Locust Simulation Tutorial: RF Signal Generation from Trapped Charged Particles

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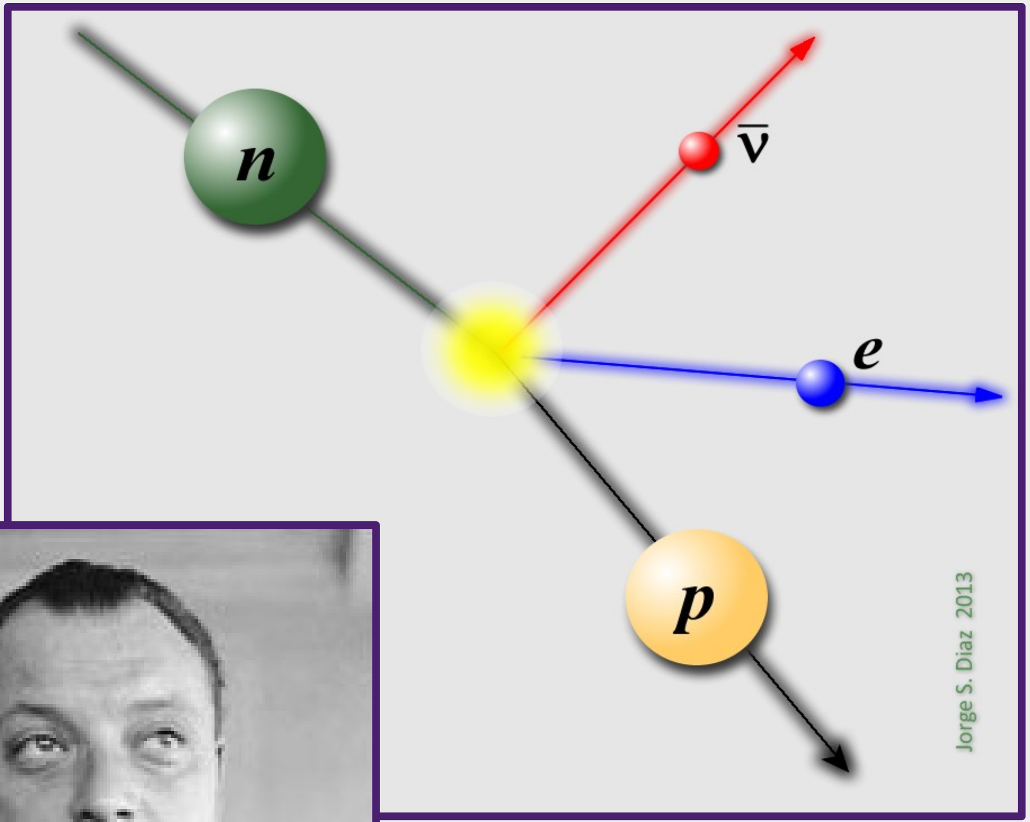
Outline

- Motivation: Project 8 experiment.
- Why do we need a new simulation? Compare Locust with existing particle physics simulation packages.
- Purpose of the simulation
  - Generate the same data that we should see from the real experiment.
  - This allow us to test the feasibility and systematics of the real experiment.
- Logistics and examples.
  - Generating and processing a signal.
  - Running the simulation on HPC.
- This pdf sits online at https://github.com/project8/locust_mc/blob/develop/Config/NNPSSTutorial/NNPSSTutorial.pdf

Neutrinos in radioactive decay

- Neutrino first postulated in 1930 by Wolfgang Pauli to preserve energy conservation in radioactive decays.
- Integral part of Fermi's theory of beta decay in 1933, precursor to theory of the weak interaction.
- Neutrinos first detected in 1956 by Reines and Cowan.



Wolfgang Pauli

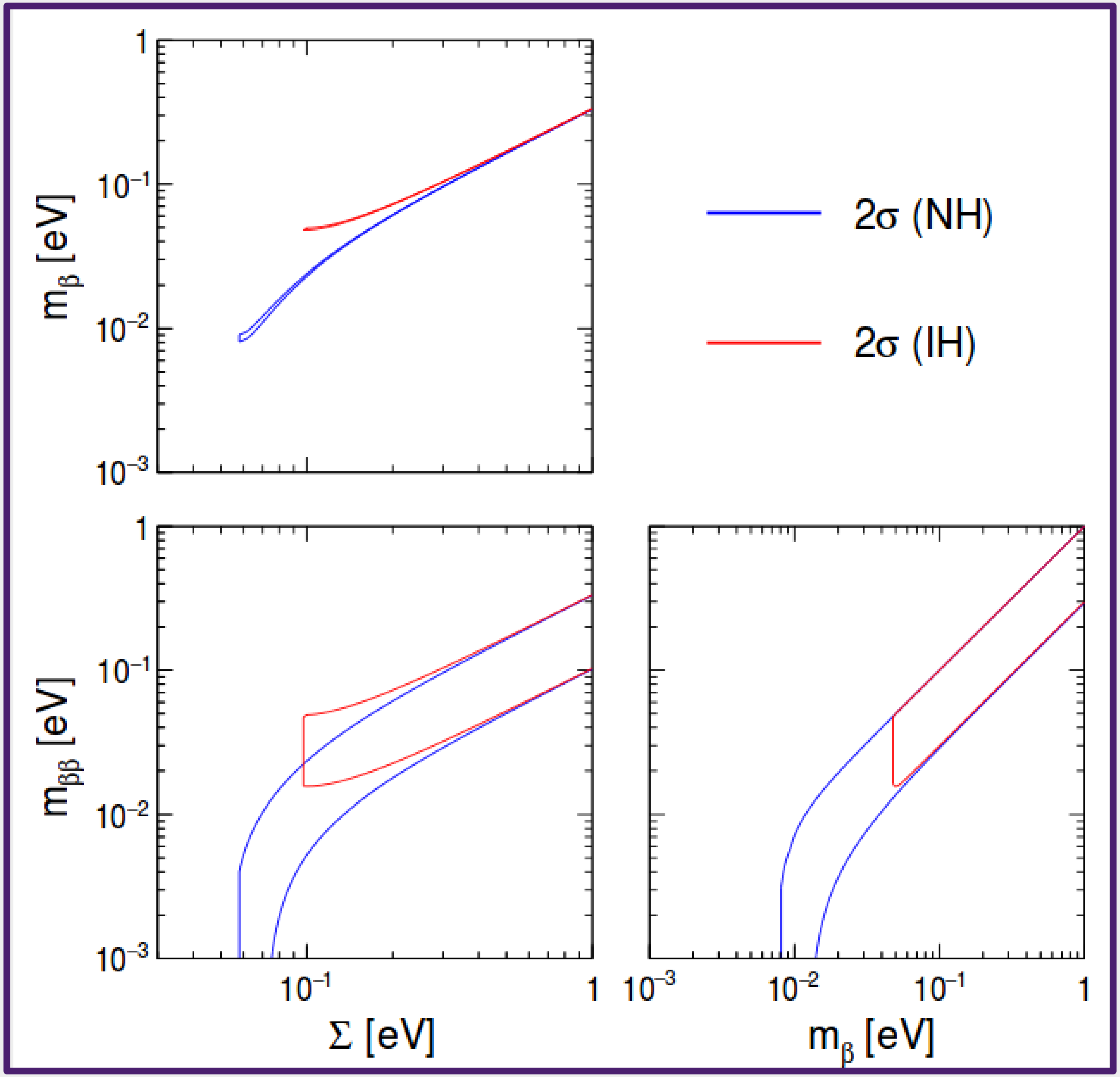
Constraints on effective masses

$$m_\beta = \sum_i m_{\nu i}$$

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_{\nu i}^2$$

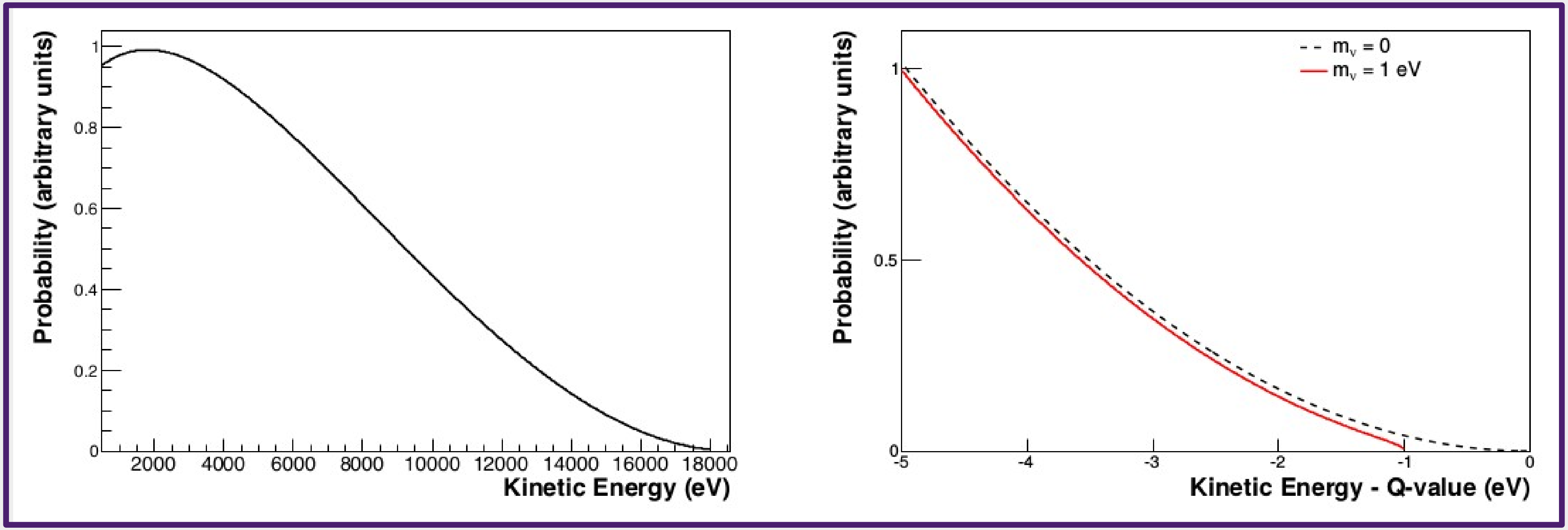
$$\langle m_{\beta\beta} \rangle = |\sum_i |U_{ei}| m_{\nu_i} e^{i\alpha_i}|$$

Constraints on masses from cosmology and from direct measurements can be compared.



F. Capozzi et al., Nucl. Phys. B, 00 (2016)

T_2 beta decay



$$
\begin{aligned}
\frac{dN}{dE_e} = &\frac{G_F^2 m_e^5 \cos^2\theta_C}{2\pi^3\hbar^7}|M_{\rm nuc}|^2 F(Z,E_e)p_e E_e \\
&\times \sum_{i,k}|U_{ei}|^2 P_k(E_{\rm max}-E_e-V_k)\sqrt{(E_{\rm max}-E_e-V_k)^2-m_{\nu i}^2} \\
&\times \Theta(E_{\rm max}-E_e-V_k-m_{\nu i})
\end{aligned}
$$

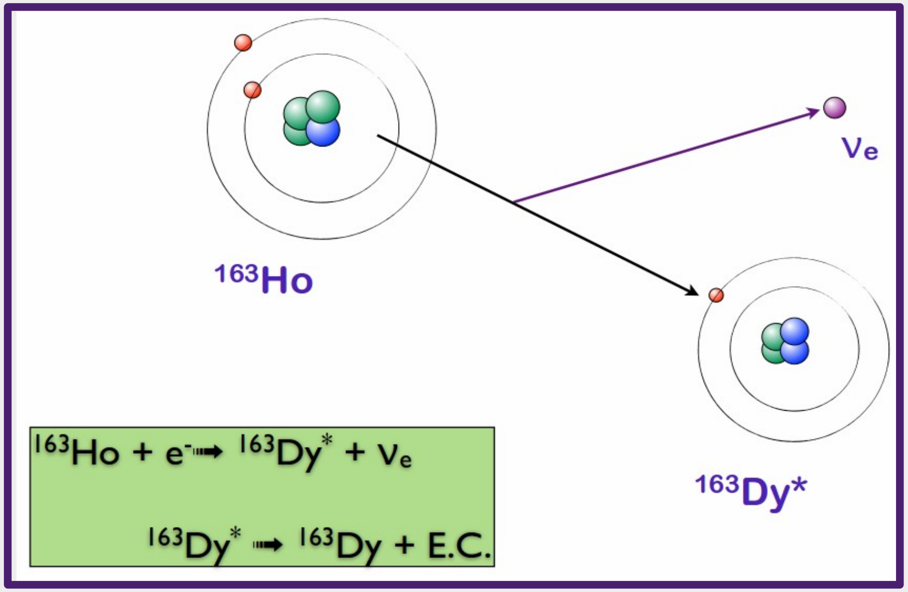
e.g., L. I. Bodine, Ph.D. Thesis, University of Washington (2015)

