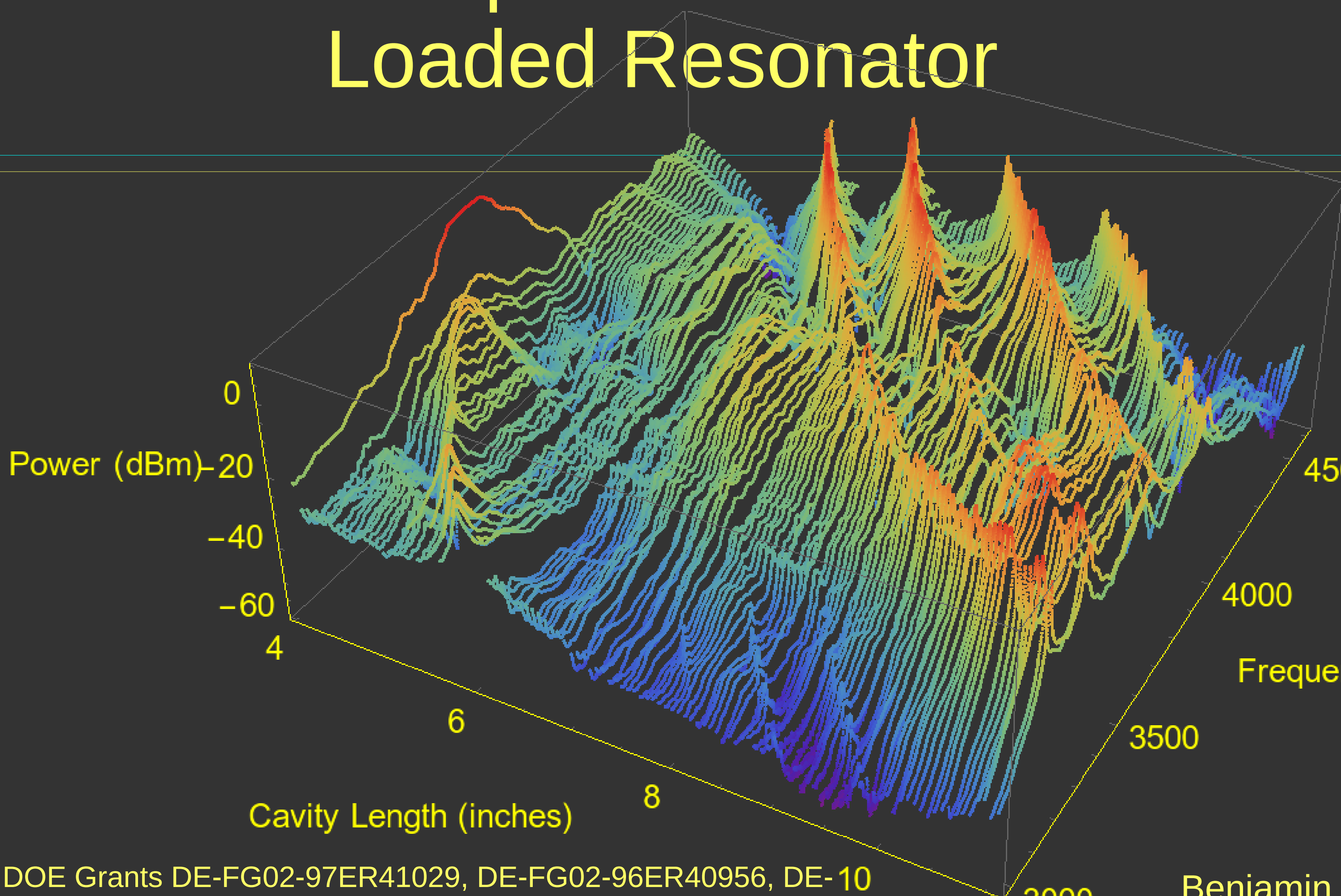
The Electric Tiger Experiment

a Proof-of-Concept for the Periodic Dielectric Loaded Resonator



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Benjamin J Phillips
UNIVERSITY of WASHINGTON

Motivation | Design Goals

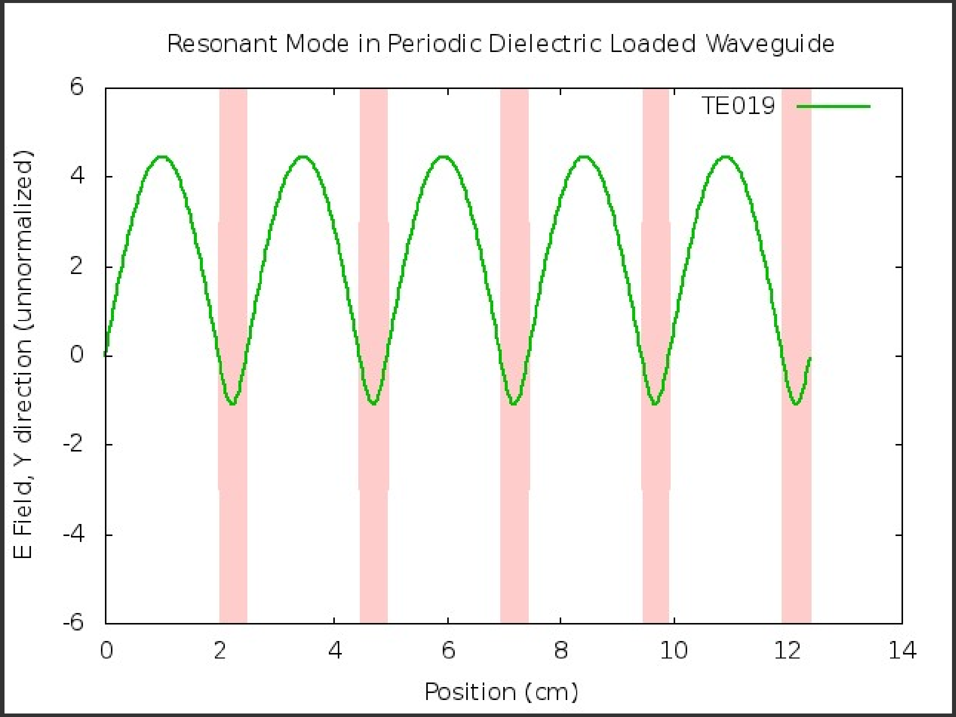
- Experiment to search high frequency regions (4 – 7 GHz)
- Rapid prototyping with on-hand materials
- Cavity is reasonably simple to tune (e.g. manageable mode crossings)
- Lay foundations for experiments that rely on dielectrics (very high frequency searches)

Motivation

The P.D.L.R. Design

- Makes use of dielectric media inside a resonant cavity
- Dielectric media compresses wavenumber – prevents form-factor integral from going to zero

$$F \propto \frac{\left(\int_V E \cdot B dV\right)^2}{\int_V E^2 dV \int_V B^2 dV}$$

