EPPg μv
Ghent University
Experimental Particle
Physics and gravity

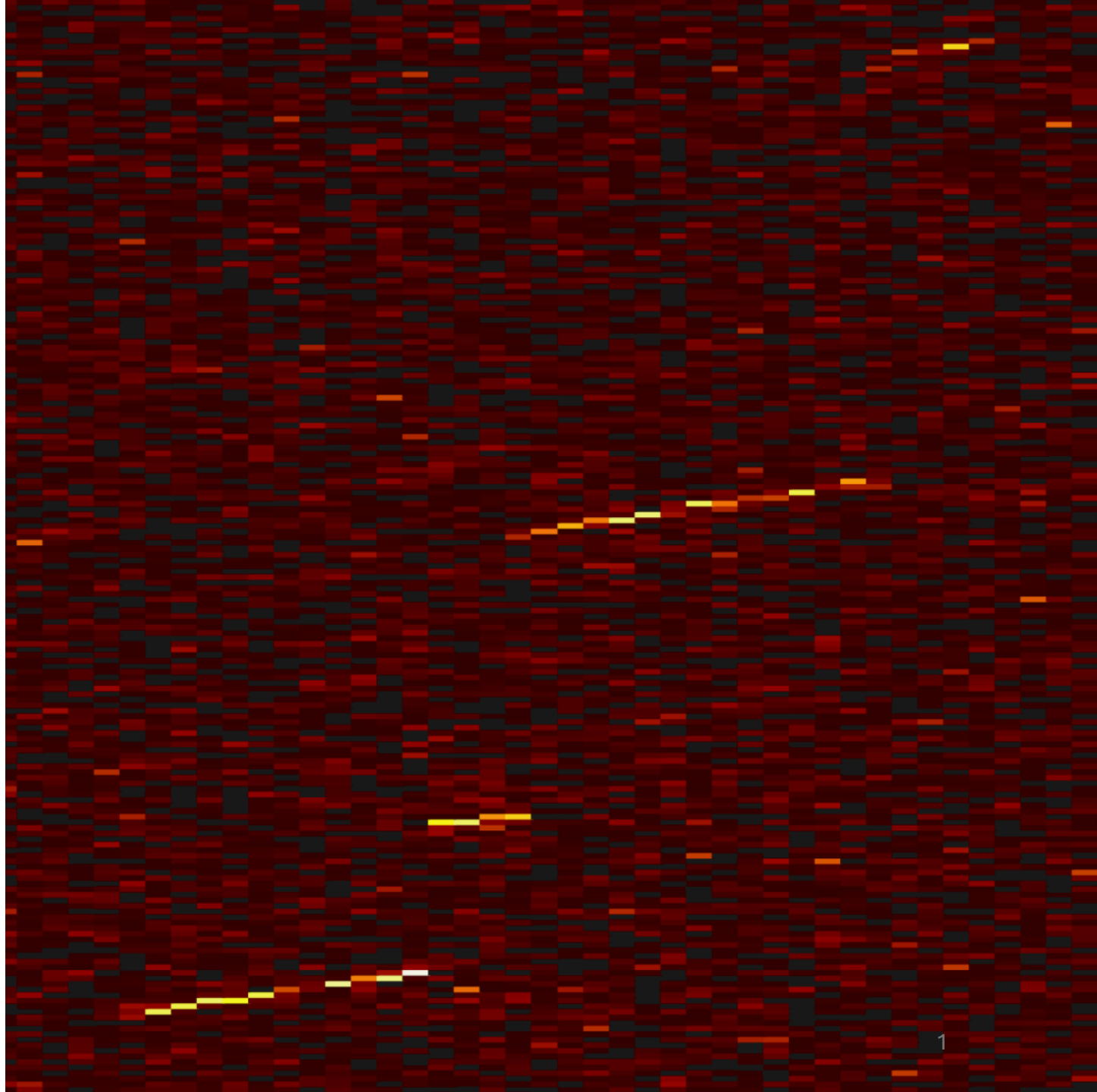
PROJECT 8

Scaling CRES to large volumes in Project 8

Multi-mode cavity design for the Low Frequency Apparatus

September 18, 2026
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, 47th Course

