\nu\text{ correlation}} + \overbrace{b\frac{m_e}{E_e}}^{\text{Fierz term}} + \frac{\langle \vec{J} \rangle}{J} \cdot \left(\underbrace{A\frac{\vec{p_e}}{E_e}}_{\beta\text{ asym}} + \underbrace{B\frac{\vec{p_\nu}}{E_\nu}}_{\nu\text{ asym}} + \underbrace{D\frac{\vec{p_e}\times\vec{p_\nu}}{E_e E_\nu}}_{T-\text{violating}} \right) + \ldots \right]$$

General idea:

$$H_{total} = H_{SM} + H_{new} = C_{SM}\,\hat{O}_{SM} + \sum C_{new,\,i}\,\hat{O}_i$$

Lee-Yang effective couplings

$$C_i = \frac{G_F}{\sqrt{2}} V_{ud} \bar{C}_i$$

$$\bar{C}_V = g_V(1 + \epsilon_L + \epsilon_R)$$

$$\bar{C}_A = -g_A(1 + \epsilon_L - \epsilon_R)$$

$$\bar{C}_S = g_S \epsilon_S$$

$$\bar{C}_T = 4 g_T \epsilon_T,$$

Non-standard effective couplings

$$b = \pm 2\gamma(Z)\,\frac{\left[\frac{g_S}{g_V}\epsilon_S - 4\left(\frac{\langle\sigma\tau\rangle}{\langle\tau\rangle}\right)^2 \frac{g_T}{g_V}\frac{g_A}{g_V}\epsilon_T\right]}{1 + \left(\frac{\langle\sigma\tau\rangle}{\langle\tau\rangle}\right)^2 \left(\frac{g_A}{g_V}\right)^2}$$

Effects of new physics

$$\delta O \sim \frac{C_{new,\,i}}{C_{SM}} \left(\frac{2\,M_W}{\Lambda}\right)^2$$

To reach Λ ~10 TeV need $\delta O \sim 10^{-4}$

⟨στ ⟩ and ⟨τ ⟩ are the Gamow-Teller and Fermi nuclear β-decay matrix elements, respectively

g_i : nucleon form factors

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$\bar{C}_T = 4g_T\epsilon_T,$

310. Using effective field theory to tie together low- and high-energy searches for new physics

Emanuele Mereghetti (Los Alamos Nation...

03/09/2022, 11:00

Physics at High Energies | Plenary talk | Plenary

Effects of new physics

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$$\left[\frac{g_S}{\ldots}\epsilon_S - 4\left(\frac{\langle\sigma\tau\rangle}{\ldots}\right)^2 \frac{g_T}{\ldots}\frac{g_A}{g_V}\epsilon_T \right] \ldots \Big)^2$$

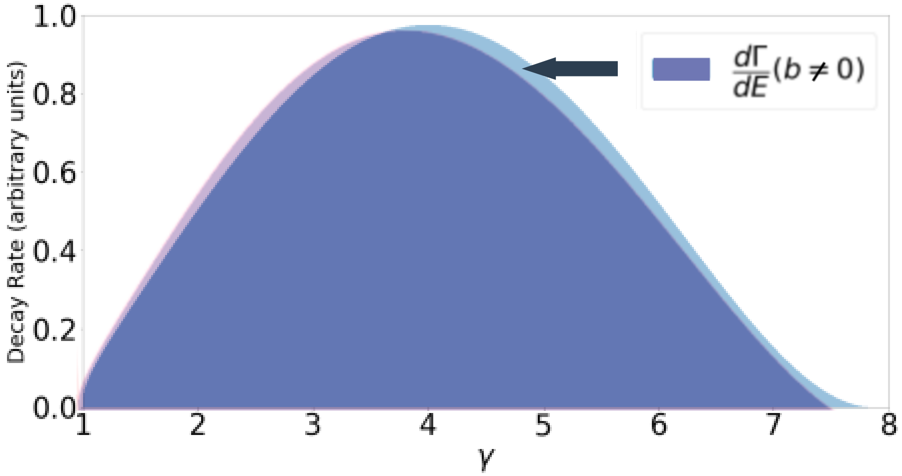
...w-Teller and Fermi nuclear β-decay matrix elements, respectively

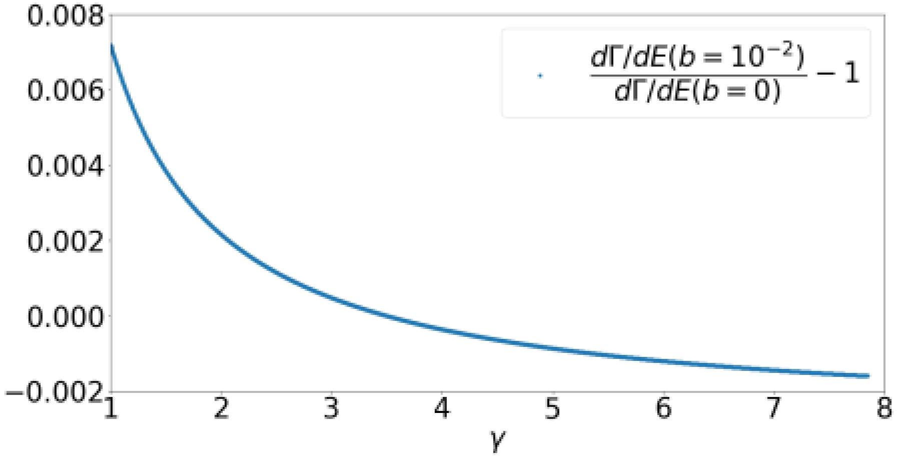
g_i : nucleon form factors

Fierz interference, and non-(V−A) couplings

Jackson, Treiman and Wyld (Phys. Rev. 106 and Nucl. Phys. 4, 1957)

$$\frac{d\Gamma}{dE_e} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (E_o - E_e)^2 \xi \left[1 + b\frac{m_e}{E_e}\right]$$



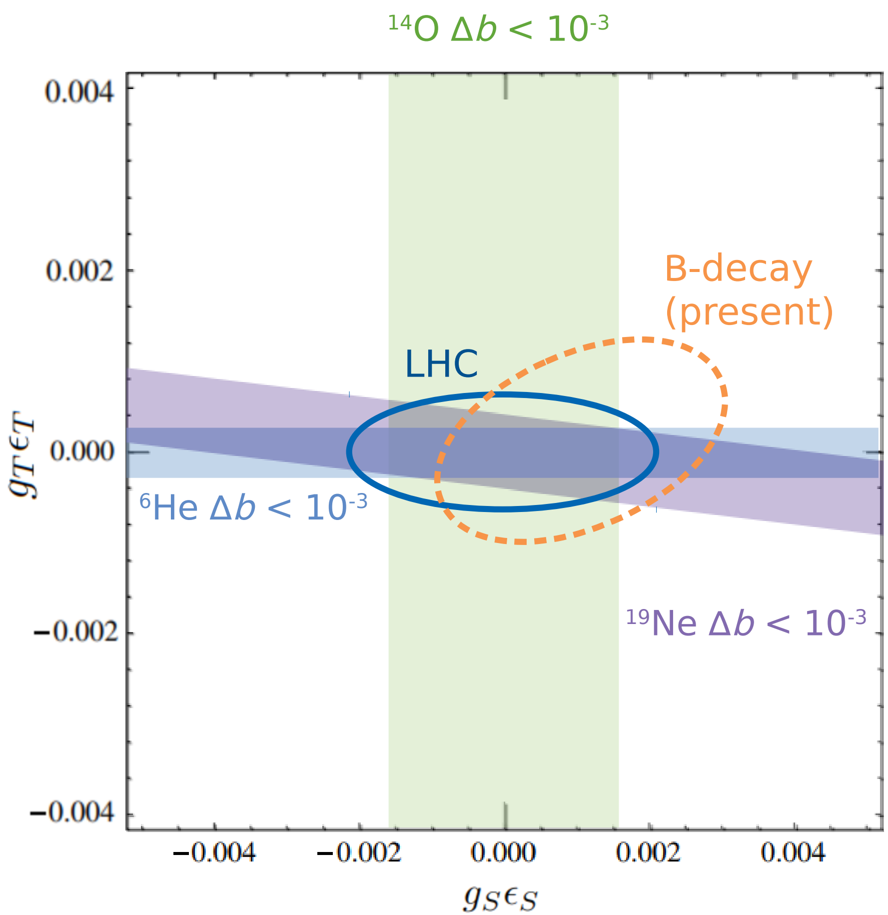


b **is the so-called "Fierz interference" term. Sensitive to scalar and tensor couplings. eg. for tensor:**

$$\frac{dN}{dE} \propto |\langle f|\, H_{int}^A + H_{int}^T\, |i\rangle|^2$$

$$\langle u_+|\, \bar{\psi}_e^L O_A \psi_\nu^L\, |i_l\rangle \langle i_l|\, \bar{\psi}_\nu^L O_T \psi_e^R\, |u_+\rangle \propto \sqrt{1-p/E}\sqrt{1+p/E} = \frac{\sqrt{E^2-p^2}}{E} = \frac{m_e}{E}$$

Fermi, Gamow-teller, and mixed decays give us sensitivity to scalar and tensor couplings



^{14}O

Fermi matrix element

$$b = \pm 2\gamma(Z=7)\frac{\langle\tau\rangle^2 g_V g_S\epsilon_S - \cancel{4\langle\sigma\tau\rangle^2 g_A g_T\epsilon_T}}{\langle\tau\rangle^2 g_V^2 + \cancel{\langle\sigma\tau\rangle^2 g_A^2}}$$

$$b_F = 2\gamma g_S\epsilon_S$$

^{6}He

Gamow-Teller matrix element

$$b = \pm 2\gamma(Z=3)\frac{\cancel{\langle\tau\rangle^2 g_V g_S\epsilon_S} - 4\langle\sigma\tau\rangle^2 g_A g_T\epsilon_T}{\cancel{\langle\tau\rangle^2 g_V^2} + \langle\sigma\tau\rangle^2 g_A^2}$$

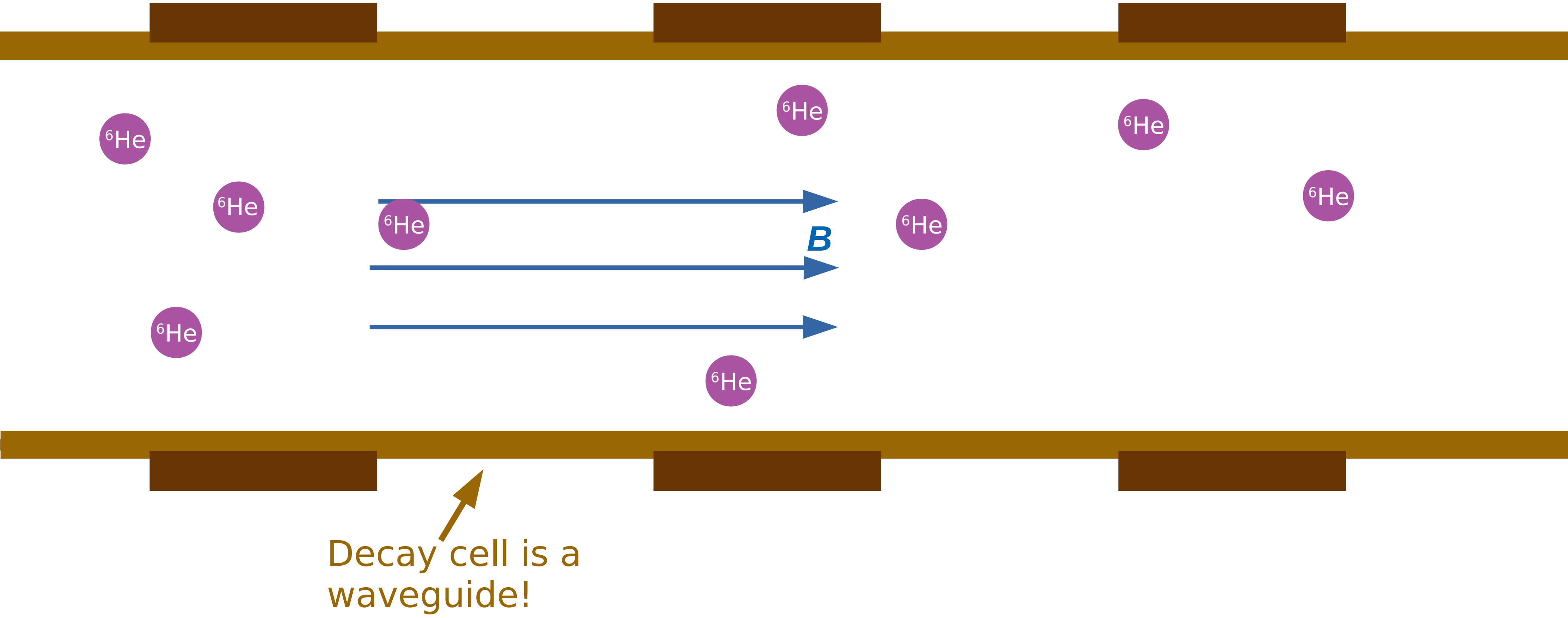
$$b_{GT} = -(8\gamma g_T\epsilon_T)/\lambda$$

^{19}Ne

$$\frac{b(^{19}\mathrm{Ne})}{\gamma(Z=9)} = \frac{\frac{b(^{14}\mathrm{O})}{\gamma(Z=7)} - \rho^2\frac{b(^{6}\mathrm{He})}{\gamma(Z=3)}}{1+\rho^2}$$

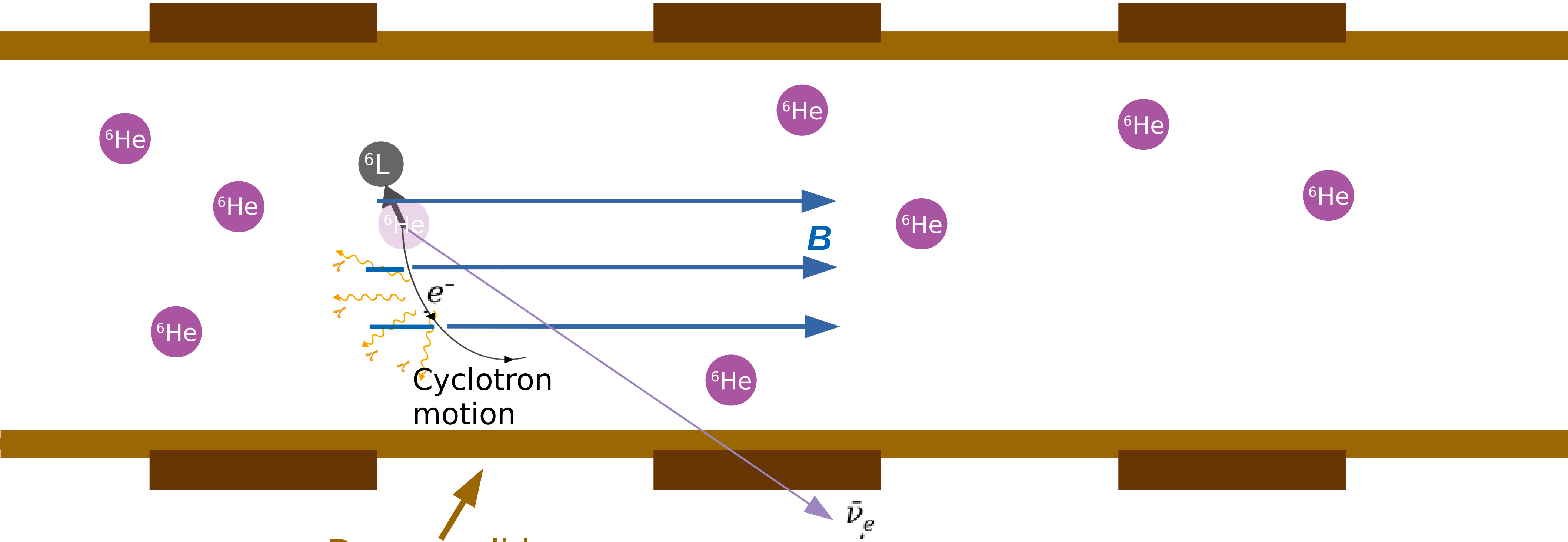
where $\rho = \frac{\langle\sigma\tau\rangle}{\langle\tau\rangle}\frac{g_A}{g_V}\sqrt{\frac{1+\delta_{\mathrm{NS}}^A}{1+\delta_{\mathrm{NS}}^V}\frac{f_A}{f_V}} \approx 1.6$

What is CRES (Cyclotron Radiation Emission Spectroscopy)?



What is CRES (Cyclotron Radiation Emission Spectroscopy)?