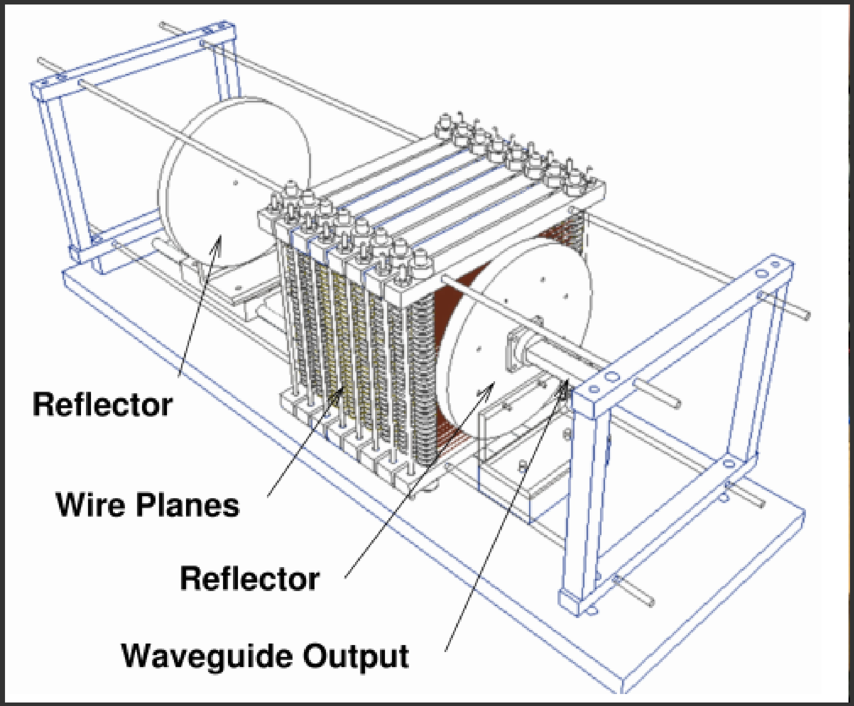


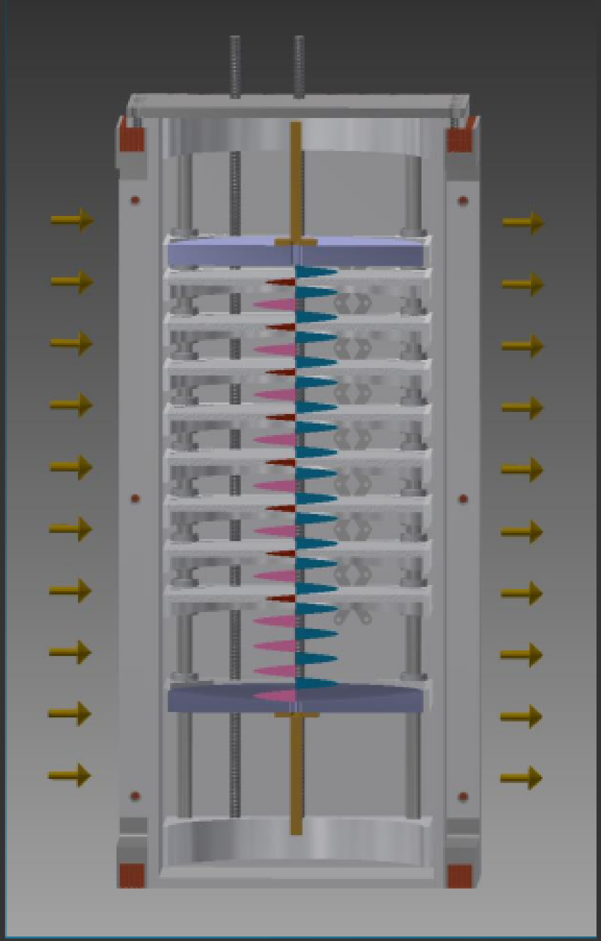
Motivation

Laying Foundations

- Resonant cavities that use dielectrics are difficult to tune – dielectrics have to be moved in unison

- Tuning procedures developed by Electric Tiger can be used by these types of experiments (e.g. Orpheus)

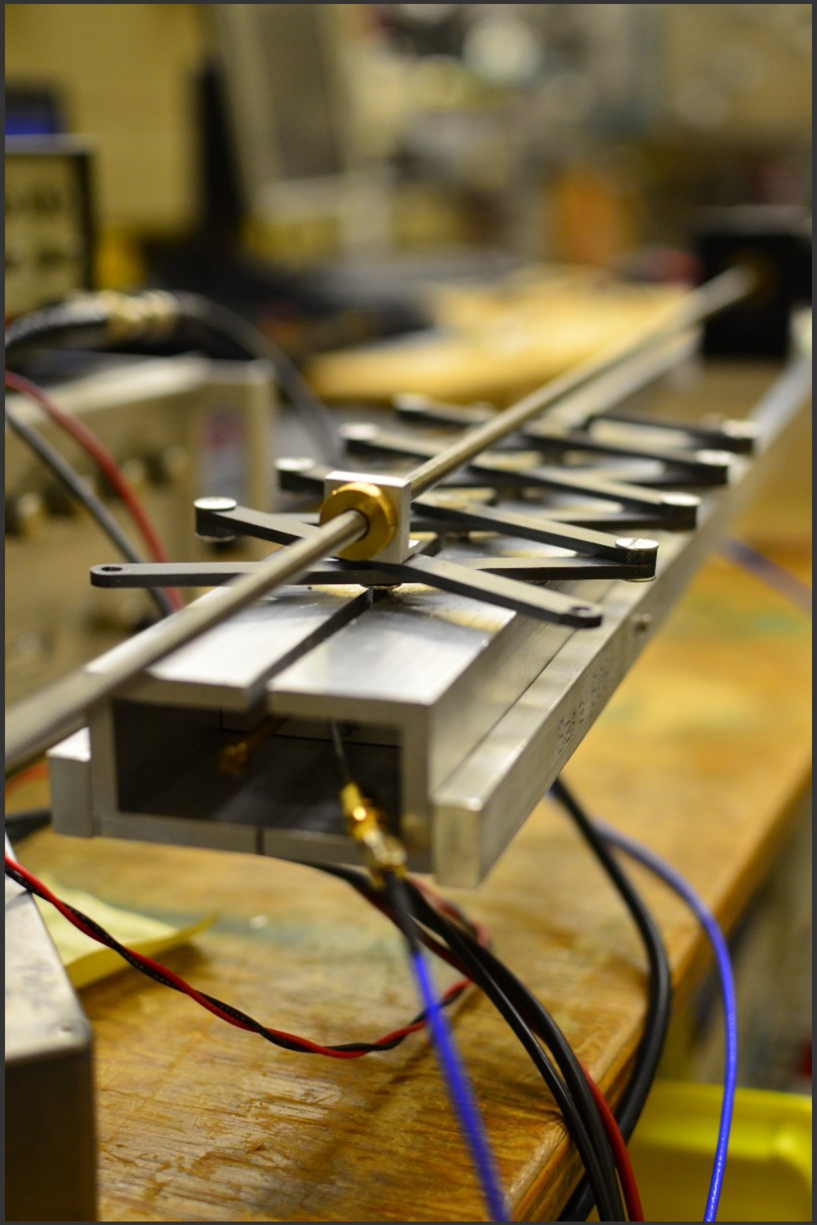




Implementation

Construction of Cavity

- Rectangular waveguide with one stationary antenna, one movable
- Dielectric media is provided by three nylon blocks
- Tuning is provided by scissor-jack and stepper motor driving auger screw
- Cavity length is measured by string potentiometer
- Cavity design limits mode Quality Factor



