Zero-deadtime processing in beta spectroscopy for measurement of the non-zero neutrino mass

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For the Project 8 Collaboration

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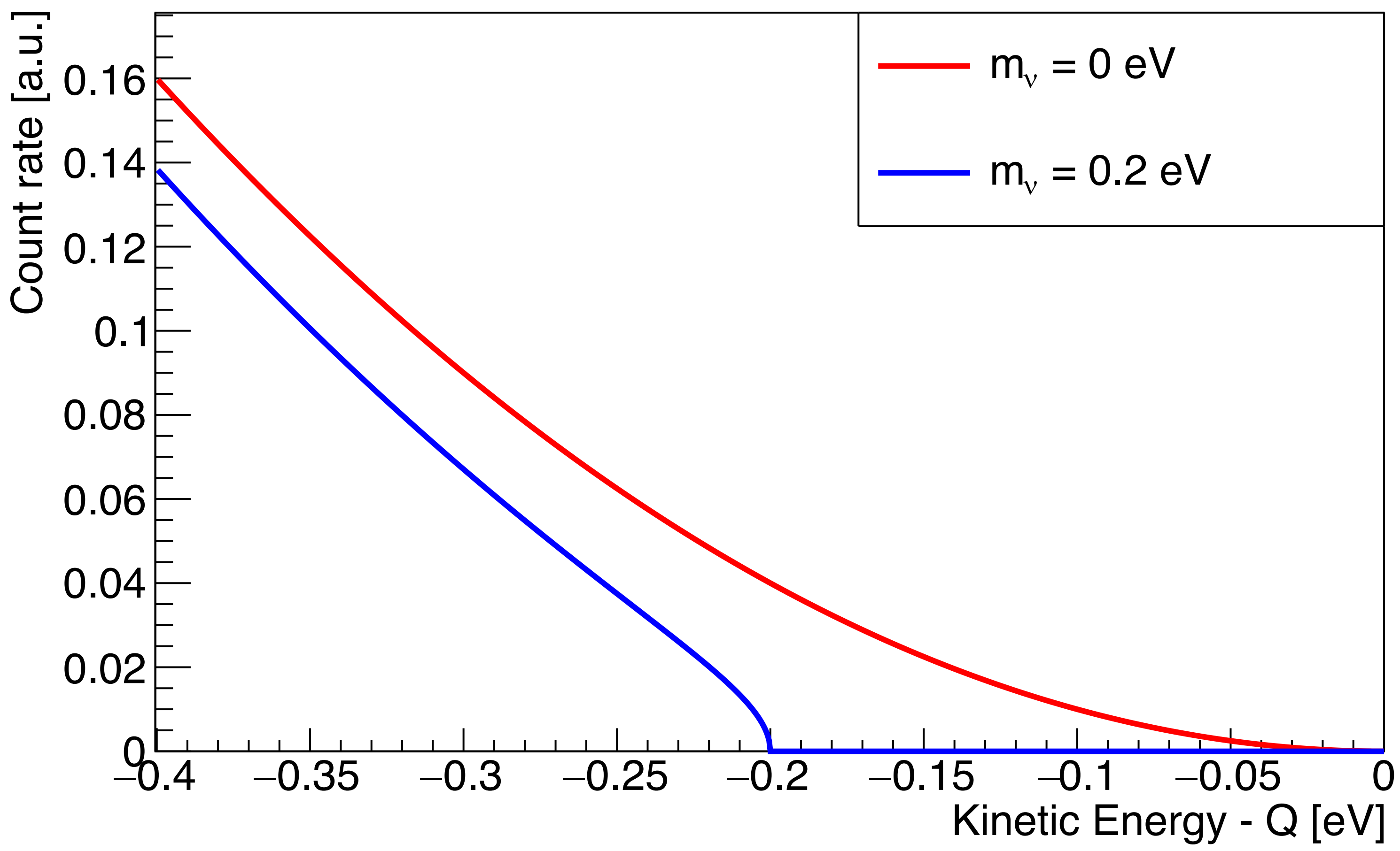
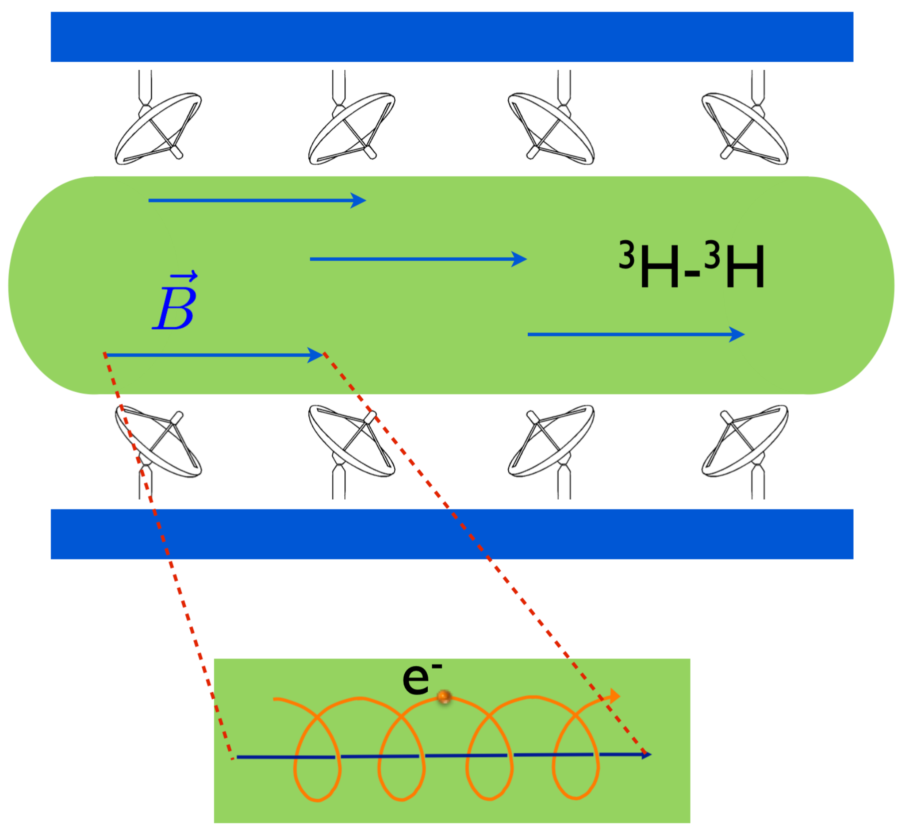
The tritium endpoint method and Cyclotron Radiation Emission Spectroscopy (CRES)