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

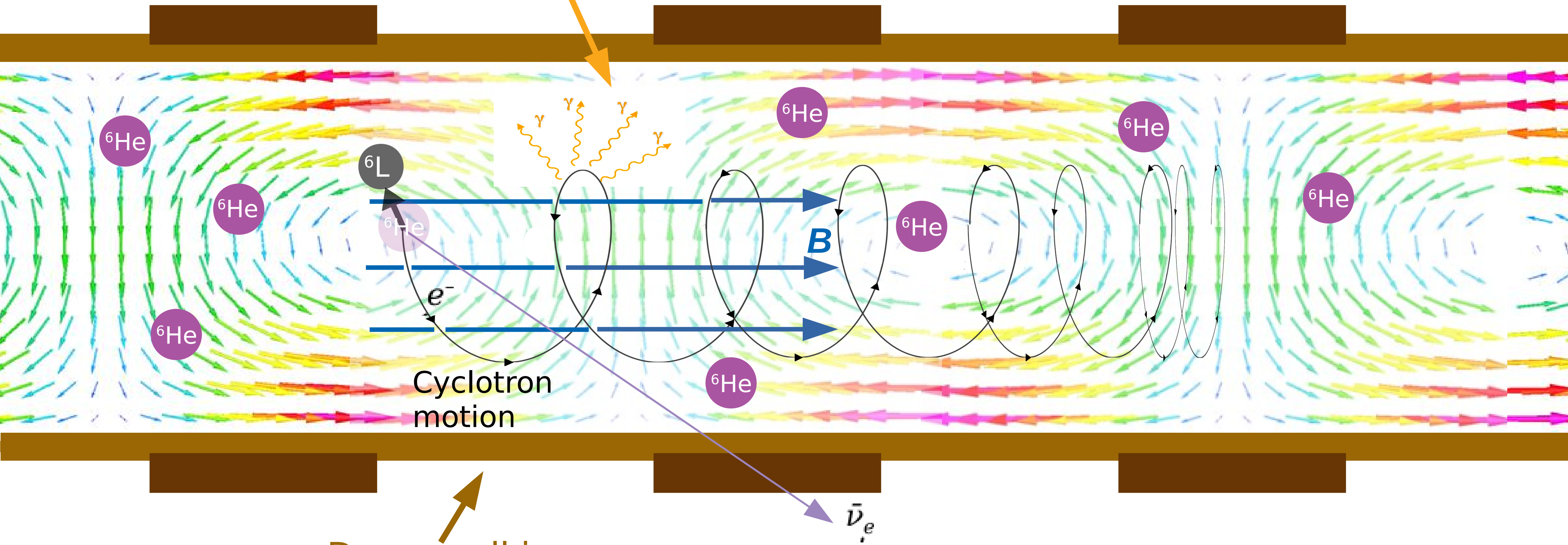


Decay cell is a waveguide!

What is CRES (Cyclotron Radiation Emission Spectroscopy)?

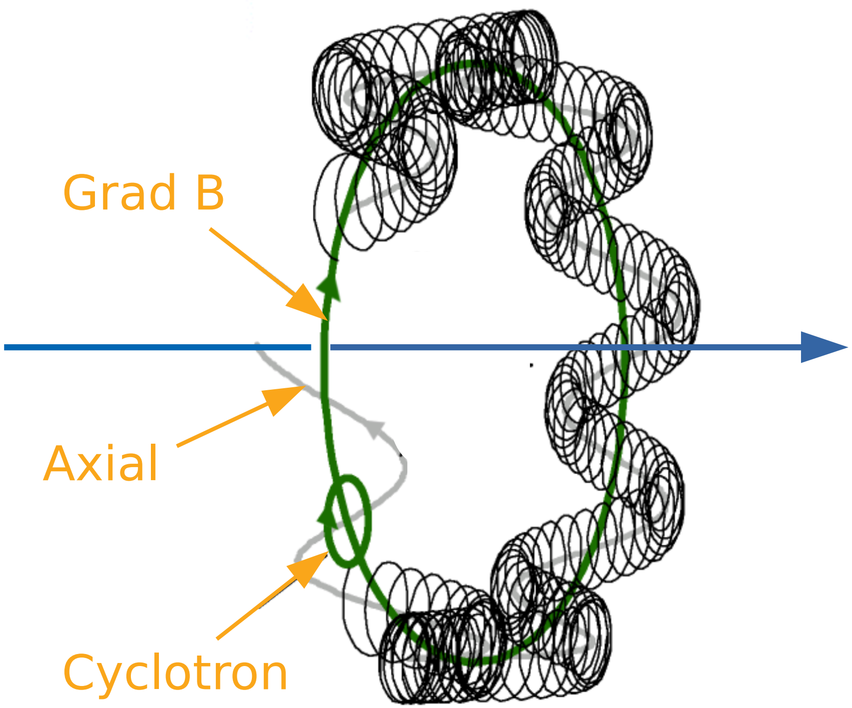
Cyclotron radiation couples to Propagating modes. We measure TE_{11}
(~fW power radio-waves)

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



Decay cell is a waveguide!

Trapping betas in a magnetic bottle, in a waveguide



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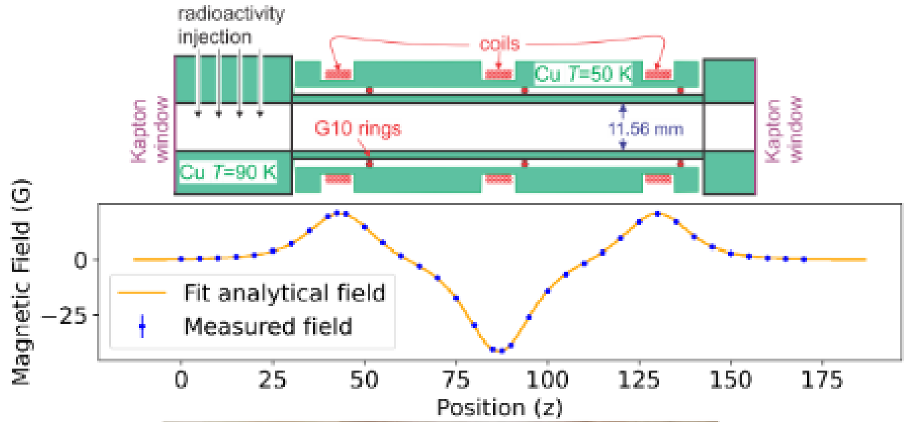
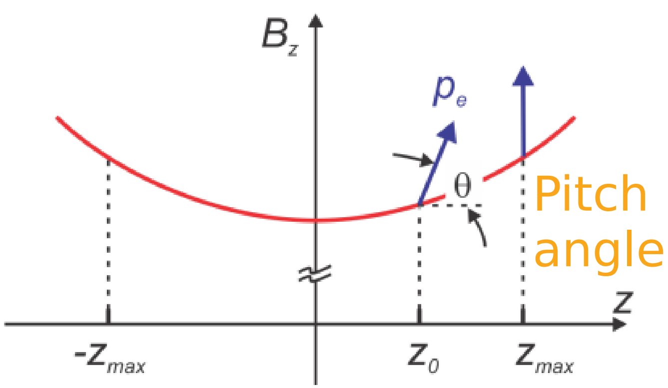
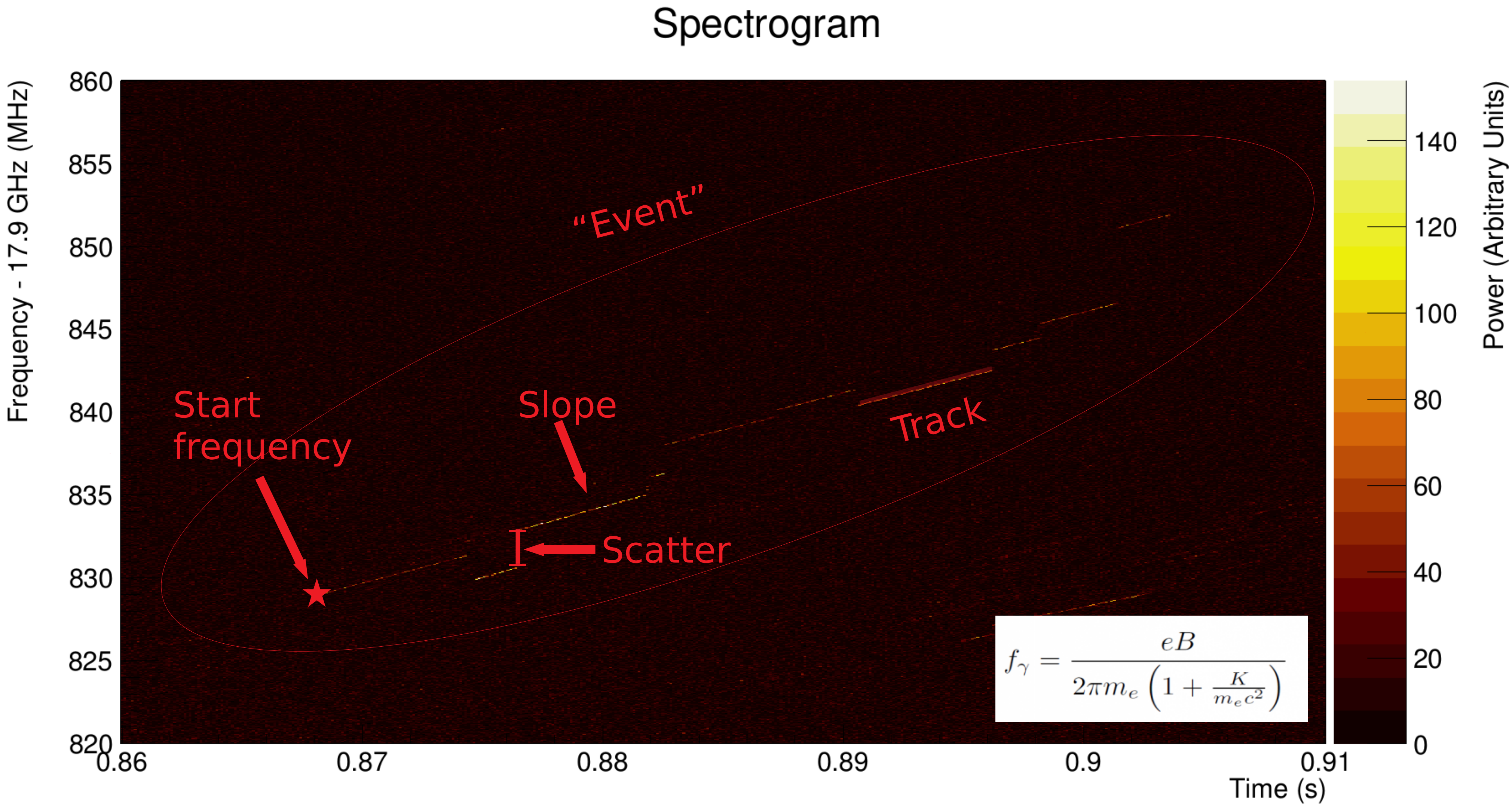




CRES signals



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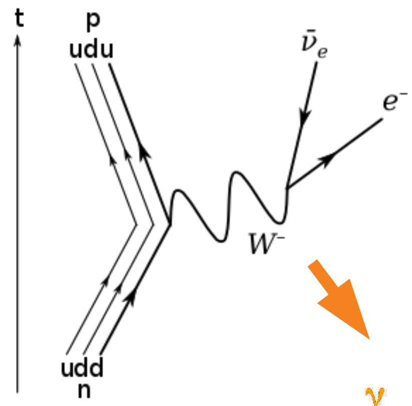
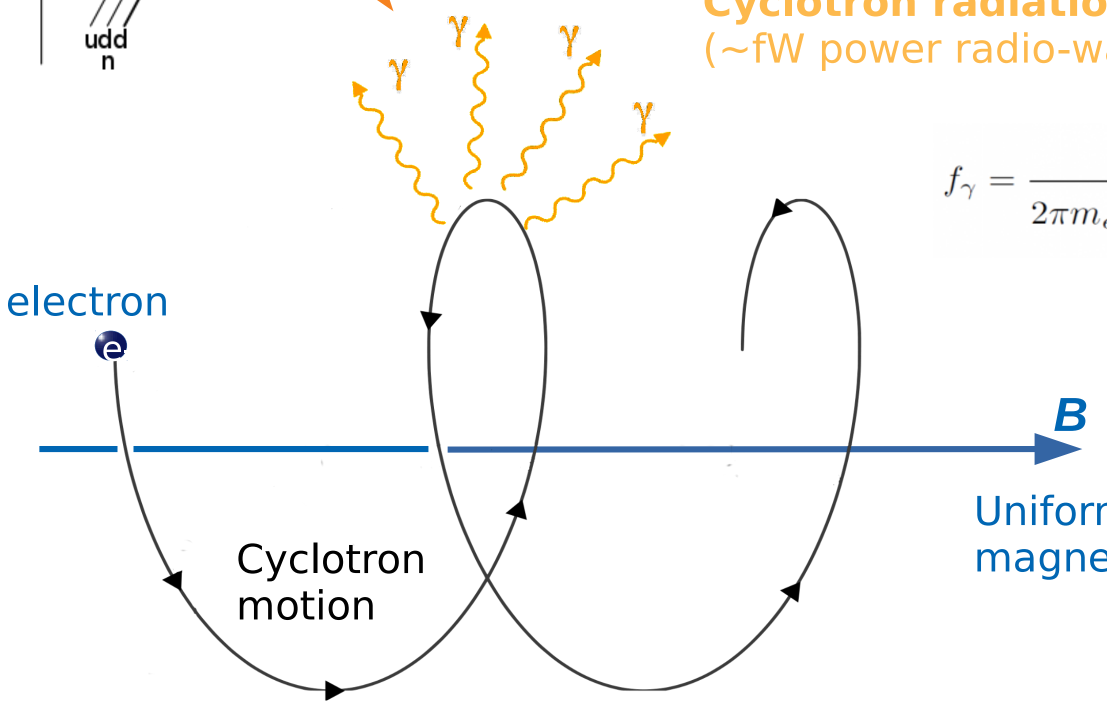
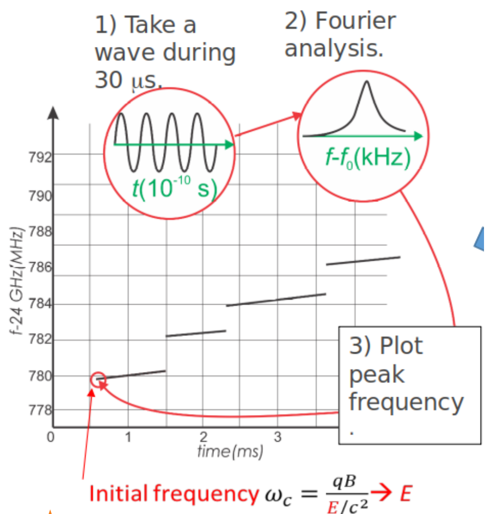


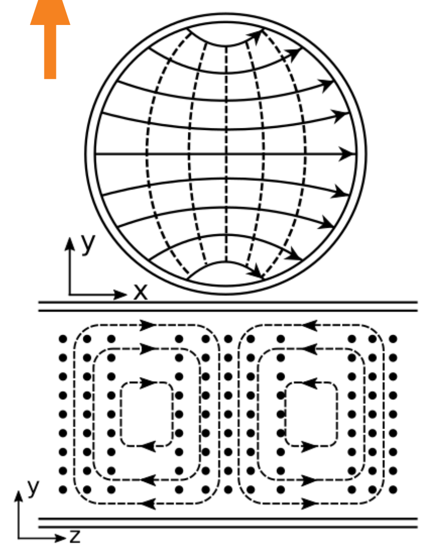
Measuring the kinetic energy of a beta, created in a nuclear decay, by observing the resulting cyclotron radiation of that beta as it moves in a strong magnetic field.

Cyclotron radiation
(~fW power radio-waves)

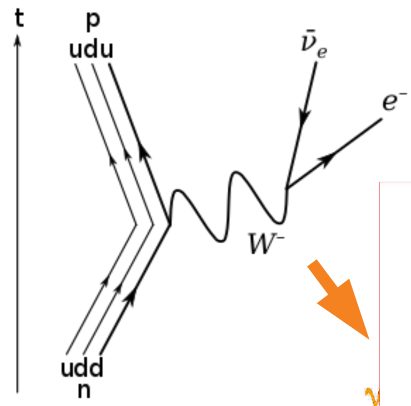
$$f_\gamma = \frac{eB}{2\pi m_e\left(1 + \frac{K}{m_e c^2}\right)}$$







What is CRES (Cyclotron Radiation Emission Spectroscopy)?



Measuring the kinetic energy of a beta, created in a nuclear decay, by observing the resulting cyclotron

Relativistic Cyclotron Radiation Detection of Tritium Decay Electrons as a New Technique for Measuring the Neutrino Mass

Benjamin Monreal
Department of Physics, University of California, Santa Barbara, CA[*]

Joseph A. Formaggio
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge MA
(Dated: November 1, 2018)

PROJECT 8

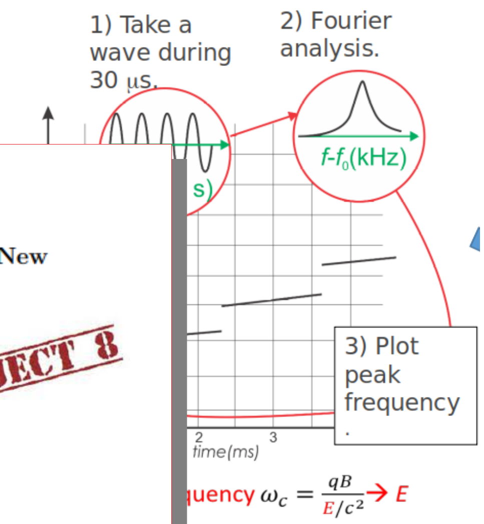
904.2860v1 [nucl-ex] 18 Apr 2009

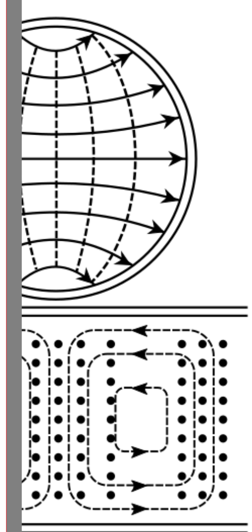
The shape of the beta decay energy distribution is sensitive to the mass of the electron neutrino. Attempts to measure the endpoint shape of tritium decay have so far seen no distortion from the zero-mass form, thus placing an upper limit of $m_{\nu\beta} < 2.3$ eV. Here we show that a new type of electron energy spectroscopy could improve future measurements of this spectrum and therefore of the neutrino mass. We propose to detect the coherent cyclotron radiation emitted by an energetic electron in a magnetic field. For mildly relativistic electrons, like those in tritium decay, the relativistic shift of the cyclotron frequency allows us to extract the electron energy from the emitted radiation. We present calculations for the energy resolution, noise limits, high-rate measurement capability, and systematic errors expected in such an experiment.