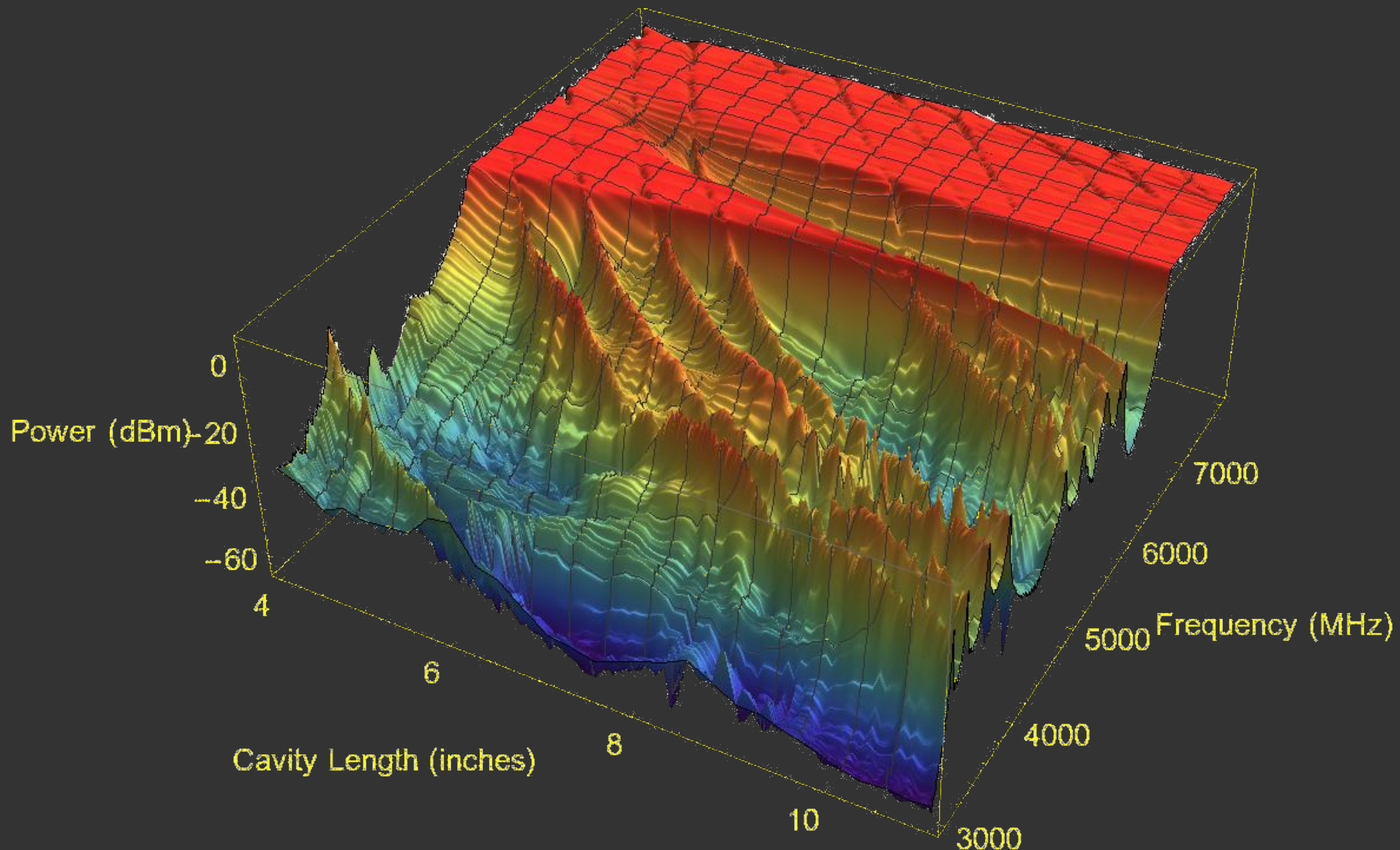
Implementation

Magnetic Field

- Rectangular cavity geometry permits use of constant z-axis magnetic field
- Magnetic field provided by 1.54 Tesla DC Magnet

Implementation

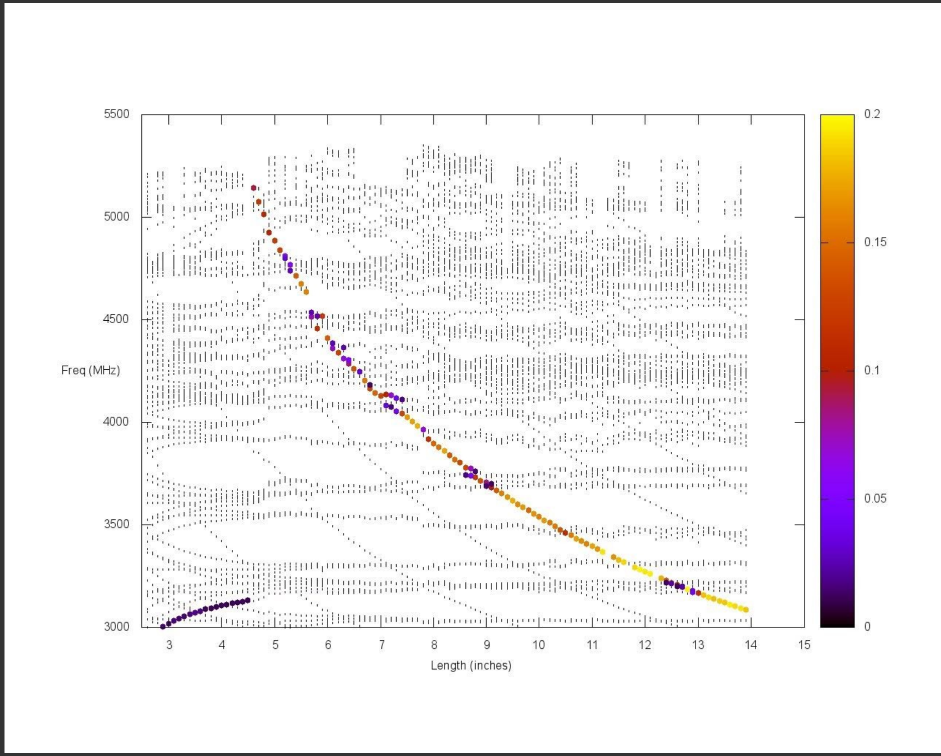
Cavity Structure (Transmission)

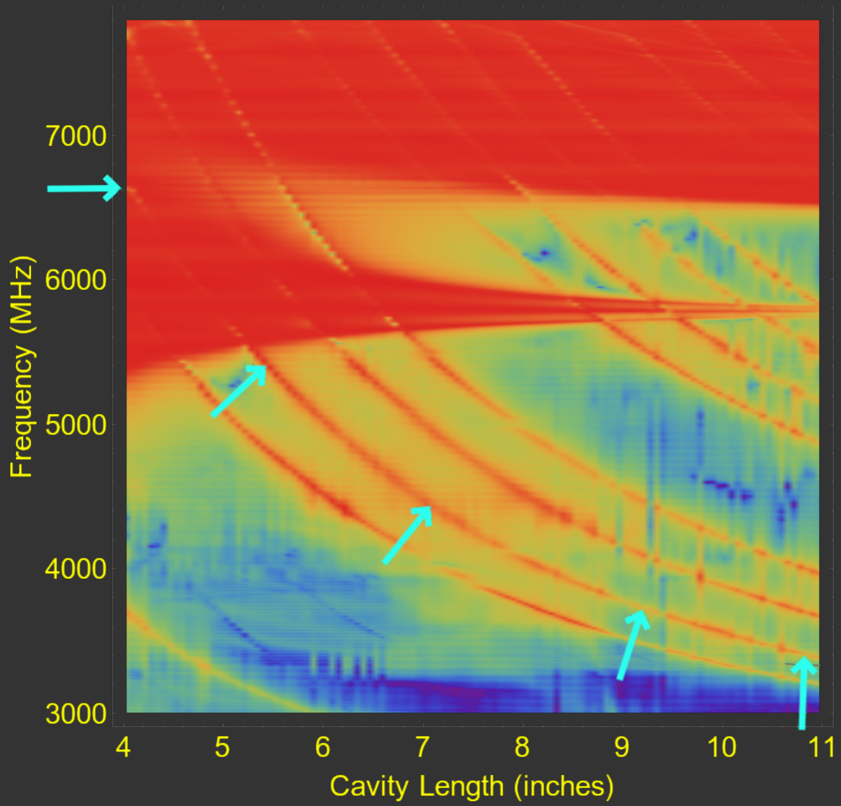


- Cavity has a non-trivial amount of static structure
- Modes are broad and amplitude is not always significantly higher than static structure

