An FPGA-based Trigger for the QTNM Experiment

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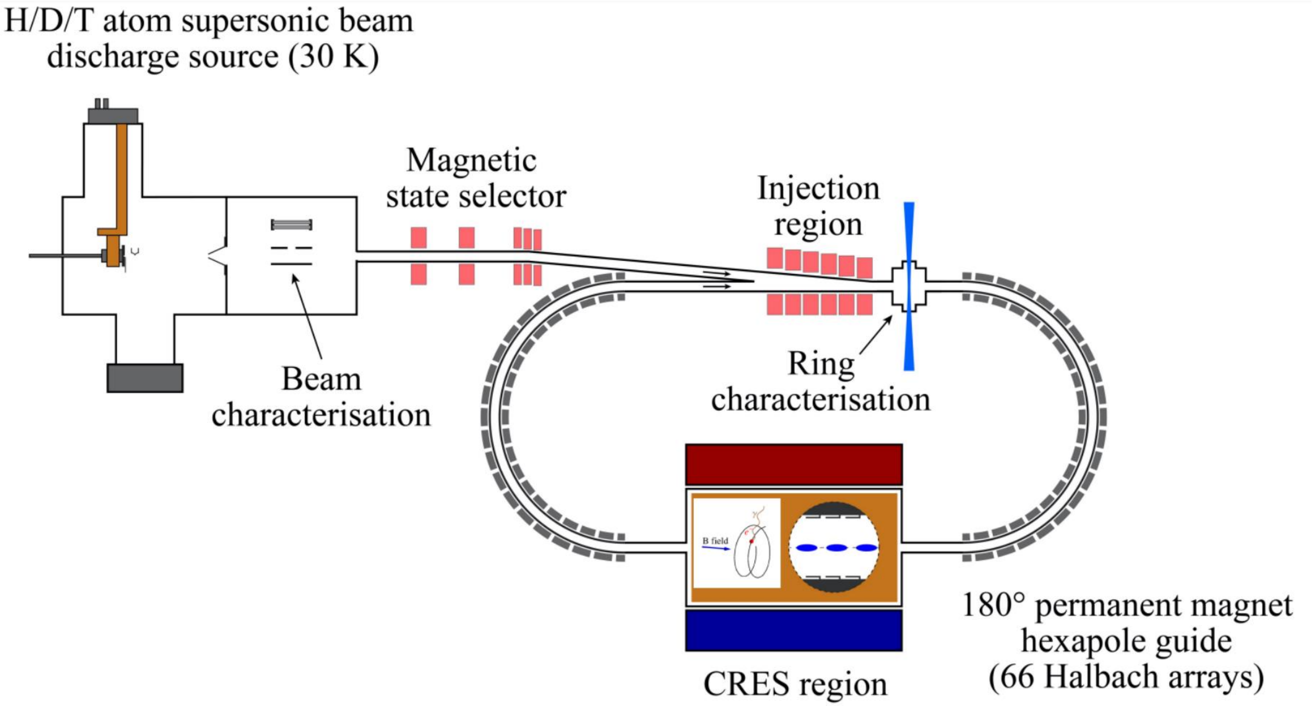
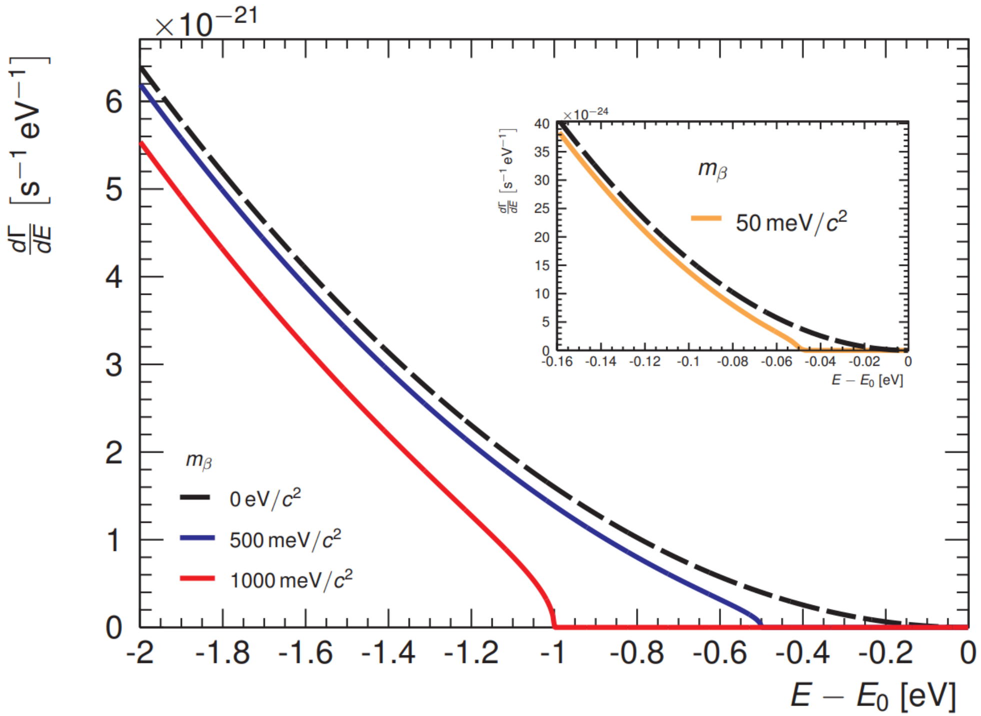
QTNM