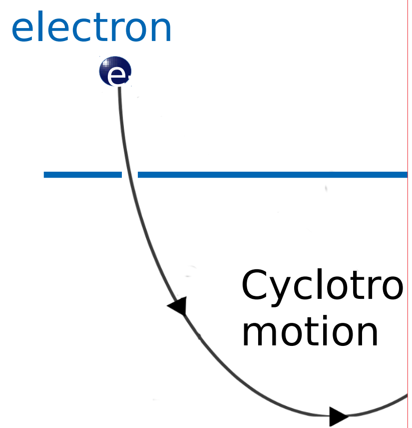
Introduction. Ever since Enrico Fermi's theory of beta decay [1], it has been known that the neutrino mass has an effect on the decay kinematics. Measurements have always suggested that this mass is very small, with successive experiments giving upper limits [2][3], most recently $m_{\nu\beta} < 2.3$ eV. The upcoming KATRIN tritium experiment[4] anticipates having a sensitivity of 0.20 eV at 90% confidence. Oscillation experiments, however, tell us with great confidence that the tritium beta decay neutrinos are an admixture of at least two mass states, at least one of which has a nonzero mass, such that the effective mass must satisfy $m_{\nu\beta} > 0.005$ eV under the normal hierarchy or $m_{\nu\beta} > 0.05$ eV in the inverted hierarchy [5]. The neutrino mass is an important component of precision cosmology [6], and it may reflect physics at the GUT scale [7]; this provides a strong motivation to find a way

field direction. Second, the electron emits coherent cyclotron radiation [9] at frequency $\omega = 2\pi f$; for a wide range of parameters, the power emitted is large enough to be detectable but not so large as to rapidly change the electron's energy. This radiation spectrum therefore is sensitive to the electron energy, and its detection gives us a new form of non-destructive spectroscopy.

Experimental concept. Consider the arrangement shown in Fig. 1. A low-pressure supply of tritium gas is stored in a uniform magnetic field generated by a solenoid magnet. Tritium decay events release electrons with $0 < E < 18575$ eV (and velocity $0 < \beta < \beta_e$ where $\beta_e = 0.2625$) in random directions θ relative to the field vector. The electrons follow spiral paths with a velocity component $v_{||} = \beta cos(\theta)$ parallel to the magnetic field. Each electron emits microwaves at frequency ω and a



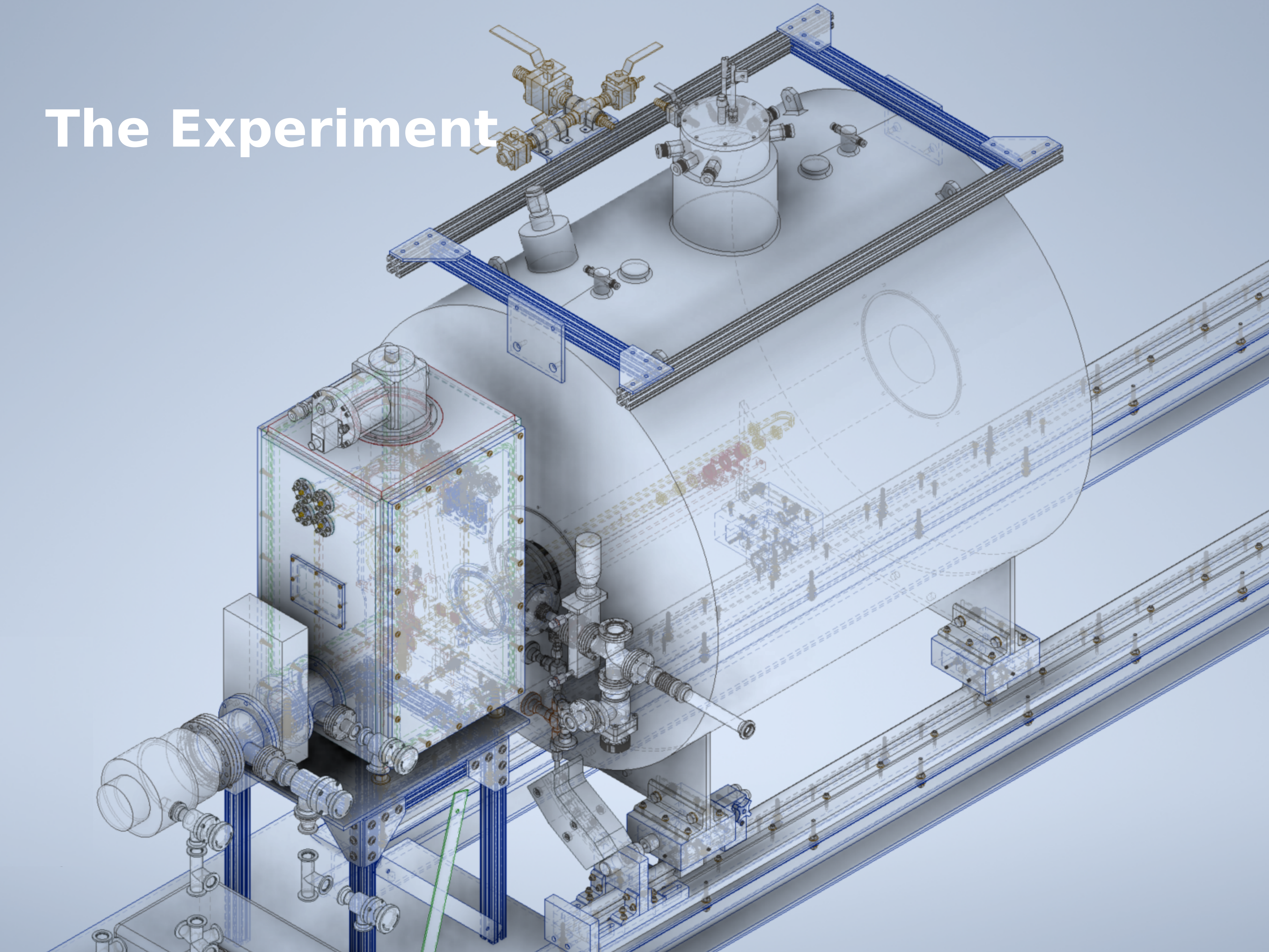


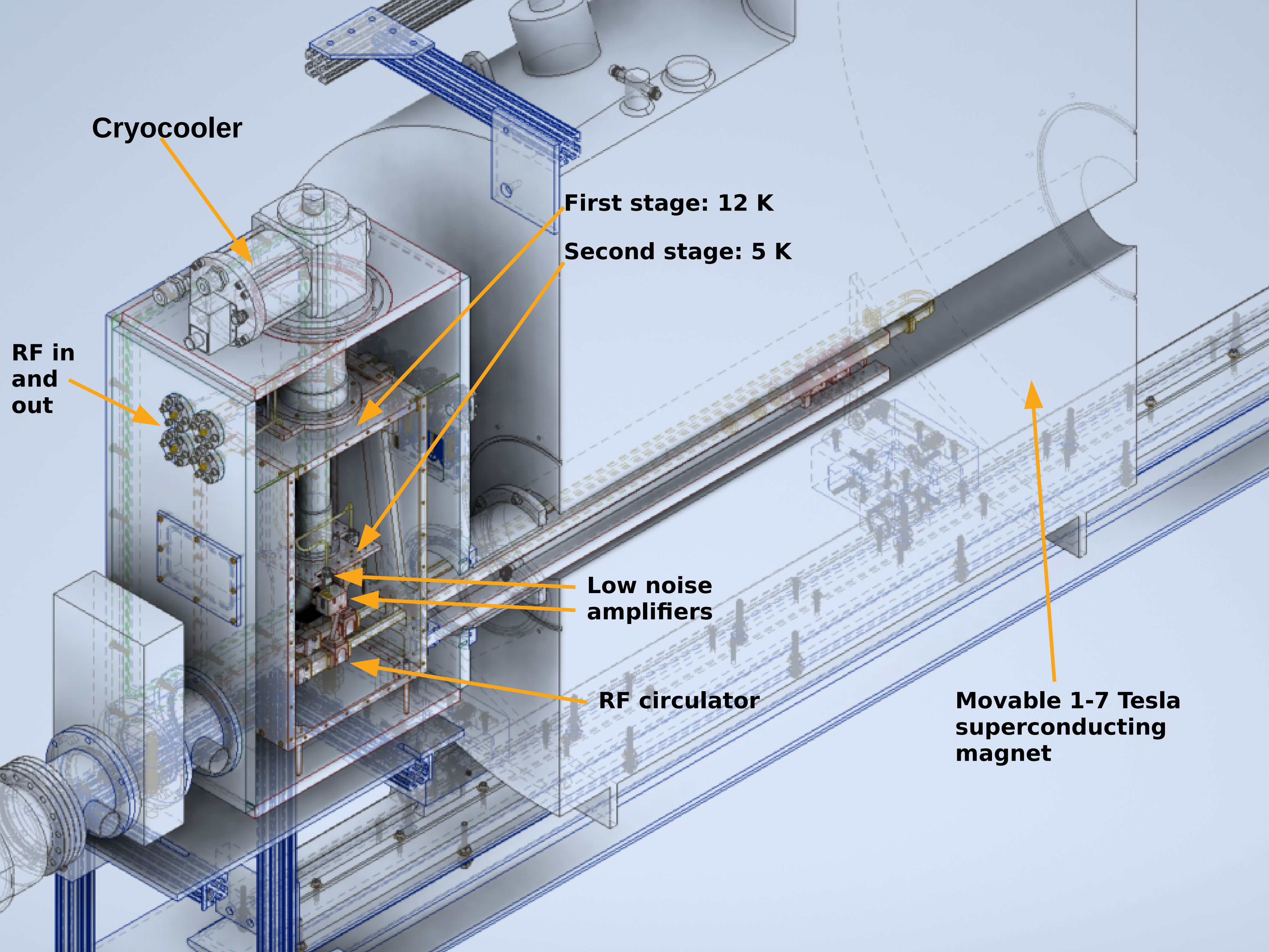


^{6}He-CRES Experimental program overview

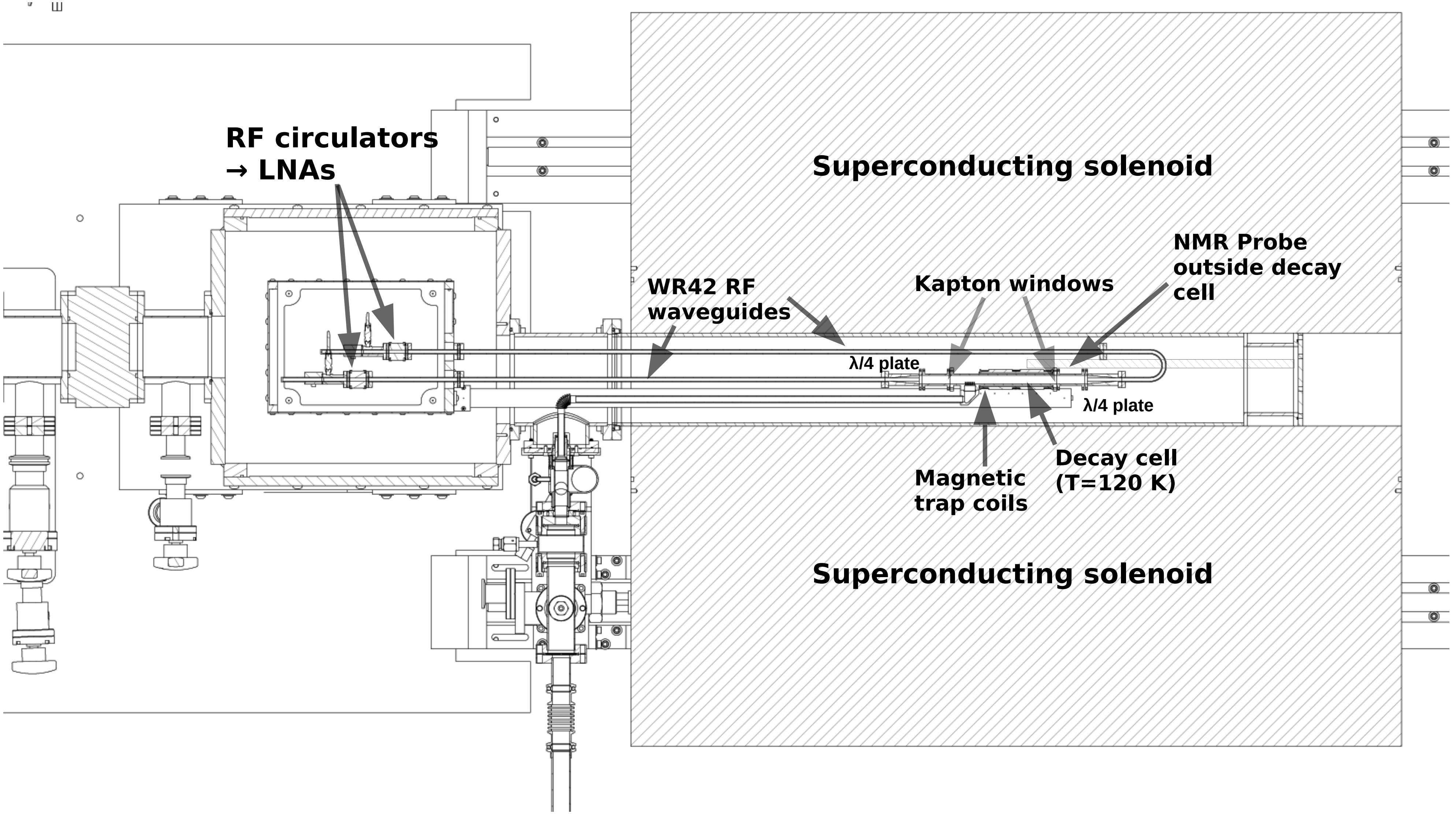
- Use CRES to preform broadband beta spectrum measurements.
- Fit spectrum to get Fierz Interference term, *b*.
- Complementary nuclei for BSM scalar and tensor couplings. (^{6}He, ^{19}Ne, [^{14}O maybe later])
  - Phase 1: Take ratio
  - Phase 2: Extract b independently for each decay we study.

The Experiment



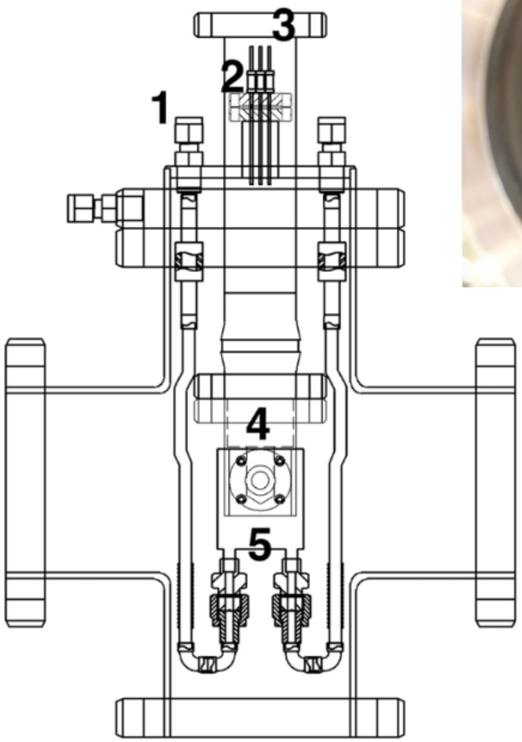

Cryocooler
First stage: 12 K
Second stage: 5 K
RF in and out
Low noise amplifiers
RF circulator
Movable 1-7 Tesla superconducting magnet

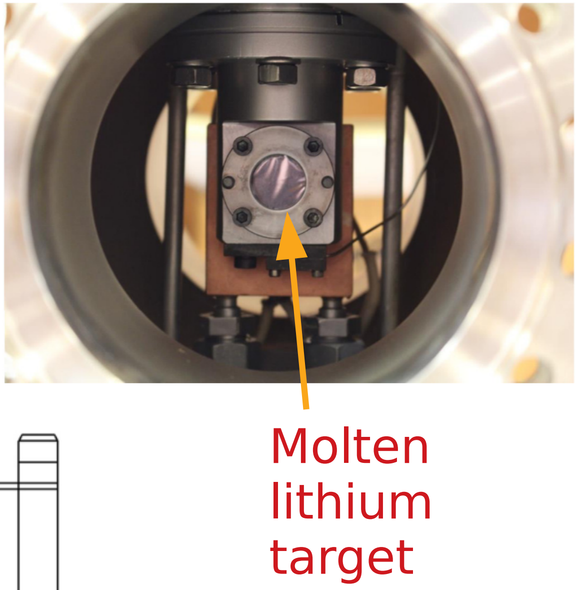
RF System

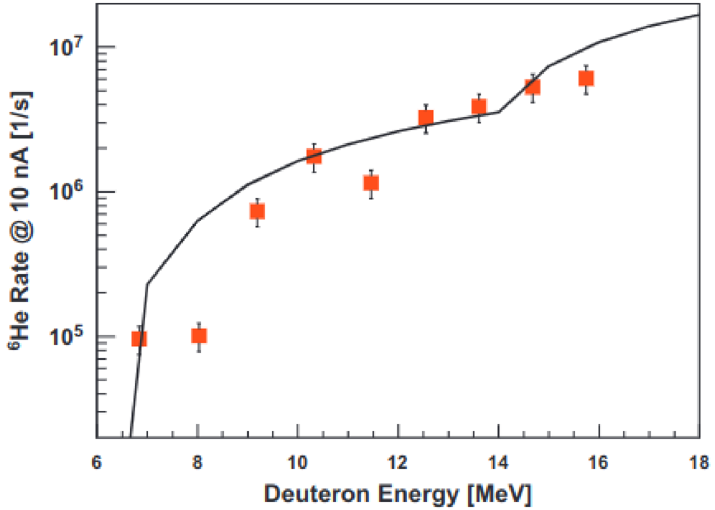


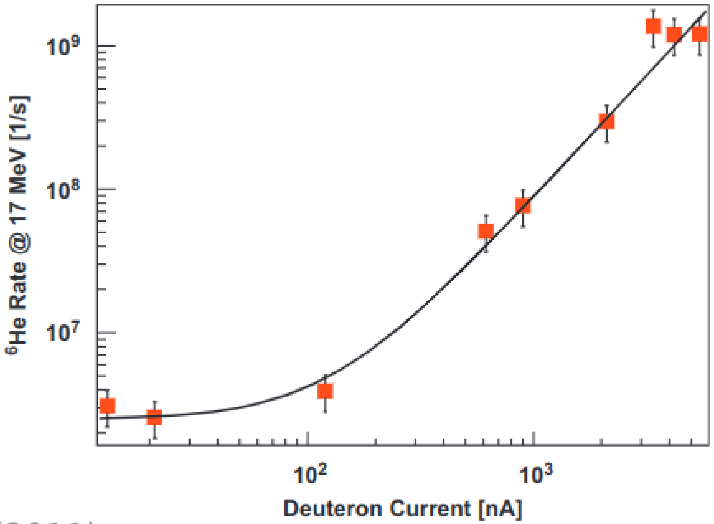
RF circulators
→ LNAs
Superconducting solenoid
NMR Probe
outside decay
cell
WR42 RF
waveguides
Kapton windows
λ/4 plate
λ/4 plate
Decay cell
(T=120 K)
Magnetic
trap coils
Superconducting solenoid