Implementation

Cavity Structure (Transmission)

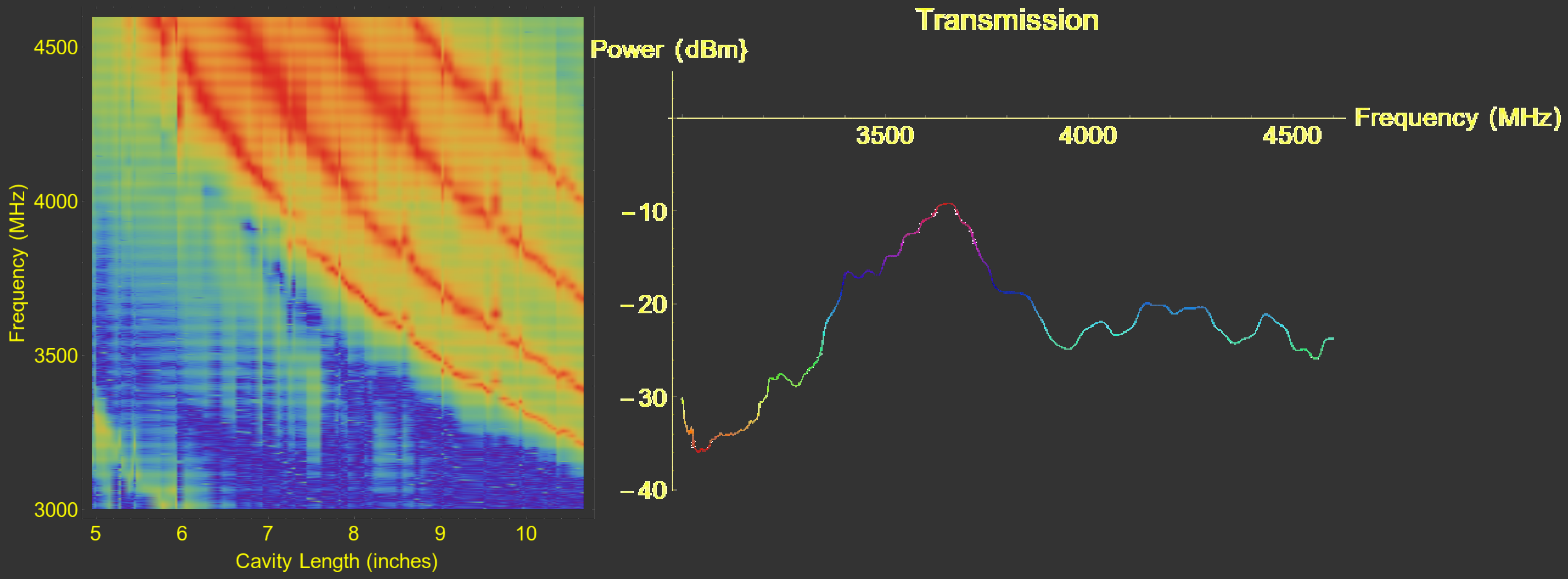




- Simulations of cavity determines mode that couples best with axion field
- Mode moves over a wide frequency range, ~3.5 – 6.5 GHz, including regions currently blocked by RF components