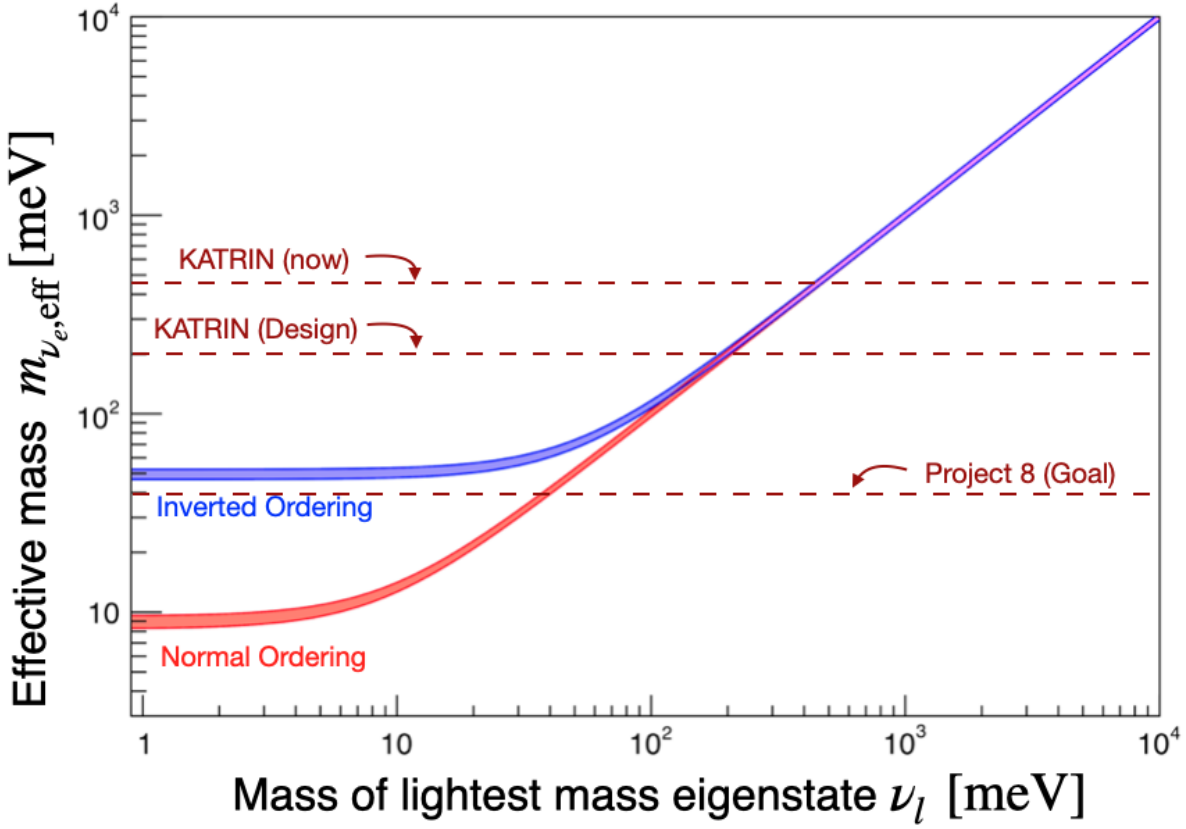
Svitlana Hoienko



Project 8 – next-generation neutrino mass experiment

Goal: achieving a sensitivity $m_\beta < 40$ meV/c^2

- new technology needed to go beyond KATRIN
- Project 8 aims to reach minimal mass allowed by inverted ordering
- need excellent energy resolution and very high statistics



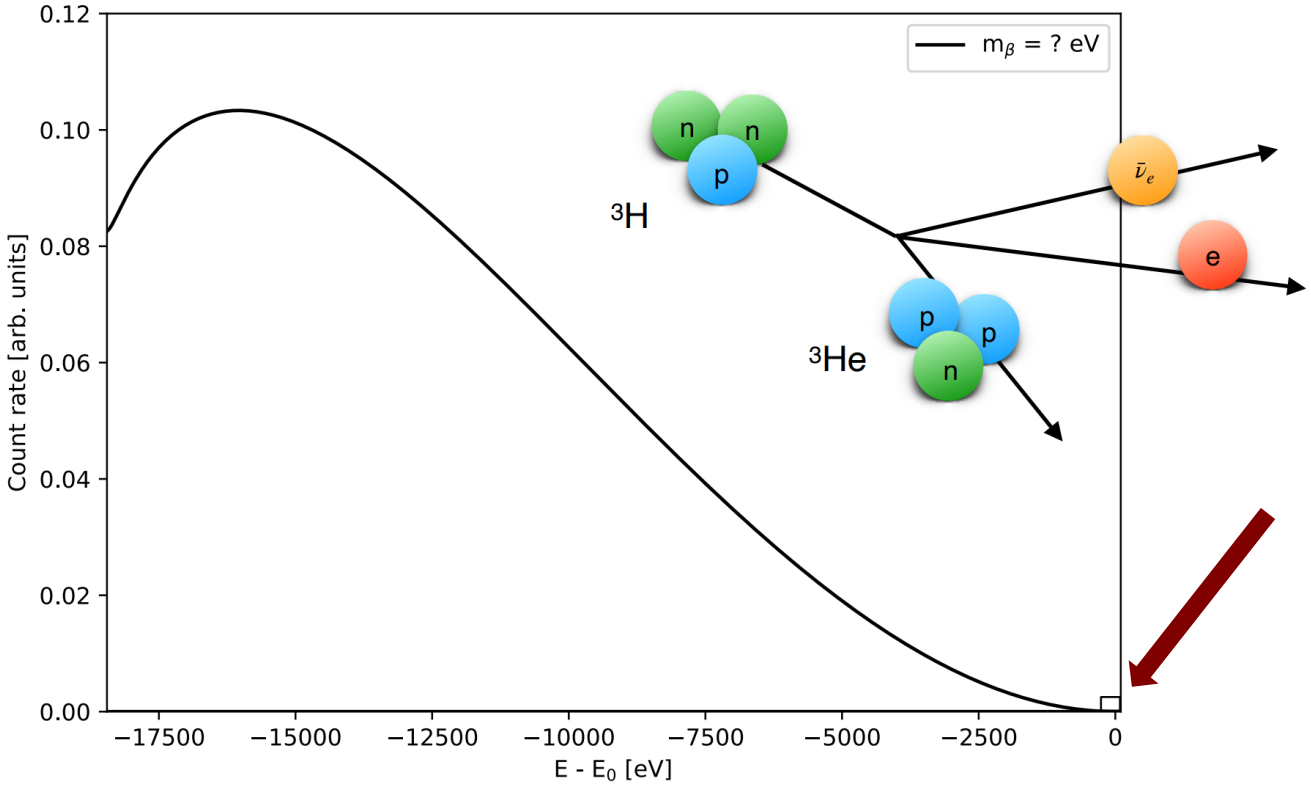
Credit: H. Binney

How do we measure the neutrino mass?