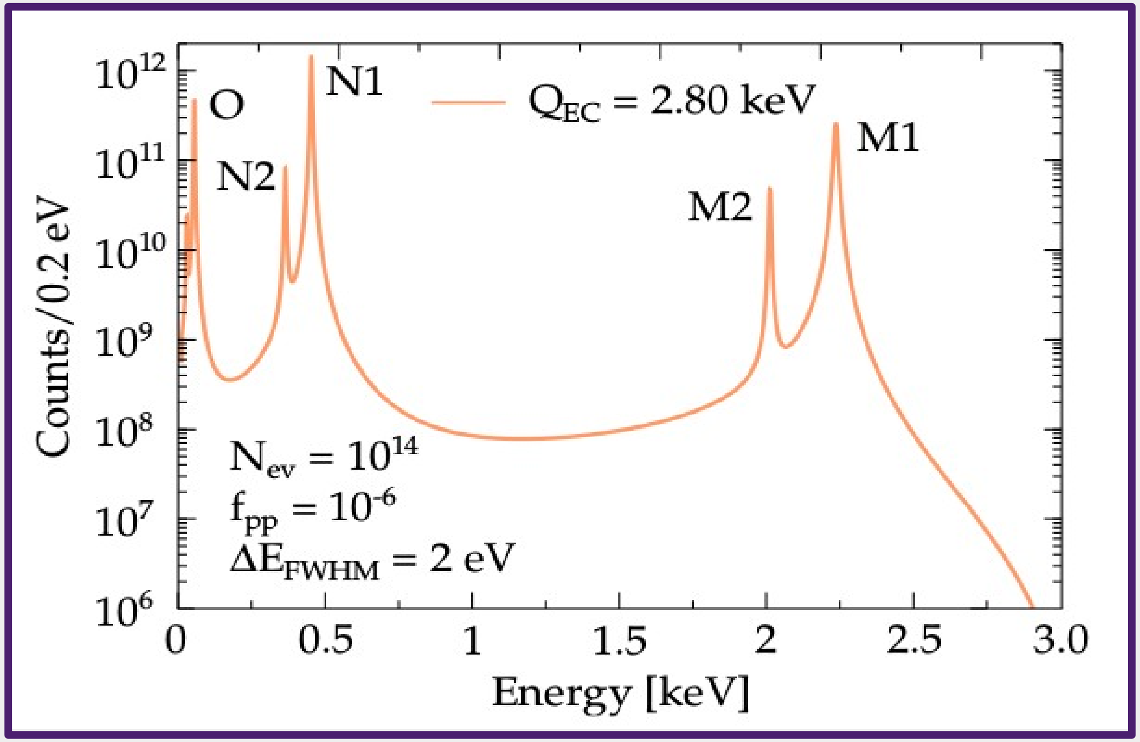
Direct measurements of effective neutrino mass

- Electron capture from ^{163}Ho
  - Holmes, Echo, NuMecs
- T_2 beta decay
  - Mainz/Troitsk
  - KATRIN: Karlsruhe Tritium Neutrino Experiment
  - Project 8

Decay of ^{163}Ho by electron capture

- Proposed in 1982 by DeRejula and Luisignoli.
- ^{163}Ho decays to ^{163}Dy by EC. De-excitation emission is measured by xray calorimetry.
- Holmes, ECHo, NuMECS experiments.
- Measurement of distortion of EC xray spectrum at end point due to m_{ν}.
- Resolution is presently defined by xray calorimetry and atomic calculations.



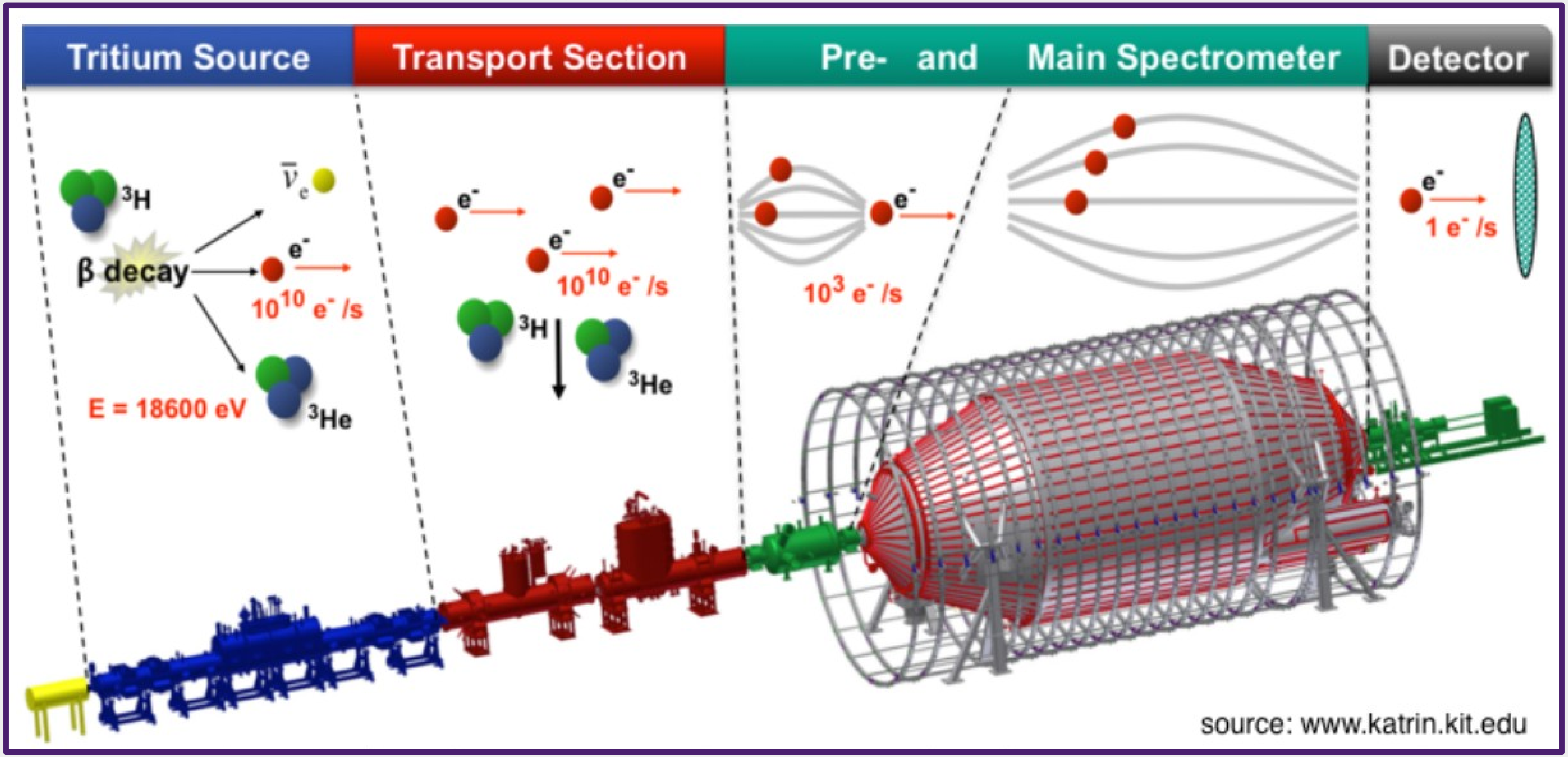


KATRIN

Diameter of spectrometer is 10 m.

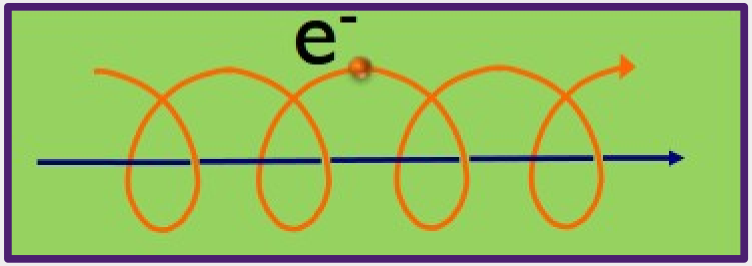
Required vacuum is 10^{-11} mbar.

Projected sensitivity is $m_\nu < 0.2$ eV.



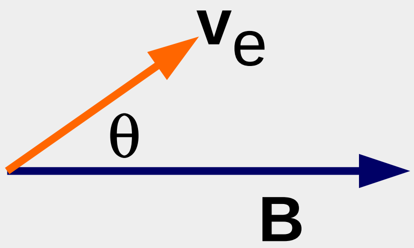
Project 8: Cyclotron Radiation Emission Spectroscopy (CRES)*

Pioneered by the Project 8 collaboration in 2015. Measure energy of single electrons indirectly by detecting boosted cyclotron frequency:



$$f_\gamma \equiv \frac{f_c}{\gamma} = \frac{eB}{2\pi\gamma m_e}$$

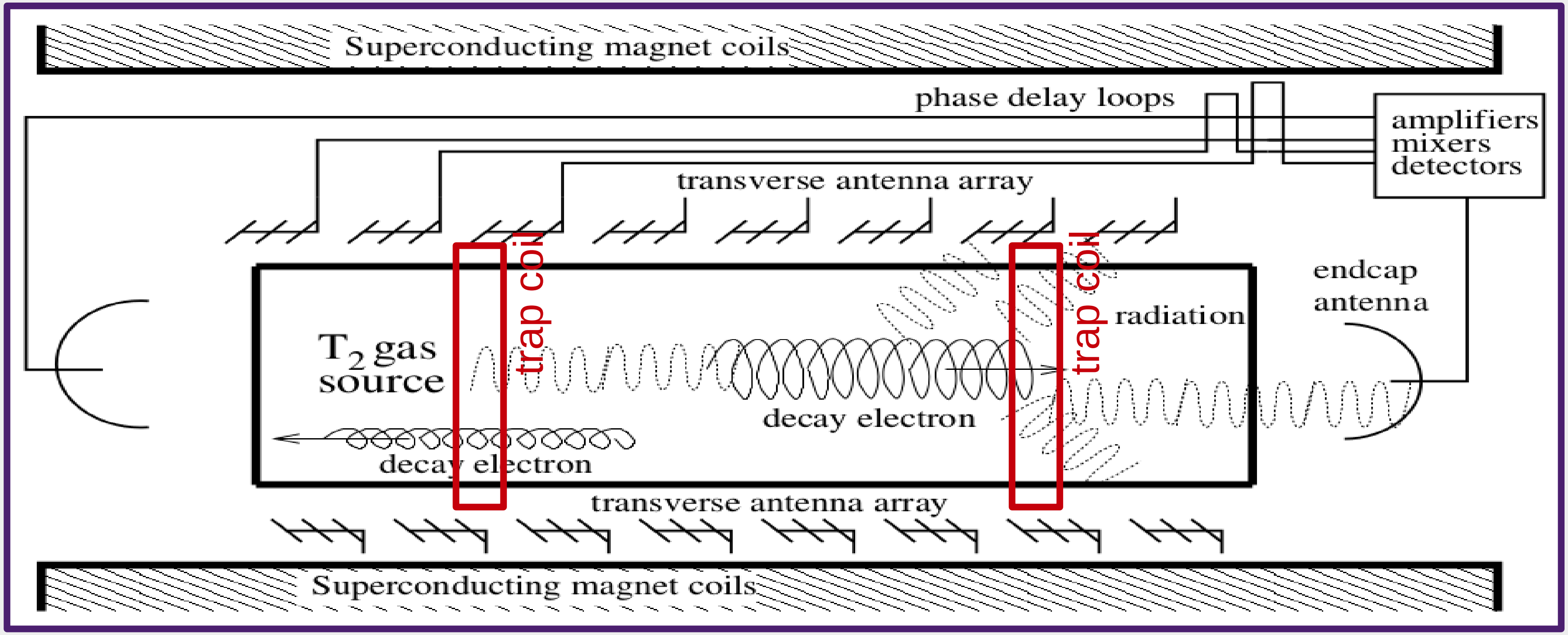
$$P(\gamma,\theta) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{e^4}{m_e^2 c}B^2(\gamma^2-1)\sin^2\theta$$



Emitted power depends on pitch angle θ but cyclotron frequency does not.

*B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2009)

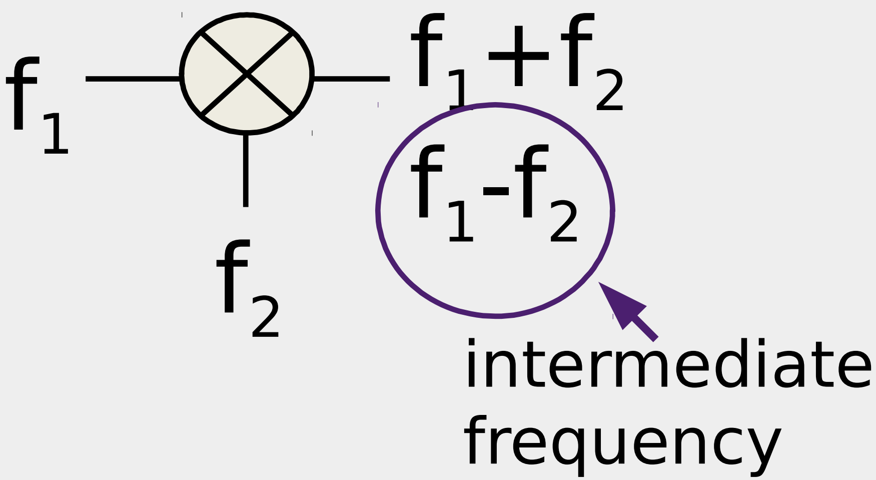
Cyclotron Radiation Emission Spectroscopy (CRES)



- Trap electrons emitted from a radioactive source gas in a 1 T magnetic field and collect the cyclotron emission.
- Voltages induced in the antennas are filtered and digitized.
- Time of measurement determines frequency resolution.

