Event detection and reconstruction in Project 8 Phase II

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Neutrinos in Cosmology, in Astro-, Particle- and Nuclear Physics
Erice – September 21, 2017

PRISMA

PROJECT 8

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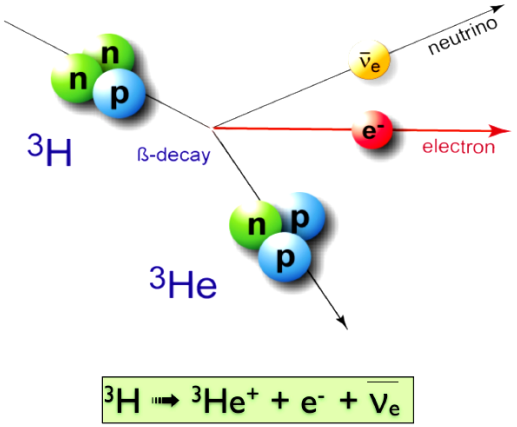
Project 8 – Towards a new neutrino mass experiment

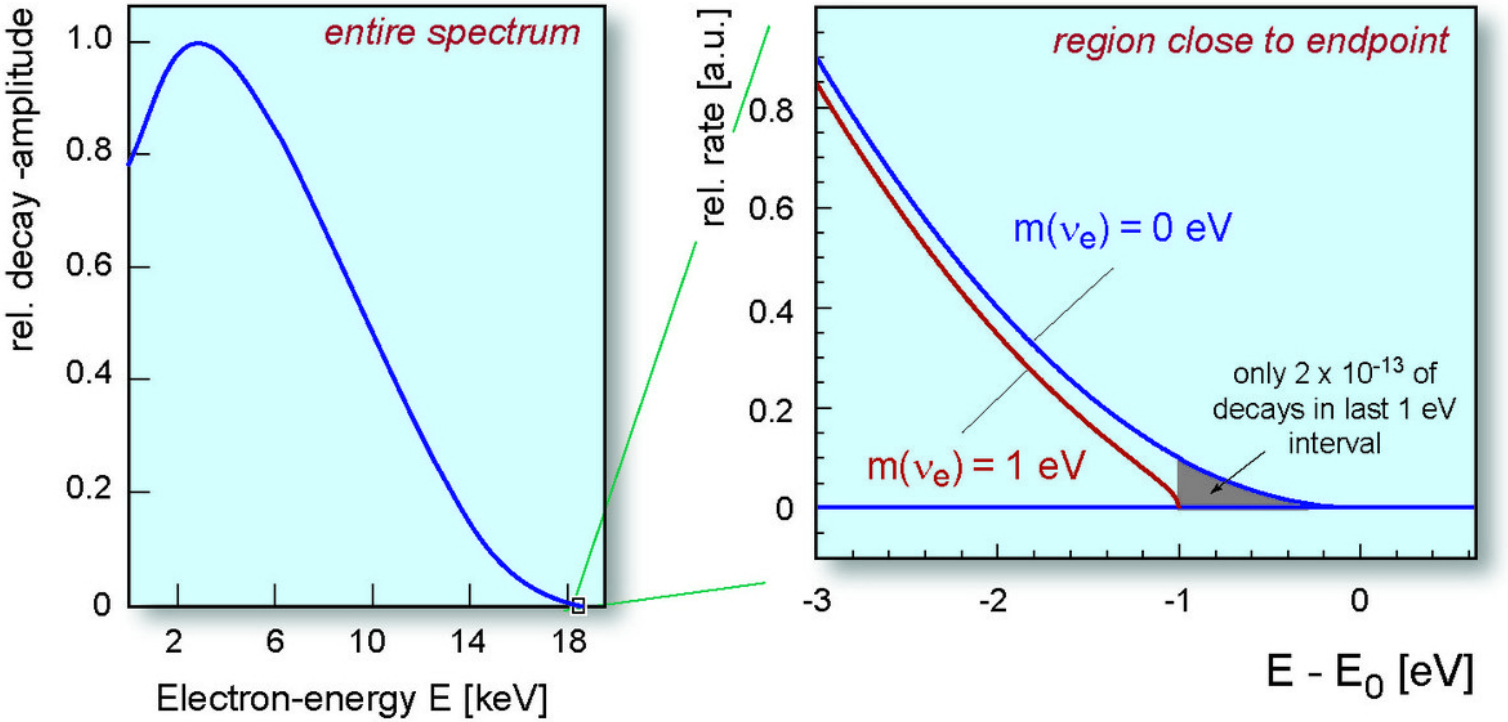
Tritium beta decay

- Spectrum shape near endpoint changes with ν-mass

$$\frac{dN}{dE} \sim F(Z,E)\, p_e (E+m_e)(E_0-E)\sqrt{(E_0-E)^2-m_{\nu_e}^2}$$

$$m_\beta = \sqrt{\sum_i |U_{ei}^2|\, m_i^2}$$

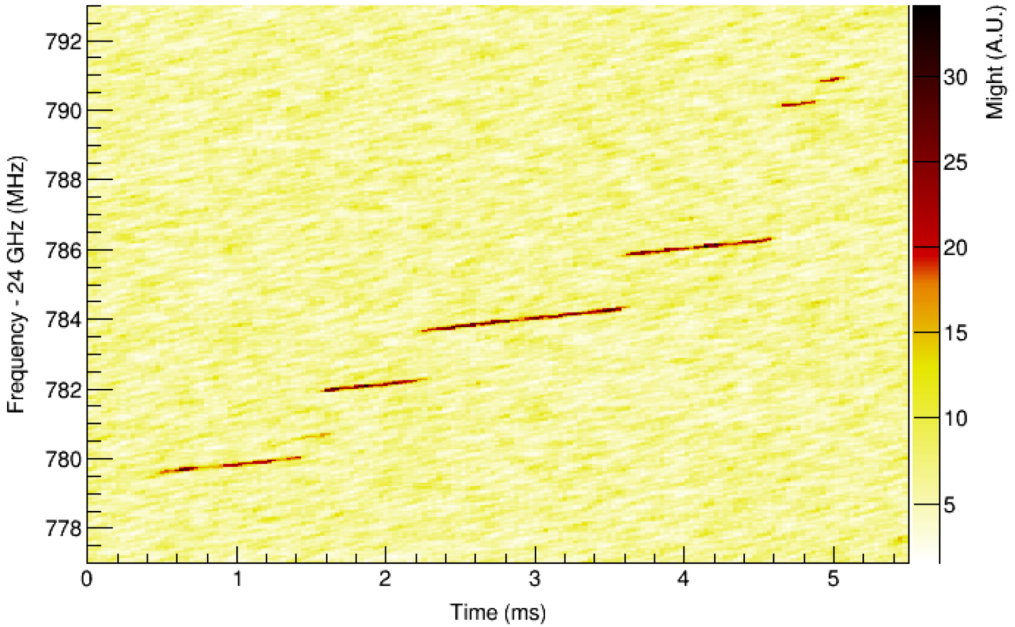


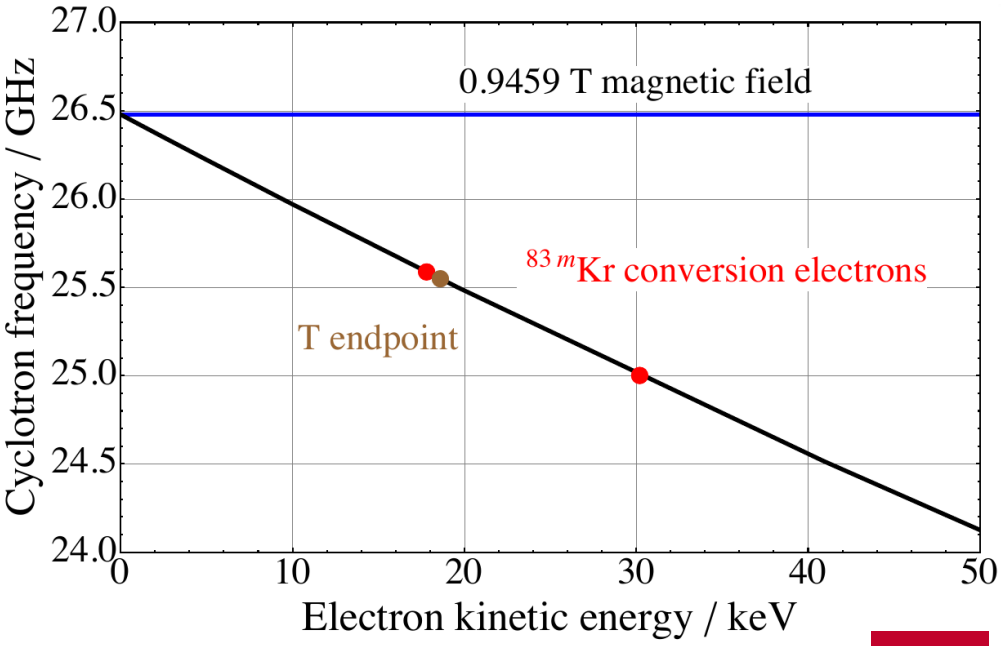


Project 8 – Towards a new neutrino mass experiment

Cyclotron Radiation Emission Spectroscopy

- Cyclotron frequency (relativistic) $f_\gamma = \frac{f_c}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{kin}}$
- High resolution with sufficiently long observation time
- Trap electrons in magnetic field and detect emitted radiation
- Reconstruct event





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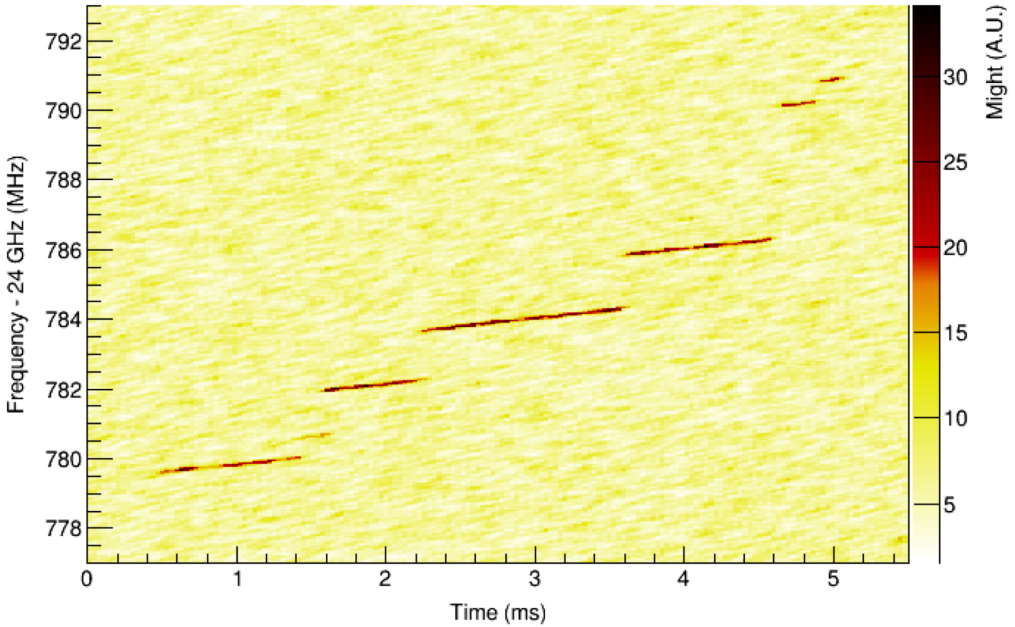
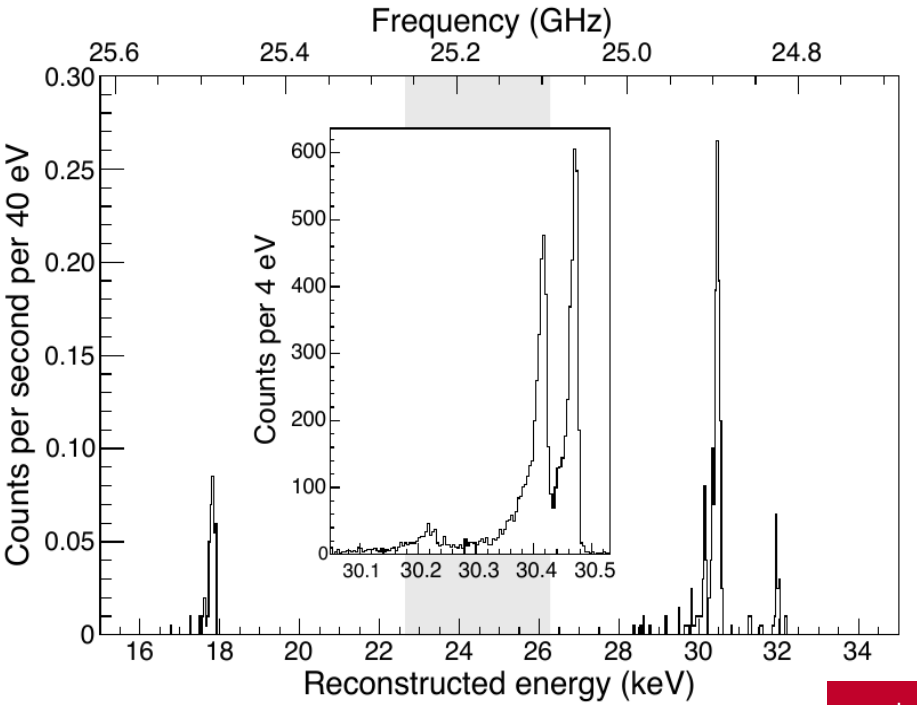
Project 8 – Towards a new neutrino mass experiment

Cyclotron Radiation Emission Spectroscopy

- Cyclotron frequency (relativistic) $f_\gamma = \frac{f_c}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{kin}}$
- High resolution with sufficiently long observation time
- Trap electrons in magnetic field and detect emitted radiation
- Reconstruct event → reconstruct spectrum from start frequencies

