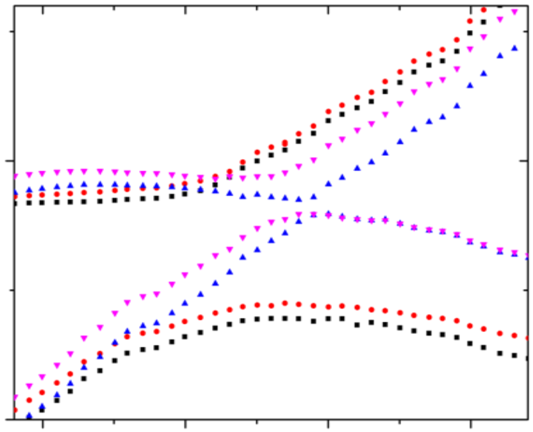


Reaching the 5-9 μeV Range with ADMX: Multi-Cavity Array

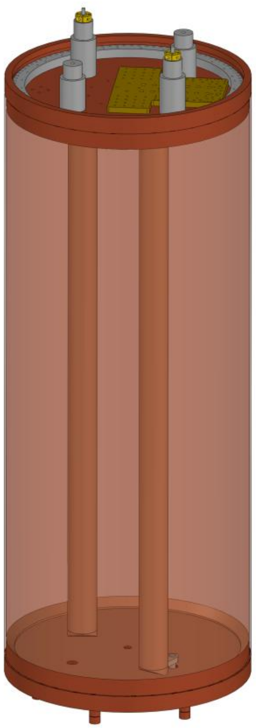
Jihee Yang, Joe Gleason, David Tanner, Neil Sullivan

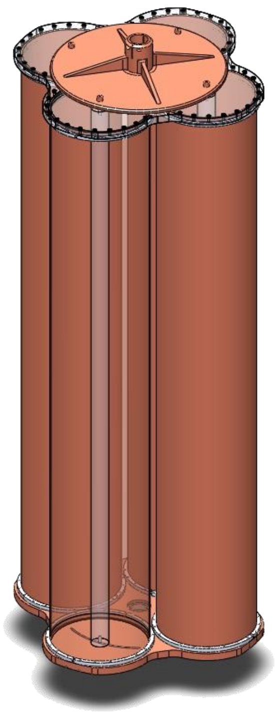
3rd Workshop on Microwave Cavities and Detectors for Axion Research
Livermore, CA, August 22nd, 2018

Contents

- Introduction
  - 4 cavity array (overview)
- Tests Performed (Prototype, RT bench test)
  - RF testing
  - Cavity tuning
- Summary
  - Lessons learned
  - Issues revealed
- Future Work

Multi-cavity Array Concept





- Why? Higher axion mass range
- Size

  Ø 42 cm => Ø 16 cm
- Frequency

  600~900 MHz => 1.5~2.2 GHz (metal)

4 Cavity Array Testing

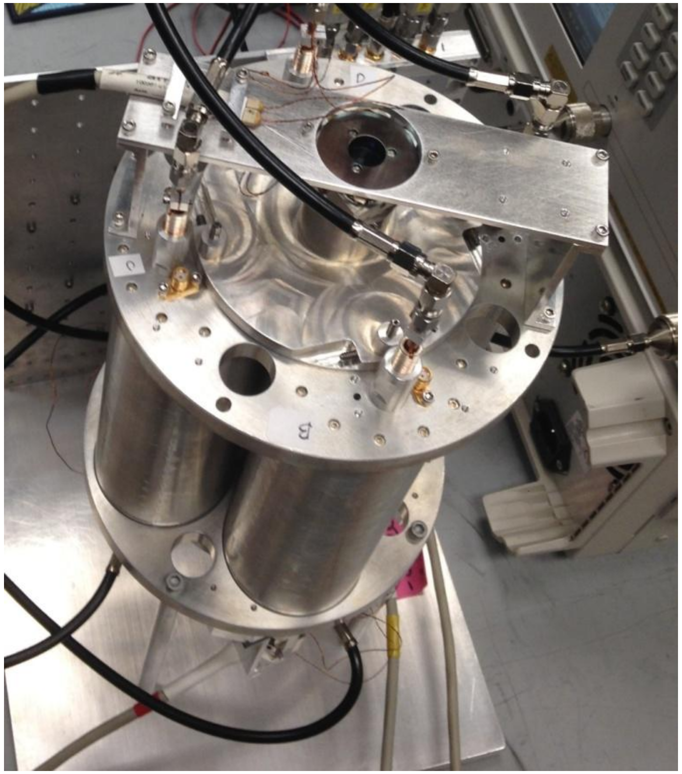
Prototype v1

Prototype v2

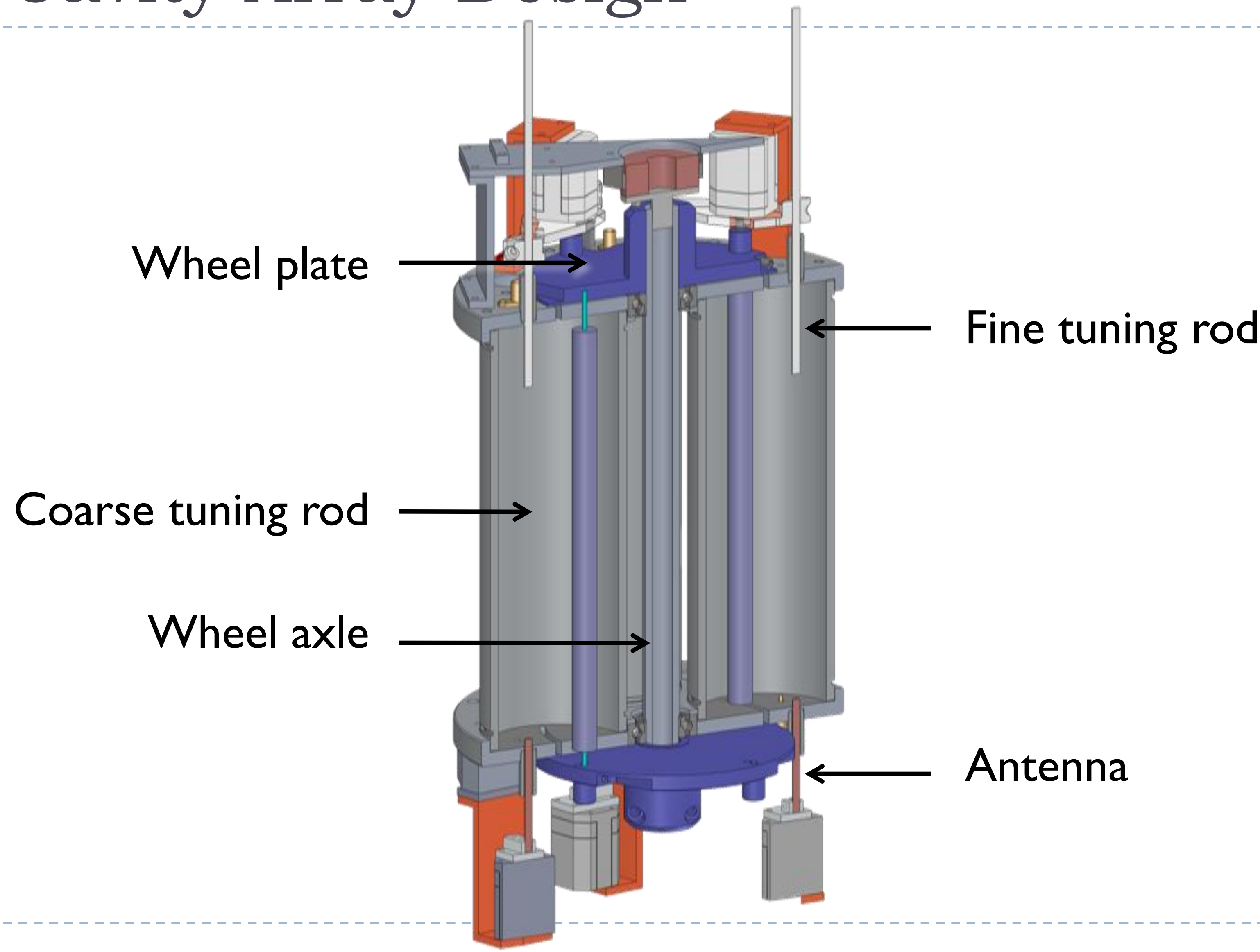
Full Scale Array

4 Cavity Array Testing

Prototype v1 bench test (RT)



