PROJECT 8

Simulation Approaches in the Project 8 Experiment

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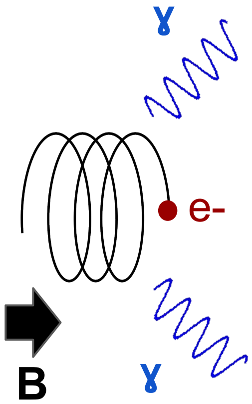
PTOLEMY Collaboration Meeting
Princeton University, Nov. 6-7, 2023

Wright Laboratory

Yale

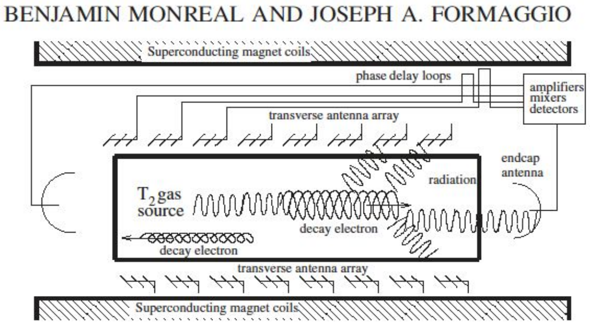
CRES and Project 8



CRES: Cyclotron Radiation Emission Spectroscopy.

A new type of spectroscopy proposed by Monreal and Formaggio (PRD 80 (2009) 051301). Nondestructive to electrons trapped magnetically.

Using derived f_{cyc} as a proxy for energy, $f_{cyc} = eB / 2\pi\gamma m_e$, Project 8 aims to constrain neutrino mass m_β to within 40 meV.

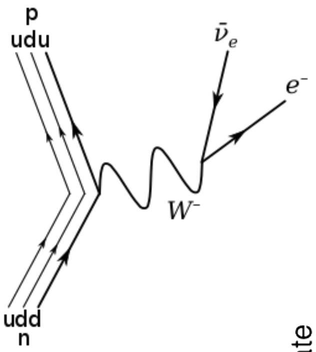


Subset of Project 8 collaborators at the recent Cavity Workshop, held at Great Camp Sagamore, NY. Full list of collaborators: www.project8.org .

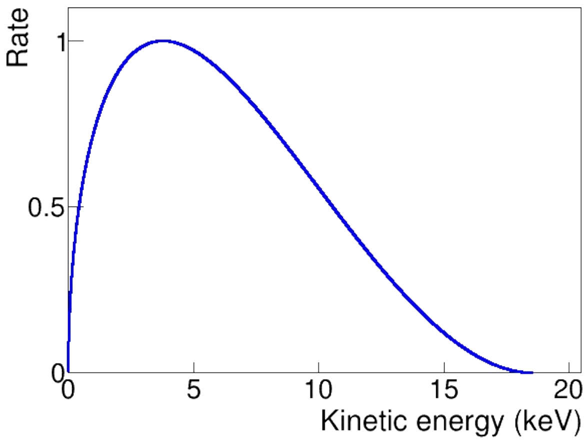
Tritium beta decay and m_β

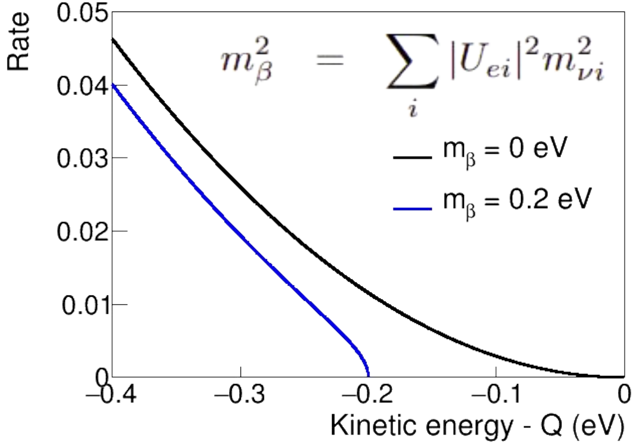
$$^3H \rightarrow {}^3He + \beta^- + \bar{\nu}_e$$

$$(1/2^+) \rightarrow (1/2^+)$$



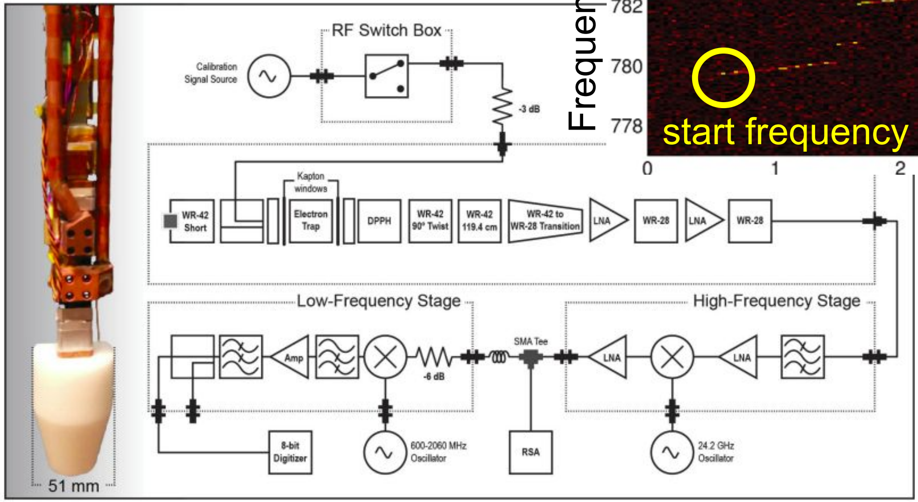
- Allowed Fermi decay, Q = 18.6 keV
- β- spectrum, E_{max} = 18.6 keV
- Distortion near E_{max} is defined by $^3H_2$ kinematic excitation and by m_β. See Bodine, Parno, Robertson PRC 91, 035505 (2015).
- Present state of the art in direct measurement is $m_\beta \leq 0.8$ eV/c^2 by KATRIN, Aker et al. (KATRIN) Nat. Phys. 18 160-166 (2022).

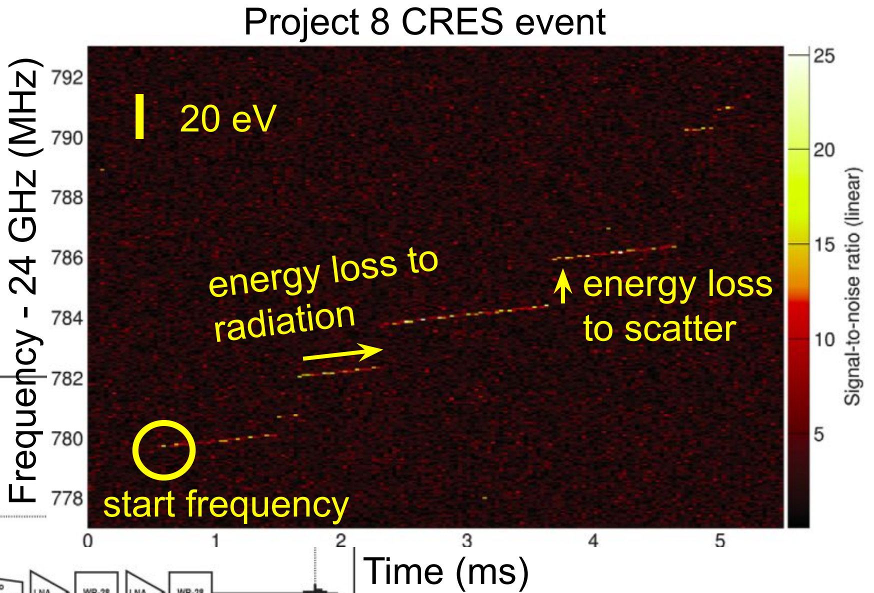




CRES data in Project 8

- First demonstrated in 2015 (PRL 114 (2015) 162501).
- 30 keV conversion electrons from a gaseous ^{83m}Kr source.
- Heterodyne detection, FFT in signal processing leads to raw spectrogram in frequency and time.





Simulation objectives

- Simulate and study CRES experiment designs.
- Simulate present and future Project 8 demonstrators, validate with data as it becomes available, and understand volume scaling relations.
- Study and anticipate systematics in CRES experiments.
- Support offline physics analysis.
  - Configurable data sets
  - Parameter studies
  - Validation work
  - End to end analyses
- Aim for compatibility with existing tools, in simulation/analysis and in coordinated infrastructure upgrades.

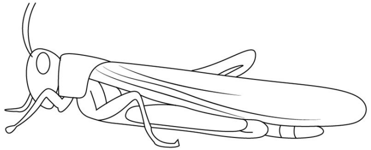
Simulation resources in Project 8

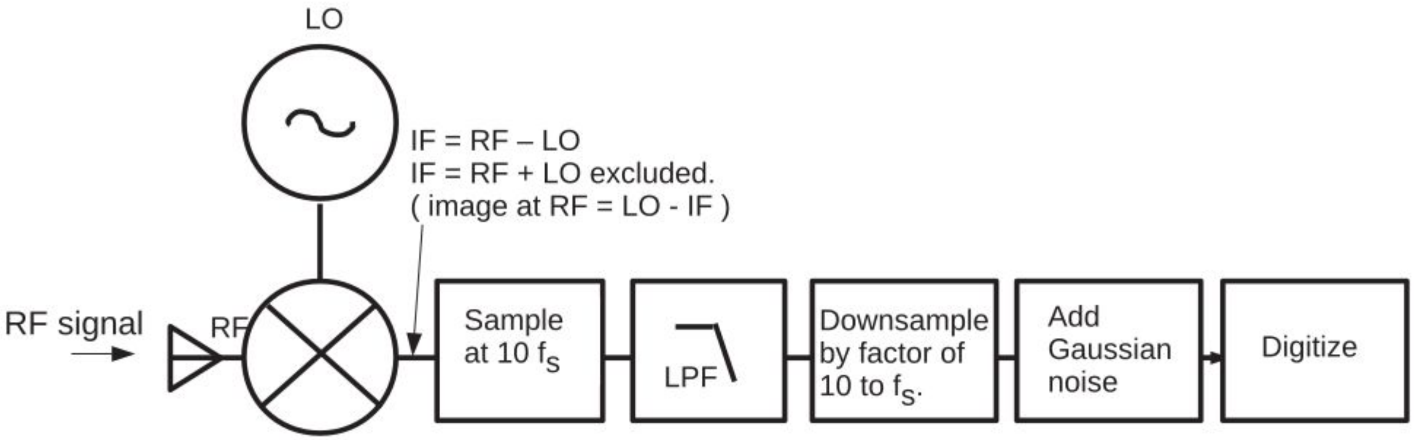
- Commercial and other publicly available simulation packages
  - Can efficiently address targeted technical questions in Project 8.
  - Several packages are in routine use: HFSS, Comsol, Scikit-RF, CST.
  - ATD simulation work: Sparta, Molflow+, Comsol, CST, Kassiopeia.
- Custom simulation software, integrated with Project 8 tools
  - Necessary to address questions unique to the experiment.
  - Developed and/or integrated within Project 8.
    - Locust* RF signal calculations driven with theoretical models
    - Kassiopeia** field and trajectory calculations, integrated with Locust
- Theoretical models
  - Critical for our understanding.
  - Can be developed independently, or integrated with other calculations.

