Quantum Technologies for Neutrino Mass

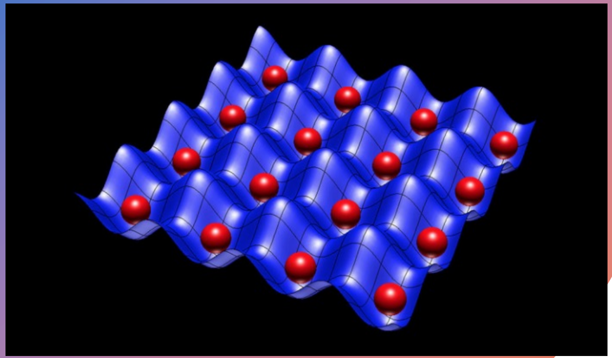
UCL · UNIVERSITY OF OXFORD · UNIVERSITY OF CAMBRIDGE · NPL National Physical Laboratory · WARWICK THE UNIVERSITY OF WARWICK · Prifysgol Abertawe Swansea University

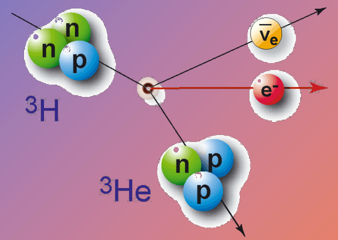
Determination of Neutrino Mass with Quantum Technologies

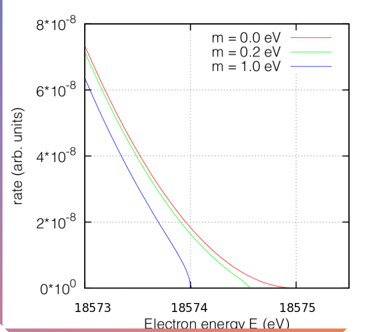
Ruben Saakyan (UCL)
on behalf of the
QTNM Collaboration

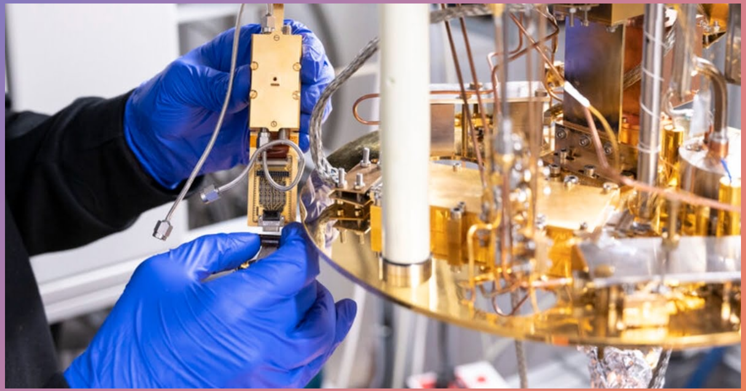
30 years of TLK

24 May 2023









- ***QTNM – a partnership between particle physics, cold matter, and quantum sensors***
- ***Enabled by Quantum Technologies for Fundamental Physics programme – QTFP***

- Community-driven process from 2018 to explore application of quantum tech for fundamental physics.
- Experts from particle and cold atom physics, AMOPP, quantum electronics, etc

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Quantum Technologies for Fundamental Physics

On 30 September STFC and EPSRC will open a research call for the Quantum Technologies for Fundamental Physics (QTFP) programme. This is a new programme which, building on the investments of the National Quantum Technology Programme, aims to demonstrate how the application of quantum technologies will advance the understanding of fundamental physics questions.

The call has total funding of c.£36m and will look to fund up to seven projects of £2m and above each (80% fEC). Requests for over £5m should contact the office before applying. The call will be for research consortia, i.e. joint proposals with a common research programme from groups of researchers in more than one organisation. Successful applications will require interdisciplinary research teams comprising researchers from both the fundamental physics and quantum technology communities.

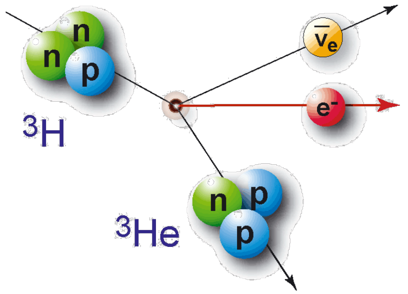
The call's fundamental physics remit covers quantum science, astronomy, particle physics, particle astrophysics and nuclear physics. Applications to the call will be expected to show how quantum technologies will enhance or enable their research area of interest.

The call will be open to all individuals and organisations eligible for UKRI funding. PSREs are asked to contact the office to check if they are eligible. Grants will commence on 1 May 2020 and end no later than 30 September 2023. Successful projects will be expected to show tangible outcomes and results within the lifespan of the funding. The standard STFC/EPSRC expectation for Research Organisations to contribute to the cost of equipment at around the 50% level will apply.

Applicants will be required to complete an online Intention to Submit form on the STFC website by 31 October 2019 prior to submitting a full application. The closing date for full proposals will be 3 December 2019. Full details on the call, including the application process and assessment criteria, will be published on the STFC website.

- ***£40M investment in 2019 from new UKRI money***
- ***Funding started in 2020/1 following competitive process***
- ***7 large projects funded in Wave 1 including QTNM***

QTNM



Goal

Neutrino mass measurement from ^3H β-decay via cyclotron radiation emission spectroscopy using latest advances in quantum technologies.