4 Cavity Array Design



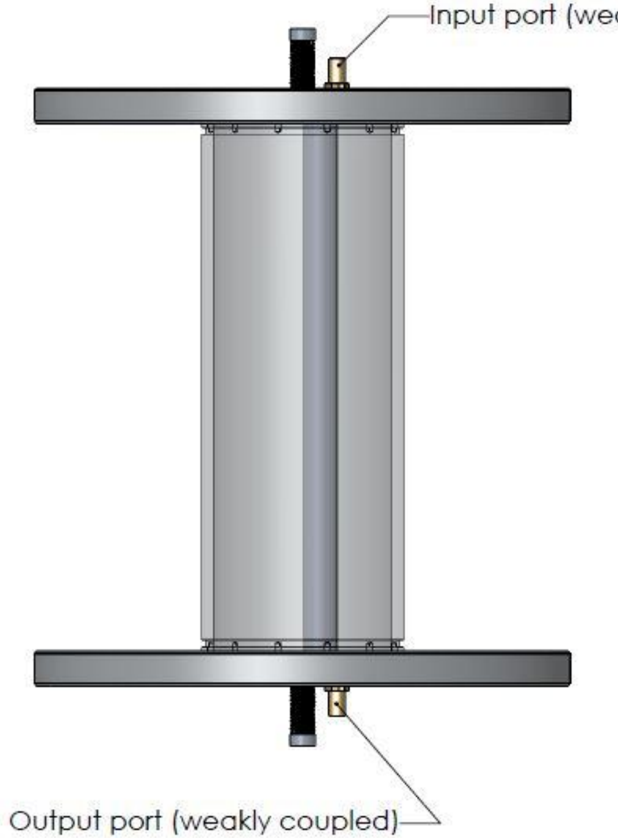
4 Cavity Prototype Testing

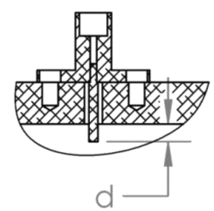
- Al prototype
  - Scale : dia (x2.9) smaller, length (x5.5) shorter
  - Frequency : 1.5 GHz => 4.4 GHz
- Main interests
  - RF testing
    - Mode map : mode-crossing
    - Power spectrum : Q factor, cavity f spreads
  - Cavity tuning
    - Cavity Locking (Synchronizing) method
    - Mechanical (Piezo actuator) performance

Tests Performed

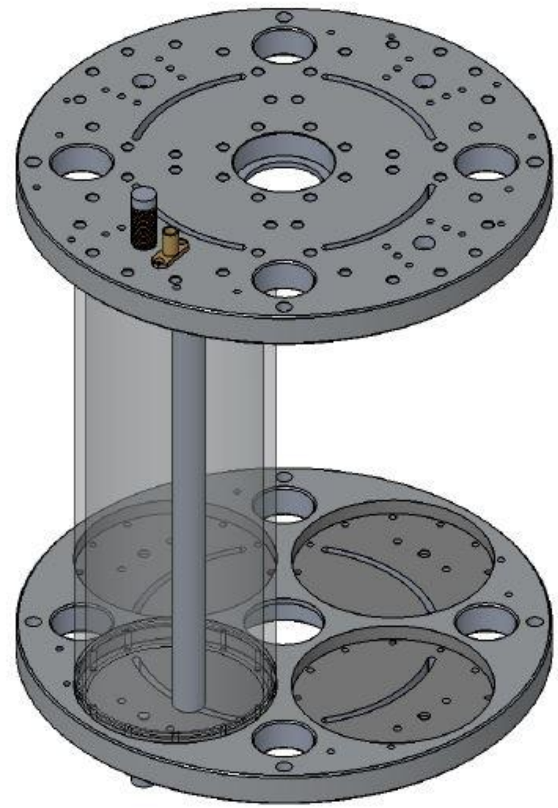
Mode Map (mode-crossing)
Power Spectrum (Q factor, f spread)
Piezo Actuator Test

RF Test Setup



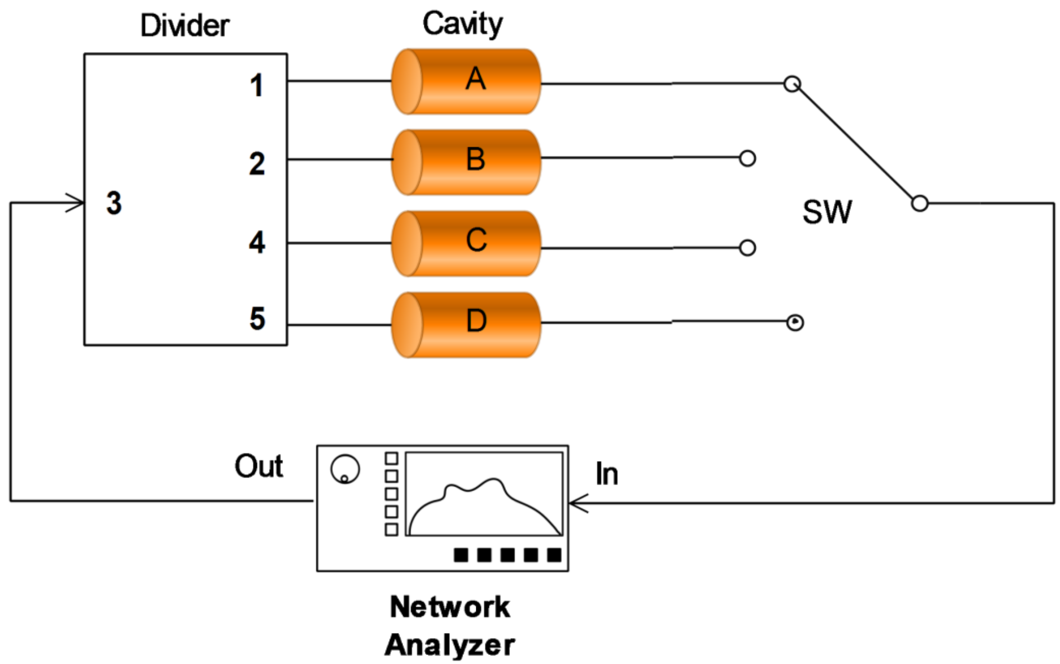


Section View
(Jack antenna)



