LC Circuit Based Low-Frequency Axion Search

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LLNL Microwave Cavity Workshop
Gainesville, FL
1/12/2017

Outline

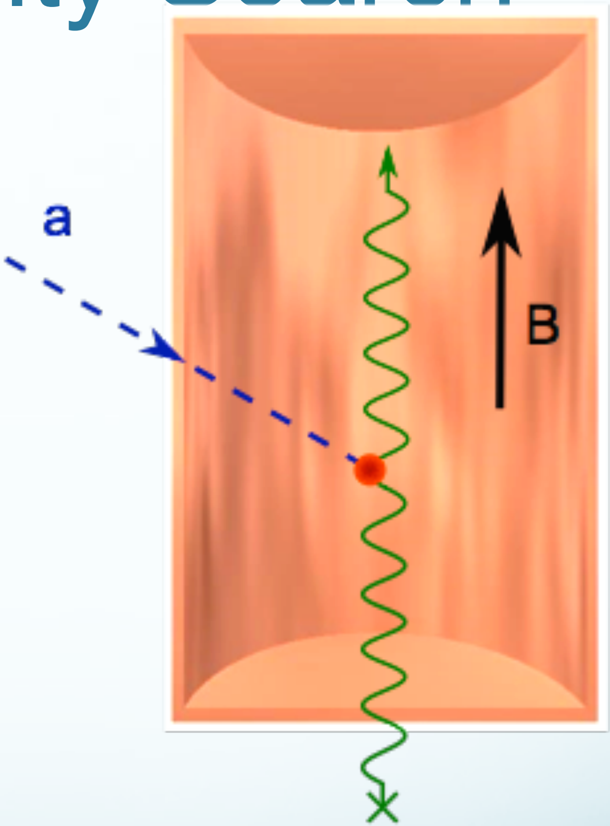
- Introduction and Background
  - Introduction to the Axion
  - ADMX Microwave Cavity Search
  - LC Circuit Low Frequency Search
- Work Completed So Far
  - Loop Antennae
  - Varactor Tuning
  - 4K Dunk Tests
  - Shielding
- Future Proposed Work

The Axion

- Comes from a possible resolution the Strong CP problem
- Weakly interacting, massive, pseudoscalar Goldstone Boson
- Light axions are a good cold dark matter candidate
- We should look for it!

ADMX Microwave Cavity Search

- Sikivie Haloscope Detection Scheme
- Current ADMX strategy
- Hard to scale in size for lower frequencies



Proposal for Axion Dark Matter Detection Using an *LC* Circuit

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Department of Physics, University of Florida, Gainesville, Florida 32611, USA
(Received 31 October 2013; revised manuscript received 22 January 2014; published 31 March 2014)

We show that dark matter axions cause an oscillating electric current to flow along magnetic field lines. The oscillating current induced in a strong magnetic field $\vec{B}_0$ produces a small magnetic field $\vec{B}_a$. We propose to amplify and detect $\vec{B}_a$ using a cooled *LC* circuit and a very sensitive magnetometer. This appears to be a suitable approach to searching for axion dark matter in the 10^{-7} to 10^{-9} eV mass range.

DOI: 10.1103/PhysRevLett.112.131301 PACS numbers: 95.35.+d, 14.80.Va

LC Circuit Idea

- Axion field alters Maxwell's Equations

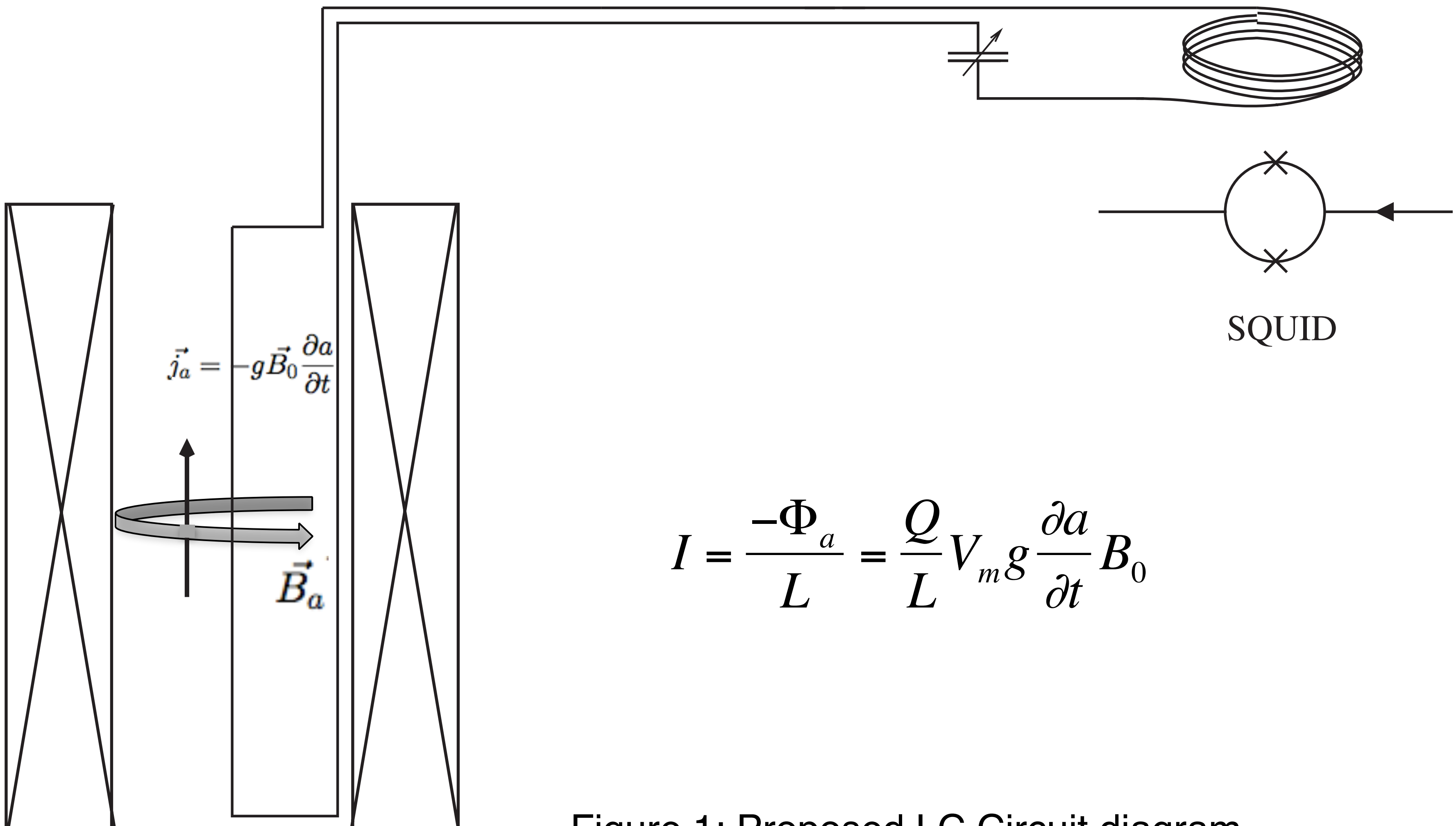
$$\vec{\nabla}\cdot \vec{E} = g\vec{B}\cdot \vec{\nabla}a + \rho_{el}$$

$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = g(\vec{E} \times \vec{\nabla}a - \vec{B}\frac{\partial a}{\partial t}) + j_{el}$$

- In the presence of an external magnetic field $\vec{B}_0$

$$\vec{\nabla} \times \vec{B}_a = \vec{j}_a = -g\vec{B}_0 \frac{\partial a}{\partial t}$$

LC Circuit Sketch



$$I = \frac{-\Phi_a}{L} = \frac{Q}{L} V_m g \frac{\partial a}{\partial t} B_0$$

Figure 1: Proposed LC Circuit diagram, adapted from [1] Sikivie et al.

