The QTNM project: Status and overview

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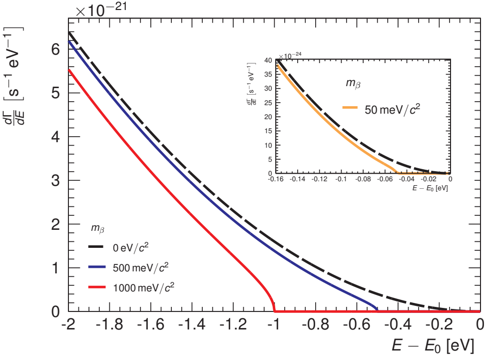
Outline

- CRES for determining neutrino mass
- Overview of Quantum Technologies for Neutrino Mass
- Overview of CRESDA
- Project updates
  - Quantum-noise-limited microwave sensors
  - Field sensing with Rydberg atoms
  - Atomic production and confinement
  - Modelling tools
- Summary

ν mass from T β-decay spectrum

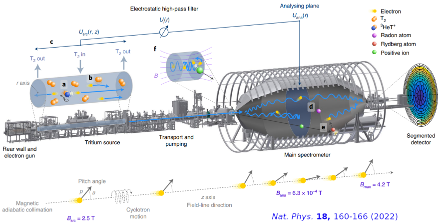
- Neutrino masses readily accessed through tritium β-decay spectrum
- Non-zero neutrino masses distort the very end of the electron energy spectrum
- Model-independent method of measuring the neutrino masses



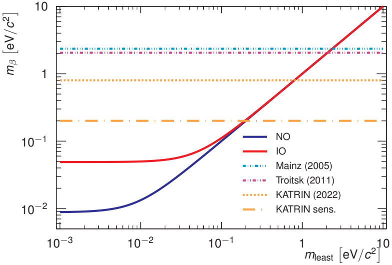
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

$$\mathrm{T} \rightarrow {}^3\,\mathrm{He} + e^- + \bar{\nu}_e$$

Current limits on m_β



Nat. Phys. **18,** 160-166 (2022)



- Current best limits on m_β are produced by MAC-E filters
- In particular, the KATRIN experiment – $m_\beta < 0.8$ eV/c^2
- Expected final sensitivity of 0.2 eV/c^2
- 70 m long beamline, spectrometer is 9.8 m in diameter and 23.3 m in length held at pressure of 10^{-11} mbar

Current experimental limitations

- To increase statistical power, can increase source size
- However, source thickness is limited by $\sigma n \leq 1$ to avoid collisional losses
- For a MAC-E filter:

$$\frac{\Delta E}{E} = \frac{B_{\text{ana}}}{B_{\text{src}}} = \left(\frac{R_{\text{src}}}{R_{\text{ana}}}\right)^2$$

- Therefore, increasing R_{src} requires a corresponding increase in the spectrometer size

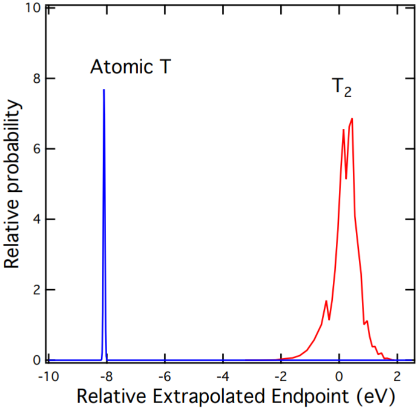
Current experimental limitations

Impractical to scale KATRIN up

We require a different technique for $m_\beta < 0.2$ eV$/c^2$.