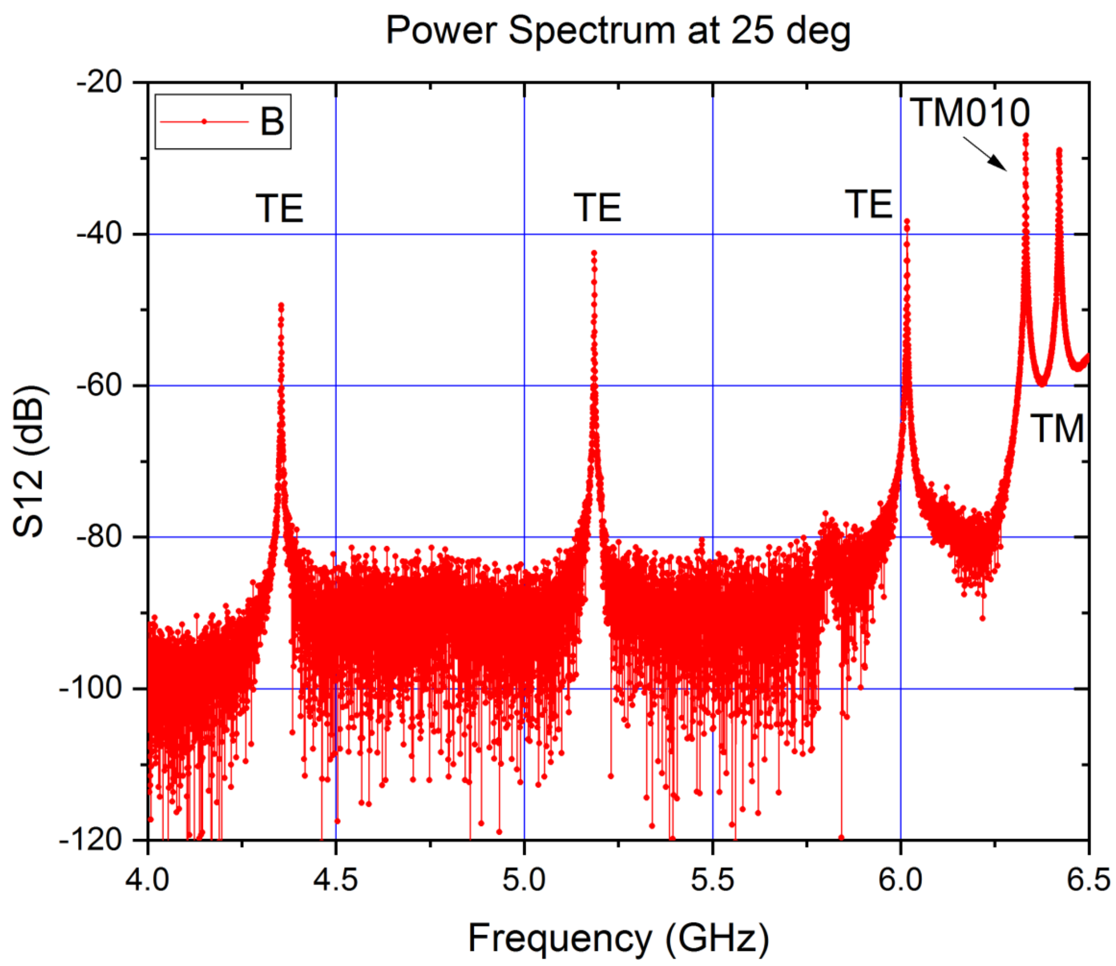
Coarse tuning
Full mechanical range : 53.0 deg
Tuning range : 26.5 deg