Implementation

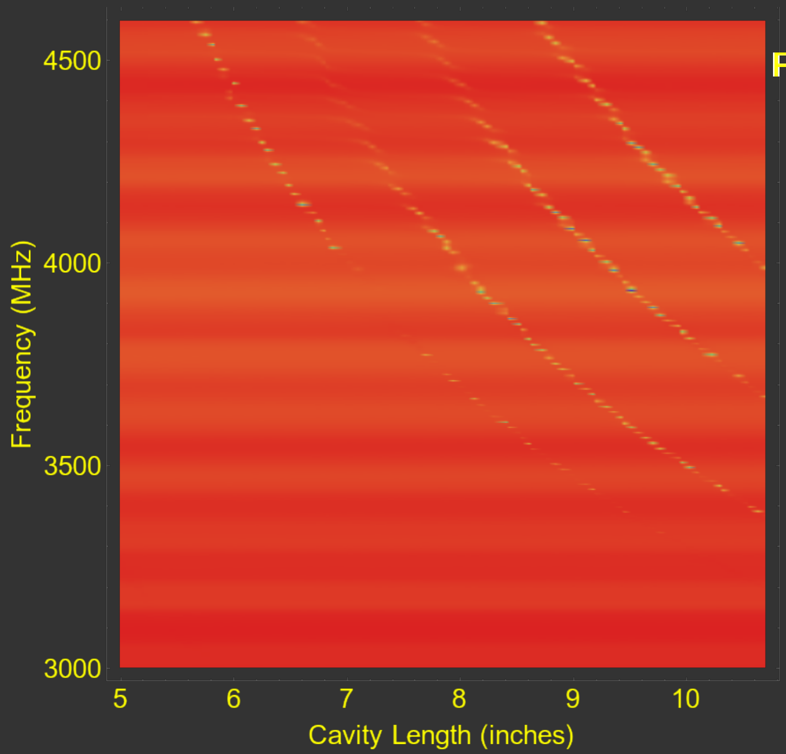
Transmission

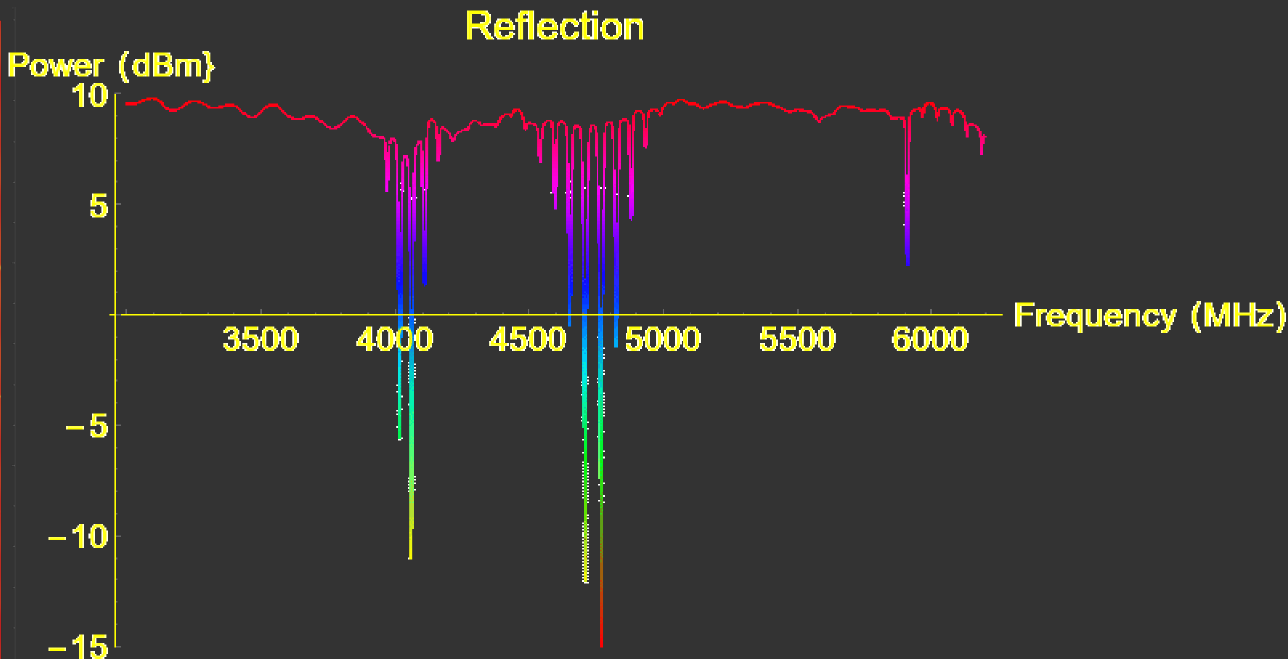


- Static structure in transmission measurements makes modes difficult to follow
- Q's of ~ 250
- Traditional approaches (e.g. Lorentzian fitting) are unsuitable

Implementation

Reflection





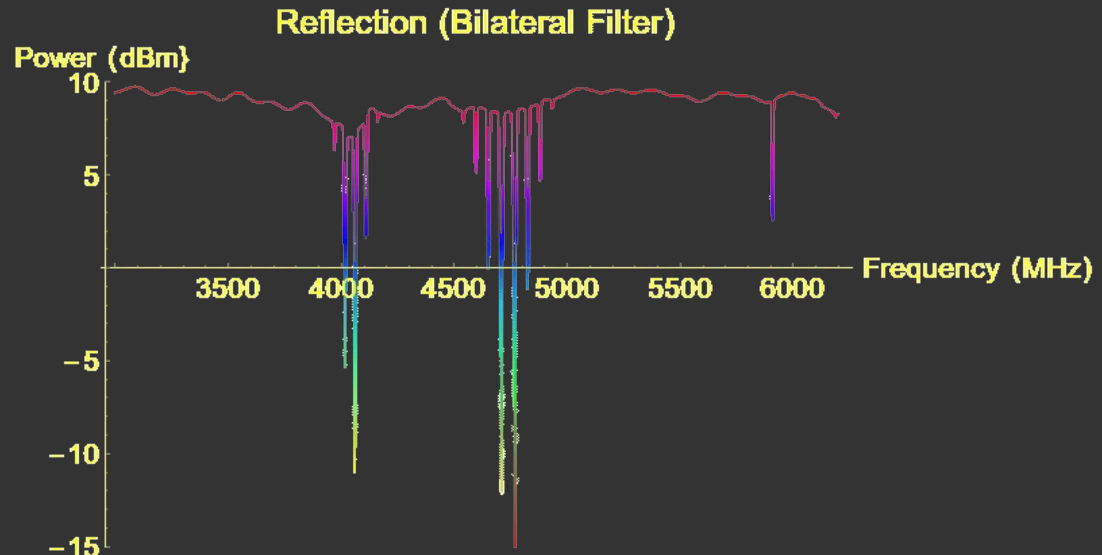
- Reflection modes show much less static structure

- Strategy: Identify and follow modes in reflection, switch to transmission to take data

Implementation

Filtering

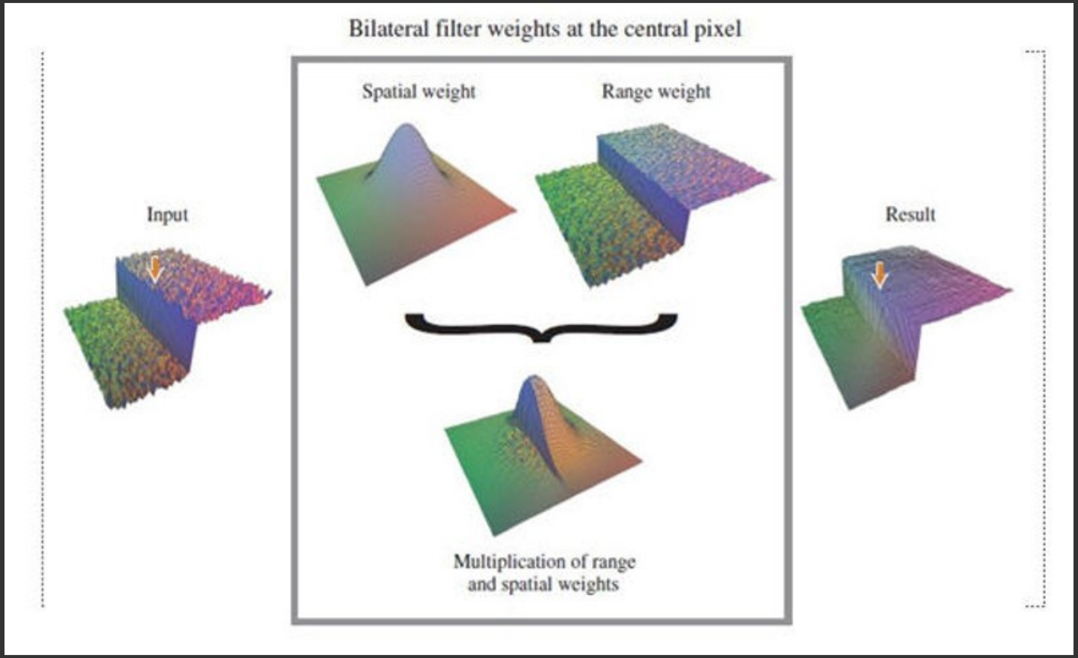
- Even in reflection, traditional mode-tracking techniques are not appropriate
- Simple band-pass filters either suppress actual peaks, or amplify static structure
- Solution: Use non-linear filters – suppress noise while preserving peaks



Implementation

Non-Linear Filters

- Mode Identification scheme only needs heuristic idea of what a peak is
- Criteria is ~ f'[n] < 0 & f'[n+1] > 0
- Since we only need a loose idea of what a peak is, namely that it is 'sharp', we can use filters that do not linearly modify signal power
- Use bilateral filter, a specific example of a non-linear convolution



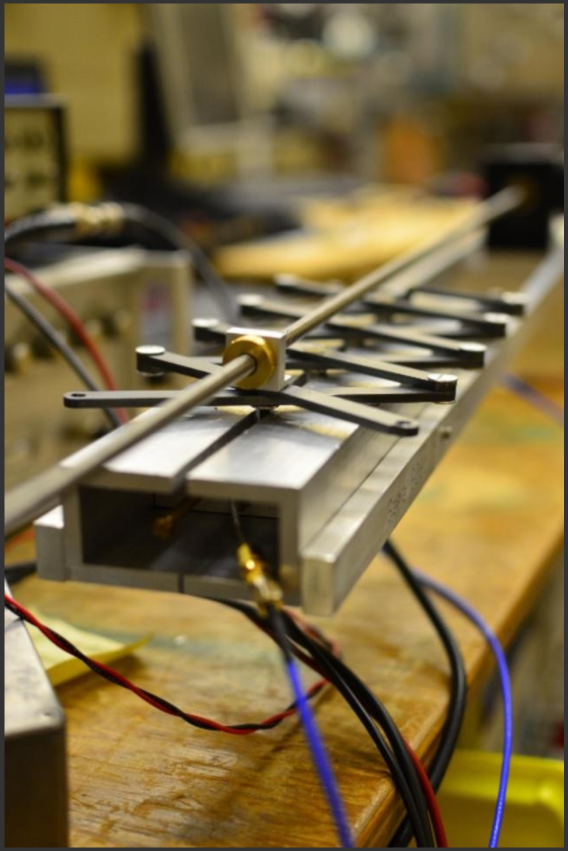
$$f * g(n) \equiv \sum_{k=-M}^{M} f(k)g(f(n) - f(k))h(n-k)$$