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

Tritium β-spectroscopy is the leading technique for direct neutrino mass measurement

Credit: J. Stachurska



Beta Decay Spectrum

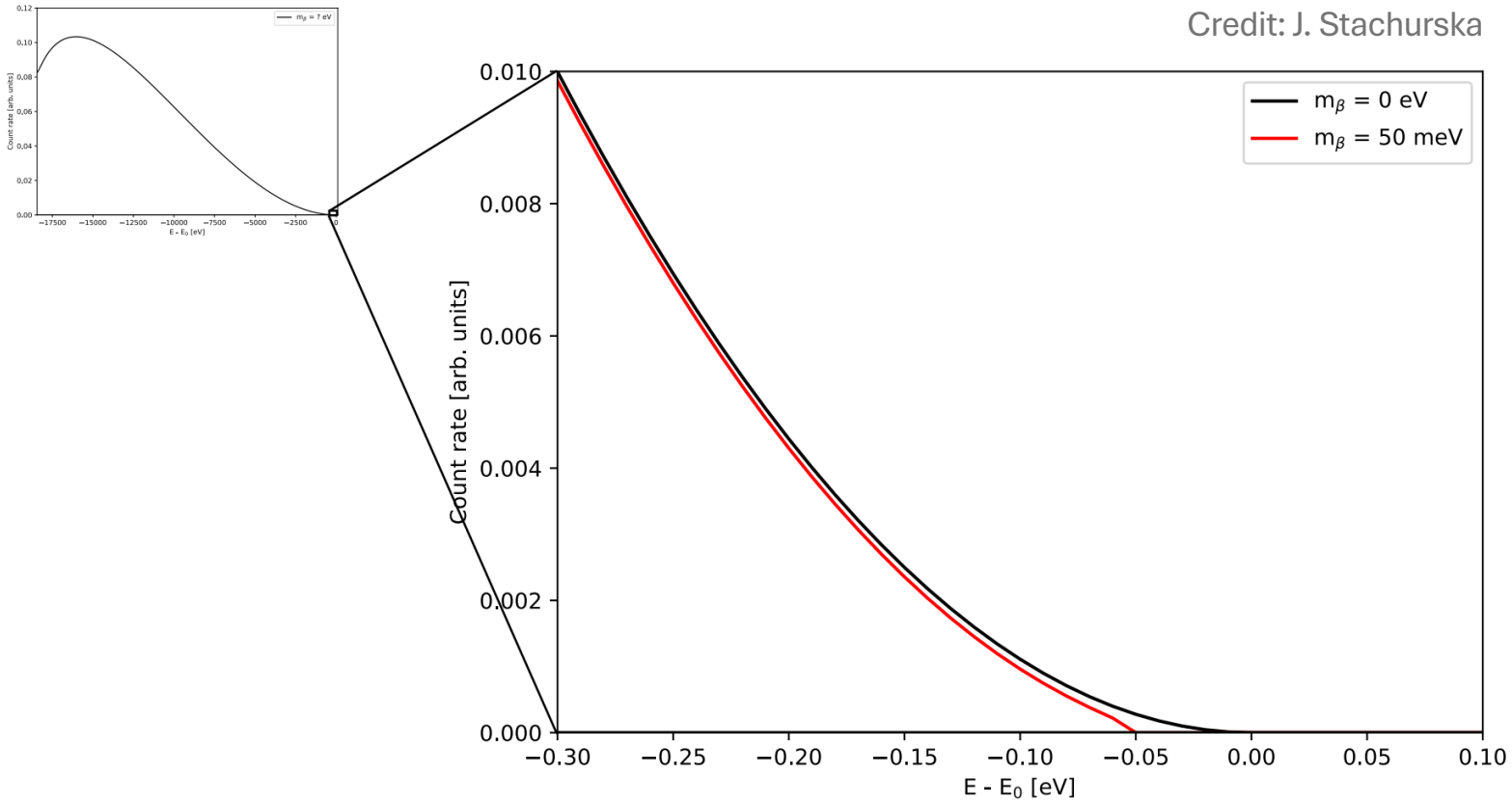
How do we measure the neutrino mass?

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

A non-zero neutrino mass modifies the spectrum only very close to the endpoint.

This effect is extremely small, and events in this region are rare.

Credit: J. Stachurska

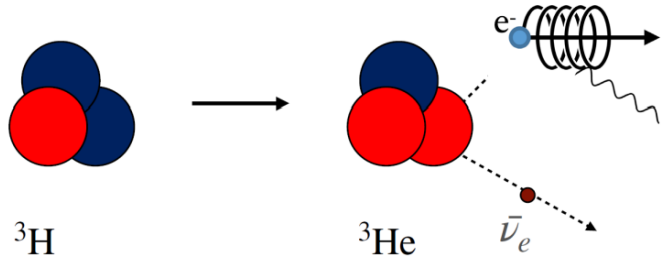


The atomic tritium endpoint spectrum under different neutrino mass scenarios both having the same extrapolated endpoint energy.