Current experimental limitations

arXiv:2102.00594 [nucl-ex]



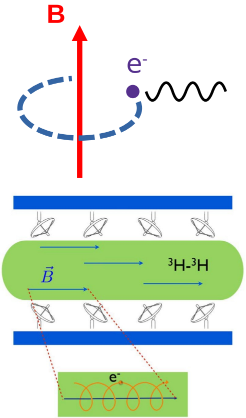
- Molecular tritium has rotational and vibrational excitations that broaden the endpoint peak
- This broadening presents a systematic effect for neutrino mass experiments using T_2
- Endpoint energy for T_2 is several eV higher than for atomic T

Production and preservation of atomic tritium is a key challenge for any future experiment

CRES overview

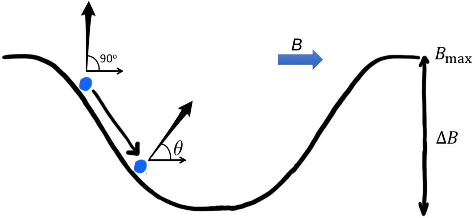
- **Cyclotron Radiation Emission Spectroscopy**
- Concept pioneered by Project 8 collaboration [1]
- β-decay electrons immersed in B-field emit EM radiation – frequency depends only on electron energy and B-field strength
- $E_{\text{kin}} = Q_\beta = 18.6\,\text{keV}$, $B = 1\,\text{T}$
- $f = 27\,\text{GHz}$, $\lambda \sim 1\,\text{cm}$, MW radiation
- Radiation collected with antenna, waveguide or resonant cavity

$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\text{kin}}/c^2}$$



QTNM

Electron trapping



Phys. Rev. C **99**, 055501 (2019)

$$\theta \geq \sin^{-1}\left(\sqrt{1 - \frac{\Delta B}{B_{\text{max}}}}\right)$$

- Trap β-decay electrons in a 'no-work' trap where they can be continuously observed for 10s or 100s of µs, undergoing periodic motion
- Local minimum in magnitude of background B-field
- Require trapping field of order 1 mT against 1 T background
- Trap design has large effect on range of observed frequencies – key to understand this

CRES advantages

- Frequency measurements can reach precision of $\Delta f/f \sim 10^{-6}$

A. L. Schawlow
"Never measure anything but frequency"

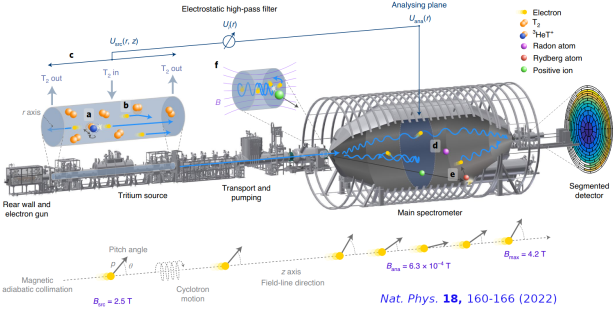
CRES advantages

- Frequency measurements can reach precision of $\Delta f/f \sim 10^{-6}$
- The source (tritium gas) is transparent to microwave radiation

CRES advantages

- Frequency measurements can reach precision of $\Delta f/f \sim 10^{-6}$
- The source (tritium gas) is transparent to microwave radiation
- No losses while transporting e^- from the source to the detector

Unlike MAC-E filters, no need to transport electrons from source to detector – fewer electrons lost to scattering



Nat. Phys. **18,** 160-166 (2022)

CRES advantages

- Frequency measurements can reach precision of $\Delta f/f \sim 10^{-6}$
- The source (tritium gas) is transparent to microwave radiation
- No losses while transporting e^{-} from the source to the detector
- Differential spectrum measurements

- MAC-E filters are ‘integral filters’ – intensity above a point in the spectrum is counted
- Extra time required for measuring background, spectrum intensity, endpoint energy
- Differential spectrometers do not have this issue

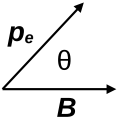
CRES challenges

- Radiated powers are very small

$$\text{Radiated power} \approx \frac{2\pi e^2 f_0^2}{3\epsilon_0 c}\frac{\beta^2 \sin^2\theta}{1-\beta^2}$$

where $f_0 = \frac{1}{2\pi}\frac{eB}{m_e} = 27.9925\,\text{GHz}$ for $B = 1\,\text{T}$

