EPPg μν
Ghent University
Experimental Particle
Physics and gravity

PROJECT 8

Exploring Cyclotron Radiation Emission Spectroscopy (CRES) Features in Project 8

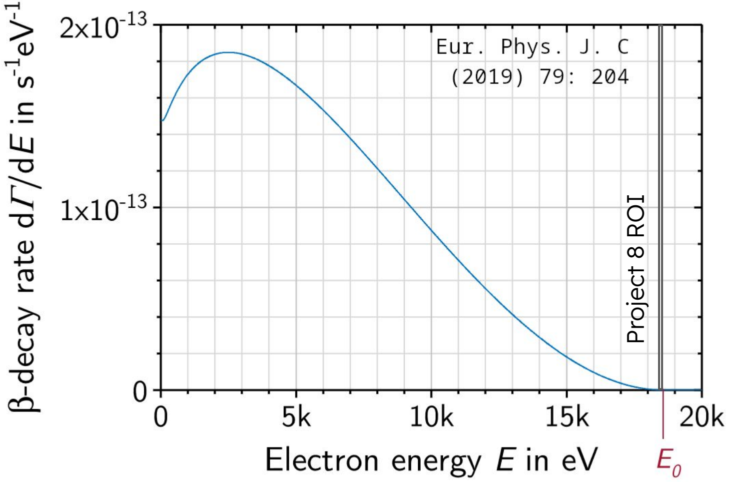
Jan Küpperbusch

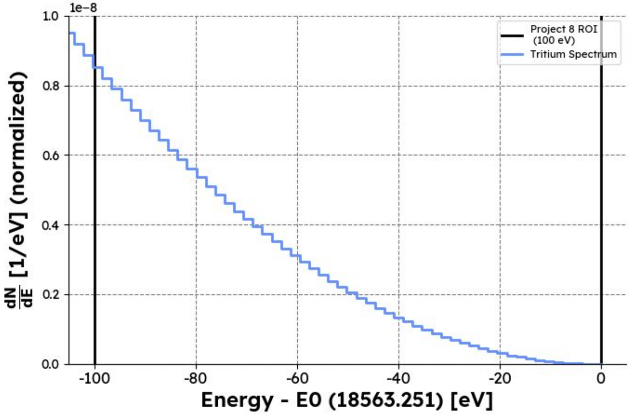
September 18th, 2026

INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, 47th Course

Direct Neutrino Mass Measurements

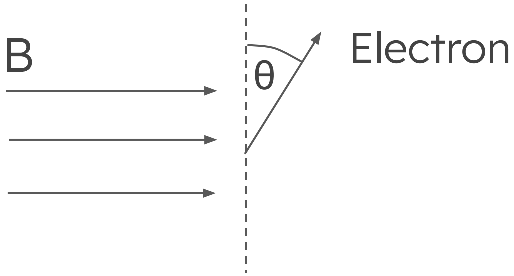
Idea: Measure the electron energy spectrum from atomic tritium beta decays

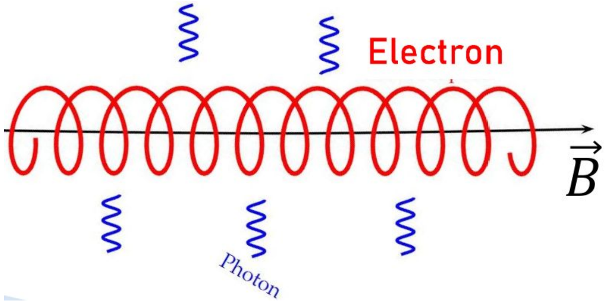




Rate in the final eV makes up ~1e-6 of the total amount of signals
(assuming no endpoint effects of the neutrino mass)

The CRES technique



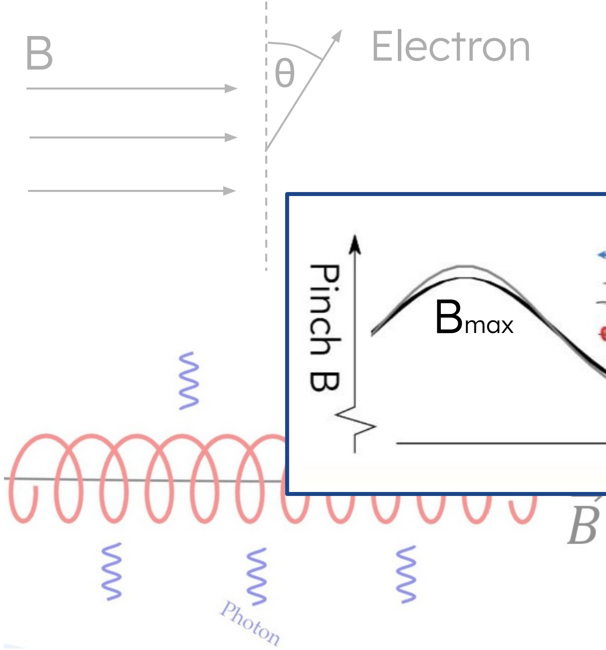


Measure Frequency to reconstruct the energy: **C**yclotron **R**adiation **E**mission **S**pectroscopy

(Non-destructive time-dependent cyclotron frequency measurements)

$$f_c(t) = \frac{1}{2\pi} \frac{eB(x(t))}{m_e + E_{\text{kin}}(t)/c^2}$$

The CRES technique



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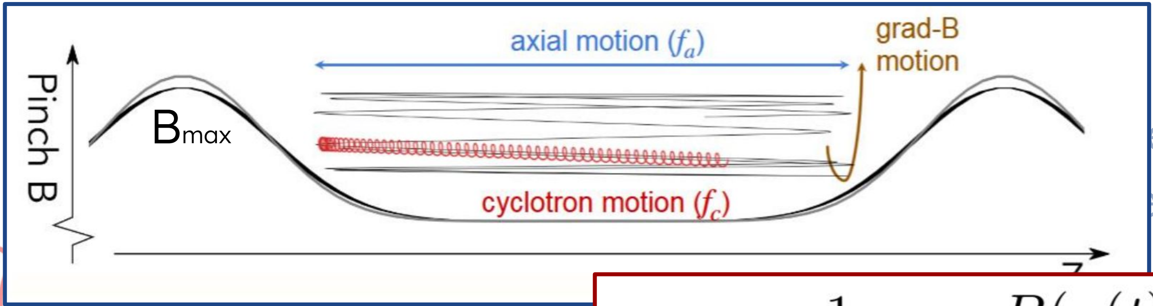

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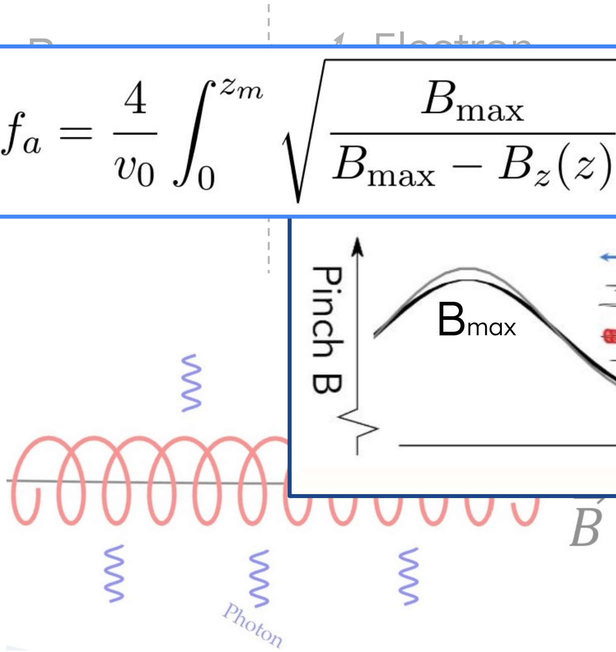
The CRES technique



$$f_a = \frac{4}{v_0} \int_0^{z_m} \sqrt{\frac{B_{\max}}{B_{\max} - B_z(z)}} dz$$