Cyclotron Radiation Emission Spectroscopy

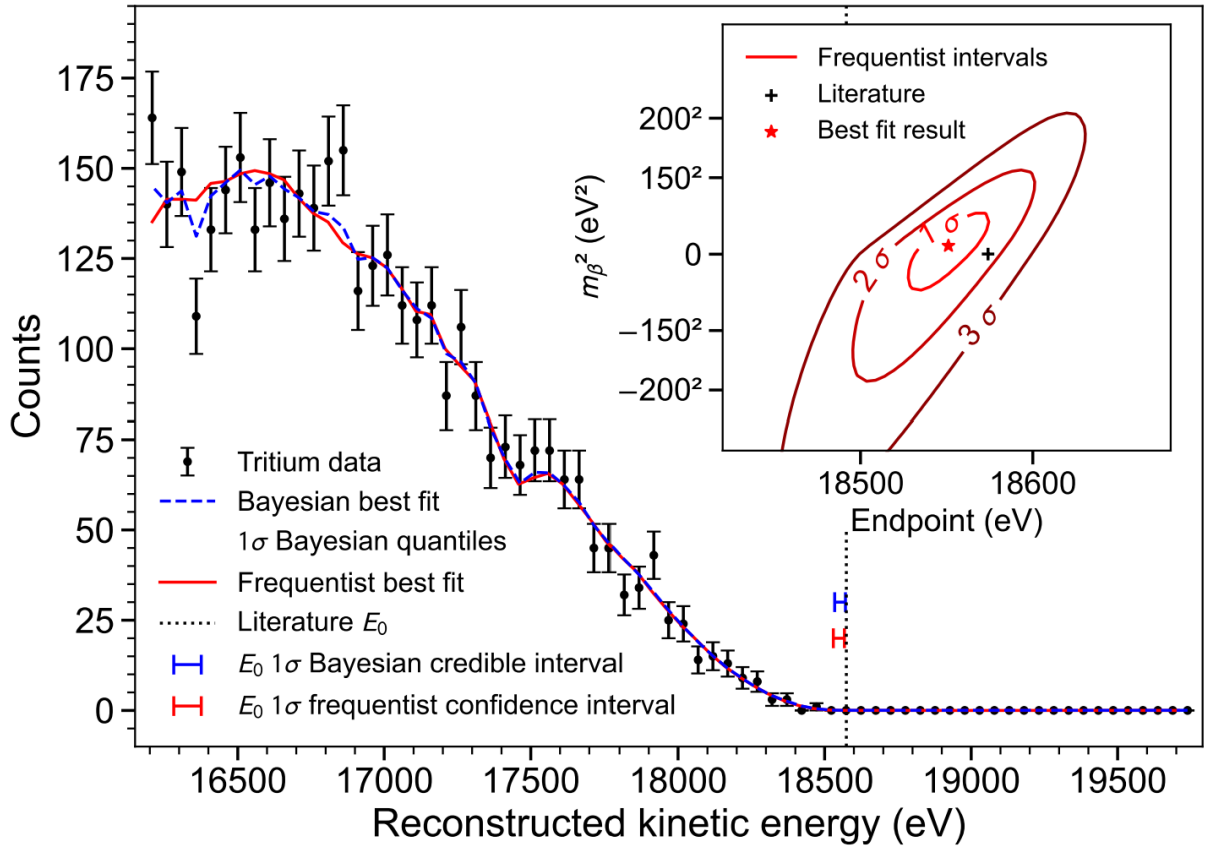
- Electron in B-field: cyclotron motion & radiation:

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



- 10^{-13} of all tritium decays occur within the final 1 eV of the spectrum

Project 8 Collaboration, Phys. Rev. C 109, 035503 (2024)



Project 8 Phase II tritium result obtained with a small-volume CRES apparatus.

How to achieve large volume and high power?

Resonant cavities provide an attractive way of scaling Project 8 to large volumes

- High volume efficiency
- Power enhancement on resonance

Neutrino mass sensitivity

↓

need more endpoint electrons

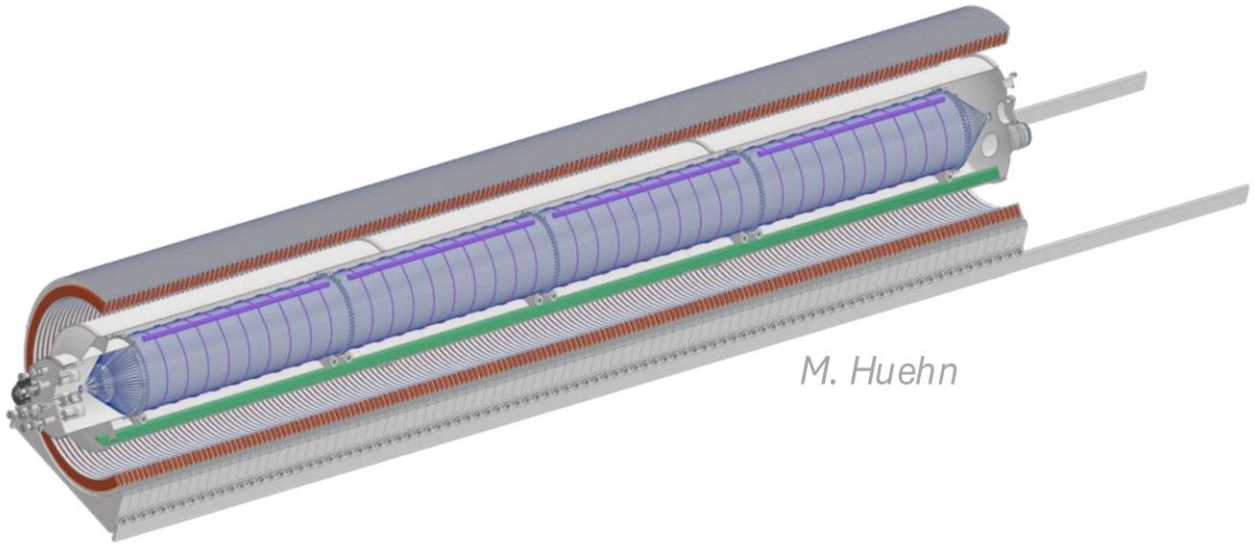
↓

need larger effective detection volume

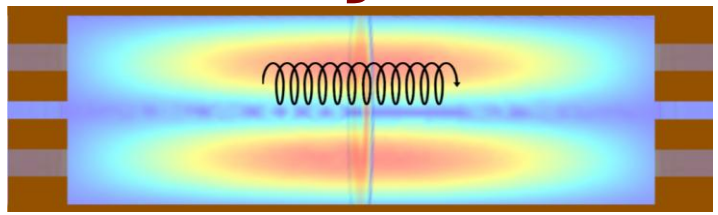
LFA

(Low **F**requency **A**pparatus**)**

Magnetic field ~ 21mT
Frequency ~ 560MHz



Eigenmodes of the cylindrical cavity



arXiv:2601.07848 [physics.ins-det]