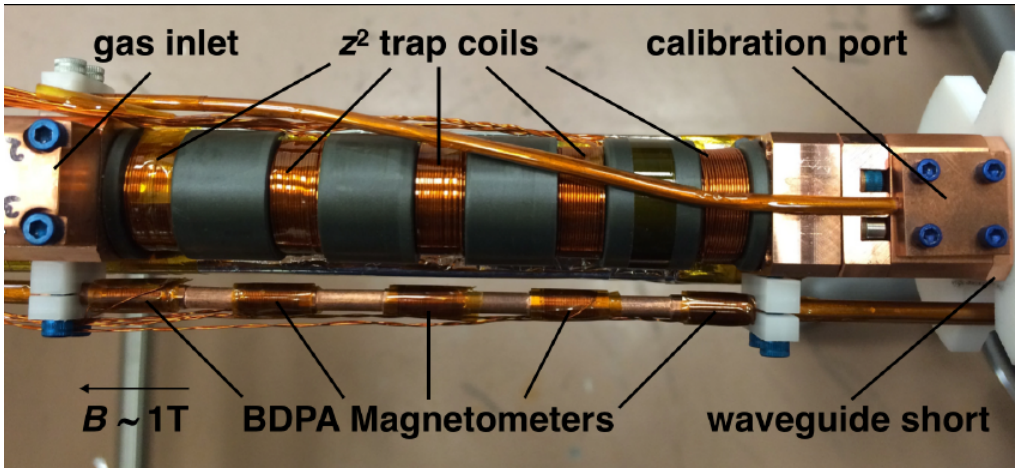


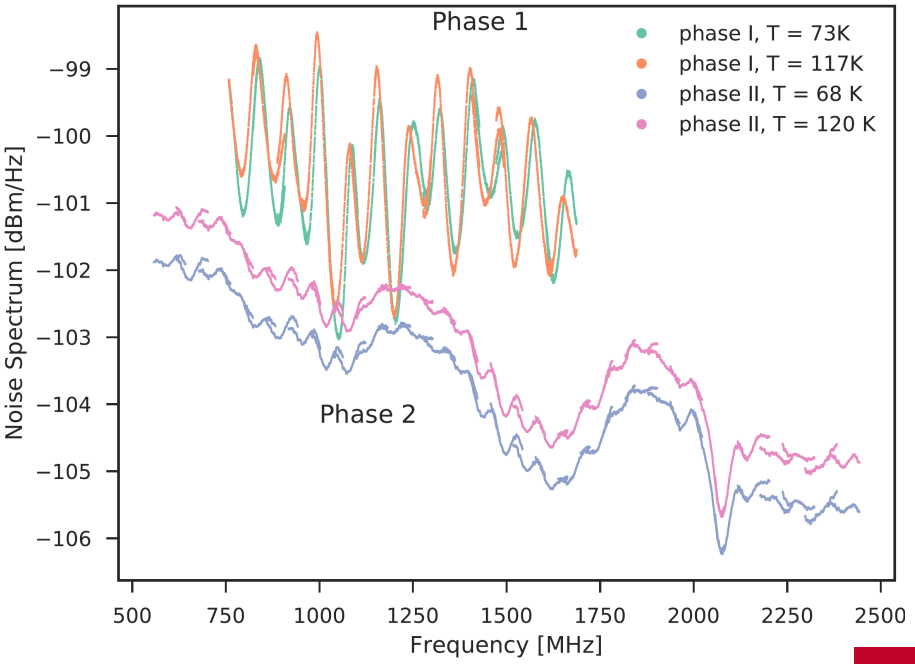


Phys. Rev. Lett. 114, 162501 (2015)

Project 8 – Phase II

- Goal: First T_2 spectrum with CRES
- Circular waveguide
- 5 trap coils for more flexible trapping field geometry
- Colder amplifier and microwave circulator reduce RF background
- 2016 - 2017:
  Fabrication and commissioning of new detector insert (still ^{83m}Kr)
- 2017:
  Completion of tritium gas system
- Switch to T_2 soon

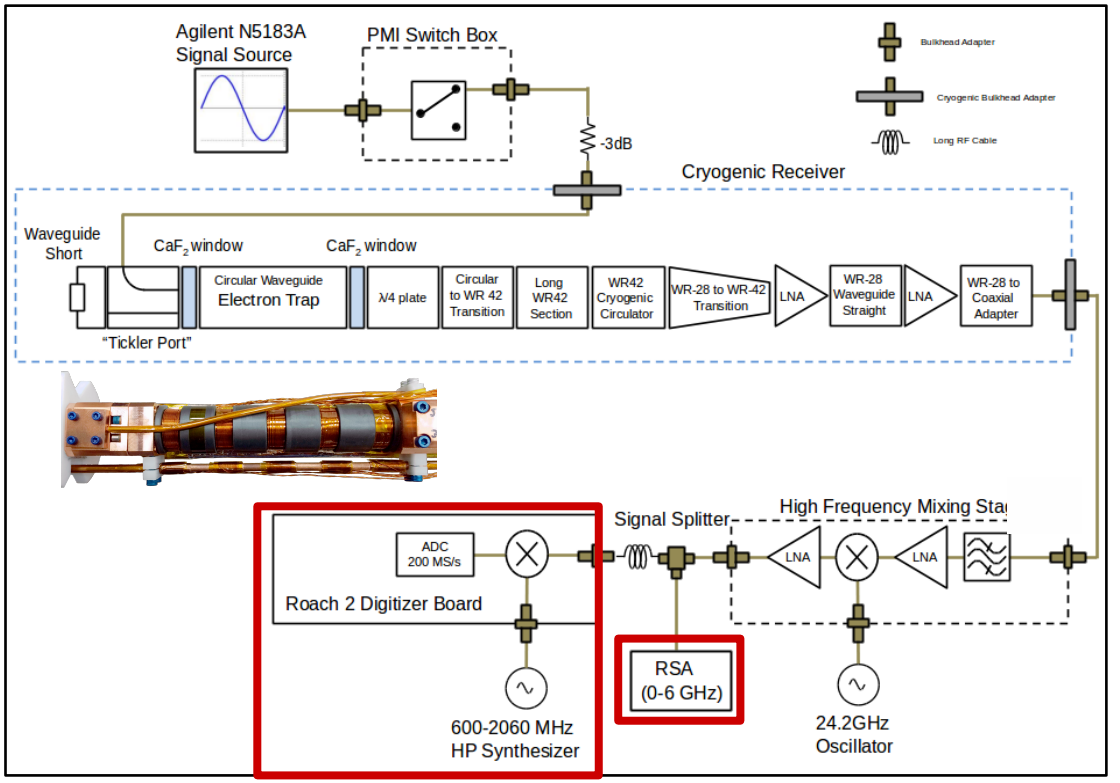


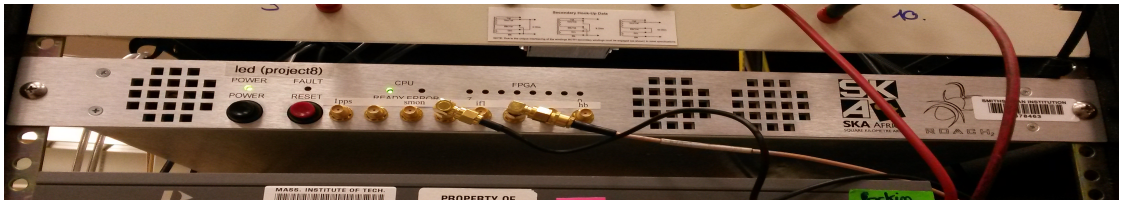


Analyst: R. Cervantes

Phase II – DAQ

- Amplification of the RF Signal
- Down-mixing with 24.2 GHz
- Real-Time Spectrum Analyzer
  - Triggering digitizer
  - Limited triggers/min
- ROACH2:
  - **R**econfigurable **O**pen **A**rchitecture **C**omputing **H**ardware
  - Developed for astronomy
  - Trigger under development





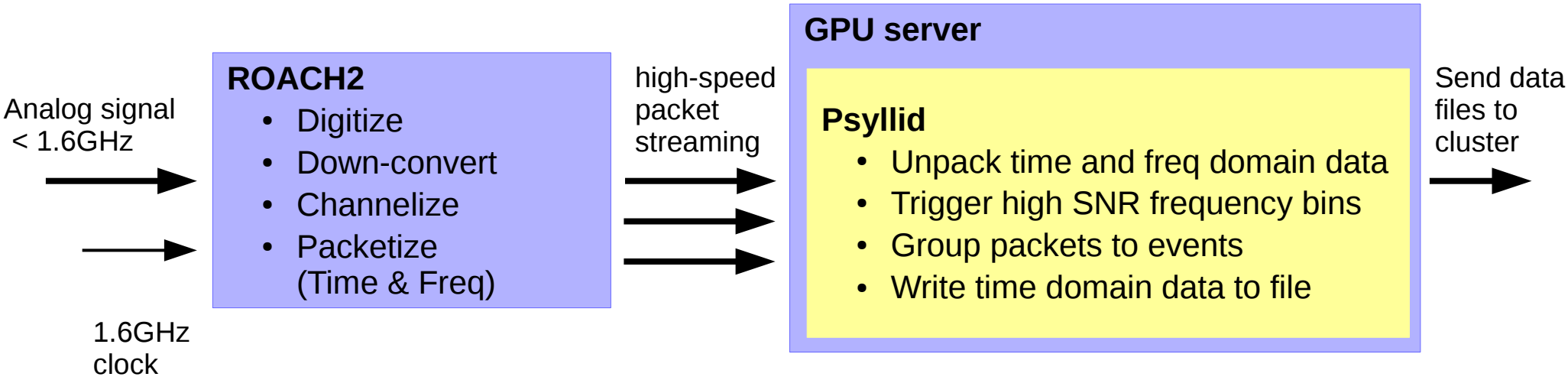
Phase II – DAQ with the ROACH2

ROACH2

- FPGA board with two ADCs
- Down-conversion, FFT, time and frequency domain data streaming

Psyllid

- Data acquisition package for the ROACH2 system
- Receive data, trigger and write to files



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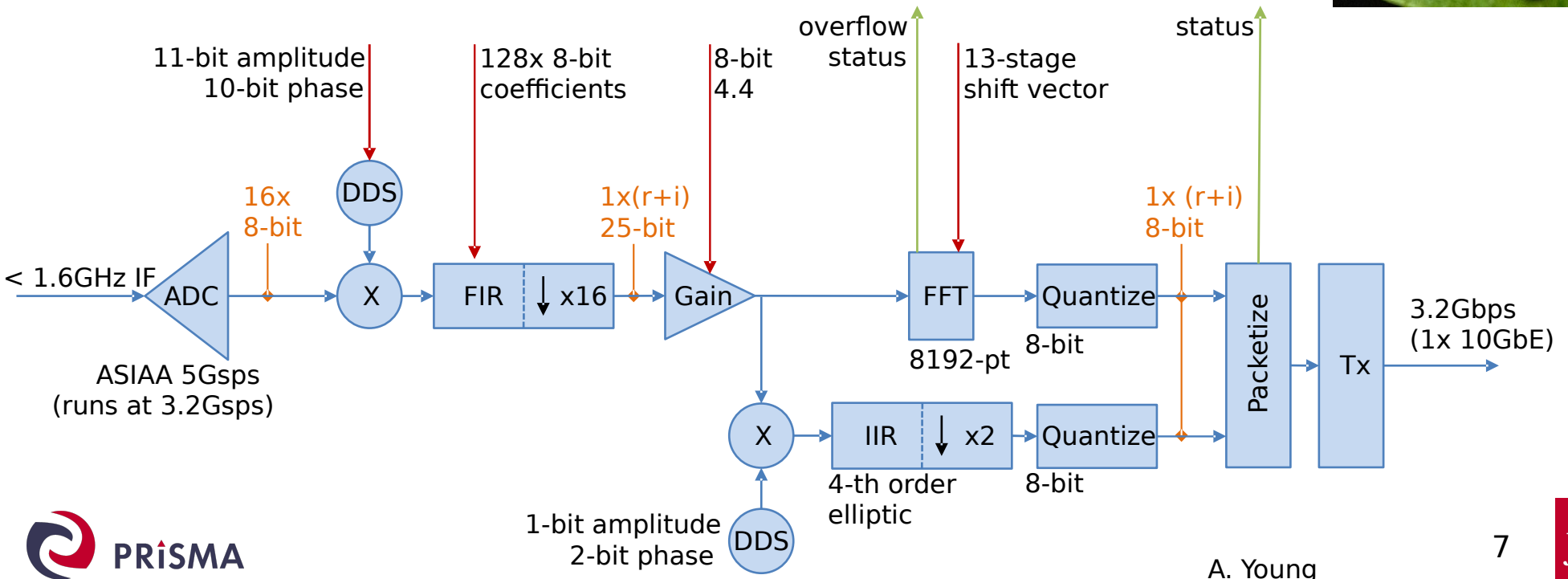

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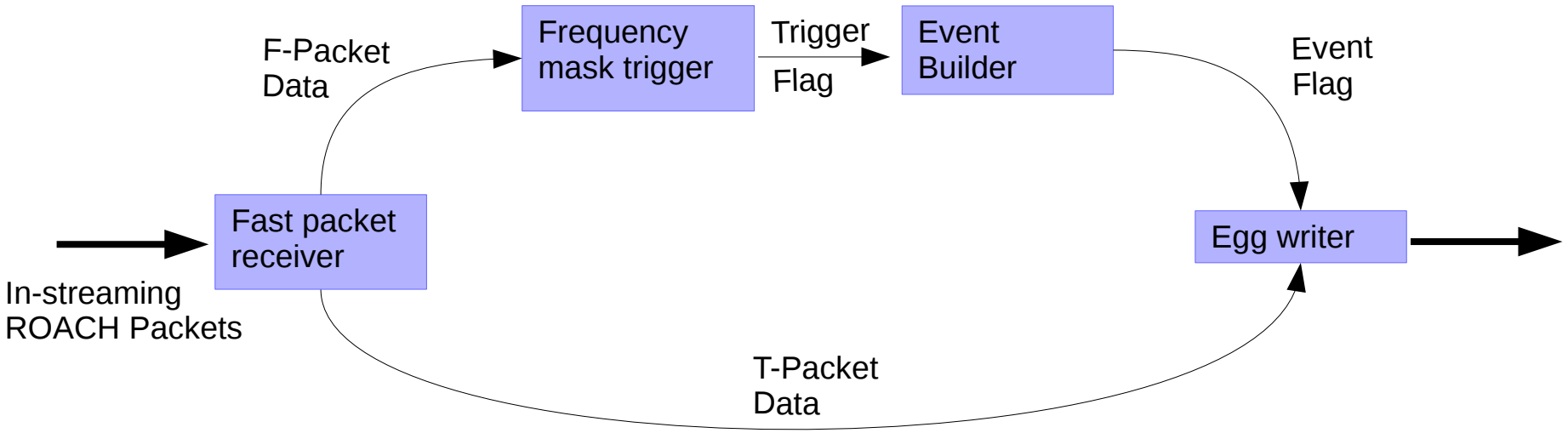