B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2009)

Heterodyne detection



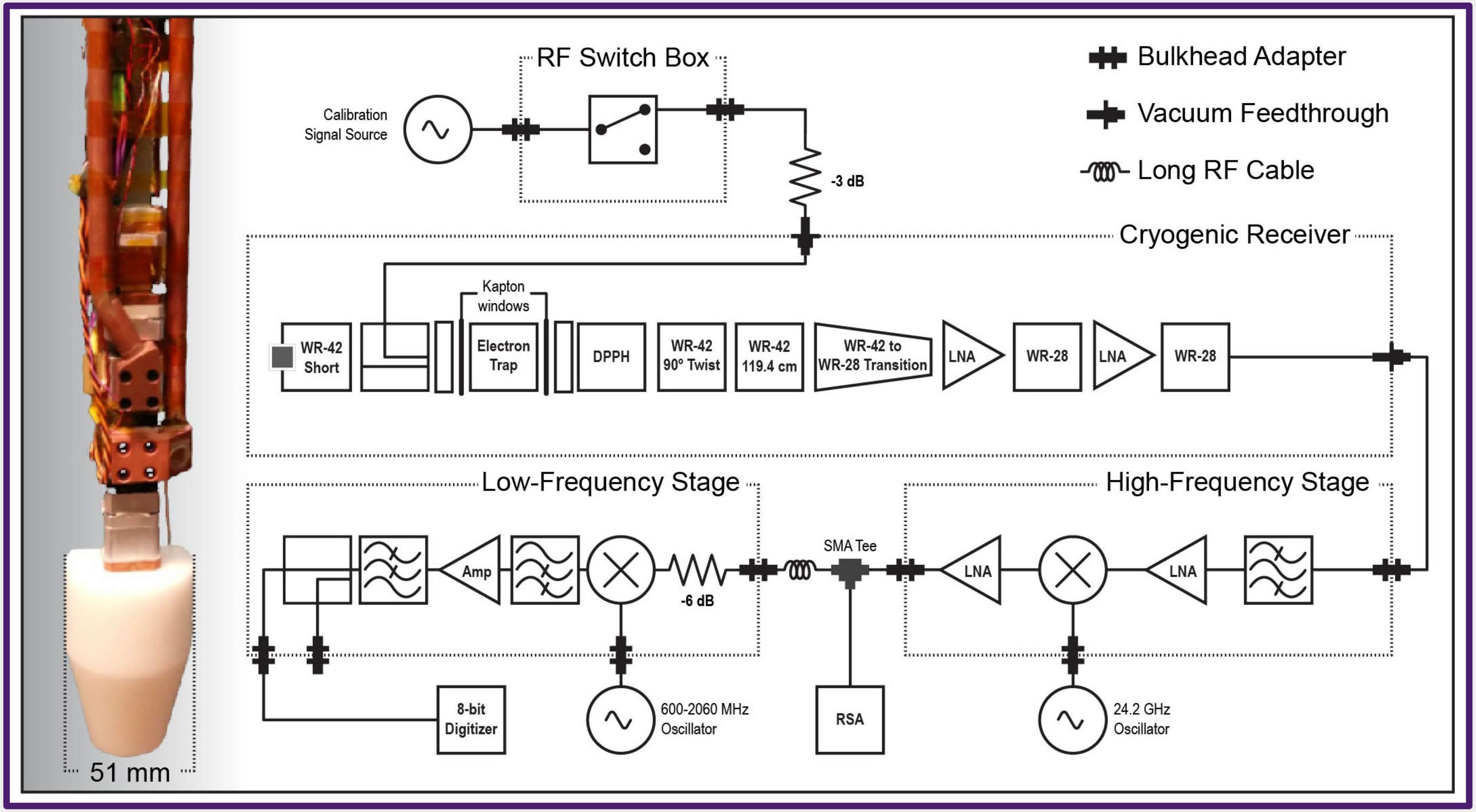
“Never measure anything but frequency.”

Dr. Arthur Schawlow

- Voltages are sampled in time after mixing down from 26 GHz to tens of MHz.
- Frequency spectrum is calculated by FFT.
- 18 keV electrons in 1 T gives SNR of ~10 in waveguide.

Frequency resolution = $1/\tau$.

Project 8 Phase 1 prototype schematic



D. M. Asner et al., PRL **114**, 162501 (2015)

How can we simulate the RF signal generation?

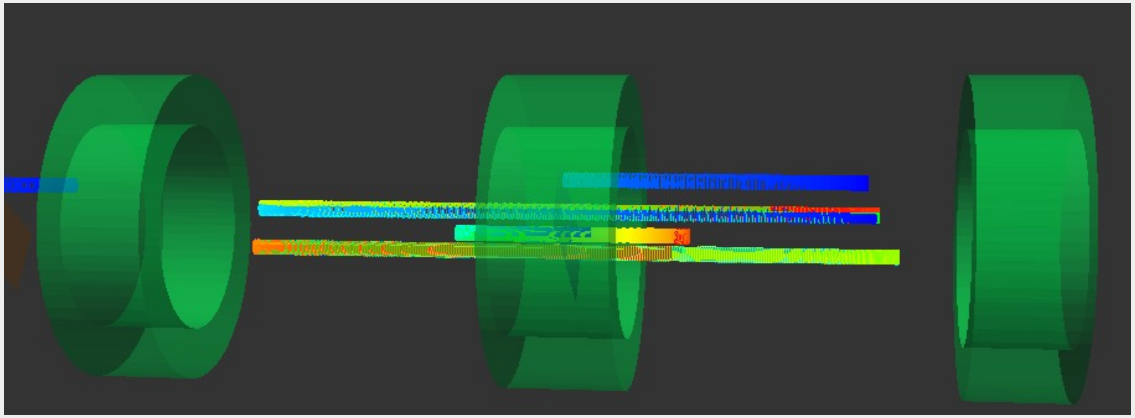
Status of existing particle physics simulation software packages

- Geant4: Particle tracking and kinematics
- Comsol and HFSS: EM field solutions
- Kassiopeia: Flexible, modular in-situ field solutions with simultaneous particle trajectory calculations (Furse et al., NJoP 2017).
- Locust: New simulation interface with Kassiopeia to model RF signal generation from particle trajectories, developed for Project 8.

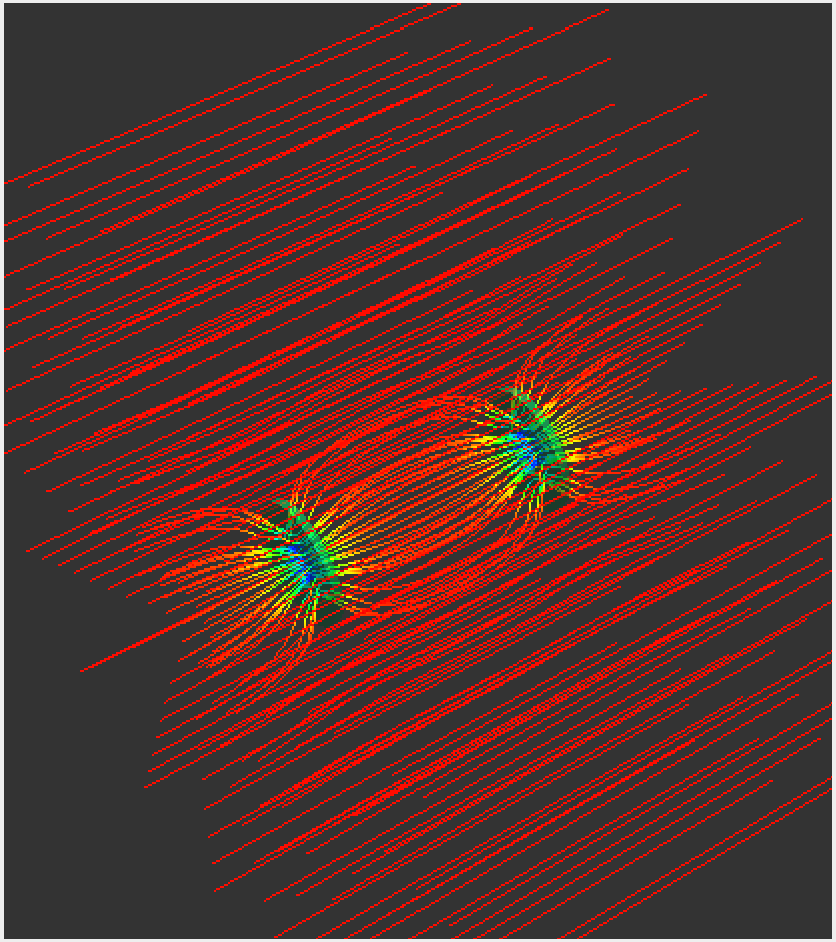
Trajectory calculations in EM field solutions with Kassiopeia simulation

Simultaneous field solutions and trajectory calculations.

Trajectories of five 18 keV electrons, four trapped in a magnetic bottle. Field lines not shown. Range of initial (x_0,y_0,z_0).



Magnetic bottle created by pinch coils in a constant magnetic background field.

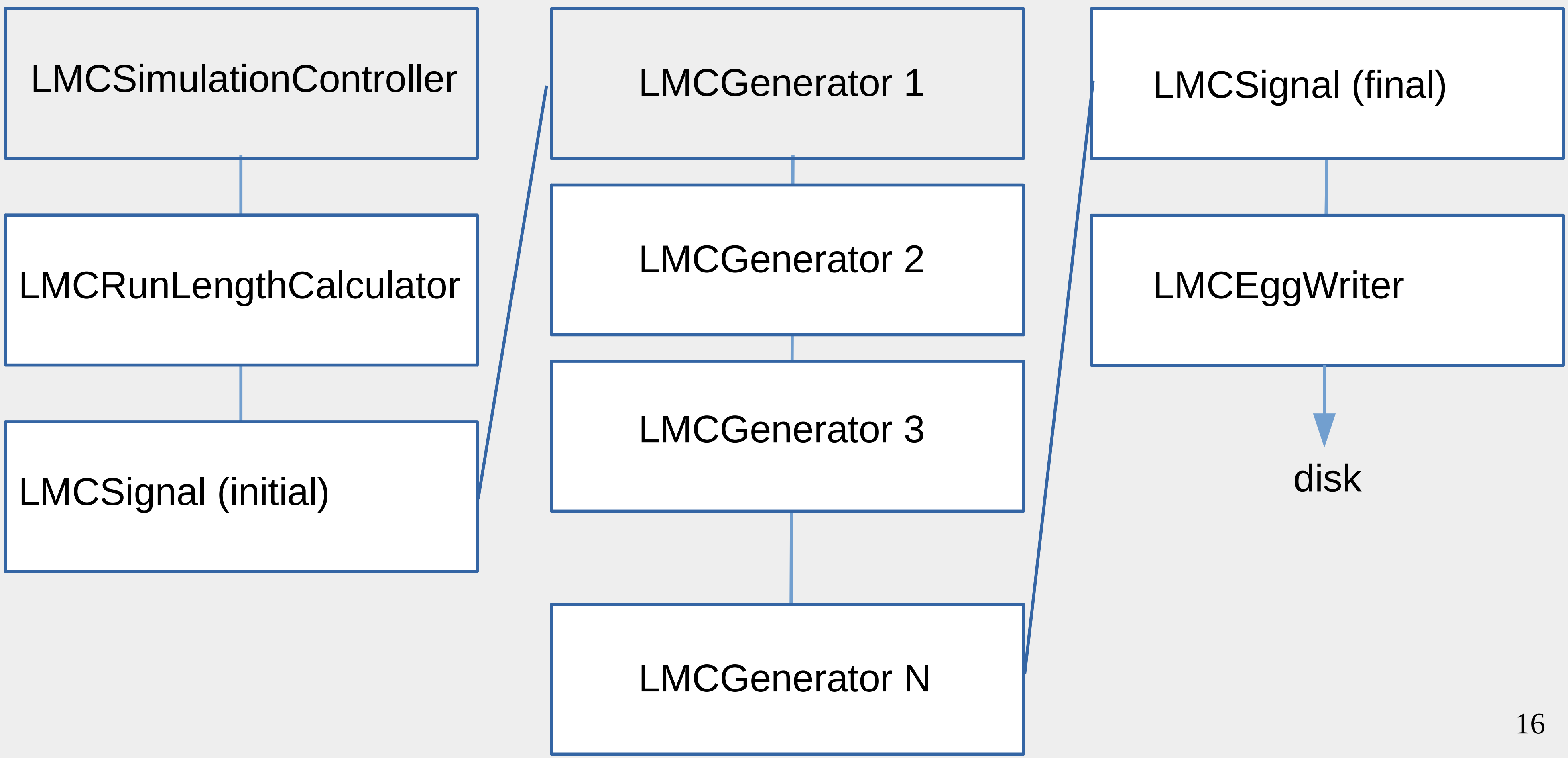


Locust simulation software block diagram

Configuration parameters are read from the json file.