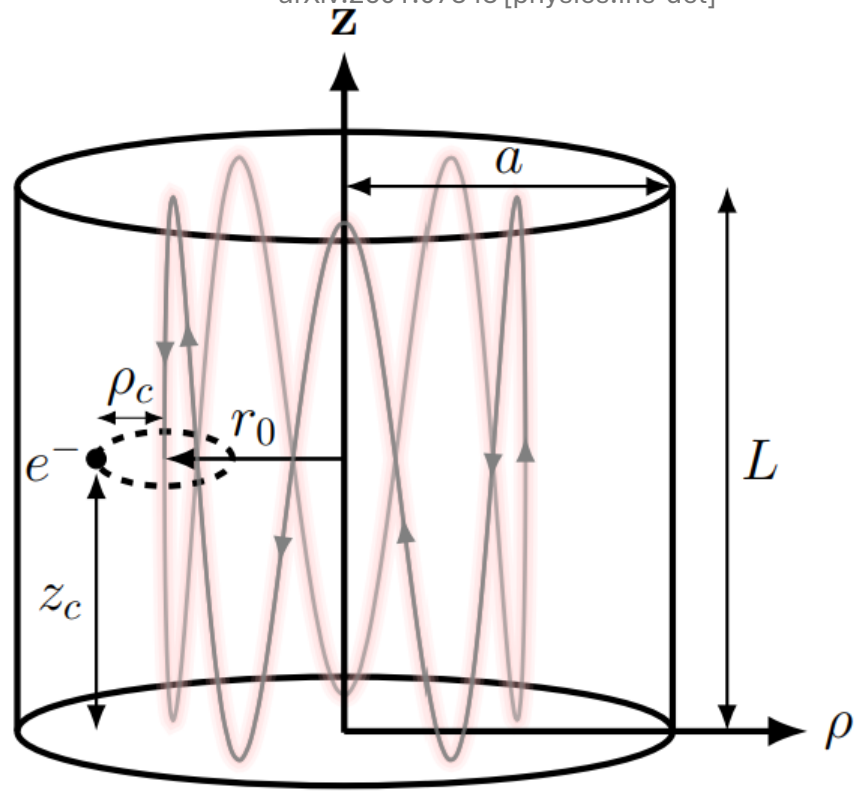
- only interested in modes with purely circumferential wall currents ($\mathrm{TE}_{0,n,p}$).

The resonant frequencies of the transverse-electric(TE) modes, to which electrons couple well, are:

$$f_{mnp}^2(TE) = \frac{c^2}{4\pi^2}\left[\left(\frac{X'_{mn}}{a}\right)^2 + \left(\frac{p\pi}{L}\right)^2\right],$$

$$m = 0, 1, 2 \ \ldots\ ;\ n, p = 1, 2, 3 \ldots$$

X'_{mn} – the nth zero of the derivative of the mth Bessel function.

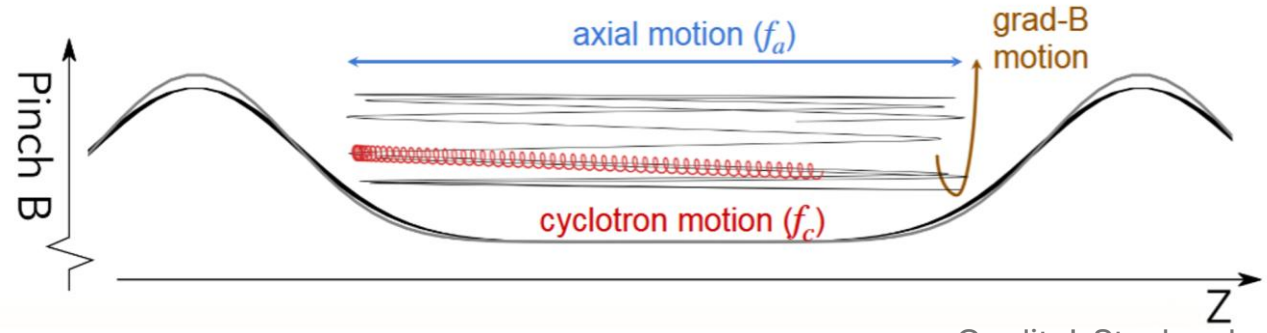


Cylindrical cavity of radius a and length L.