^{6}He Source: ^{7}Li(d,^{3}He)^{6}He



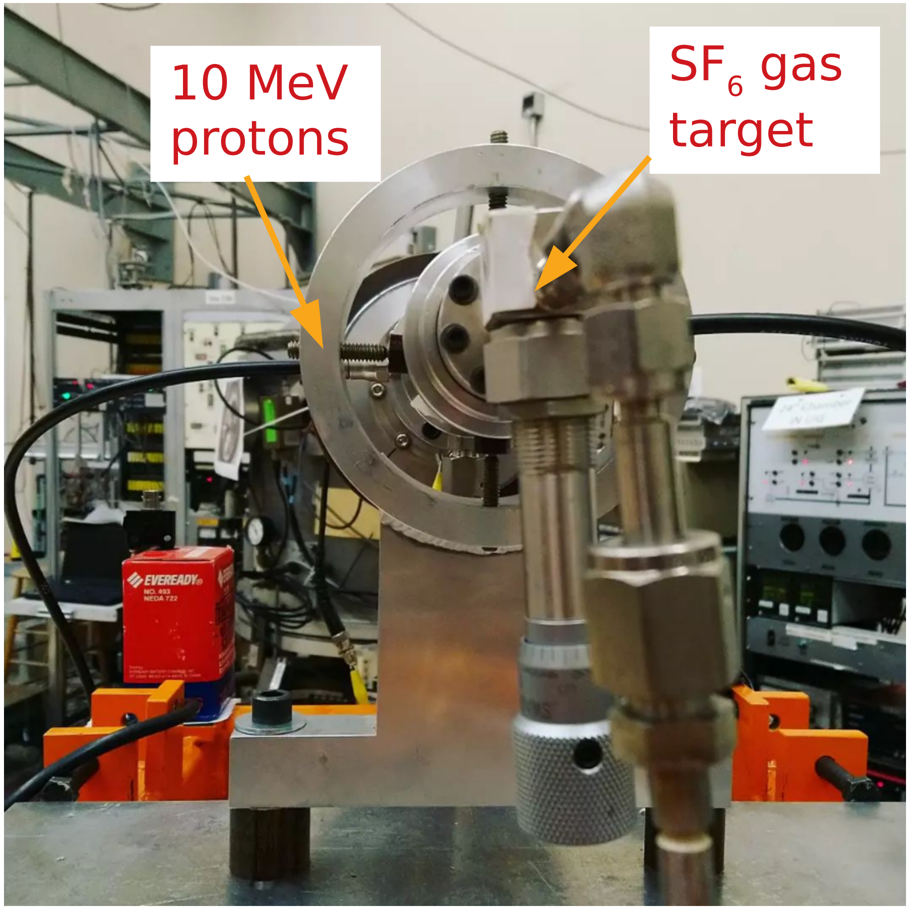


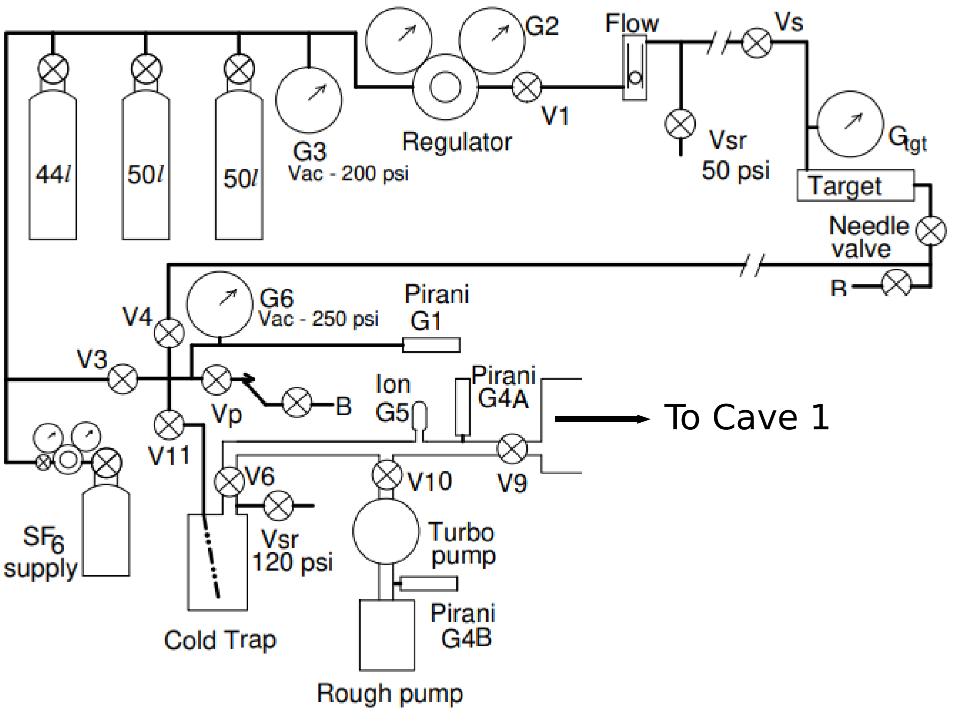




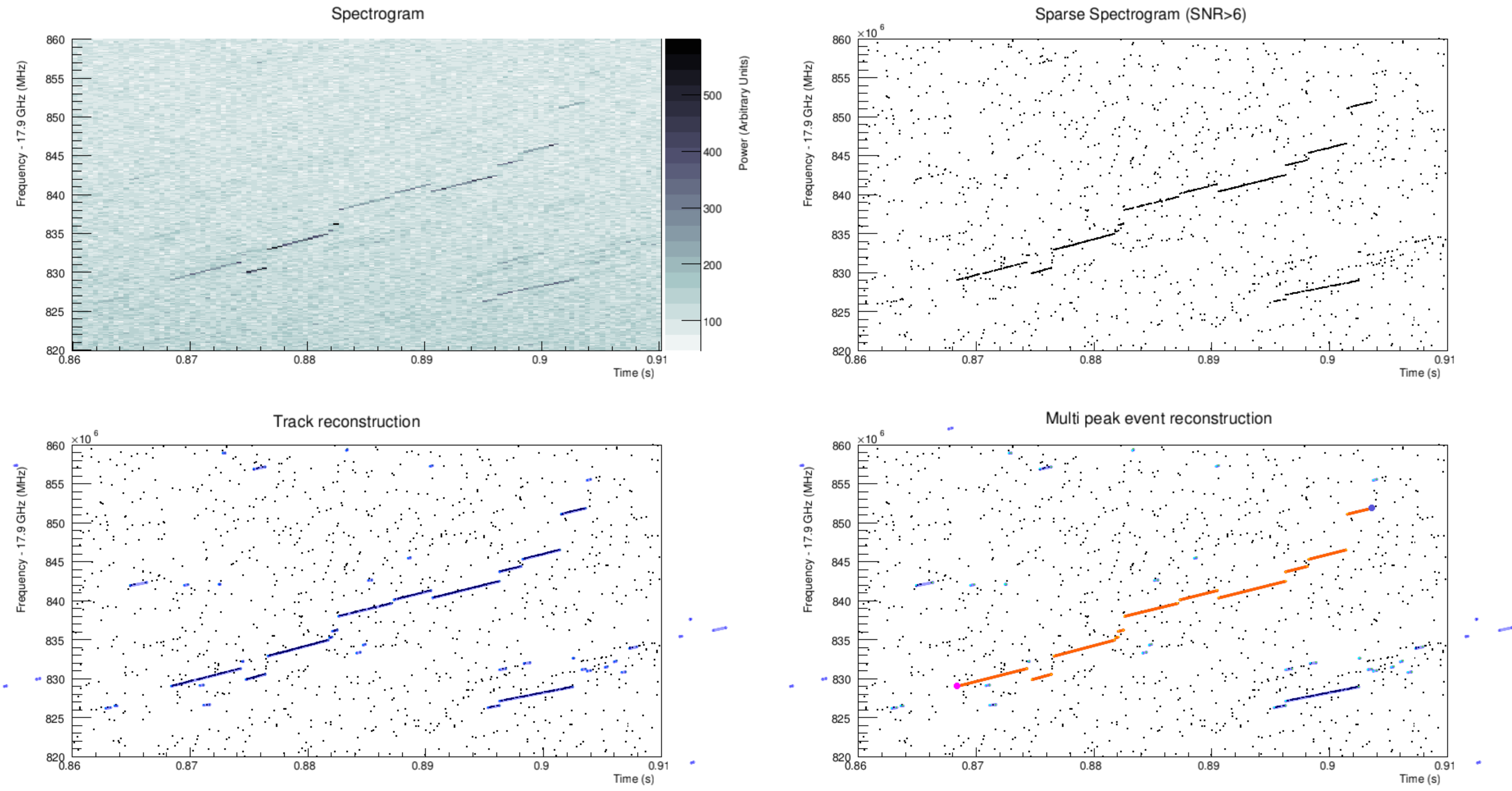
A. Knecht et al., Nucl. Instrum. Methods Phys. Res., Sect. A 660, 43 (2011)

^{19}Ne Source: ^{19}F(p,n)^{19}Ne





Analysis: Track and event reconstruction (<100 keV)



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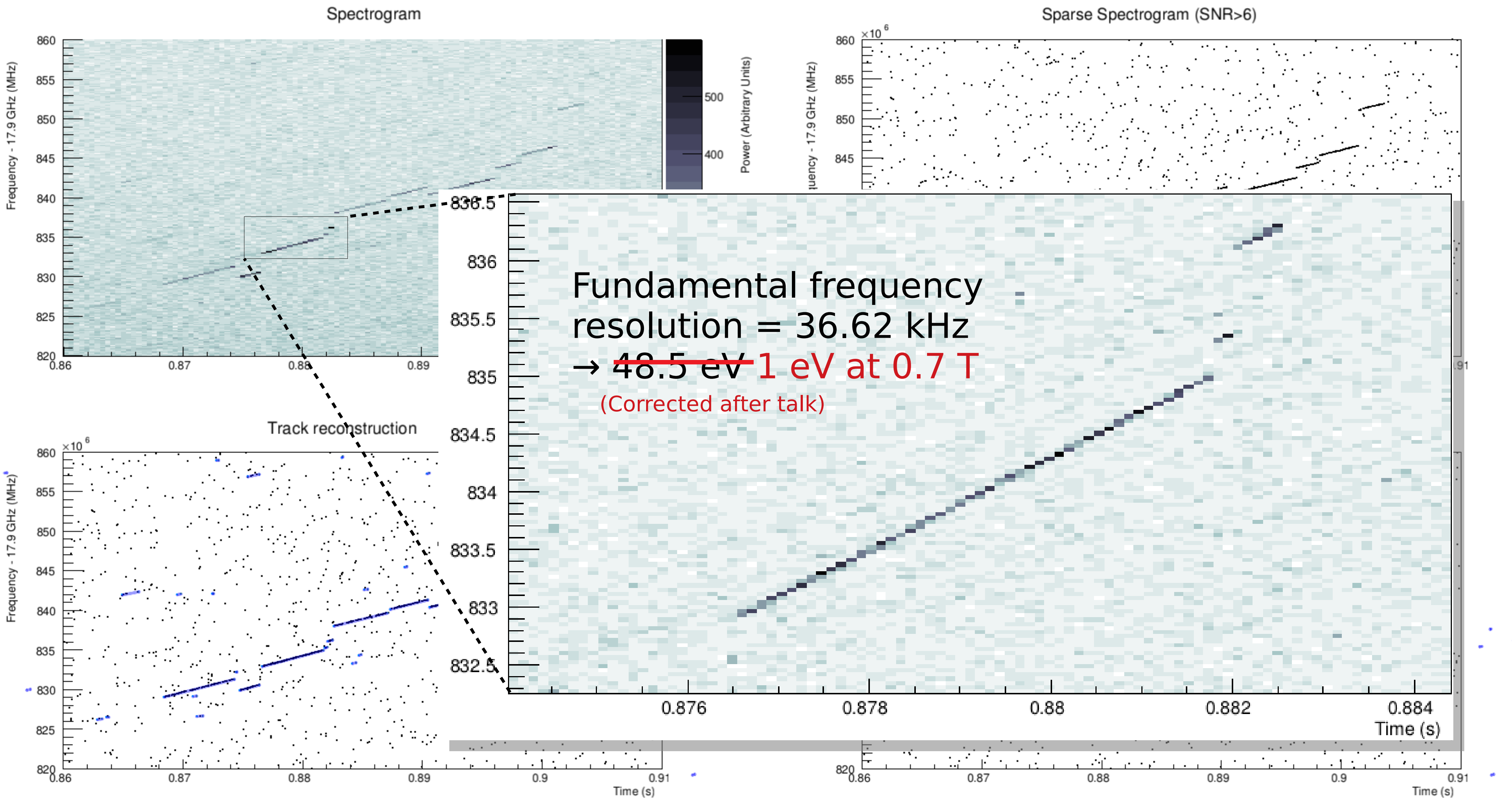
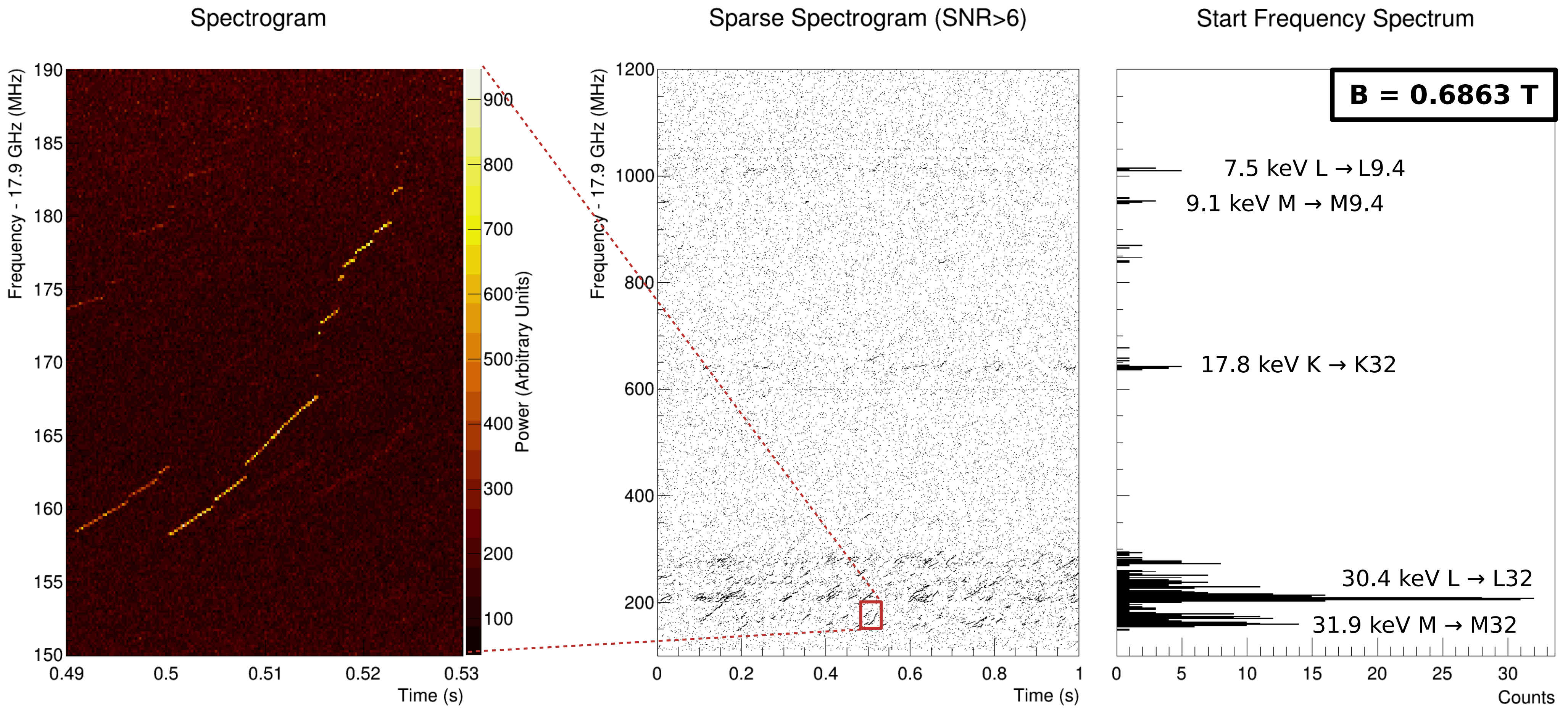
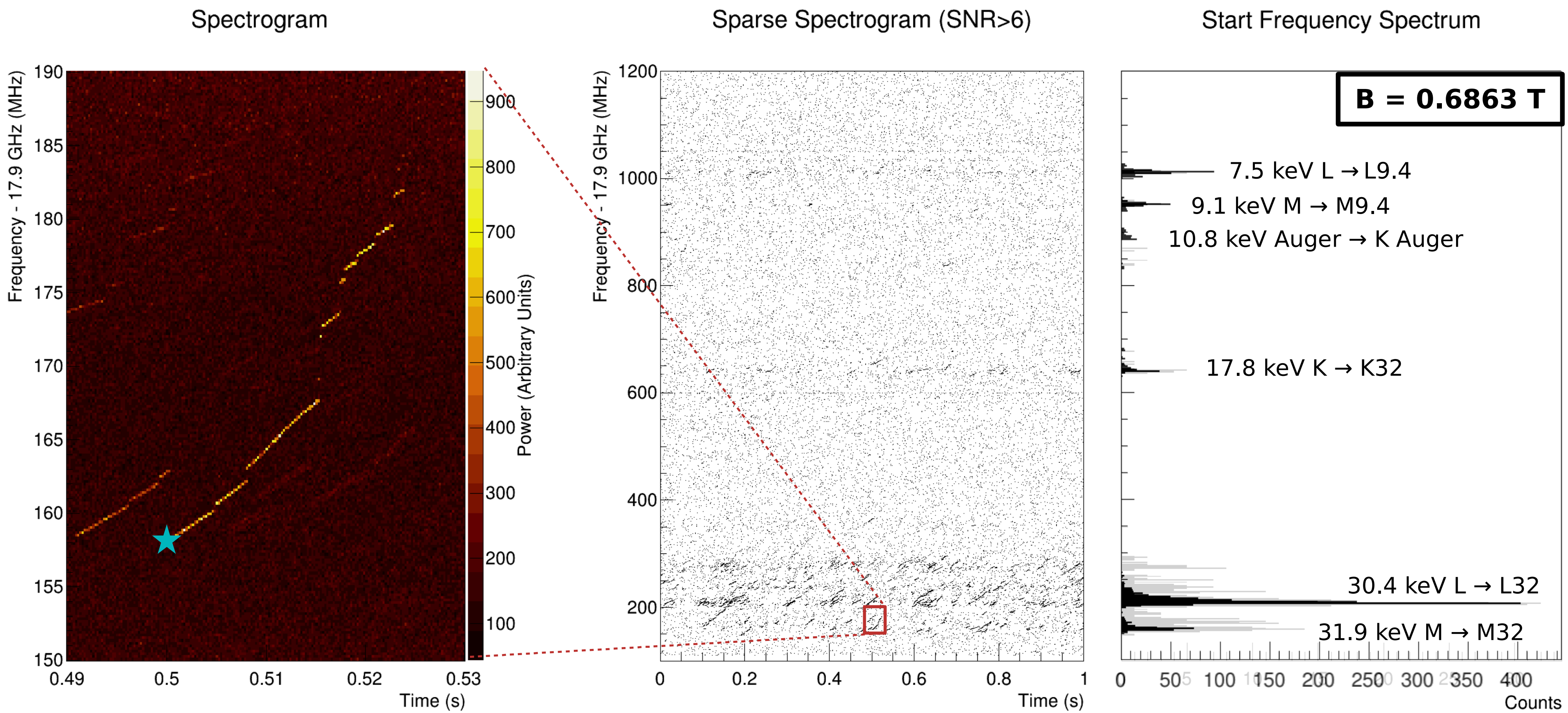