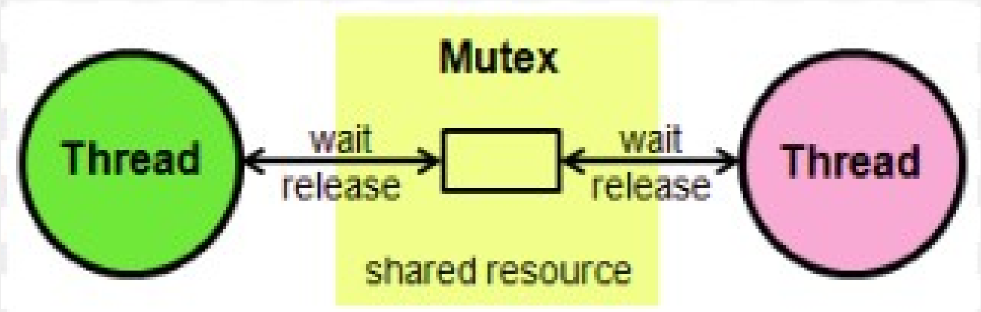
Generators populate and modify the LMCSignal object.

Final LMCSignal object is a time series of voltages to be written to file.



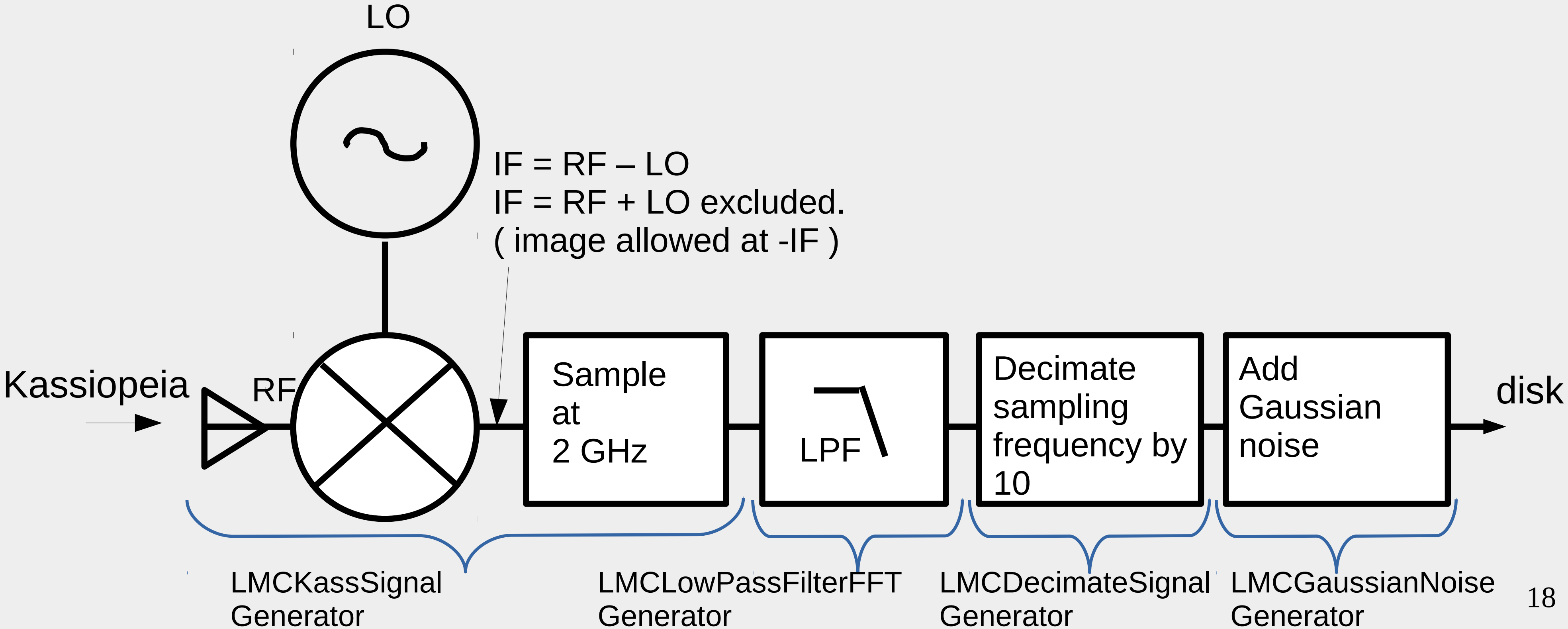
How do the Kassiopeia and Locust simulations interact?

- They are compiled into one executable.
- Only one of them runs at a time, while the other locks control of a std::mutex object.
- Kassiopeia runs for e.g. 0.5 ns at a time, then unlocks the mutex. Locust takes control of the mutex, calculates one voltage, and then hands control of the mutex back to Kassiopeia.



Locust simulation example
RF block diagram

- Use the energy losses reported by Kassiopeia to guide input.
- Generate antenna voltages at RF sampling frequency. Mix down to baseband with algorithmic receiver.



Why do we need the RF receiver block diagram in the simulation?

- Lab experiment has an RF receiver. The main purpose is to lower the signal frequency from e.g. GHz to MHz for efficient sampling and data management.
- Signal generated with Locust should have the same format as the empirical data. This provides a comparison for lab data analysis.
- Signal post-processing needs a signal as input. Signal properties constrain information that can be derived from signal processing.
  - e.g. Information that might be in the signal: voltage amplitude, voltage phase.
  - Information that might not be in the signal: large bit depth for higher accuracy, phase continuity, missing energy.
  - Signal properties (or missing properties) can help tell us whether the experiment will work (or not).

List of examples in this tutorial

- Visual Tool Kit (VTK) output.
- Single electron in a waveguide with one antenna.
- Driving the simulation with a tunable test signal.
- Larger number of single electrons in a waveguide, run in parallel on hpc.
- Single electron in an array of multiple antennas.
- Checking the magnetic field map.

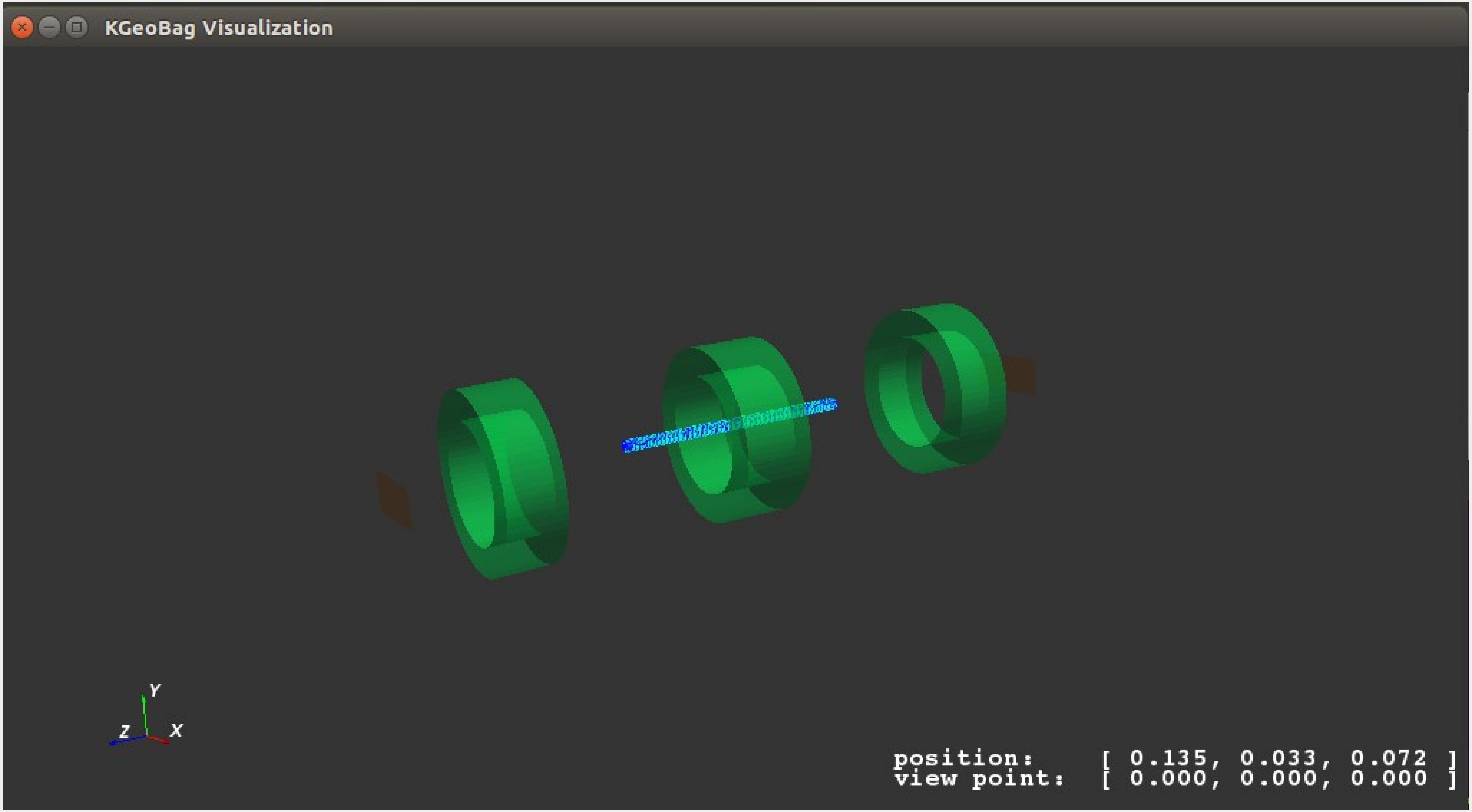
Steps to get started

- ssh -Y netID@grace.hpc.yale.edu
- module load Tools/nnpss
- setup_dirs.sh
- cd project8/manageTutorial
- cp /home/hep/baker/ps48/project8/manageTutorial/* .
- cp /home/hep/baker/ps48/locust_mc/Config/NNPSSTutorial/* ~/locust_mc/Config/NNPSSTutorial/

Example 0: Look at VTK output of a trajectory calculation with Kassiopeia

1) ssh to Grace cluster: ssh -Y netID@grace1.hpc.yale.edu .
2) Log in to compute node: srun --x11 --pty -c 4 -p interactive bash
3) cd project8/manageTutorial/
4) LocustSim config = ~/locust_mc/Config/NNPSSTutorial/LocustTutorialTemplate.json
5) Output should appear as on next slide if:
   - Kassiopeia has been compiled with VTK.
   - The vtk window has been instantiated in the xml file.
   - OpenGL version on your laptop is compatible with that on the cluster.
   - Otherwise this example is more suitable to run on a standalone laptop.

Example 0: Look at VTK output of a trajectory calculation with Kassiopeia, cont.



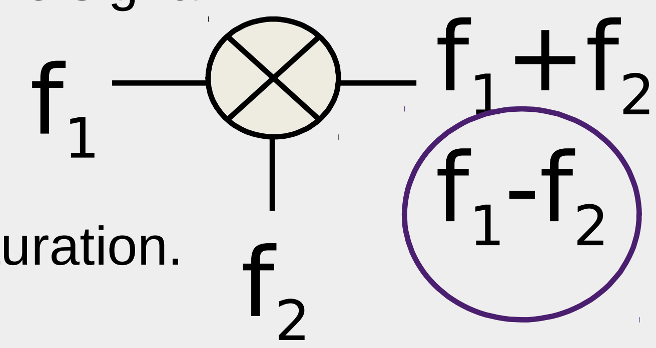
Logistics and examples of simulated RF signal generation

Questions before and after Locust

- Questions to ask before running Locust:
  - How much of the physics should appear in the generated signal?
  - Is there other physics that will not appear in the generated signal?
  - How will we tell the difference?
- Questions to ask after running Locust:
  - Did we measure the physics that we needed?
  - If not, how should we change the detection hardware? Describe the hardware change algorithmically in Locust, and generate a new signal.

Some more detailed questions before/after running Locust

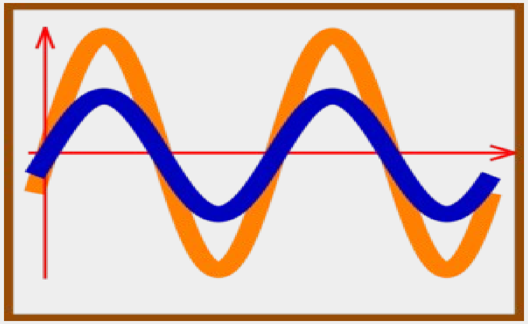
- Did we detect the signal?
  - Is the local oscillator tuned to put the signal in our baseband window spanning from $-f_{Nyquist}$ to $+f_{Nyquist}$?
  - An easy way to check this is to interrupt the simulation and print the RF frequency to the terminal. IF = RF – LO.
  - Otherwise check the processed data to look for the signal.
- Was the digitizer range set correctly?
  - Locust prints ~100 digital voltages at completion.
  - Look for values of 0 and 255. These indicate saturation.
  - Too many 127 and 128s mean too much range.
  - Adjust the digitizer range in the json file “digitizer” parameters.