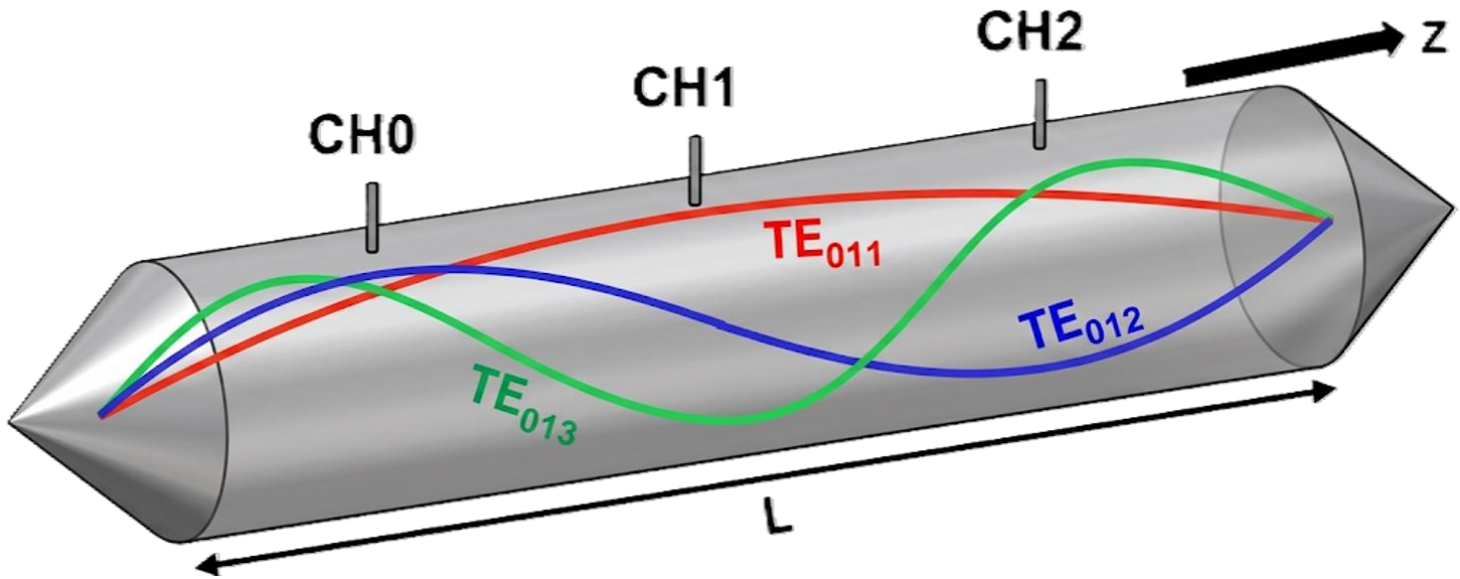
Credit: J. Stachurska

Cavity CRES is complex

- electron–mode coupling depends on electron position and trajectory
- many closely spaced electromagnetic modes



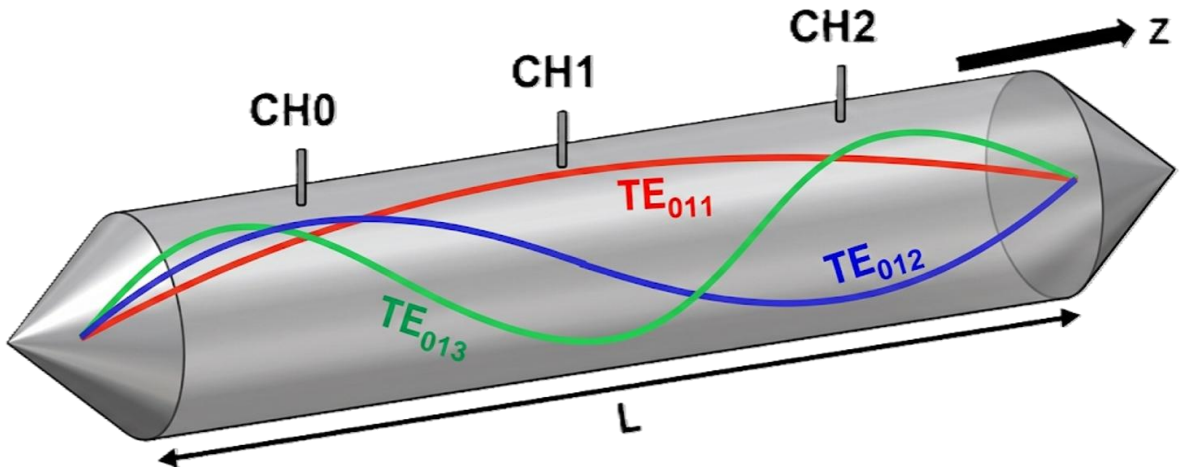
Credit: J. Stachurska

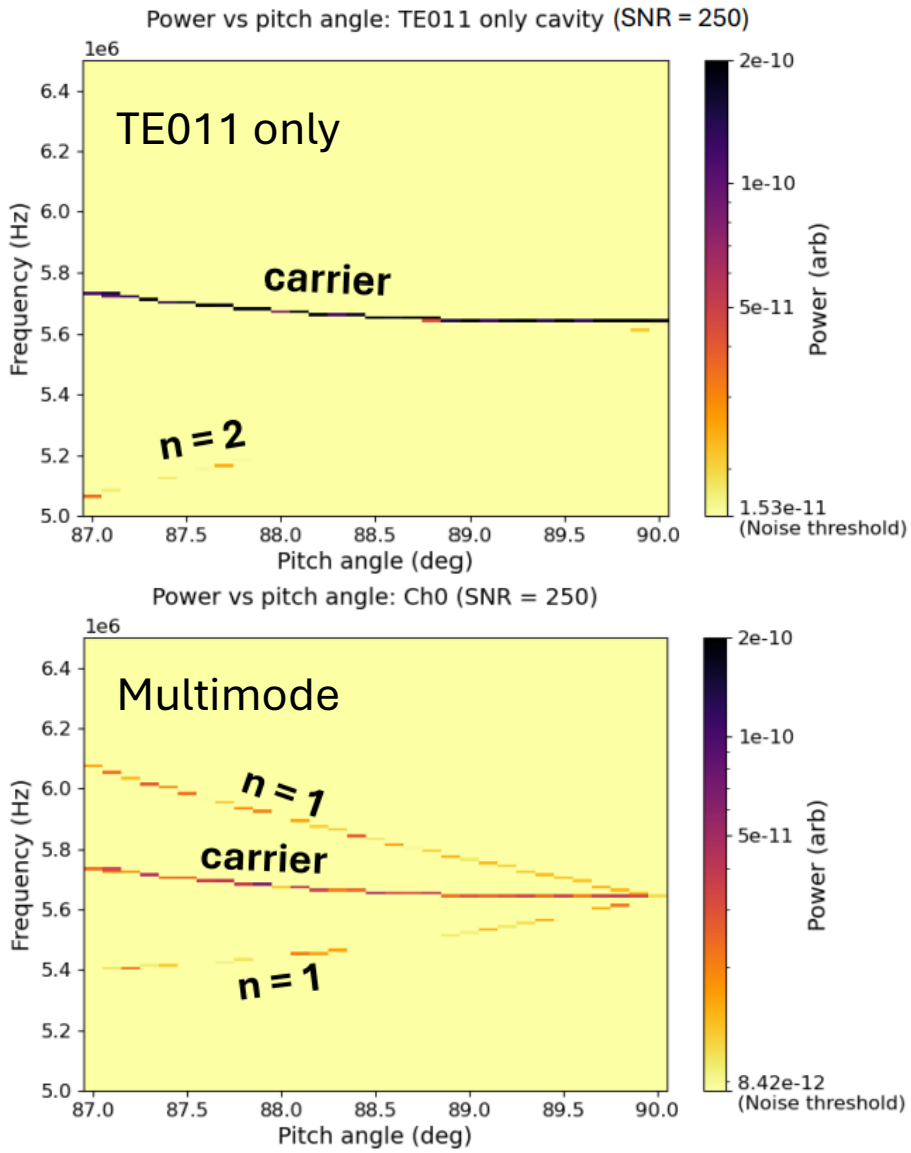


Multi-mode cavity

- limited information available in single mode
- sidebands are not always well detectable
- multi-mode cavities help recover more information