Measure Frequency to reconstruct the energy: **C**yclotron **R**adiation **E**mission

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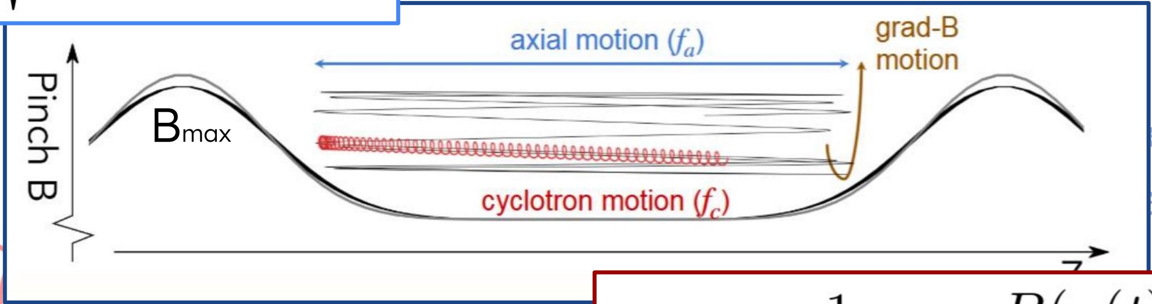
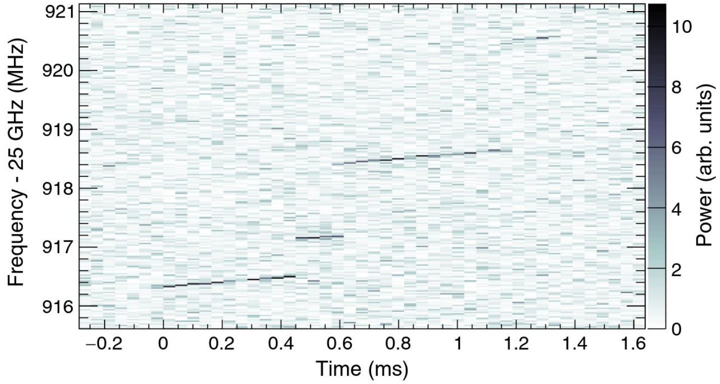


$$f_c(t) = \frac{1}{2\pi} \frac{eB(x(t))}{m_e + E_{\text{kin}}(t)/c^2}$$

The Cavity CRES Apparatus (CCA)



Project 8 Waveguide Spectrogram
Phys. Rev. Lett. 131 (2023) 10, 102502

Project 8 CCA Cavity + Waveguide readout (Credits: J. Peña)

CCA involves a first resonant cavity read out by a waveguide

- Axial frequency reconstruction possible
- Purcell enhancement of the radiated power

but also strong reliance on

- Correct alignment
- Magnetic field modelling
- Simulation-based reconstruction

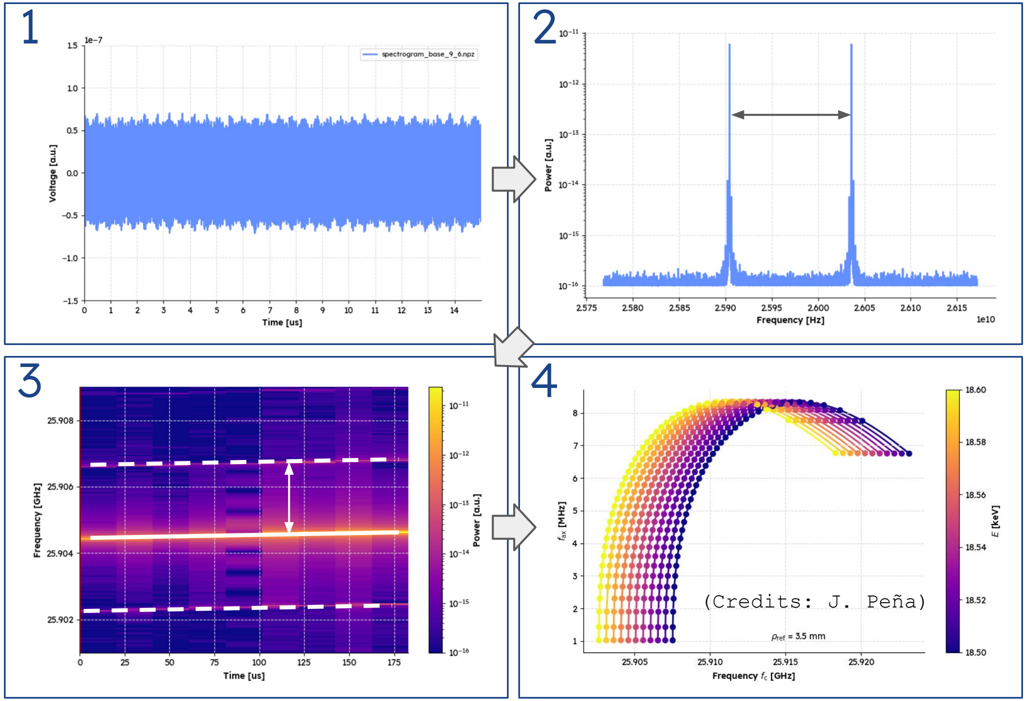
The CCA reconstruction

Voltage Timeseries

Short-scale frequency spectrum

Spectrogram and track ID (Dependent on the TE mode)

Map axial and cyclotron frequency to energy



The CCA reconstruction

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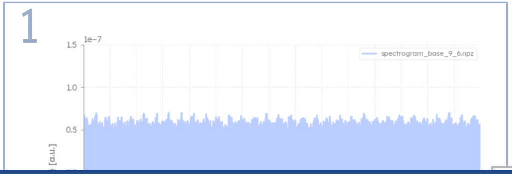

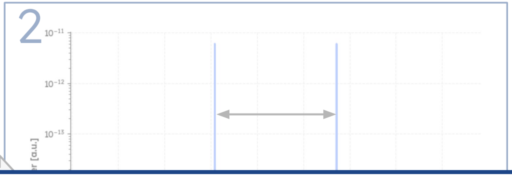

Voltage
Timeser

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Short-scale
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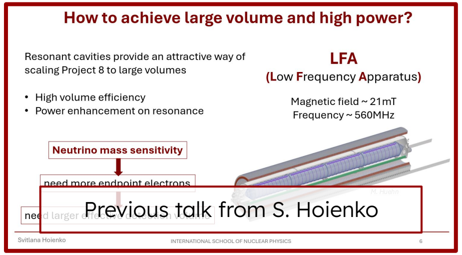
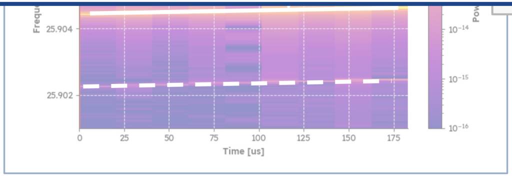
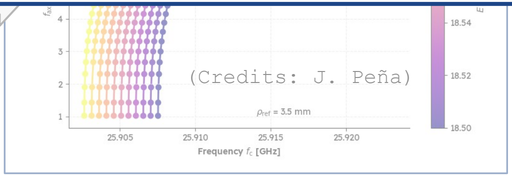
energy

What happens once we go to bigger volumes?