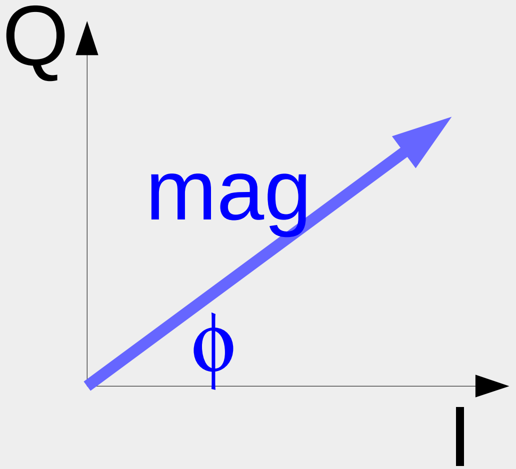


- What is the digitizer bit depth?
  - It is hard-wired to 8 bits at the moment.

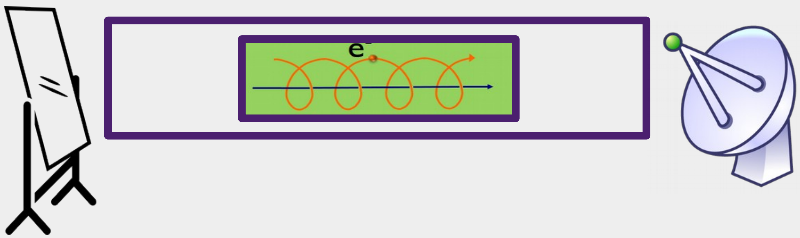
What are we actually going to do?

- Generate a time series of complex voltages (LMCSignal object).
- Each voltage sample will have a real part (I) and an imaginary part (Q).
- First we calculate the voltage I sampled at time t with phase $\phi(t)$, and then we derive Q from it by lagging the voltage phase 90^o.
- In the offline data stream we will have the voltage magnitude and phase information. $\phi = \mathrm{atan}(Q/I)$.





Locust example 1: Magnetically trapped electron radiates in a waveguide with one antenna



- What is the signal?
  - Power radiated by the electron.
- How will we detect it?
  - Generate voltages on an antenna by, e.g., $P = V^2/R$.
- What is the voltage amplitude V?
  - Consider the power in the waveguide mode(s) that propagate to the antenna.
  - $V = \text{sqrt}(50\Omega\ P)$, if it is changing with time we have AM.
- What is the voltage phase ϕ?
  - Require ϕ to advance continuously as $\phi(t)$ += f'(dt); it changes as FM.
  - f' is the frequency observed right at the antenna, including Doppler shift.
- What physics is not in the signal?
  - Waveguide modes that do not propagate.
  - Frequency of radiation observed anywhere but at the antenna.
  - We might reconstruct the missing physics with post-simulation analysis.

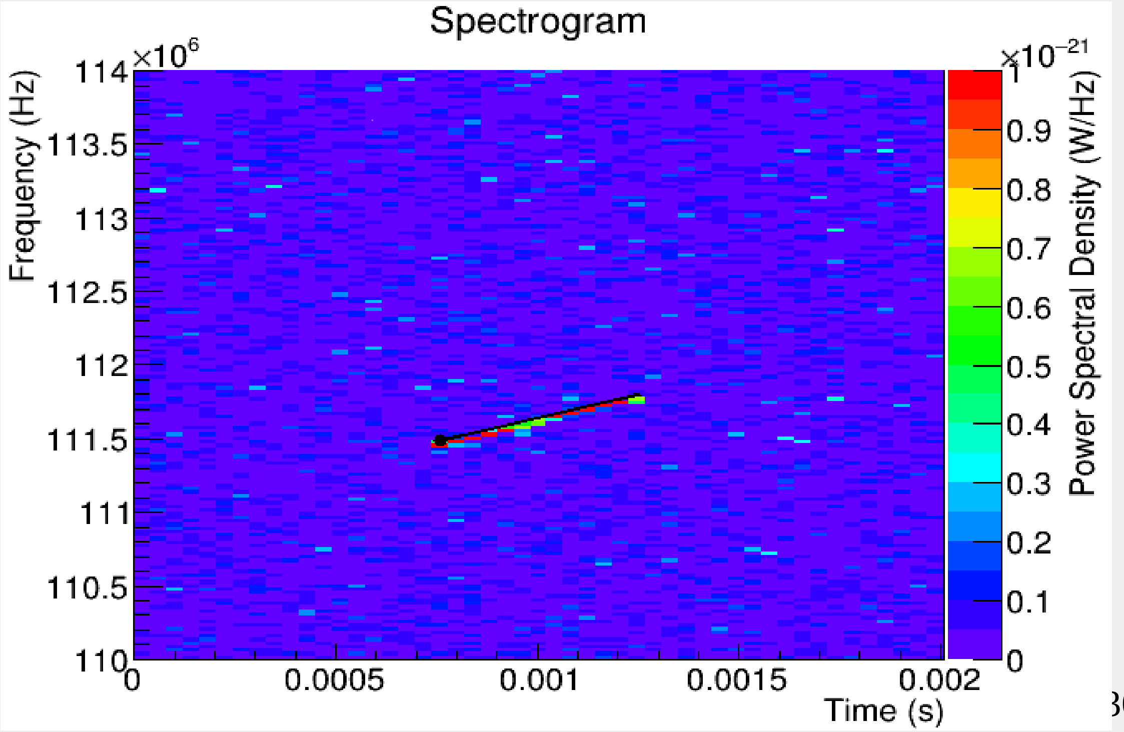
Locust example 1: Magnetically trapped electron radiates in a waveguide with one antenna, cont.

- How do we implement this in software?
  - Inside the Locust generator LMCKassSignalGenerator we have populated the LMCSignal object with a time series of complex voltages.
    - $V_I(t) = V_0(t)\cos(\phi(t))$; $V_Q(t) = V_0(t)\sin(\phi(t))$
    - $V_0(t)$ and $\phi(t)$ are calculated as on previous slide.
    - Sampling rate is chosen according to bandwidth needs.
- How do we run this on Yale HPC?
  - cd ~/project8/manageTutorial
  - emacs SimulateSeed &, note 4 cpus, output file.
  - ./SimulateSeed
  - Wait 30 minutes. Check that the file locust_jobSeed55 is growing.

Locust example 1: Magnetically trapped electron radiates in a waveguide with one antenna, cont.

- Check to see whether the slurm job has finished, and that there is an egg file in ~/data/SimulationTutorial.
  - squeue -u netID
  - ls -l ~/data/Simulation/Tutorial/*.egg
- Log on to a compute node: srun --x11 --pty -c 4 -p interactive bash
- cd ~/project8/manageTutorial
  - ./ProcessOneSpectrogram
  - root -l
  - .L PlotExample()
  - PlotTrack()
  - PlotStartFreqs()
  - PlotSlopes()

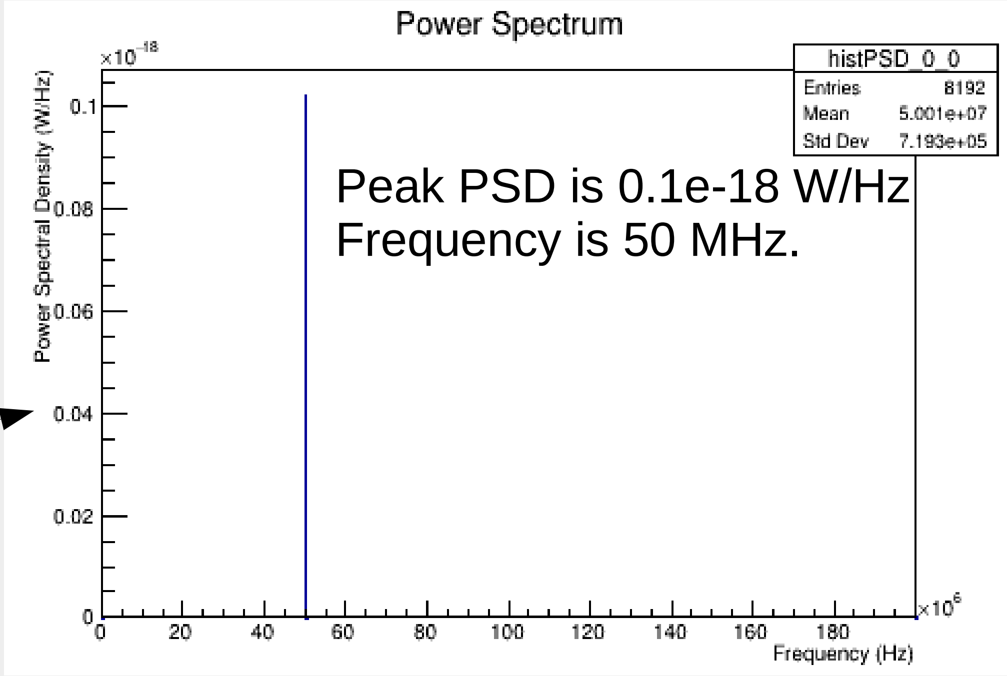
output



Locust example 2: Drive the receiver with a complex sine wave

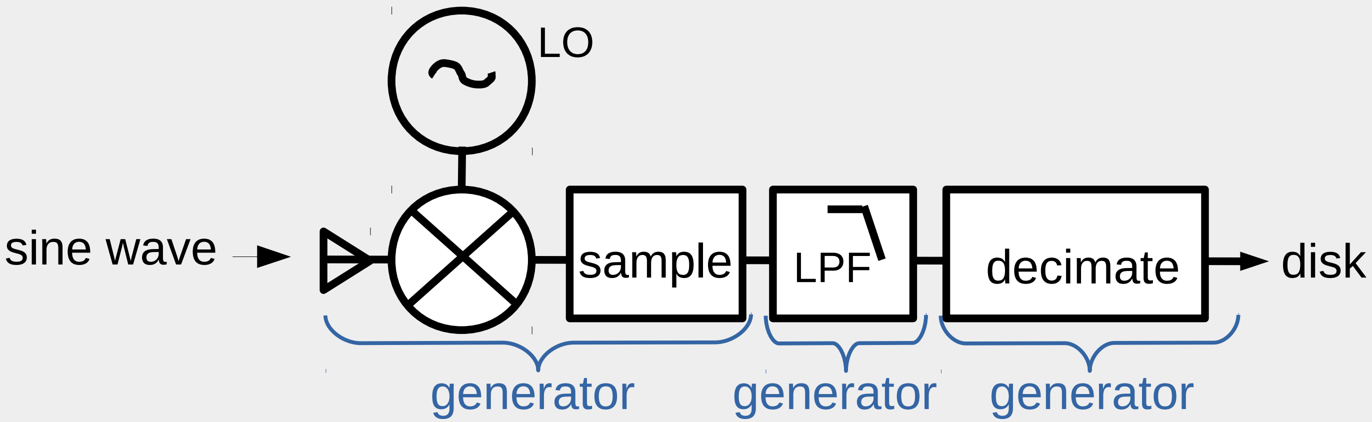
- Log on to a compute node: srun --x11 --pty -c 4 -p interactive bash
- Open the sine wave config file: emacs ~/locust_mc/Config/NNPSSTutorial/LocustSineWave.json &. Check which generators are listed, see that “lo-frequency” = 20.15 GHz.
- LocustSim config=~/locust_mc/Config/NNPSSTutorial/LocustSineWave.json
- Katydid -c ~/locust_mc/Config/NNPSSTutorial/katydid_basic.json
- cd ~/project8/manageTutorial
  - root -l
  - .L PlotExample.c
  - PlotTestSignal()

output



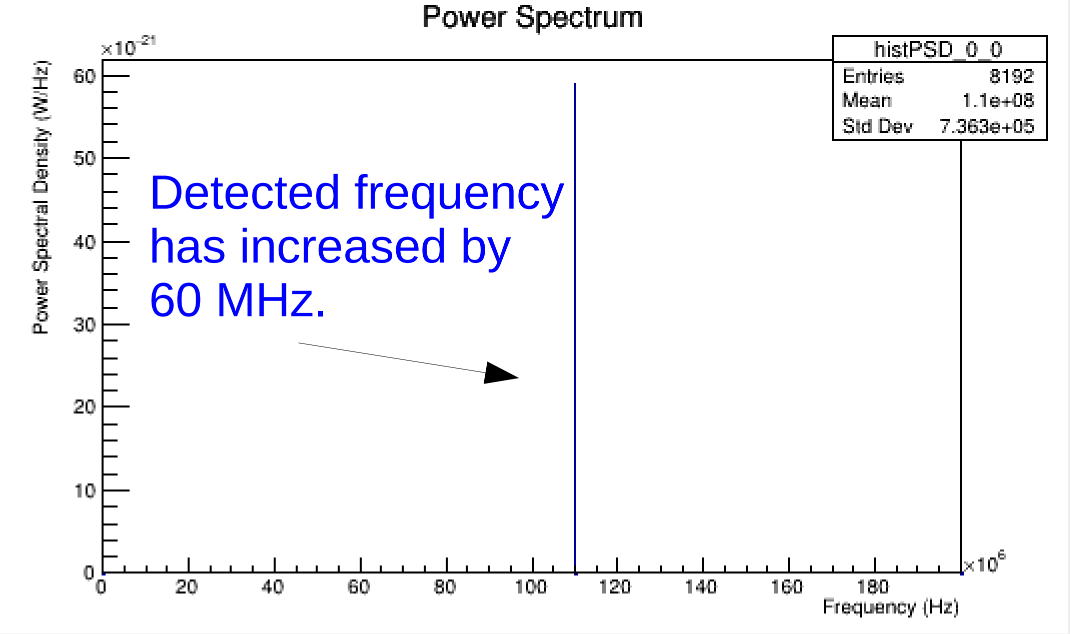
Locust example 2: Check the frequency and normalization of the complex sine wave

- Open the generator: emacs /home/hep/baker/ps48/locust_mc/Source/Generators/LMCTestSignalGenerator.cc &
- Scroll to DoGenerateTime() function and look at this line: aSignal->LongSignalTimeComplex()[ch*aSignal->TimeSize()*aSignal->DecimationFactor() + index][0] += sqrt(50.)*5.e-8*cos(voltage_phase-LO_phase);
- We are modifying the (multichannel, complex, oversampled, in-phase) LMCSignal object by adding a voltage to it. The antenna impedance is 50Ω, the voltage amplitude is 5.e-8 volts, and the frequency after downmixing will be (test_frequency-fLO_frequency).
- Power in the sine wave should be V^2/R = (5.e-8)(5.e-8)/50. = 2.5e-15/50. W. Checking the PSD histogram we see PSD = 0.1e-18 W/Hz with a bin width of 200.e6/8192, for a total power of 2.44e-15 W. The 50Ω has been applied in Katydid post-processing.
- Signal frequency is 50 MHz, which in this post-processing configuration, is 50 MHz below DC. The frequency span shown corresponds to -100 MHz through 100 MHz.