Strategy

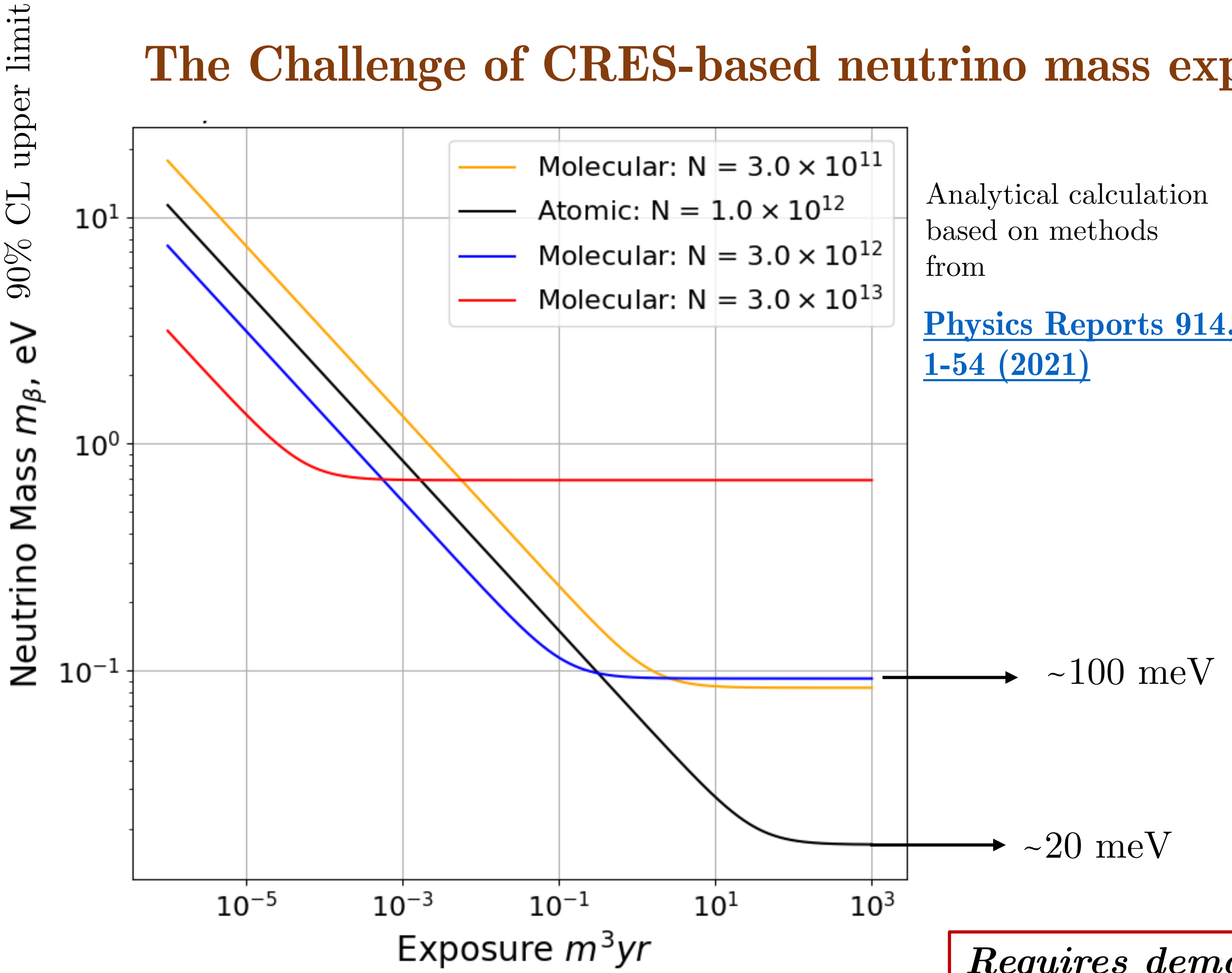
CRESDA = CRES Demonstrator Apparatus

Phased approach:

CRESDA0 → CRESDA-Tritium → 100 meV → 50 meV → O(10 meV)

CRESDA0 is funded by Wave 1 of QTFP (2021-2025)

The Challenge of CRES-based neutrino mass experiment with ^3H



Analytical calculation based on methods from

[Physics Reports 914, 1-54 (2021)]