Previous talk from S. Hoienko





Pileup in the Low Frequency Apparatus (LFA)

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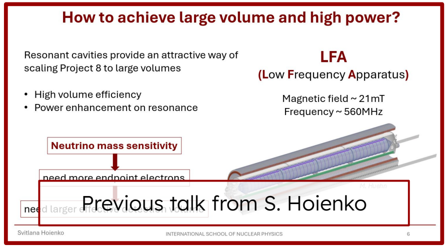
Lower radiation power P~f²

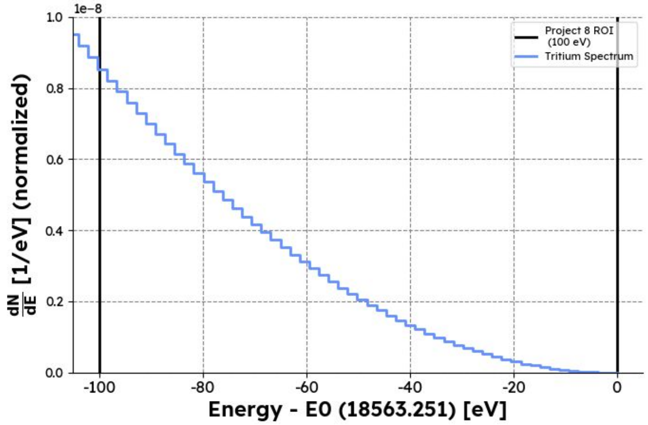
(560 MHz, currently 25.9 GHz)

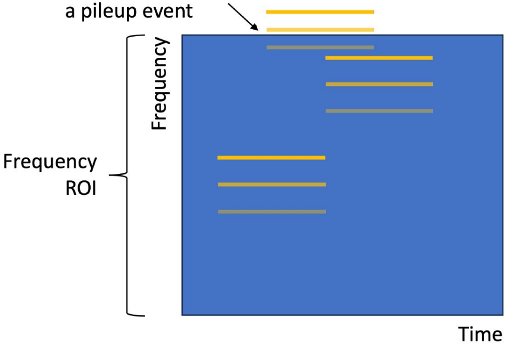
Probability of signal pileup will increase

(higher statistics)

https://www.arsmundi.de





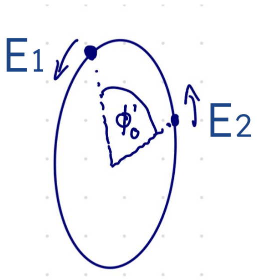


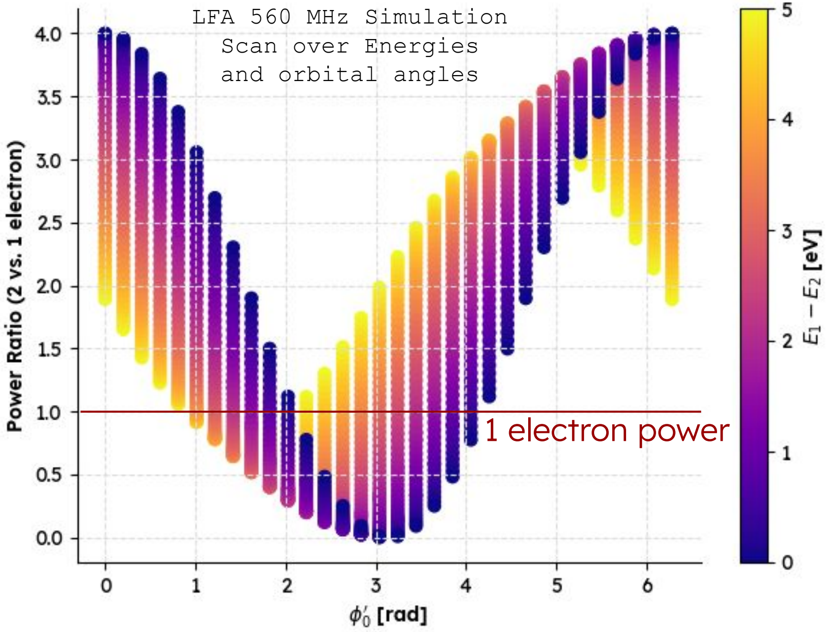
<- how does this pileup look like?

Credit: H. Binney

LFA: Parametrization of power in pileup events

Scenario: Two "chasing" electrons





Mean power calculation and simulational result agree on a (dimensionless) power ratio factor

Ψ(Δf) (or equivalently, Ψ(ΔE))

$$\Psi = 2 + 2\alpha \cos(\varphi_0 + \beta) \qquad \text{with } \alpha = \text{sinc}(\Delta\omega T/2),\ \beta = \Delta\omega T/2$$

LFA: Parametrization of power in pileup events

Scenario: Two "chasing" electrons

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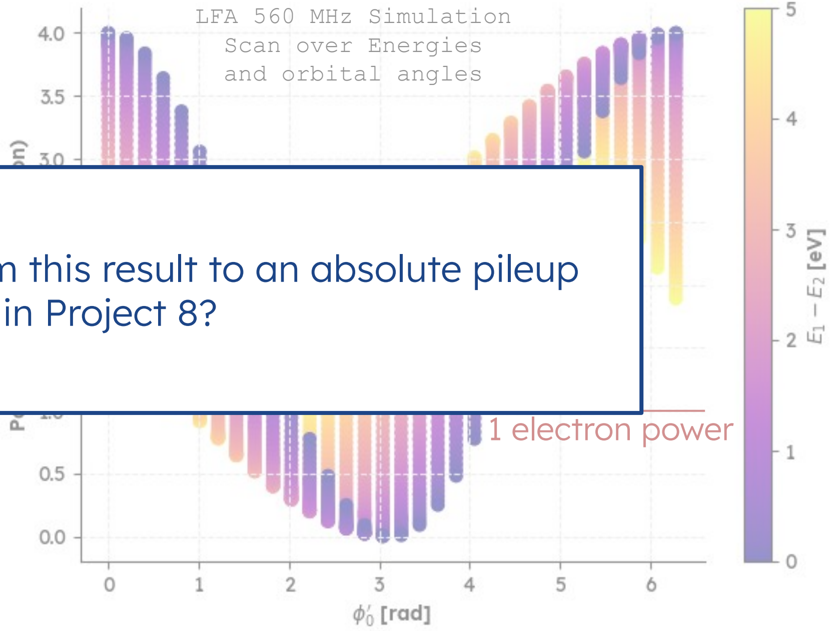
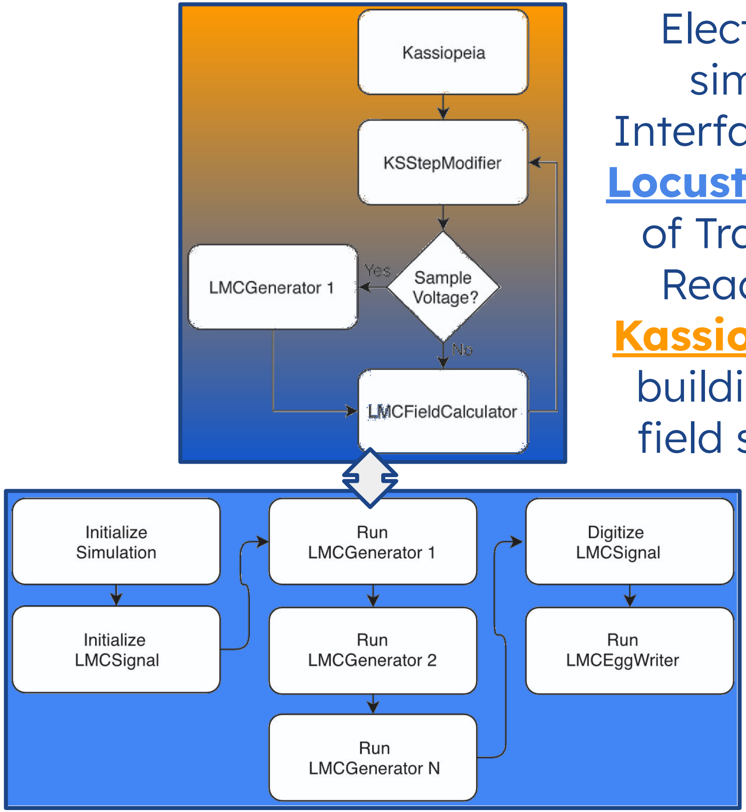