Kr Data and track reconstruction



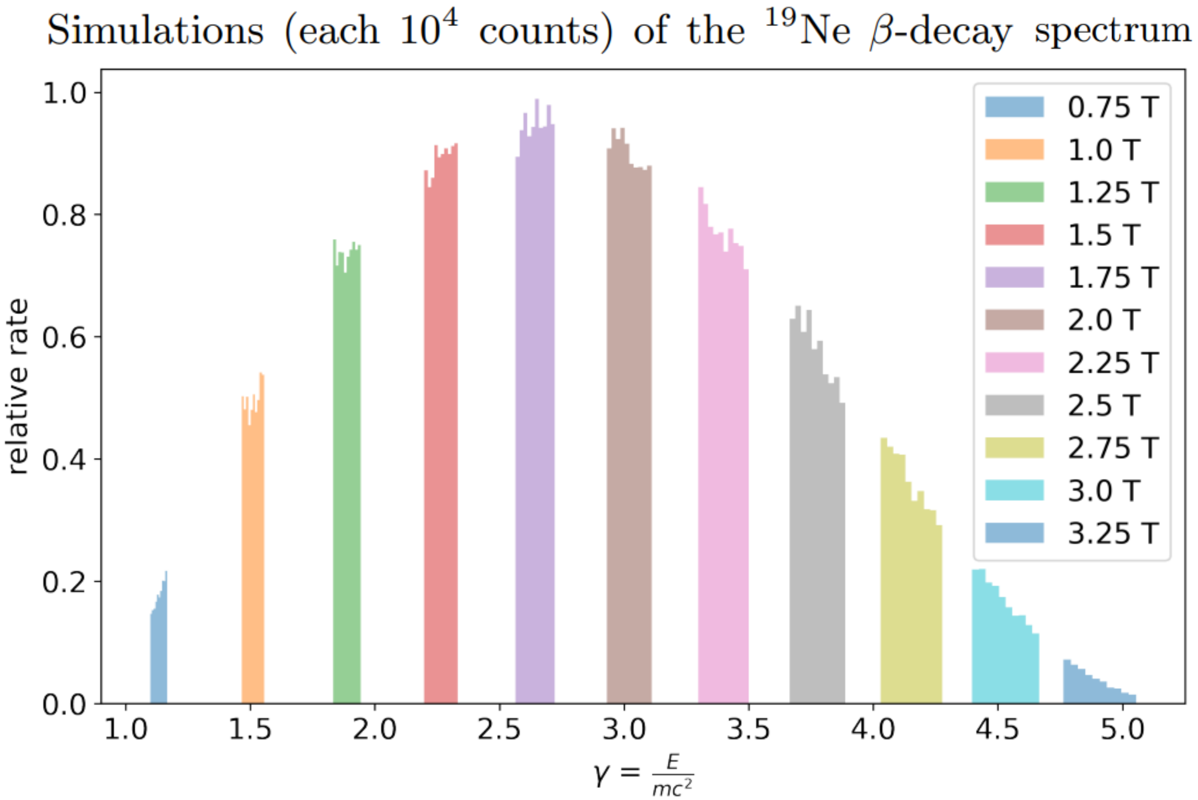
$$f_\gamma = \frac{eB}{2\pi m_e \left(1 + \frac{K}{m_e c^2}\right)}$$

Kr Data and EVENT reconstruction



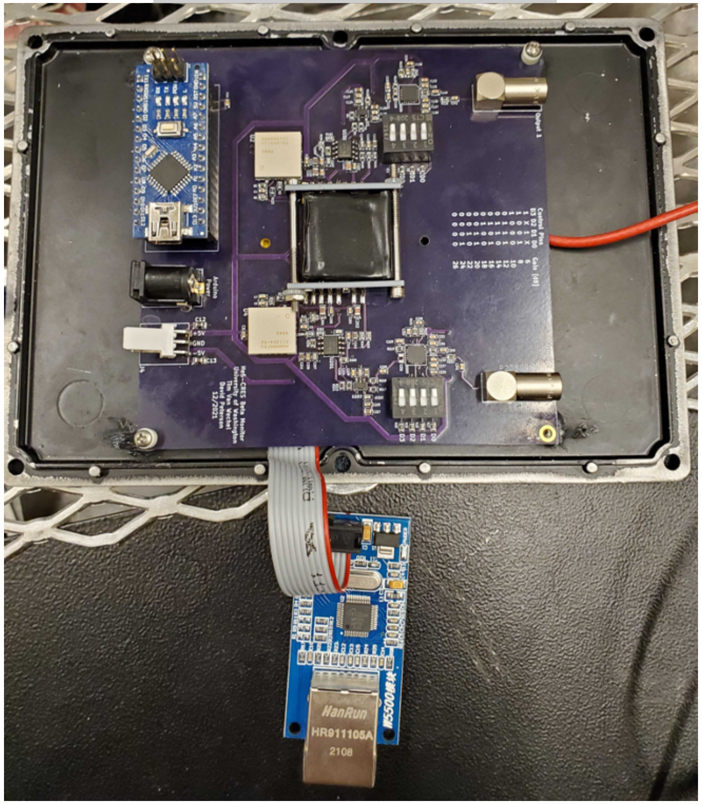
$$f_\gamma = \frac{eB}{2\pi m_e \left(1 + \frac{K}{m_e c^2}\right)}$$

Measuring a beta spectrum in pieces

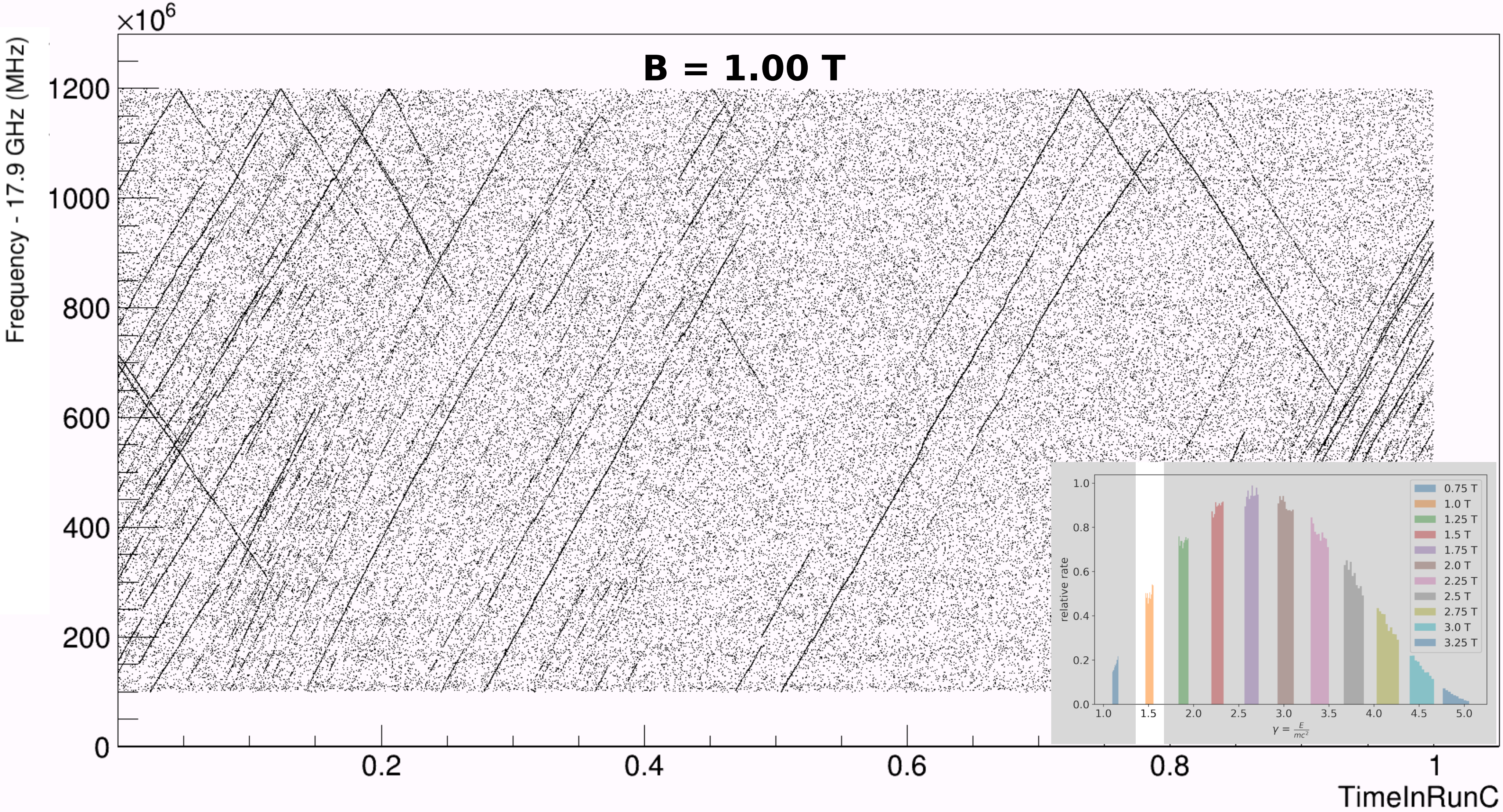


^{19}Ne endpoint ~ 2.2 MeV
^{6}He endpoint ~ 3.5 MeV

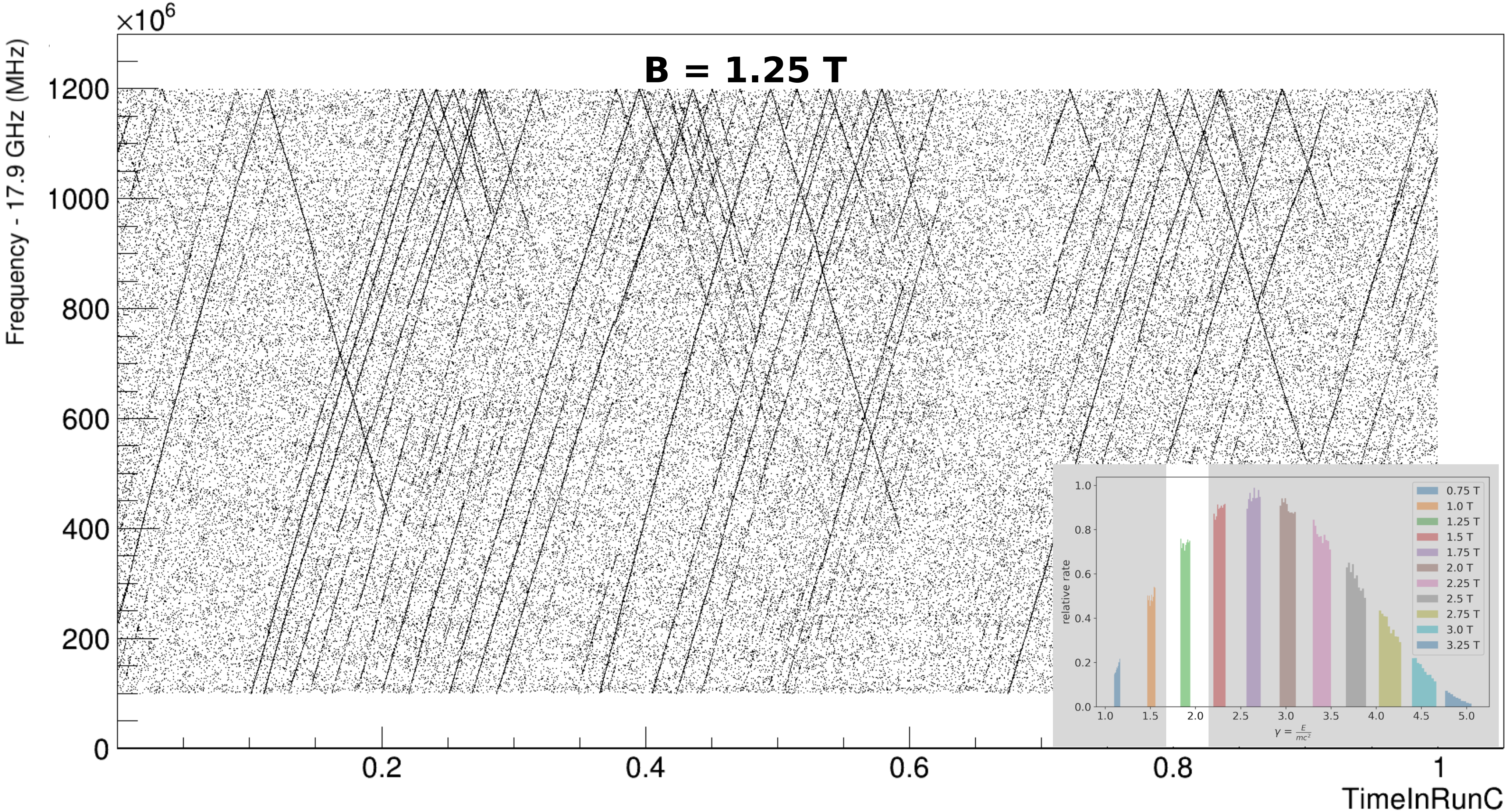
Development of a stable beta monitor with SIPMs