$\sigma_B = 0.1ppm$

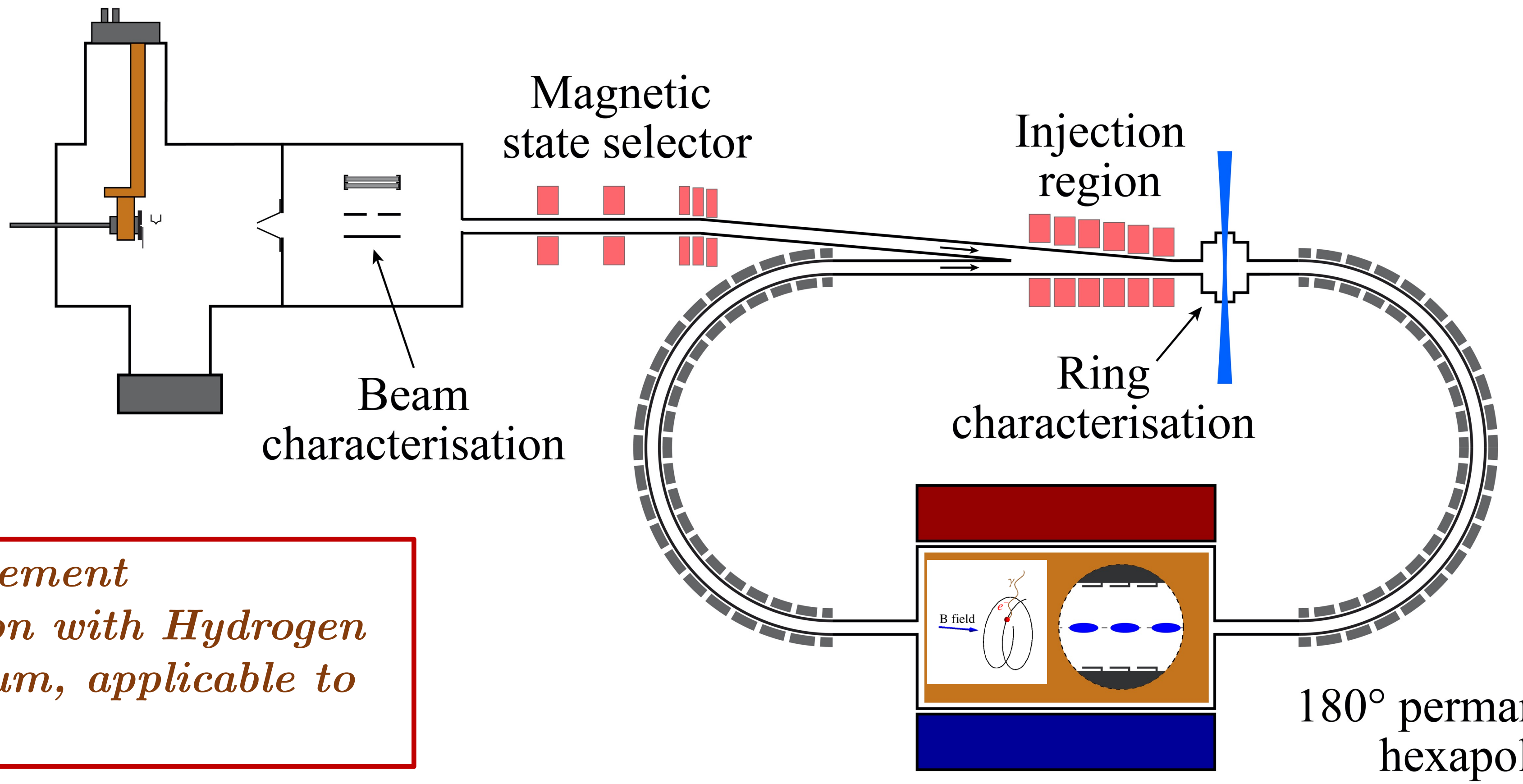
$b = 10^{-6}\,\sec^{-1}\,eV^{-1}$

$\frac{\delta\sigma_i}{\sigma_i} = 0.01$

$\frac{\sigma_f}{f} = 0.1\text{ppm}, \sigma_E = 0.05\ eV$

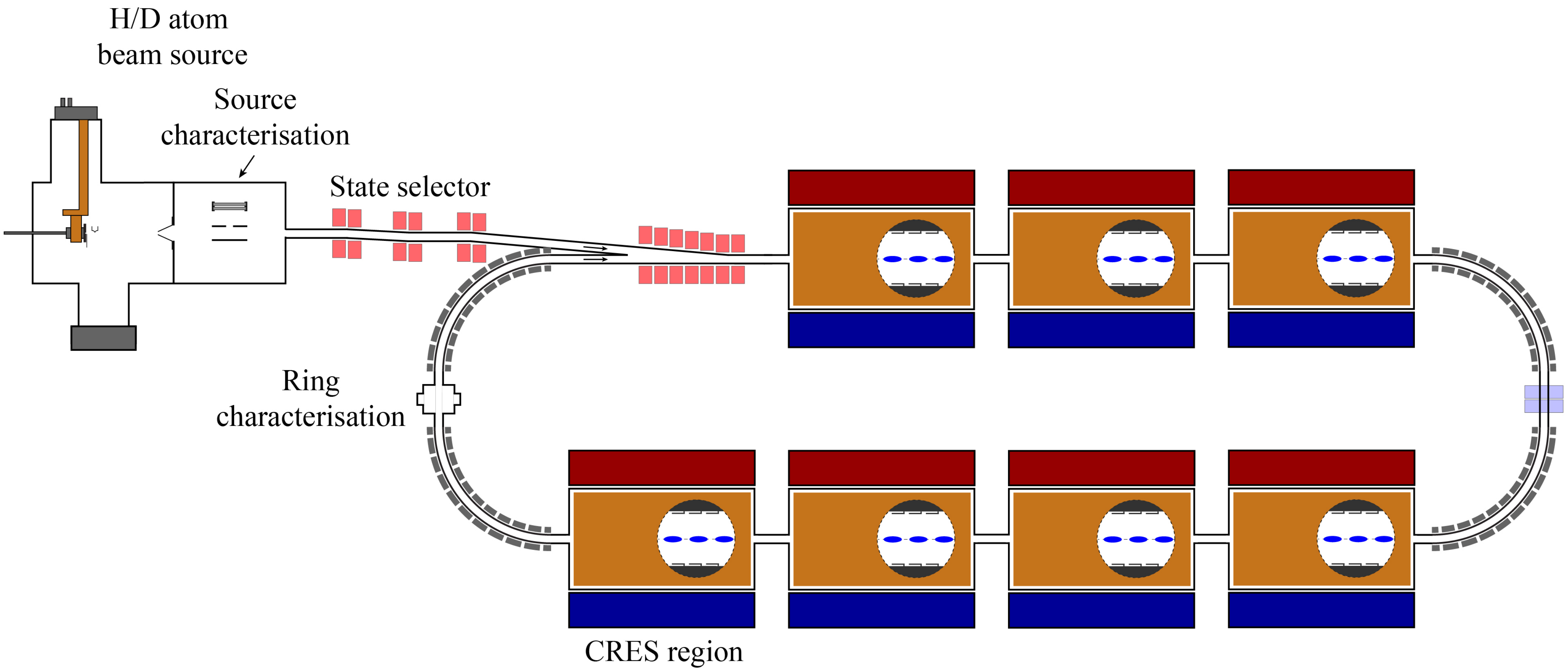
Requires demonstration of key technologies (including quantum)

CRESDA Schematics

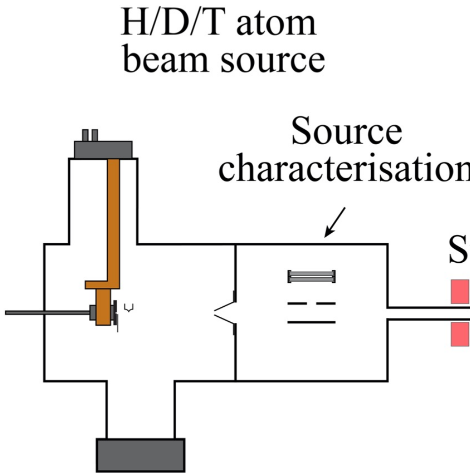


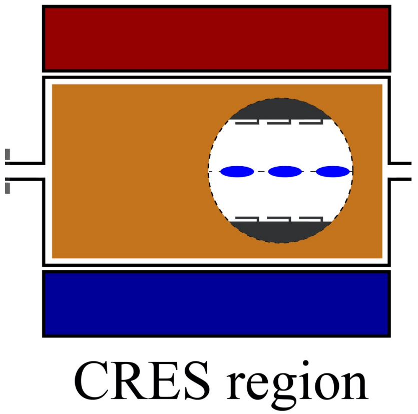
Atom confinement demonstration with Hydrogen and Deuterium, applicable to Tritium

Scalability of Storage Ring Concept



- **CRESDA0 – Demonstration of key individual technologies**
- **A pathfinder for CRESDA-T and final experiment**
- **Separate setups for**
  - **atomic experiments – atom source, injection, storage ring confinement**
  - **CRES of single electrons (electron gun injection)**





CRESDA0 Goals

- Production and confinement of H-atoms, $\geq 10^{12}$ cm^{-3}, scalable to 10^{20} atom × yr exposures
- B-field mapping with $< 1\ \mu$T abs precision and ~1mm spatial resolution
- CRES of O(10keV) electrons scalable to ~m^3 detection volumes with $\leq$ 1ppm frequency resolution (O(~0.1 eV) for 18.6 keV electrons)

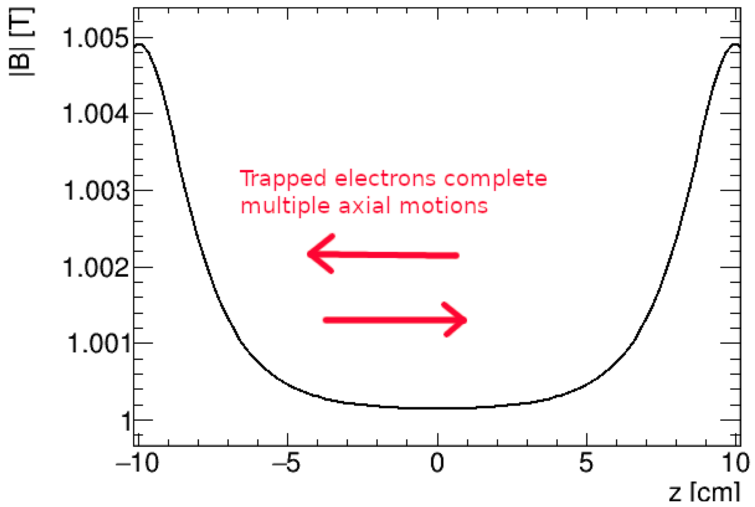
quantum technologies

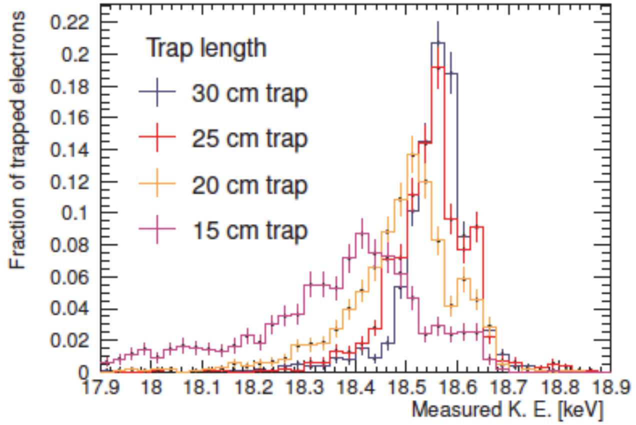
Challenges of Cyclotron Radiation Emission Spectroscopy

$$f = \frac{f_0}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E/c^2} \qquad P = \frac{2\pi e^2 f_0^2}{3\varepsilon_0 c}\frac{\beta^2 \sin^2\theta}{1-\beta^2}$$