RF Test Setup

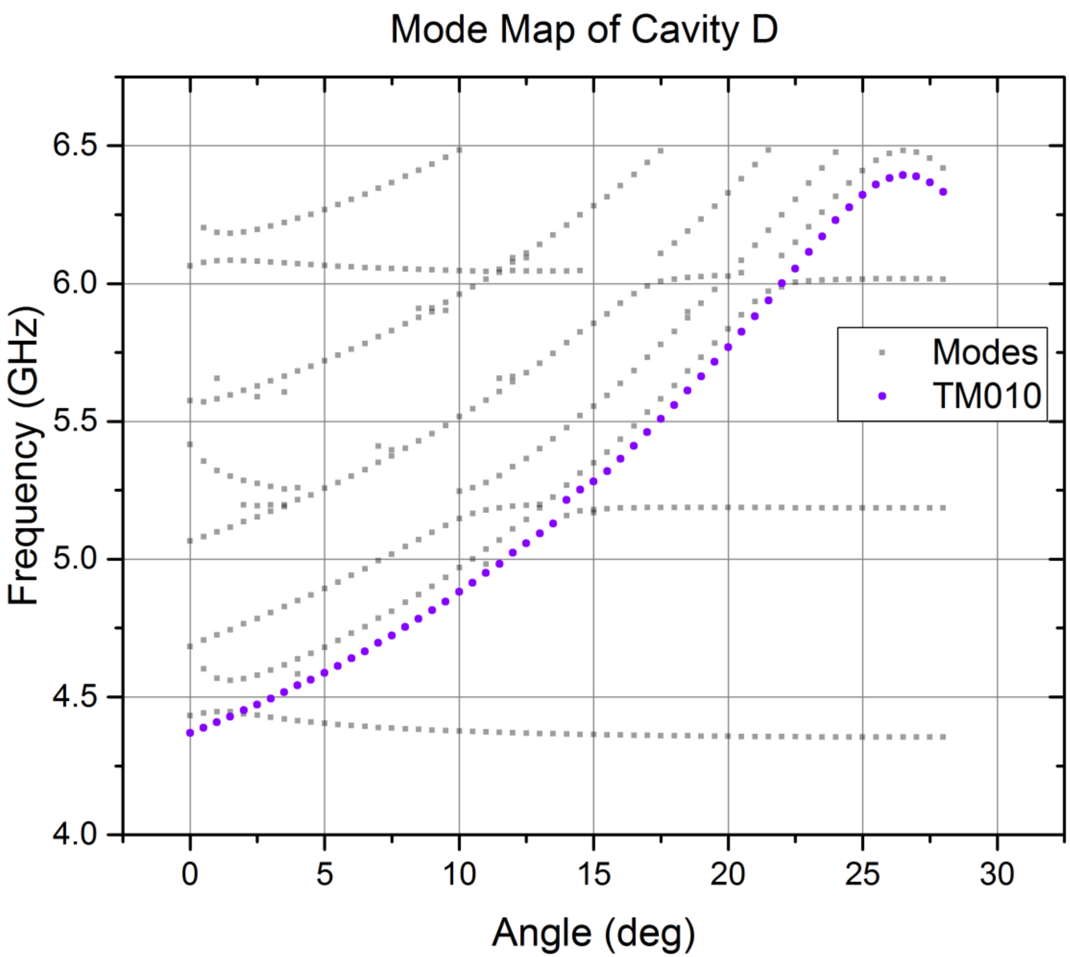


- Transmission (S12) or reflection (S11) measurements

Power Spectrum



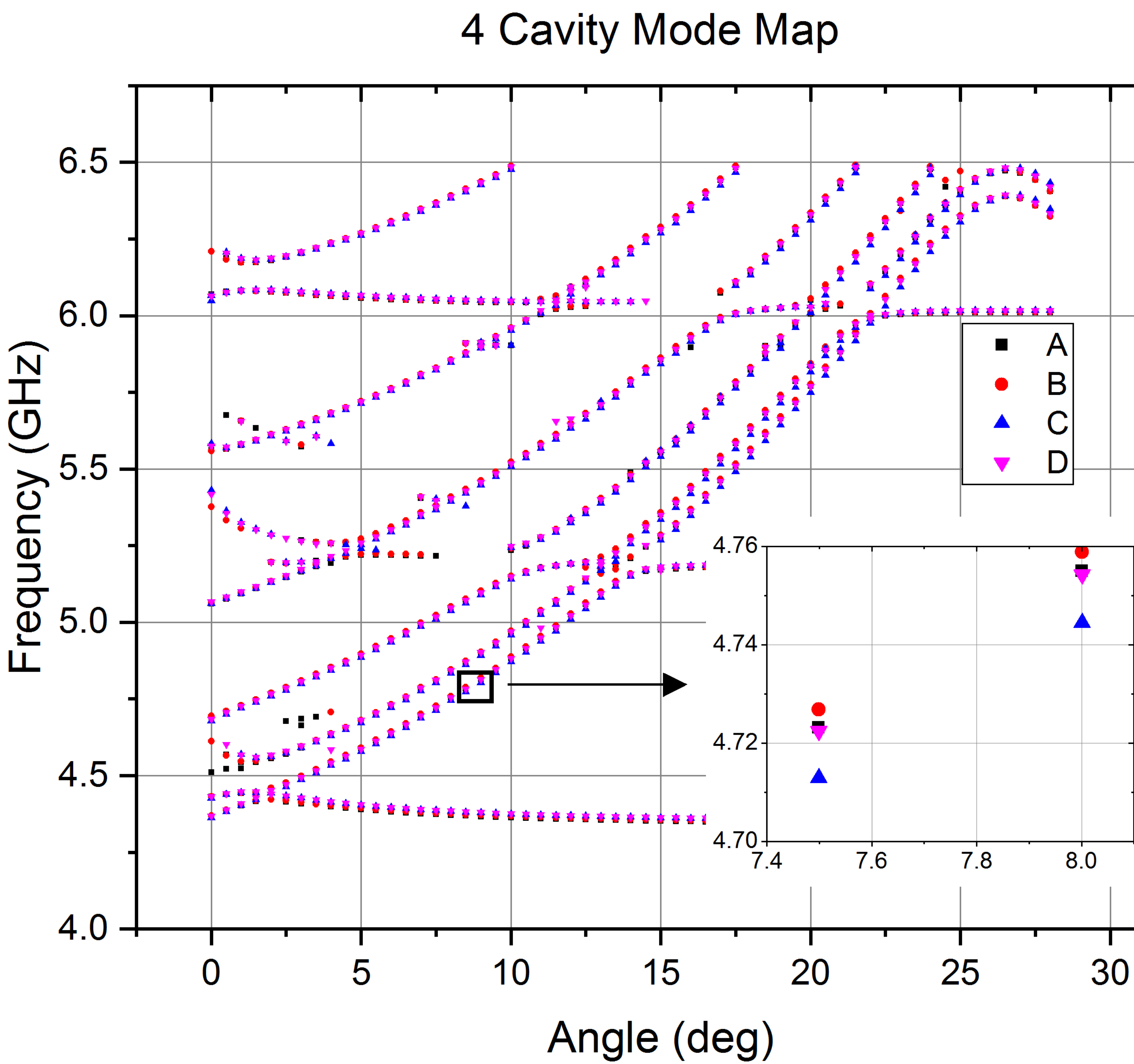
Mode Map



- Tuning range : 26.5 deg
- TM010 mode 4.4~6.3 GHz

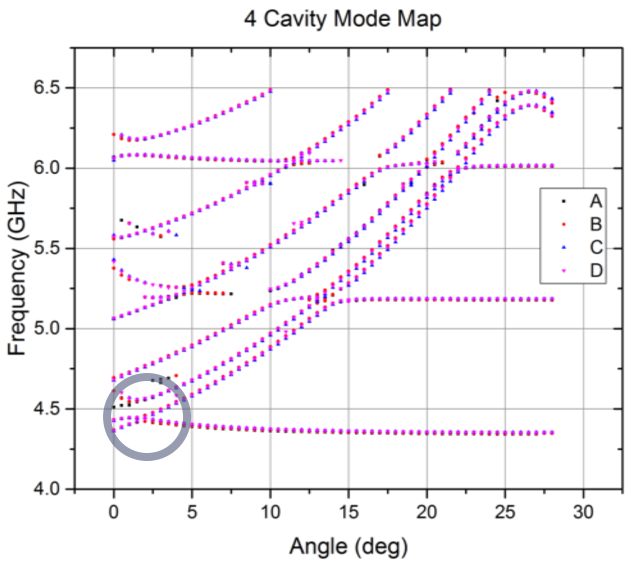