Let G_{σ_s} and G_{σ_r} be Gaussians with σ_s and σ_r respectively

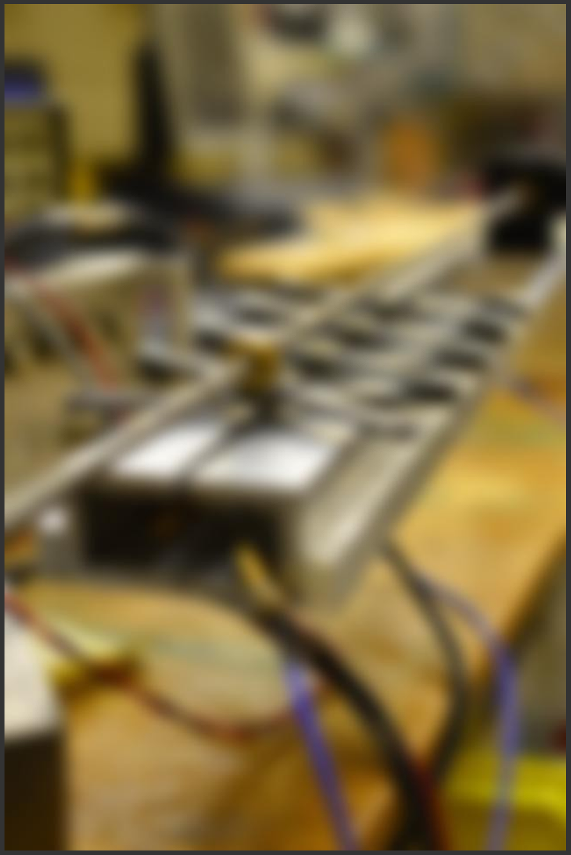
$$BL(n) = \sum_{k=-M}^{M} f(k)G_{\sigma_r}(f(n) - f(k))G_{\sigma_s}(n-k)$$

Implementation

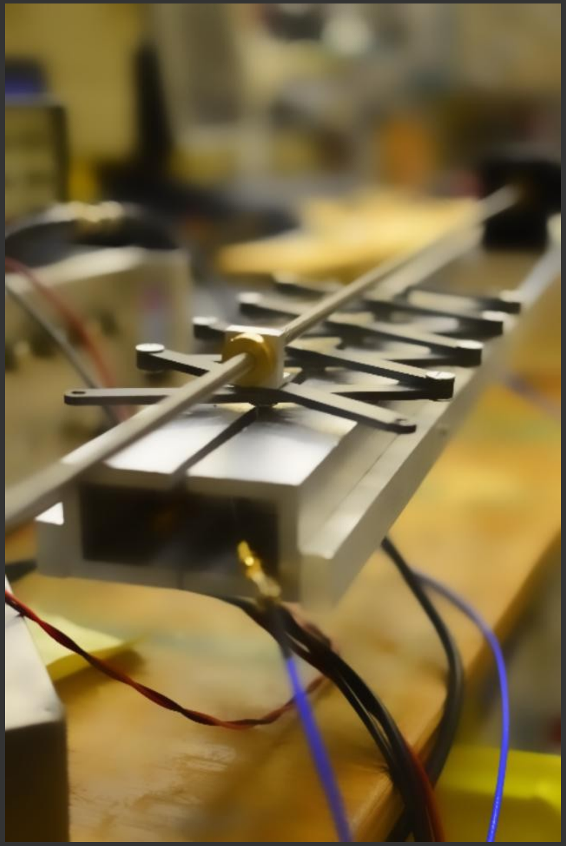
Non-Linear Filters



Original



Gaussian Blur



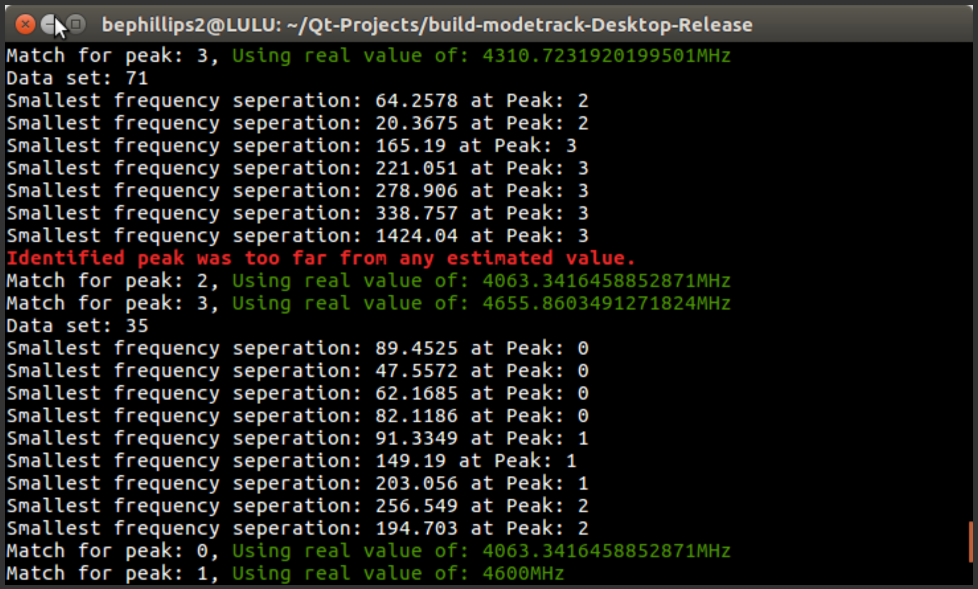
Bilateral Filter

- Effects of Bilateral filter are more obvious when looking at 2D figures
- Low-pass filters (Gaussian Blurs) suppress noise, but erase features
- Bilateral filter suppresses noise while preserving edges

Implementation

Thoughts on Mode Maps

- Why not rely on the mode map alone?
- Electric Tiger has a high degree of mechanical slop
- Modes tend to vanished at certain cavity positions
- Goal is to divorce mode tracking procedure from mode map
- Current mode tracking procedure uses mode map – real peaks can be ~ 175 MHz away from mode map