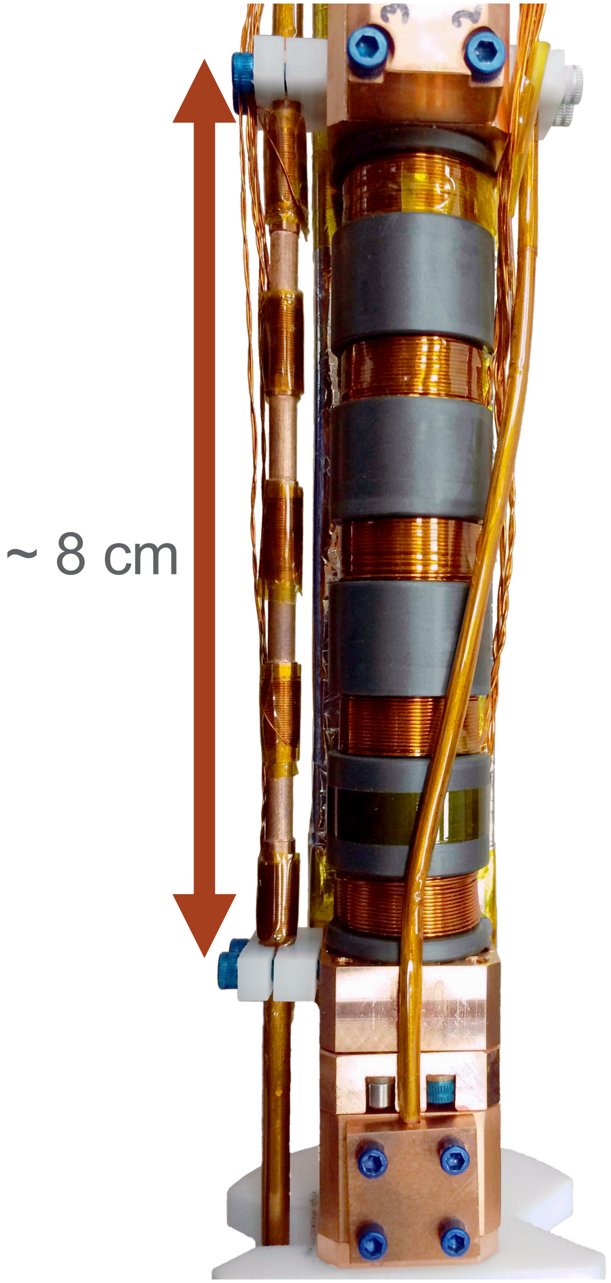




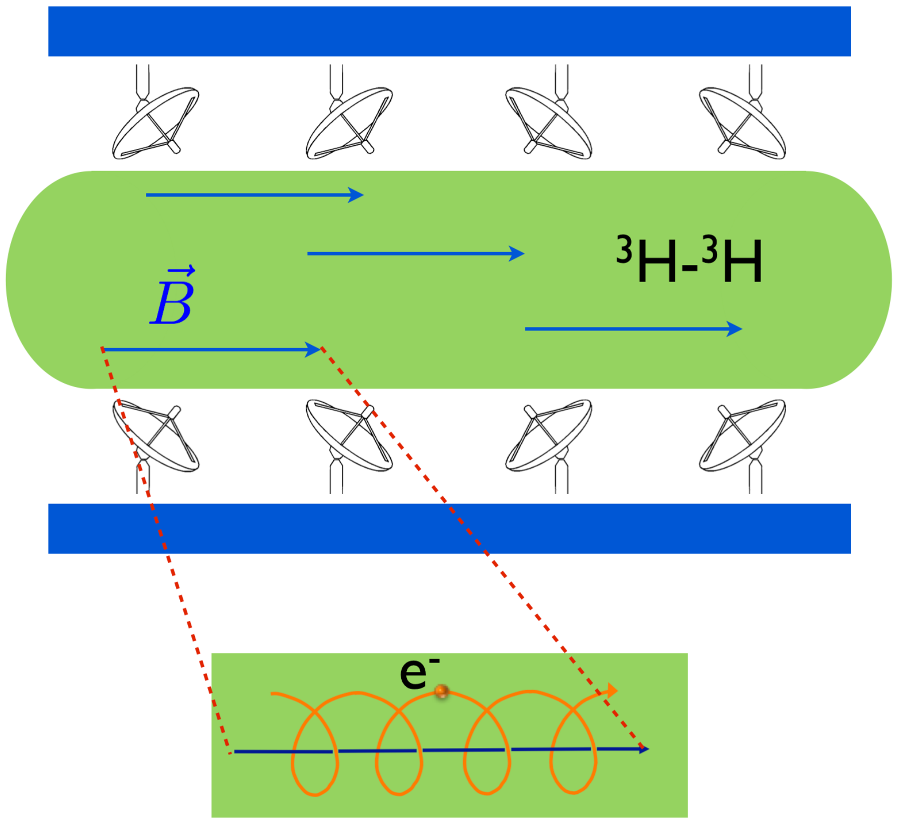
$$F_{cyclotron} \propto \frac{B}{T + m_e c^2}$$

$$\frac{dN}{dE} \propto F(Z,E)p_e(T + m_e c^2)(E_0 - T)\sqrt{(E_0 - T)^2 - m_\beta^2 c^4}$$