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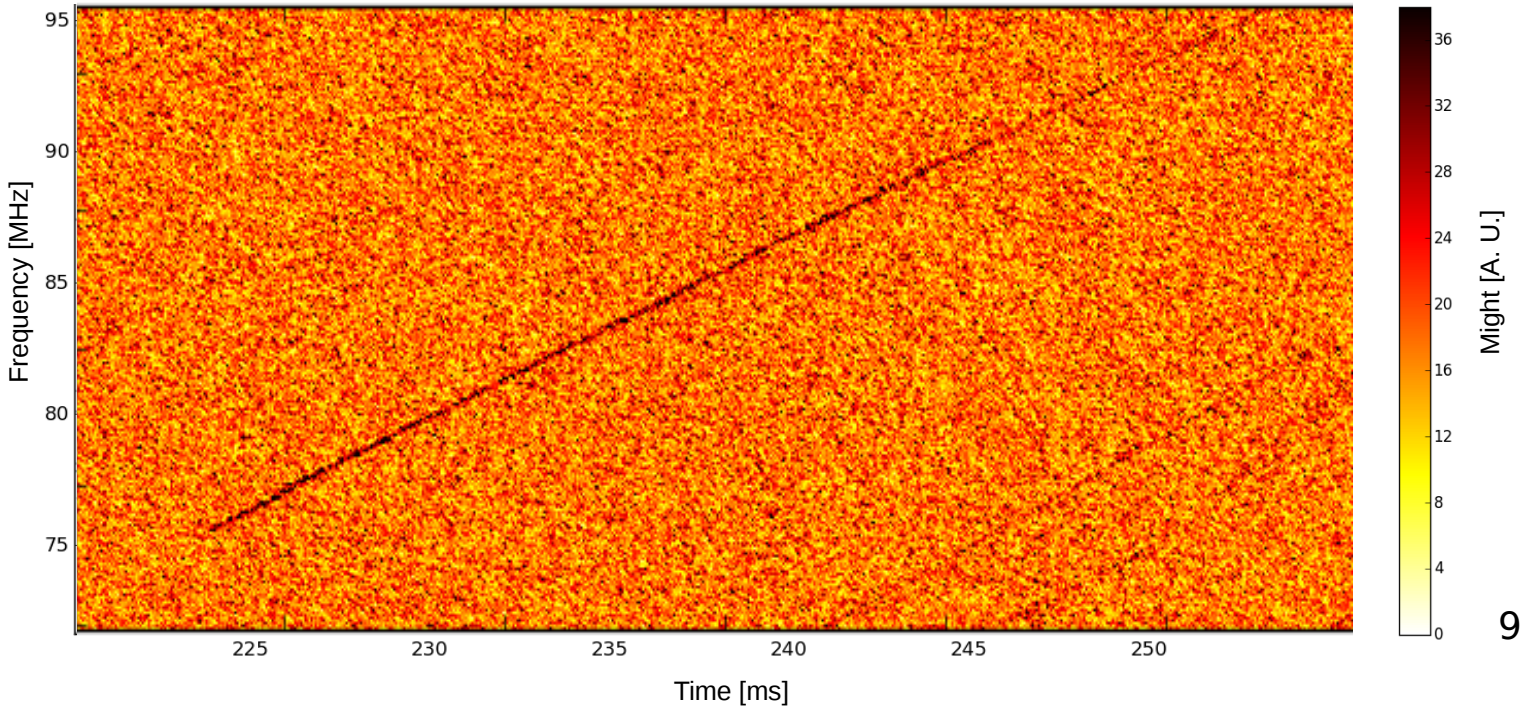

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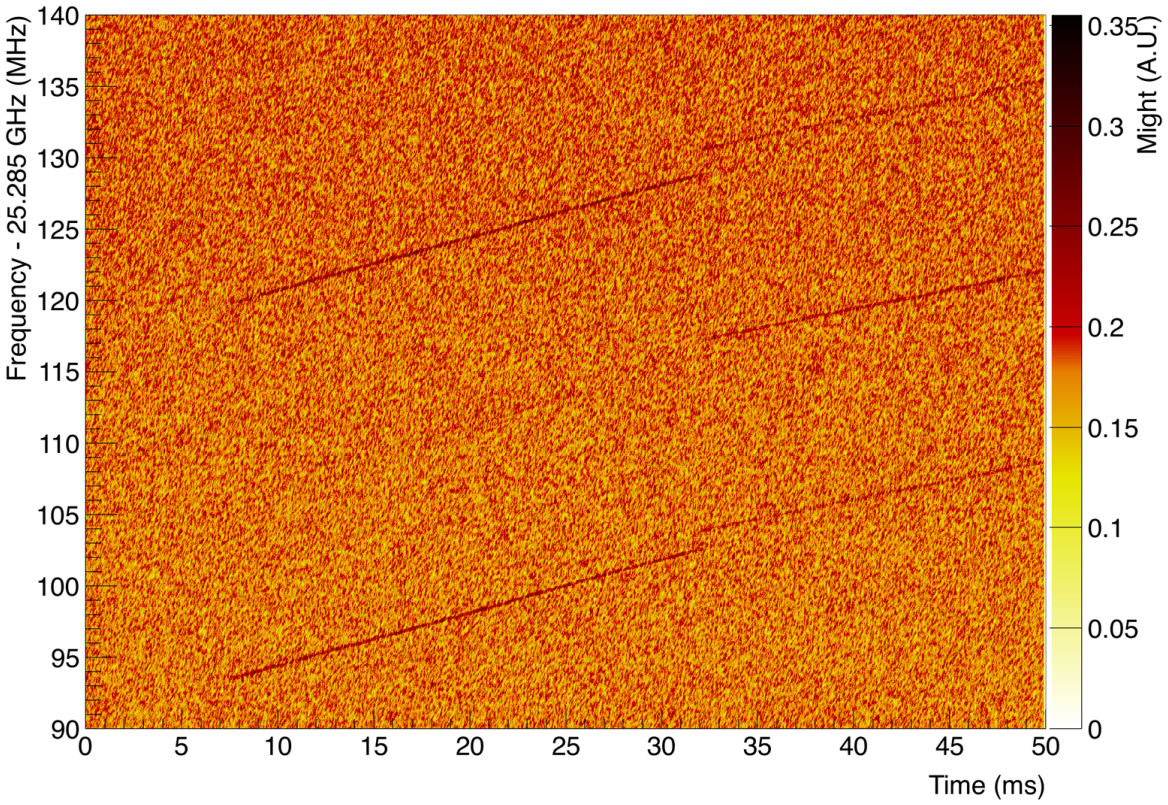
Track reconstruction

Take time slices from data and compute FFT



Track reconstruction

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↓

Calculate background power by averaging over all slices

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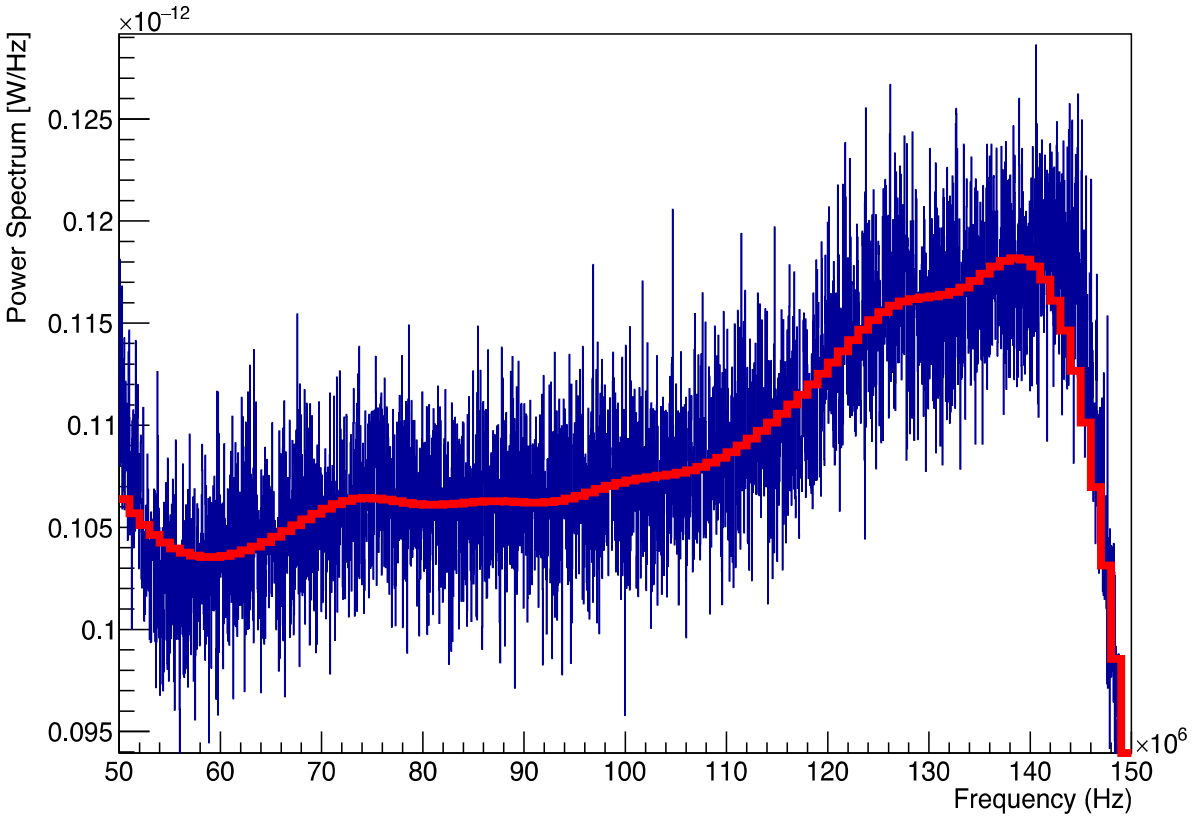

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Calculate SNR of every bin

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Remove all points with SNR < threshold

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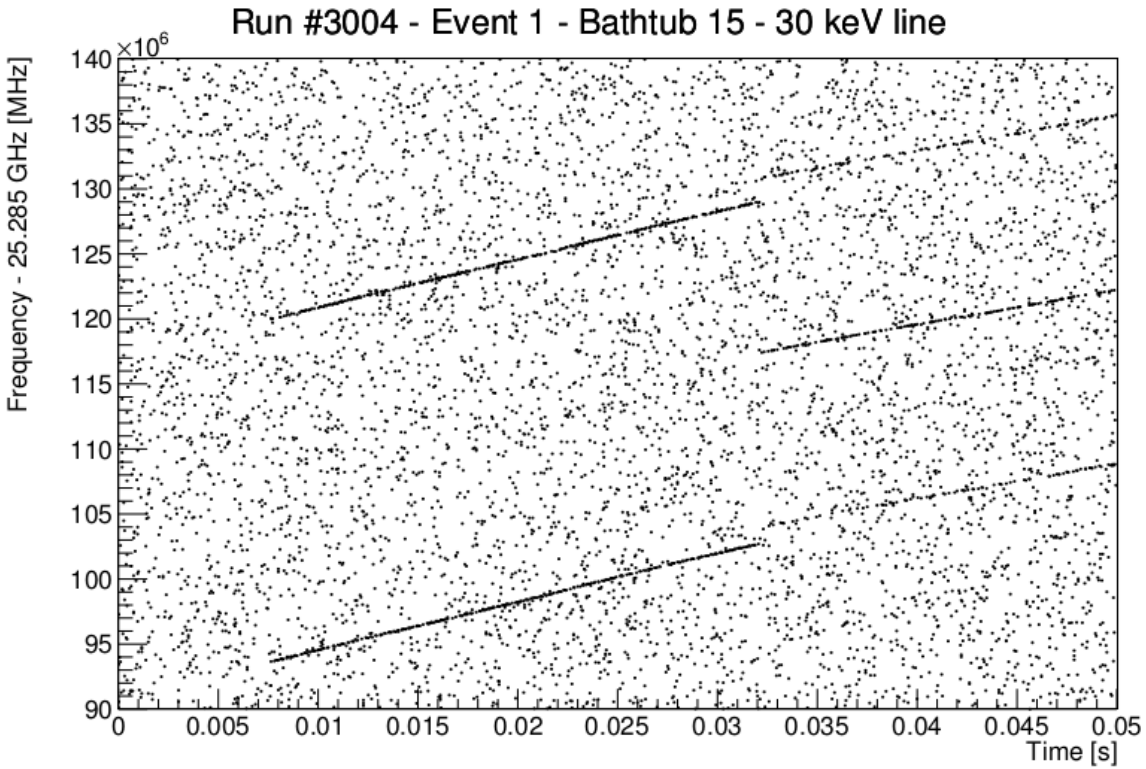