- Tritium endpoint electrons (18.6 keV, $\gamma \approx 1.0364$) emit P~1fW at f~27 GHz in a 1T B-field
  - Depending on design only fraction of this power is collectable
- ΔE ~ 0.1 eV → Δf ~ 5 kHz Need $t_{obs} \sim \frac{1}{\Delta f} \sim$ 100's of μs observation time

- Need to trap electrons to achieve required resolution
- Introduces complexities in electron radiation line shape



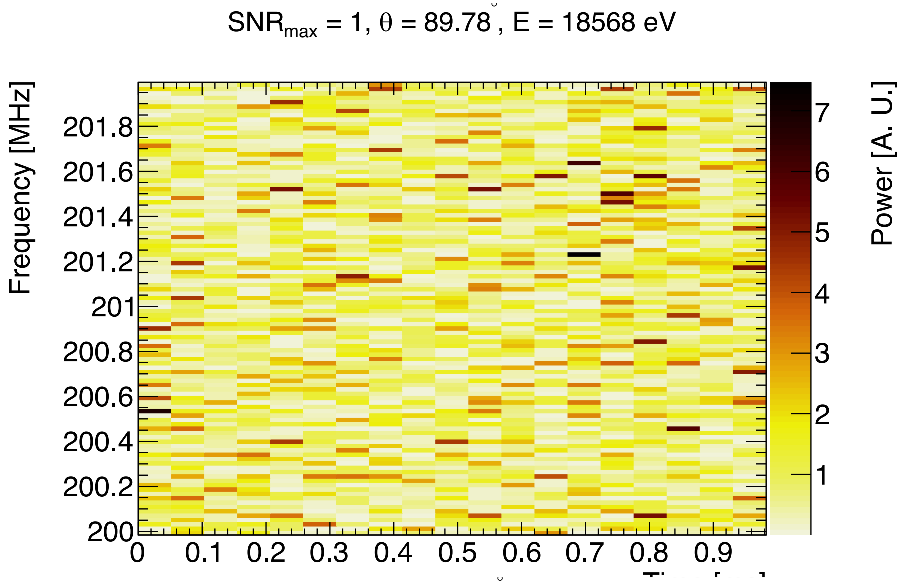


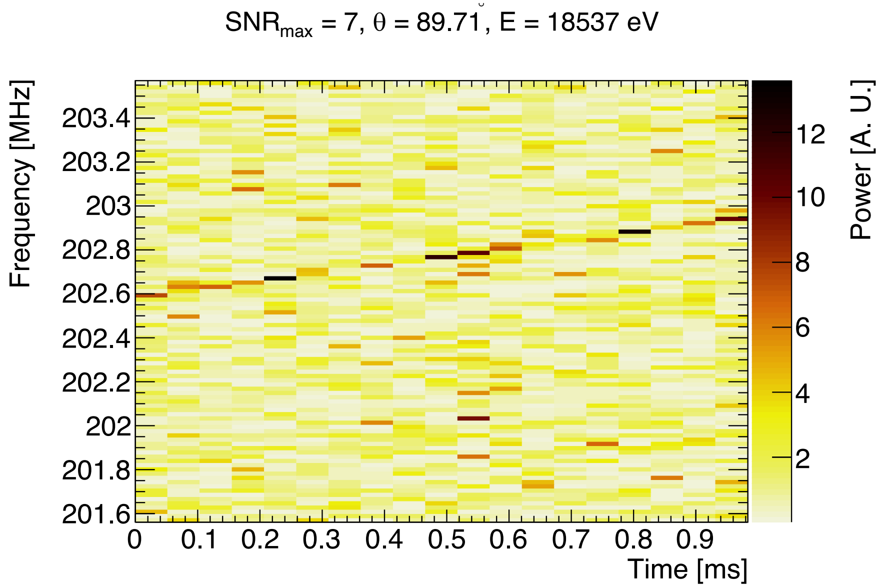
See S. Jones poster on simulations for QTNM

Challenges of **C**yclotron **R**adiation **E**mission **S**pectroscopy

Often conflicting requirements for detecting sub-fW MW-signal:

- Good S/N
- Fast measurement
- High efficiency
- Complex trade-off between Field of View and "antenna gain"





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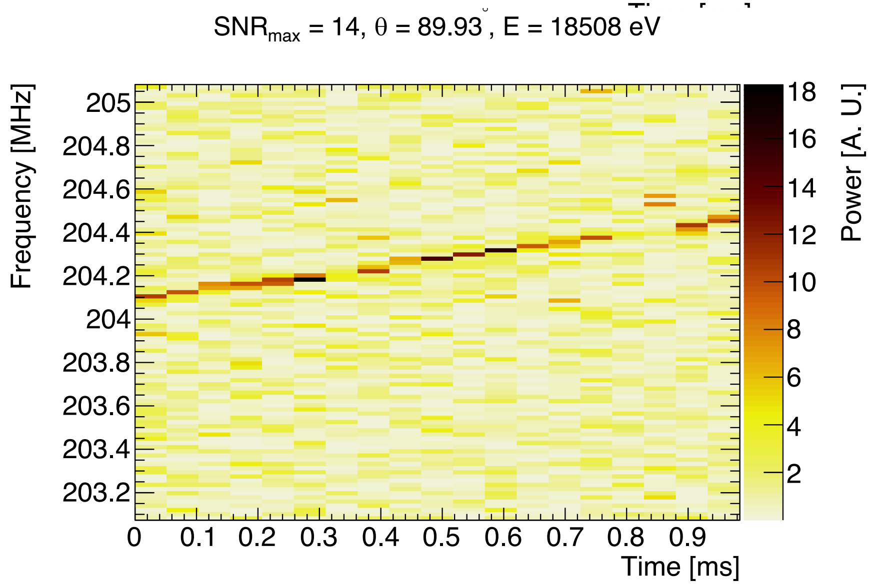
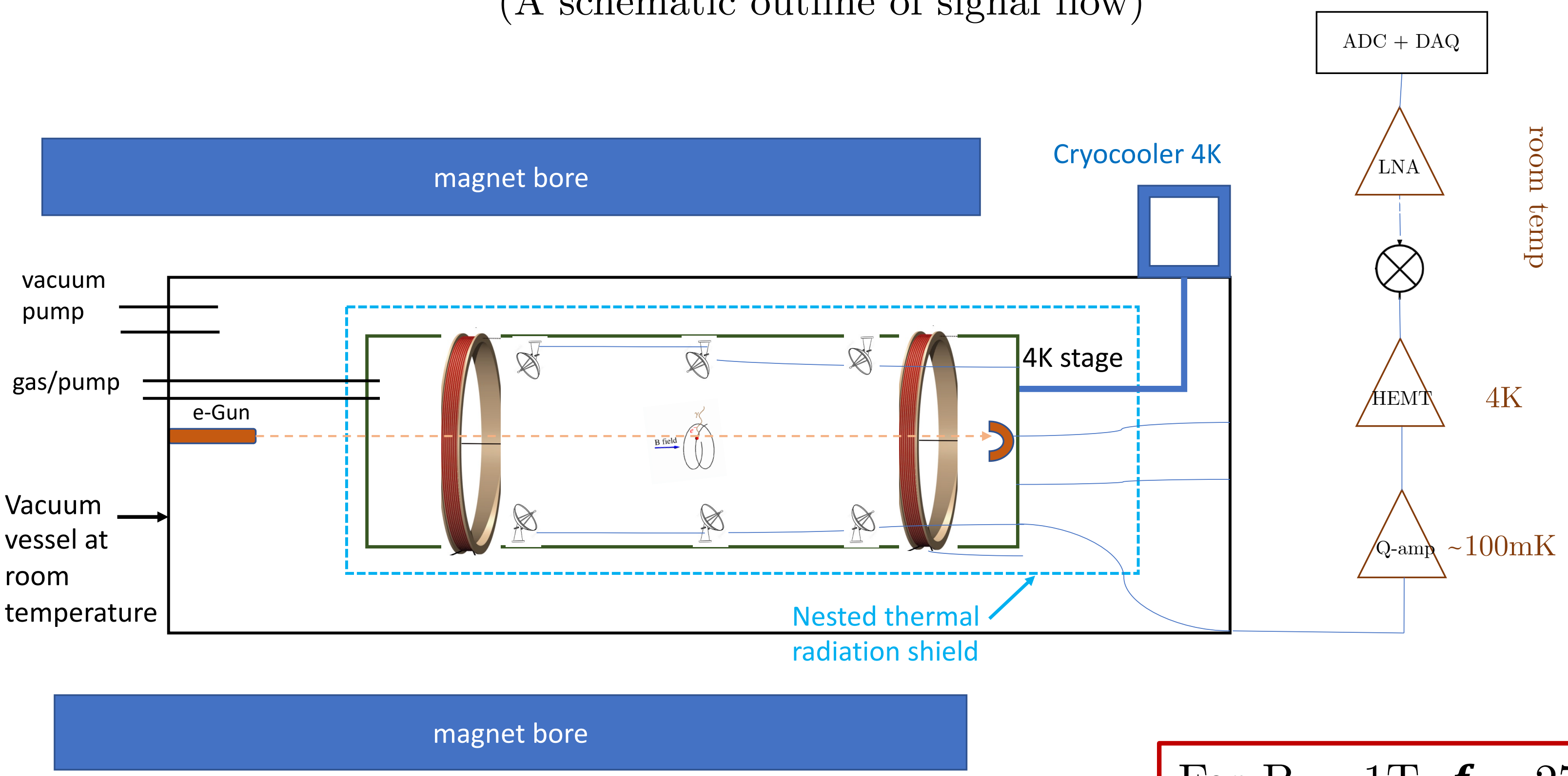