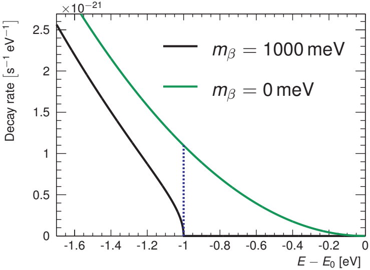
$P = 1.17\,\text{fW}$ for $B = 1\,\text{T}$ and $\theta = \frac{\pi}{2}$



CRES challenges

- Radiated powers are very small
- Need to trap and observe $\sim 10^{20}$ tritium atoms for $\sim$ year

- Last eV of the spectrum contains 2.9×10^{-13} of the events
- Necessitates an intense source



CRES challenges

- Radiated powers are very small
- Need to trap and observe $\sim 10^{20}$ tritium atoms for $\sim$ year
- Magnetic and electric fields need to be extremely well constrained

$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\text{kin}}/c^2}$$

- Understanding of B field experienced by electron key to extracting E_{kin} from any frequency measurement

Any unintended E fields (e.g. from adsorbates or imperfections on cold surfaces) will change electron's energy

QTNM overview

Quantum **T**echnologies for **N**eutrino **M**ass Collaboration

- **Proposal goal: build a demonstrator apparatus for determining neutrino mass via CRES from tritium β-decay – CRESDA**

QTNM first phase

Key goals of first phase (to March 2025):

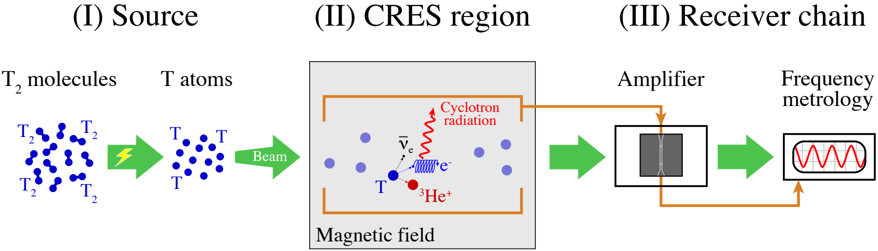
1. Develop and fabricate, quantum-noise-limited microwave sensors for a high resolution, high efficiency CRES apparatus
2. Magnetic field mapping with $< 1\,\mu\mathrm{T}$ absolute precision and ~ 1 mm spatial resolution using Rydberg states as quantum sensors
3. Demonstration of production and confinement of H/D atoms with densities of $\mathcal{O}(10^{12}\,\mathrm{cm}^{-3})$ with methods suitable for T
4. Develop modelling tools for T β-decay spectroscopy and neutrino mass measurements

Potential project pathway

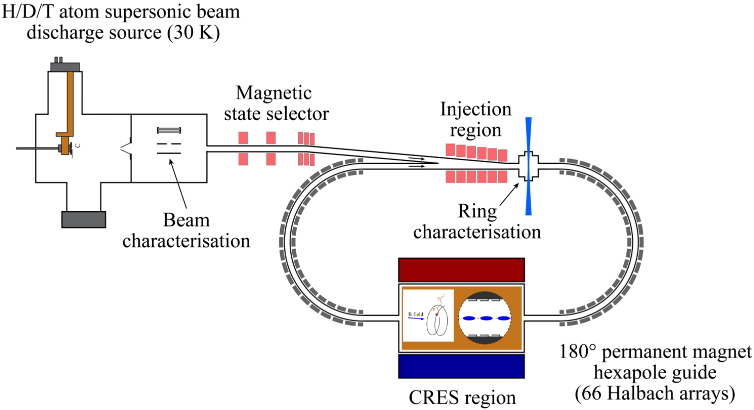
Quantum **T**echnologies for **N**eutrino **M**ass Collaboration