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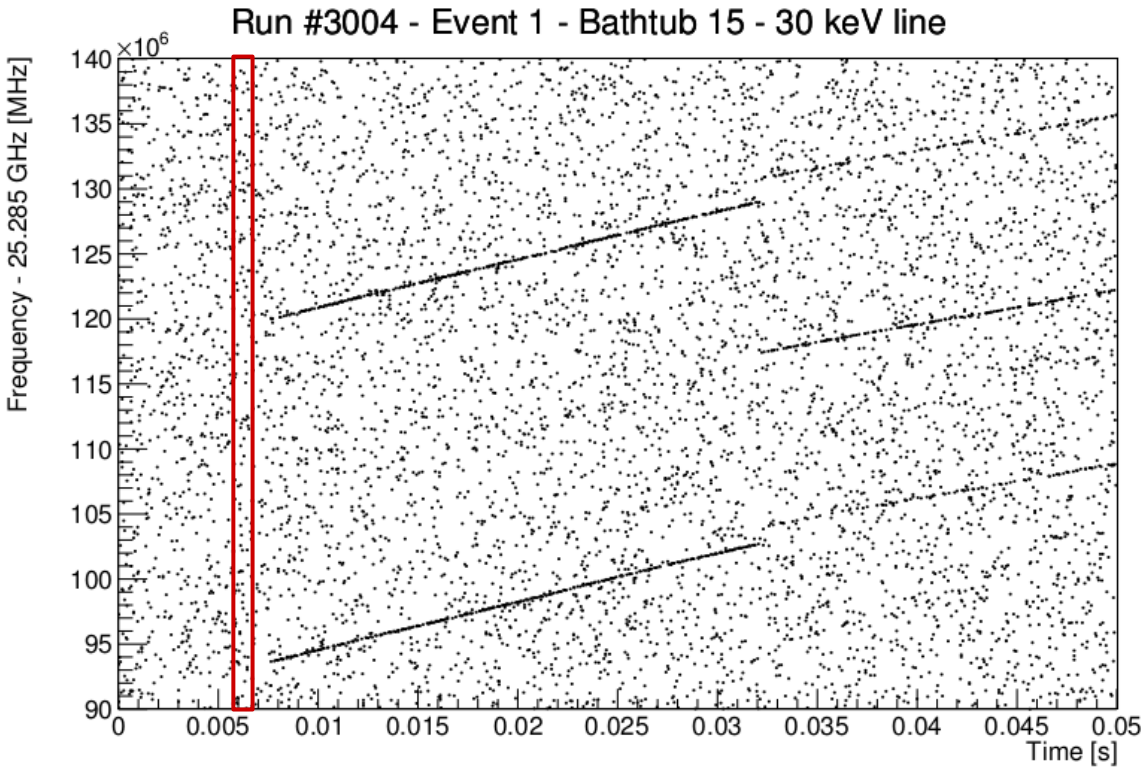

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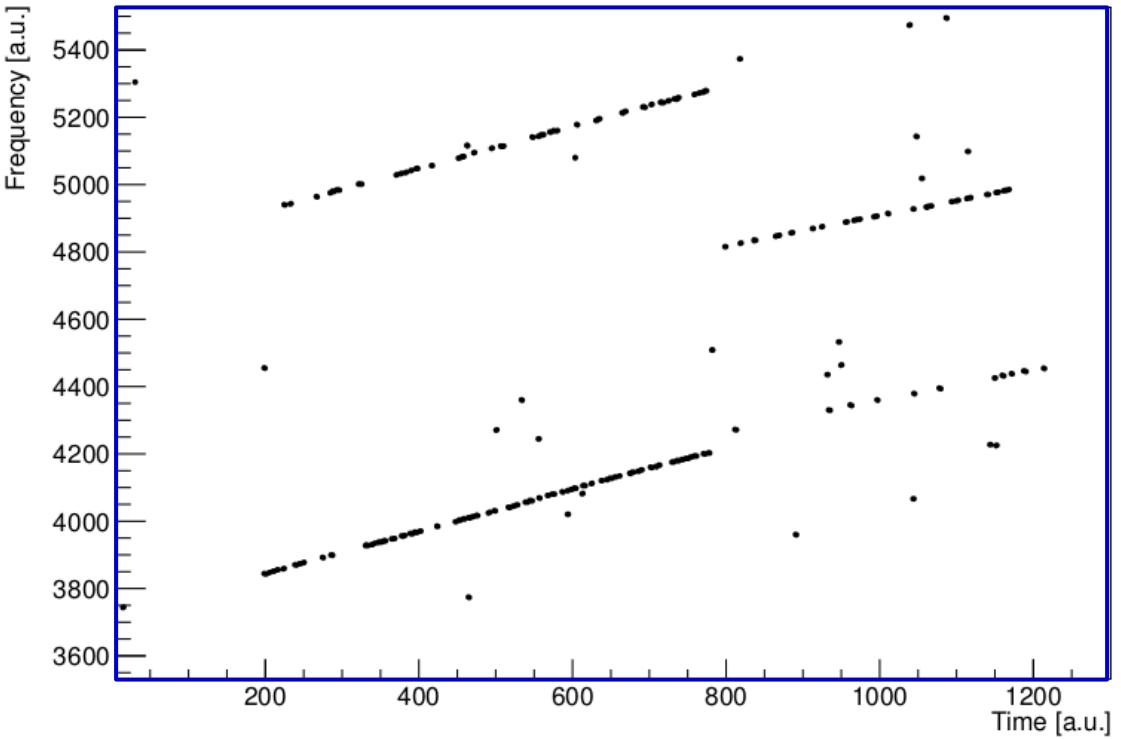

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Cluster nearby points together

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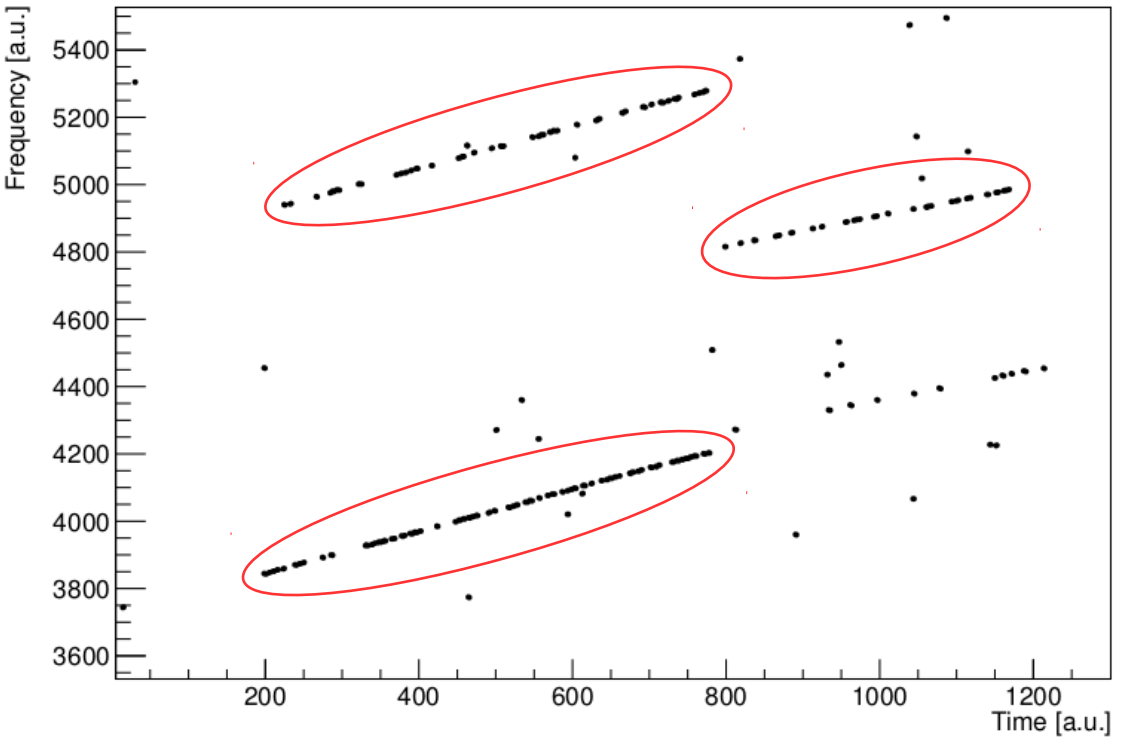

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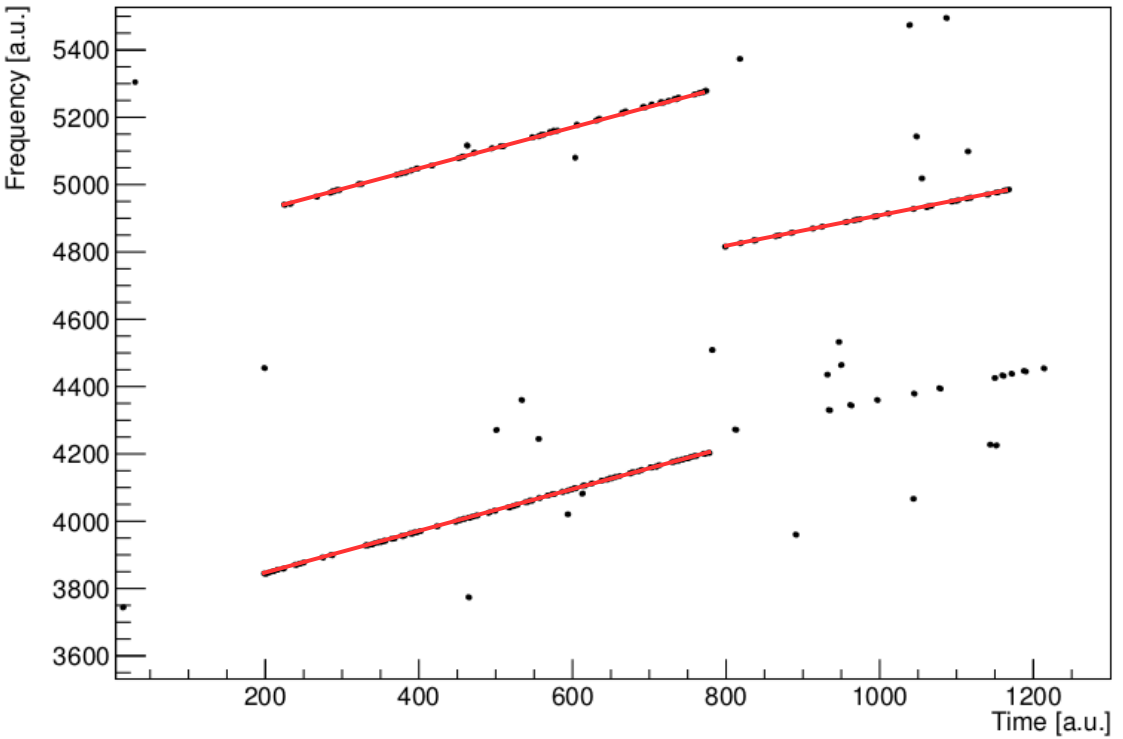
Calculate track properties



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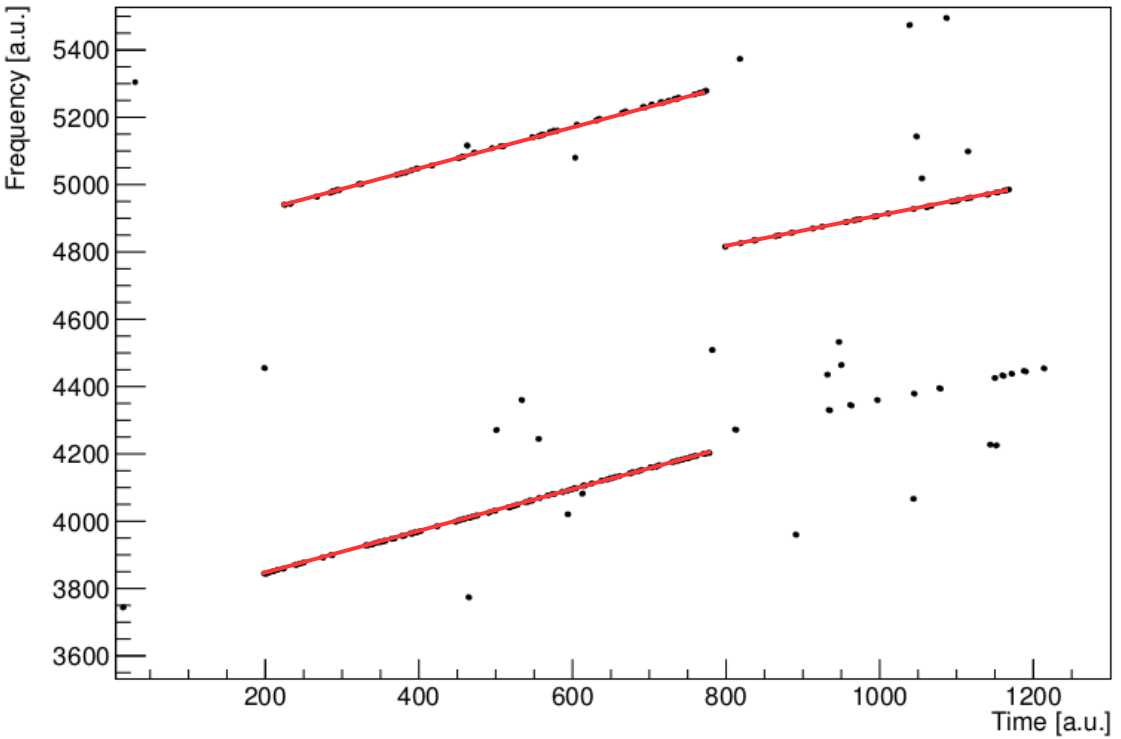


→ Very successful in Phase I event reconstruction

→ For some trap configurations in Phase II, the performance is currently less good