The current and next phase

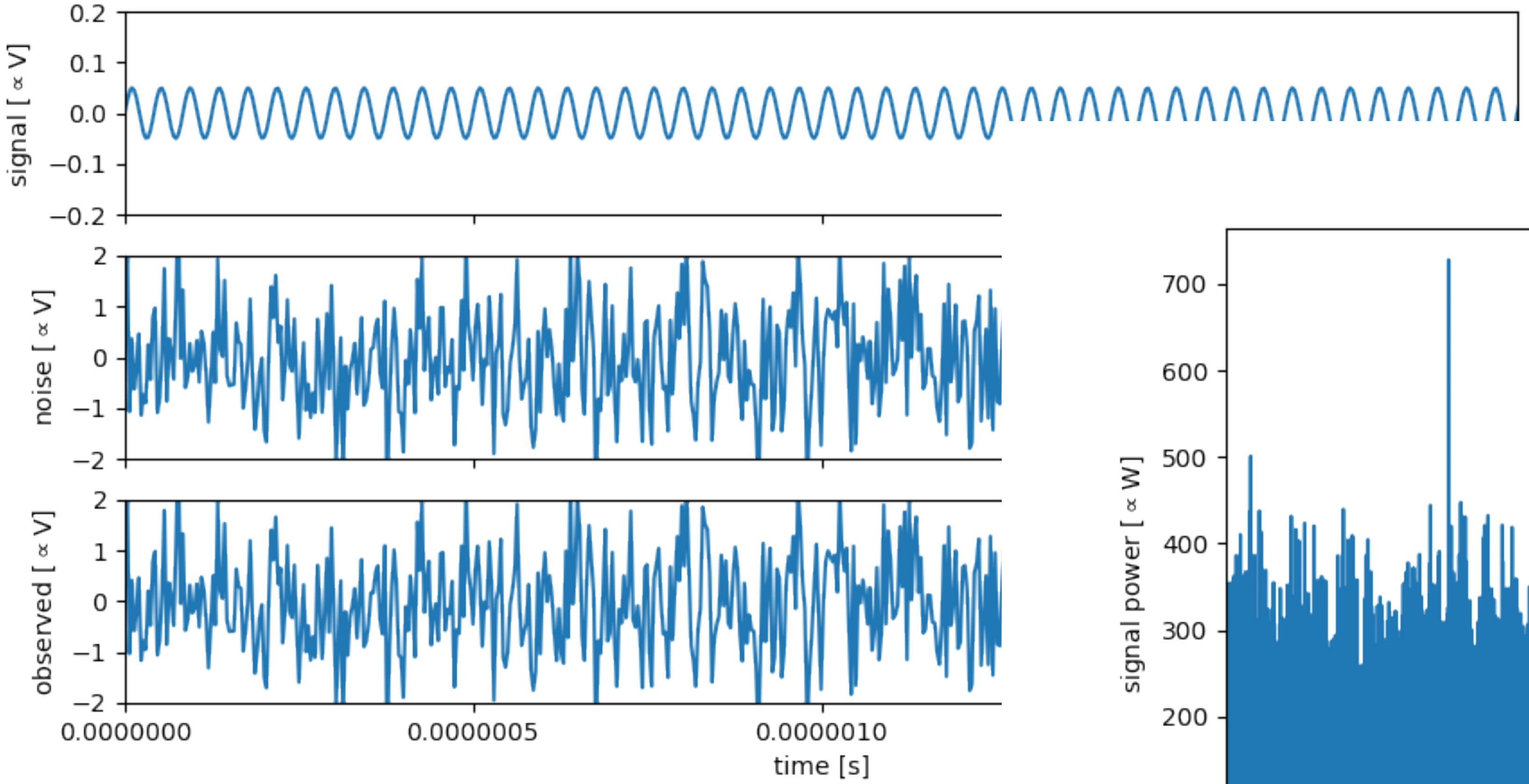


- Current phase (left) has minimal trapping volume; trap is inside waveguide
- Next phase expects ~100cm^3 of trapping volume to show scalability; many channel readouts required
- Final phase requires > 1m^3 in order to achieve sufficient statistics