*Project 8, 2019 New J. Phys. 21 113051, **Furse et al., 2017 New J. Phys. 19 053012

Locust* simulation software

- Developed in C++ within Project 8.
- Integrated with Project 8 DAQ libraries.
- Functionality models an RF receiver and digitizer.
- Interfaces are modular and flexible to allow for arbitrary input signals.

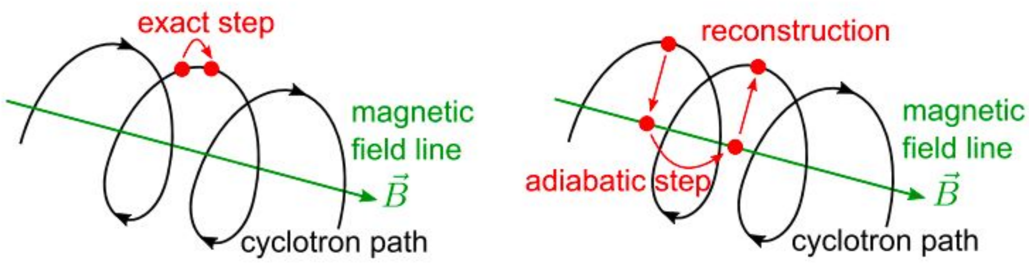




*Project 8, New J. Phys. 21 113051

Kassiopeia* simulation software

- Developed by the KATRIN collaboration.
- Highly advanced calculations of electron trajectories and energy losses in EM fields.
- Adaptable EM field solutions with configurable source geometries.
- Modular and flexible; C++ based code.

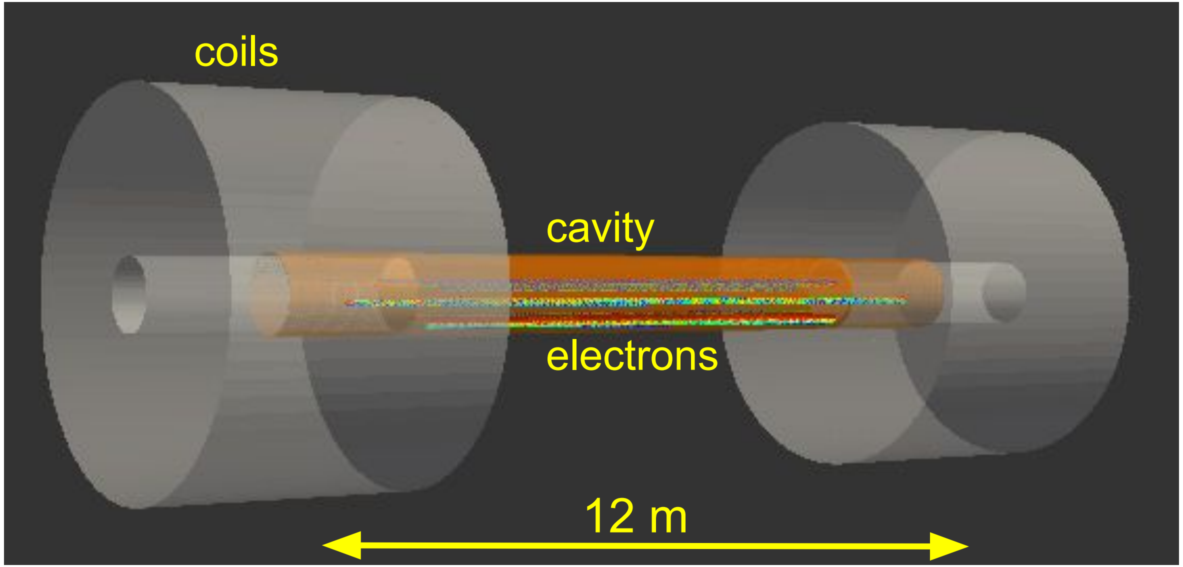


(a) Exact trajectory (b) Adiabatic trajectory

*Furse et al., 2017 New J. Phys. 19 053012

Kassiopeia example

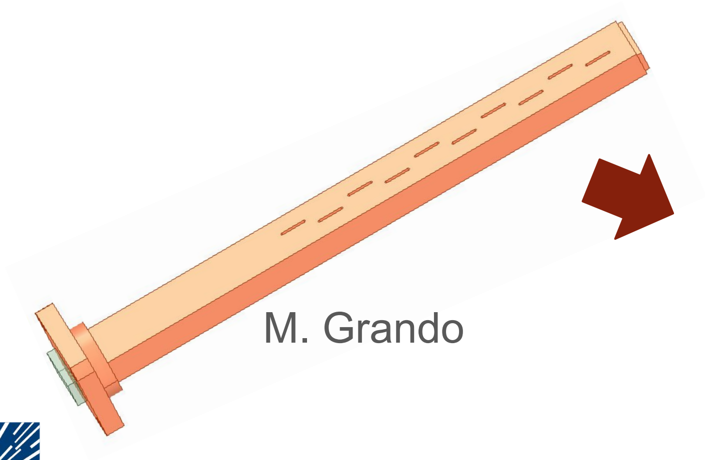
- 325 MHz trap for T2 endpoint experiment.
- Resonant cavity is shown with diameter 1.12 m.
- 5 electron trajectories are calculated inside the cavity.



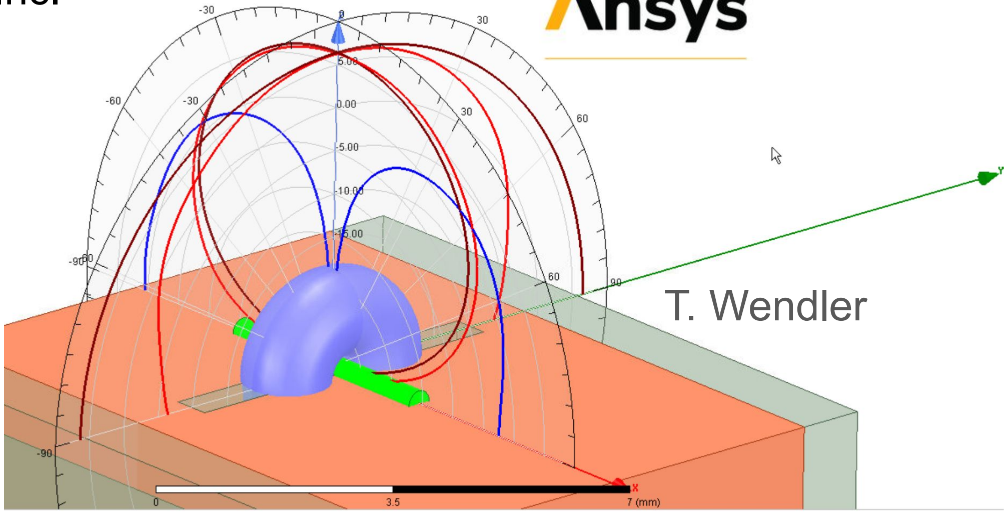
Furse et al., 2017 New J. Phys. 19 053012

High Frequency Simulation Software (HFSS)

- Highly advanced, industry-standard finite element method solver for EM structures.
- Commercially developed by Ansys, Inc.



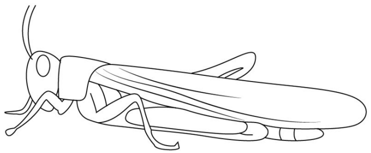
M. Grando



T. Wendler

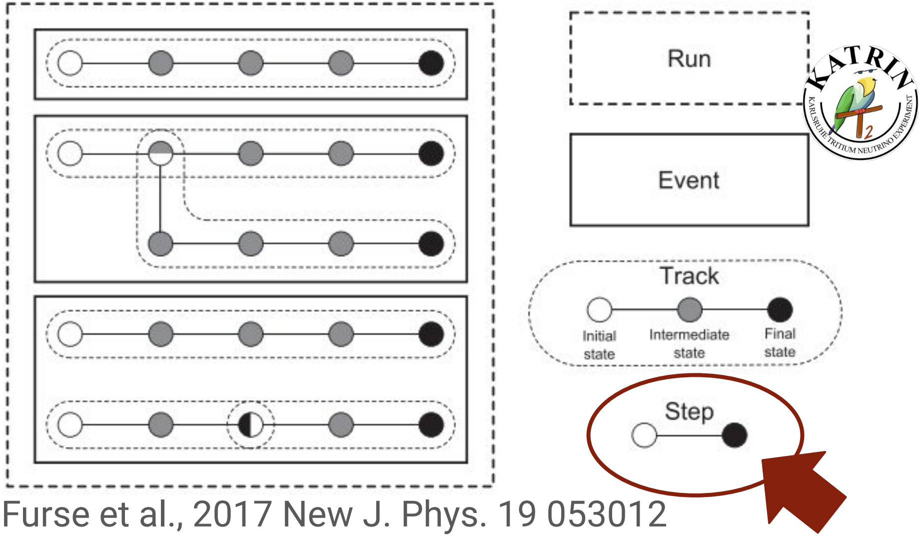
Integrating software packages (carefully)

- Challenge: We have multiple highly refined calculations (e.g. theory, Kassiopeia, and HFSS), each developed separately, and each representing years of scientific and technical development by world-leading experts.
- To combine these advanced calculations nondestructively, we need to consider the interfaces between them.
- Locust is well-suited for this purpose - flexibility allows for careful software integration with minimal loss of information.