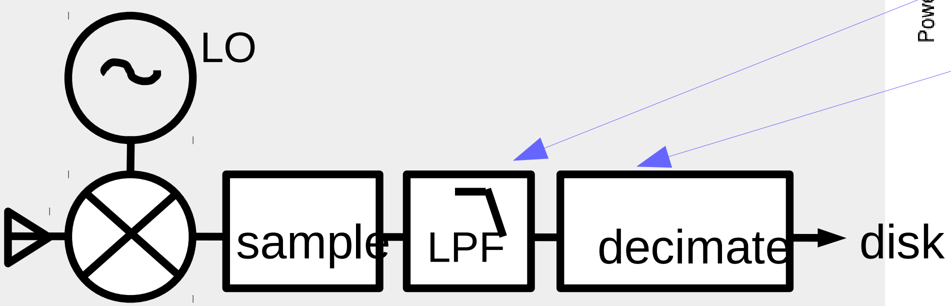
Locust example 2: Try tuning the LO (complex sine wave, continued)

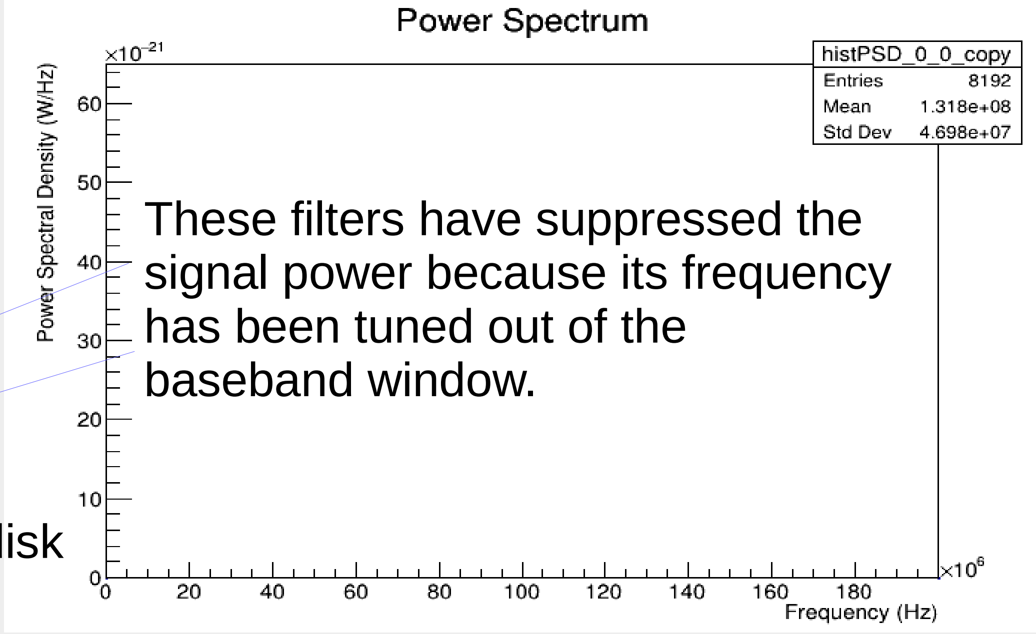
- emacs ~/locust_mc/Config/NNPSSTutorial/LocustSineWave.json
  - Look at the config parameters in the “test-signal” generator. Decrease the “lo-frequency” by 60 MHz from 25.15e9 to 25.09e9 Hz.
  - Save the file.
- LocustSim config=~/locust_mc/Config/NNPSSTutorial/LocustSineWave.json
- Katydid -c ~/locust_mc/Config/NNPSSTutorial/katydid_basic.json
- cd ~/project8/manageTutorial
  - root -l
  - .L PlotExample.c
  - PlotTestSignal()



Locust example 2: Now tune the signal all the way out of the window (sine wave, continued)

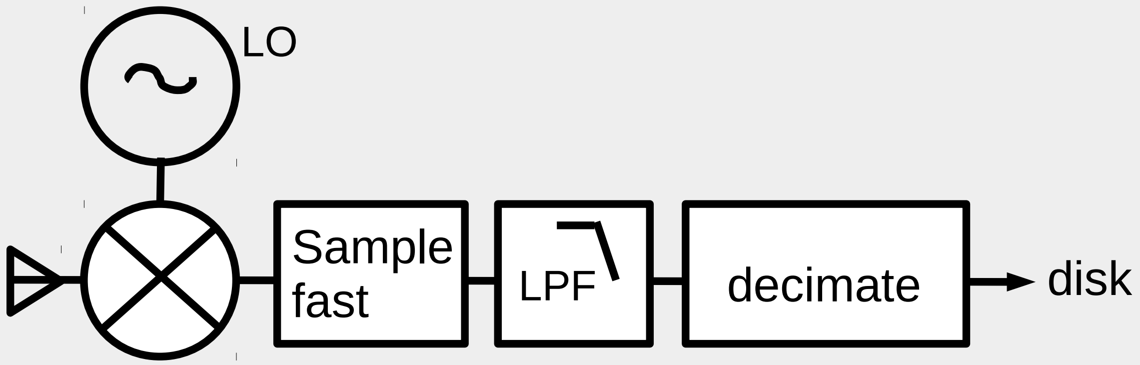
- emacs ~/locust_mc/Config/NNPSSTutorial/LocustSineWave.json
  - Look at the config parameters in the “test-signal” generator. Decrease the “lo-frequency” by another 100 MHz from 20.09e9 to 19.99e9 Hz.
- LocustSim config=~/locust_mc/Config/NNPSSTutorial/LocustSineWave.json
- Katydid -c ~/locust_mc/Config/NNPSS/katydid_basic.json
- cd ~/project8/manageTutorial
  - root -l
  - .L PlotExample.c
  - PlotTestSignal()



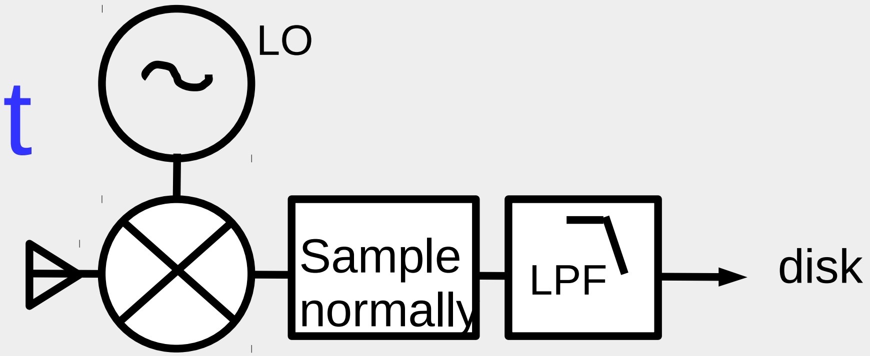


About the filtering (1)

Why this?

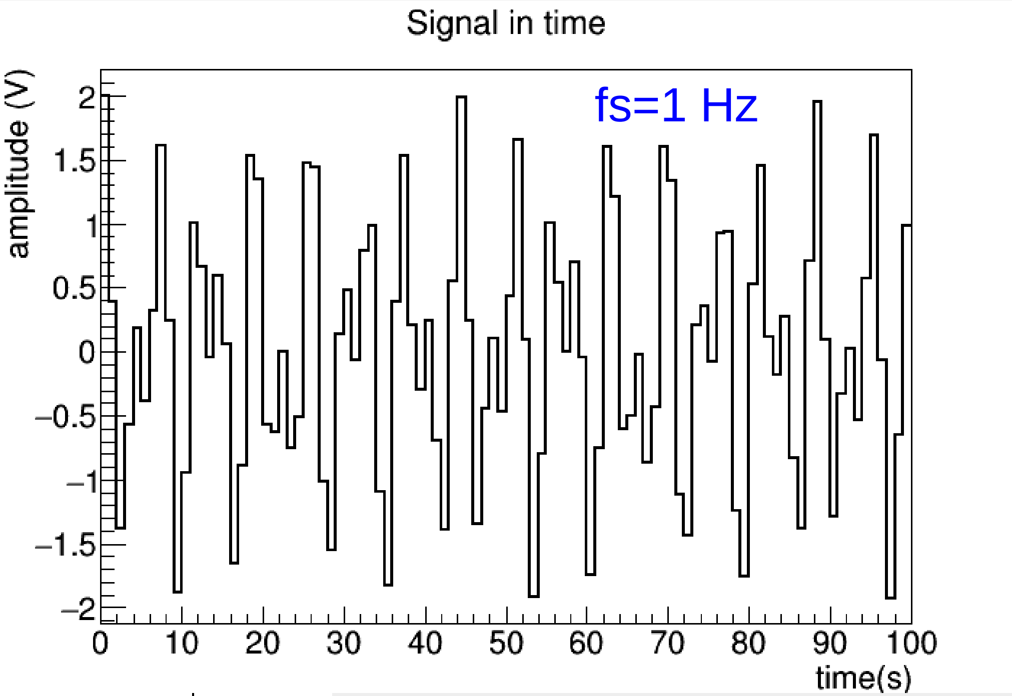


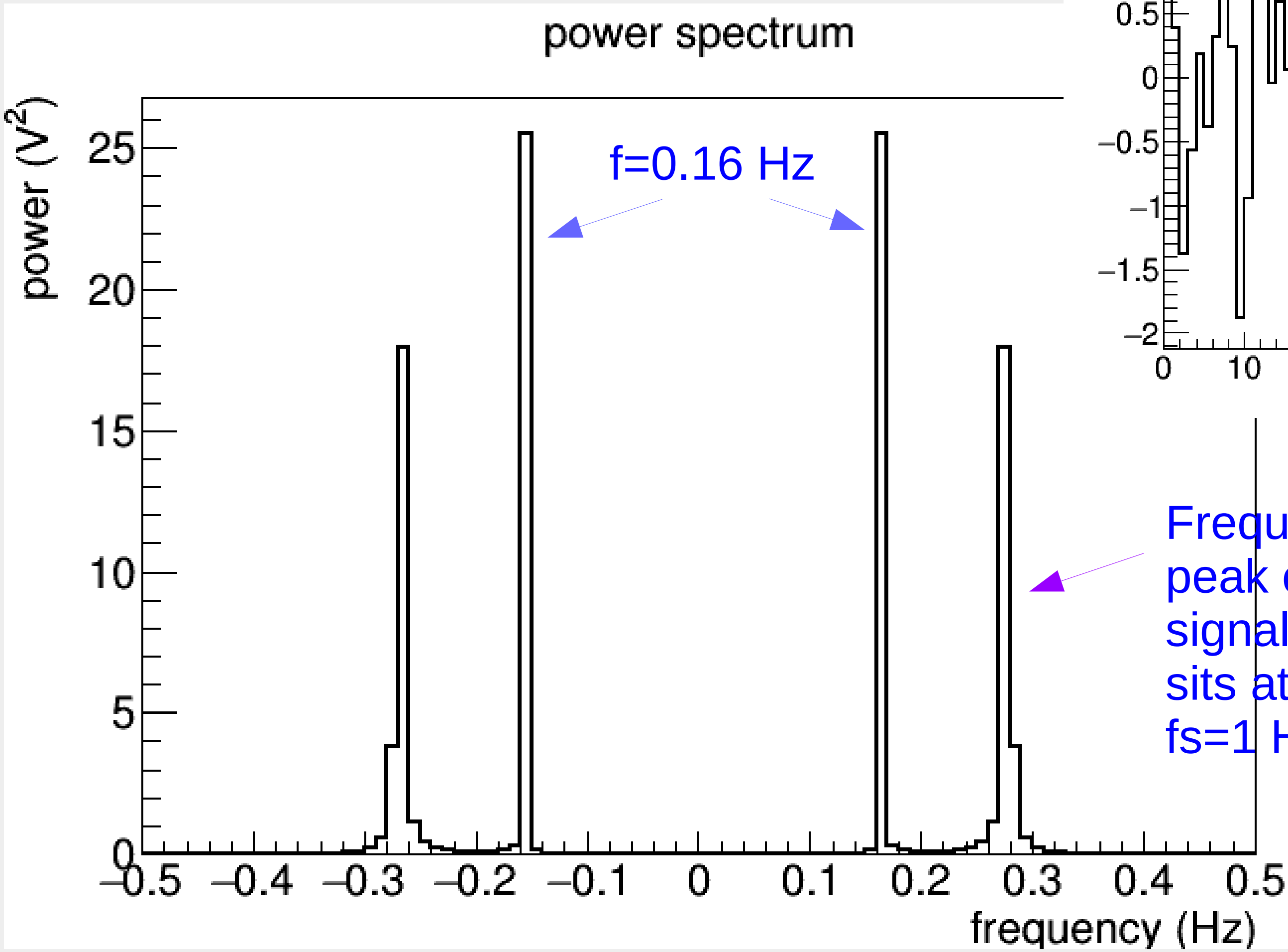
And not this?