CRES Magnet Assembly for CRESDA0

(A schematic outline of signal flow)



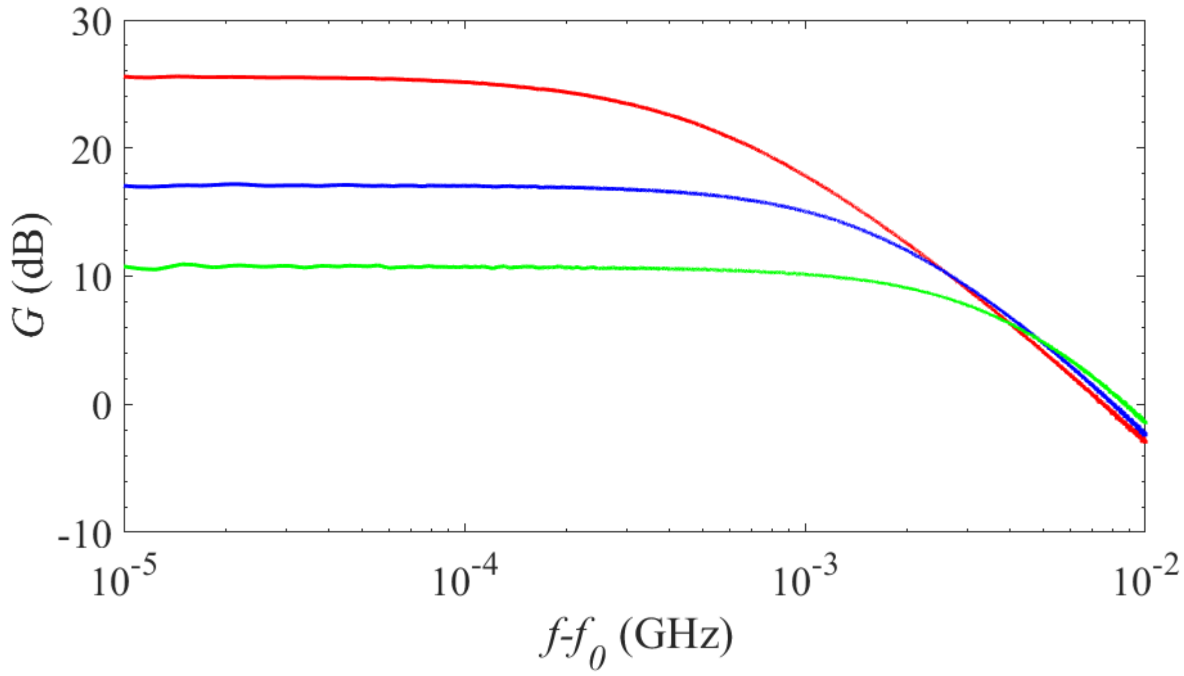
Design options under study

- Antenna arrays
- Waveguides
- Magnetic field optimisation
- Dual stage amplification
- Parametric amplifiers
- SLUG amplifiers

For B = 1T, f ~ 27 GHz

- Collectable power from electron cyclotron radiation is < 1fW
- Need to collect radiation fast (~100 μs but the faster the better)
- State-of-the-art HEMT amplifiers noise temperature ~10K
- CRES requires amplifiers with noise $\leq$ 1K → ***Quantum Amplifiers!***