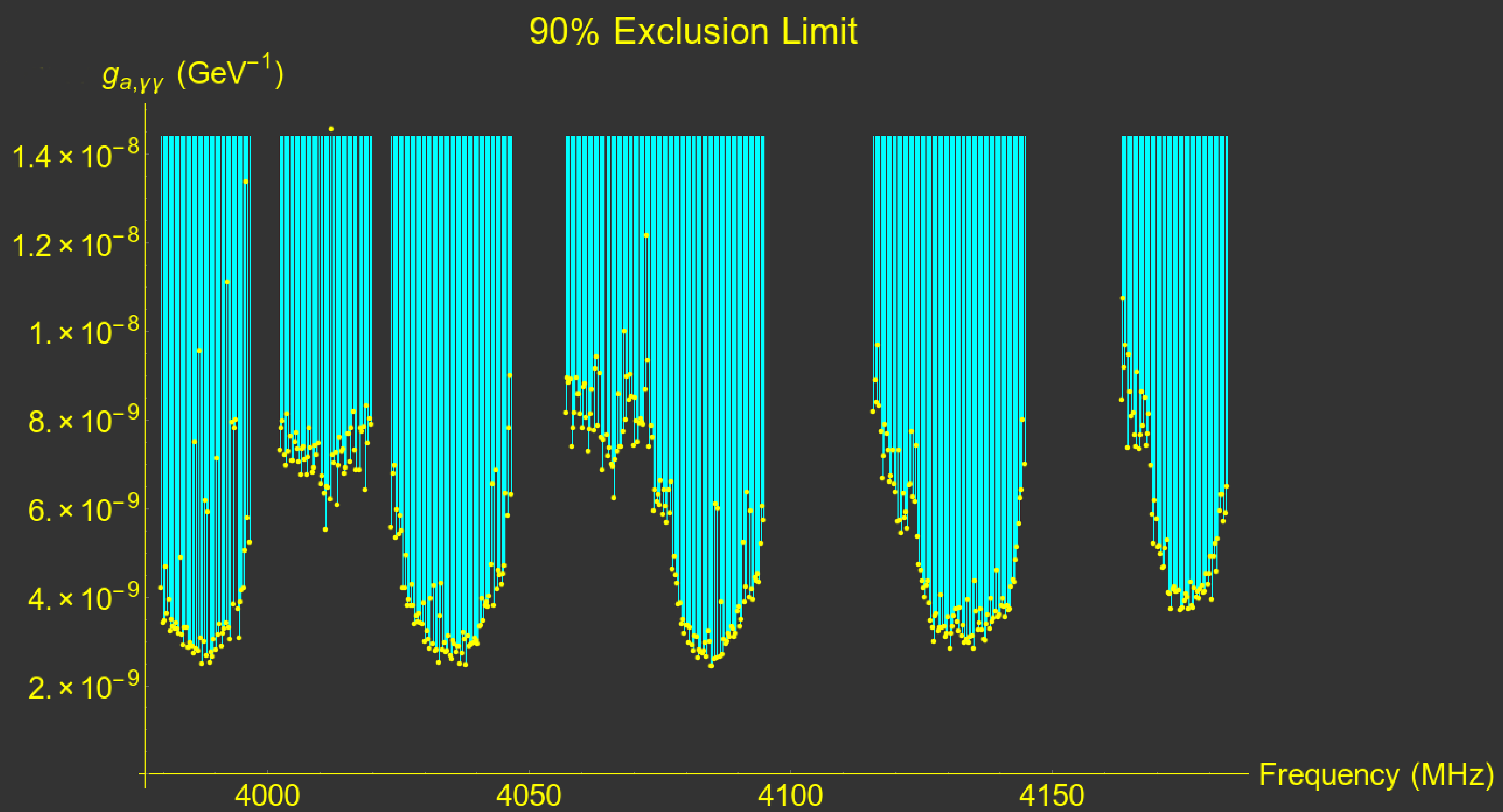
Data Collection

Preliminary Results

- Initial data run performed at room temperature
- Exclusion limits set in 4-4.2 GHz Range using rudimentary equipment
- Sensitivities of ~10^{-9}
- Mode tracking scheme was able to follow modes throughout tunable range
- Experiment ran autonomously for ~8 days

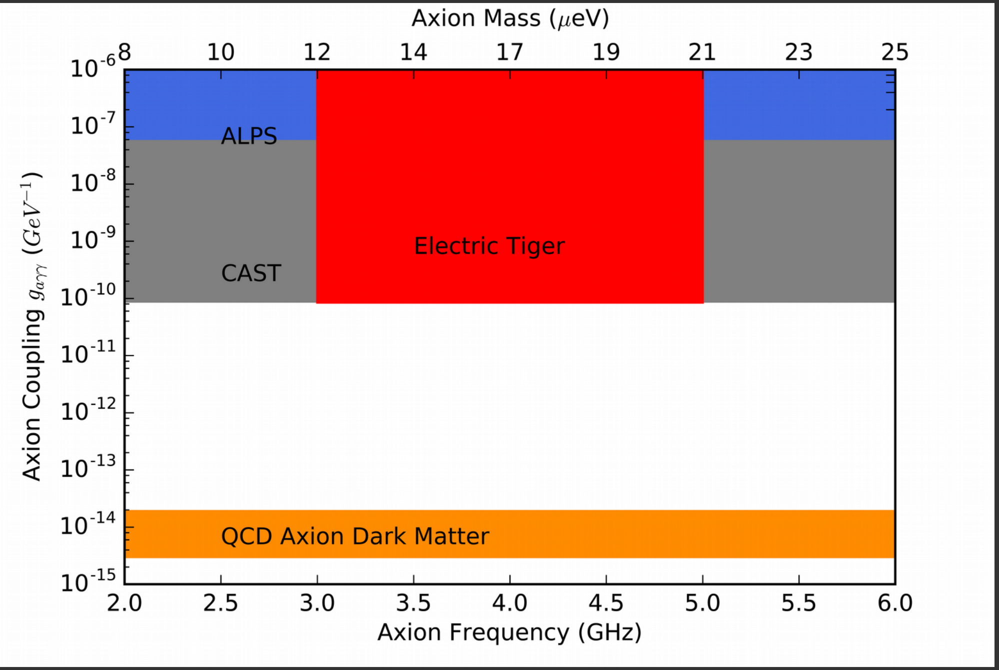
Data Collection

Preliminary Results



Data Collection

Next Steps



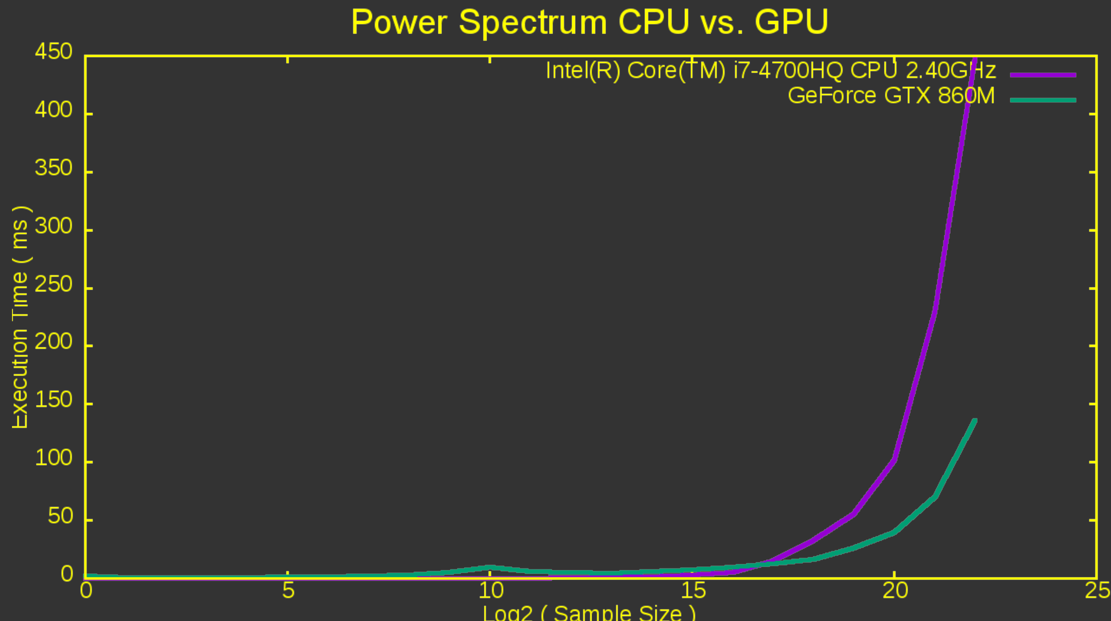
Projected Sensitivity for 8 week integration time