How do we abstractly move from this result to an absolute pileup description in Project 8?

$$\Psi = 2 + 2\alpha \cos(\varphi_0 + \beta) \qquad \text{with } \alpha = \mathrm{sinc}(\Delta\omega T/2),\ \beta = \Delta\omega T/2$$

Project 8 simulations: Locust/Kassiopeia



Electron track simulation: Interface between Locust (Simulation of Trap/Cavity/ Readout) and Kassiopeia (Track building and EM field simulation)

Locust: C++ software for simulation of RF detection

A Ashtari Esfahani[1], S Böser[2], N Buzinsky[3], R Cervantes[1], C Claessens[2], L de Viveiros[4], M Fertl[1,2], J A Formaggio[3], L Gladstone[5], M Guigue[6], K M Heeger[7], J Johnston[3], A M Jones[6], K Kazkaz[8], B H LaRoque[6], A Lindman[2], E Machado[1], B Monreal[5], E C Morrison[6], J A Nikkel[7], E Novitski[1], N S Oblath[6], W Pettus[1], R G H Robertson[1], G Rybka[1], L Saldaña[7], V Sibille[3], M Schram[6], P L Slocum[7], Y-H Sun[5], J R Tedeschi[6], T Thümmler[9], B A VanDevender[6], M Wachtendonk[1], M Walter[9], T E Weiss[3], T Wendler[4] and E Zayas[3]

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3 Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, United States of America
4 Department of Physics, Pennsylvania State University, State College, PA 16802, United States of America
5 Department of Physics, Case Western Reserve University, Cleveland, OH 44106, United States of America
6 Pacific Northwest National Laboratory, Richland, WA 99354, United States of America
7 Wright Laboratory and Department of Physics, Yale University, New Haven, CT 06520, United States of America
8 Lawrence Livermore National Laboratory, Livermore, CA 94550, United States of America
9 Institut für Kernphysik, Karlsruher Institut für Technologie, Karlsruhe, Germany

E-mail: penny.slocum@yale.edu

Keywords: RF, radiation detection, simulation, antenna, C++

New J. Phys. 21 113051 (2019)

Kassiopeia: a modern, extensible C++ particle tracking package

Daniel Furse[1], Stefan Groh[2], Nikolaus Trost[3], Martin Babutzka[2], John P Barrett[1], Jan Behrens[4], Nicholas Buzinsky[1], Thomas Corona[5,6], Sanshiro Enomoto[7], Moritz Erhard[2], Joseph A Formaggio[1], Ferenc Glück[3,8], Fabian Harms[3], Florian Heizmann[2], Daniel Hilk[2], Wolfgang Käfer[2], Marco Kleesiek[2], Benjamin Leiber[2], Susanne Mertens[9], Noah S Oblath[1], Pascal Renschler[2], Johannes Schwarz[3], Penny L Slocum[10], Nancy Wandkowsky[3], Kevin Wierman[5,6] and Michael Zacher[4]

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3 Institute for Nuclear Physics (IKP), Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany
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5 Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599, United States of America
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8 Wigner Research Institute for Physics, Budapest POB 49, Hungary
9 Max Planck Institute for Physics, Munich & Technical University Munich, D-80333 Munich, Germany
10 Department of Physics, Yale University, PO Box 208120, New Haven, CT 06520, United States of America

New J. Phys. 19 053012 (2017)

Project 8 simulations: Hopper, the new Kid in town

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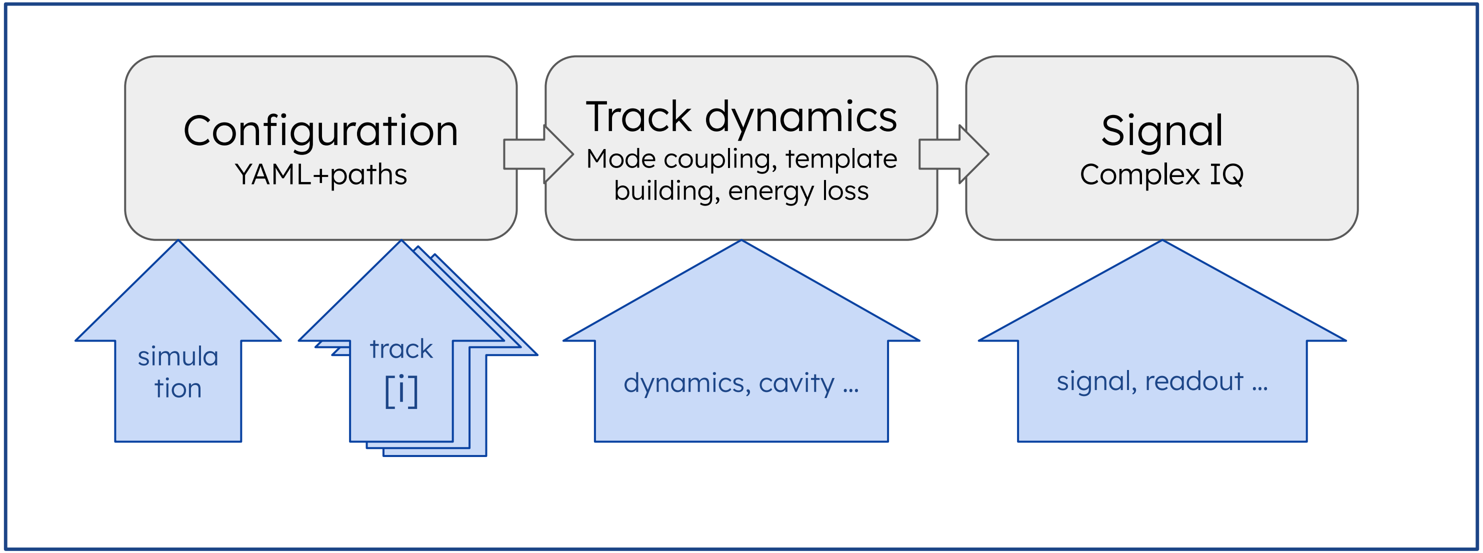
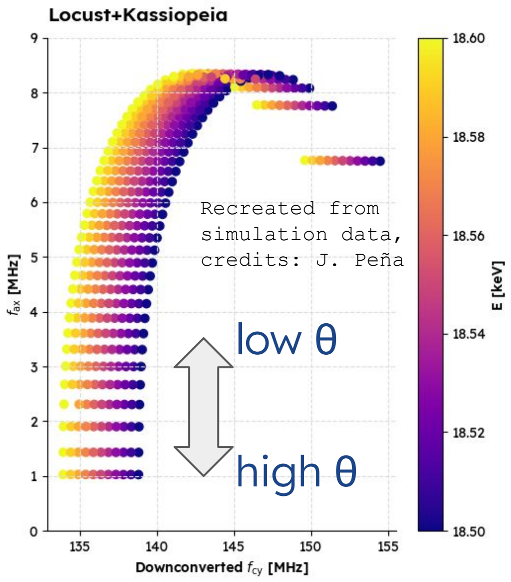
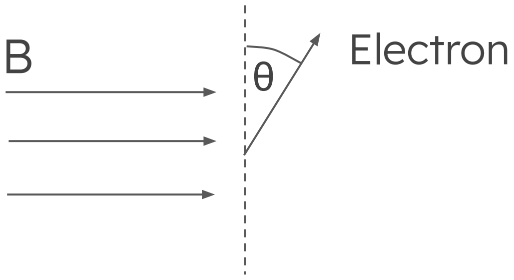