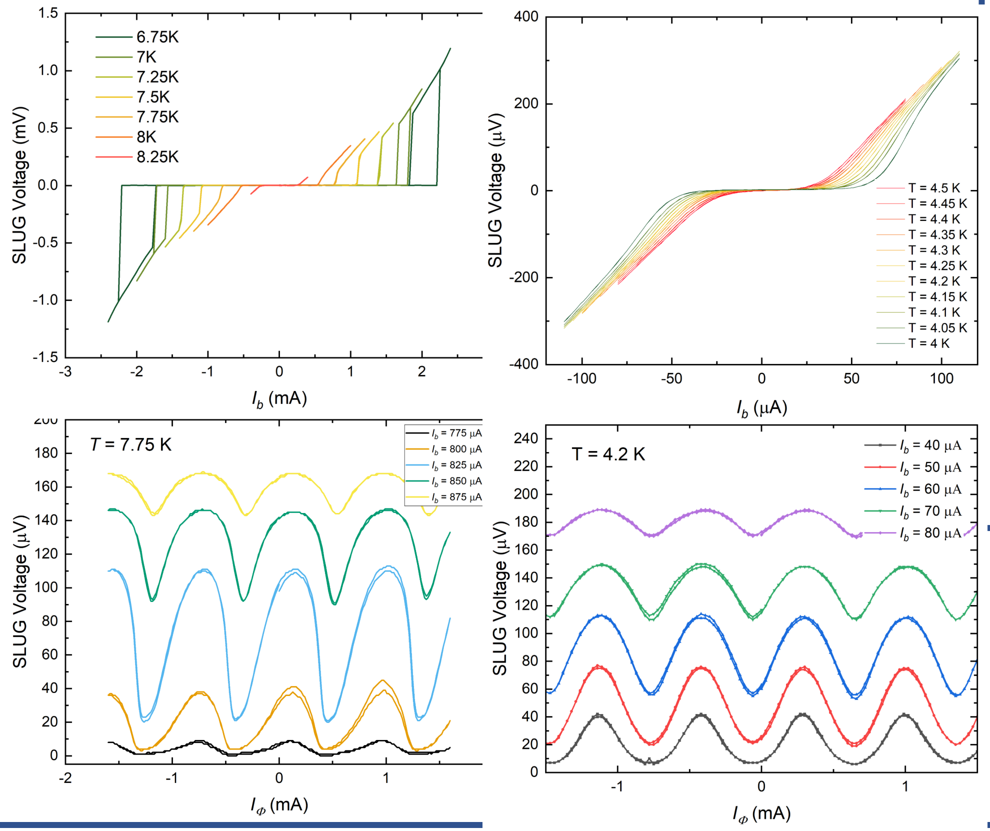
Parametric Amplifier

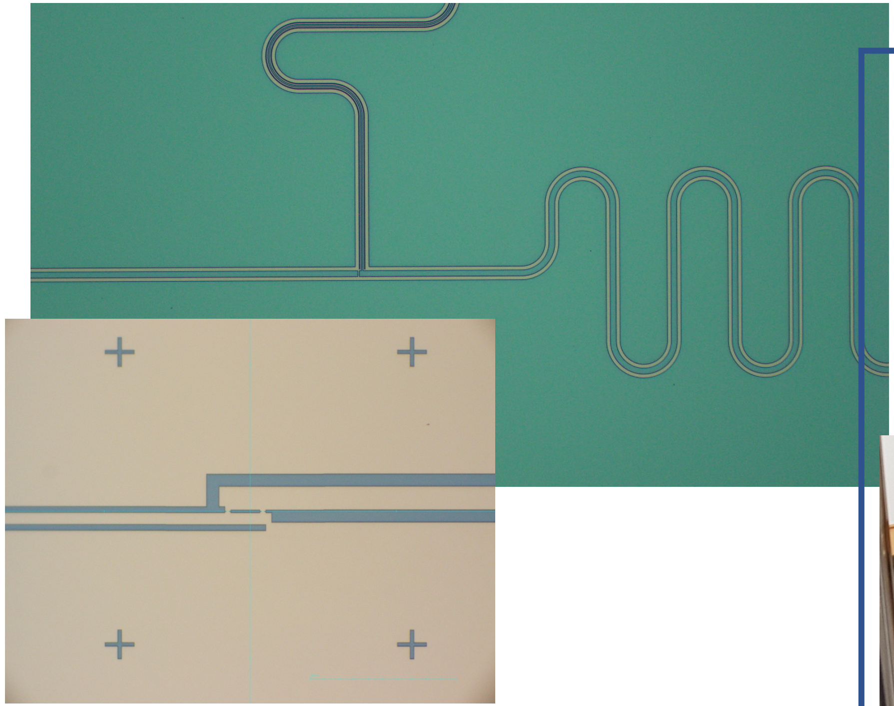


- NbN, Nb, Al, Ti paramps fabricated and tested at 18 GHz
- A noise measurement system assembled and calibrated
- Promising potential for operating at high-temp (4K) → possibility of two-stage amplification (100mK and 4K) with affordable parametric devices – potentially a game changer for multiple antenna arrays readout

SLUG MW-Amplifier

- ***Development of a high frequency microwave amplifier*** operating at 28 GHz, based on the SLUG (**S**uperconducting **L**ow-inductance **U**ndulatory **G**alvanometer) and utilising nanobridge weak link Josephson junctions



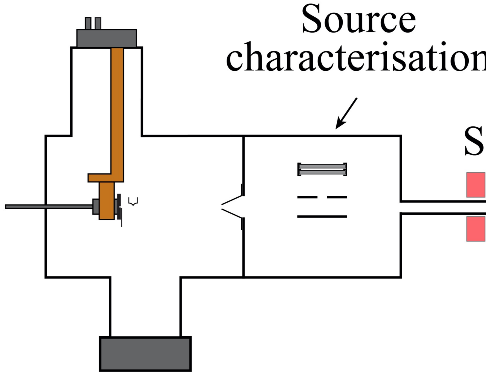


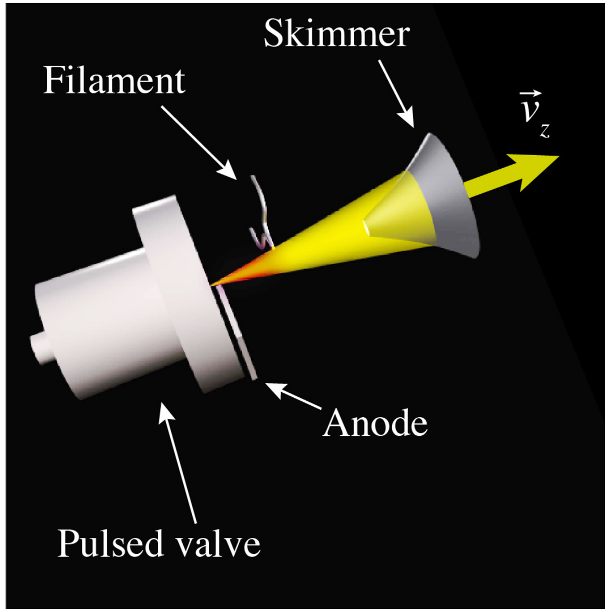
Fabrication of second generation devices is ongoing. Testing to begin soon in newly installed Bluefors dilution refrigerator.