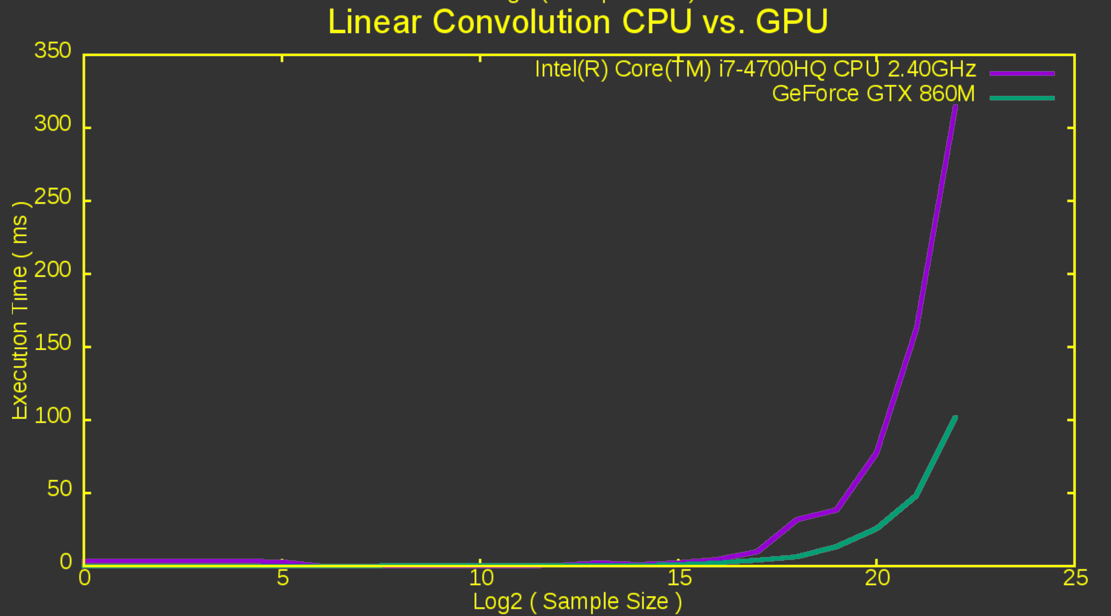
- Initial data run made use of Signal Analyzer – collected ~10^5 points per spectra, averaged ~10^4 signals
- Next data run will make use of digitizer – 10^8 points per spectra, virtually unlimited number of averages
- Longer integration times
- Cryogenic temperatures

"Side Effects"

High Performance Signal Processing

- Wide band-widths and fast digitization rates require very fast data processing
- Use GPU for signal processing operations to keep up with data stream
- GPU - accelerated methods are completely general and can be used by other experiments





"Side Effects"

Analysis Procedures

- Analysis procedure developed by Electric Tiger is generic
- Applicable to wide variety of resonate cavity searches
- May be incorporated into ADMX analysis in the near future

Algorithm 7 Construction of the Grand Spectrum

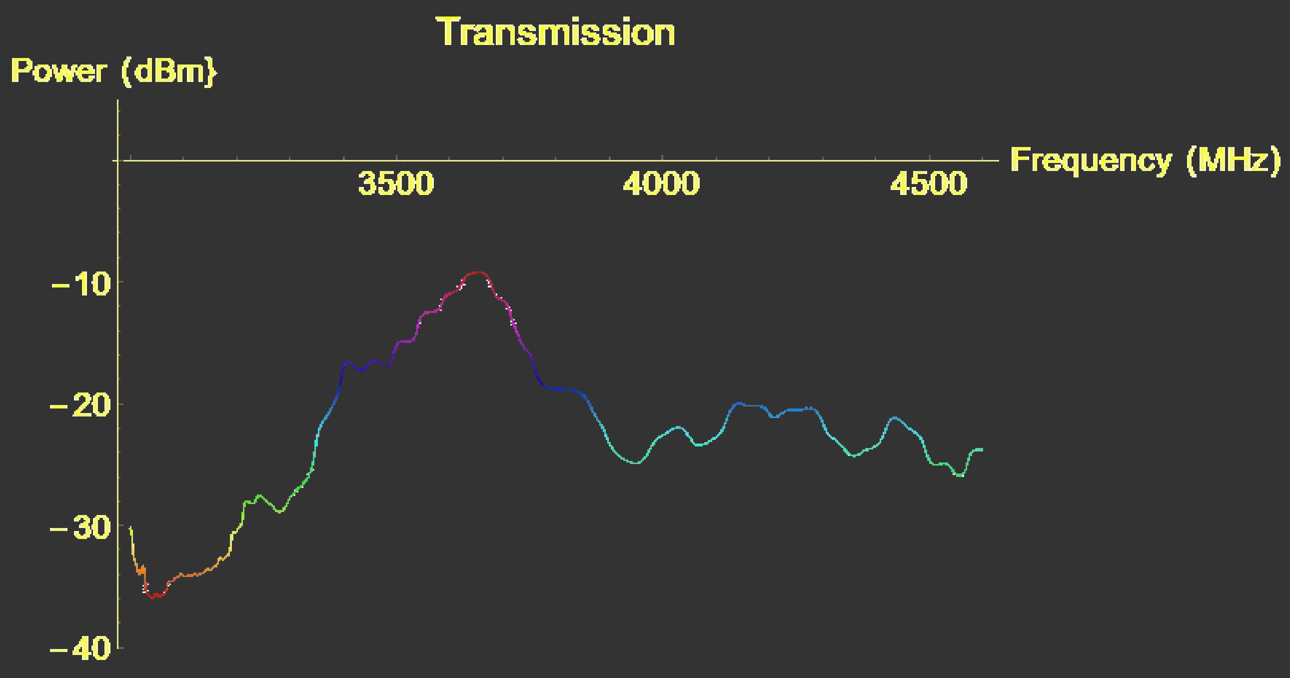
Input: $\mathcal{S}$

Let $k = \lfloor (f_{max} - f_{min})/bw \rfloor$
Let GS $= 0_{2,k}$
for each k **do**
  Let $f_{center} \leftarrow$ center frequency of bin k
  for each $s \in \mathcal{S}$ **do**
    if $f_{center} \in \Omega_s$ **then**
      $j \leftarrow$ bin at $\omega_s^{-1}(f_{center})$
      if $GS_{1,k} \neq 0$ **then**
        Let $\tau_0 \leftarrow \frac{1}{\delta_{GC}(k)^2}$
        Let $\tau_1 \leftarrow \frac{1}{\delta_{S_i}(j)^2}$
        $GS_{1,k} \leftarrow \frac{\tau_0 * GC(k) + \tau_1 * S_i(j)}{\tau_0 + \tau_1}$
        $GS_{2,k} \leftarrow \sqrt{\frac{1}{\tau_0 + \tau_1}}$
      else $GS_{1,k} = 0$
        $GS_{1,k} \leftarrow s_{1,k}$
        $GS_{2,k} \leftarrow s_{2,k}$
      end if
    else $f_{center} \notin \Omega_s$
      continue
    end if
  end for
end for

Output: GS

Conclusion

The two roles of Electric Tiger



- Platform to address concerns raised by other searches
- Electric Tiger is validation of the P.D.L.R. Design – will search in unexplored axion-like particle parameter space