- Quantum Technologies for Neutrino Mass
- The aim is to investigate methods and techniques for measuring the absolute neutrino mass scale using atomic tritium beta decay.





CRES

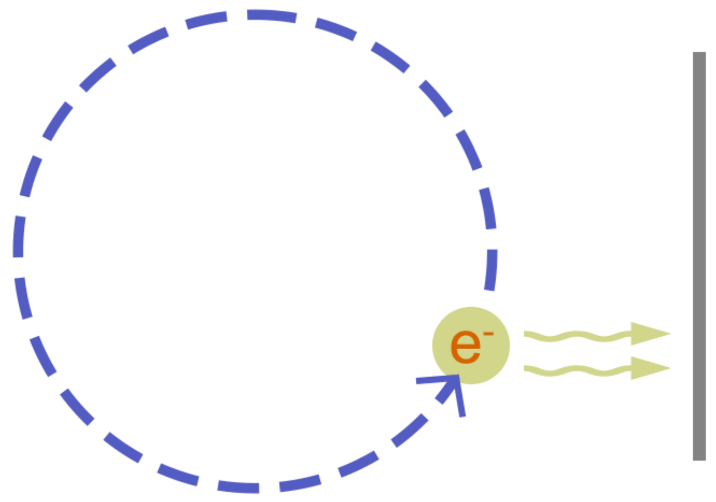
- Cyclotron Radiation Emission Spectroscopy
- When an electron undergoes cyclotron motion in a magnetic field, it emits radiation.
- The frequency of this radiation is linked to the magnetic field strength and the kinetic energy of the electron.

$$\Omega_c = \frac{eB}{\gamma m_e} = \frac{eB}{m_e + K_e/c^2}$$

- Can form the energy spectrum by measuring frequency and magnetic field.
- Tritium beta decay is random, so need a trigger to detect these signals.