Recent development - Written in python - Capable of multi-electron pileup
Currently benchmarked against Locust/Kassiopeia

Comparing two simulation packages

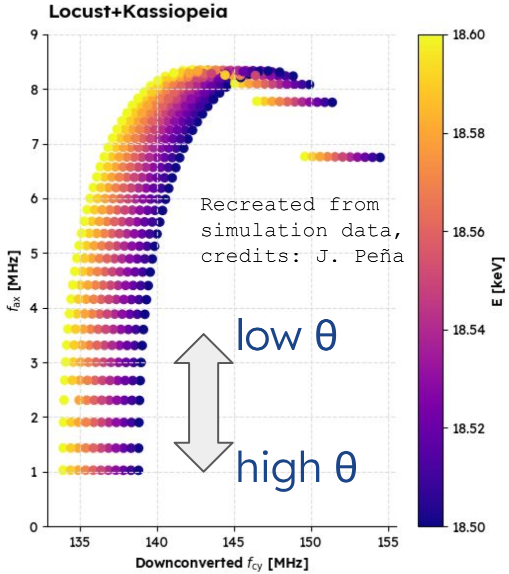


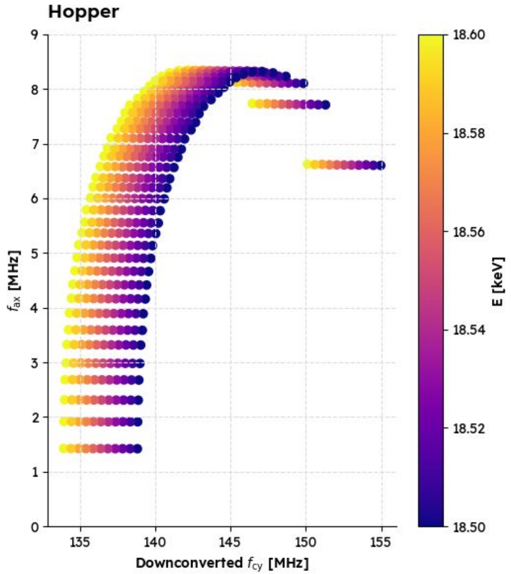
Locust: Given pitch angle and energy configuration results in specific axial and cyclotron frequency

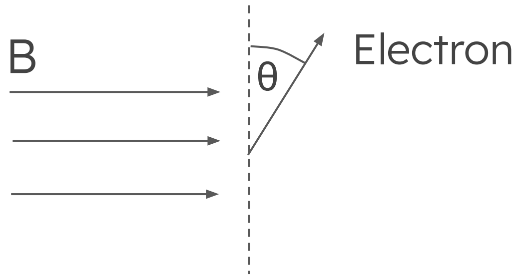


Scan over Pitch angle θ and electron energy E

Comparing two simulation packages





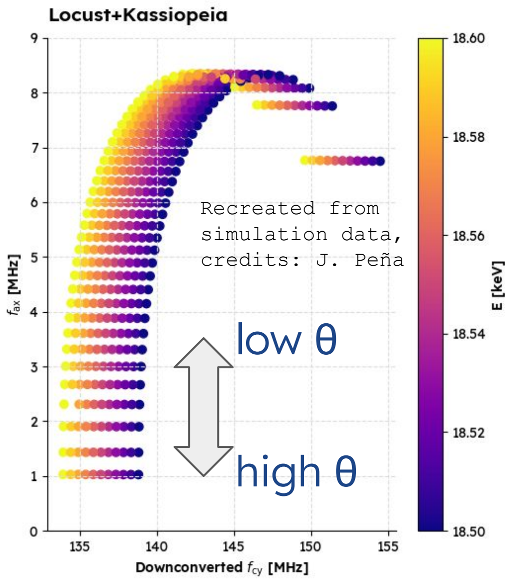


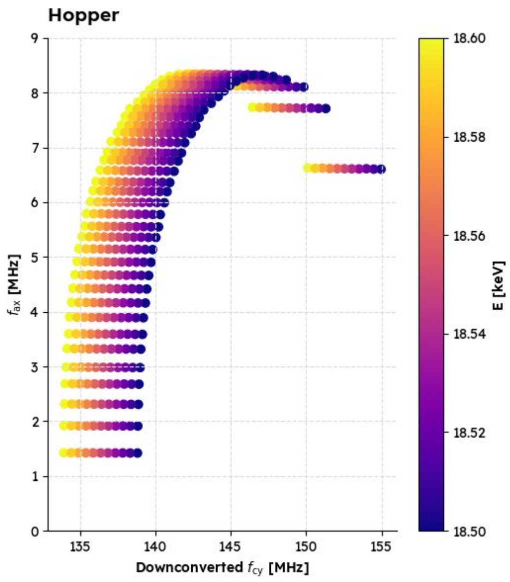
Scan over Pitch angle θ and electron energy E

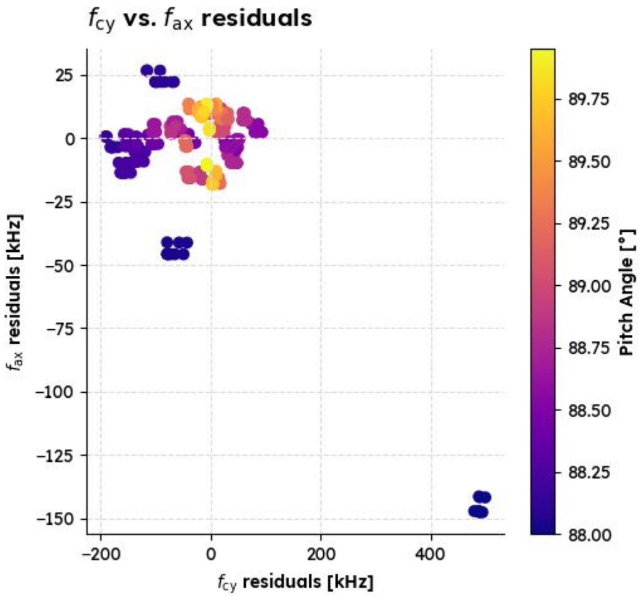
Locust: Given pitch angle and energy configuration results in specific axial and cyclotron frequency

Hopper may create these results much faster, but is it correct?

Comparing two simulation packages







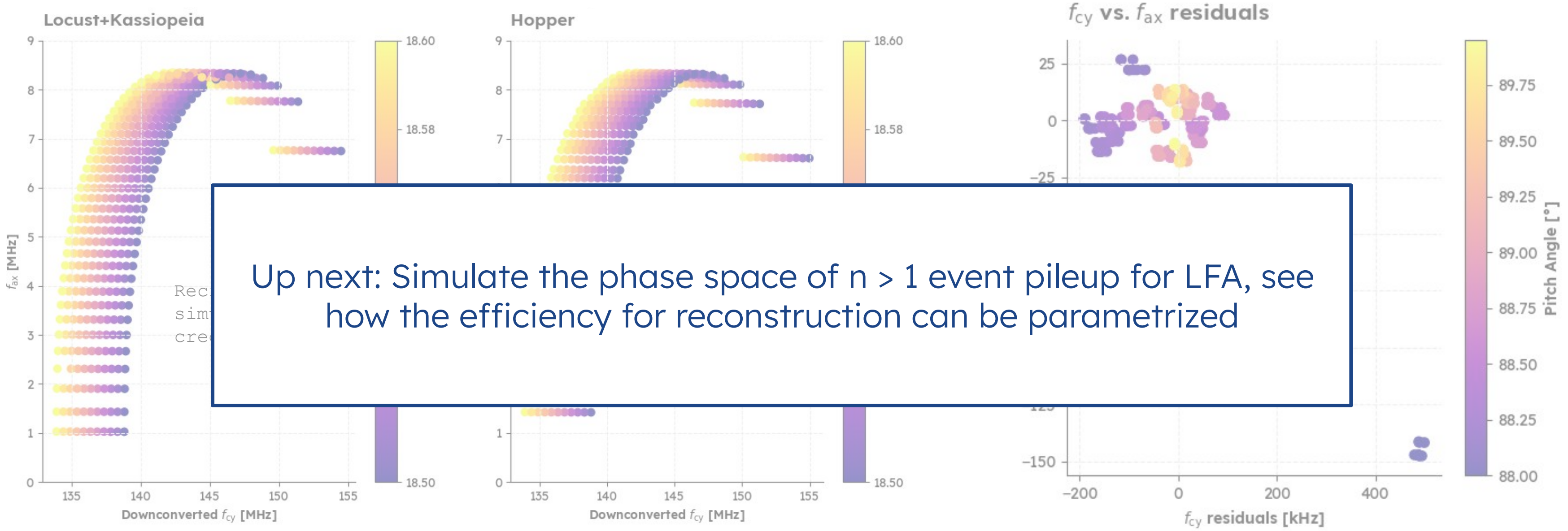
Locust: Given pitch angle and energy configuration results in specific axial and cyclotron frequency