New track reconstruction algorithm

Take time slices from data and compute FFT

↓

Calculate background power by averaging over all slices

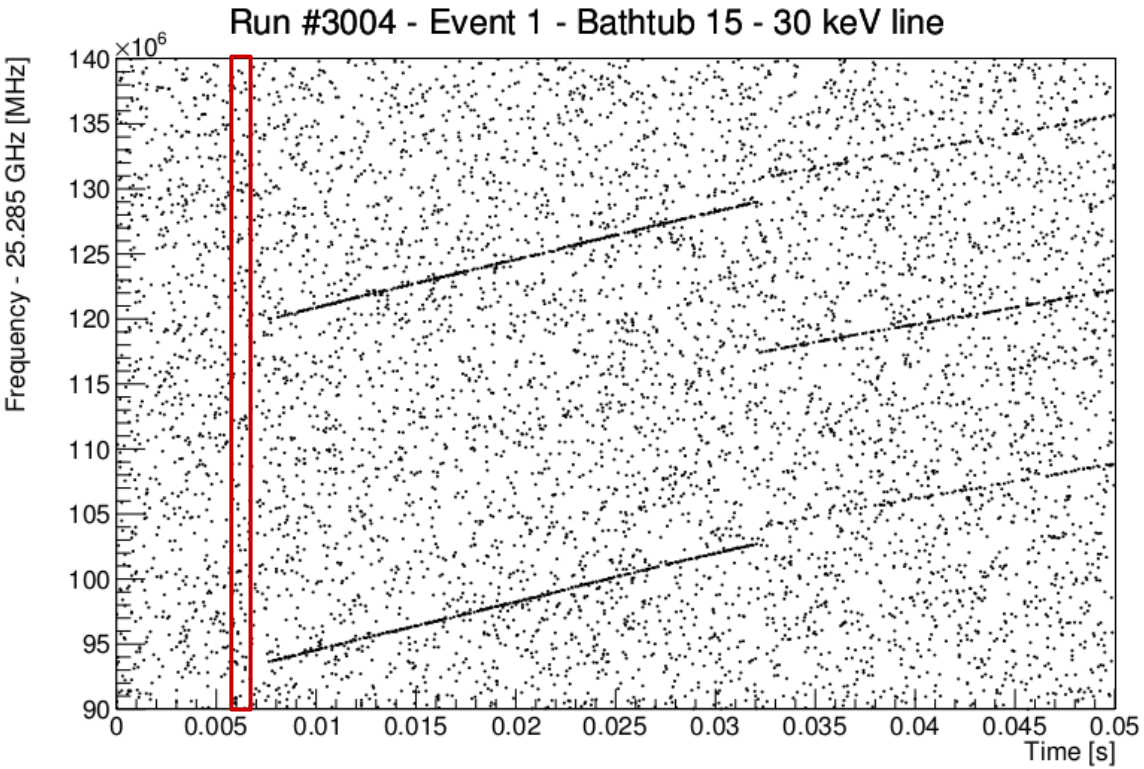
↓

Calculate SNR of every bin

↓

Collect all points in slice with SNR < threshold

↓



New track reconstruction algorithm

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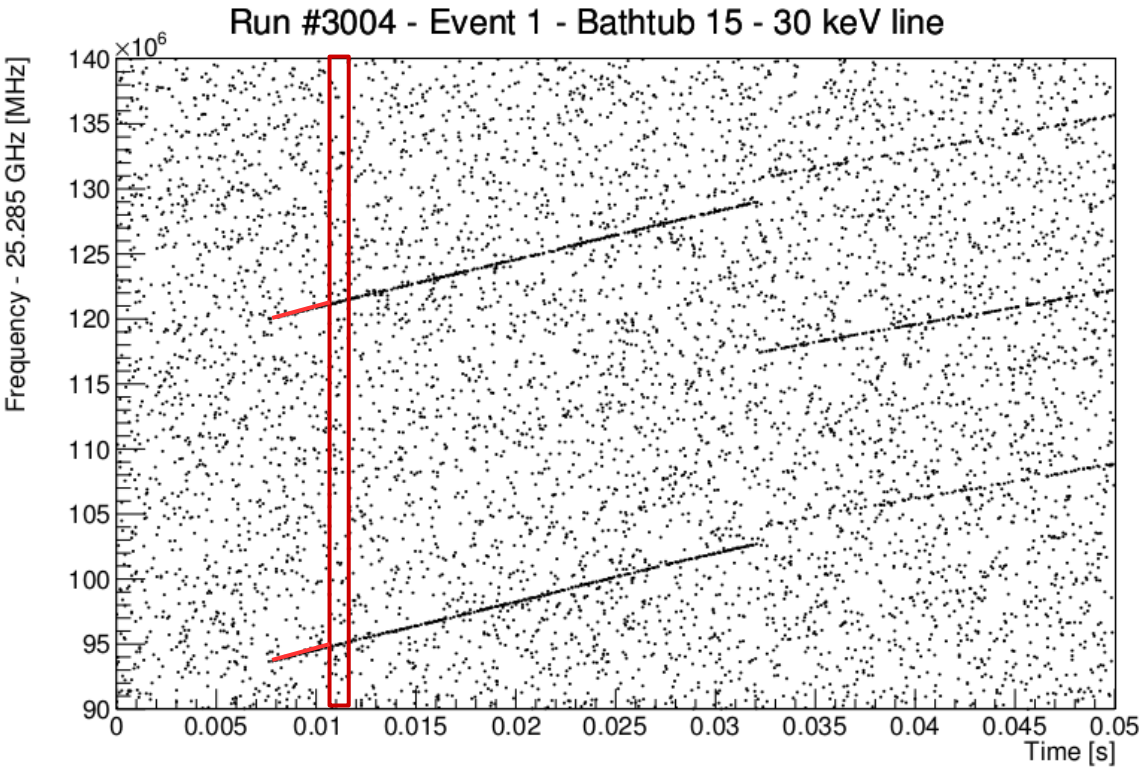
Check whether matching line exists or start new line

↓



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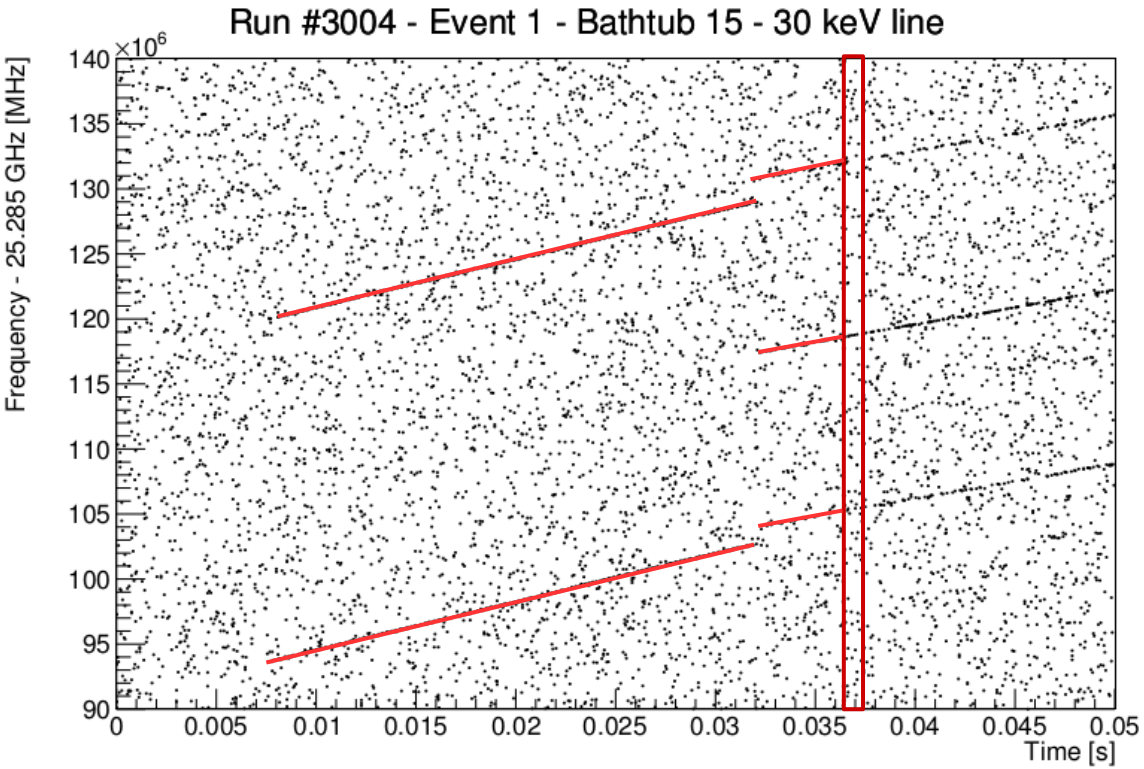
0.5ms after last added point, set line inactive (delete if $N_{points} < 3$)



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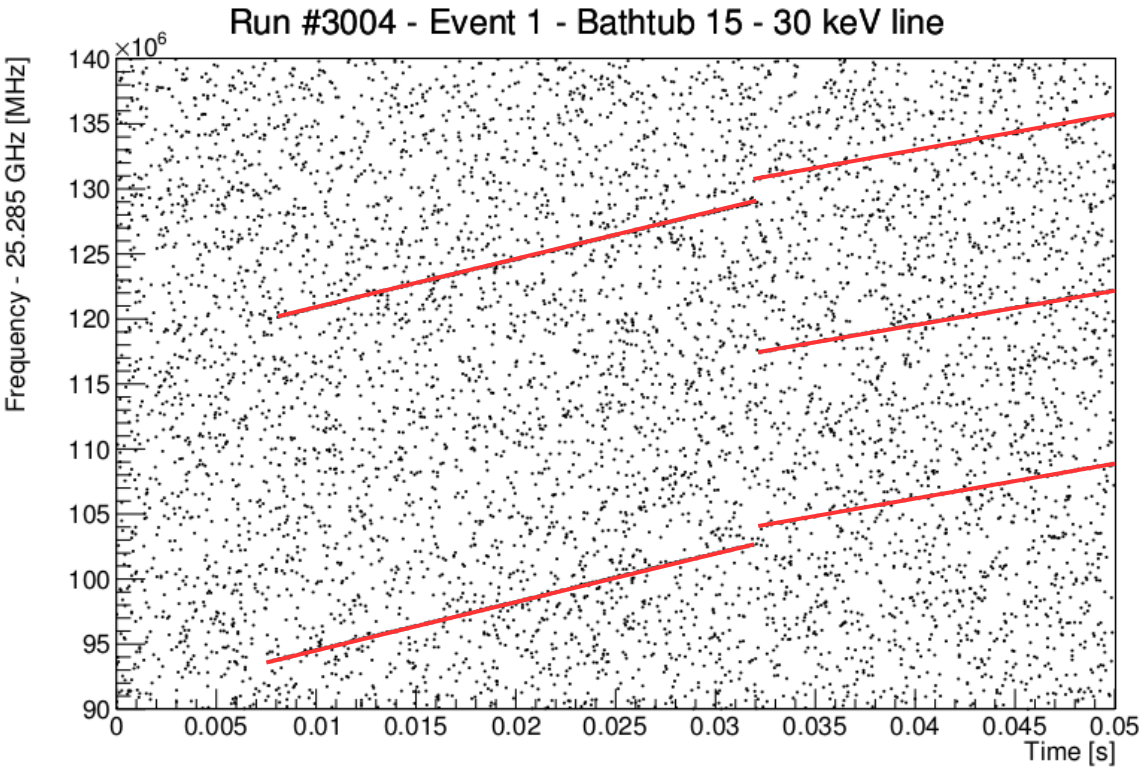
D. Furse (2015), “Techniques for Direct Neutrino Mass Measurement Utilizing Tritium β-Decay”, MIT



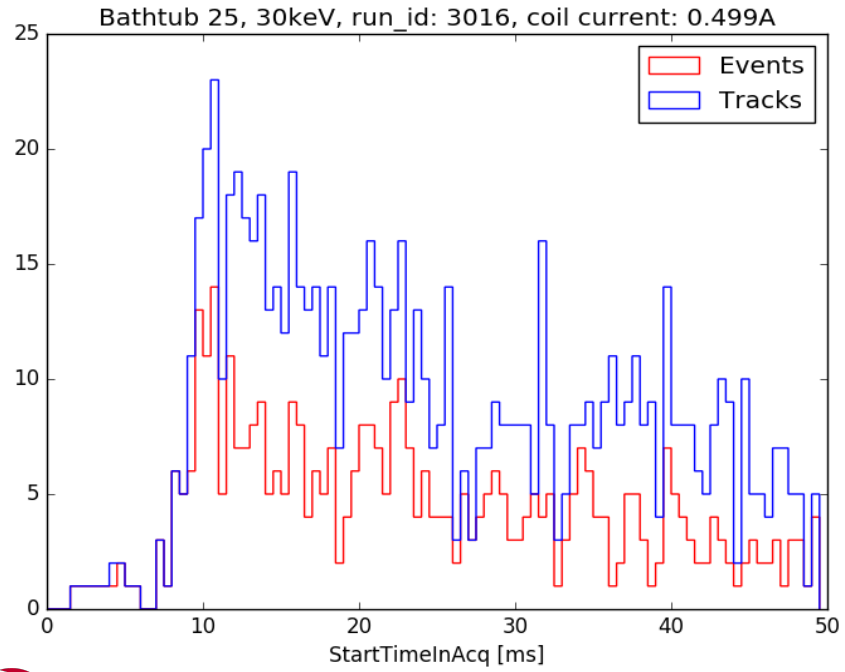
→ Completely sequential reconstruction algorithm

→ Implement as real-time trigger?