About the filtering (2)

Using a test signal with a low ($1/2\pi$) and high frequency ($8/2\pi$) component $V(t) = \cos(t) + \cos(8t)$ we can see what happens to the high-f signal for fs=1 Hz.

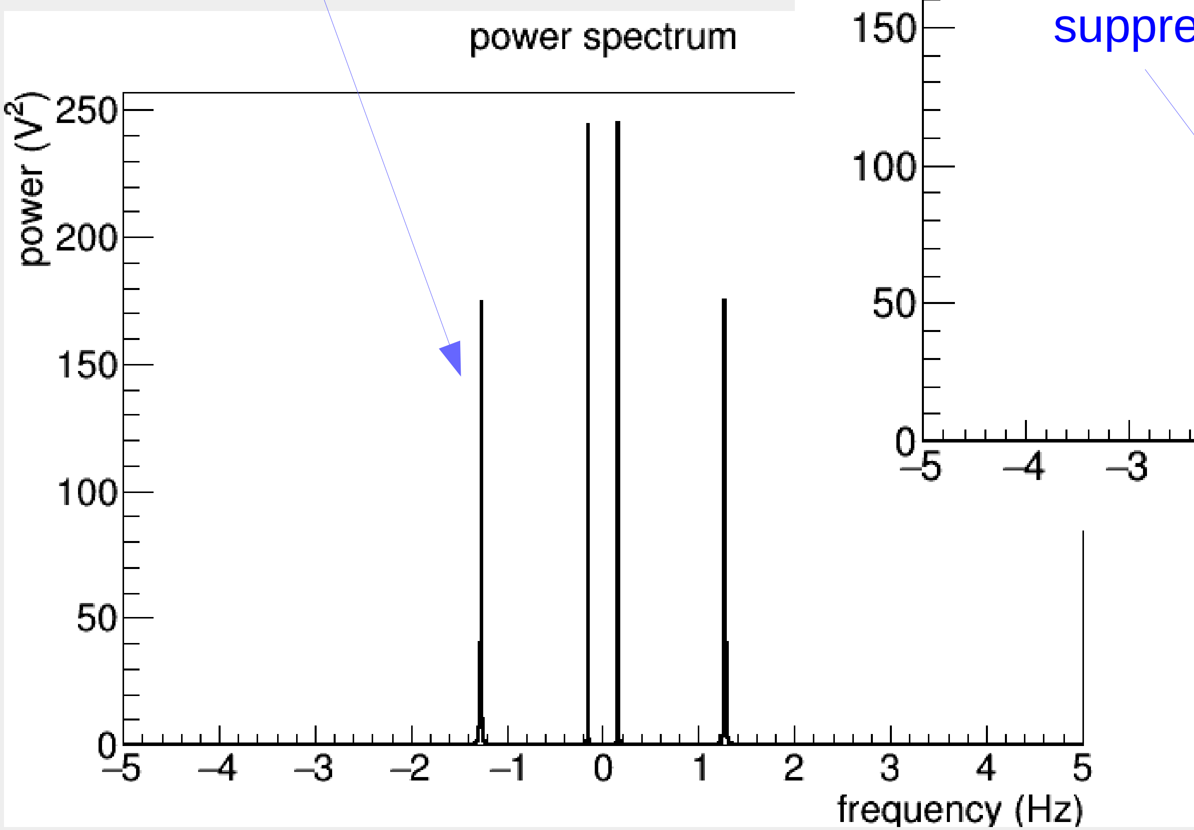


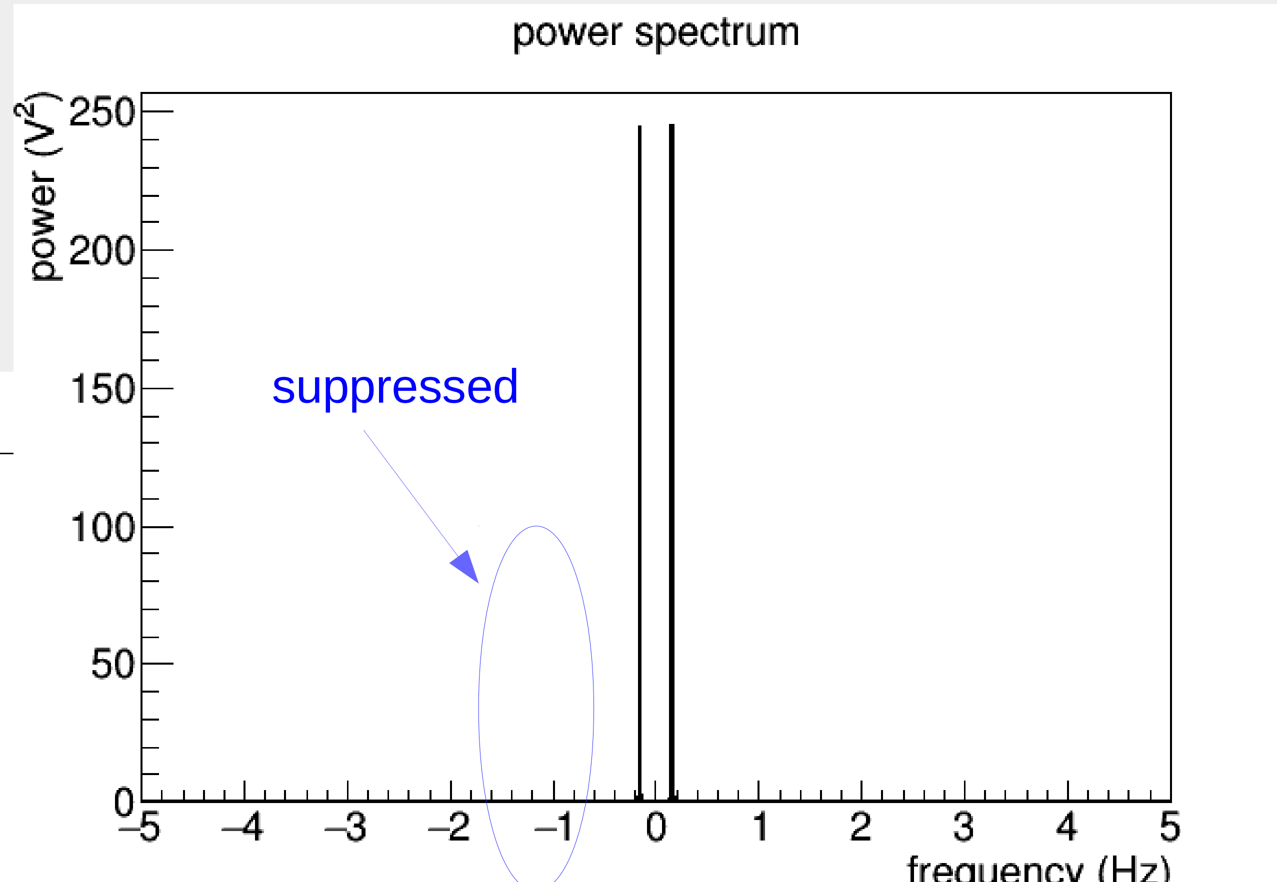


Frequency aliasing: This peak corresponds to the signal with f = 1.27 Hz but sits at ~0.3 Hz because fs=1 Hz is too slow.

About the filtering (3)

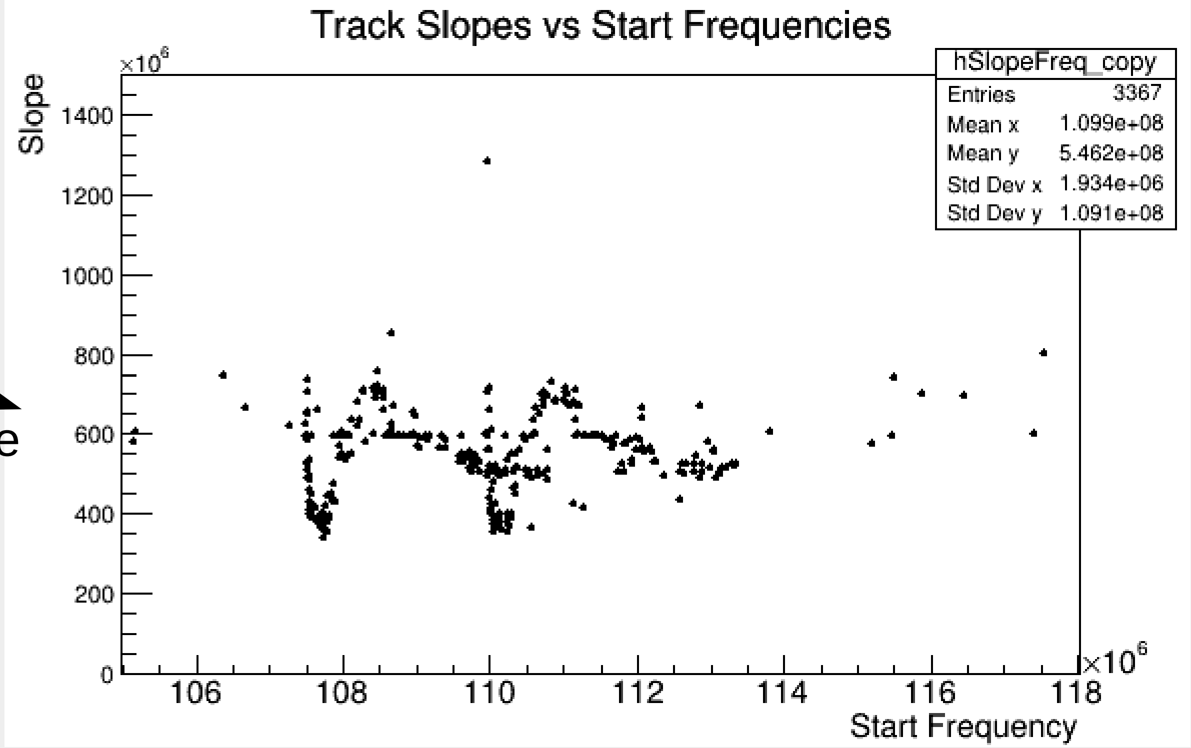
Sampling faster: Now the signal with f=(8/2π)=1.27 Hz is measured correctly and can be suppressed with a LPF in the frequency domain at 0.5 Hz.