- Basic technology demonstration (2021–2025)
- Tritium demonstrations at Culham (beyond 2025)
- Final neutrino mass experiment with $\sim$ 10 meV to 50 meV sensitivity at Culham or similar facility (2030–2040)

CRESDA scheme



CRESDA outline



H/D/T atom supersonic beam
discharge source (30 K)

Magnetic
state selector

Injection
region

Beam
characterisation

Ring
characterisation

180° permanent magnet
hexapole guide
(66 Halbach arrays)

CRES region

Non-tritium electron source under development for initial CRES region tests

Microwave collection

Multiple options currently being explored.

Antenna arrays

- Can use beamforming techniques to localise electron – useful to precisely determine *B* field experienced by electron
- Many channels may be required to collect sufficient power
- Option being explored currently include patch antennas

Circular antennas (waveguides or cavities)

- Large fraction of radiated power may be collected with one or a few probes
- For cavities, Purcell effect results in increase in power emitted by electron
- Size of cavity coupled to wavelength of radiation → bigger volumes, lower *B* fields

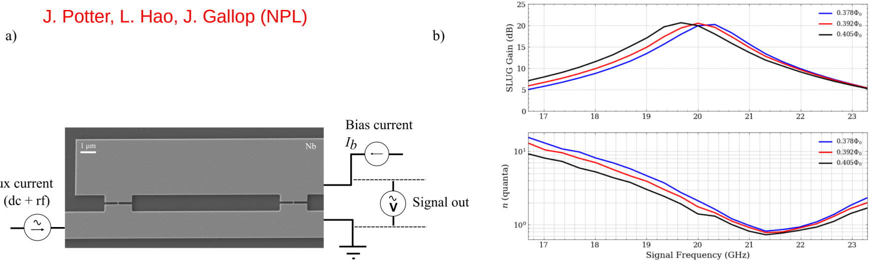
Framework devised for understanding signal and noise of inward-looking phased arrays [2] – potentially first study of its kind.

Quantum-limited microwave amplifiers

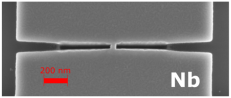
- State-of-the-art HEMT amplifiers have noise temperatures of about 7 K
- Overall added-noise of readout chain is dominated by the first-stage amplifiers
- Collaboration has been pursuing two pathways towards quantum-limited amplifiers:
  - Want added-noise to be close to standard-quantum-limit of half a quantum
  - **S**uperconducting **L**ow-Inductance **U**ndulatory **G**alvanometer (SLUG)
  - Superconducting kinetic inductance parametric amplifiers

SLUG amplifiers

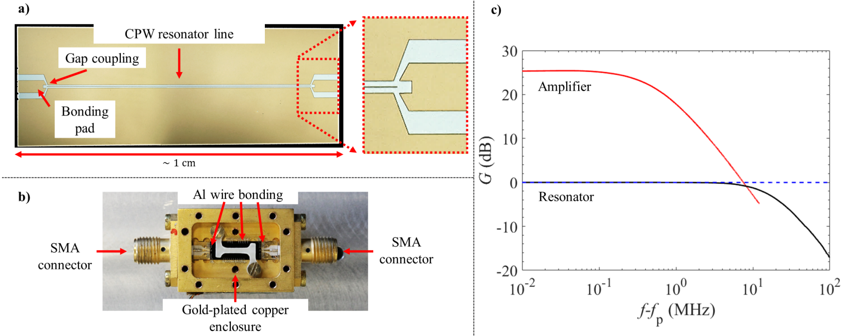
J. Potter, L. Hao, J. Gallop (NPL)



- **S**uperconducting **L**ow-inductance **U**ndulatory **G**alvanometer
- Amplifiers based on nanobridge SLUGs have been comprehensively modelled, demonstrating potential for high gain over large bandwidths
- SLUG elements with Nb nanobridges fabricated by several methods have been characterised in detail [3]