=> ~70 MHz/deg

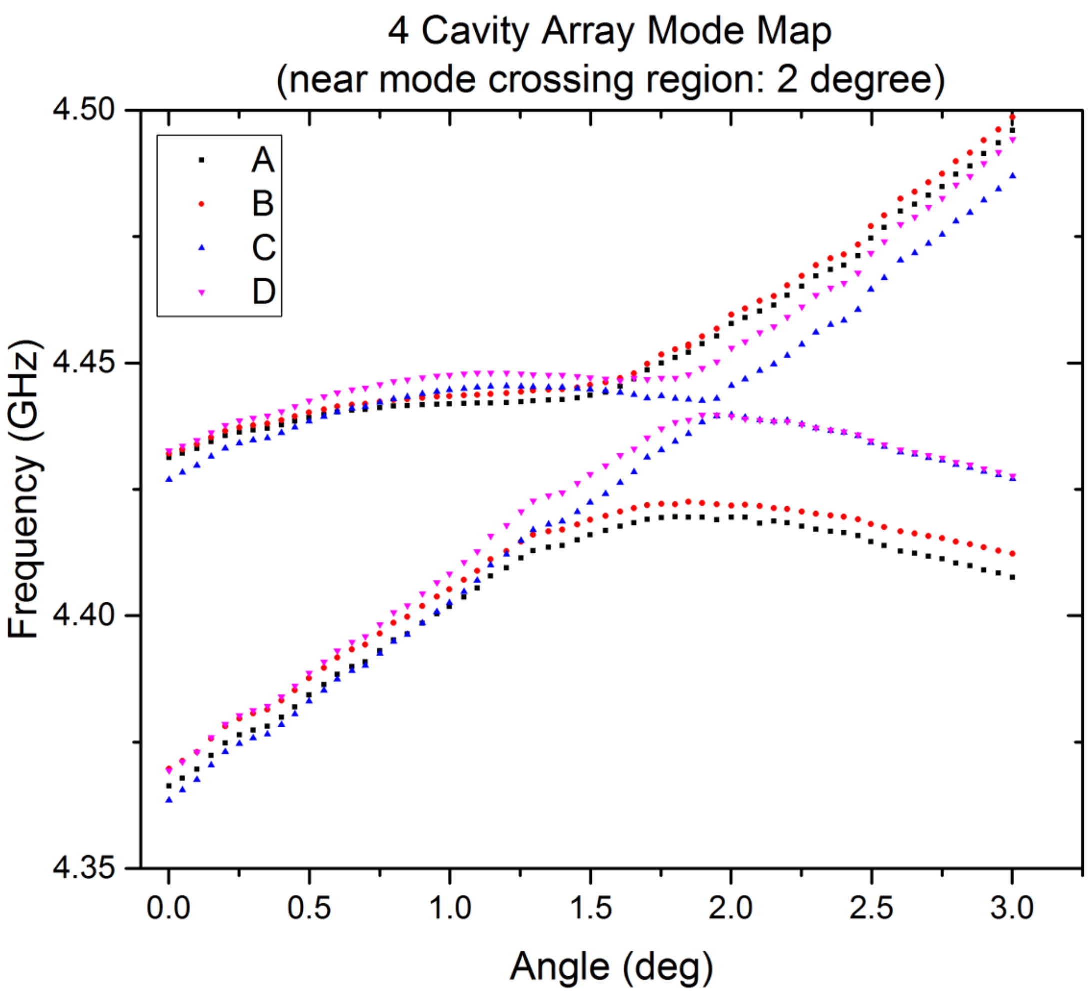
*Note: min. 70 kHz/step



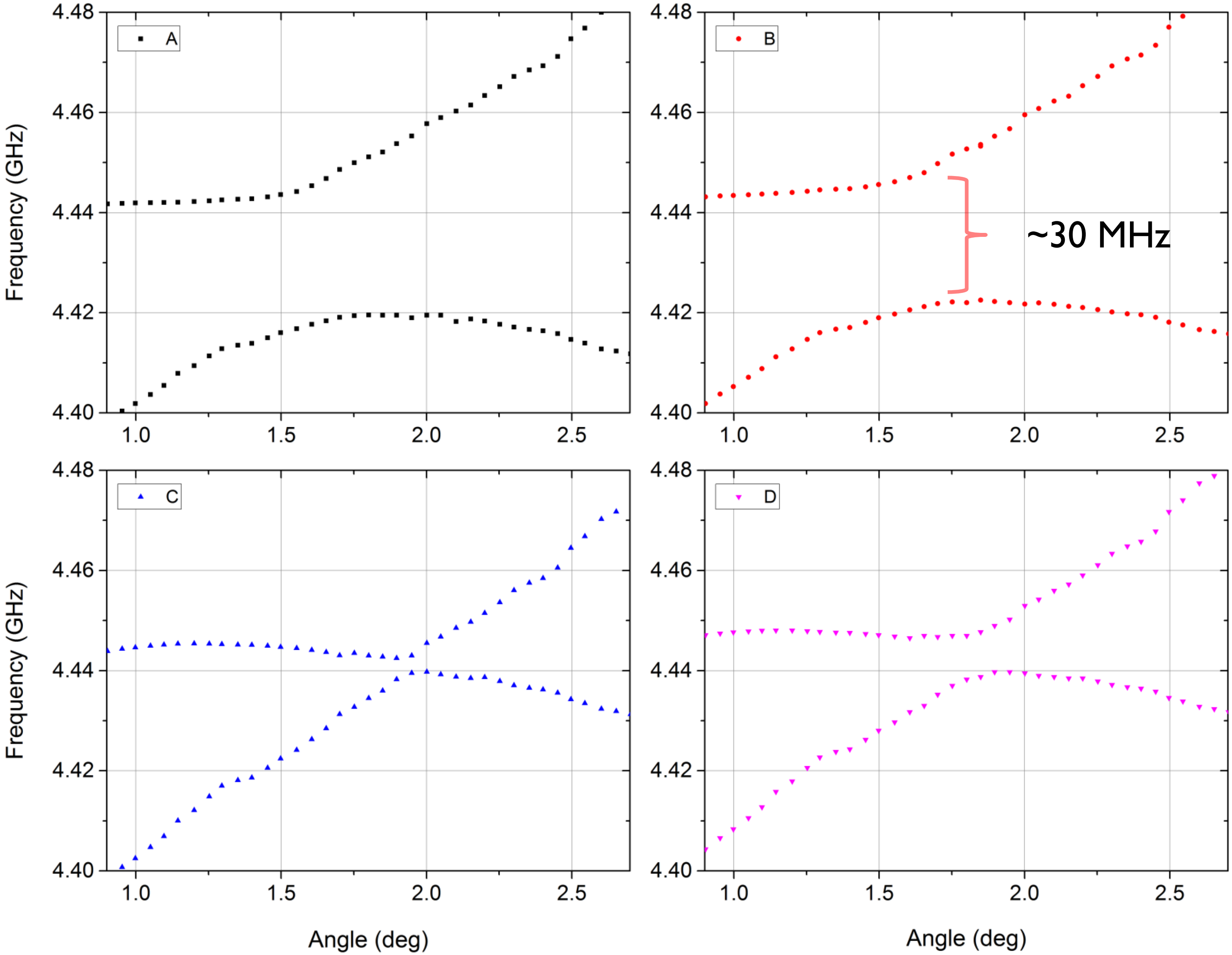
4 Cavity Mode Map
Frequency (GHz)
Angle (deg)
6.5
6.0
5.5
5.0
4.5
4.0
0
5
10
15
20
25
30
A
B
C
D
4.76
4.74
4.72
4.70
7.4
7.6
7.8
8.0

Mode Map (mode-crossing)