Hopper may create these results much faster, but is it correct?

Current results show bigger residuals towards low pitch angles (high axial frequency)

Residuals: <2.5 % (f_{ax}), <0.4 % (f_{cy})

Comparing two simulation packages



Up next: Simulate the phase space of n > 1 event pileup for LFA, see how the efficiency for reconstruction can be parametrized

Locust: Given pitch angle and energy configuration results in specific axial and cyclotron frequency

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Summary

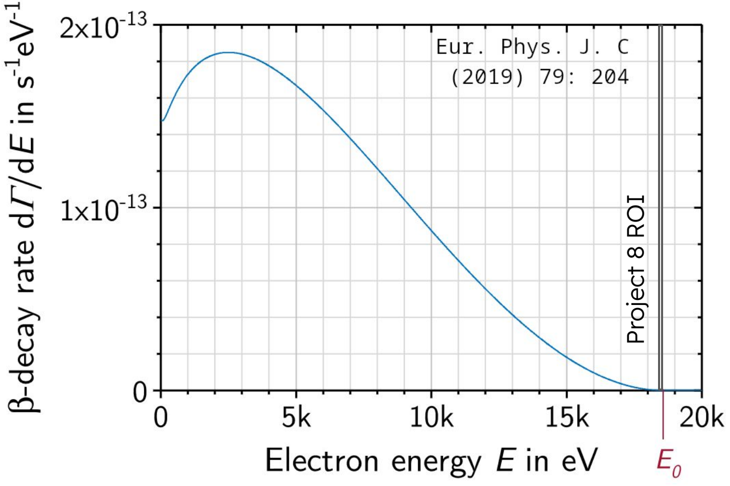
- Project 8: Non-destructive electron spectrometry
- Cavities:
  - Increase information gain through resonant amplification
  - allow axial frequency measurement
- Challenges:
  - Power decreases with lower frequency
  - High statistics require a well-prepared reconstruction
- Simulation:
  - Locust/Kassiopeia: Physics-wise gold standard, workhorse
  - Hopper: Developed for large simulation sets

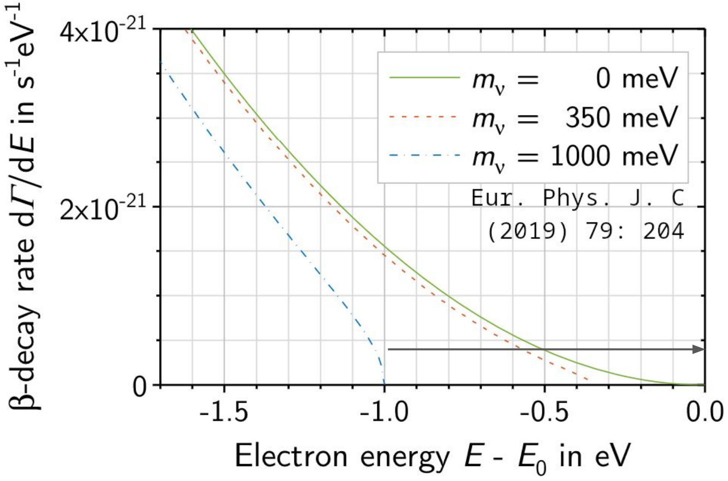
Thank you for your attention!
Questions?

Backup

Direct Neutrino Mass Measurements

Idea: Measure the electron energy spectrum from atomic Tritium beta decays





Distortion of the high energy tail is related to the neutrino mass

$$\left.\frac{dN}{dE}\right|_{\mathrm{End}} \sim (E - E_0)\sqrt{(E - E_0)^2 - m_\beta^2}$$

The PROJECT 8 Experiment

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21 Institutions, three countries, over 60 graduate- or higher researchers

Multi-stage experiment aiming to lower the experimental limit for m_β using atomic tritium

Tritium Beta Spectrum and Neutrino Mass Limit from Cyclotron Radiation Emission Spectroscopy

A. Ashtari Esfahani,[1,a] S. Böser,[2] N. Buzinsky,[3,b] M. C. Carmona-Benitez,[4] C. Claessens,[1,2] L. de Viveiros,[4] P. J. Doe,[1] M. Fertl,[2] J. A. Formaggio,[3] J. K. Gaison,[5] L. Gladstone,[6] M. Grando,[5] M. Guigue,[7] J. Hartse,[1] K. M. Heeger,[8] X. Huyan,[5,c] J. Johnston,[3] A. M. Jones,[5,d] K. Kazkaz,[9] B. H. LaRoque,[5] M. Li,[3] A. Lindman,[2] E. Machado,[1] A. Marsteller,[1] C. Matthé,[2] R. Mohiuddin,[6] B. Monreal,[6] R. Mueller,[4] J. A. Nikkel,[8] E. Novitski,[1,e] N. S. Oblath,[5] J. I. Peña,[3] W. Pettus,[10,f] R. Reimann,[2] R. G. H. Robertson,[1] D. Rosa De Jesús,[5] G. Rybka,[1] L. Saldaña,[8] M. Schram,[5,g] P. L. Slocum,[8] J. Stachurska,[3] Y.-H. Sun,[6] P. T. Surukuchi,[8] J. R. Tedeschi,[5] A. B. Telles,[8] F. Thomas,[2] M. Thomas,[5,h] L. A. Thorne,[2] T. Thümmler,[11] L. Tvrznikova,[9,i] W. Van De Pontseele,[3] B. A. VanDevender,[1,5] J. Weintroub,[12] T. E. Weiss,[8] T. Wendler,[4] A. Young,[12,j] E. Zayas,[3] and A. Ziegler[4]
(Project 8 Collaboration)

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[5] *Pacific Northwest National Laboratory, Richland, WA 99354, USA*
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[9] *Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
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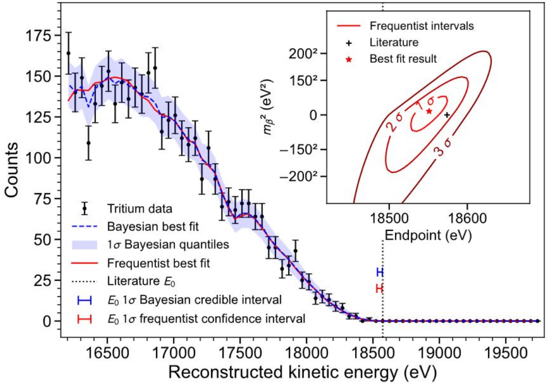
[11] *Institute of Astroparticle Physics, Karlsruhe Institute of Technology, 76021 Karlsruhe, Germany*
[12] *Center for Astrophysics | Harvard & Smithsonian, Cambridge, MA 02138, USA*
(Dated: March 20, 2023)