Locust-Kassiopeia interface

- Modularity in both Locust and Kassiopeia supports tight integration of Locust-Kassiopeia in the time domain.
- Cross-package communication happens after each trajectory step in Kassiopeia.



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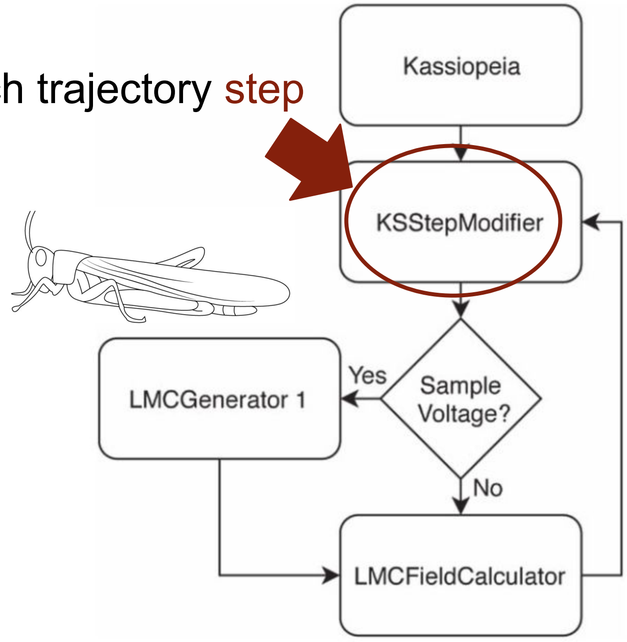
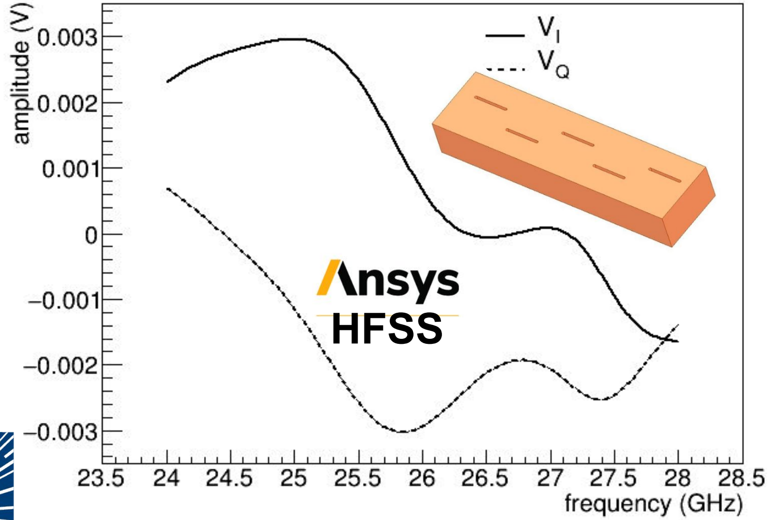
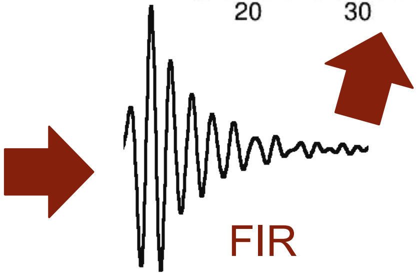


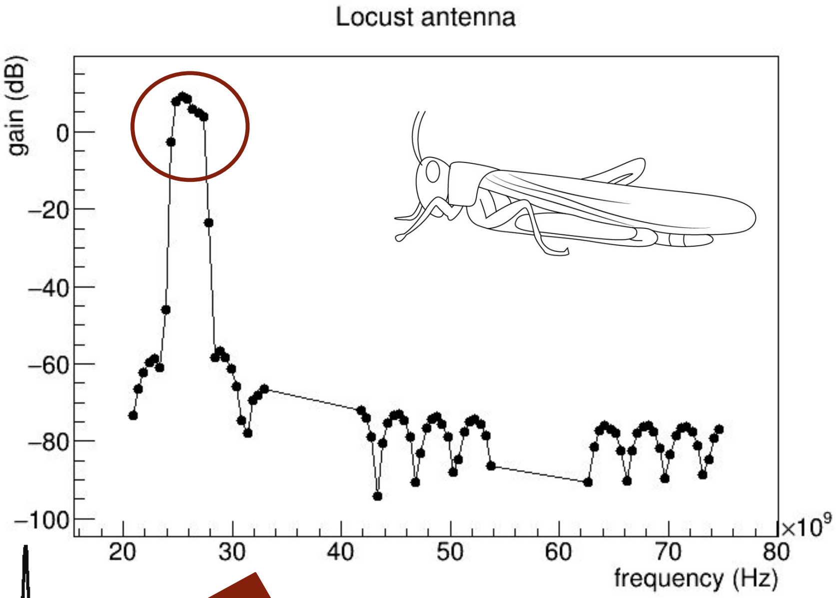
Project 8, 2019 New J. Phys. 21 113051

Locust-HFSS interface

- Interface relies on Linear Time-Invariant (LTI) system theory.
- LTI antenna model is configured in HFSS.
- Locust EM fields drive the LTI antenna FIR.

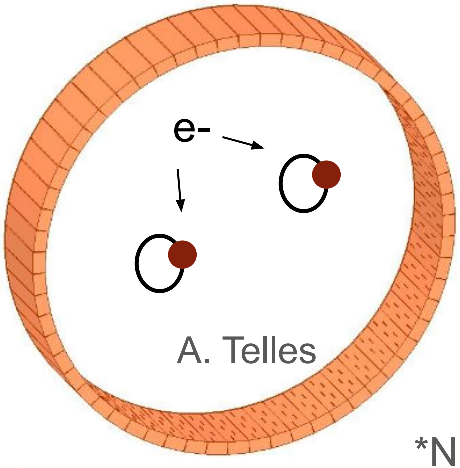


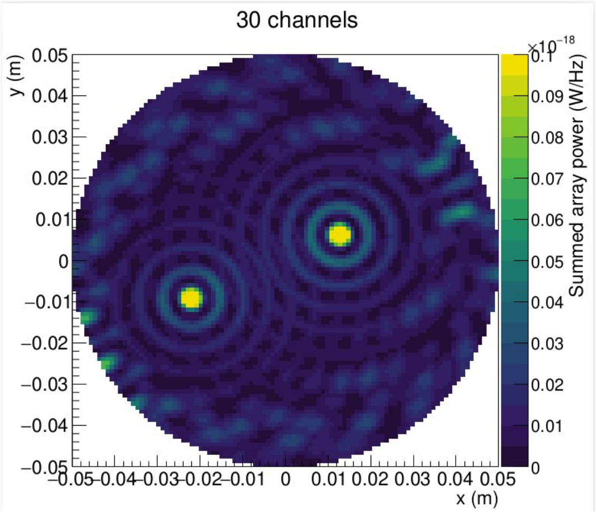




Kassiopeia-Locust-HFSS combined

- Time-dependent Locust-Kassiopeia EM fields* drive the HFSS hardware model and receiver.
- Accurate complex voltage signals are extracted for reconstruction.
- Reconstructed signals provide both cross checks and design diagnostics.





Reconstructed signals

*N. Buzinsky, Ph.D. dissertation, MIT.

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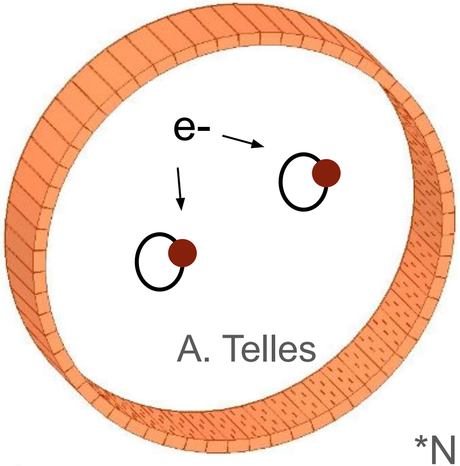

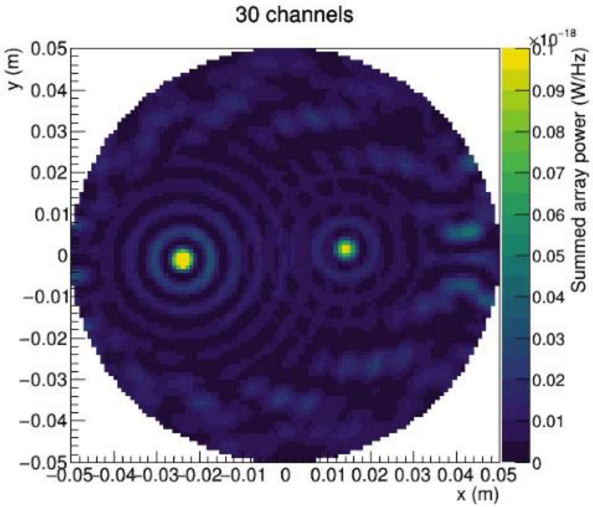

Reconstructed signals

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Locust and analytic calculations

- Analytic EM models* can also drive the software receiver in Locust.
- Or, discrete steps in analytic models can also be implemented as components in larger workflows. Example: The single-mode cavity response model by H. Robertson and A. Marsteller:
  - Kassiopeia e- current acts as an impulse that drives a Green's function in Locust.
  - The Green's function is derived from a damped harmonic oscillator.
  - The Locust-Kassiopeia interface is preserved.