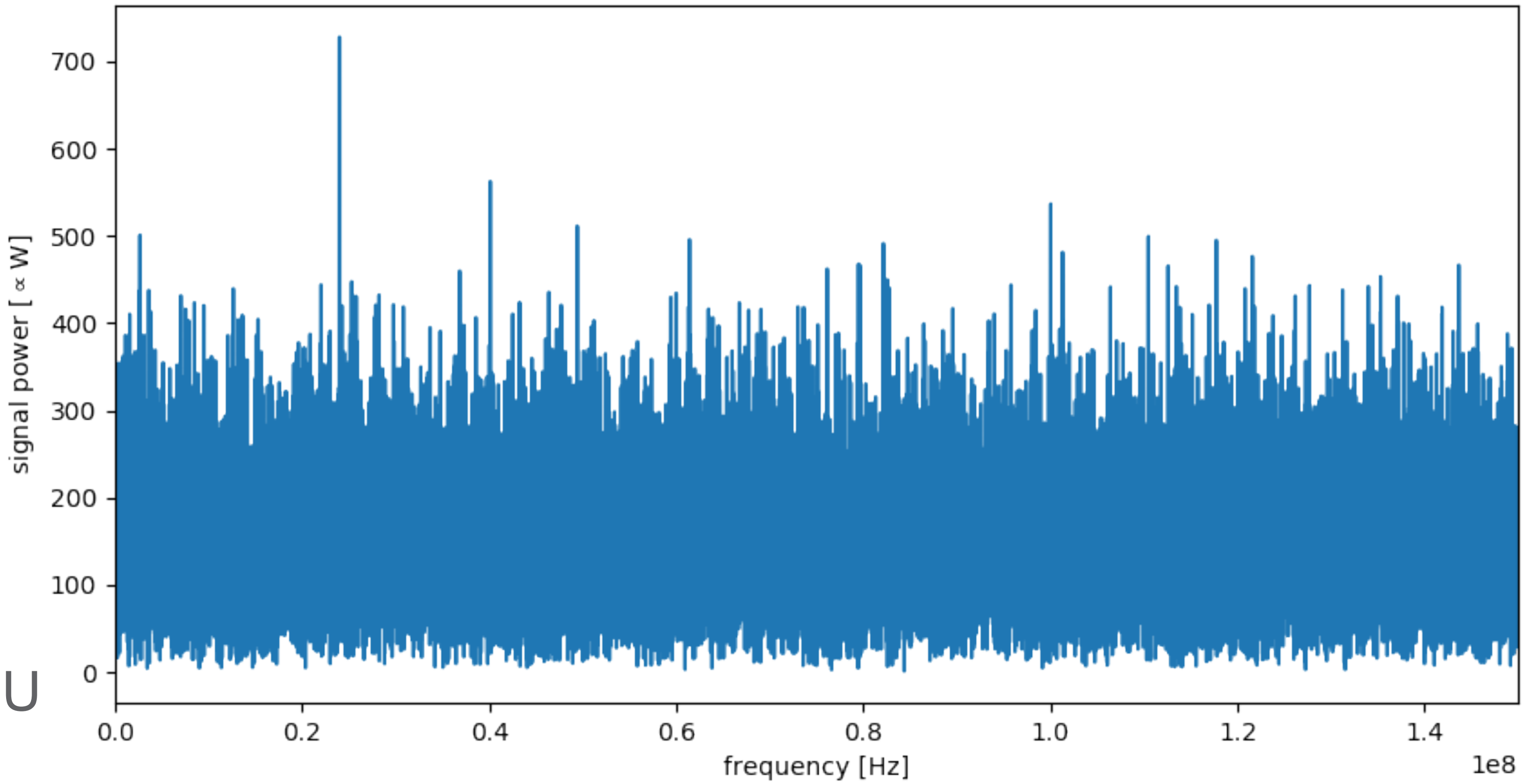


Signals visible in the frequency domain

Signal is buried in time domain

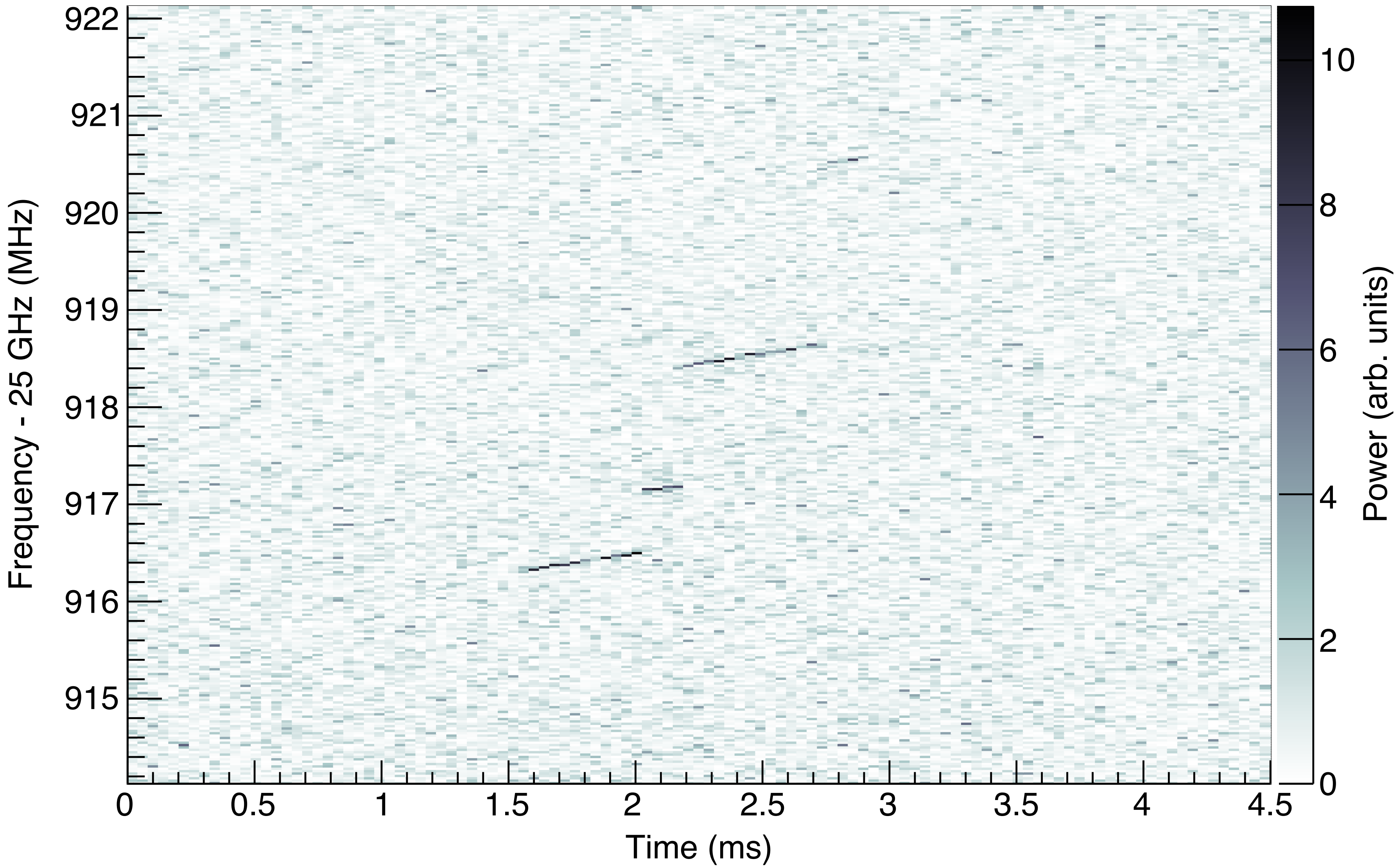


But visible in frequency domain



1. FPGA captures ADC data and does FFT
2. Both domains transmit via 10 GbE for CPU processing
3. Trigger on sequential frequency domain triggers but record time data for offline reconstruction