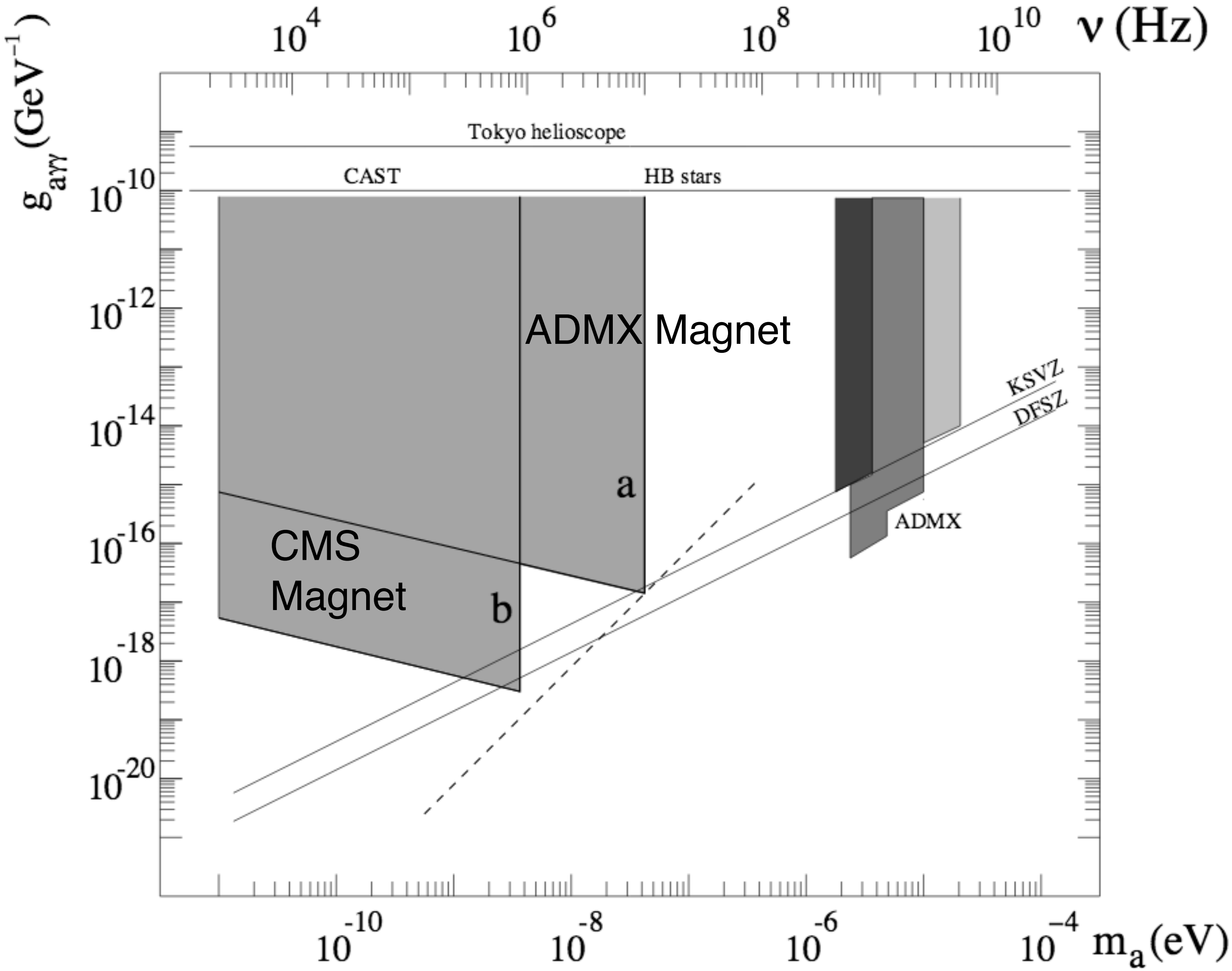
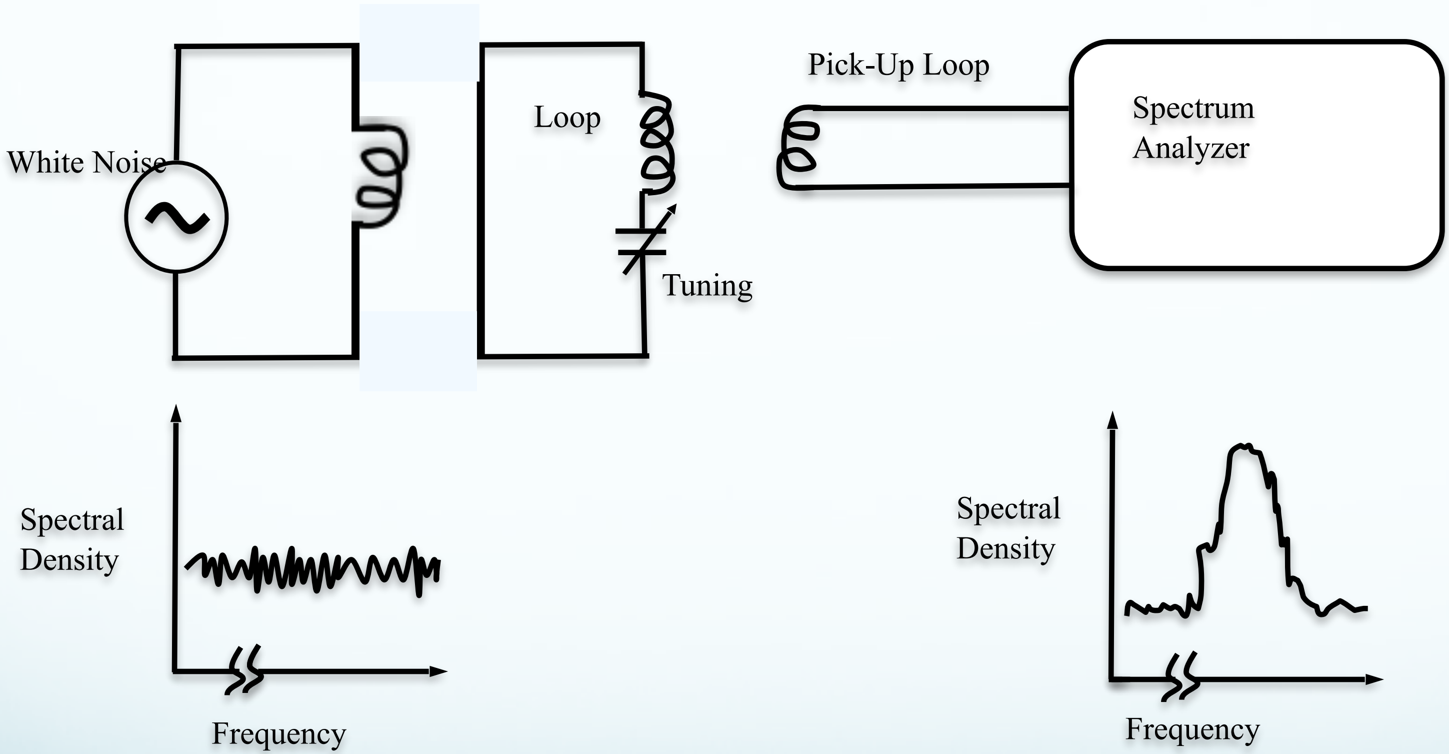


Figure 2: ADMX past and present search results and future LC circuit exclusion, adapted from [1] Sikivie et al.