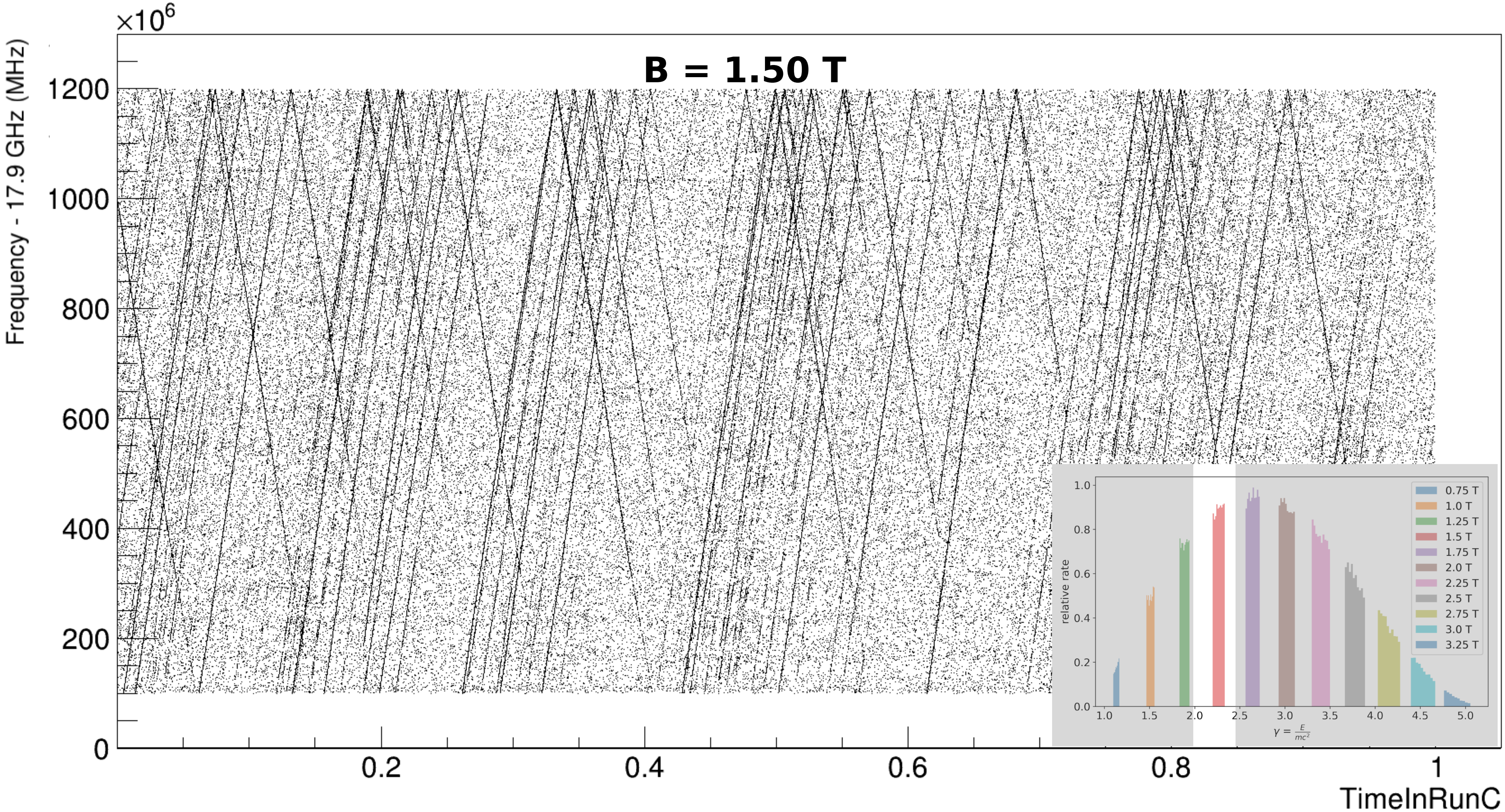
Higher energies → higher slopes



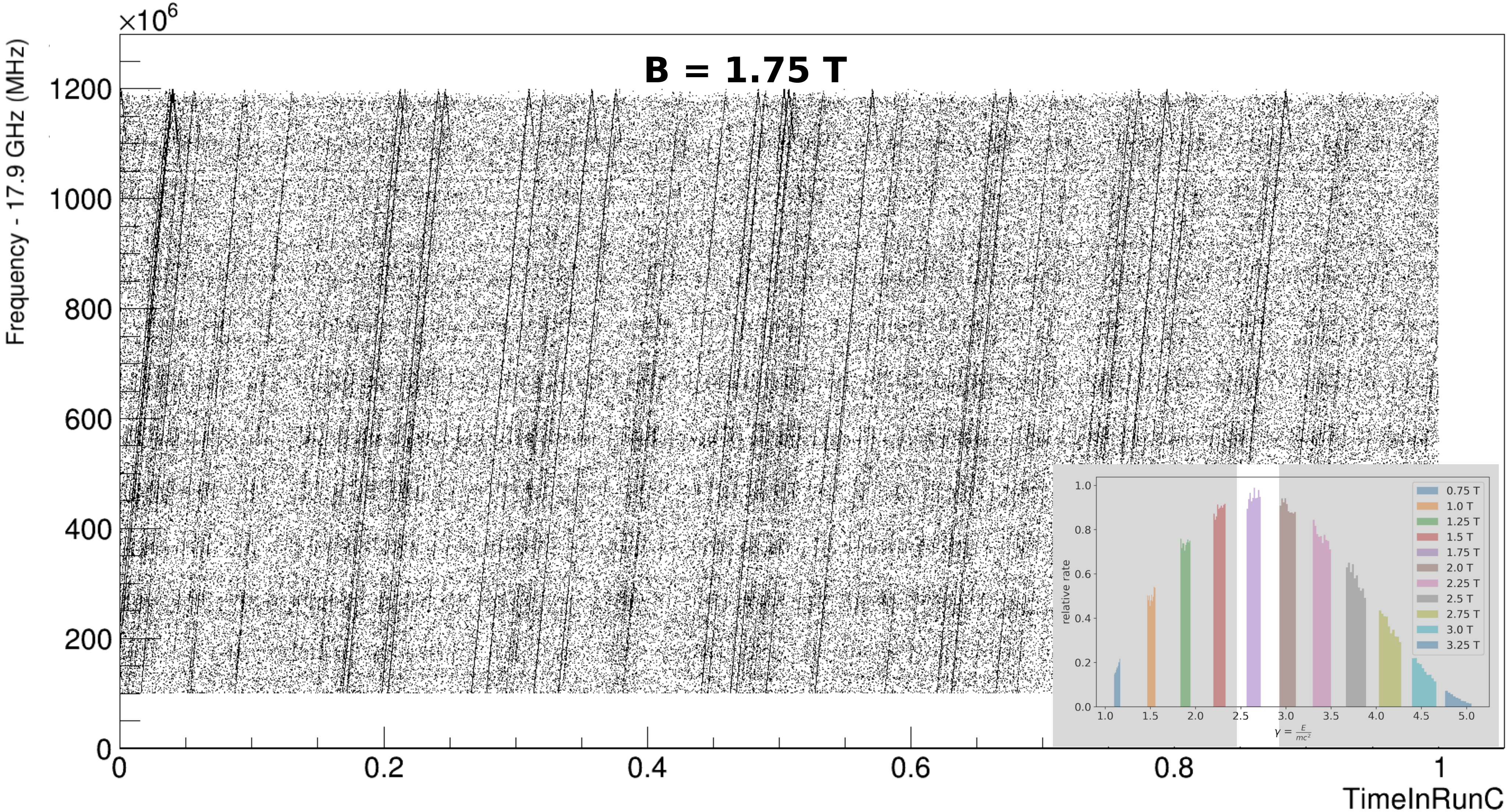
Higher energies → higher slopes



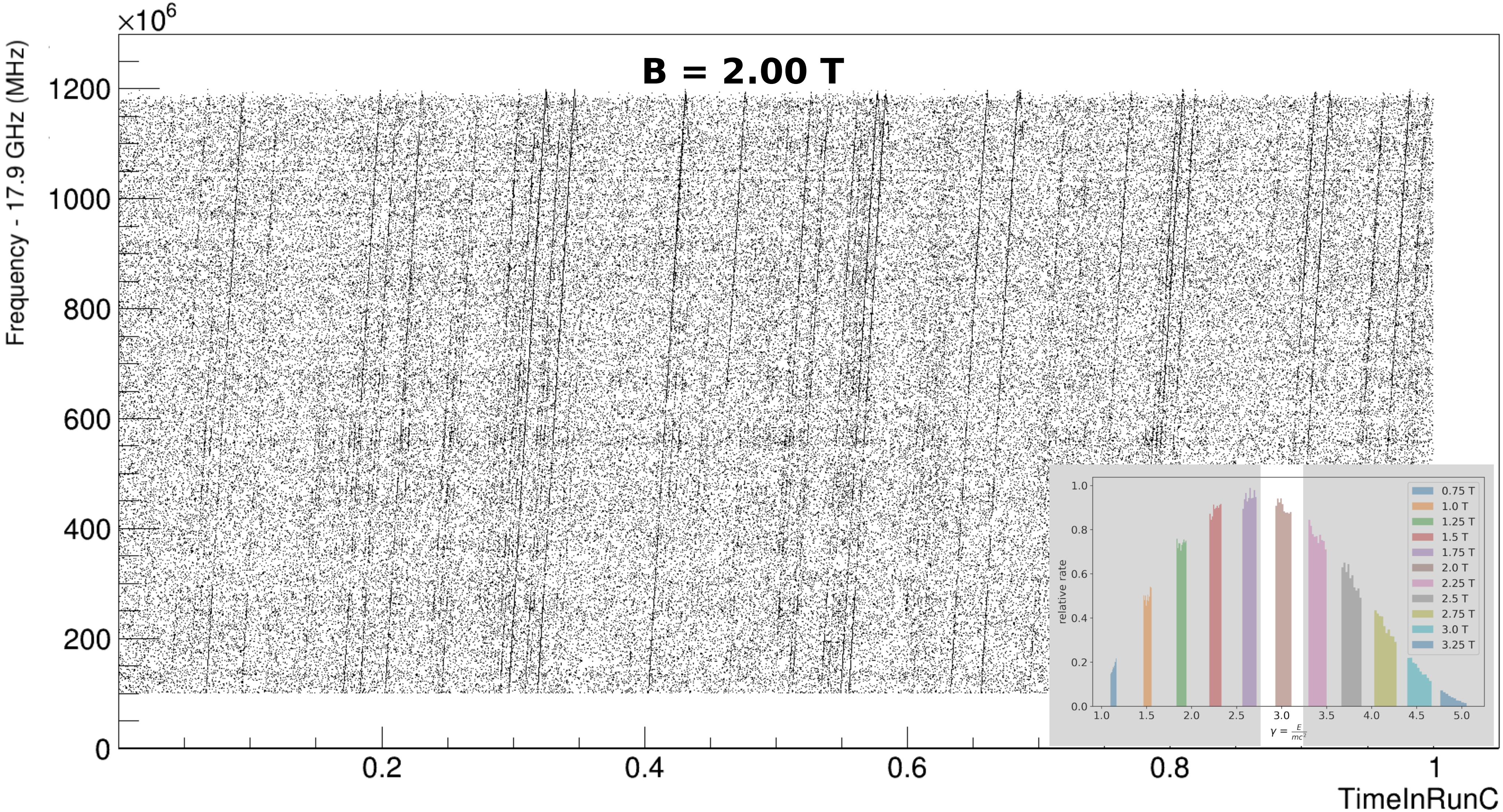
Higher energies → higher slopes



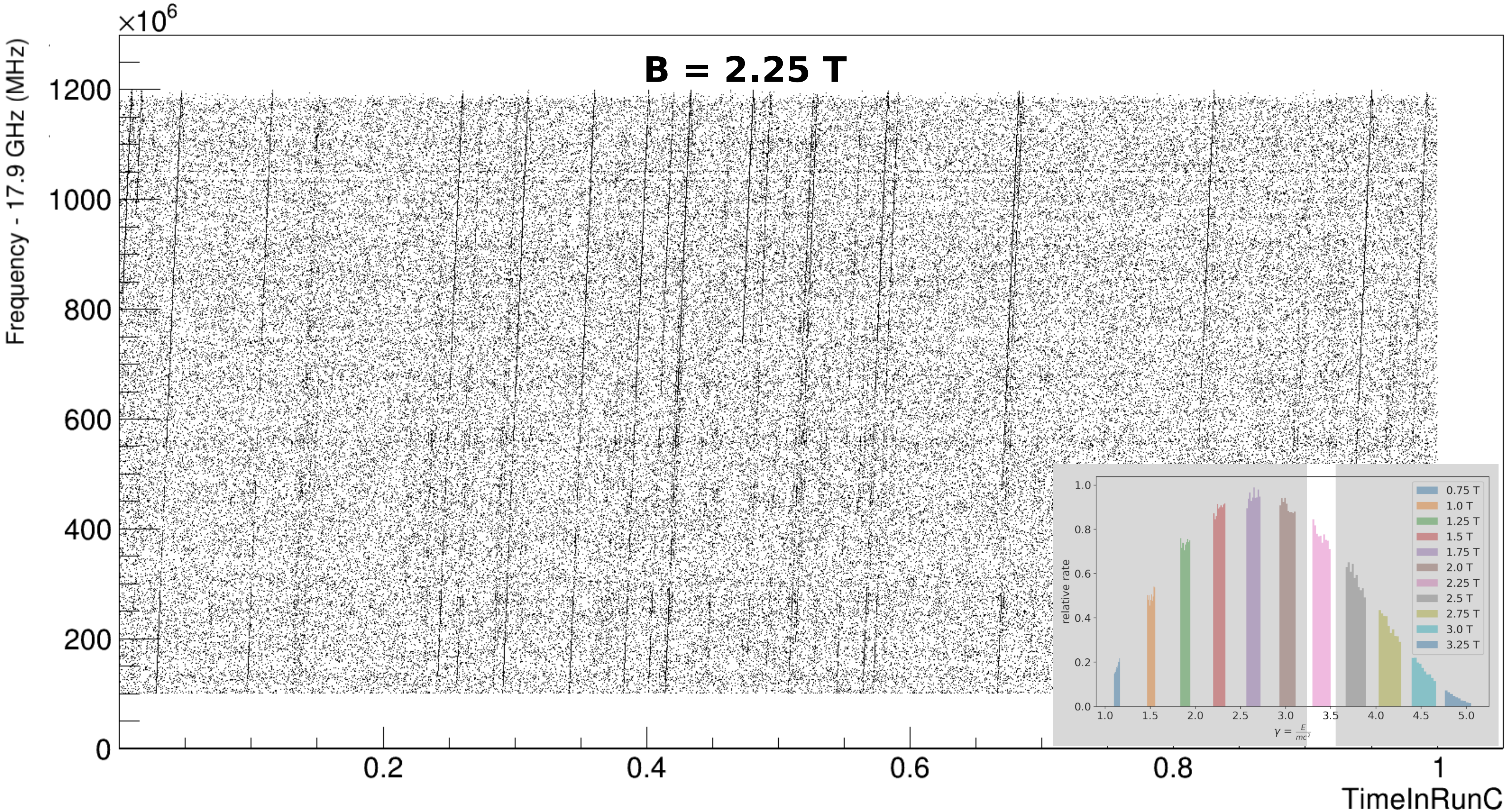
Higher energies → higher slopes



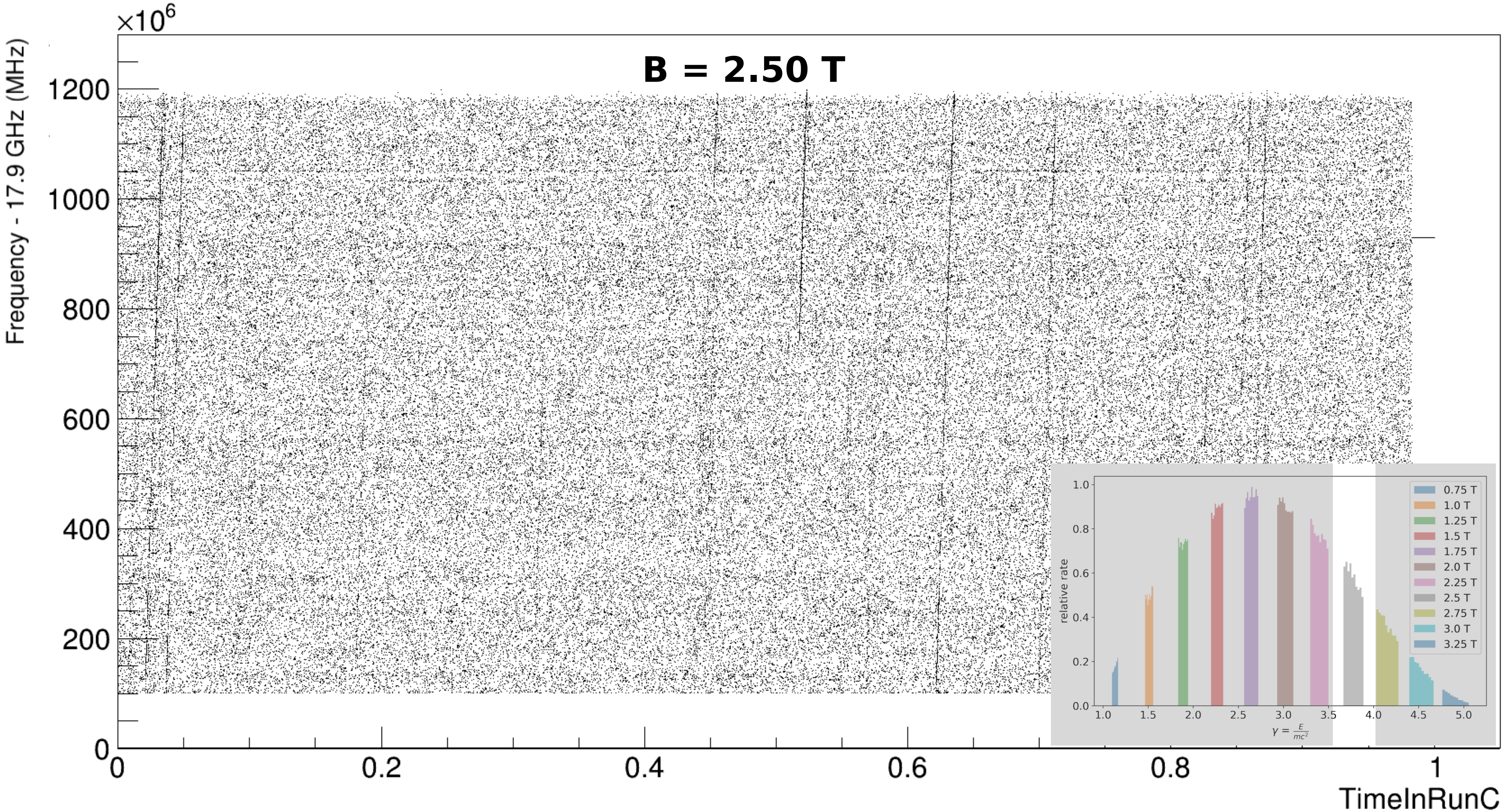
Higher energies → higher slopes



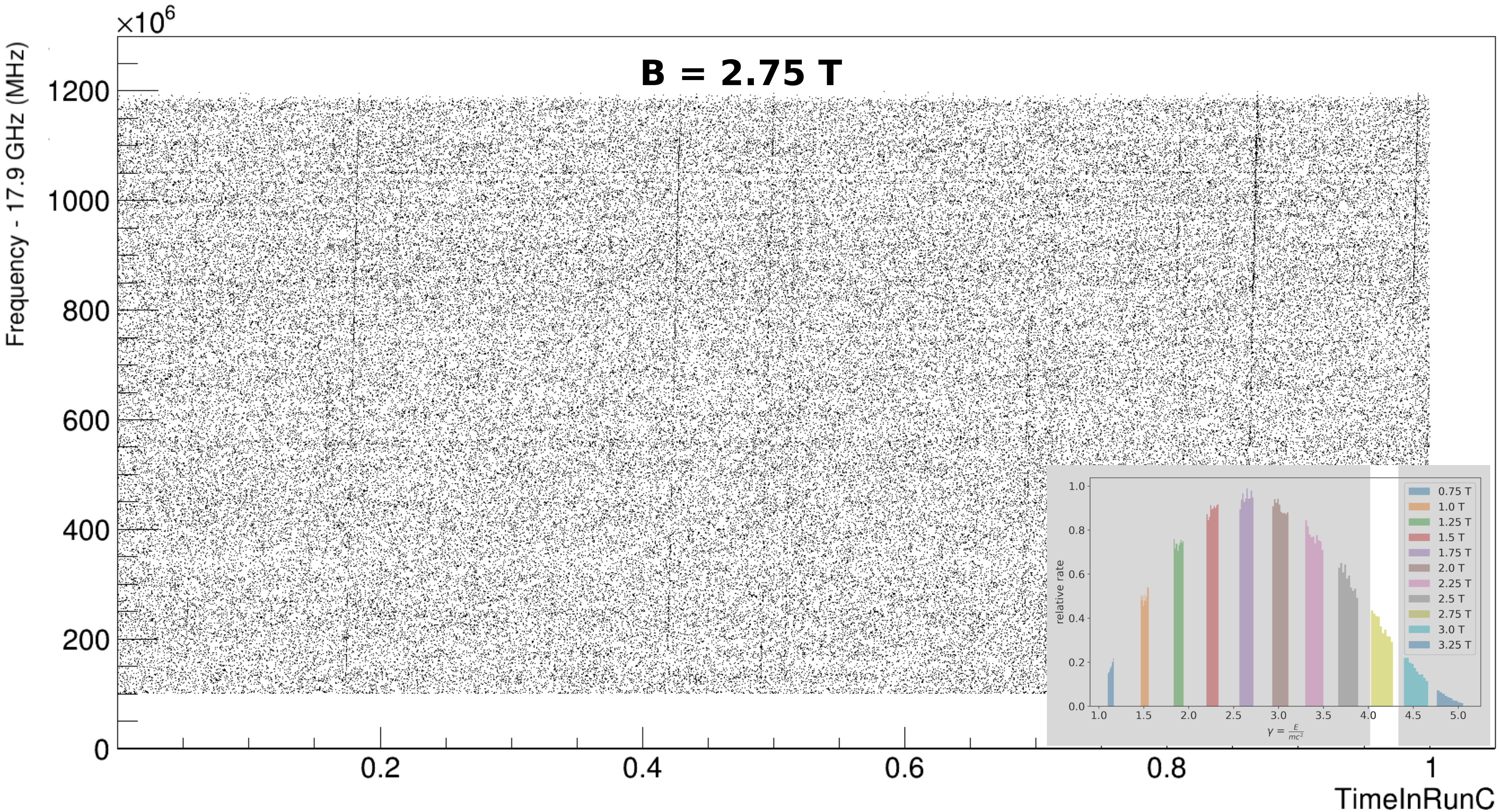
Higher energies → higher slopes



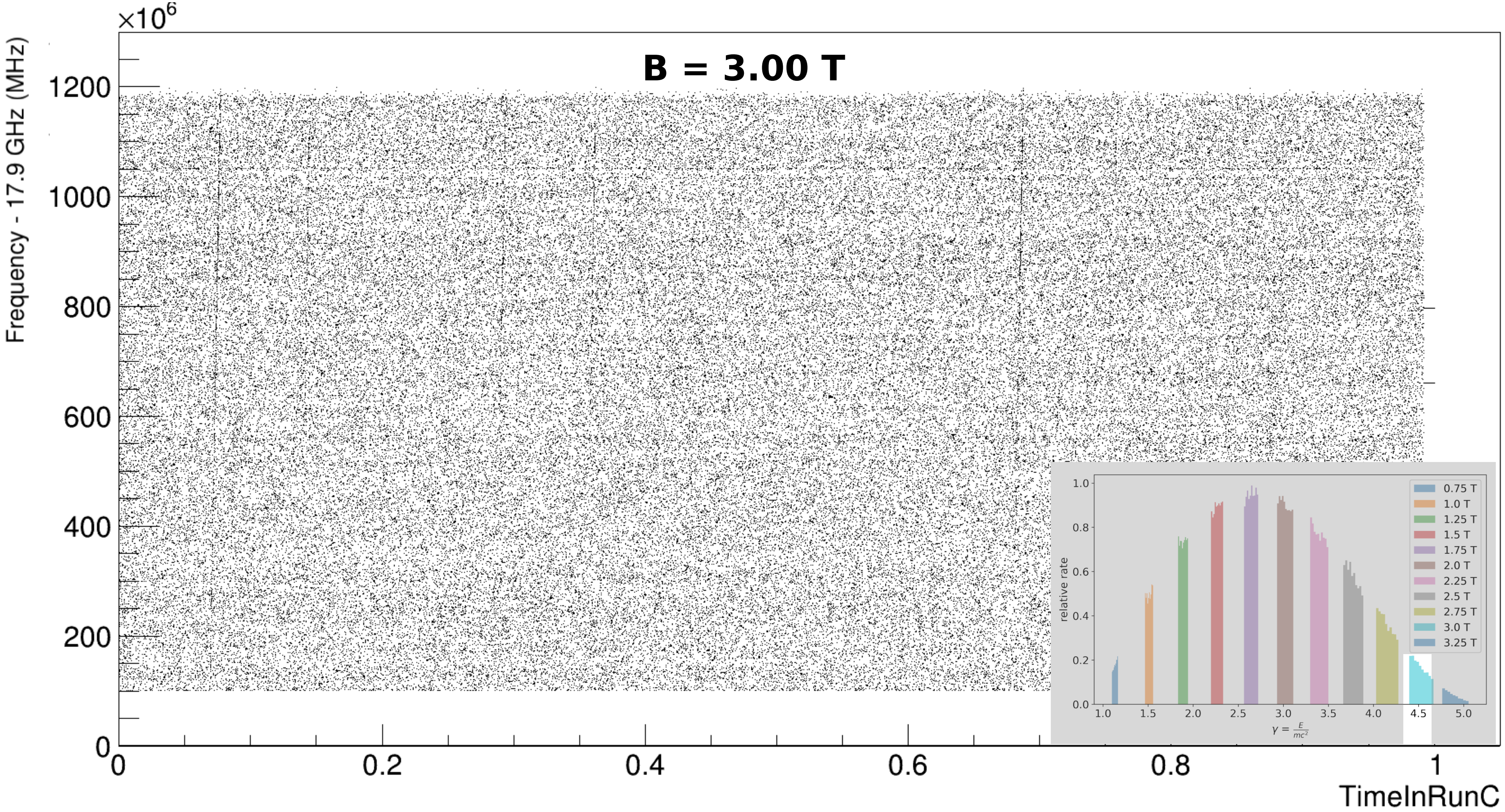
Higher energies → higher slopes



Higher energies → higher slopes



Higher energies → higher slopes

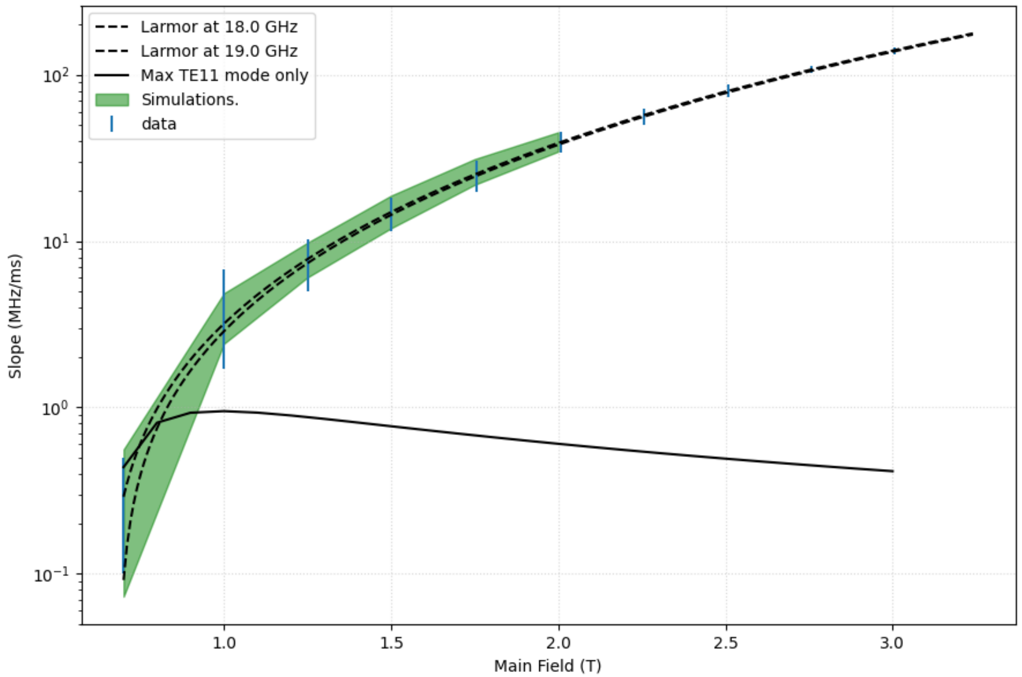


Higher energies → higher slopes

Track slope is a measure of the true power loss of the beta.

$$\frac{df}{dt} = \frac{f}{E}\frac{dE}{dt}$$

- We observed much higher slopes than expected
- Required us to develop robust description of radiation of a relativistic charged particle in a waveguide
- Average slope well described by relativistic Larmor power radiated in free space



Total power radiated in a circular waveguide:

$$P_{\text{tot}} = P_{\text{TE}} + P_{\text{TM}}$$