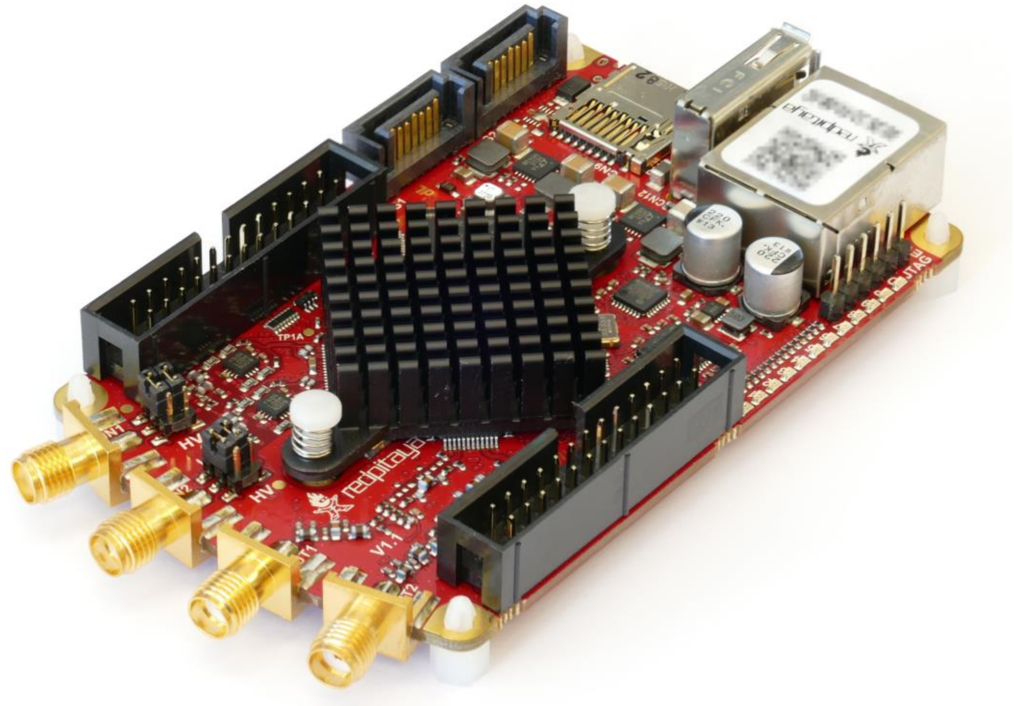
Typical Signal

- The electron moves in a cyclotron orbit, so the base form of the signal is sinusoidal.
- As the electron loses energy, the frequency of the radiation increases, forming an approximately linearly chirping sine wave.
- The signal from a single electron is very small (less than 1fW).
- As a result, even small contributions from thermal background or amplifier noise can quickly overwhelm the signal.
- Given that the Signal-to-Noise Ratio (SNR) can be extremely small (as low as 0.04), an atypical form of trigger will be necessary to detect electrons of interest.
  - For this purpose, a lock-in amplifier trigger and matched filter trigger have been investigated.



FPGA

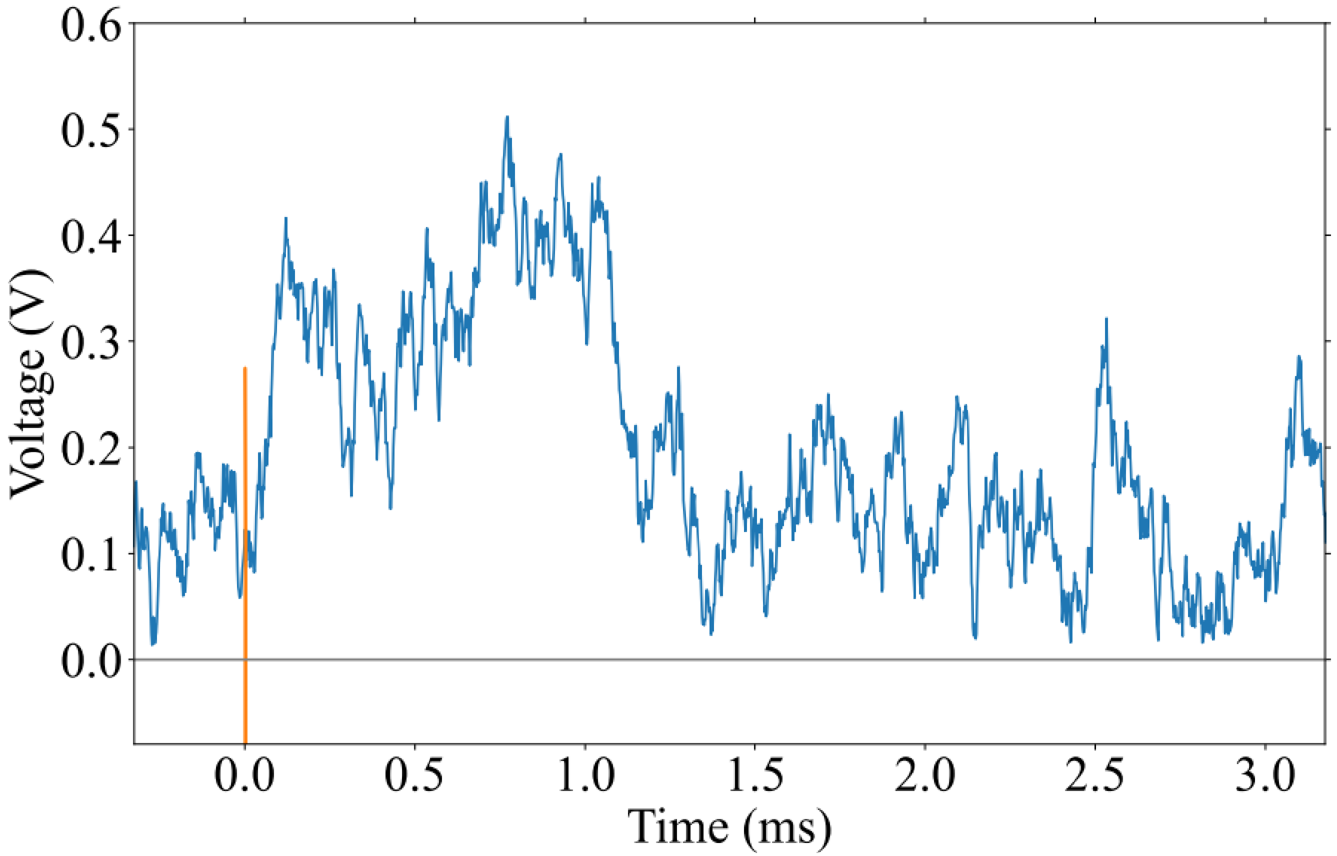
- Field-Programmable Gate Arrays
- A form of programmable hardware, which can be customised using a hardware description language to perform specialised tasks.
- For this project, used a Red Pitaya STEMlab 125-14
- Two variants, one with a Xilinx Zynq Z-7010 FPGA and one with a larger Z-7020.