Our first tritium event



- Vertical bands: power spectra of sequential 30μs intervals
- Online trigger considers only threshold with recurrence requirement
- Offline reconstruction does more sophisticated clustering

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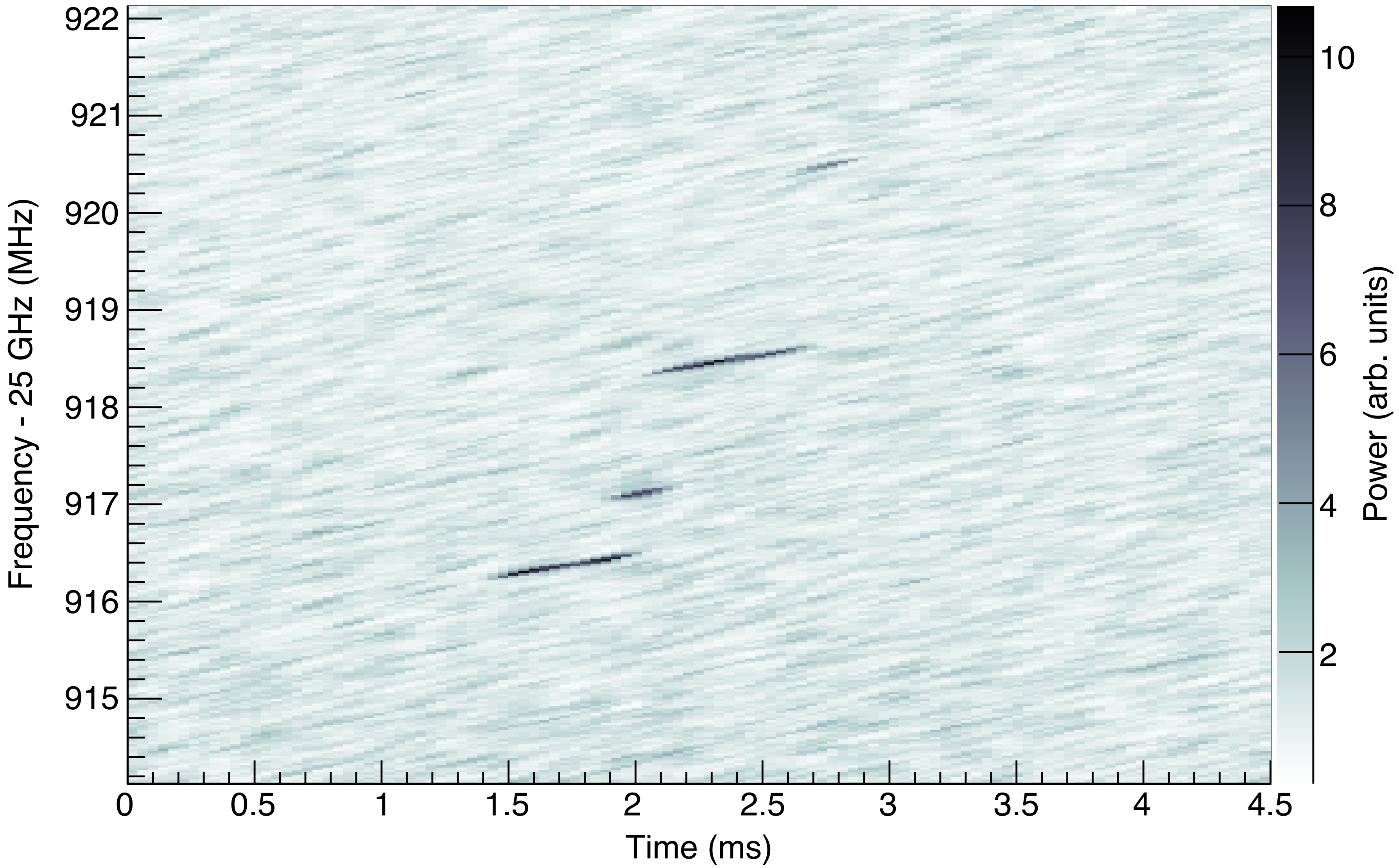