Superconducting kinetic inductance parametric amplifiers



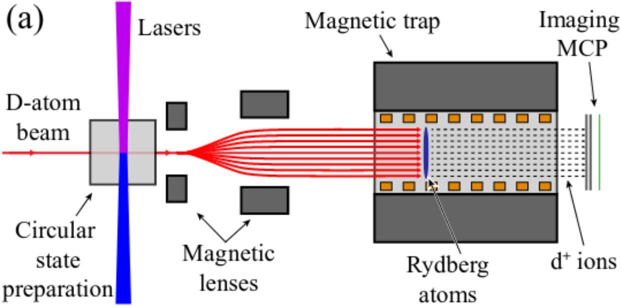
Zhao *et al.*, *Supercond. Sci. Technol.* **36** 105010 (2023)

- Members at Oxford and Cambridge have designed, fabricated and tested high-gain parametric amplifiers based on superconducting resonators [4] – TRL 7/8 expected by end of grant period
- Superconducting NbN optimised as amplifier material
- Can also be operated at 4 K – potential for two-stage amplification

Magnetometry & electrometry

- Measuring electron energy with resolution of 10^{-6} requires that *B*-field be known to similar level
- Stray *E*-fields must also be quantified and minimised
- Rydberg atoms can be used as quantum sensors for in-situ field mapping

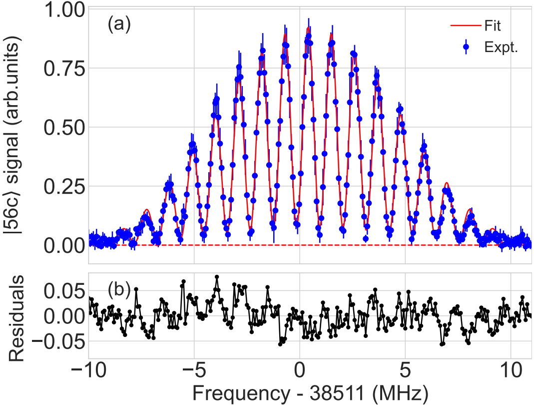
Magnetometry & electrometry



S. Hogan, J. Zou (UCL)

- Circular Rydberg states prepared in beam and passed through CRES volume
- Pulses of microwave radiation drive Rydberg-Rydberg transitions – sensitive to *E* & *B* fields

Magnetometry & electrometry

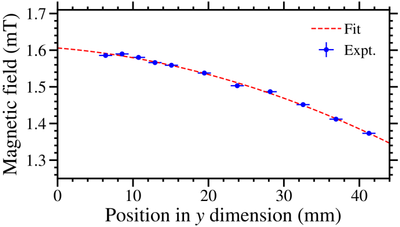


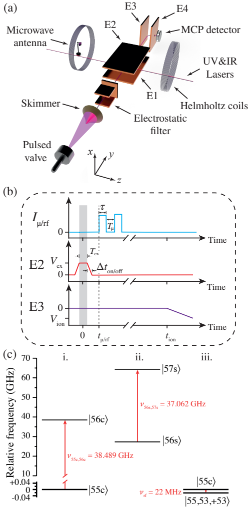
Zou & Hogan, *Phys. Rev. A* **107** 062820 (2023)

- Ramsey spectroscopy then used to determine the field experienced by the atoms in question

Magnetometry & electrometry results

- Current results at field of $\approx 1.3\,\mathrm{mT}$:
  - Absolute field precision of $\pm 2\,\mu\mathrm{T}$, relative $\pm 900\,\mathrm{nT}$
  - Spatial resolution in 1D of $\pm 0.87\,\mathrm{mm}$
  - Electrometry precision of $85\,\mu\mathrm{V\,cm}^{-1}$
- Paper detailing method and results published in 2023 [5]
- Next steps: Prove viability at higher fields ($\sim 0.1\,\mathrm{T}$) and move towards 3D mapping