Lock-In Amplifier

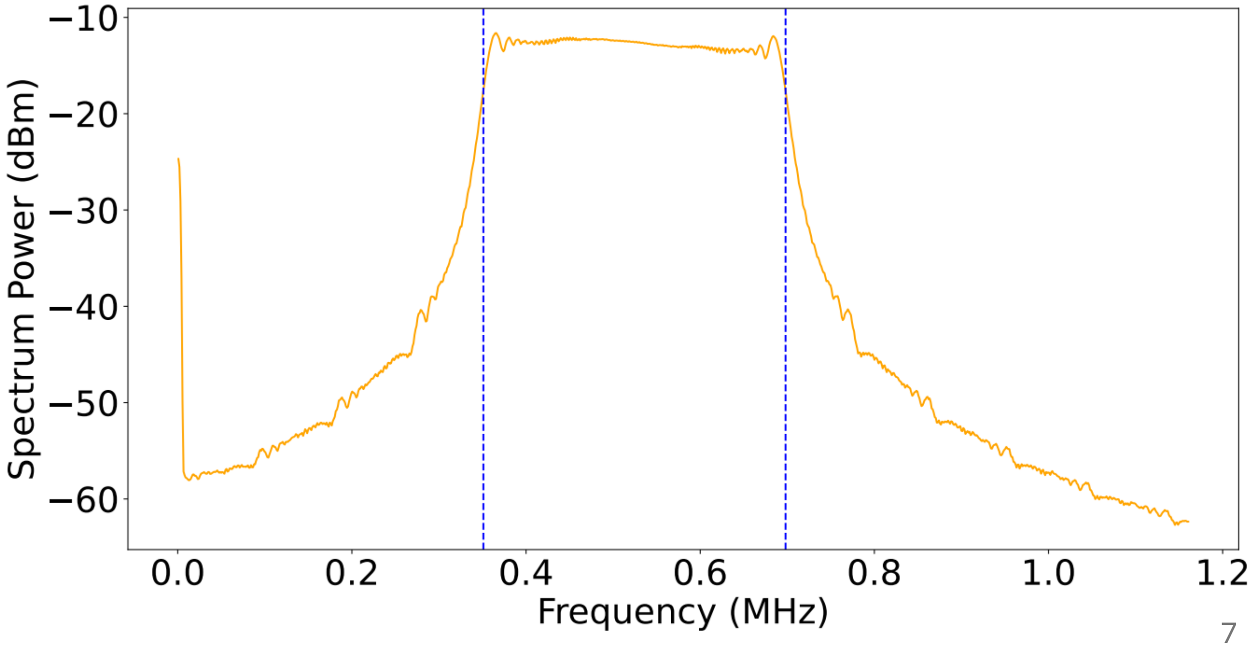
- Lock-in amplifiers (LIAs) are often used for high-noise signal detection.
- Produce an increased response when a signal is present that matches the reference, which can form the basis of a trigger decision.
- They are typically very expensive, but a system has been developed for the Red Pitaya STEMlab FPGA system.