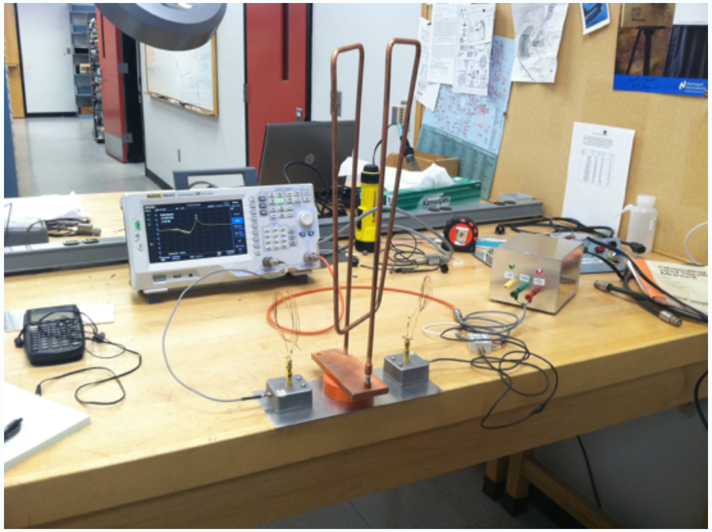
Overall Design Strategy

- For a significantly sensitive search:
  - need a high Q
  - need tunability
- Build loops and measure performance metrics
- Understand losses limiting these metrics

Prototype Testing



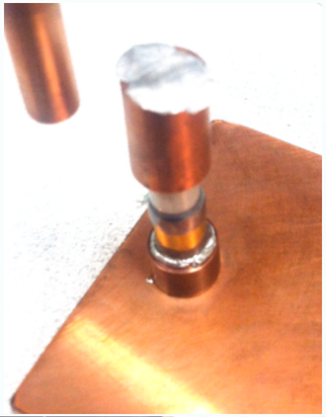
First Loop: Room Temperature



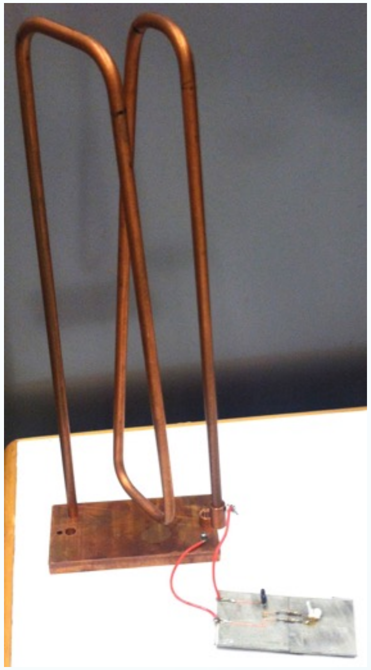
- Dimensions
  - 11 cm x 36 cm
  - L = 1.23 µH
  - C = 1–30 pF (Piston Trimmer)
- Tuning Range
  - 22 MHz – 50 MHz
  - Looks like limiting stray capacitance ≤ 8 pF
- Q = 339@22MHz
- Q = 357@22MHz with Indium-Filled Junctions
- Q = 600@25MHz in Dewar

First Loop: 77K

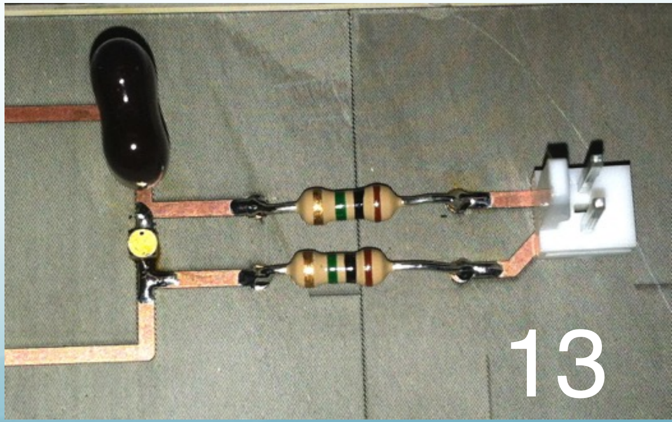
- Initial cooling attempt failed….
- Shimmed indium in all junctions
- Did see improvements from cooling!
  - Q = 934 @21.3 MHz
  - Q = 1092 @21.3 MHz (weaker coupling)
  - Q = 1213 (1 hr settling)

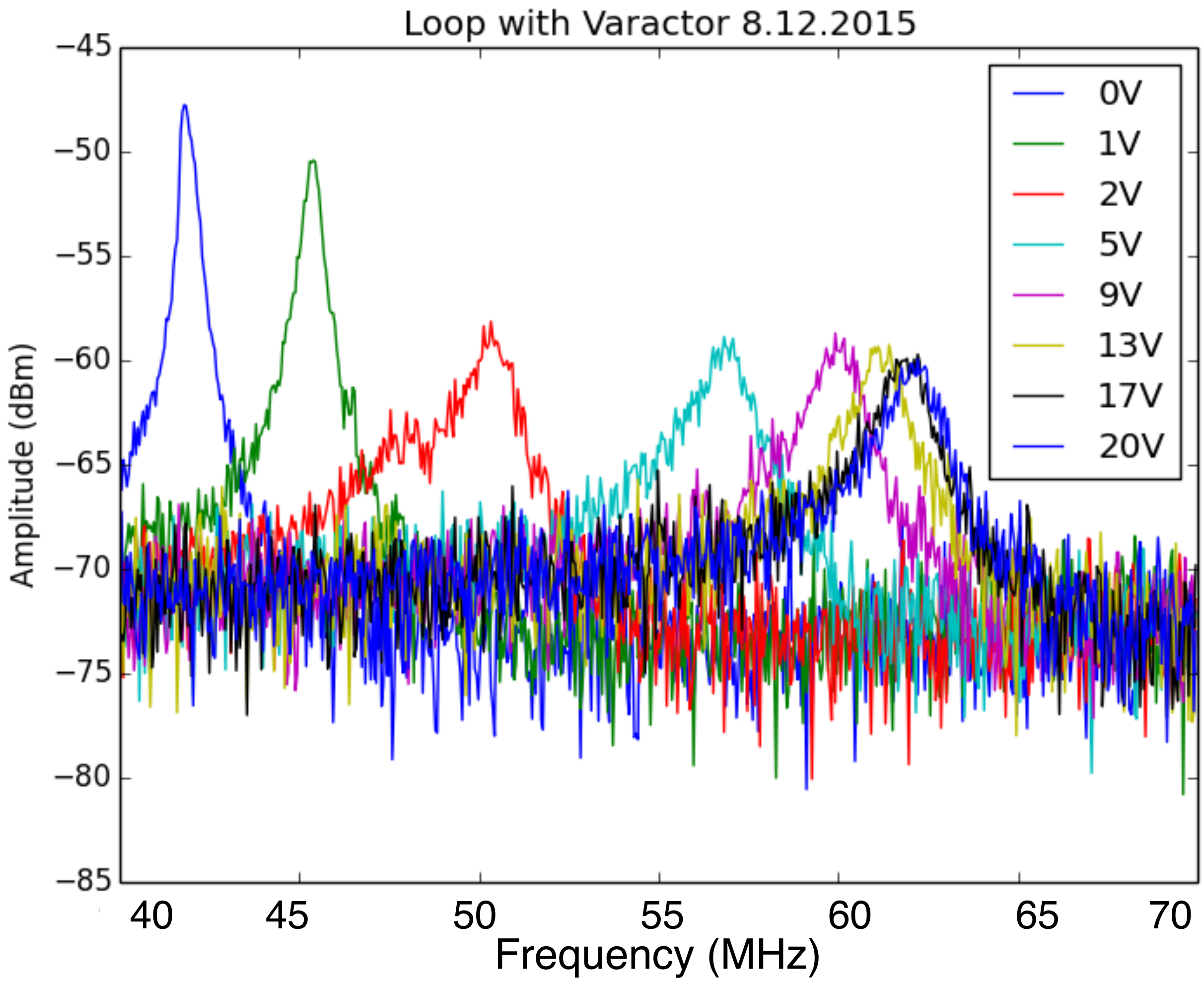


Varactor Tuning



- Voltage-tuned variable capacitor
- Advantages over mechanical tuning
- MACOM MA46H202-1056
  - 0.6pF-10pF (20V-0V)
  - Q~2000 (50MHz, 4V)




Loop with Varactor 8.12.2015
Amplitude (dBm)
Frequency (MHz)
0V
1V
2V
5V
9V
13V
17V
20V
−45
−50
−55
−60
−65
−70
−75
−80
−85
40
45
50
55
60
65
70