Kass e- current & coupling

$$A(t) = \sum_n f(nT, z, v_z) G(t, nT),$$

$$= \sum_n A_0 \sin\left(\omega_c\left(nT + \left|\frac{z}{v_p}\right|\right) + \varphi\right) \cos\left(\frac{\pi}{L} z\right) J_1\left(X'_{01}\frac{r}{r_C}\right)$$

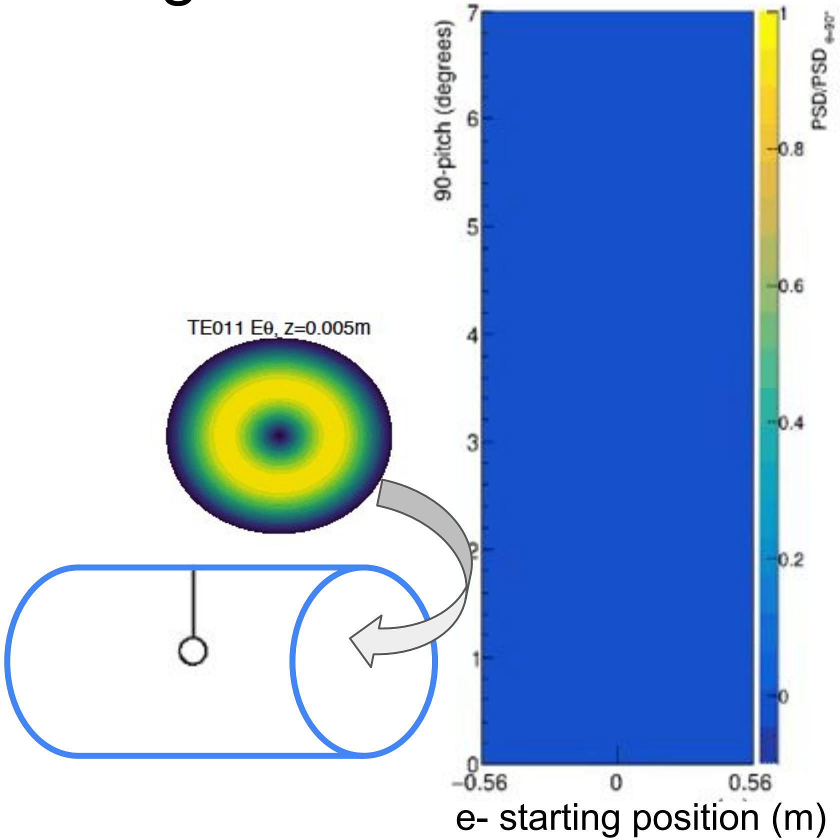
$$\Theta(nT - t) e^{-\xi\omega_C(nT-t)} \frac{\sin\left(\omega'(nT - t)\right)}{\omega'},$$

Complex discrete Green's function in Locust

*Project 8, arXiv:2303.12055

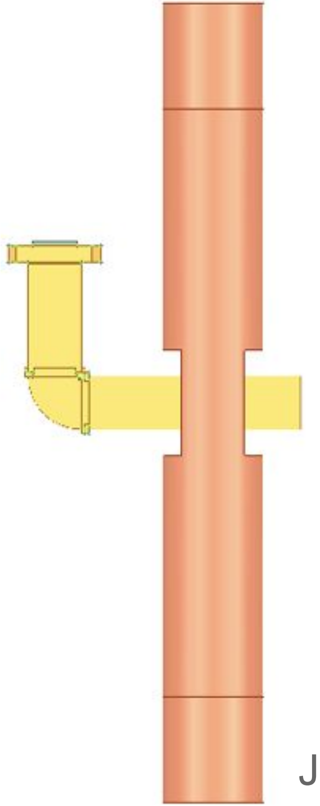
Resonant cavity simulation for testing

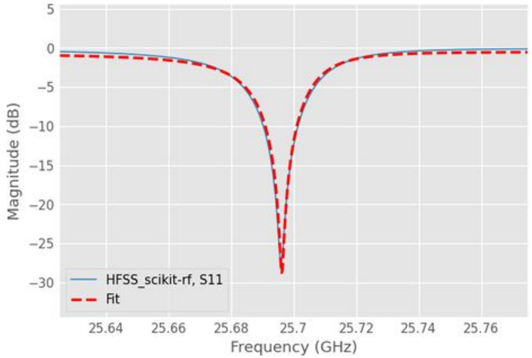
- 325 MHz single-mode TE011 cavity simulation workflow. 2D set of 18574.01 eV e- simulations in pitch angle θ and starting radial position.
- Abstract readout configuration test is shown with distortion-free probe.
- Power in azimuthal E-field scales as $J'_0(k_{01}r)$ as expected.
- Higher resolution scans in e.g. energy, θ are ongoing.

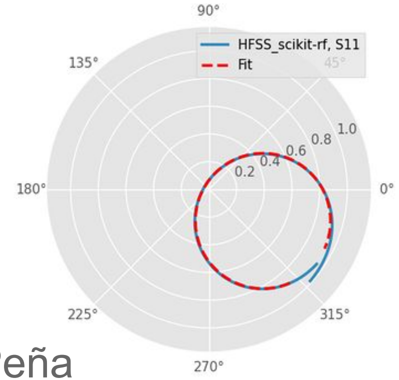


Locust-HFSS in realistic cavity designs

- More realistic readout configurations can be simulated in HFSS, SciKit-RF.
- Complex wave impedance can be exported and defined in Locust.
- Expected outcome: A more realistic simulated cavity response.
- Existing LTI framework in Locust would support this test.



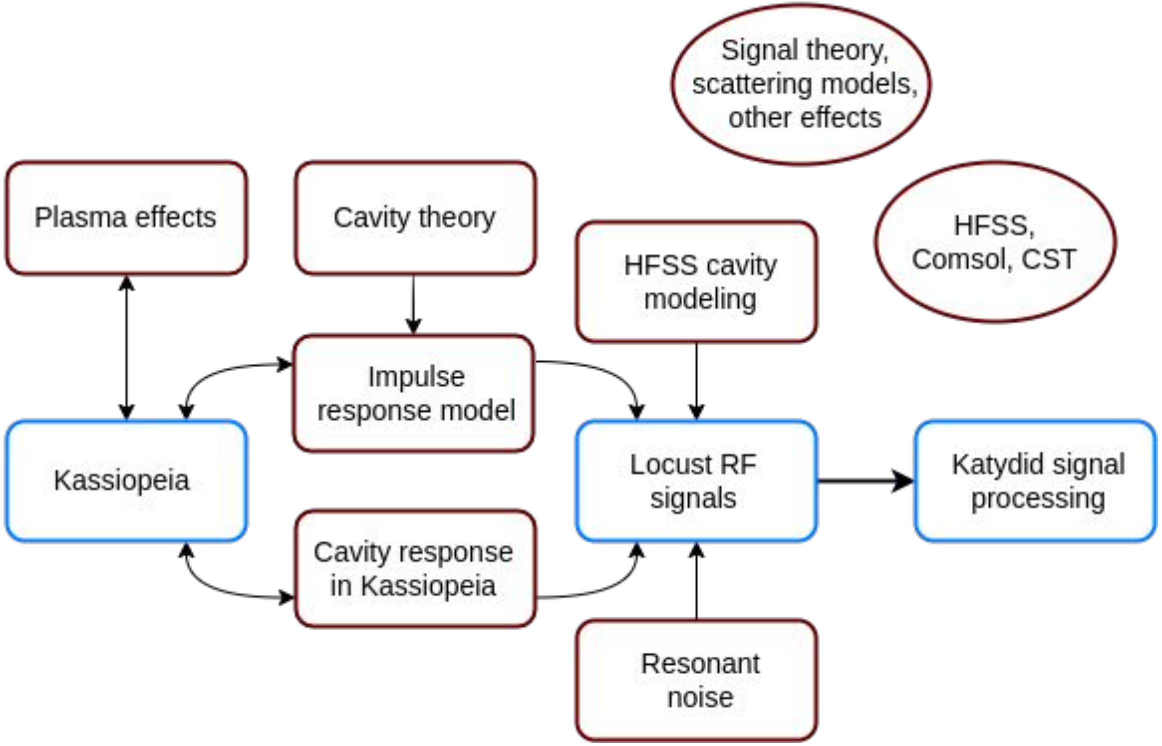




J. Peña

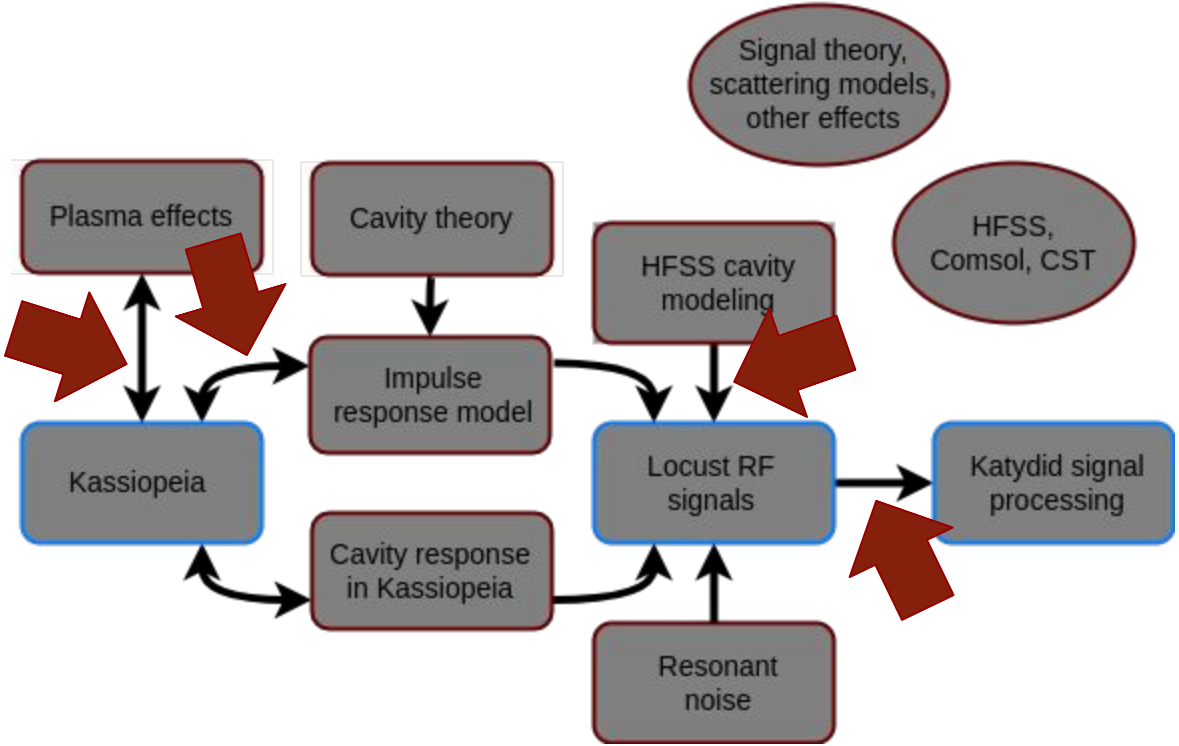
Multiple simulation paths

- Modular approach allows cross checks.
- Systematic effects can be isolated and studied.
- Multiple paths can be explored.
  - Sets of modules
  - Theory + DAQ