$$P_{\text{TE}} = \frac{q^2\omega_c\beta_\perp^2}{a^2}\,\text{Re}\left[\sum_{n,m=1}^{\infty}\frac{np_{nm}'^2}{(p_{nm}'^2 - n^2)\sqrt{n^2\omega_c^2 - (p_{nm}'/a)^2}}\frac{J_n'^2(p_{nm}'R_c/a)}{J_n^2(p_{nm}')}\right]$$

$$P_{\text{TM}} = q^2\omega_c\,\text{Re}\left[\sum_{n,m=1}^{\infty}\frac{n\sqrt{n^2\omega_c^2 - (p_{nm}/a)^2}}{p_{nm}^2}\frac{J_n^2(p_{nm}R_c/a)}{J_n'^2(p_{nm})}\right]$$

Larmor power radiated in free space:

$$P_{\text{Larmor}} = \frac{q^2\omega_c^2\beta_\perp^2\gamma^4}{6}$$

Experiment status

He6-CRES phases

Phase I: proof of principle
Observe ^{83}Kr lines
Understand RF issues and spectra
Study power distribution
Show detection of cycl. radiation from ^{6}He

Done!

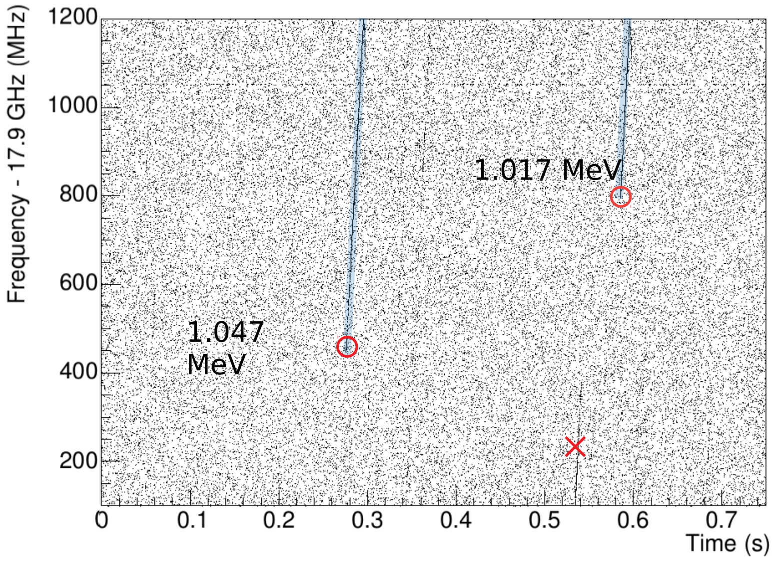
Recently demonstrated:
- 5 keV- 5 MeV capability of detection
- Measurements of $\beta\pm$ from 6He and 19Ne
- Study frequency dependent gain

Phase II: first measurement ($b < 10^{-3}$)
^{6}He and ^{19}Ne measurements.
Develop ^{14}O source.

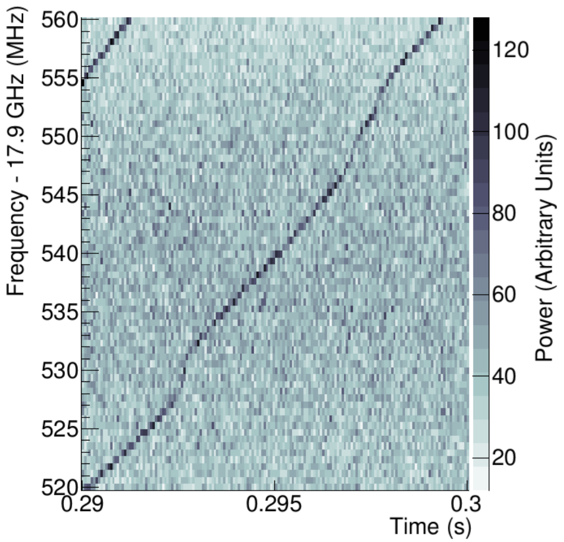
Started

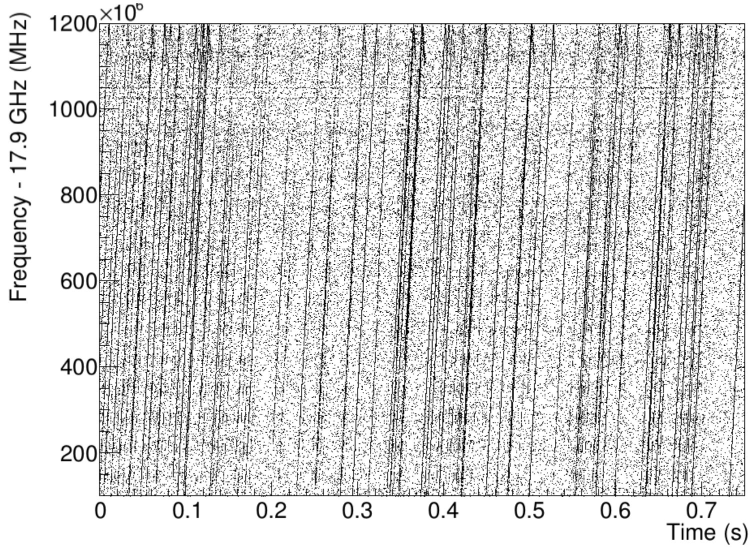
Phase III: ultimate measurement ($b < 10^{-4}$)
^{14}O measurements.
ion-trap for no limitation from geometric effect.

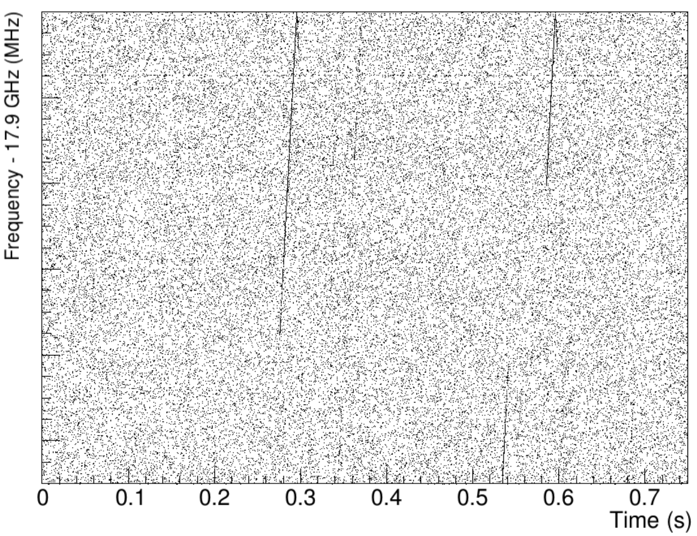
^{19}Ne data at 2.00T!