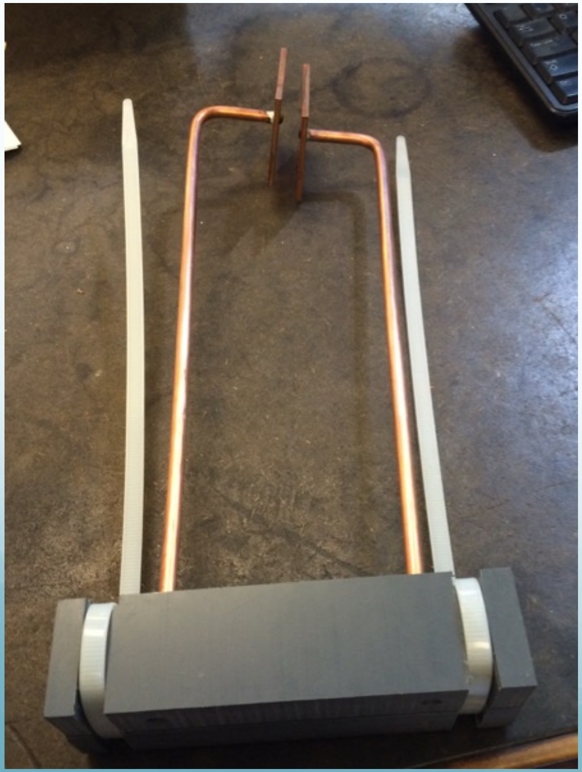
Q: 110-60

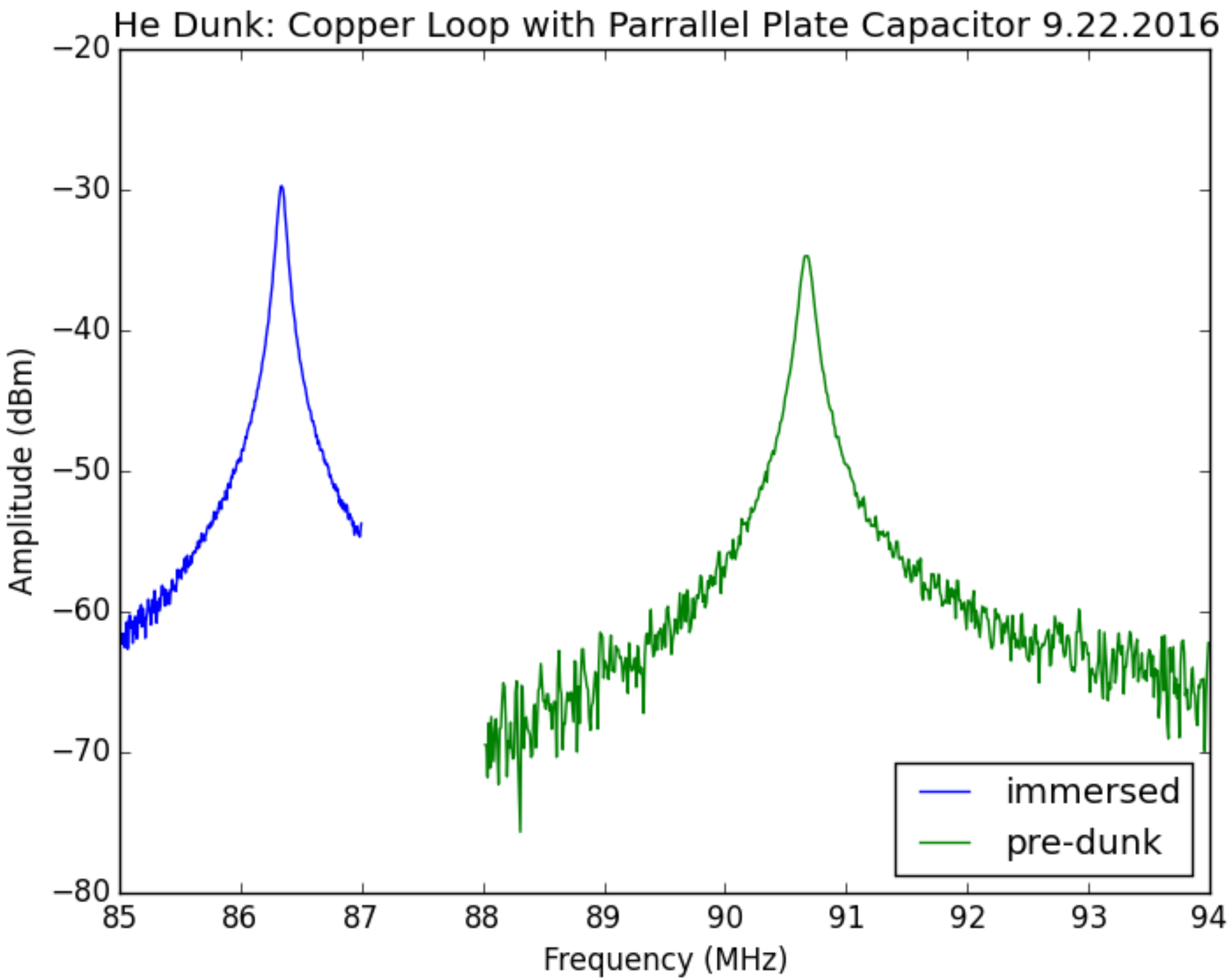
4K Dunk Setup

- Same resonant response measurements
- Electrically floated top plate
- Dunk results from:
  - copper loop with plate capacitor
  - copper loop with varactor tuning
  - NbTi loop with plate capacitor

Copper Loop Parallel Plate Capacitor

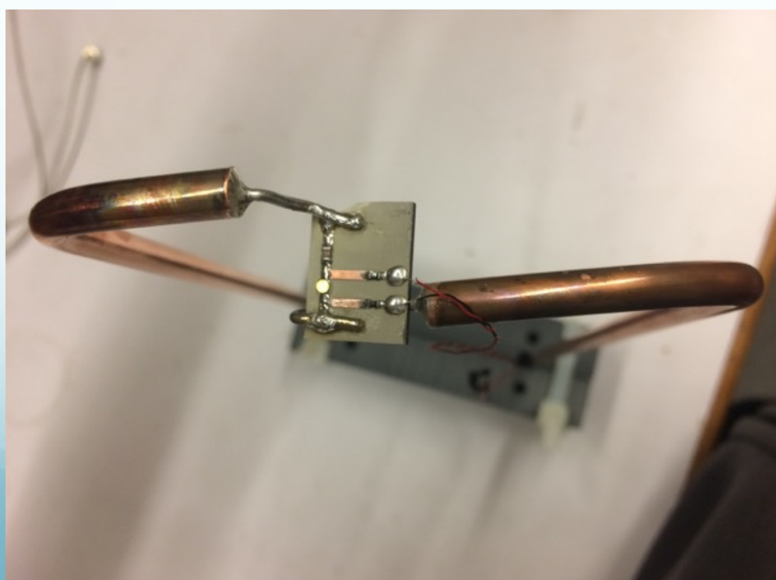
- Q~600 warm in dewar
- Max Q ~1150 immersed