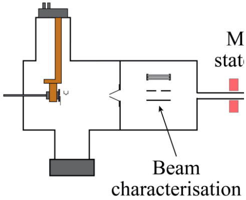


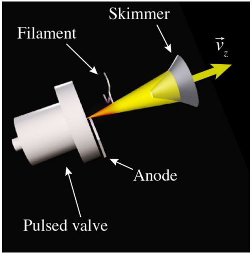


Zou & Hogan, *Phys. Rev. A* **107**, 062820 (2023)

Atomic source

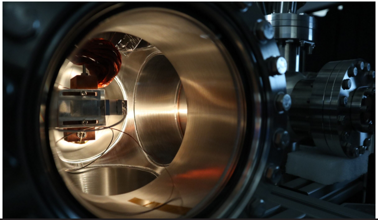
- Atomic T source is key element of any future ν mass experiment





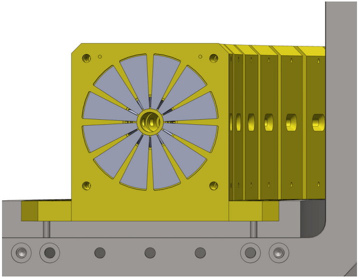
Hogan, Habilitation Thesis ETH Zurich (2012)

- Cryogenic (30 K) pulsed supersonic source
- $H_2/D_2/T_2$ dissociation using DC discharge seeded with electrons from tungsten filament
- See Stephen Hogan’s talk for further details

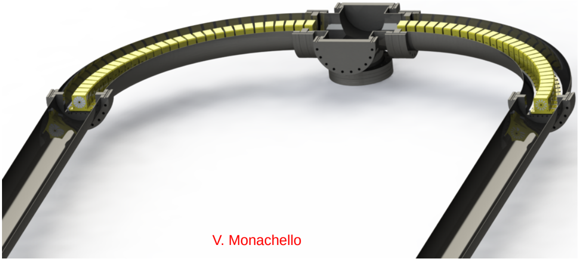


Atomic confinement

- Need to confine neutral T atoms and prevent them forming molecules on surfaces
- Ground state H/T atoms in a low-field-seeking state can be trapped using a series of hexapole magnets

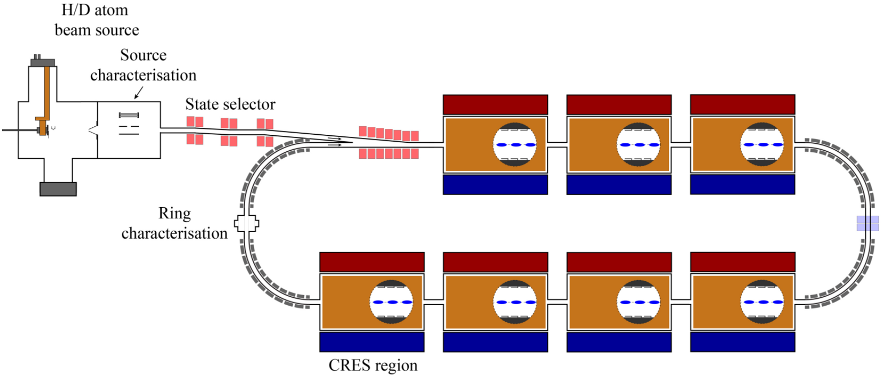


Storage ring concept


V. Monachello

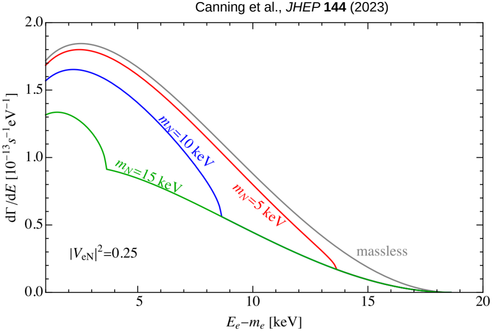
- Advantages of storage ring design include:
    - Lower atomic losses than occur when loading a trap (no deceleration and cooling required)
    - Separates magnetic field requirements for optimal high-frequency resolution CRES from magnetic trapping
    - Scalability (see next slide...)