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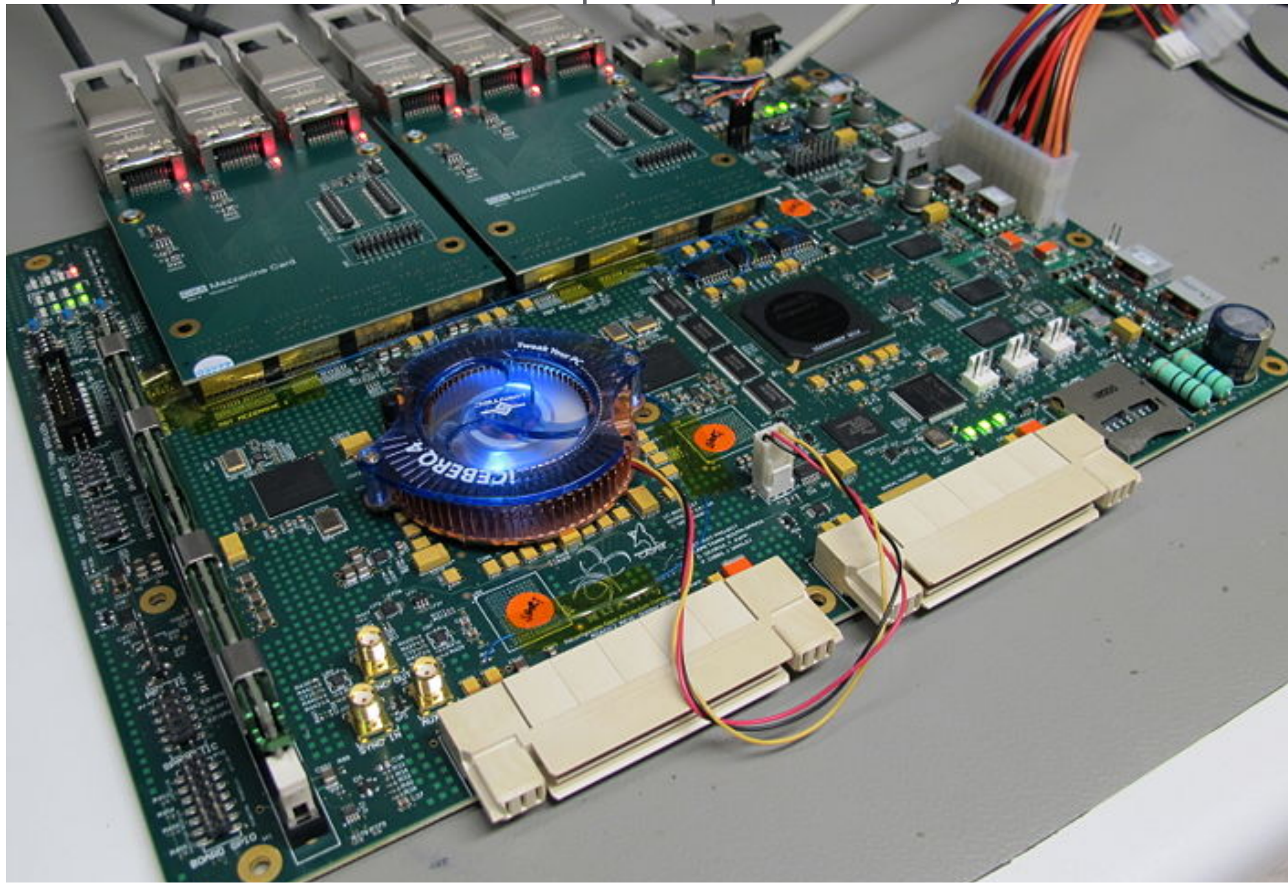
*filter applied for projector visibility only