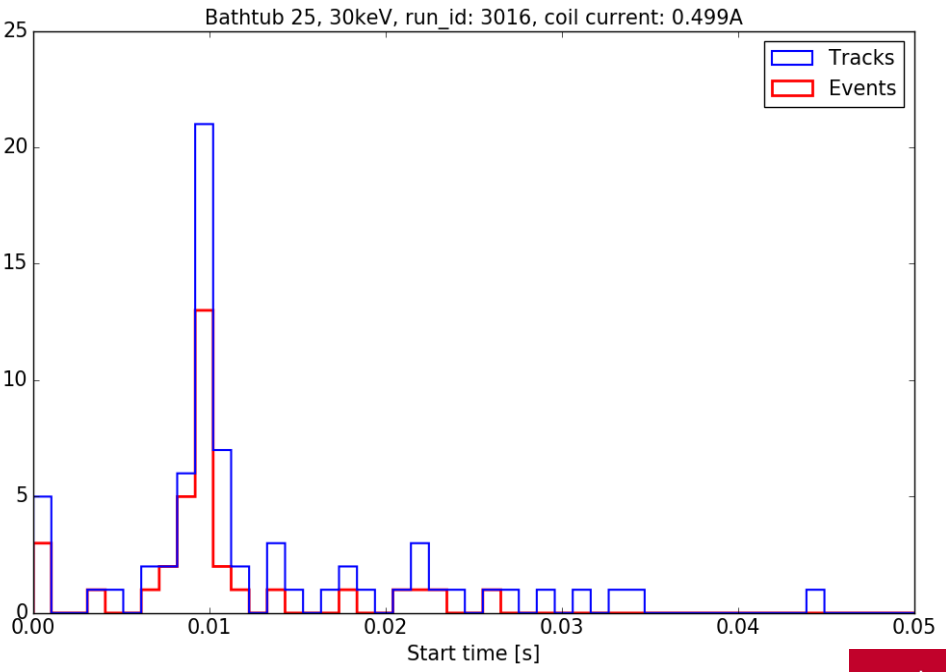
New track reconstruction algorithm

- First tests with Phase II show good performance
- Start time distribution of short run with 10 ms pre-trigger time significantly improved
- Tests ongoing
- Other track reconstruction algorithms under investigation

Tracks reconstructed with standard algorithm



Tracks reconstructed with new algorithm



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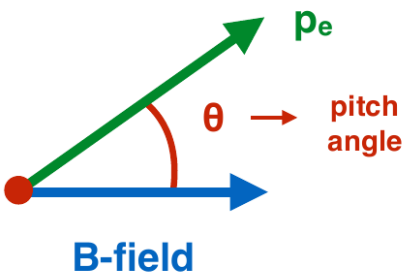
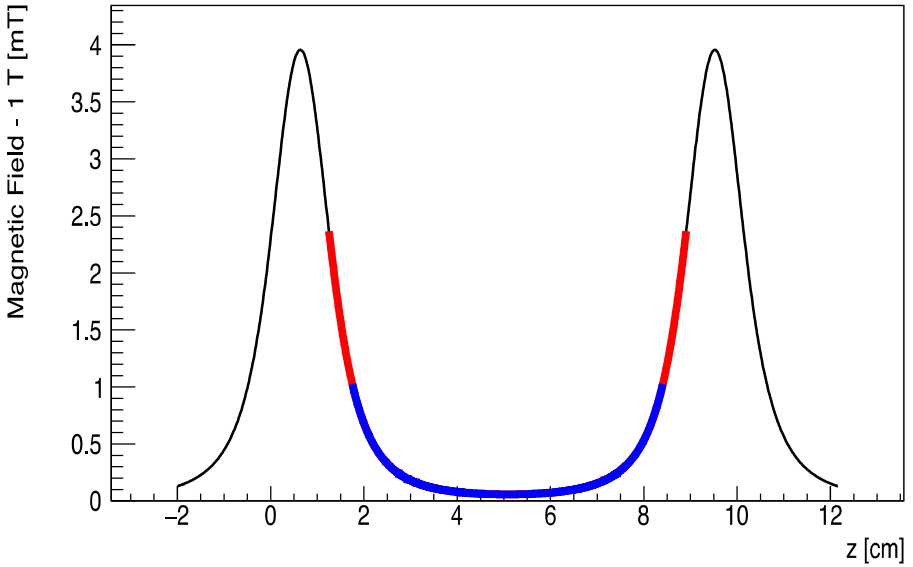
Phenomenology

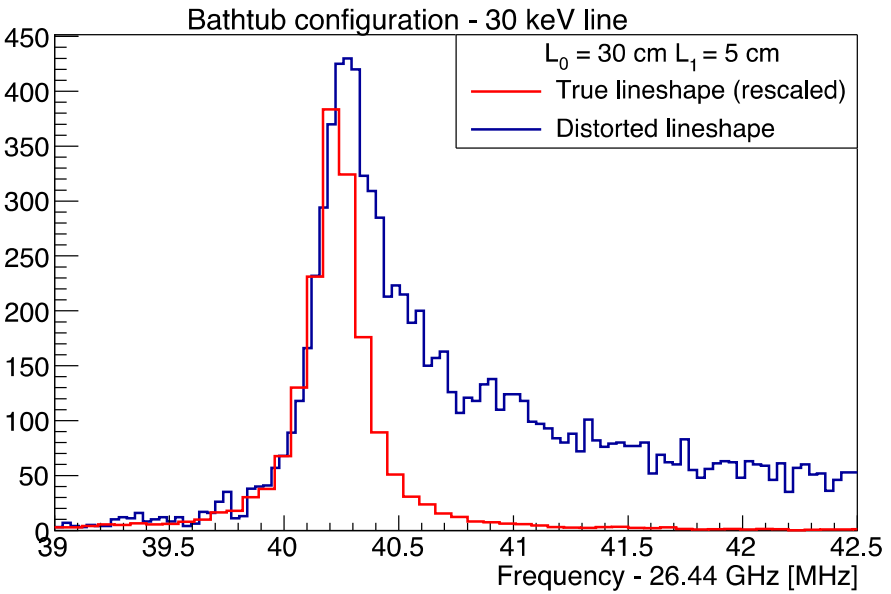
Pitch angle

- Angle between energy momentum and B-field
- Electrons with angles < 90° explore higher field regions
- Measured frequency depends on angle and B-field
- Without pitch angle correction spectral lines are distorted and broadened



$$f_s = \frac{1}{2\pi} \frac{(eB + b(\theta))}{E_{kin}/c^2 + m_e}$$



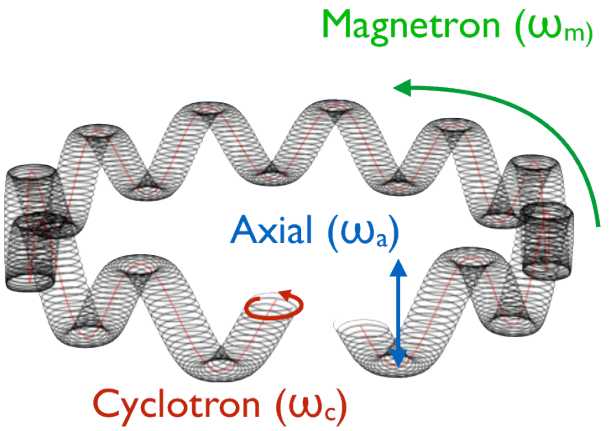


Phenomenology

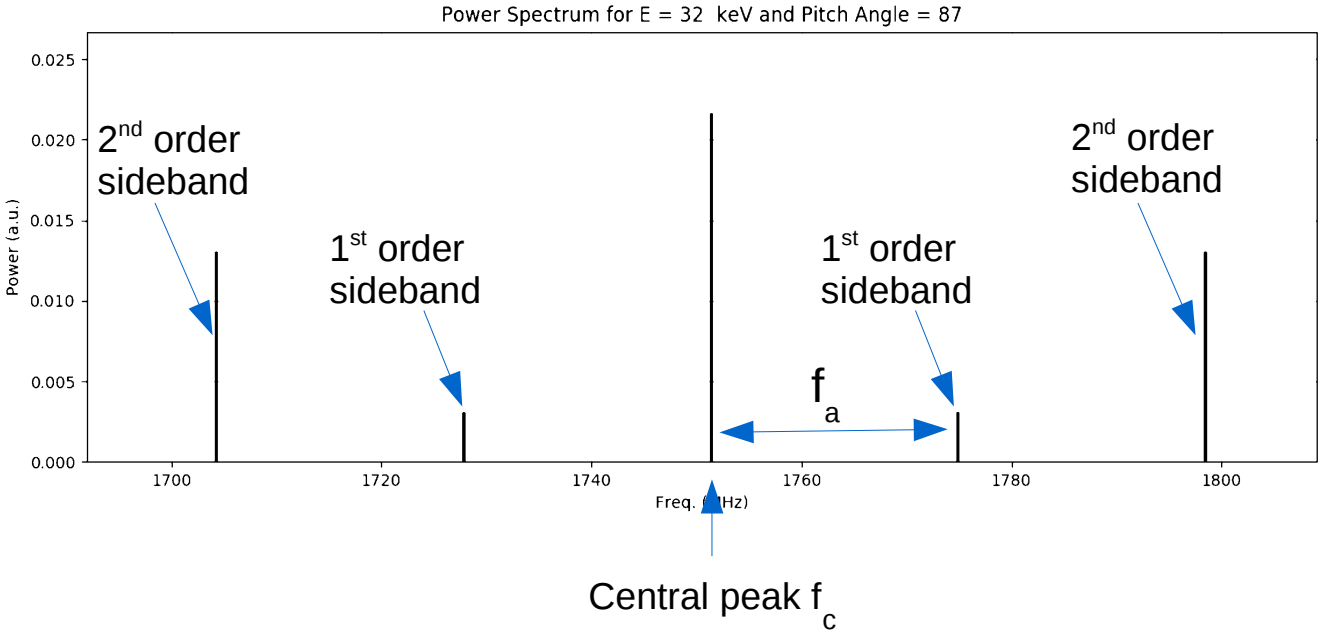
Sidebands

- Axial frequency:
  - L_0: size of flat region
  - L_1: curvature of edges
  - θ: pitch angle

$$f_a = \frac{\frac{1}{2\pi}\cdot\sqrt{\frac{2E_{kin}}{m_e}}c}{\frac{2\pi L_0}{\sin\theta}+\frac{2L_1}{\cos\theta}}$$



- Sidebands due to mixing of axial and cyclotron frequency



Analyst:
A. Esfahani

Phenomenology

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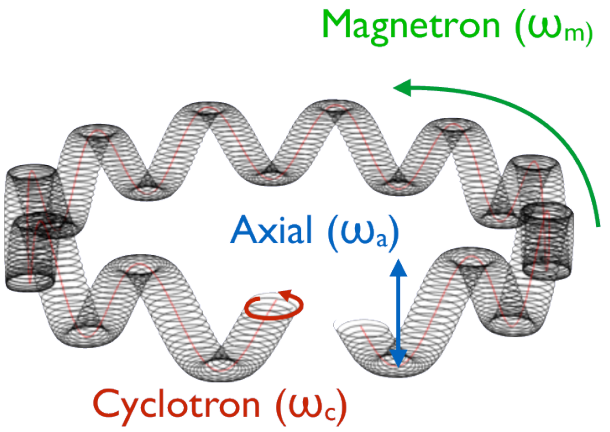
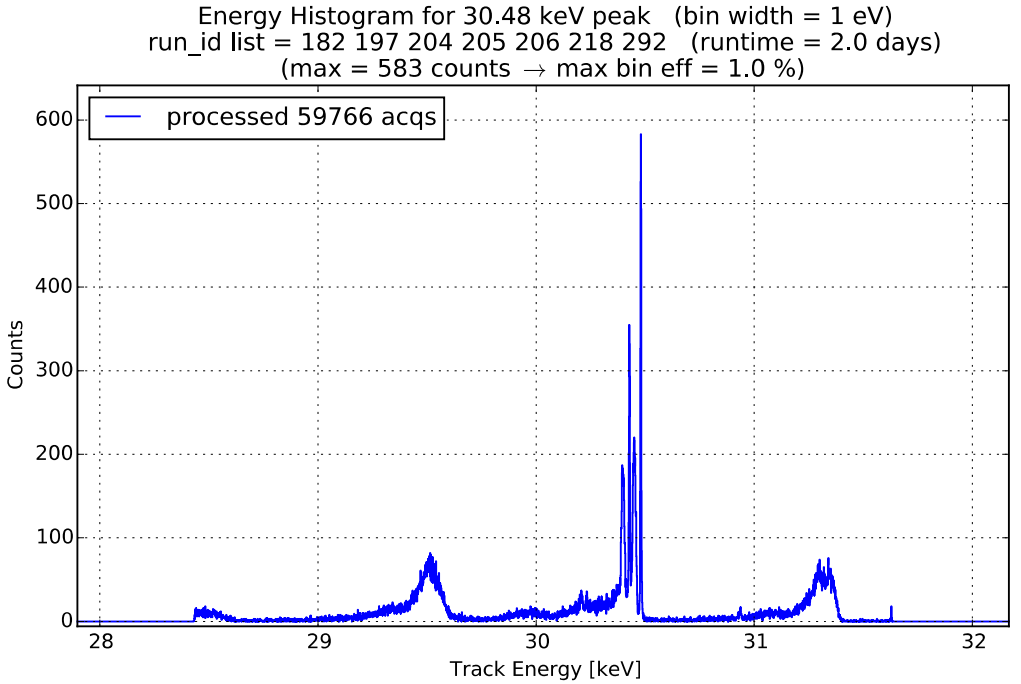


- Sidebands due to mixing of axial and cyclotron frequency
- Extra structure in the Kr-spectrum around known peaks