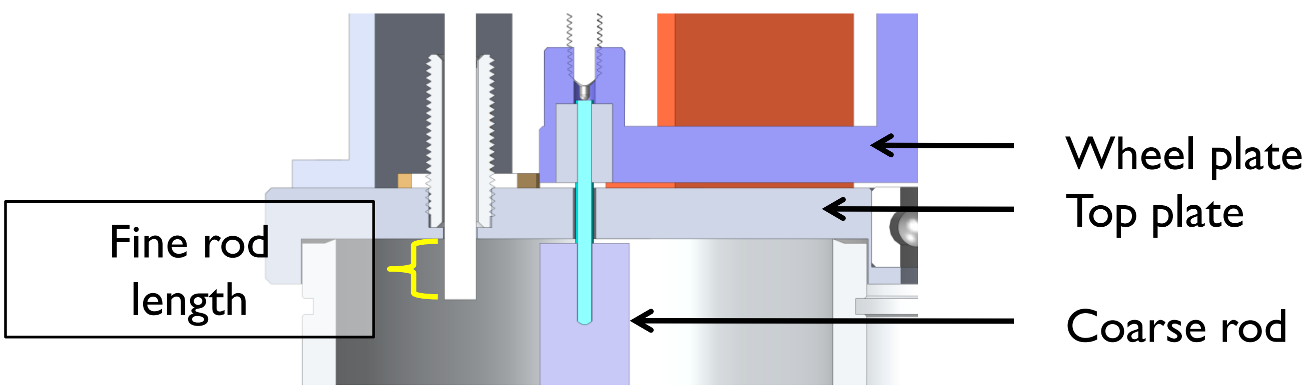


4 Cavity Array Mode Map
(near mode crossing region: 2 degree)

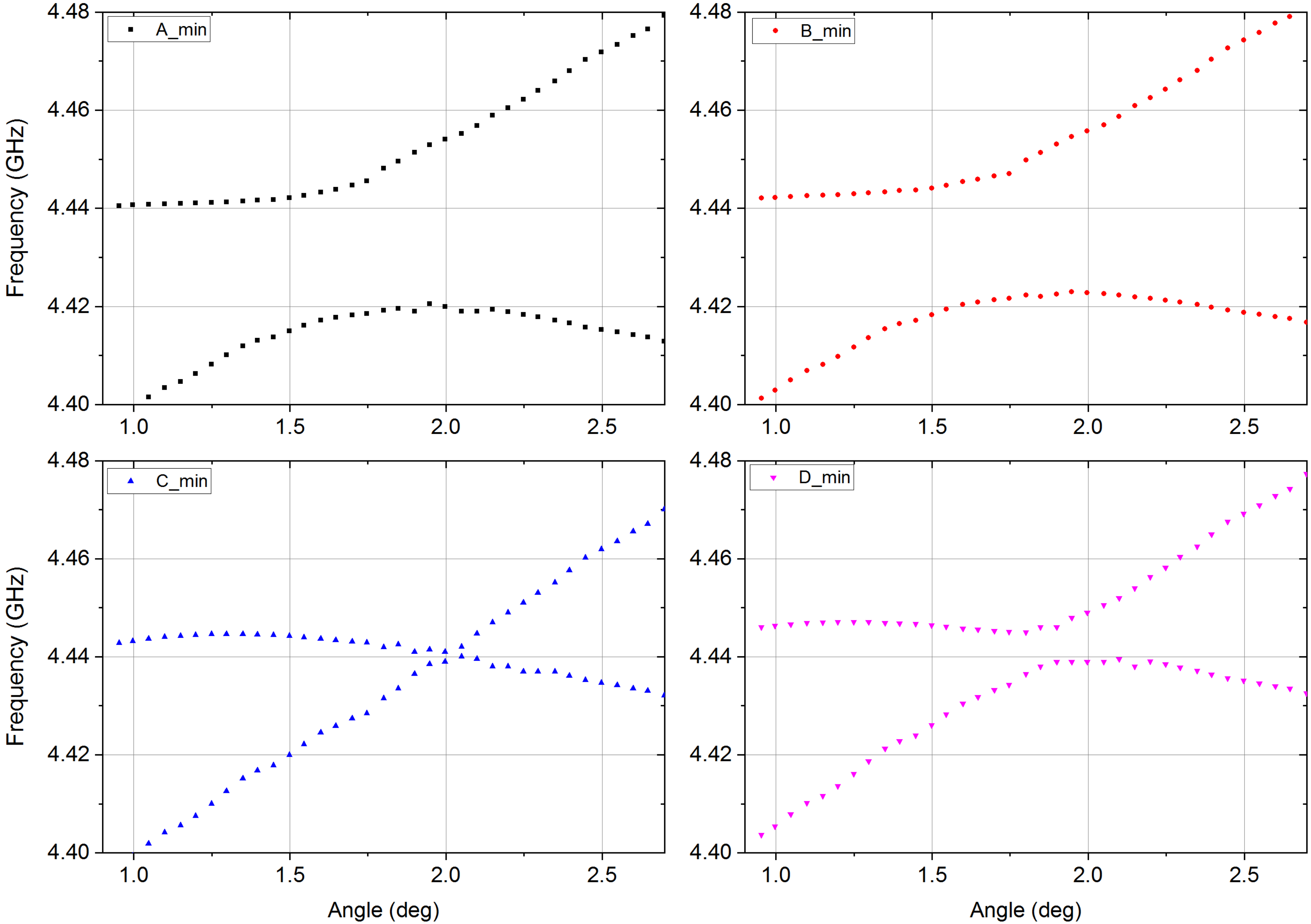


Mode Map (mode-crossing)

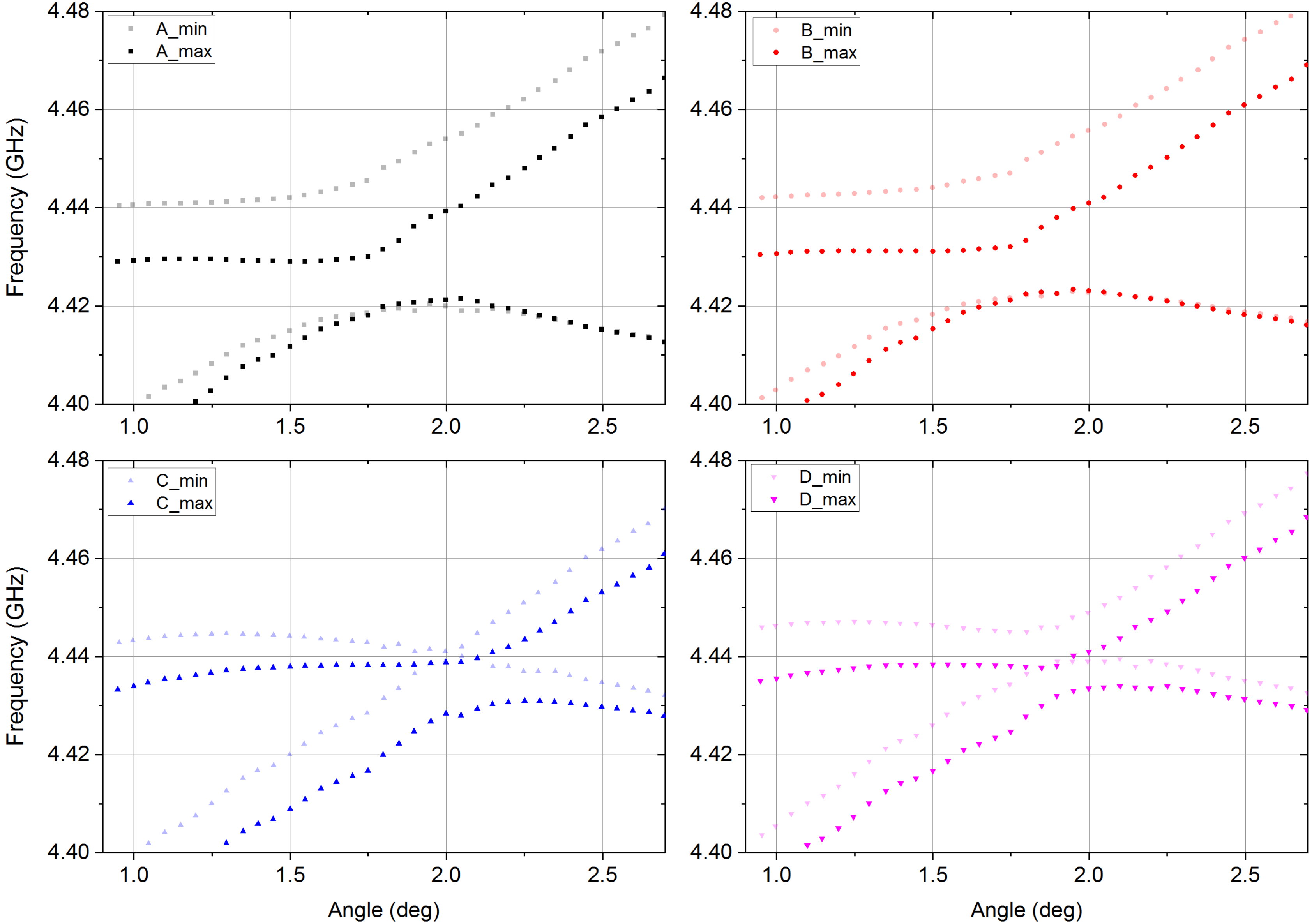
- Can we overcome mode-crossing with fine tuning rod?
  - Fine tuning range : 12 mm
- Obtained mode maps with fine tuning with extreme positions
  1. Min. length : 3 mm
  2. Max. length : 15 mm