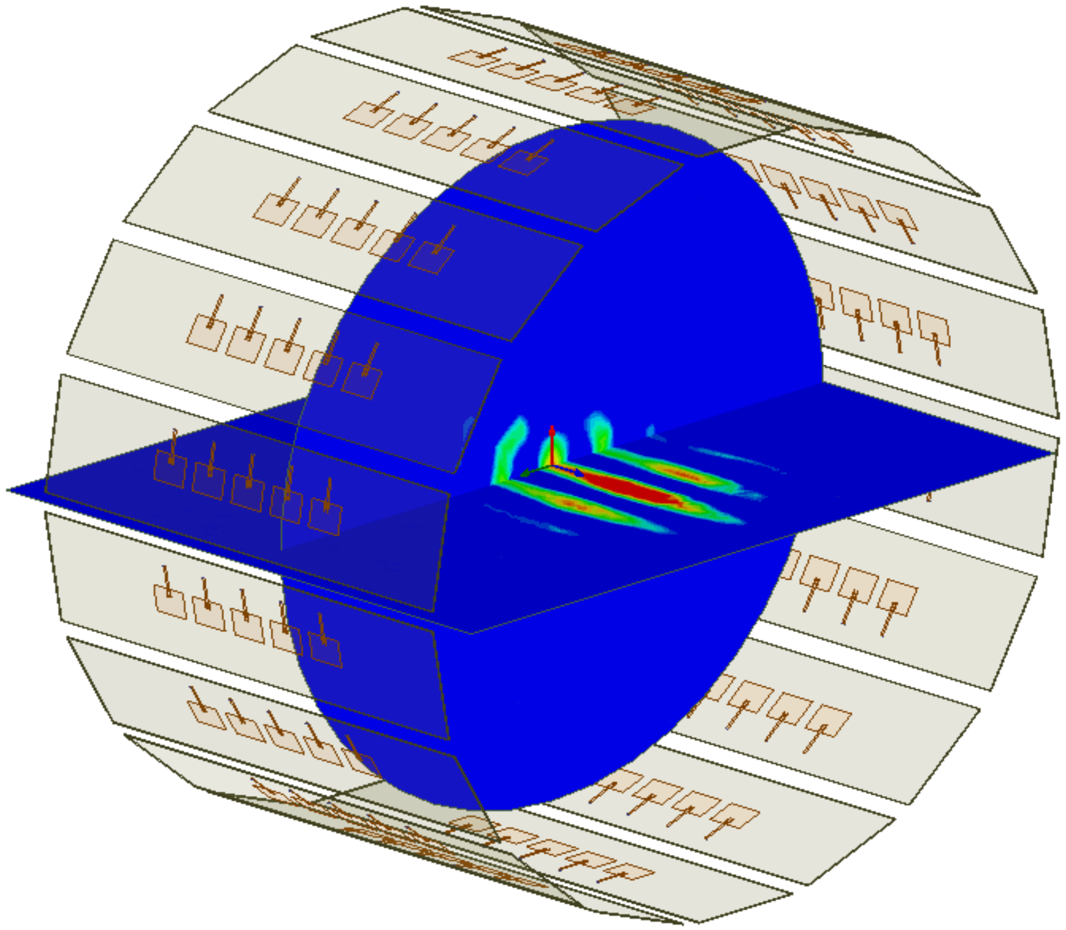
Data rates and stream processing

Photo credit: https://casper.ssl.berkeley.edu/wiki/ROACH2



- 3.2 GS/s (8 bit) from the ADC
- FPGA, for each of 3 selected bands:
  - Digital down-conversion to 100 MHz (200 MS/s)
  - Computes FFT
  - Ships both domains (400 MB/s/channel)
- CPU implements trigger logic
  - Threshold applied in frequency domain
  - Consecutive power constitutes a variable trigger
  - Time domain written to disk
  - Ring buffers between threaded processing stages
- Triggered mode can operate all 3 channels without deadtime (limited by local storage volume and site network)
- To date, we've generated roughly 230 TB of recorded data

Data challenges of a larger source



- The RF signals will be split between channels; must be combined to recover SNR (current baseline is 30-60 ADC channels)
- The raw data rate per channel doesn't go down, and data reduction has to come after a layer of processing
- More antennas improve position resolution and increase SNR, but also increases data volume and required online computation