Carrier + sideband → event reconstruction





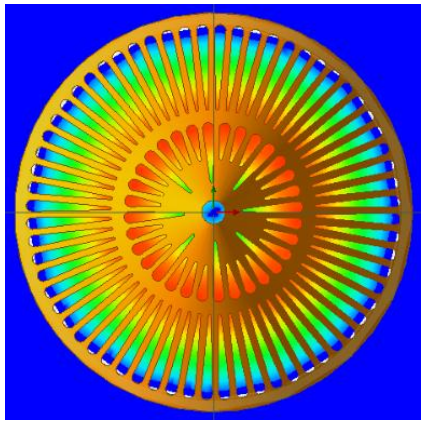
Credit: V. Ranatunga

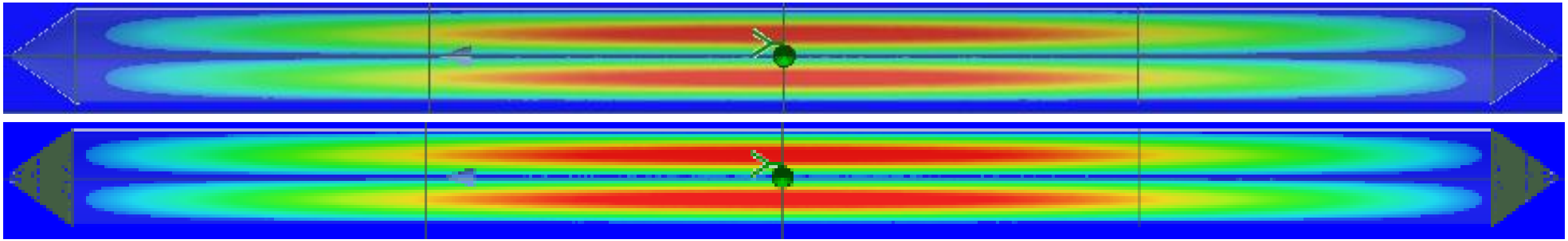
Leakage problem

Tritium pumping and recirculation require openings between the Ioffe atom trapping wires

R=32.7cm | L=10m | T=4K vacuum

Configuration	f(MHz) TE_{011}	f(MHz) TE_{012}	Q_{011}	Retained Q_{011}	Q_{012}	Retained Q_{012}
Closed	566.556	567.113	86,695	100%	86,890	100%
Open	566.529	567.061	18,763	21.6%	5,701	6.5%