Phys. Rev. Lett. 131 (2023) 10, 102502

First two stages proved that:
- CRES works using antennas and waveguides
- upper neutrino limits can be extracted

Transition from Waveguides to Cavities

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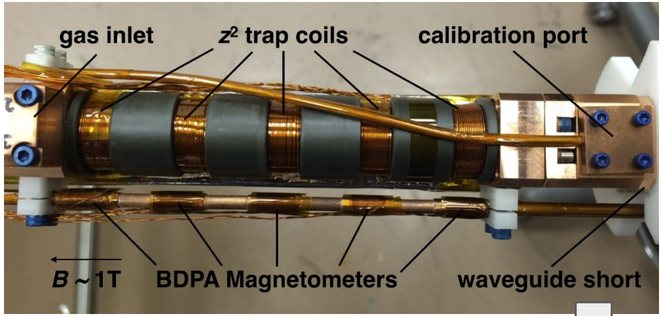
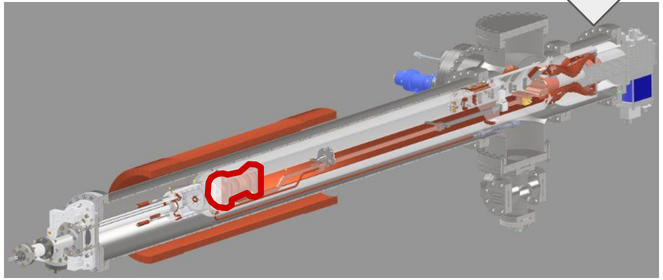


Project 8 Phase II Waveguide insert
(J. Phys. G 44 (2017) 5, 054004)



Project 8 Phase III Experimental Apparatus
(Credits: S. Kuenstner)

Phase 2 was executed in a WR-42 waveguide

Phase 3 involves a first resonant cavity read out by a waveguide

- Axial frequency reconstruction possible
- First use of cryogenic amplifiers

The Project 8 Phase III reconstruction (2nd approach)

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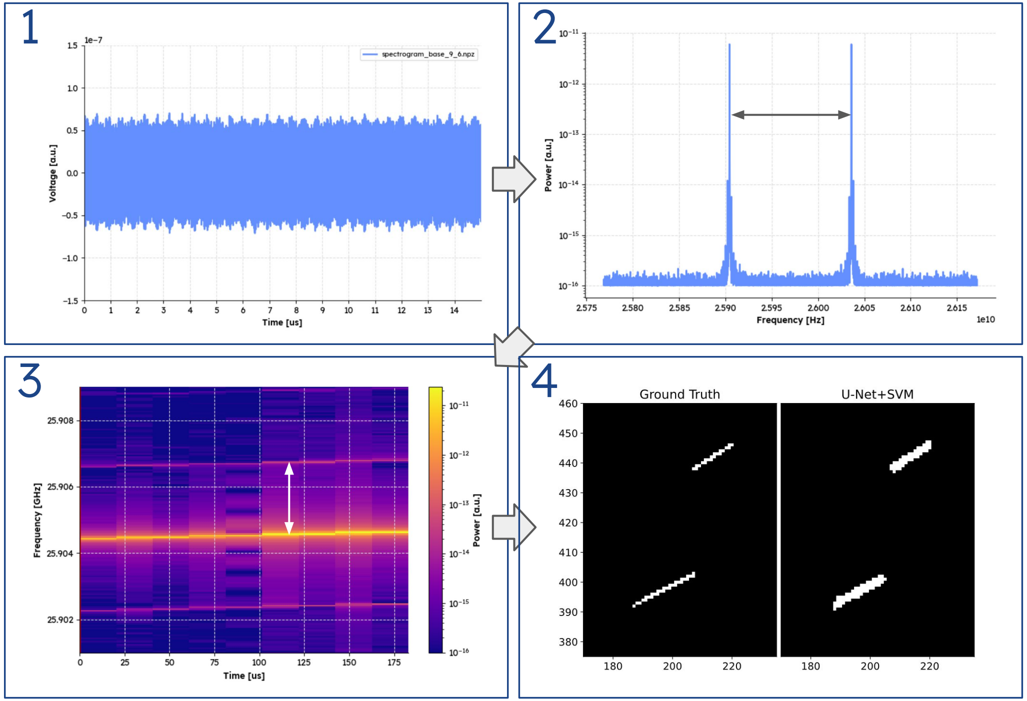
Voltage Timeseries

Spectrogram



Short-scale frequency spectrum

Map axial and cyclotron frequency to energy over machine learning (U-NET, GNN, SSM)

Mach. Learn. Sci. Tech. 5 (2024) 2, 025026

Back to reconstruction - Timeseries?

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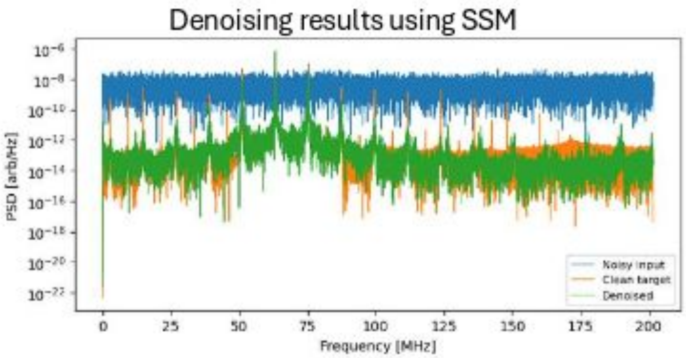
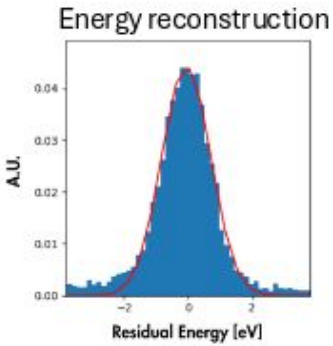
State **S**pace **M**odel (SSM):

- Machine-learning propelled time series reconstruction
- More dynamically usable than the current reconstruction
- Currently explored both in frequency and in pure time domain reconstruction



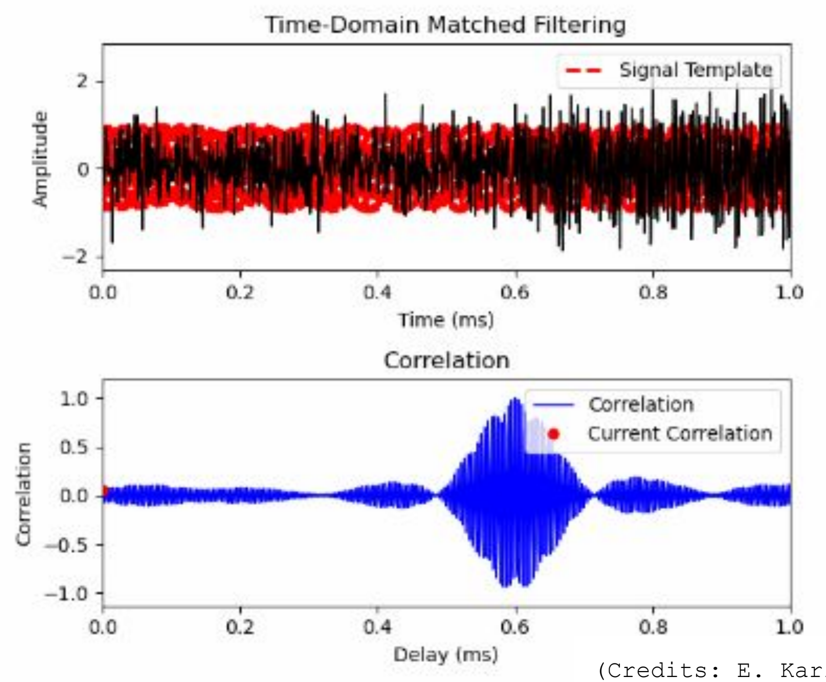


(Credits:
H. Binney,
C. Reissel,
L. Felipe Koehler Domingues)

Back to reconstruction - Timeseries?