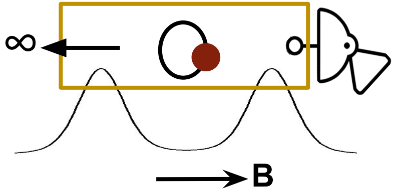
Simulation interfaces

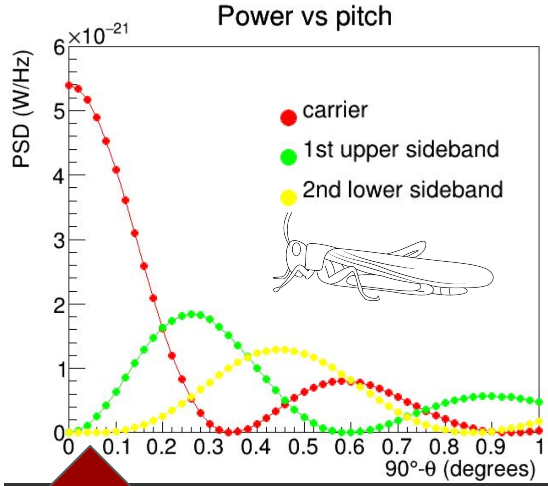
- Targeted development happens at the interfaces between packages.
- This preserves the fidelity of advanced calculations contained within each package.
- Alternate approaches (e.g. without integrating software packages) can also be useful, depending on goals.

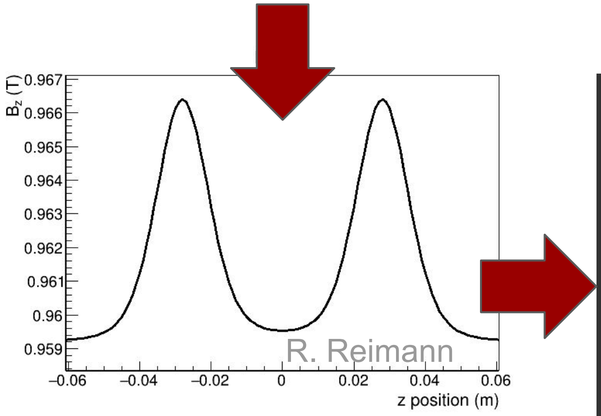


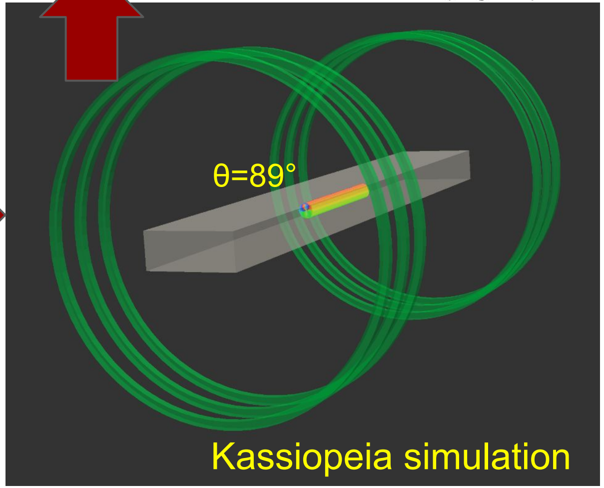
Example workflow

- 25.9 GHz cyclotron frequency
- Using Locust-Kassiopeia, calculate RF signals expected from magnetically trapped electron in waveguide. Process with Katydid analysis software.
- Discuss/validate; e.g. these results are consistent with predictions in PRC 99 (2019) no.5, 055501.



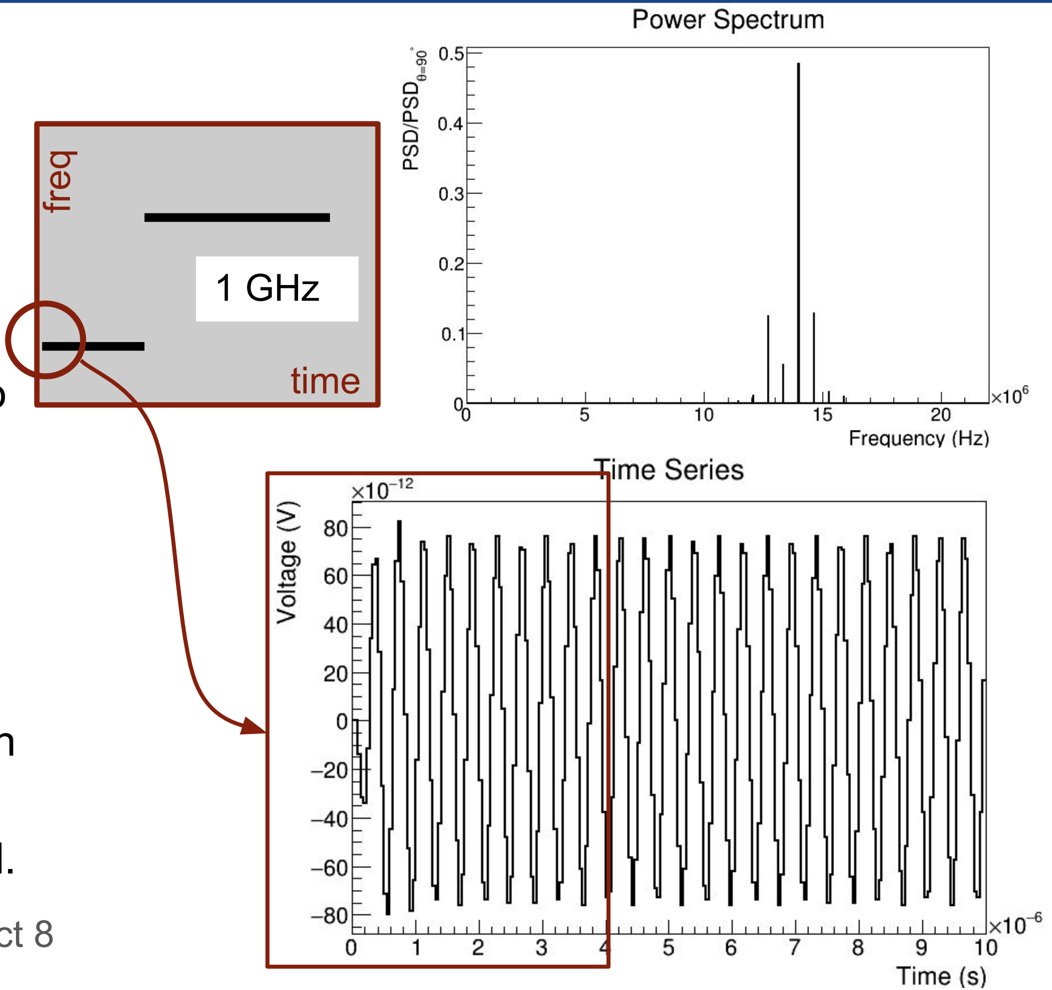






Simulated cavity signals

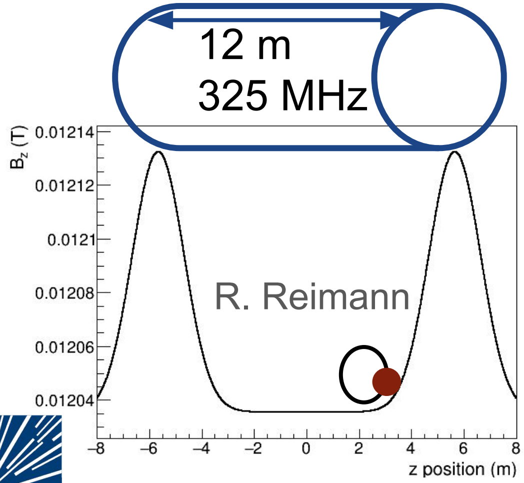
- Output format in a time series, compatible with our analysis tools.
- Cavity transient time is predicted* to be $2Q/\omega_C$ and characterizes the "ring-up" of the signal.
- Example: For a 1 GHz cavity with Q=1000, $2Q/\omega_C \sim 0.3$ μs.
- In post-processing, a typical time bin spans ~ 4 μs, which confines the signal ring-up to the first signal pixel.