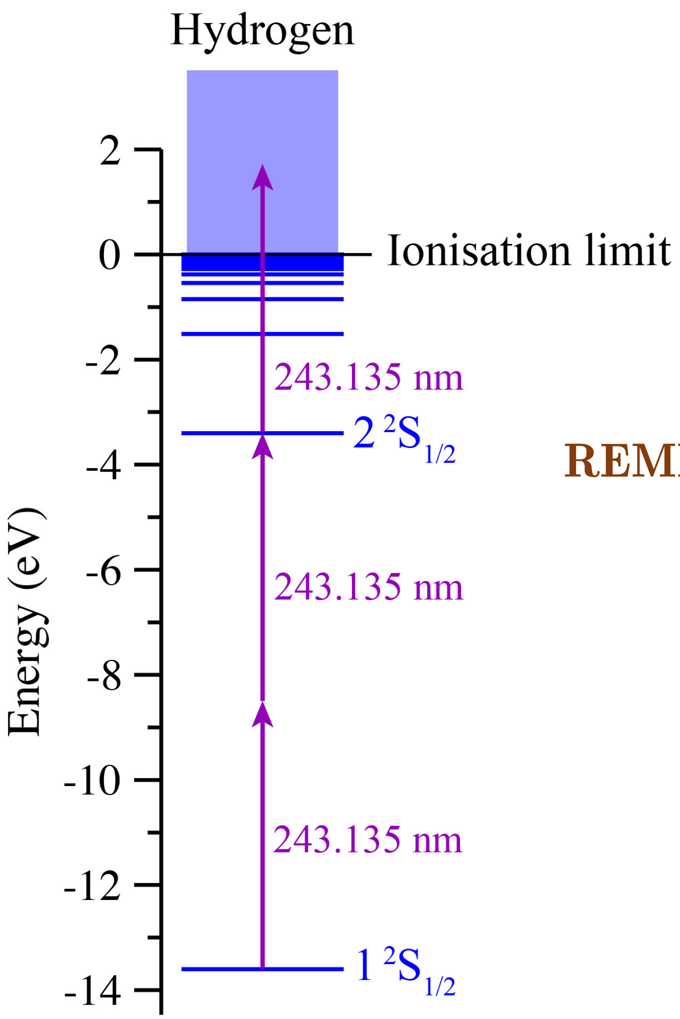
Fabrication and characterisation of first generation prototype devices complete. Nanobridges fabricated by different techniques were compared. EBL yields higher critical currents and higher operation temperature, and Ne FIB the opposite.

Procurement and installation of components for high frequency (up to 40 GHz) microwave circuit in the Bluefors is now complete. Testing and characterisation is currently underway.

H/D/T Atomic Source







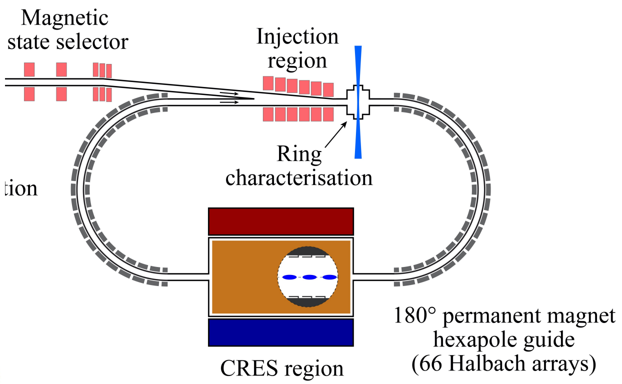
REMPI

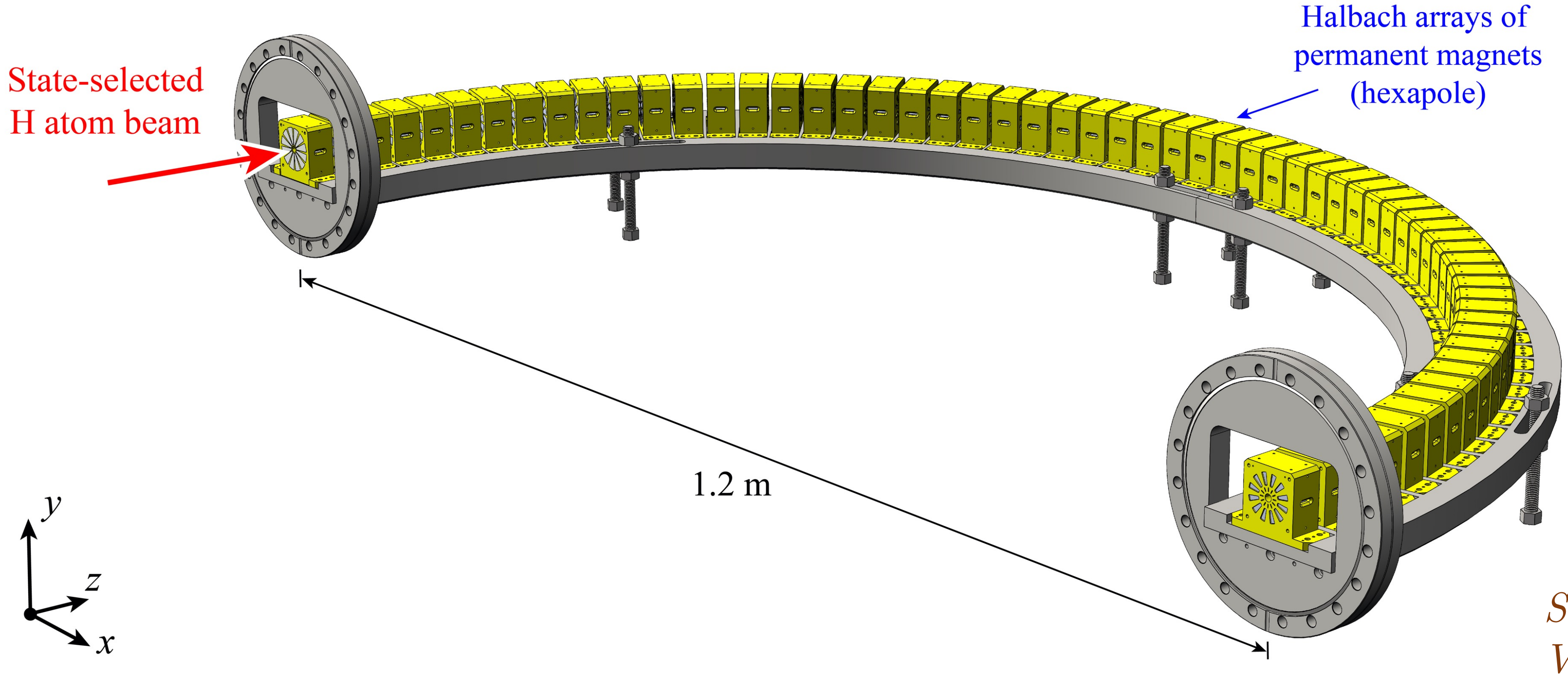
- Cryogenic (30K) pulsed supersonic source
- $H_2/D_2/T_2$ dissociation using DC discharge seeded with electron from tungsten filament
- Atomic beam characterisation using **R**esonance **E**nhanced **M**ulti **P**hoton **I**onisation (**REMPI**)

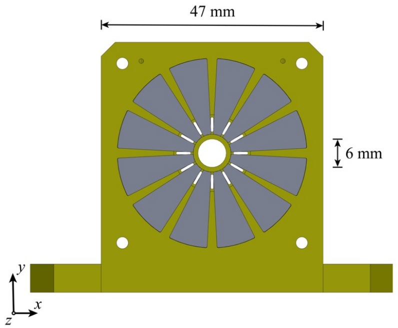
See poster by M. Fleck and V. Monachello

H/D/T-atoms confinement with storage ring

- Confine and guide spin-polarised beams of H/D/T
- Separate confinement fields from CRES field
- Aim to demonstrate stable operation up to 10^{12}-10^{13} cm^{-3} densities