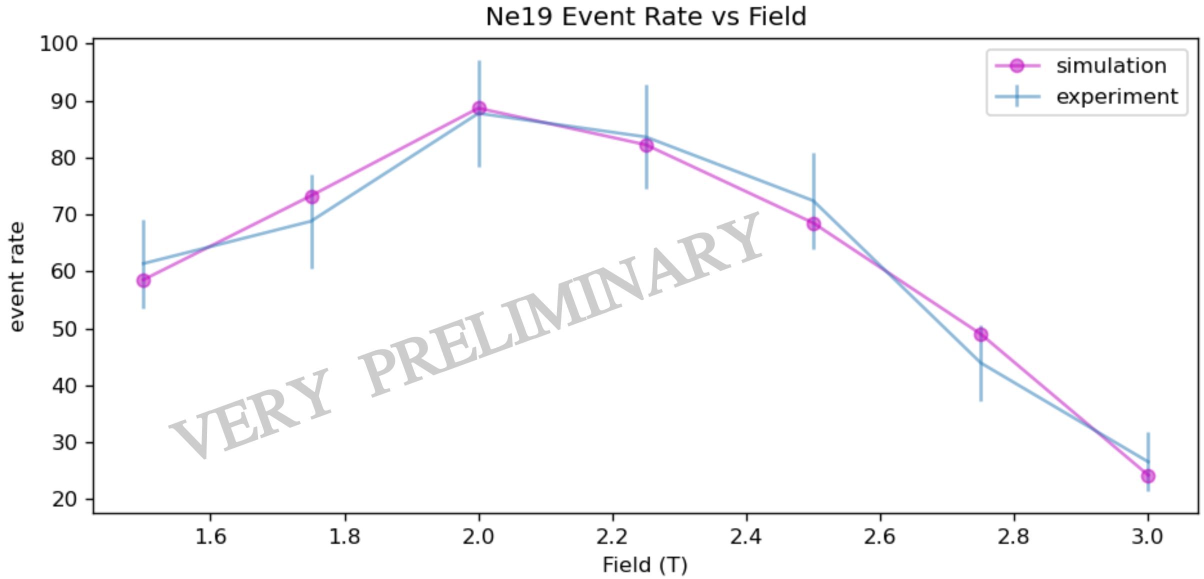


We are beginning to take data!

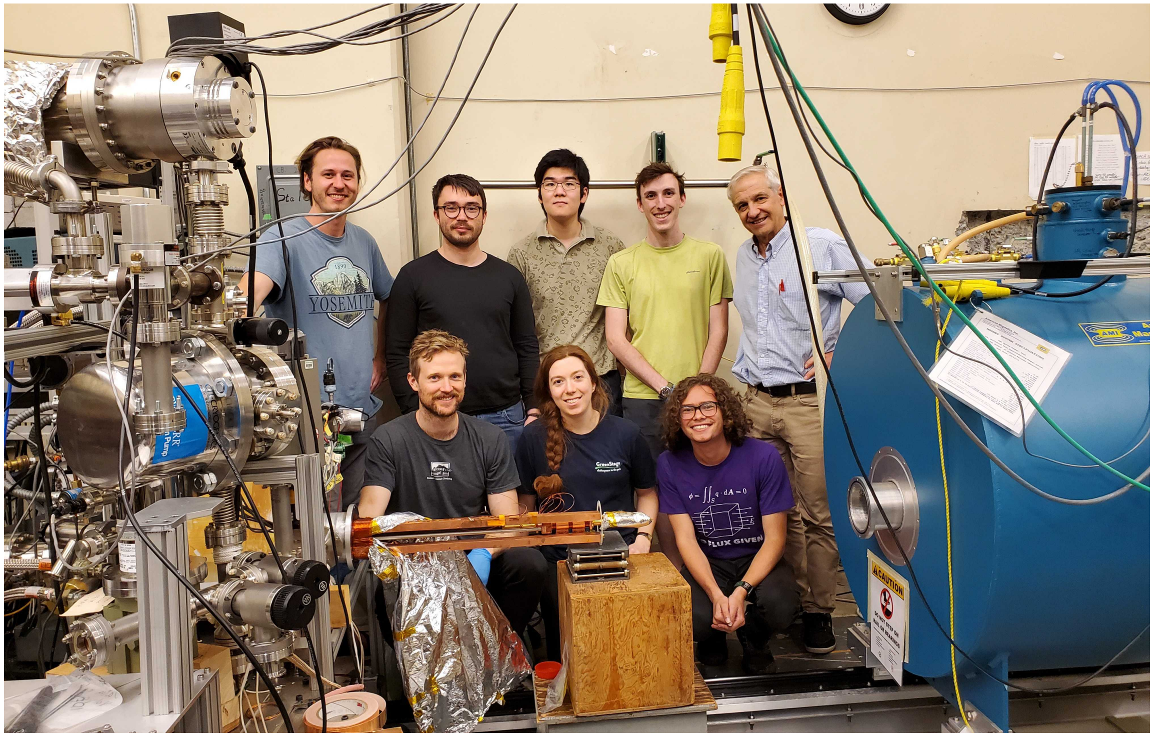








He6-CRES Collaboration



N. Buzinsky, W. Byron, W. DeGraw, B. Dodson, M. Fertl, A. Garcia, G. Garvey, B. Graner, M. Guigue, H. Harrington, L. Hayen, X. Huyan, K.S. Khaw, K. Knutsen, D. McClain, D. Melconian, P. Muller, E. Novitski, N. S. Oblath, R. G. H. Robertson, G. Rybka, G. Savard, E. Smith, D.D. Stancil, M. Sternberg, D. W. Storm, H. E. Swanson, R. J. Taylor, J. R. Tedeschi, B. A. VanDevender, F. E. Wietfeldt, A. R. Young, and X. Zhu.

(He6-CRES collaboration)

CENPA Center for Experimental Nuclear Physics and Astrophysics

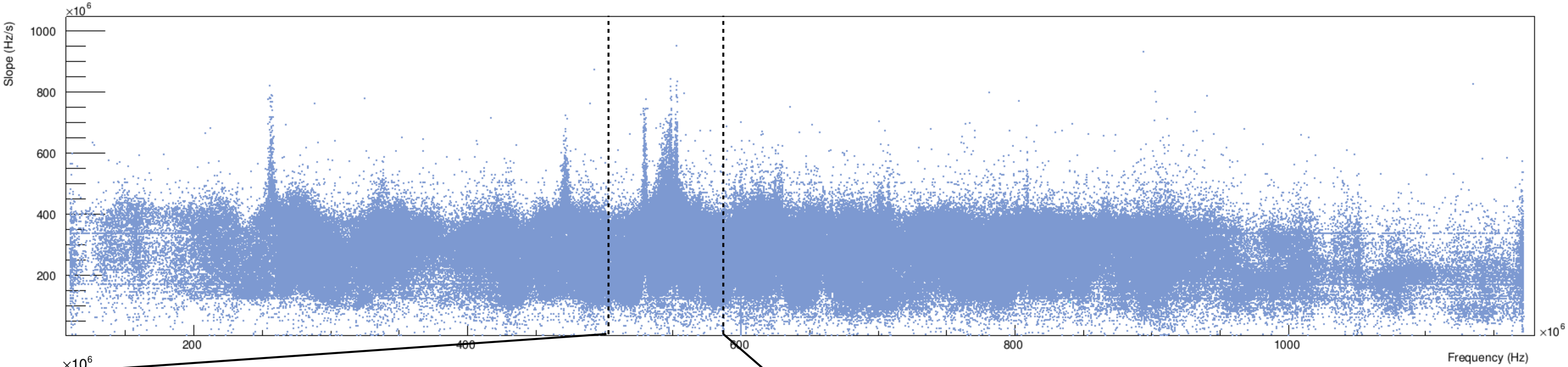
Pacific Northwest NATIONAL LABORATORY

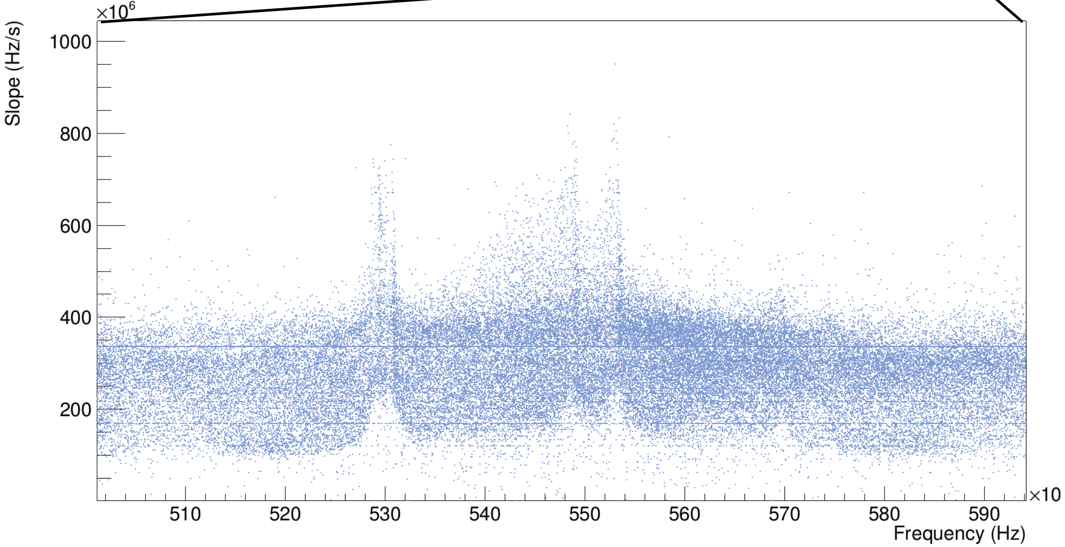
^{6}He-CRES

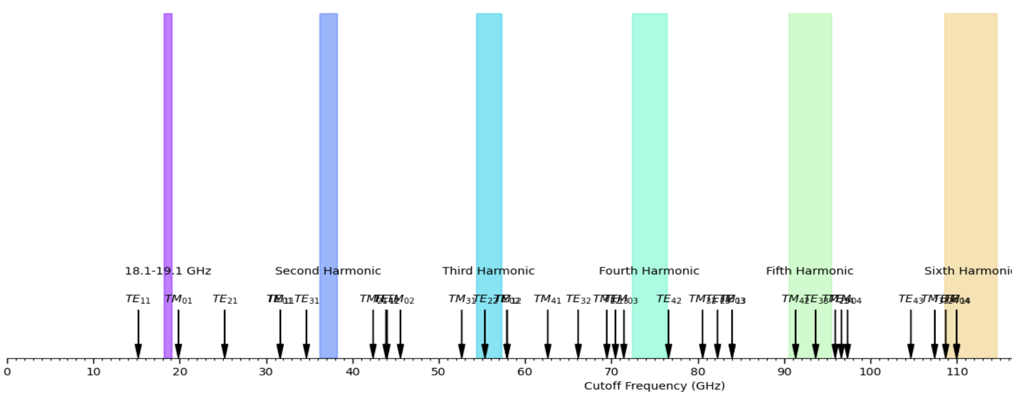
Argonne NATIONAL LABORATORY

JG|U

Backup slide 2: Power radiated by a relativistic electron in a waveguide (a study in slopes)

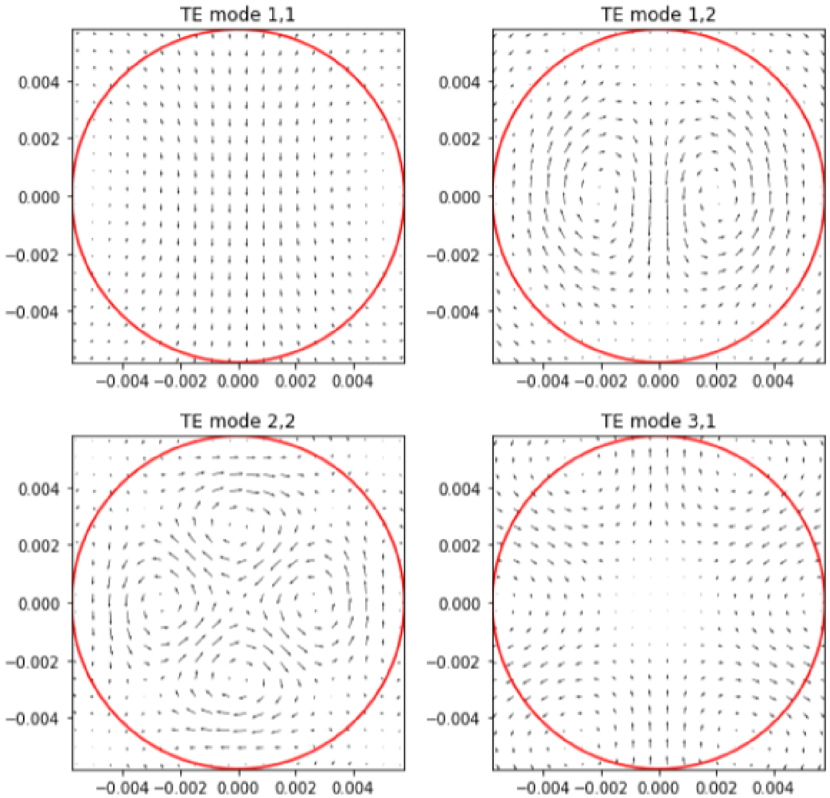






Backup slide 3: Numerical simulations

$$P_{TE} = \frac{1}{P_N}[|\frac{1}{T}\int_0^T dt\mathbf{J}(\mathrm{t})e^{-jh\omega t}\cdot\mathbf{E}^{\mp}_{\mathrm{nm,A=1}}(\mathbf{r}_0(\mathrm{t}))|^2+|\frac{1}{T}\int_0^T dt\mathbf{J}(\mathrm{t})e^{-jh\omega t}\cdot\mathbf{E}^{\mp}_{\mathrm{nm,B=1}}(\mathbf{r}_0(\mathrm{t}))|^2]$$



$$k_c = p_{nm}/a,$$

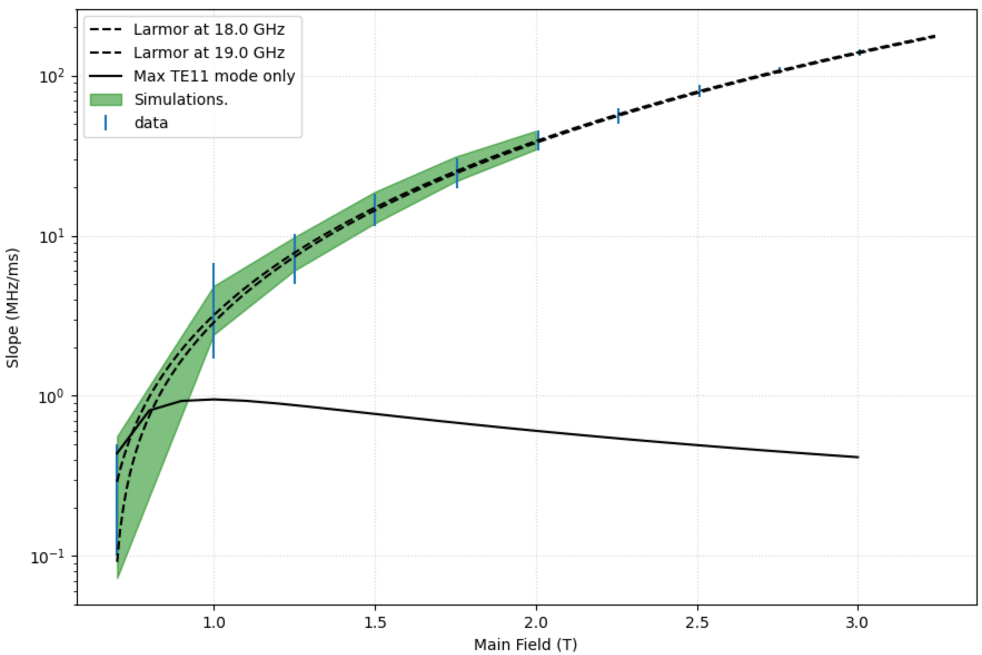
$$P_{TM,N} = \frac{\pi\omega\epsilon\beta}{2k_c^4}p_{nm}^2 J_n'^{\,2}(p_{nm}),$$

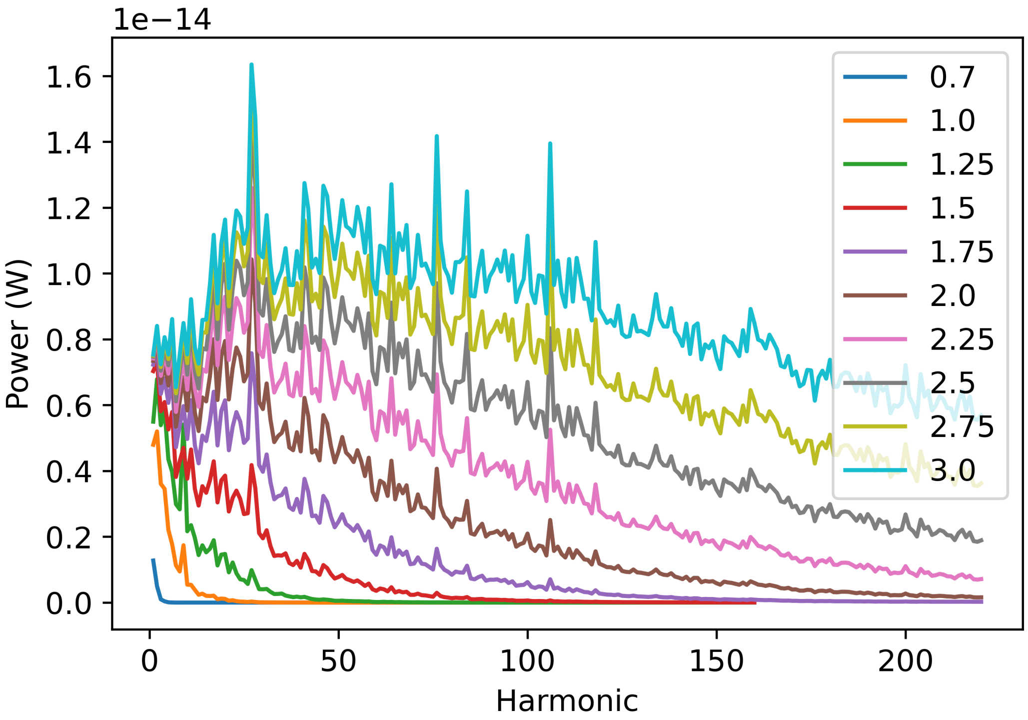
The total power up to the Hth harmonic is

$$P_T = \sum_1^H \sum_{n,m} P_{TE} + \sum_1^H \sum_{n,m} P_{TM}$$

RJ Taylor

Backup slide 4: Numerical simulations





The total power up to the Hth harmonic is

$$P_T = \sum_{1}^{H} \sum_{n,m} P_{TE} + \sum_{1}^{H} \sum_{n,m} P_{TM}$$