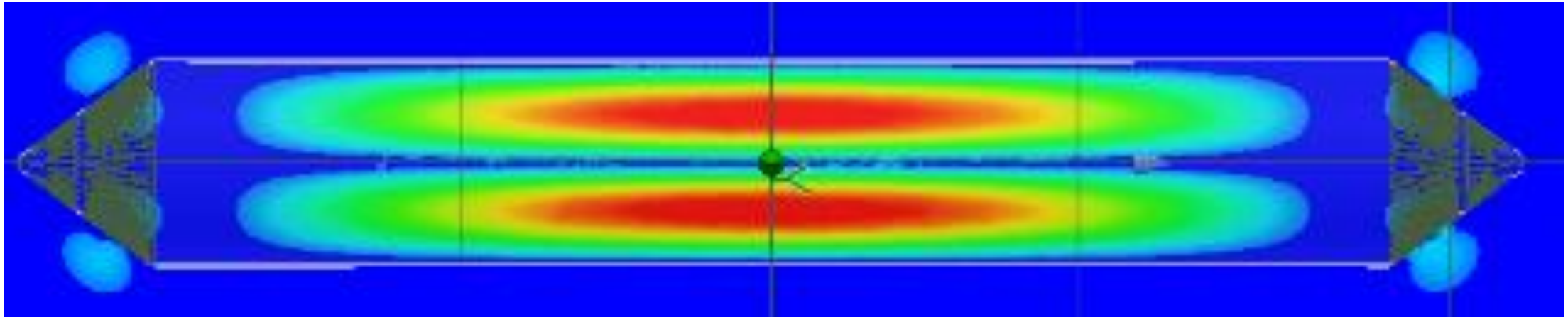




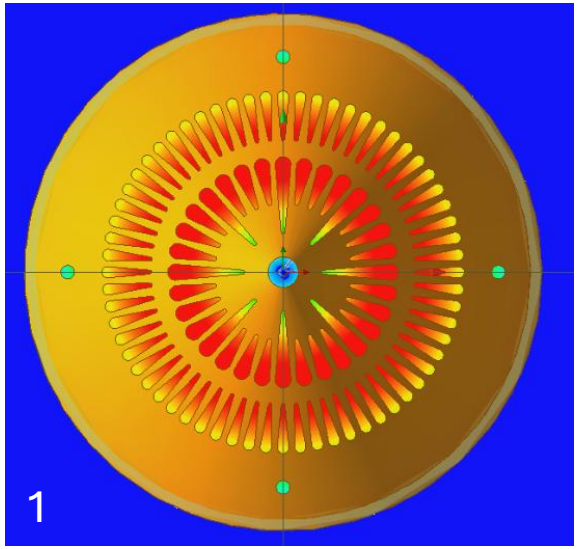
Ghent University prototype

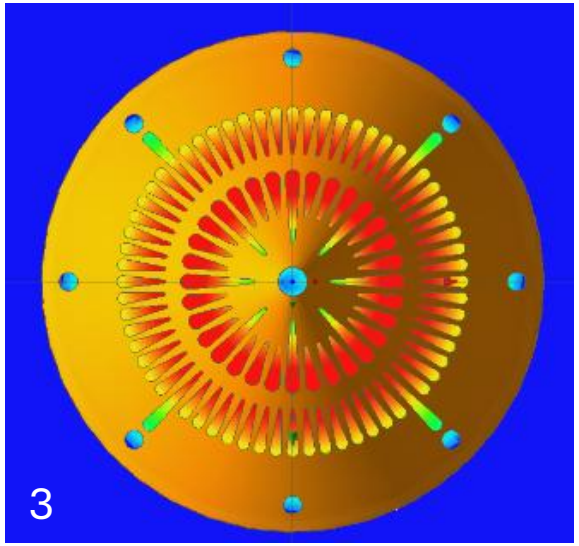
L = 4m + 30cm cones
R = 21.85cm
Target: TE01p modes

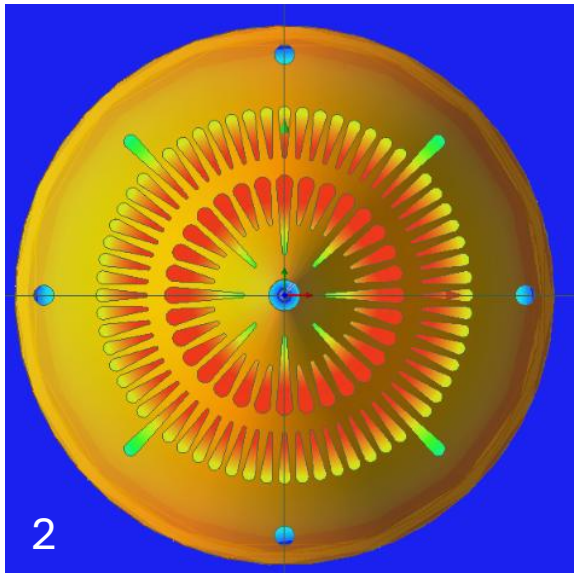
- validate HFSS against measurements
- study mode spectrum and Q
- develop/test the readout antenna

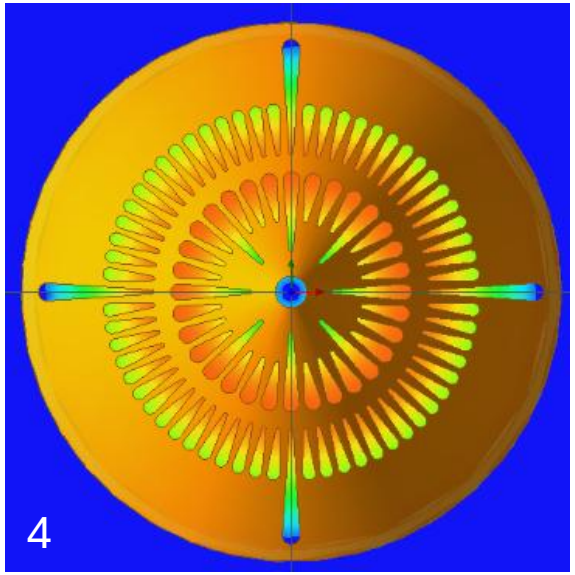


Recent progress in multi-mode cavity design









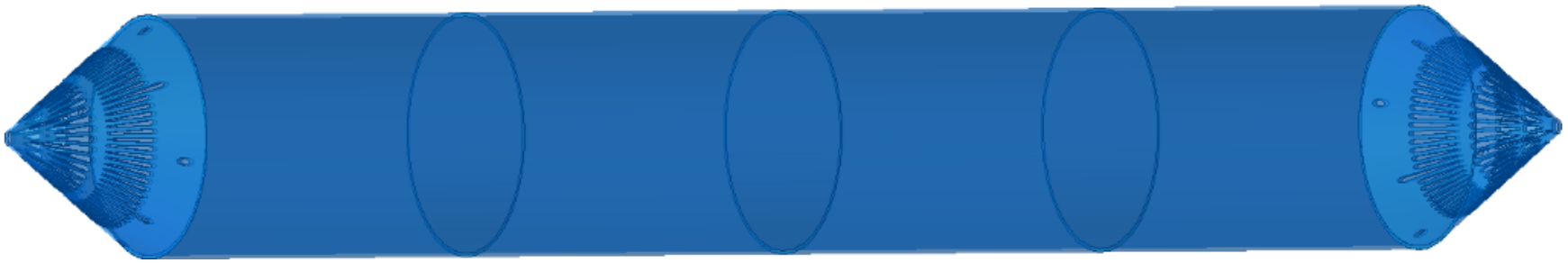
- Designs 1–3 retain > 92% of Q for both studied modes
- Large slots in Design 4 strongly degrade Q

Design	Q_{011}	Retained Q_{011}	Q_{012}	Retained Q_{012}
Closed	50505	100%	51372	100%
Open	6170	12.2%	1690	3.3%
1	50636	100%	50074	97.4%
2	50016	99%	47526	92.5%
3	50067	99.1%	47527	92.5%
4	24222	47.9%	8924	17.3%

Conclusions

- Scaling CRES to large volumes is not simply a matter of making the apparatus bigger.
- Multi-mode operation provides complementary sideband information for event reconstruction.
- Openings can reduce cavity Q by more than an order of magnitude.
- Optimized opening geometries can retain > 90% of Q for TE_{011} and TE_{012}.

The goal is a cavity that is simultaneously large-volume, multi-mode, low-loss and experimentally realisable.



Thank you! / Questions