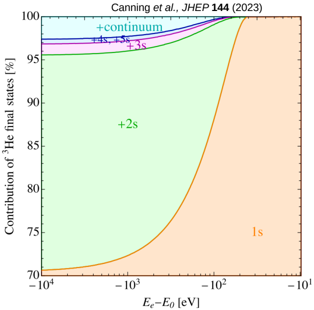
Scalability of storage ring concept



- One option: multiple CRES modules connected by single storage ring

T decay modelling


Canning et al., *JHEP* **144** (2023)


Canning *et al.*, *JHEP* **144** (2023)

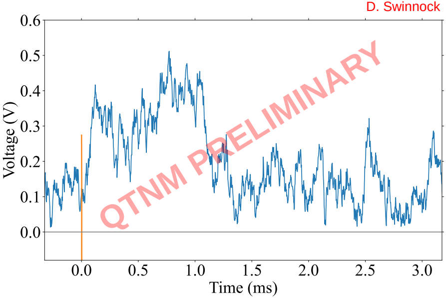
- Full differential decay rate of T calculated [6]
  - Includes differential rate w.r.t. angle between emitted electron momentum and atomic spin – relevant for atoms after state selection
  - New Physics: Differential decay rate also calculated for all possible 4-fermion effective operators Of β-decay, for active and sterile neutrinos
  - β-decay event generator based upon this available as `TBetaGenerator`

Event simulation

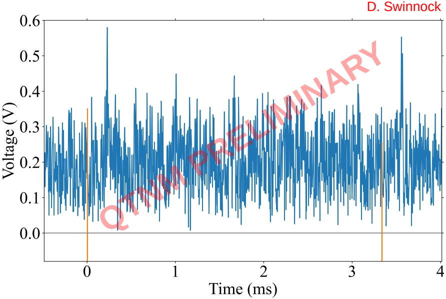
- Multiple software packages developed
- Bespoke Geant4 application:
  - Able to transport electrons through low density material
  - Custom solver allowing for correct behaviour in B field i.e. radiation losses rather than perfect energy conservation
- Software package allowing for simulation of basic readout chain:
  - Antenna models as well as excitation of waveguide and cavity modes
  - Includes simplified model of readout chain (downmixing, sampling)

Triggering

- Key consideration is making sure we can trigger on and reconstruct CRES signals while effectively rejecting background
- Lock-in amplifier (left) and matched filter (right) implemented on FPGA with 1 ms chirping sine wave to represent CRES signal



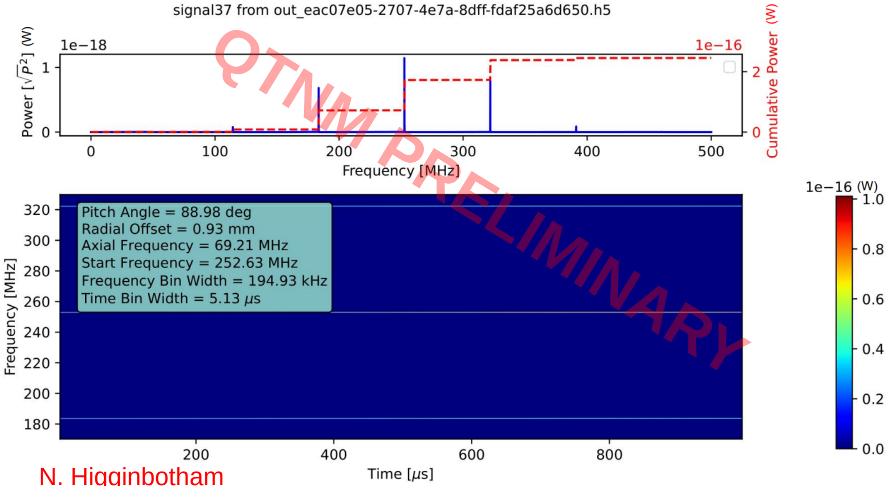
See increased response from LIA when signal present ($V_{\mathrm{RMS,\ sig}}/V_{\mathrm{RMS,\ noise}} = 0.04$)