4 Cavity Array Mode Map
(~2 deg, with fine tuning rods)

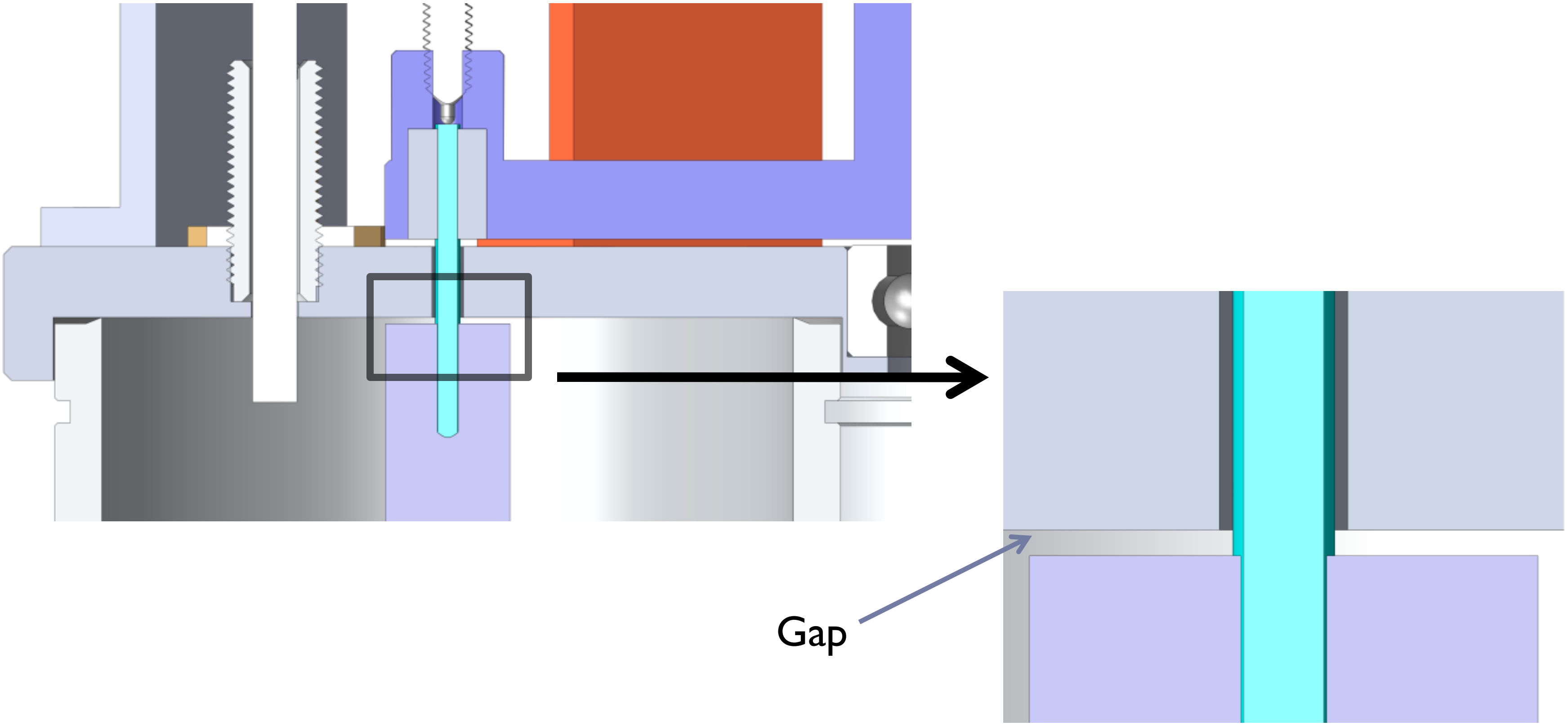


4 Cavity Array Mode Map
(~2 deg, with fine tuning rods)

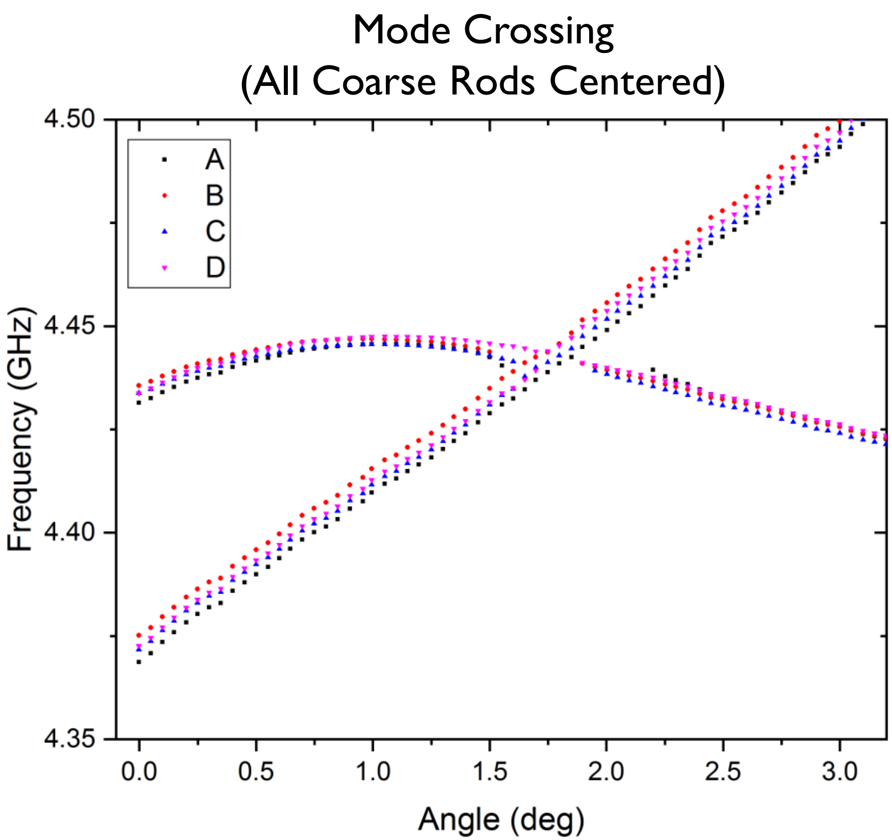


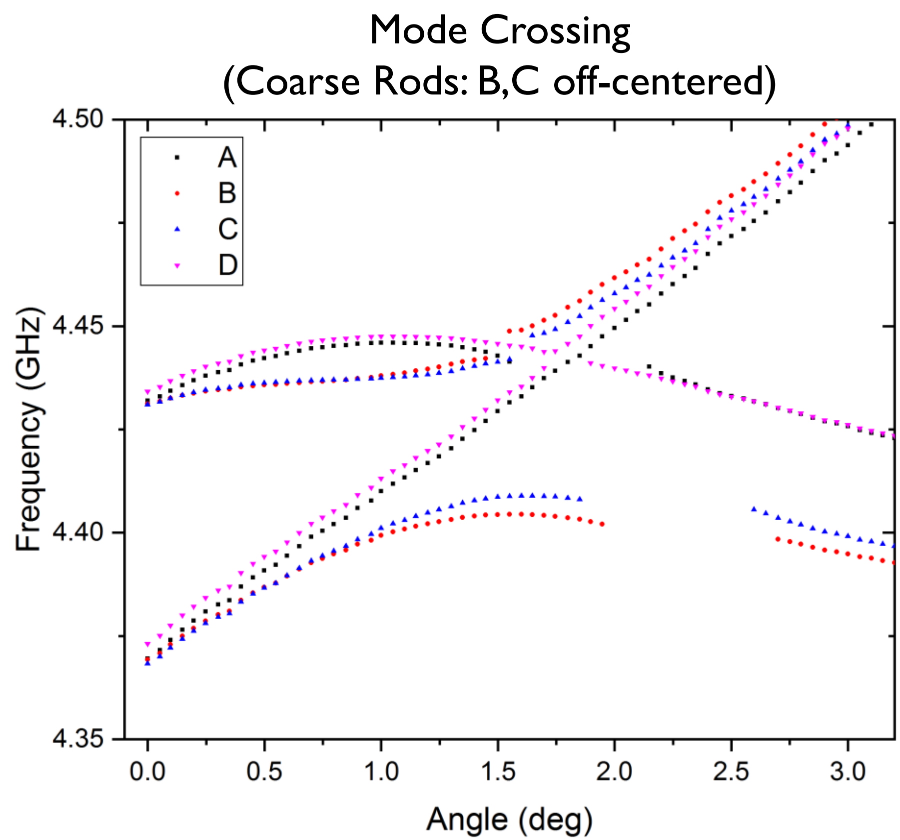
Mode Map (mode-crossing)

- Mode crossing separation change
  - Capacitance effect between coarse rod and plates?