G. Stimpson, M. Skilbeck, R. Patel, B. Green, G. Morley; Rev. Sci. Instrum. 2019; 90 (9): 094701



Chirping LIA Trigger

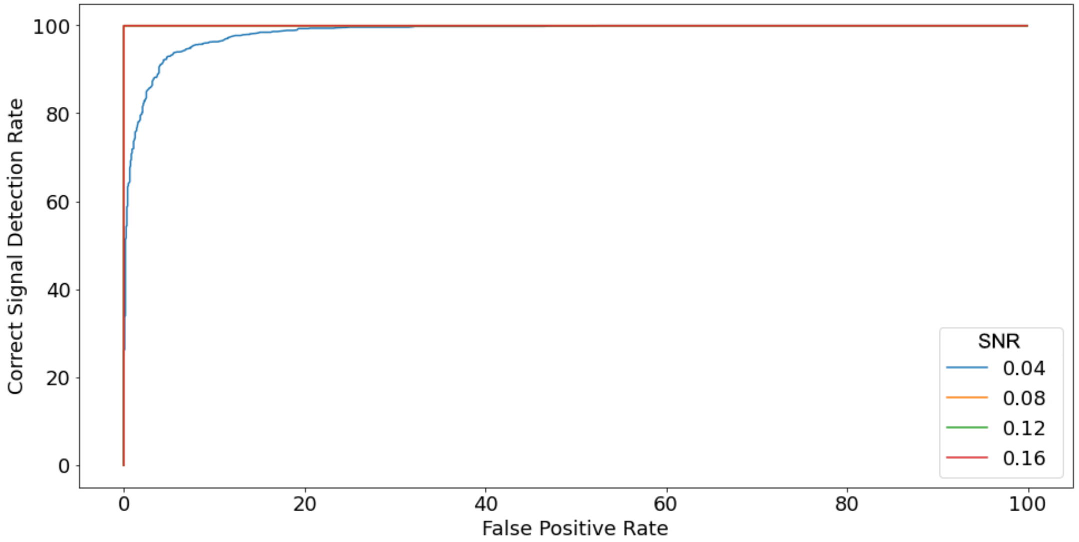
- CRES signals are not just static frequency signals, however.
- Chirping over time means the signal leaves the range of a non-chirping LIA before the filter can react to its presence.
- Instead, swap the reference for a chirping reference signal.
- Implemented a 1ms chirping sine wave reference signal – 1ms was chosen based on estimates of electron scattering.
- Triggering can be done on the FPGA using a short-time mean approach. This uses the sustained response to stay resilient to random noise spikes but still working for shorter signals.



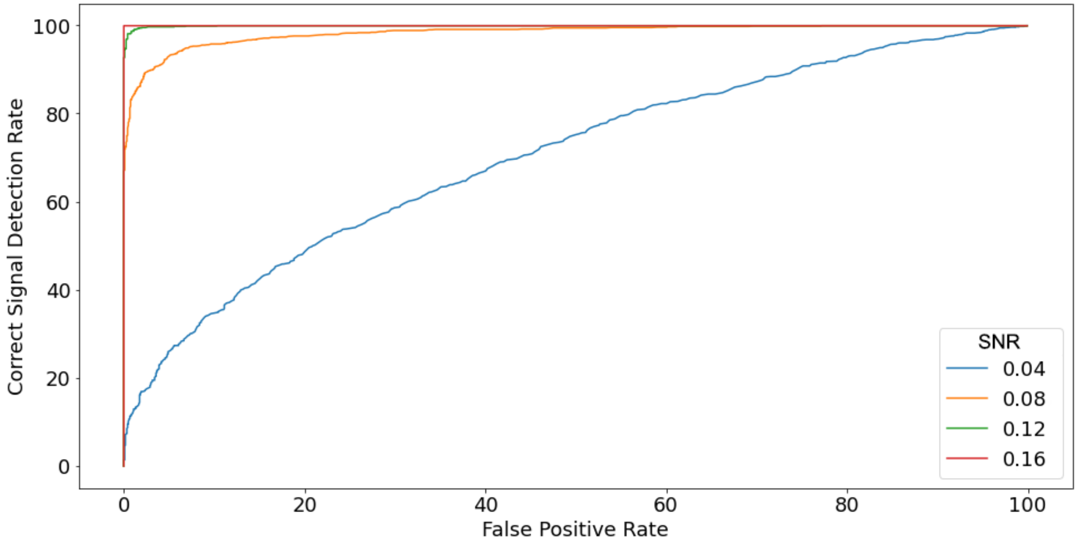
Trigger Performance (LIA)