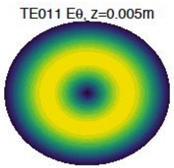


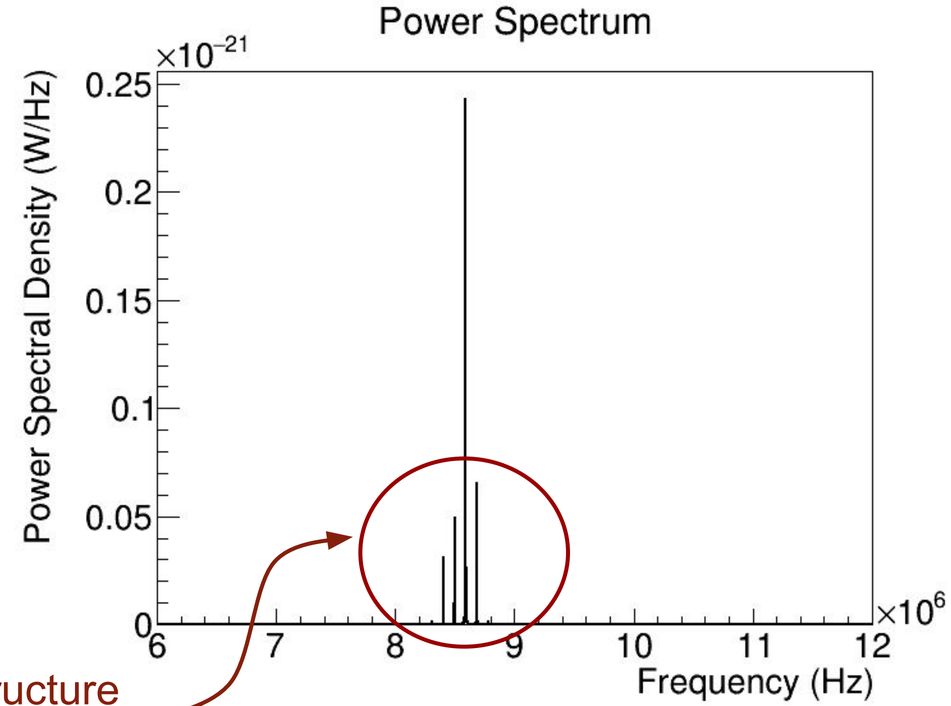
*H. Robertson and A. Marsteller, "Project 8 Kassiopeia Cavity calculations"

Noise considerations

- Simulation without noise allows visibility of signal modulation features.
- Optionally, add noise for testing signal recovery strategies.



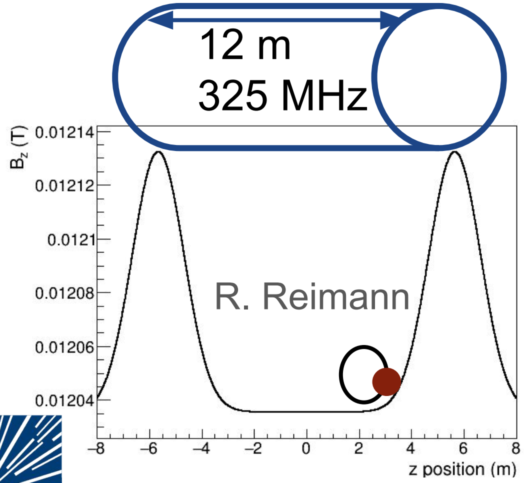


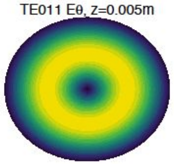


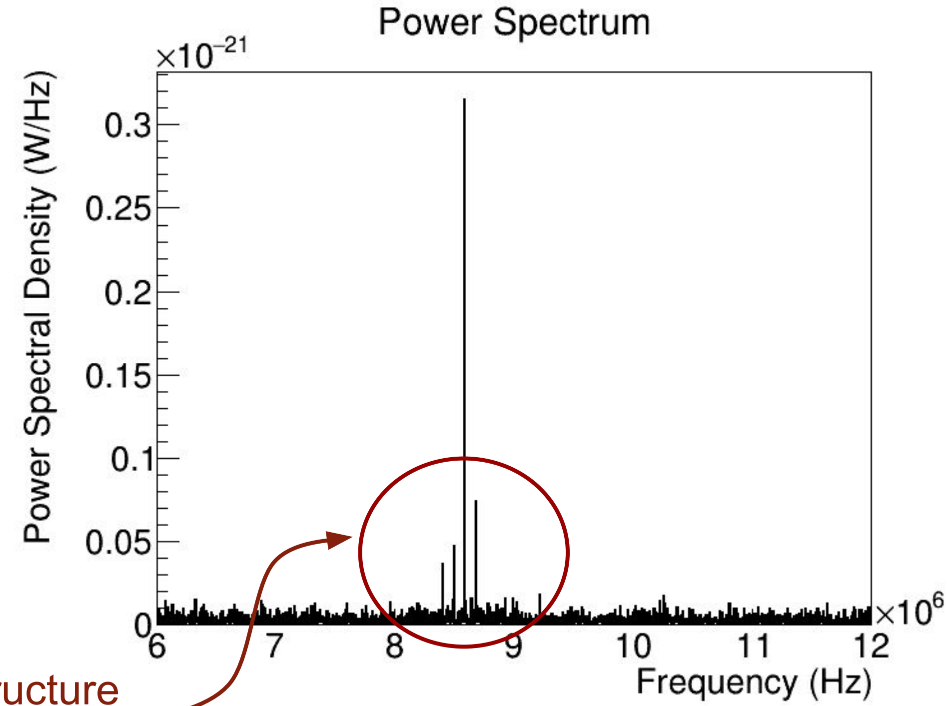
Signal structure is seen.

Noise considerations

- With low noise, signal features are still visible.
- SNR ~ 100.



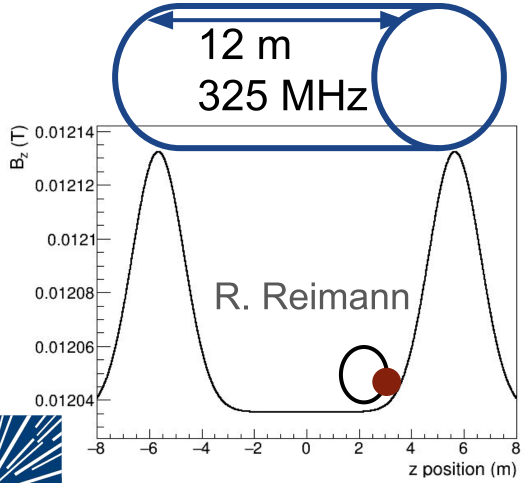


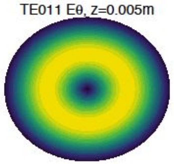


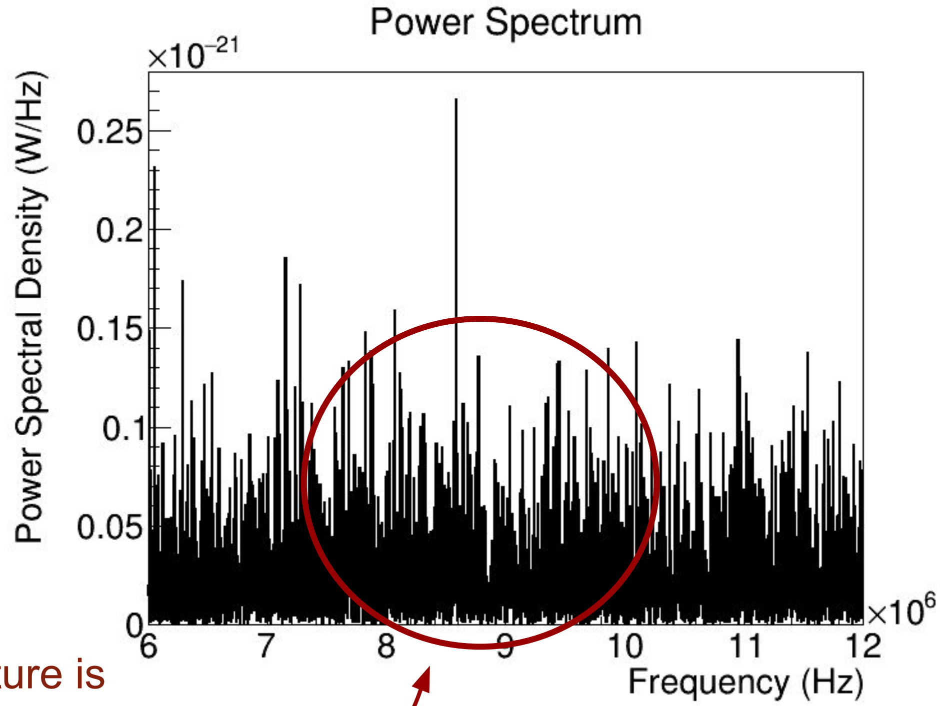
Signal structure is still seen.

Noise considerations

- Signal features are becoming somewhat less visible.
- SNR ~ 10.



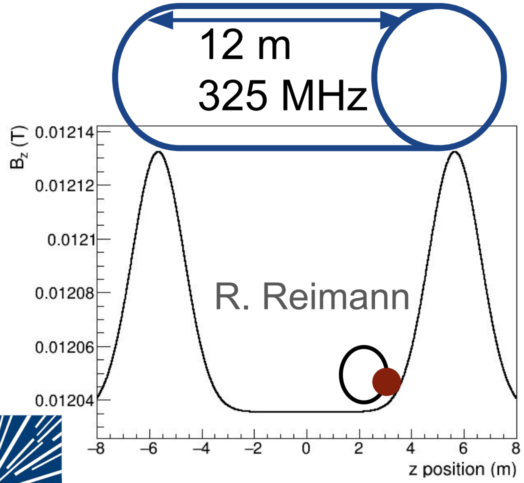


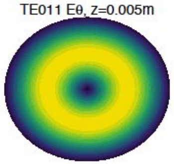


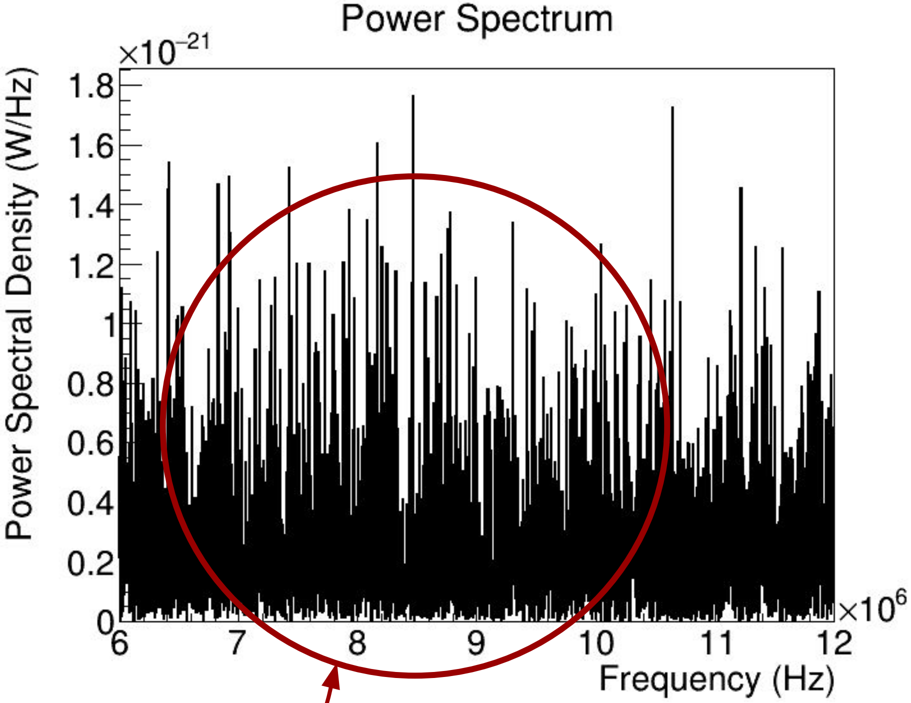
Signal structure is present, but harder to resolve.