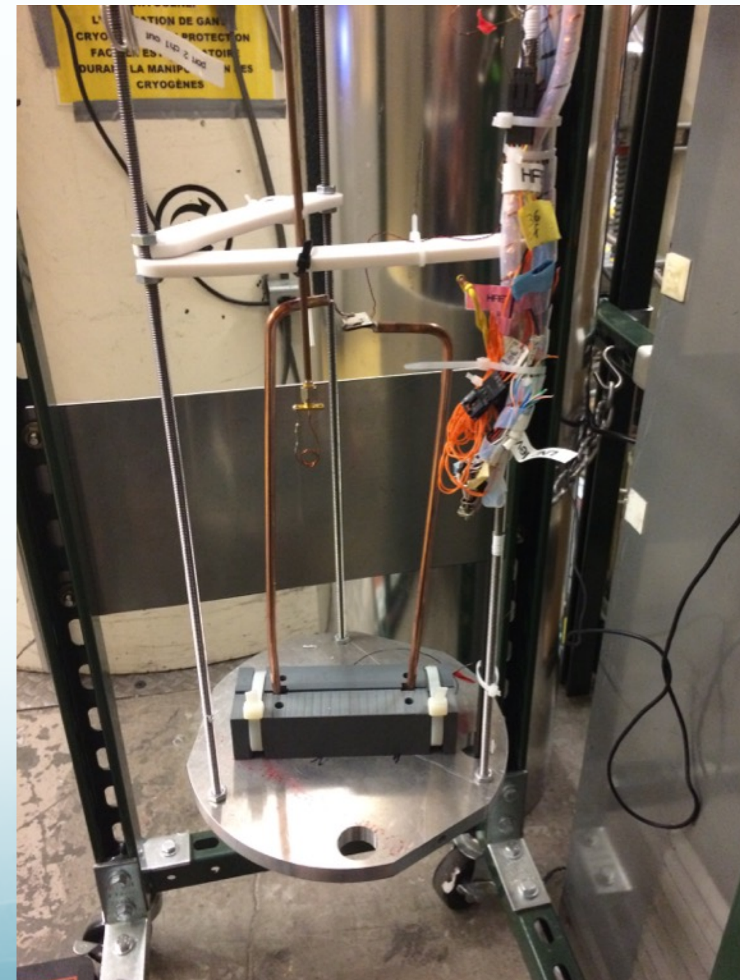


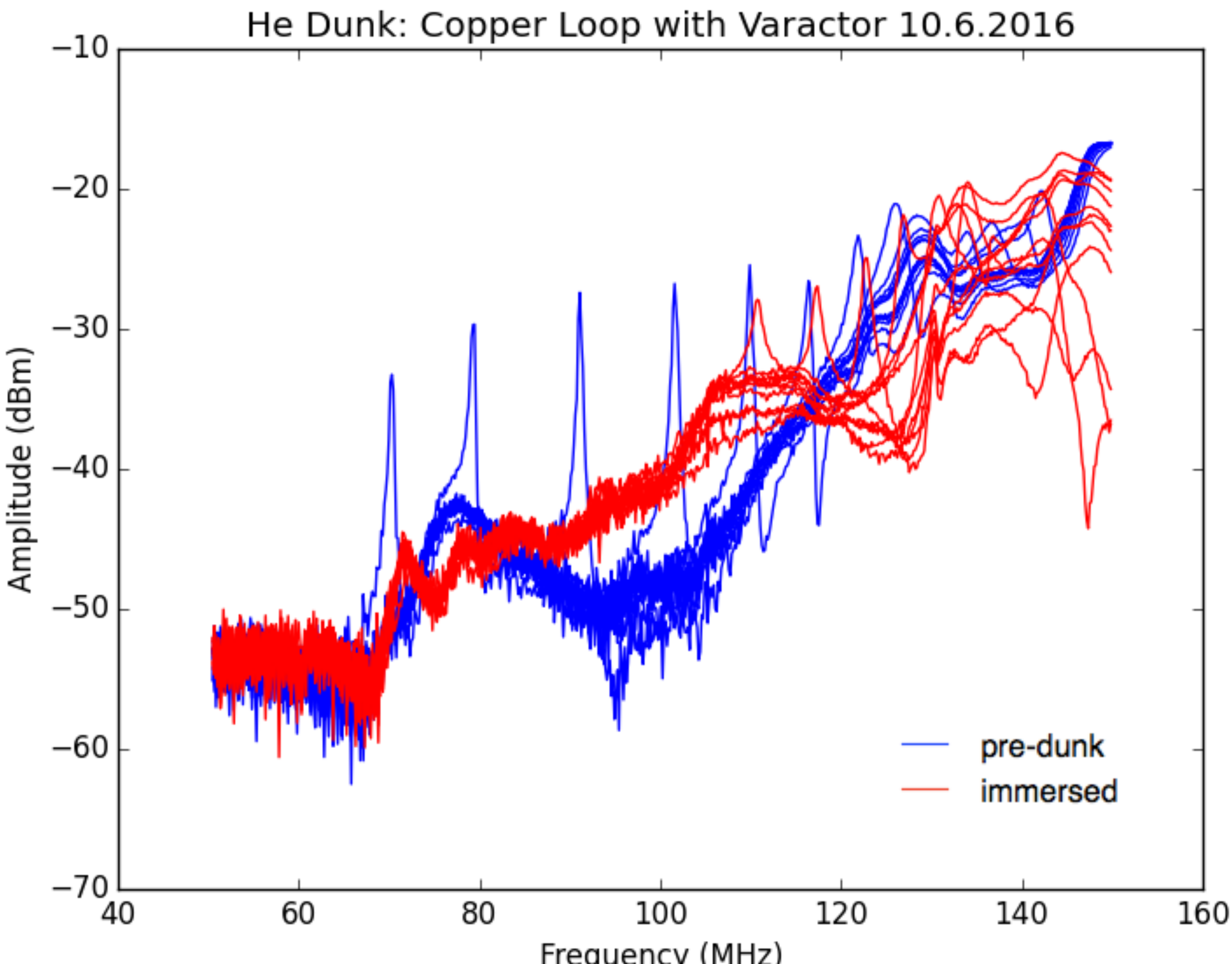

He Dunk: Copper Loop with Parrallel Plate Capacitor 9.22.2016
Amplitude (dBm)
−20
−30
−40
−50
−60
−70
−80
85
86
87
88
89
90
91
92
93
94
Frequency (MHz)
immersed
pre-dunk

Copper Loop with Varactor

- Q up to 300 warm
- Q reduced with cooling to <100
- varactor tuning tabled for now