Locust example 3: Generating more statistics

- cd ~/project8/manageTutorial/
- emacs SimulateSeed &
- Look at the range of seeds to be submitted as slurm jobs. Pick 56 through 62. Exit and submit the job: ./SimulateSeed
- It has to run for 3 hours, but we can process some pre-existing data: sbatch ProcessEggFilesBatch, then
  - root -l
  - .L PlotSpectrum.c
  - PlotKrypton()

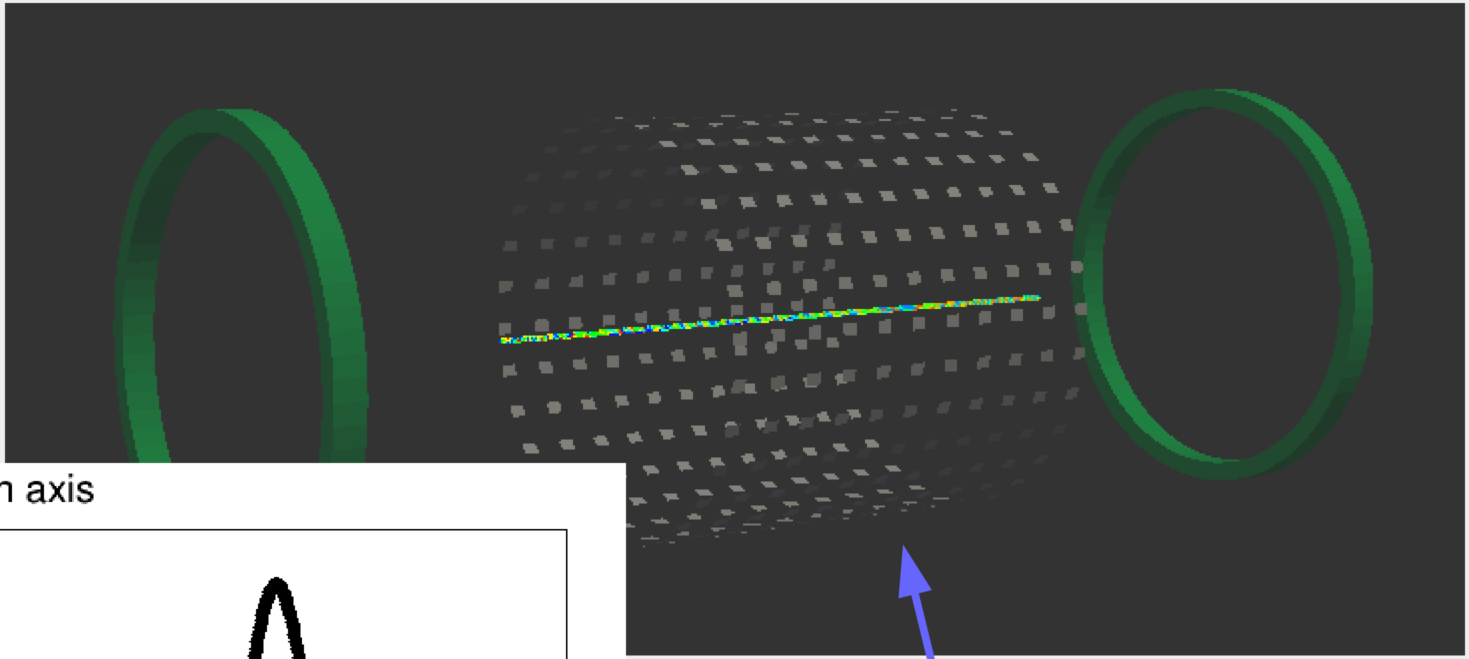


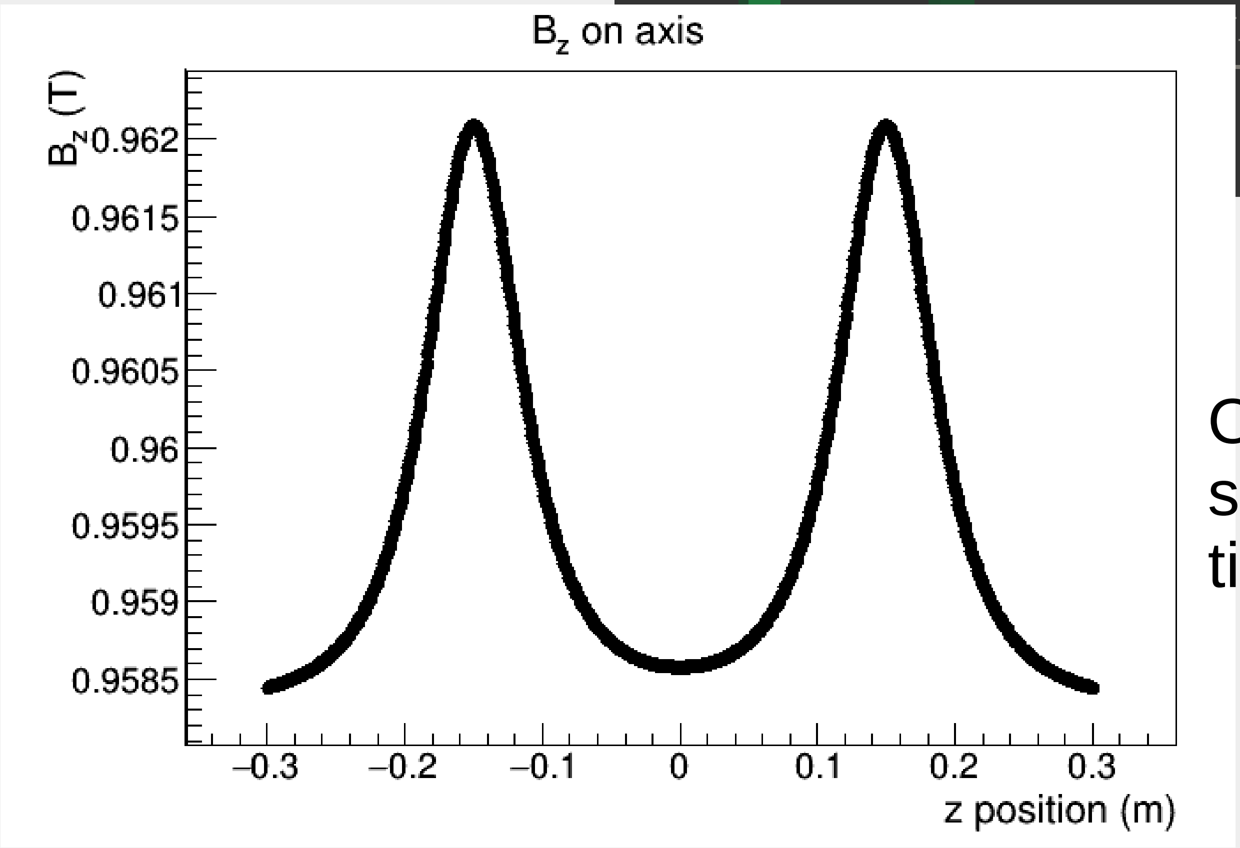
Each point represents one processed track in frequency-time space.

Locust example 4: Magnetically trapped electron radiates in free space with 30 channels

Patch array radius 5.16 cm.

Spacing 0.0108 m.





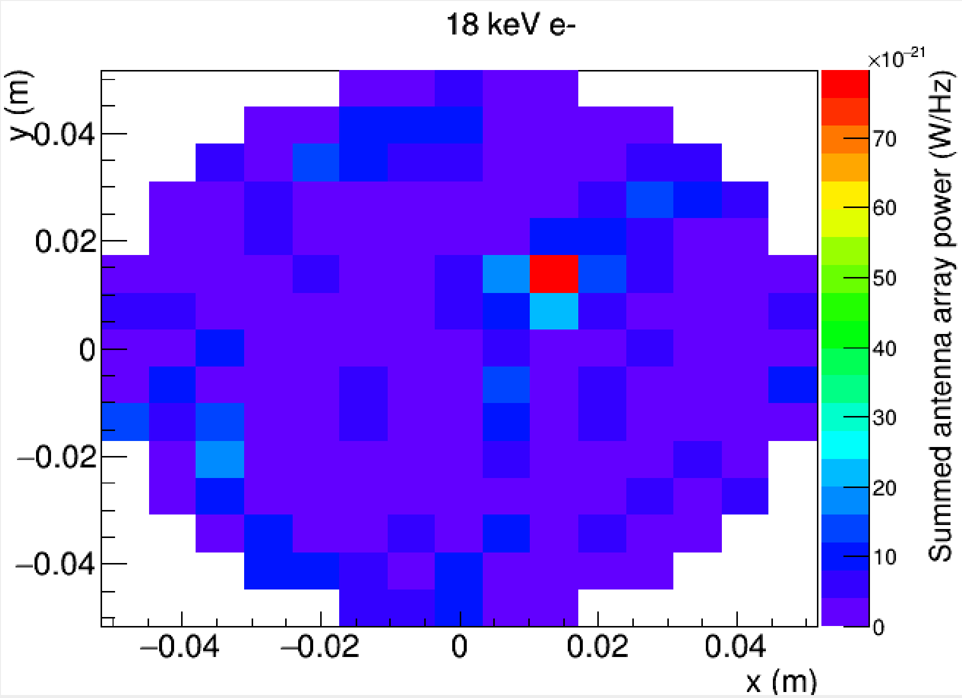
One amplifier per longitudinal strip for phased summing in time domain.

Locust example 4: Multiple receiver channels

- Check the Locust config file:
  - emacs ~/locust_mc/Config/NNPSSTutorial/LocustPhase3Template.json
  - Find the “simulation” config parameters, where “n-channels” is set to 30.
  - Check which generators will be called: “patch-signal”, “lpf-fft”, “decimate-signal”, “digitizer”.
- Check the slurm bash script:
  - emacs ~/project8/manageTutorial/SimulateMultichannel
  - Notice we request 12 cpus, which is more than for the single channel simulation.
  - Note ntask=1 still, even with multiple threads and channels.

Locust example 4: Magnetically trapped electron radiates in free space with 30 antennas

- Run the simulation:
  - cd ~/project8/manageTutorial
  - ./SimulateMultichannel
  - squeue -u netID
  - ~3 hours later it will finish.
- Process pre-existing data
  - ./ProcessMultichannelEggFiles
  - root -l
  - .L ChannelSumming.c
  - beamform()

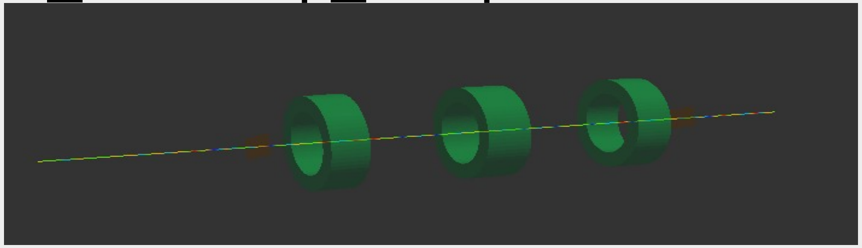


Reconstructed electron position from phase-sensitive sum

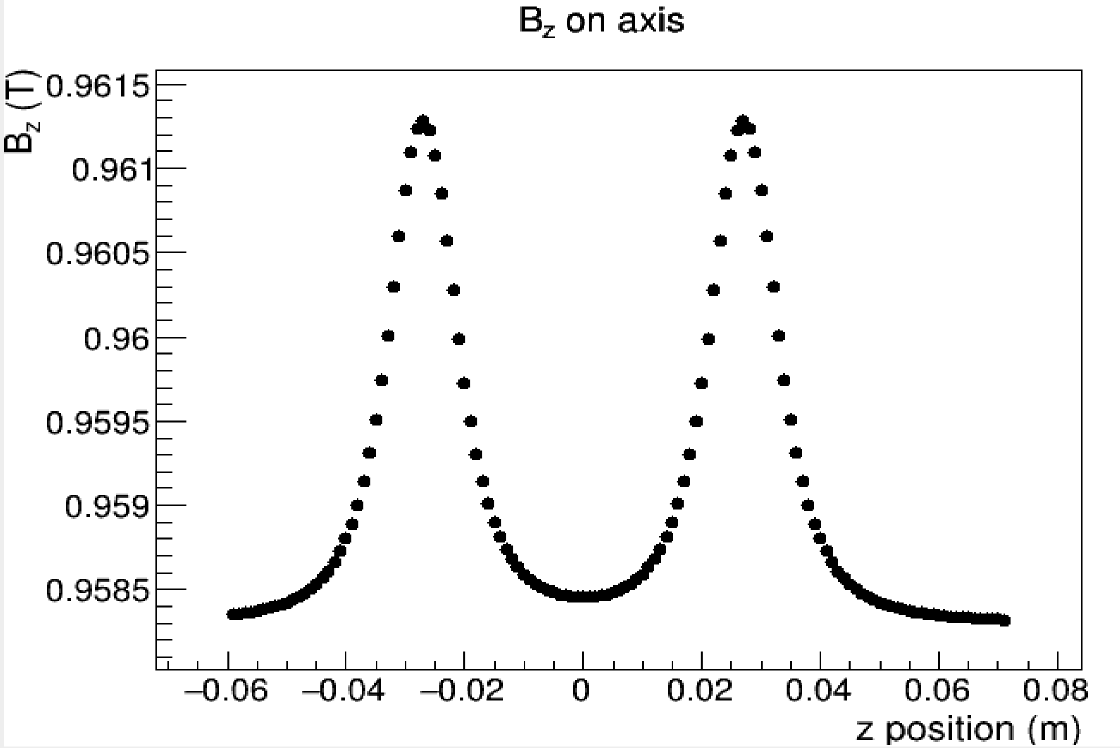
Simulation development by P. Slocum, N. Buzinsky, N. Oblath, T. Wendler

Locust example 5: Check the magnetic field map

- Kassiopeia contains a trajectory gen_bfieldlines for a charged particle moving along a selected field line.
- This is implemented in Project8Tutorial_FieldMap_Template.xml, called by Locust_FieldMap.json
  - cd ~/project8/manageTutorial
  - srun --x11 --pty -c 4 -p interactive bash
  - LocustSim config=~/locust_mc/Config/NNPSSTutorial/LocustFieldMap.json



- Plot the field map:
  - root -l
  - .L PlotFieldMap.c
  - fieldmap()



Tutorial and scripts in repositories on Github

- Simulation
  - https://github.com/project8/locust_mc.git
  - Configuration files are in the same directory referenced in this tutorial: ~/locust_mc/Config/NNPSSTutorial/ .
- Interpretation scripts
  - https://github.com/project8/scripts.git
  - Files in repository directory ~/scripts/NNPSSTutorial/ are the same as those used in this tutorial, in the directory ~/project8/manageTutorial/ .

Summary

- RF signal generation can be simulated with the Locust simulation.
  - A time series of induced voltages can be calculated one sample at a time.
  - AM and FM modulation can be applied to the voltages.
- Processing the generated signal tells us what information we have detected about an experiment.
  - It's important to know which information we have not detected.
  - It's important to know whether (or not) we can reconstruct any missing information from the signal analysis.