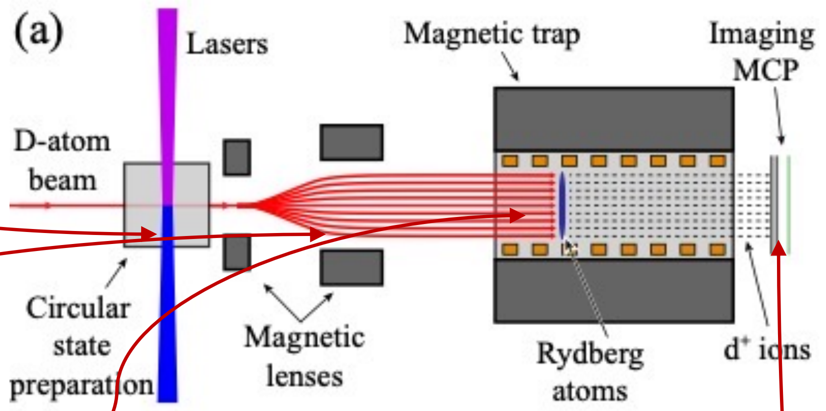






See poster by M. Fleck and V. Monachello

Precise B-field mapping using H-atoms as *quantum sensors* – Rydberg Magnetometry



H/D/T atoms are prepared in circular Rydberg states

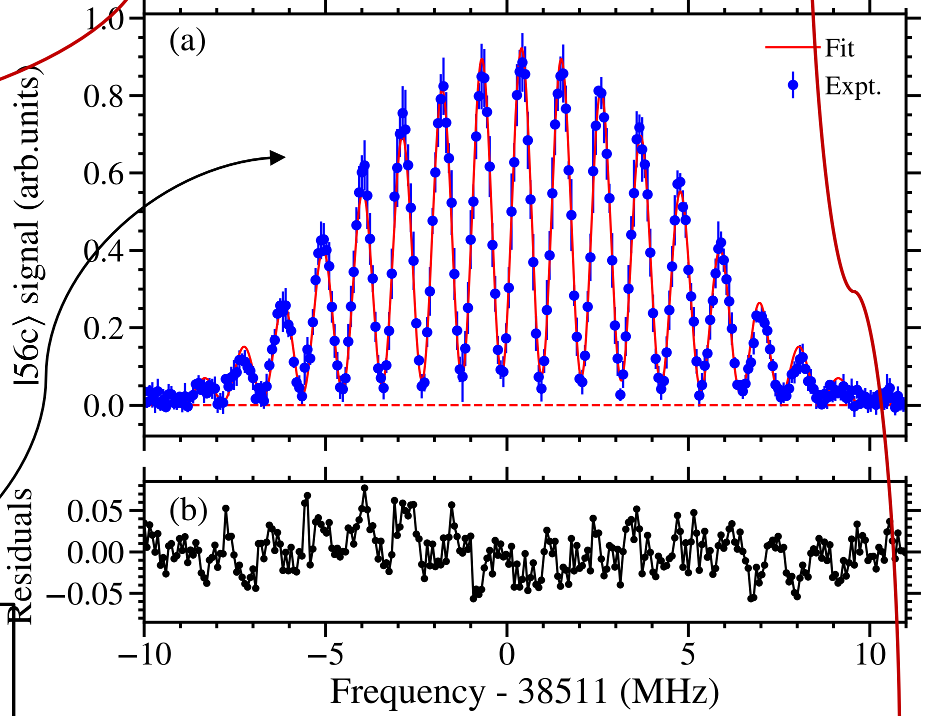
Beam is expanded to fill the CRES region

At selected time pulses of MW-radiation applied within CRES volume drive Rydberg-Rydberg transition. These transitions are sensitive to B-field variations at **$<1\mu$T level with a ~1mm spatial resolution**

Current results

- **Absolute precision ± 2 μT, relative $\pm$900nT**
- **Spatial resolution $\pm$0.87mm**
- **Electrometry abs precision ~ 85 μV/cm**
- **Limited by control of stray electric fields. Will improve**
- **Paper to be submitted**

Transitions are detected by state-selective ionisation



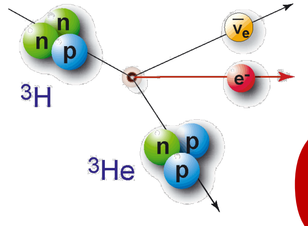
Ramsey spectrum of MW-transition between circular Rydberg states (Helium example)

See poster by M. Fleck and V. Monachello

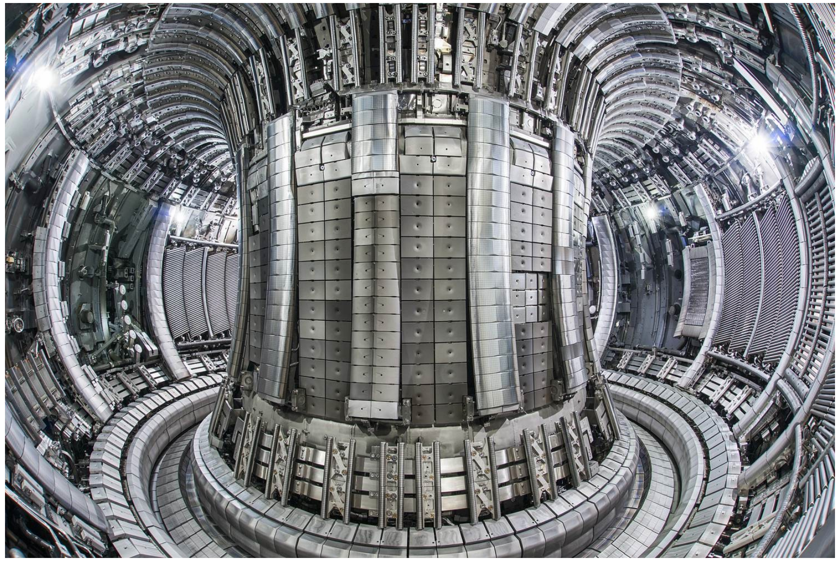
TRITON

- **TRI**tium **T**echnologies for **O**bservation of **N**eutrino properties
- Proposal being prepared for UKRI **Infrastructure Call**
- Technical feasibility study of **tritium facility** for neutrino physics at **H3AT** Centre
  - ITER fuel cycle demonstrator (1/20th), large T-inventory
- Potential host for major **neutrino mass** experiment
- **Broad physics programme** including sterile neutrino, Lorentz invariance and other new physics.
- **Impact research** (fusion): new materials, membranes for purification, new tools for tritium diagnostics

CCFE CULHAM CENTRE FOR FUSION ENERGY



QTNM



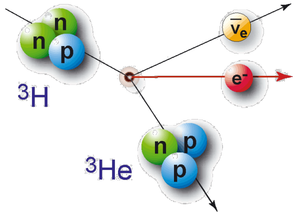
CCFE
CULHAM CENTRE FOR FUSION ENERGY

Future Outlook

(*very tentative*)

- Current project: 2021-2025
  - H/D production and confinement applicable to Tritium
  - CRESDA0: CRES of single-e with quantum noise limited electronics
- Next step. 2025-2030
  - CRESDA-T at Tritium facility (ongoing collaboration with Culham)
  - Tritium phase demonstration
- International neutrino mass project > 2030
  - Consolidate technological breakthroughs (Project-8, KATRIN, QTNM, Ptolemy…) to build and operate an experiment with a phased sensitivity: 100 meV ⇨ 50 meV ⇨ O(10 meV), plus sterile neutrino programme and more

QTNM



Happy 30th Birthday, TLK!!