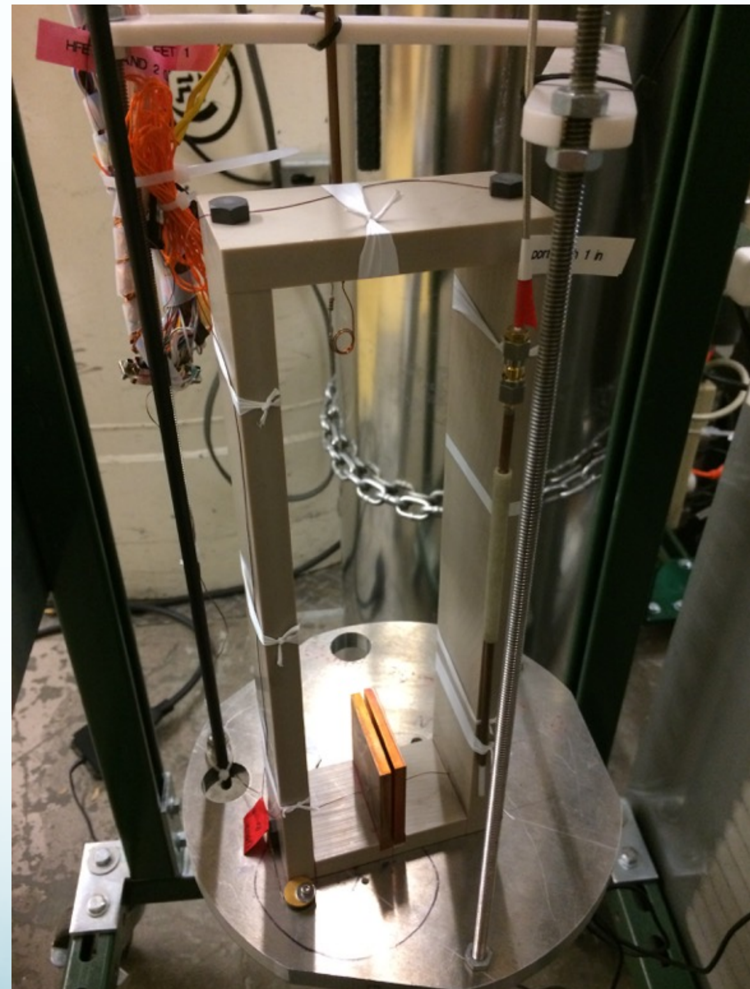


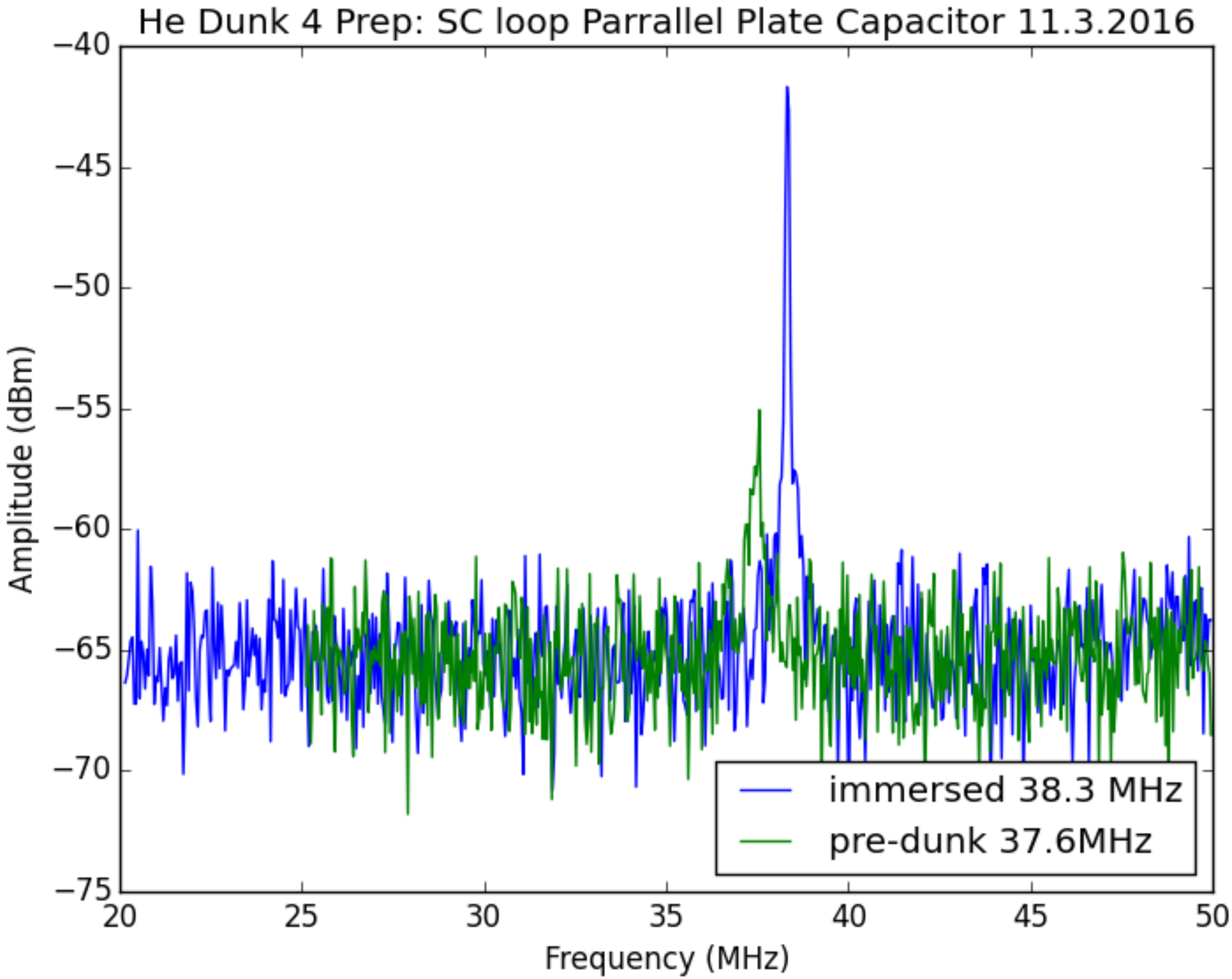


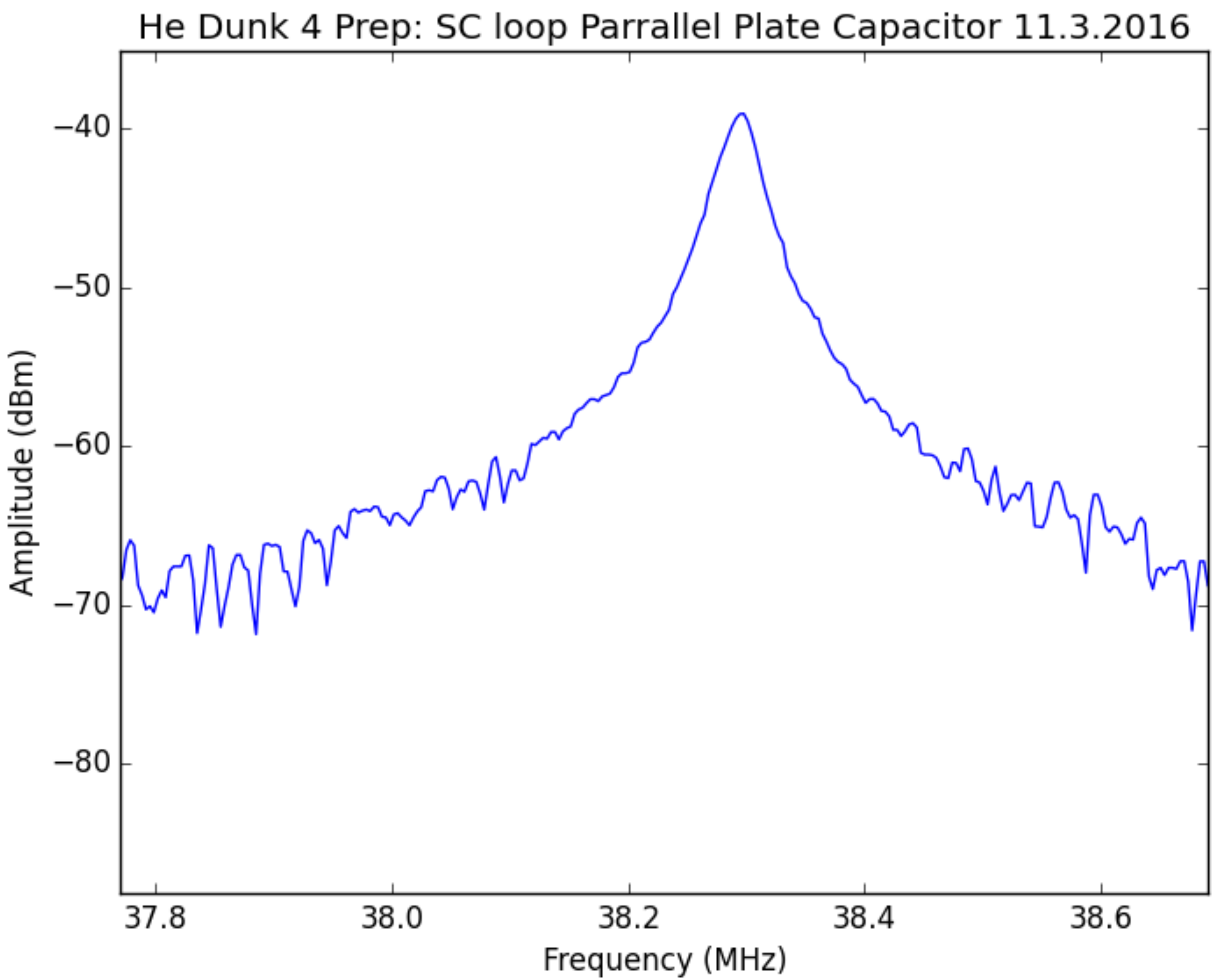
He Dunk: Copper Loop with Varactor 10.6.2016
Amplitude (dBm)
−10
−20
−30
−40
−50
−60
−70
Frequency (MHz)
40
60
80
100
120
140
160
pre-dunk
immersed

NbTi Loop with Parallel Plate Capacitor

- Copper Clad NbTi wire
- PEEK form
- OFHC copper parallel plate
- Highest Q ever attained of 1300
- Not a significant improvement over copper with LN2