Planning a multi-stage framework

Front End

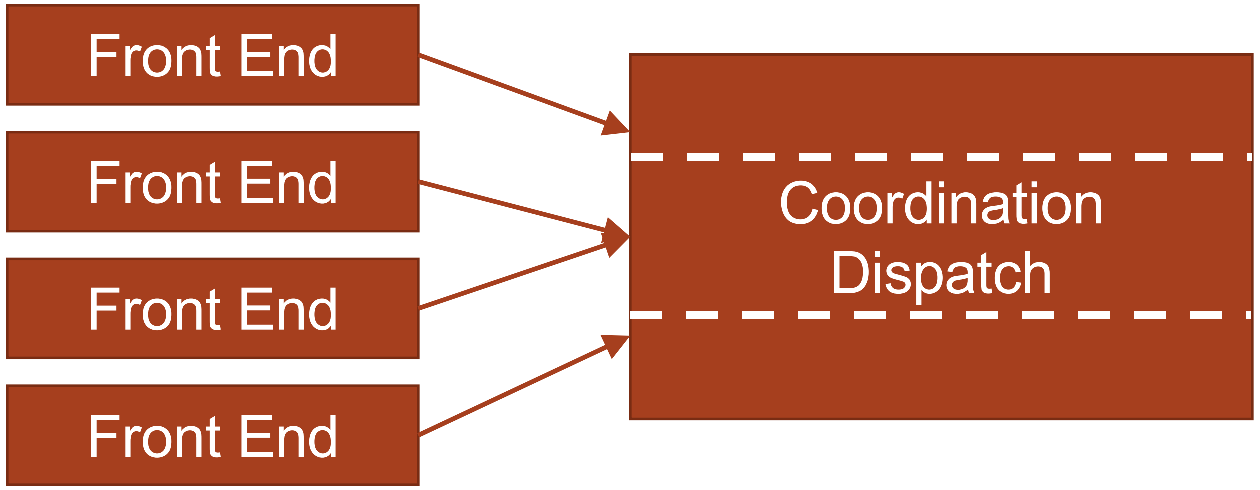
Front End

Front End

Front End

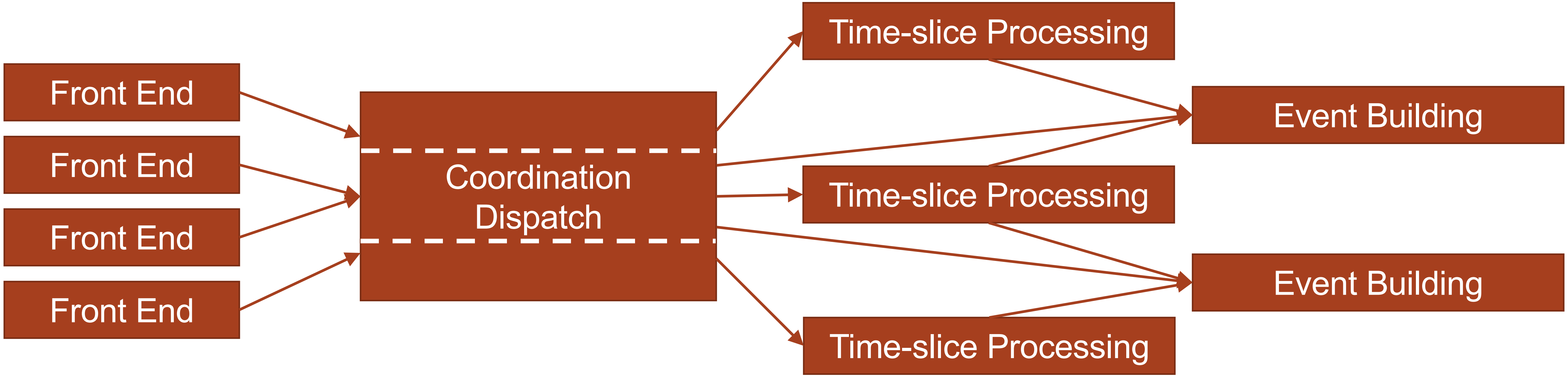
- CASPER framework enables FPGA processing of each analog channel
- Currently exploring several supported open platforms (eg SNAP2 and SKARAB)
- Boards move data onto a high-bandwidth local data network
- Each board is simultaneously sending out each data packet

Planning a multi-stage framework



- A coordination layer controls how raw data get distributed
- Provides an opportunity to re-package for subsequent processing
- Provides a point for scaling and/or staging data transfers

Planning a multi-stage framework



- Each time-slice processor deals with all of the data for a specific time interval, but does not need to process each consecutive interval
- Initial trigger logic still done using only a single time interval
- When a signal is found, adaptive event building can record the specific combination motivated by the trigger
- Stages can be developed and benchmarked independently and alternative architectures or algorithms explored

Summary

- The current online data processing system for Project 8 is able to handle CRES signals from a single analog channel, with 3 frequency bands of interest, in triggered operation without deadtime.

- The next generation of the project will need to handle not only a factor of 50 increase in the number of channels, but will require combining data from all channels prior to applying triggering logic to reduce data volume.

- We are planning a multi-stage online processing system which provides both modularity and targeted scalability, and the use of specialized architectures.

The Project 8 Collaboration

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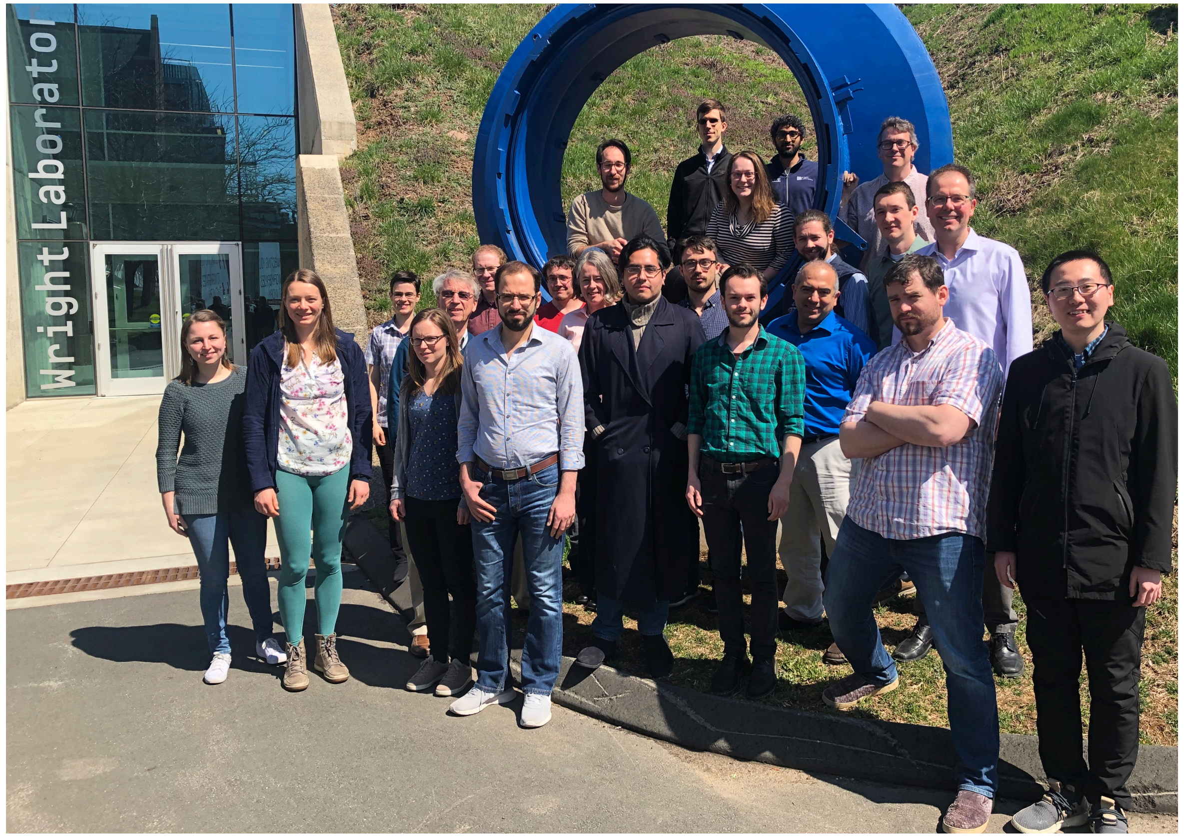

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