Time domain matched filtering:

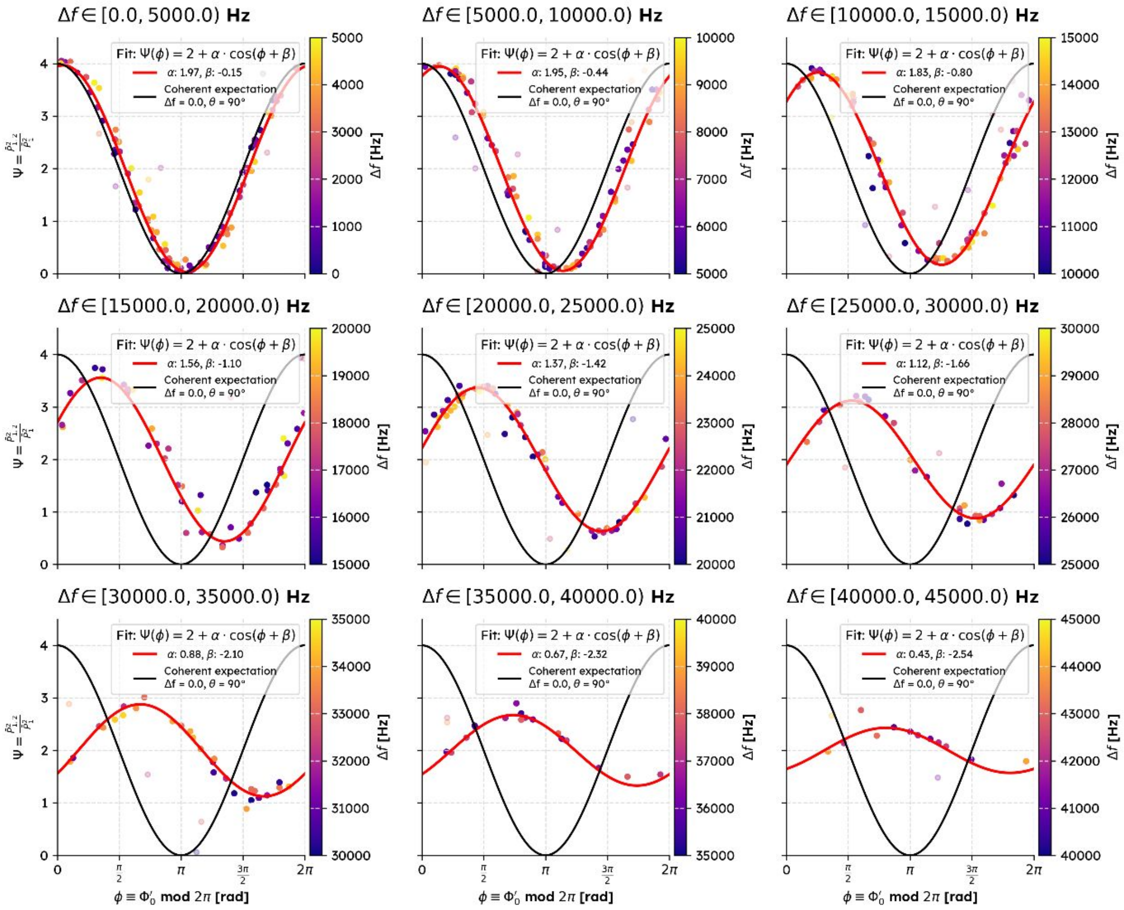
- Simulation-informed template fitting
- More conventional approach
- Computation power!



(Credits: E. Karim)

Disect sampled Locust simulations into Δf slices

- Power ratio curve shift chronically to the right
- loses coherent interference pattern



Modulation of Power ratio curves

$$P(t) \propto (s_1 + s_2)^2 = 2A^2\left[1 + \cos(\Delta\omega t + \varphi_0)\right]$$

$$\langle P \rangle = \frac{1}{T}\int_0^T P(t)dt$$

$$= 2A^2\left[1 + \frac{1}{\Delta\omega T}\left(\sin(\Delta\omega t T + \varphi_0) - \sin(\varphi_0)\right)\right]$$

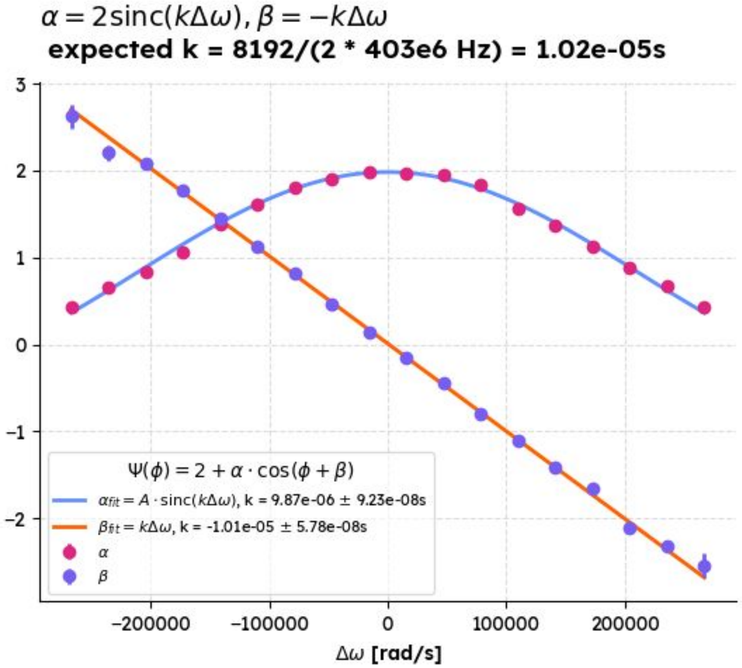
using $\sin(x+y) - \sin(x) = 2\cos(x + y/2)\sin(y/2)$, we find

$$\langle P \rangle = 2A^2\left[1 + \frac{2}{\Delta\omega T}\left(\cos\left(\varphi_0 + \Delta\omega T/2\right)\sin(\Delta\omega T/2)\right)\right]$$

$$= 2A^2\left[1 + \frac{\sin(\Delta\omega T/2)}{\Delta\omega T/2}\cos\left(\varphi_0 + \frac{\Delta\omega T}{2}\right)\right]$$

Dividing that by the average power of one particle, $\langle P_1 \rangle = A^2$, the ratio of the average powers Ψ may sufficiently be simplified to

$$\Psi = 2 + 2\alpha\cos\left(\varphi_0 + \beta\right) \qquad \text{with } \alpha = \mathrm{sinc}(\Delta\omega T/2),\ \beta = \Delta\omega T/2$$



From pairwise power modulation to a distribution

$$S(t) = \sum_i a(\omega_i) e^{i(\omega_i t + \varphi_i)}$$

$$P(\omega) = |\mathcal{F}\{S(t)\}_T|^2$$

Spectrogram FFT

$$= \left| \int_0^T dt \sum_i a(\omega_i) e^{i(\omega_i - \omega)t} e^{i\varphi_i} \right|^2$$

$$= \left| \sum_i a(\omega_i) \operatorname{sinc}\left(\frac{(\omega - \omega_i)T}{2} \right) e^{i\left(\varphi_i + (\omega_i - \omega)\frac{T}{2}\right)} \right|^2$$