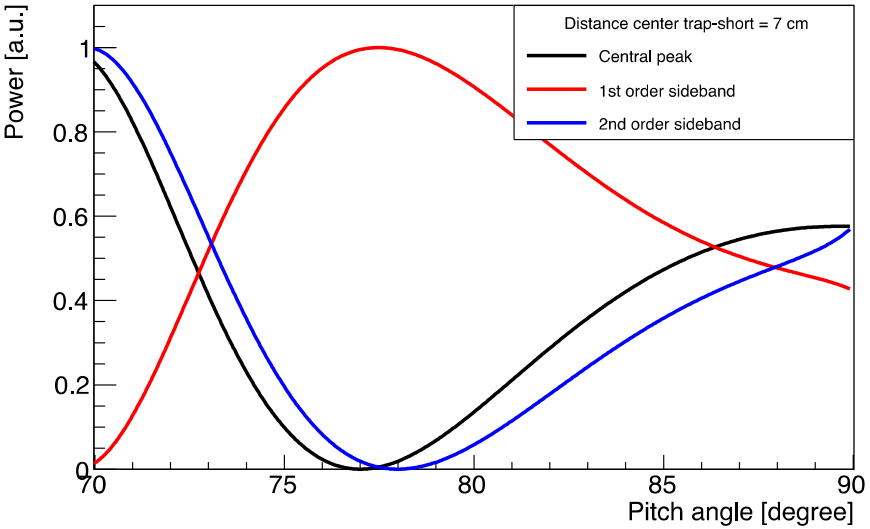


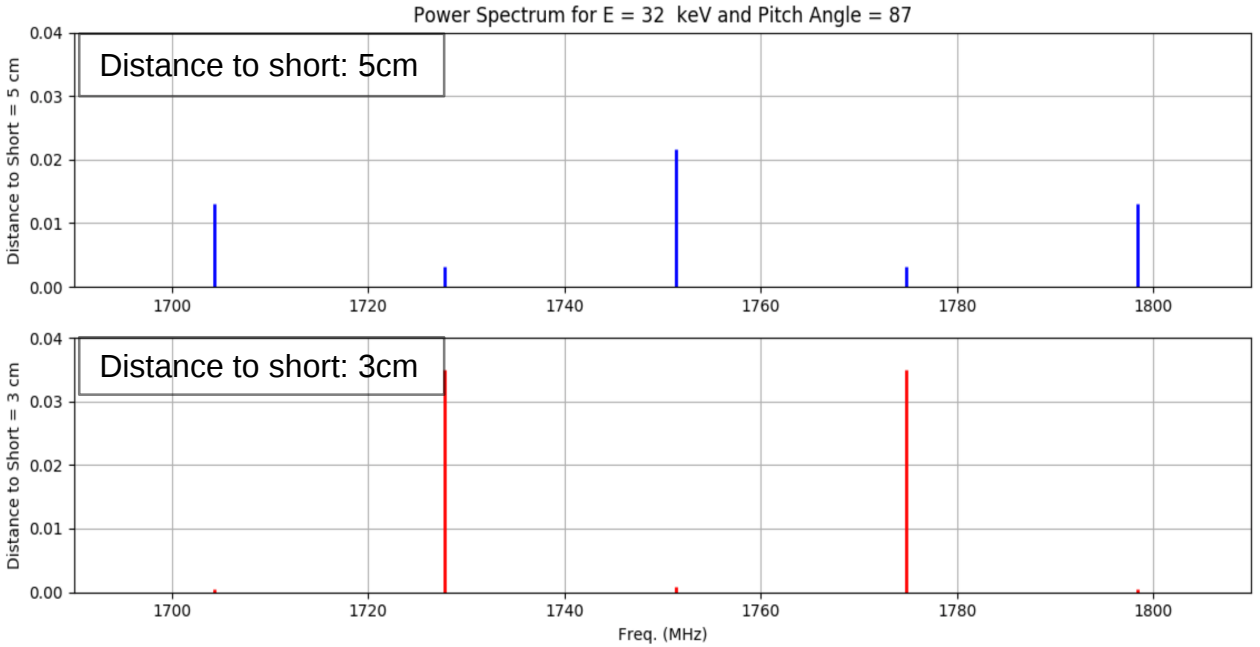
Analyst:
L. Viveiros

Phenomenology

Reflections of the short

- Received power is superposition of signal and reflection by the short
- Detected power depends on the pitch angle and distance between trap center and short





- Interference can enhance or suppress spectral lines
- Analytic model developed by A. Esfahani
- Confirmed with Phase I data

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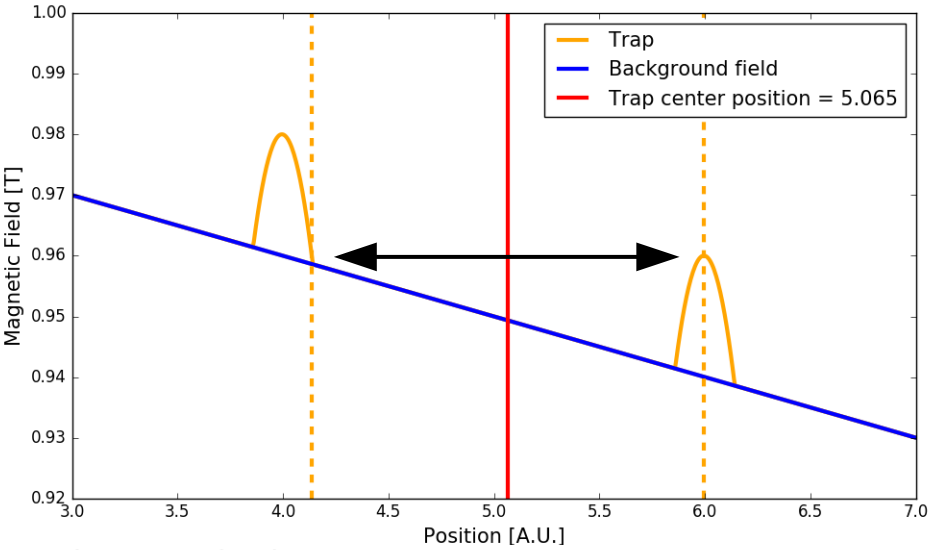
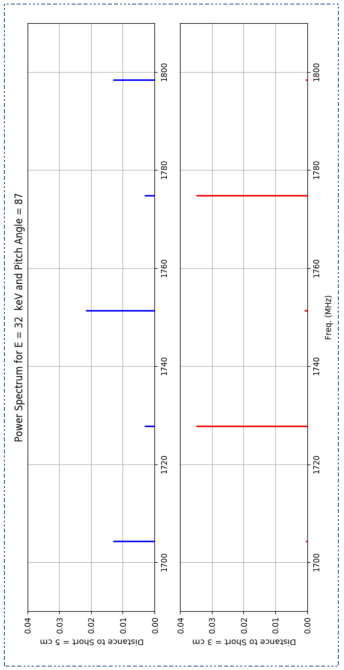
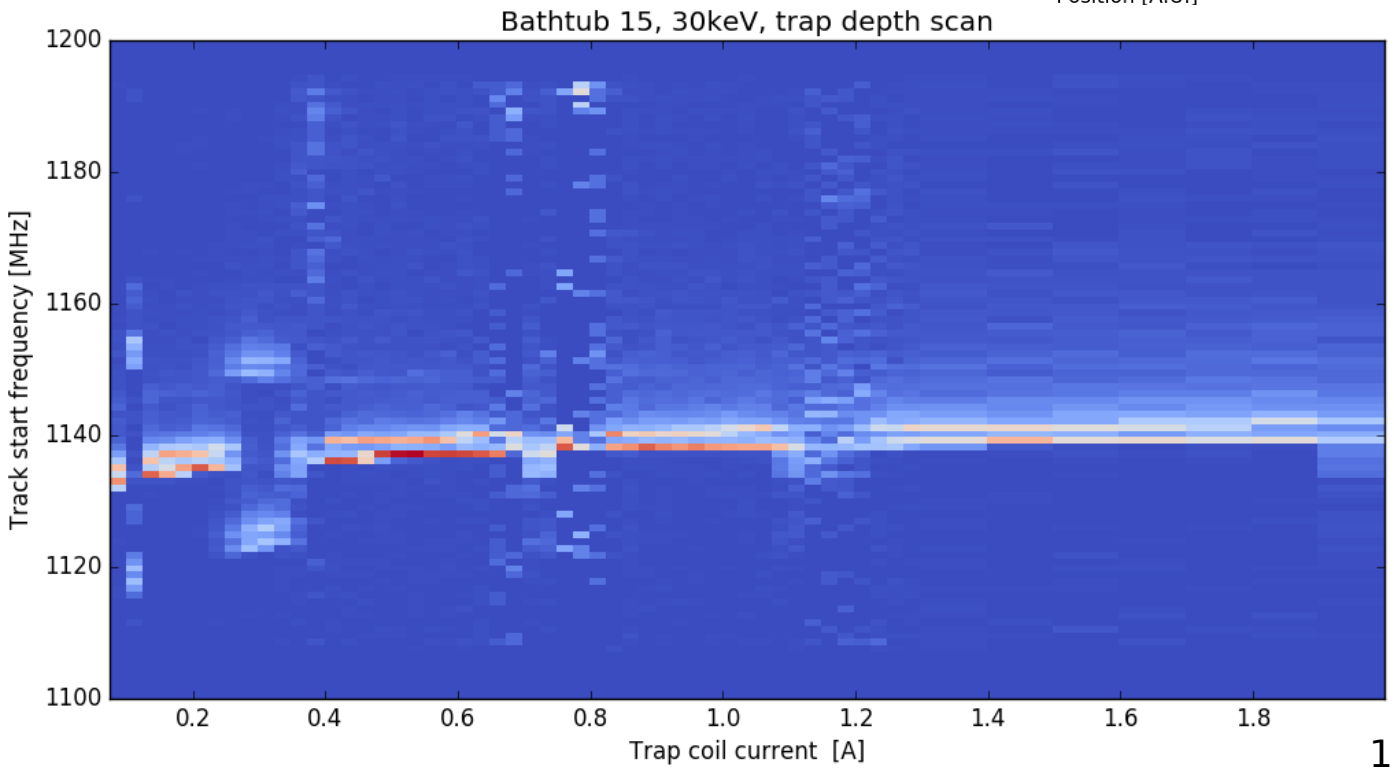
Phenomenology

Reflections of the short

- Background 1T field shows small gradient
- Changing the trap depth, changes the average distance of the electron to the short and the average sampled B-field

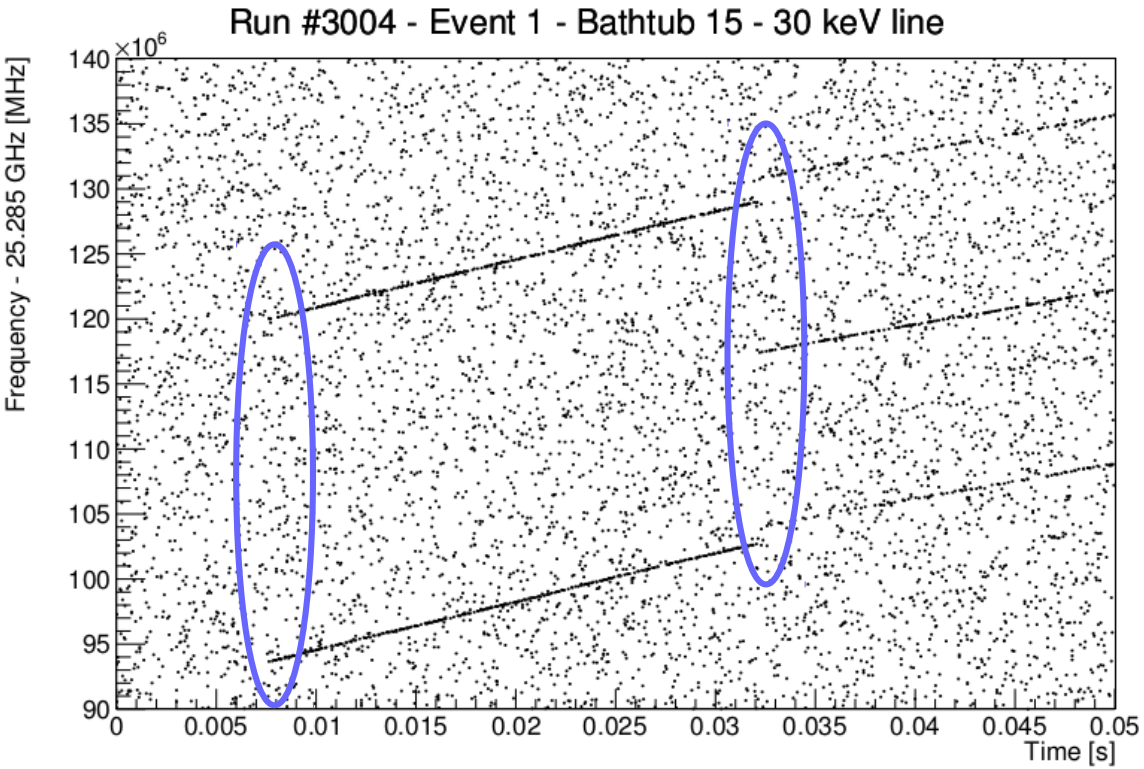






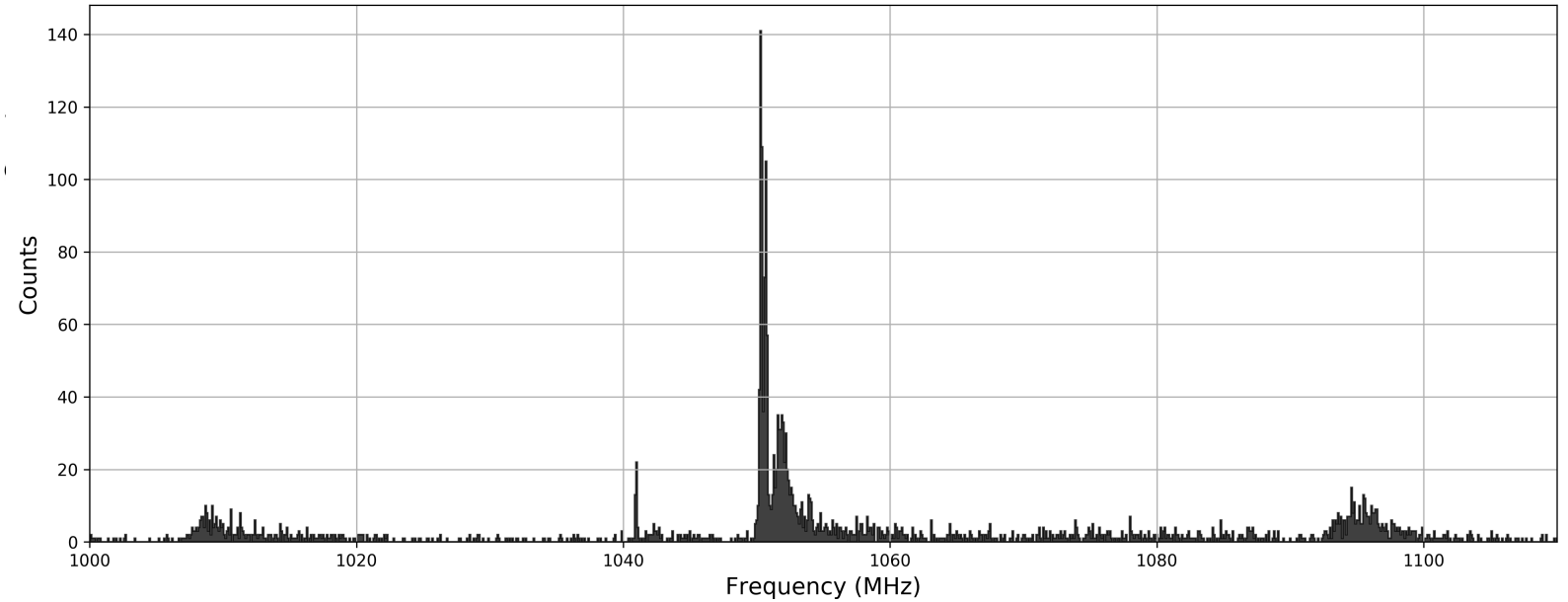
Event reconstruction

- First two tracks are sideband
  - Tracks start and end at same point in time
- Collision with rest gas atom:
  - Change of pitch angle
  - Main carrier becomes apparent
  - Sidebands are now fainter
  - Slope and frequency have changed
- Single electron event with start frequency ~106 MHz (+25.285 GHz)