He Dunk 4 Prep: SC loop Parrallel Plate Capacitor 11.3.2016
Amplitude (dBm)
−40
−45
−50
−55
−60
−65
−70
−75
20
25
30
35
40
45
50
Frequency (MHz)
immersed 38.3 MHz
pre-dunk 37.6MHz


He Dunk 4 Prep: SC loop Parrallel Plate Capacitor 11.3.2016
Amplitude (dBm)
−40
−50
−60
−70
−80
37.8
38.0
38.2
38.4
38.6
Frequency (MHz)

NbTi Loop with Parallel Plate Capacitor and Aluminum

- Aluminum 6061 shields installed and cooled
- No significant Q change
- Shields to be made superconducting, by lining with lead foil

HFSS Simulation Work

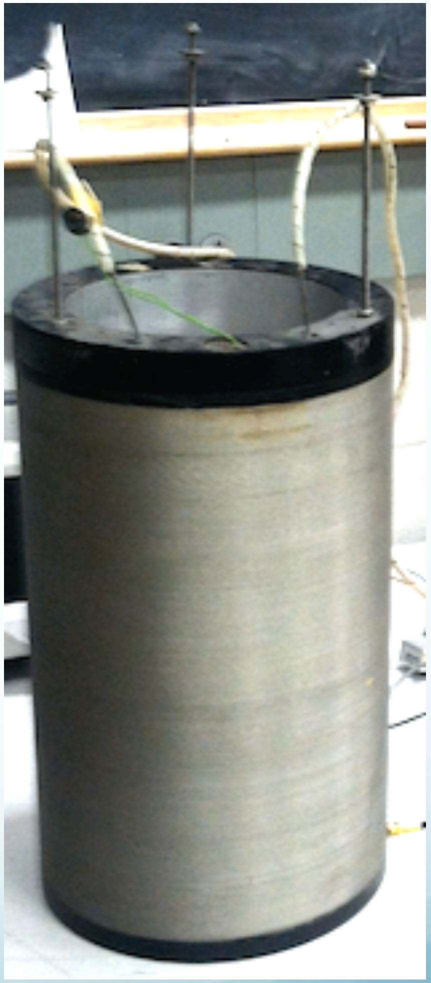
- Mark Jones (PNNL) has begun simulation work
- HFSS also estimates Q's larger than have been observed
- Trends that match
  - increased Q in dewar
  - frequency shift up in dewar
- We will explore HFSS as an additional tool to understand environment losses

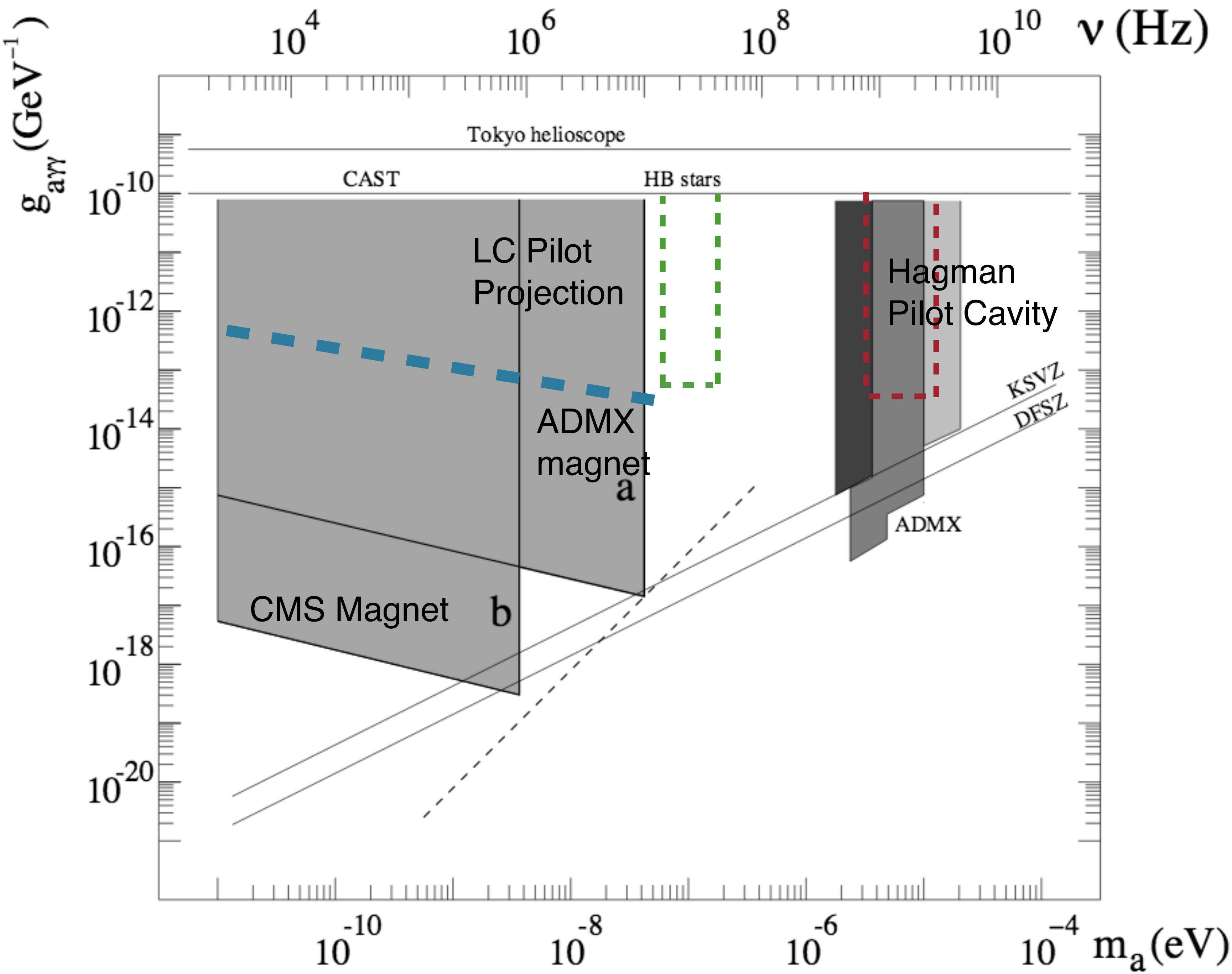
Plans Forward

- Incorporate a Superconducting Shield with the existing NbTi loop
- If a Q of 10^4 is hit, try mechanical tuning
- In the existing loop, insertion of sapphire would give a tuning range of ~18Mhz - 38Mhz
- Complete LC circuit design to be deployed in a pilot axion search

Final Prototype ^{3}He System and Magnet

- Proof of Concept Pilot Run
- ^{3}He System
  - T = 0.4 K, ~1 mW cooling power
- Magnet
  - NbTi, 8.6 T field, 17.1 cm bore,
  - 70 cm long





ν (Hz)
10^4
10^6
10^8
10^{10}
$g_{a\gamma\gamma}$ (GeV^{-1})
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
Tokyo helioscope
CAST
HB stars
LC Pilot
Projection
Hagman
Pilot Cavity
ADMX
magnet
a
KSVZ
DFSZ
ADMX
CMS Magnet
b
10^{-10}
10^{-8}
10^{-6}
10^{-4}
m_a (eV)

Status Summary

- Varactor tuned loops worsened with cooling to 4K
- Loop performance is not being limited by conductivity
- Radiation losses need to be controlled
- Will incorporate superconducting shields
- Simulation studies are in progress
- Explore low-mass axions

Acknowledgements

- Heising-Simons Foundation
- UF Graduate School Fellowship
- UF IHEPA Fellowship
- ADMX
- Department of Energy grant DE-SC0010280

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Understanding Losses

- Surface Impedance of OFHC
  - skin depth ~ 10 μm.
  - possible Q at 50 MHz of 18,500
- Radiation Resistance
  - Circular Loop at 50 MHz Limit Estimate
    - Q < 1700 at room temperature