Spike at 0.22 ms when template matches signal ($V_{\mathrm{RMS,\ sig}}/V_{\mathrm{RMS,\ noise}} = 0.16$)

Reconstruction and analysis

Simple event display developed – allowing for easy visualisation of CRES signals



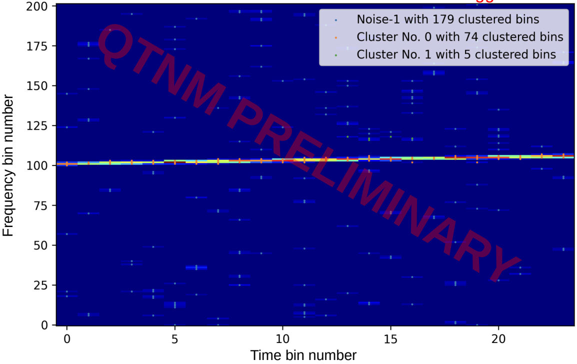
Pitch Angle = 88.98 deg
Radial Offset = 0.93 mm
Axial Frequency = 69.21 MHz
Start Frequency = 252.63 MHz
Frequency Bin Width = 194.93 kHz
Time Bin Width = 5.13 μs

N. Higginbotham

Reconstruction and analysis

- Various reconstruction methods currently being tested and evaluated
- Currently exploring track-finding algorithms for spectrograms (see image)

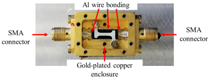
N. Higginbotham

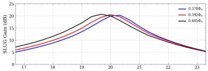


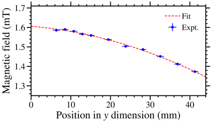
- In future, explore methods reconstructing time-domain signals as well as spectrograms

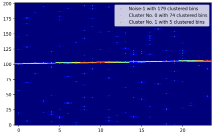
Summary

- QTNM is a collaboration utilising unique quantum technologies in a CRES-based experiment to measure the neutrino mass
- The first stage of this project will involve the construction of a demonstrator apparatus (CRESDA) to test several key components
- Several key milestones achieved:
  - Theory of inward-looking phased arrays published
  - Fabrication of superconducting parametric amplifiers – will reach TRL 7/8
  - Design of SLUG amplifiers shows promise of gain over large bandwidths
  - Quantum sensing with Rydberg atoms allows for precise electrometry and magnetometry
  - Range of modelling and analysis tools developed specifically for T β-decay spectroscopy
  - Production and characterisation of H atoms









References

[1] B. Monreal and J. A. Formaggio, Phys. Rev. D **80** (2009).

[2] S. Withington, C. Thomas, and S. Zhao, (2024), arXiv:`2401.03247 [physics.ins-det]`.

[3] G. Chapman et al., IEEE Transactions on Applied Superconductivity **34** (2024).

[4] S. Zhao et al., Supercond. Sci. Technol. **36** (2023).

[5] J. Zou and S. D. Hogan, Phys. Rev. A **107** (2023).

[6] J. A. L. Canning, F. F. Deppisch, and W. Pei, JHEP **144** (2023).

Backup

Next phase (2025-2029)

- Proposal for next QTNM phase will include:
  - CRES volume integrated with superconducting magnet, sub-K quantum amplifiers, electron injection
  - Characterisation of CRES detection: resolution, noise, efficiency
  - Possible T_2 run
  - Parallel development of atomic T source at Culham