Track classification

- Using a deep bathtub trap requires pitch angle reconstruction
- Goal: Classify a track purely by the track's properties (width, slope, ...)
- Development in progress (L. Saldana, E. Zayas)
- Train classifier with labeled tracks (sidebands or main carriers) from subset of Phase I data



Analyst: L. Saldana

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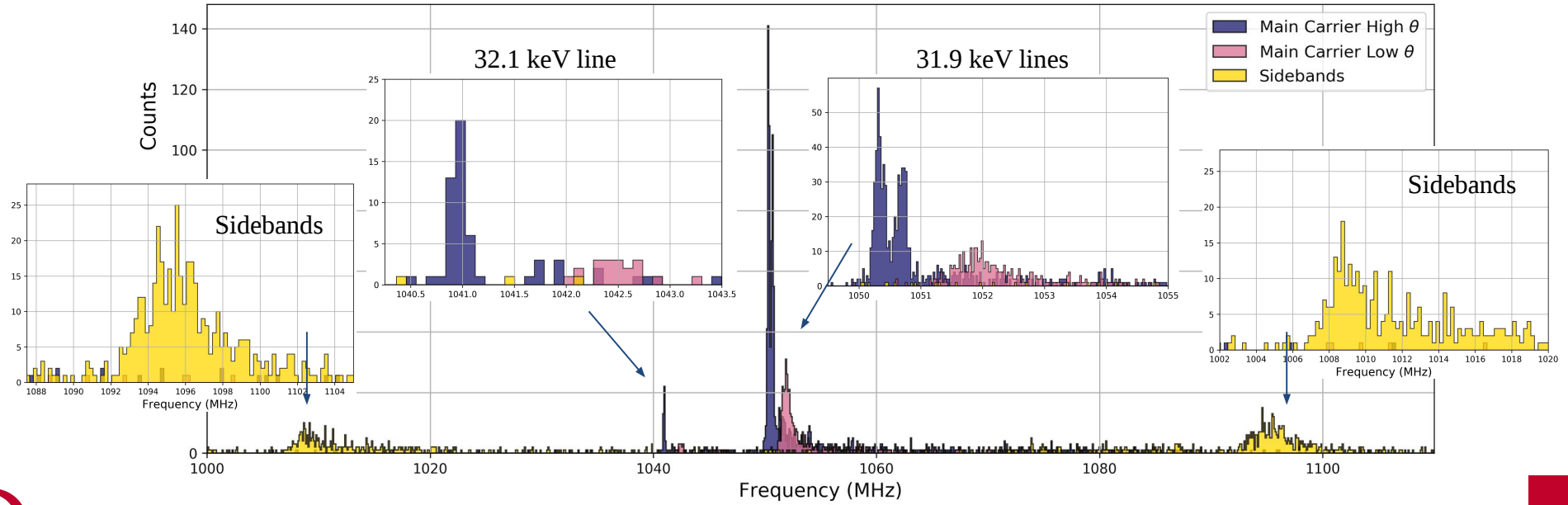
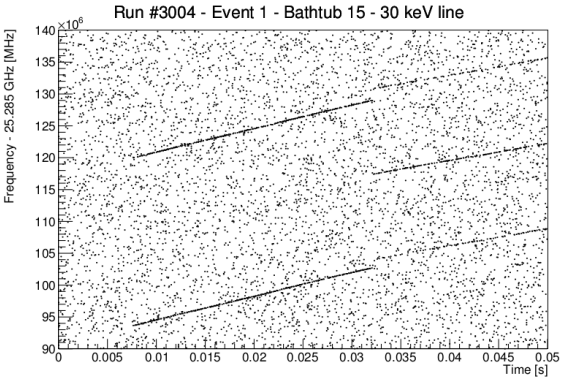
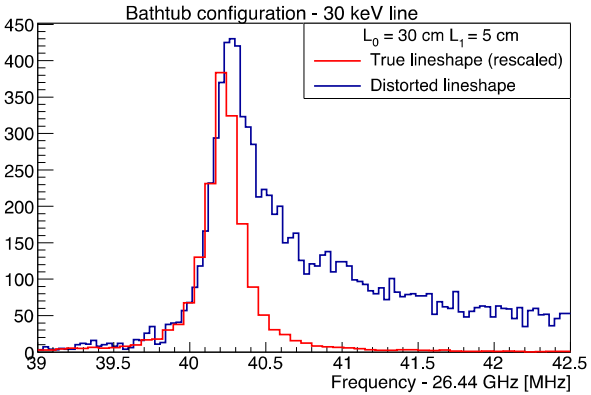
- Test on data unknown to training
- First results from Phase I data look very promising



Conclusion and outlook

- Currently taking ^{83m}Kr data with Phase II apparatus
- Commissioning of the ROACH2 digitizer
- Trigger development in progress
- Testing new track reconstruction algorithms
- Development of phenomenology that explains the data
- Pitch angle reconstruction necessary to determine true event energy
- Sidebands and received power carries information about pitch angles
- Working on high confidence classifier to distinguish sidebands from main carriers





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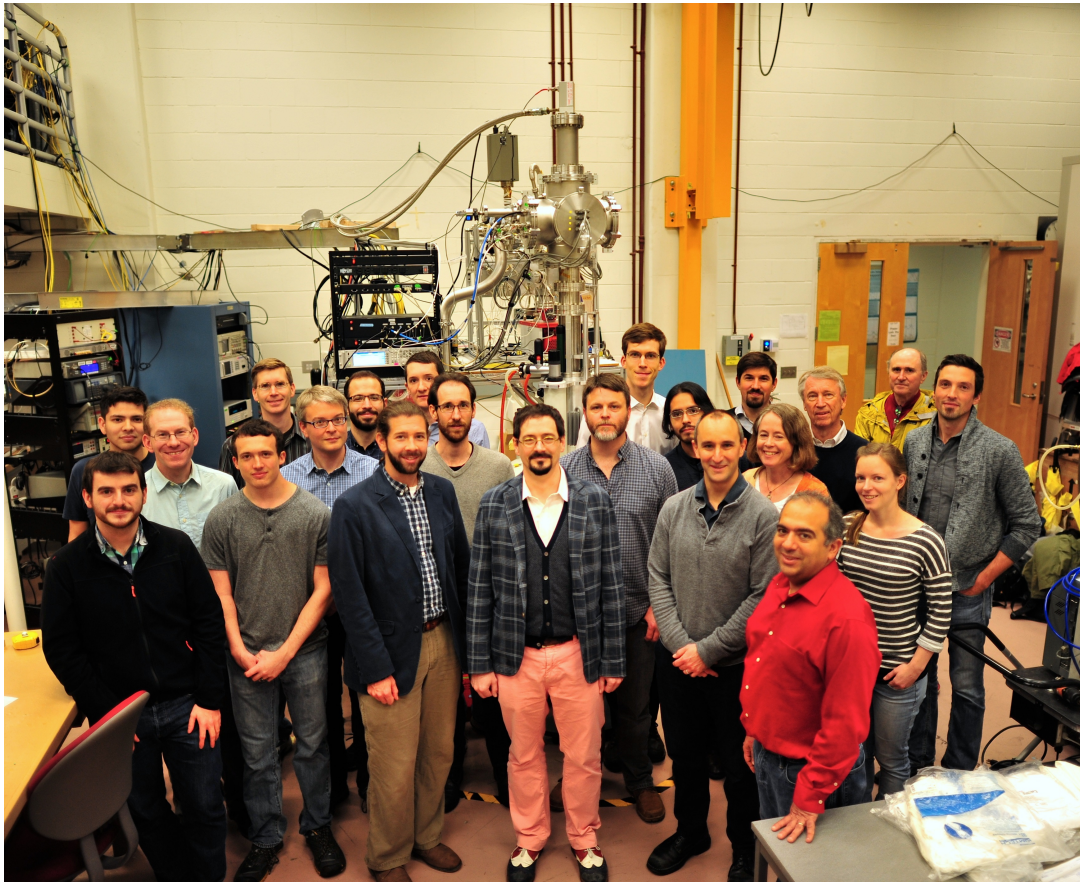

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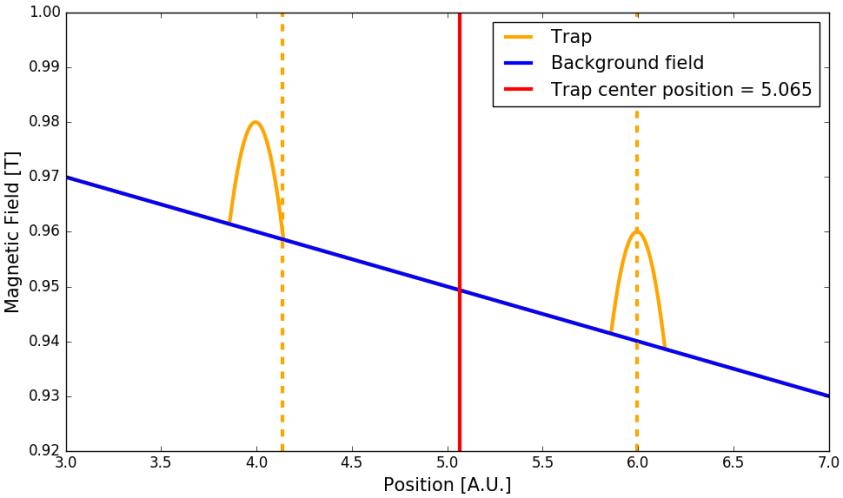
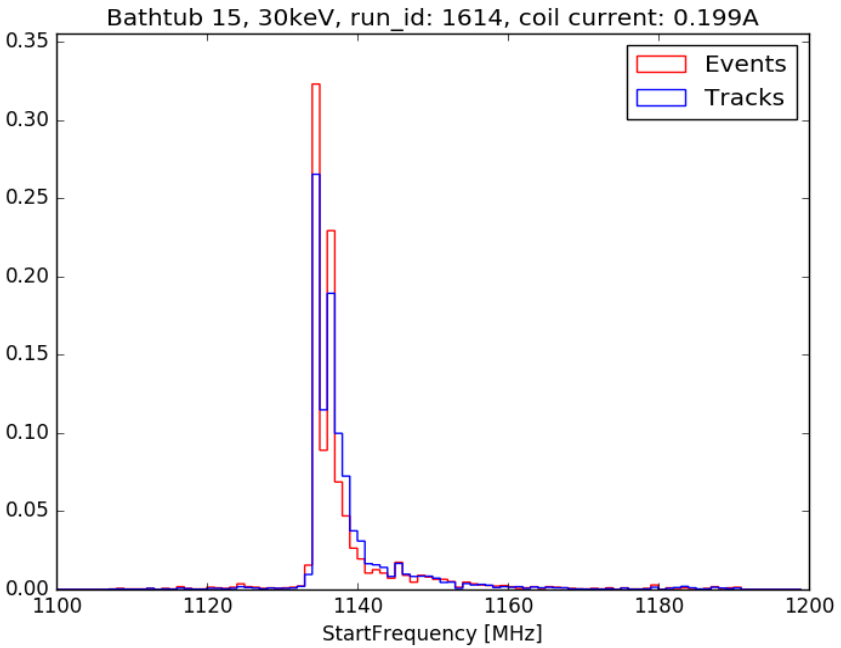
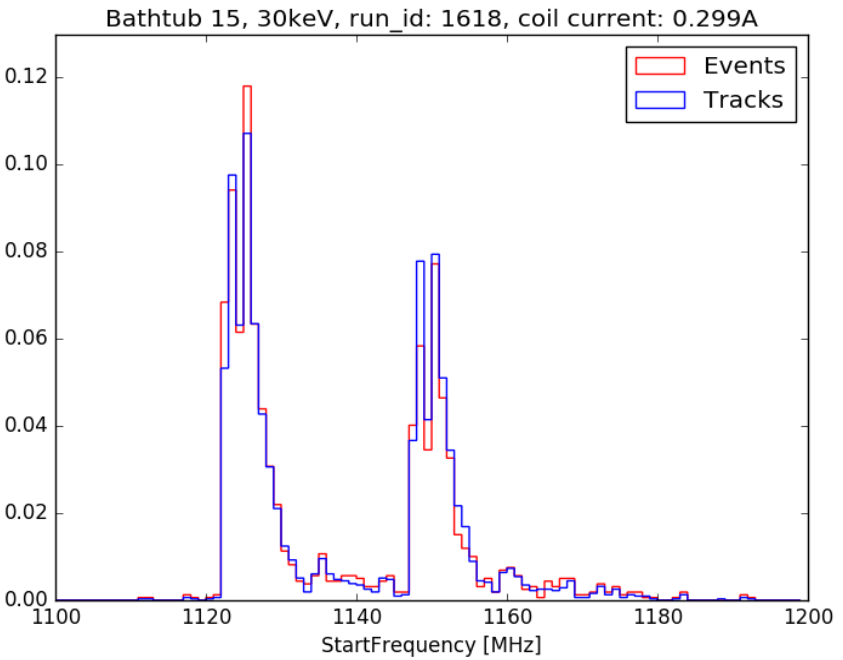
Phenomenology

Reflections of the short

- Background 1T field shows small gradient
- Changing the trap depth, changes the average distance of the electron to the short and the average sampled B-field







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