Resistivity and Temperature

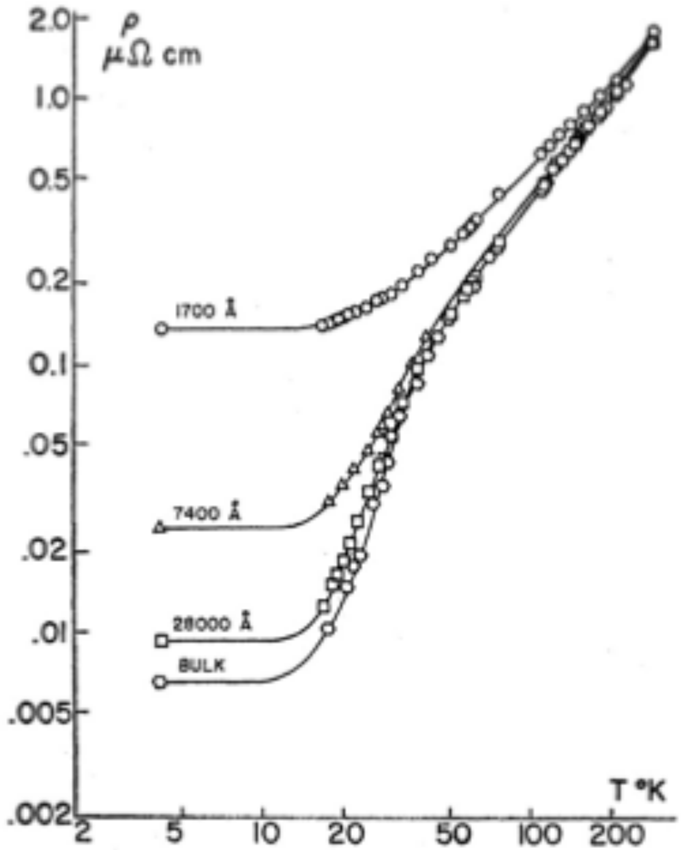
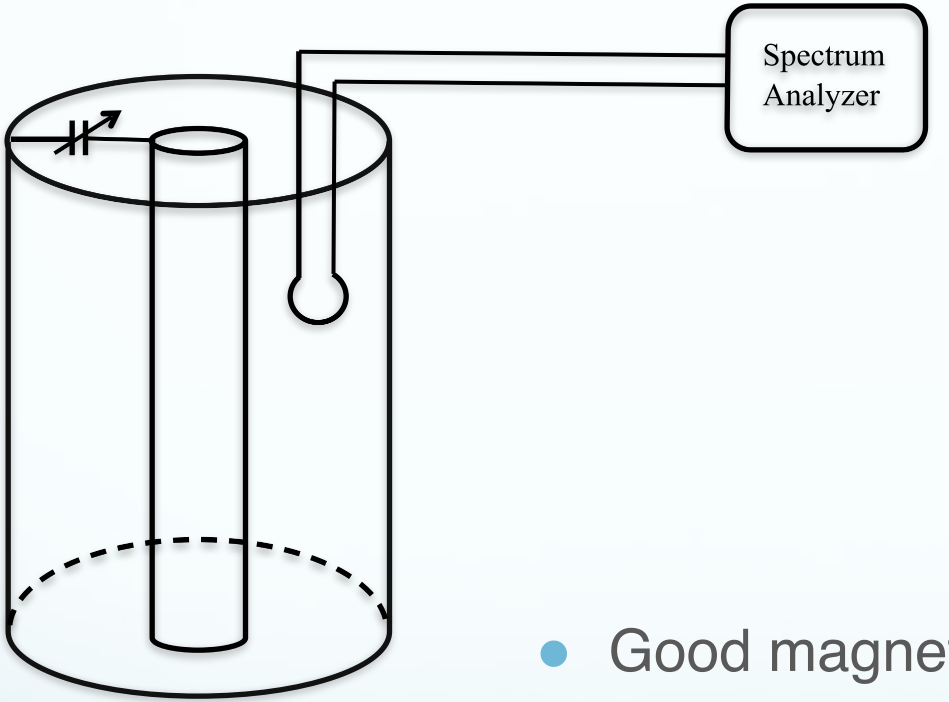
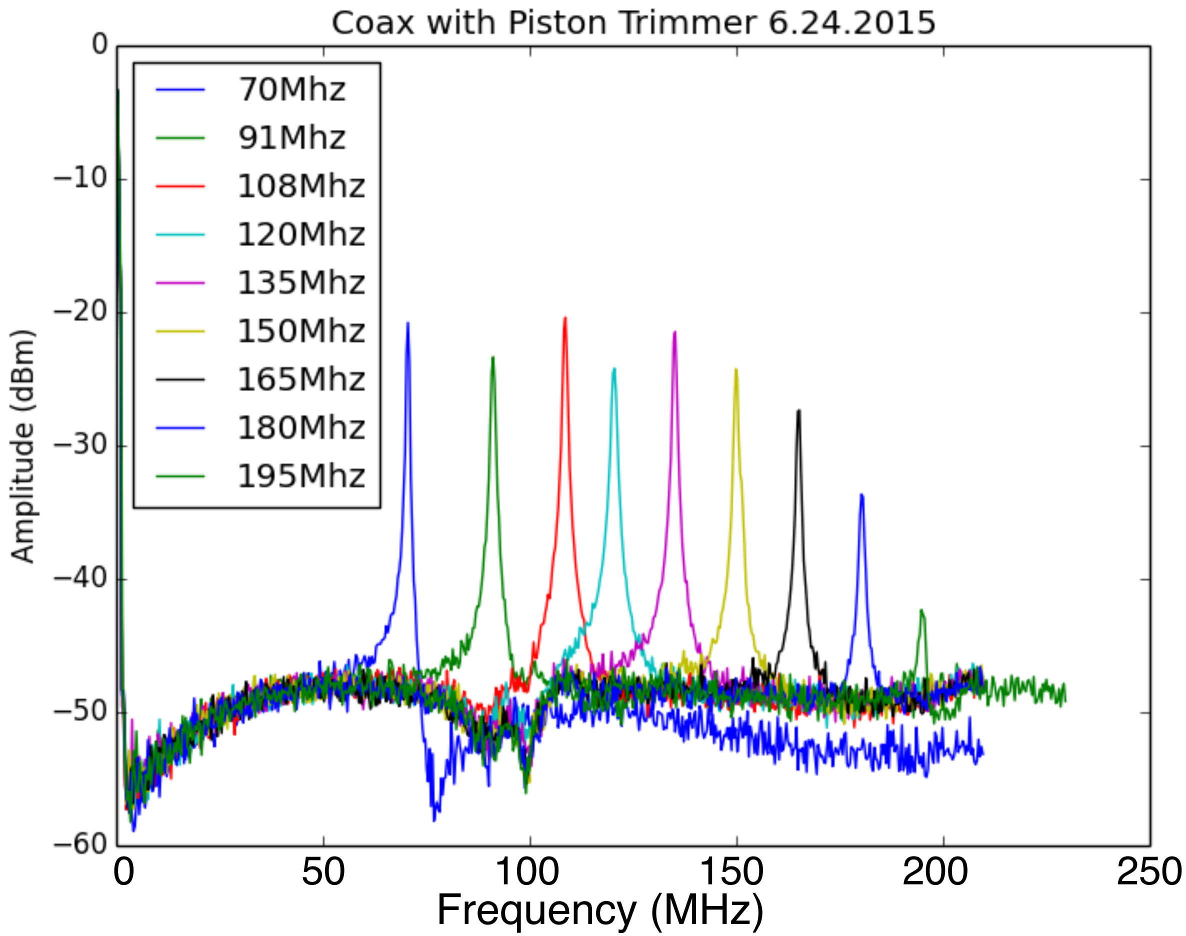


Figure 2: Silver resistivity for T=4–300K, taken from [4] Tanner, DB.

Coax Cavity Geometry



- Good magnetic field coupling
- Low self-inductance
- Already self-shielding
- Difficult to make superconducting


Coax with Piston Trimmer 6.24.2015
70Mhz
91Mhz
108Mhz
120Mhz
135Mhz
150Mhz
165Mhz
180Mhz
195Mhz
Amplitude (dBm)
Frequency (MHz)
0
−10
−20
−30
−40
−50
−60
0
50
100
150
200
250


0

Q:248 –130