- Receiver Operating Characteristic (ROC) curves show correct signal detection rate against false positive rate.
- A trigger that chooses randomly will form a line of y=x, a good trigger will move to the top left corner, with a good rate of correct detection for very low false positive rate.
- The LIA performs very well, even for lower SNRs with the full 1ms of matching between the signal and reference.
- Even for 0.1ms signals, good performance is seen at SNR > 0.08

1ms signal

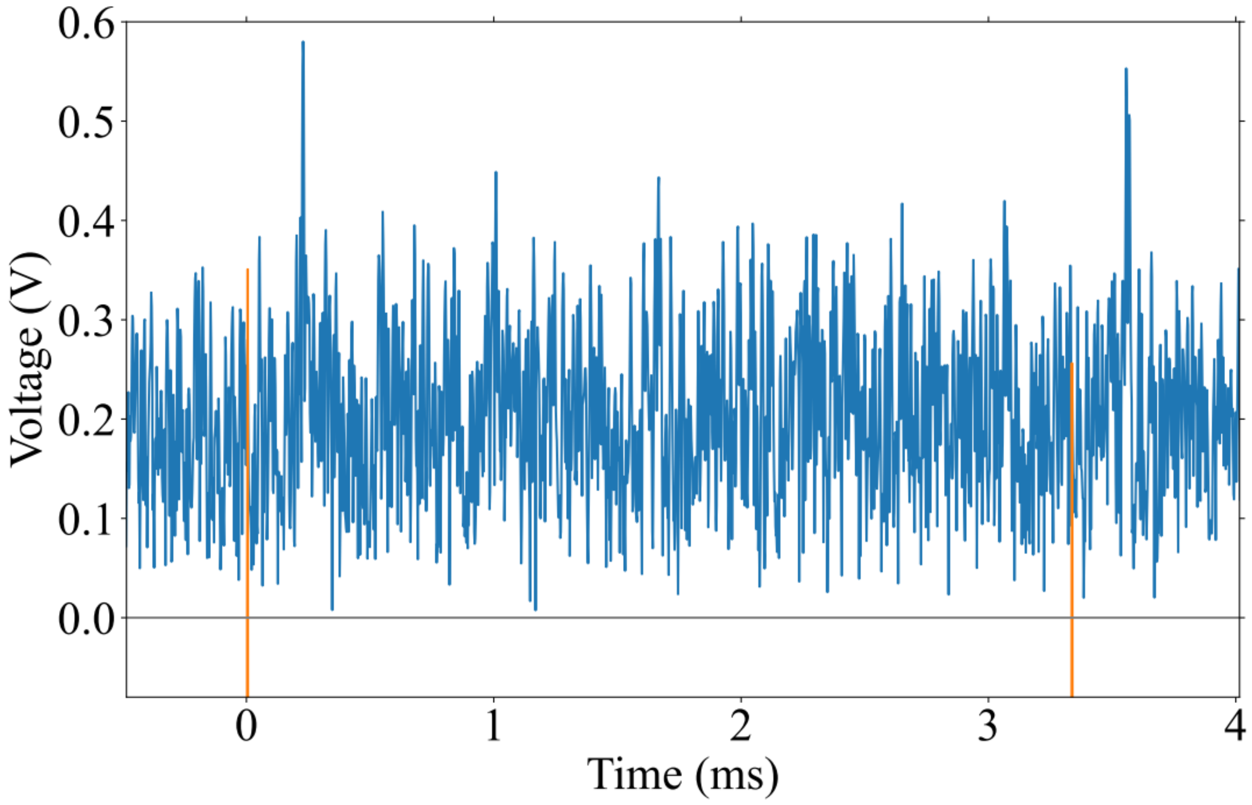


0.1ms signal



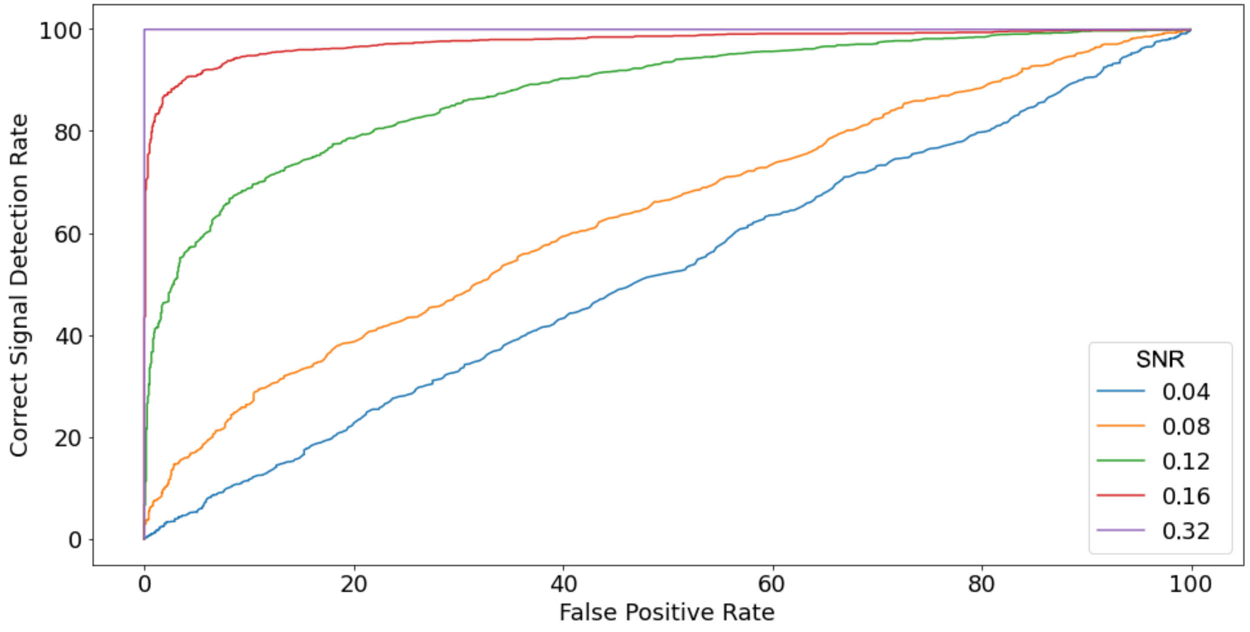
Matched Filter Trigger

- Another option for signal detection in high noise is a matched filter.
- This is mathematically optimal for Gaussian white noise.
- This has also been implemented on an FPGA.
- Requires a template which is implemented in full on the FPGA, processing this sets tighter limits on the length of the matched filter template.



Matched Filter Trigger Performance

- The matched filter is limited to a shorter length than the lock-in, and hence performs slightly worse for lower SNRs.
- The optimal configuration for the FPGA tested was a 1024-point template, which translates to a signal length of 0.16384ms, with a calculation time of 2.72µs.
- Can still achieve good performance with SNR<1.
- It can cover every possible input time, however, which has implications when scaling to the full system.



Matched Filter or Lock-In Amplifier?

- Covers all input times in one unit
- Increase performance with larger FPGA – faster processing, longer template → stronger response + wider frequency coverage
- Potentially more convenient setup for higher SNRs
- Easy to change template

- Requires multiple units to cover input times
- Increase performance with narrower filter – requires more devices to cover input times
- Better performance at lower SNR for same size FPGA
- Larger FPGA can fit multiple LIAs on one device
- Current implementation has issues with large filter bandwidths (small time constants) meaning higher SNRs are not fully exploited

Full Trigger System

- One unit alone will not cover the full frequency/time space necessary to detect any possible electron of interest.
- Instead, use many units in parallel, each checking different regions of the frequency/time space.
- Multiple LIAs are necessary to cover all possible input times.
- One MF can cover all input times, but the limits on the length of template are more stringent, so multiple units are necessary to cover more frequency range.

Conclusions

- Lock-In Amplifier and Matched Filter triggers have been developed and implemented on an FPGA system.
- Good trigger performance for SNRs < 1 has been seen.
- Ultimate choice of trigger type will depend heavily on the eventual SNR of the system.
  - This still encompasses a wide range of possibilities depending on the design of the microwave receiver system.