Noise considerations

- Signal features look similar to noise, further motivating algorithmic reconstruction testing.
- SNR ~ 1.





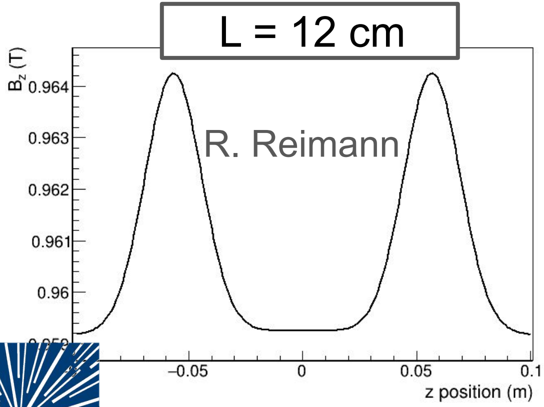


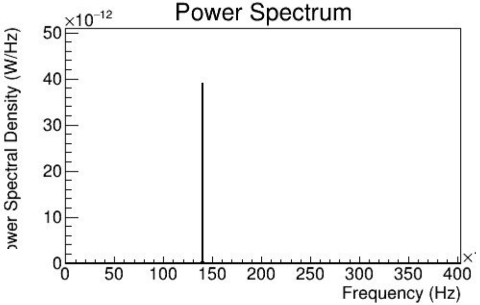
Signal recovery to be studied in offline testing.

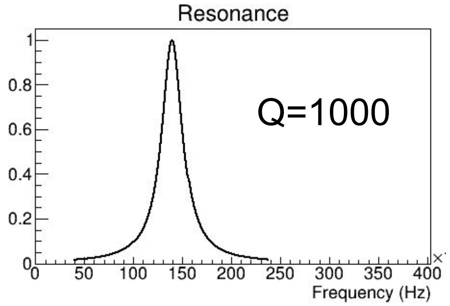
25.9 GHz cavity workflow

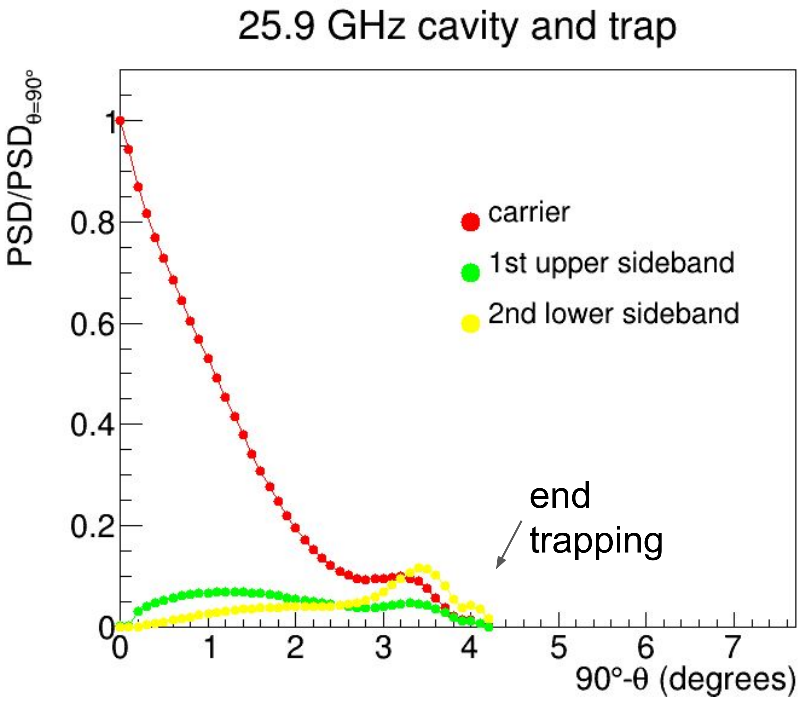
Parameterized inputs:

- Cavity frequency = 25.9 GHz
- Cavity Q = 1000
- L = 12 cm, R = 7 mm







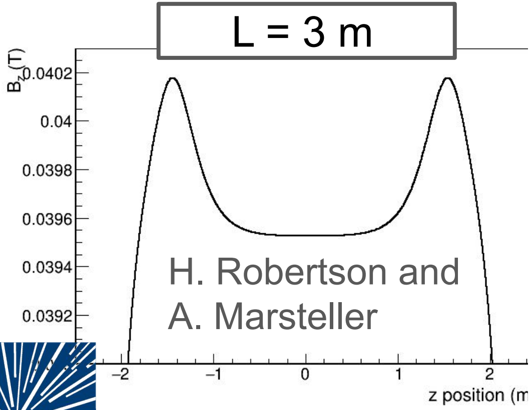


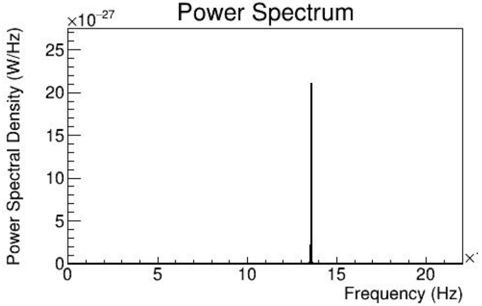
P. L. Slocum, PTOLEMY Collaboration Meeting, Nov. 6-7, 2023

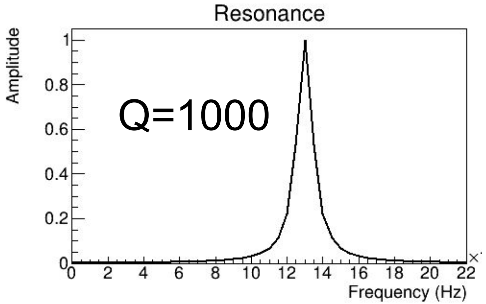
1 GHz cavity workflow

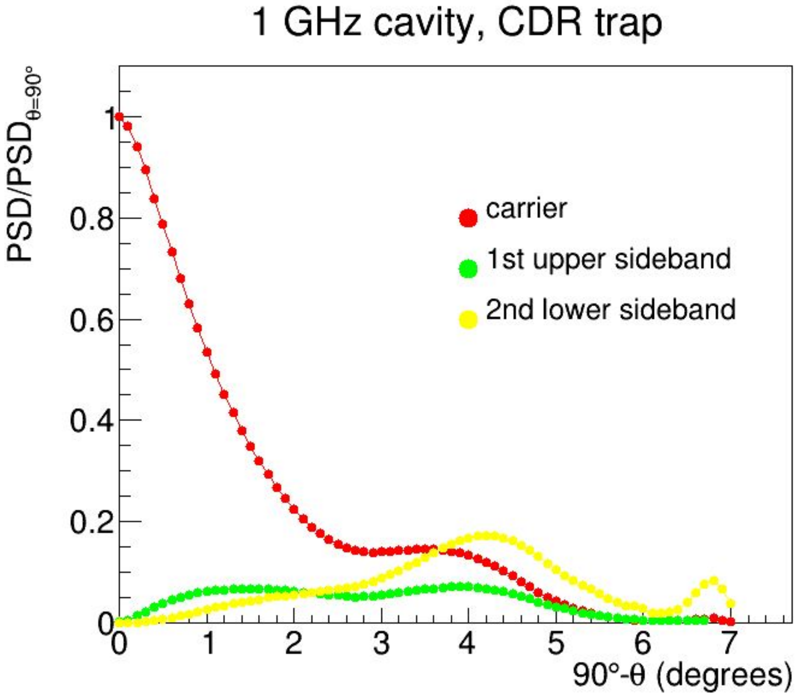
Parameterized inputs:

- Cavity frequency = 1.067 GHz
- Cavity Q = 1000
- L = 3 m, R = 18 cm





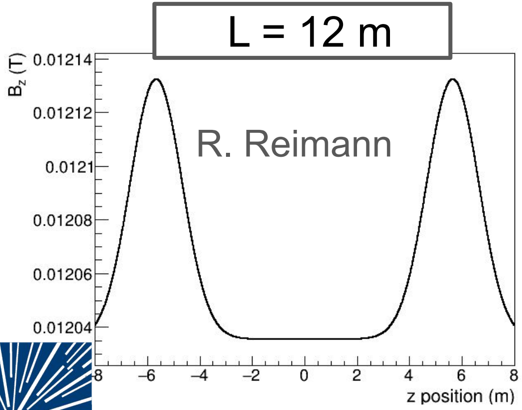


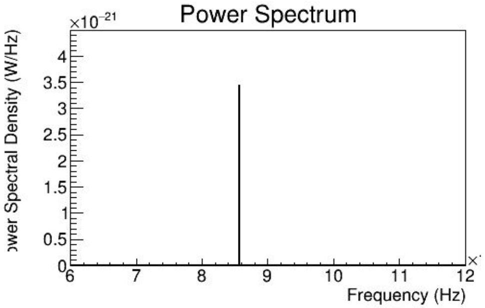


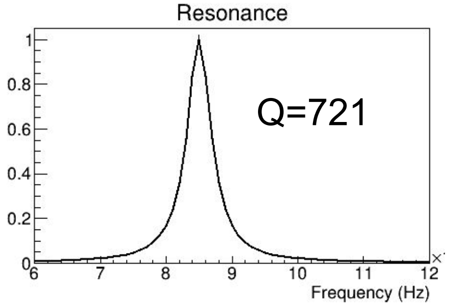
325 MHz cavity workflow

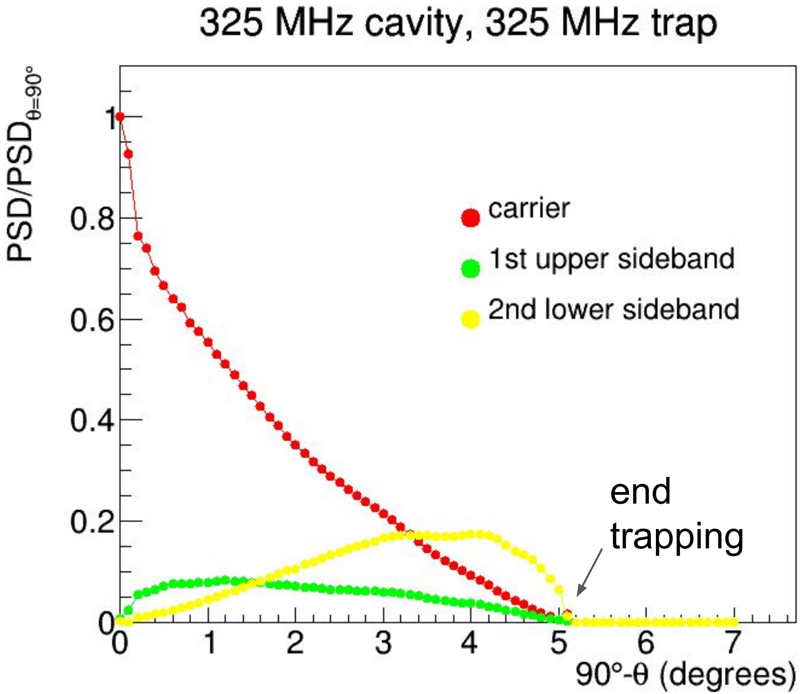
Parameterized inputs:

- Cavity frequency = 325 MHz
- Cavity Q = 721
- L = 12 m, R = 0.56 m





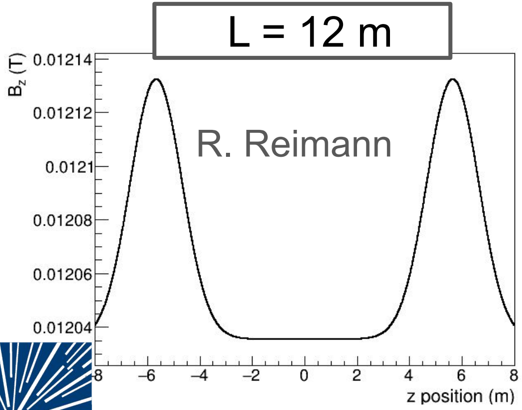


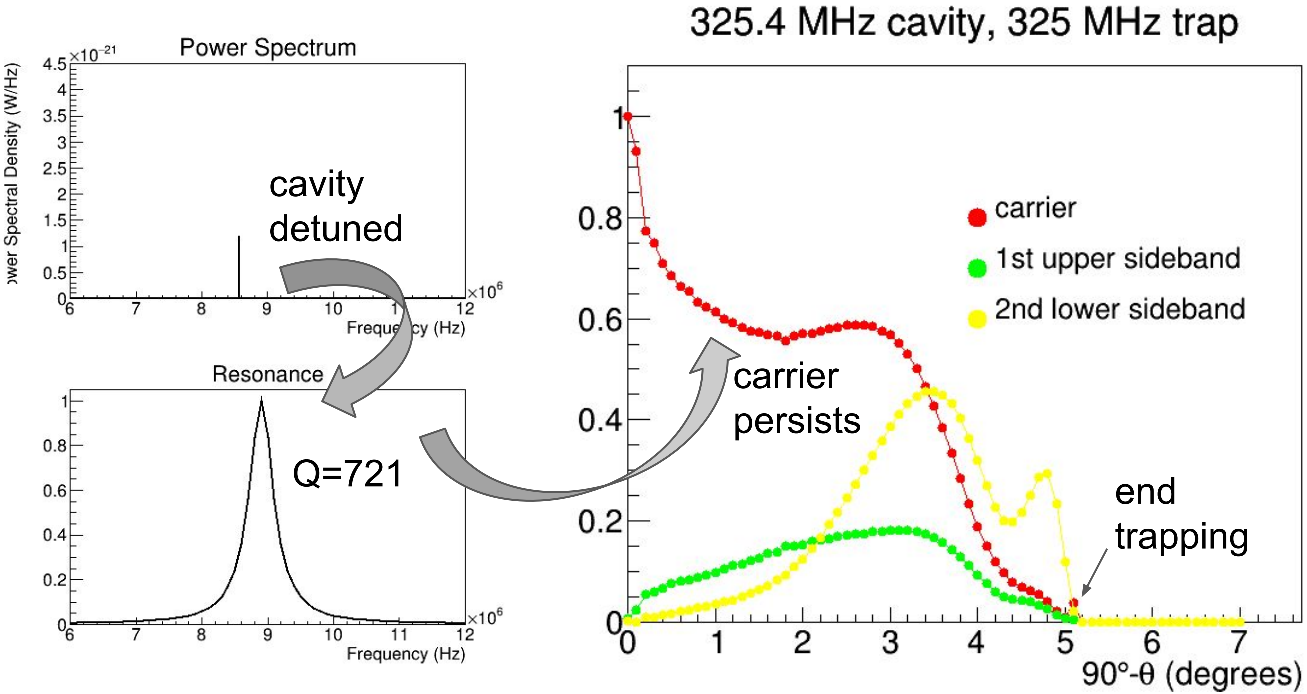


325 MHz cavity workflow

Parameterized inputs:

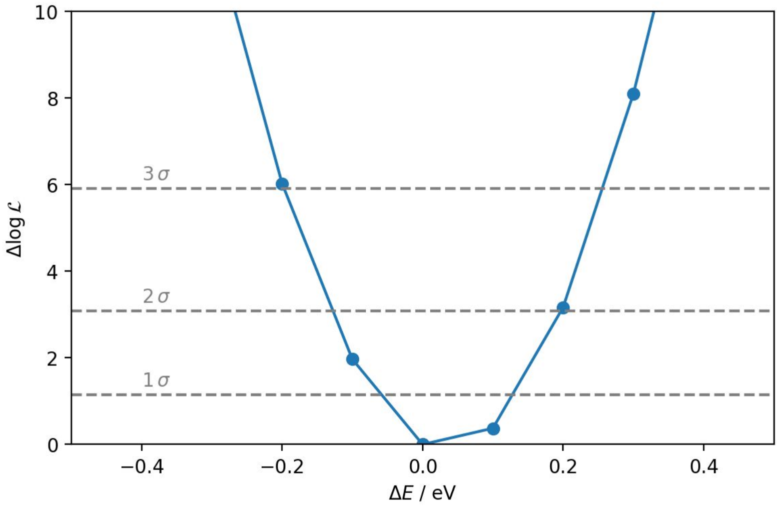
- Cavity frequency = 325.4 MHz
- Cavity Q = 721
- L = 12 m, R = 0.56 m

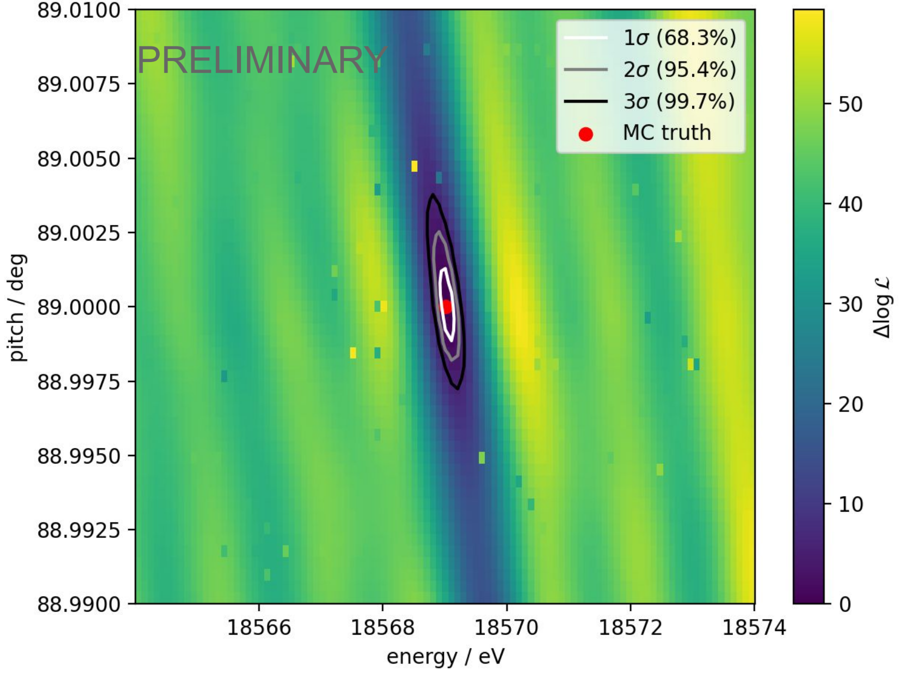




325 MHz cavity energy reconstruction

- Each pixel represents one simulation with SNR>10.
- Maximum likelihood estimator applied to simulation output.
- With optimistic assumptions, good energy resolution is seen. Work is ongoing.





Summary

- Project 8 relies on a suite of simulation tools. Our compact technical questions can often be answered with commercial software. Other unique questions have motivated software approaches that have been developed internally.
- Demonstrator experiments in Project 8 have been built into simulation workflows.
- Development and integration work is ongoing:
  - Collaboration with KATRIN on Kassiopeia development.
  - Integration of plasma effects* into our simulation framework.
- Software repositories are publicly available at github.com/project8/locust_mc and github.com/KATRIN-Experiment/Kassiopeia .

*Kellerer and Spanier 2022 JINST 17 P06029