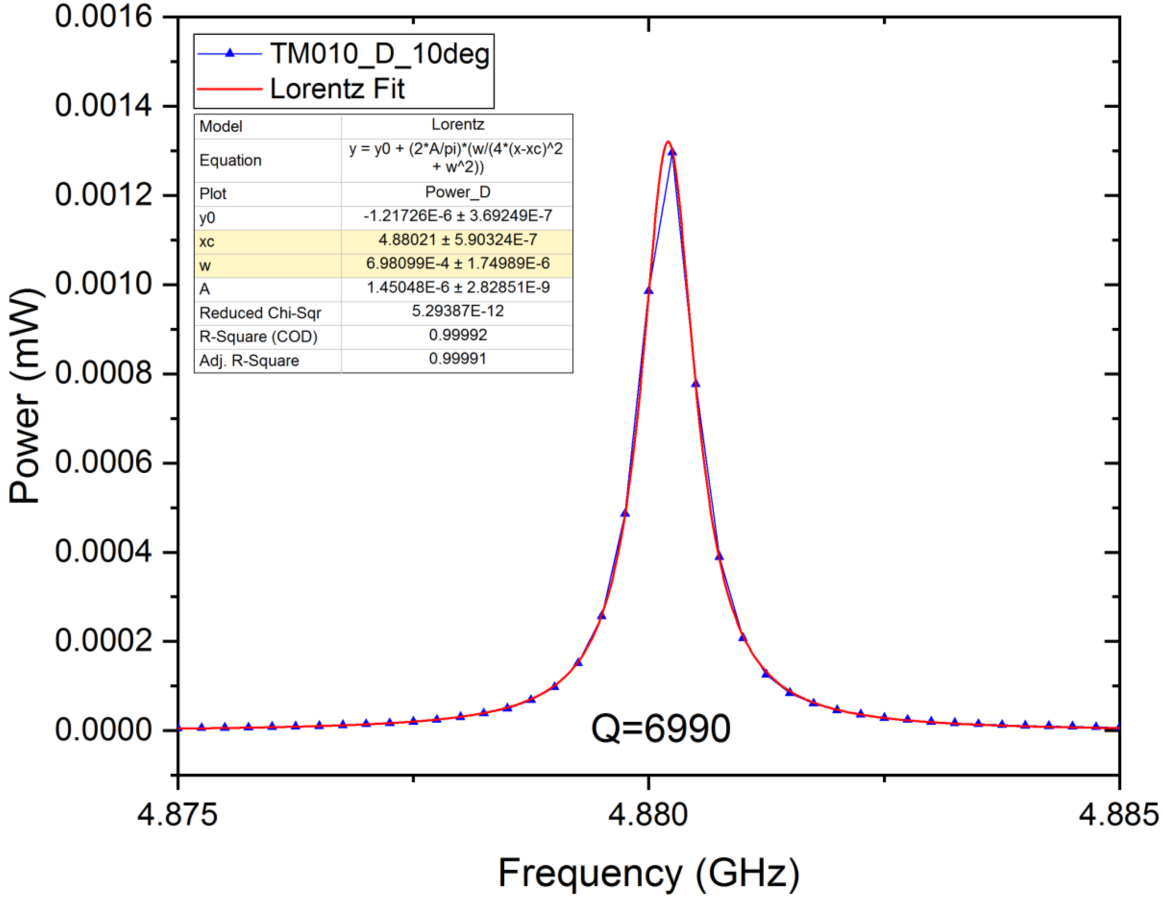
Mode Map (mode-crossing)



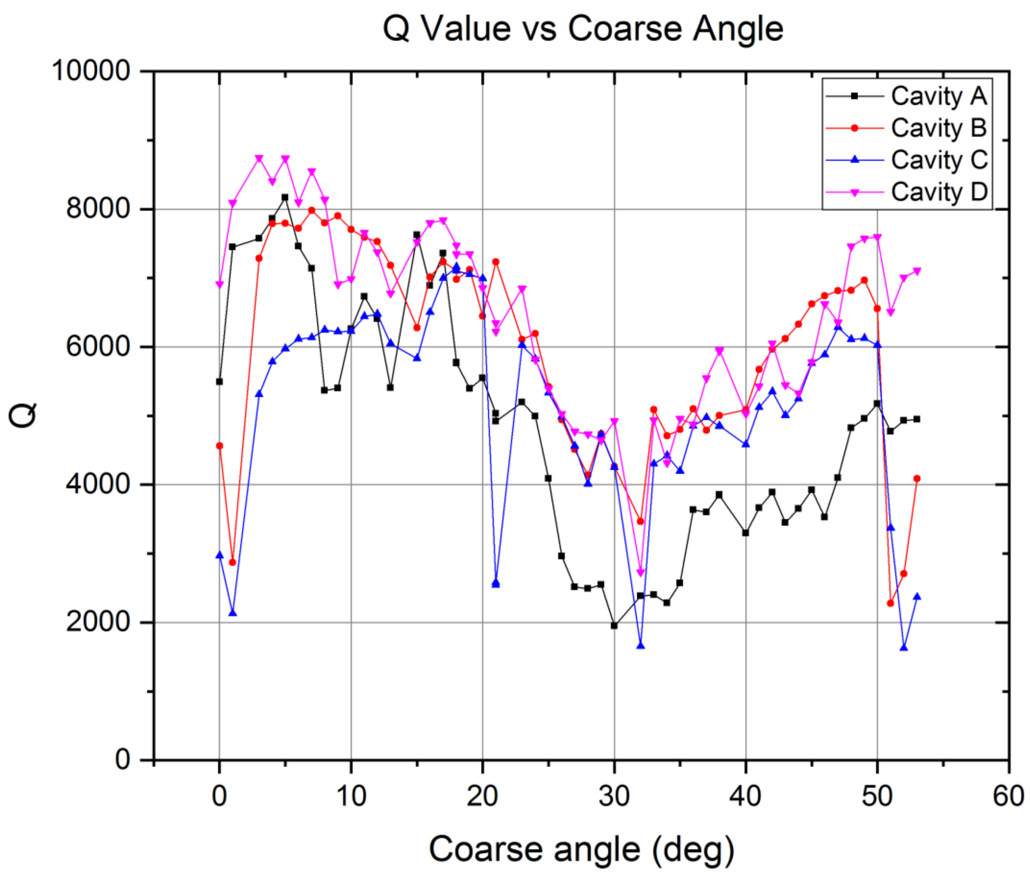


Power Spectrum

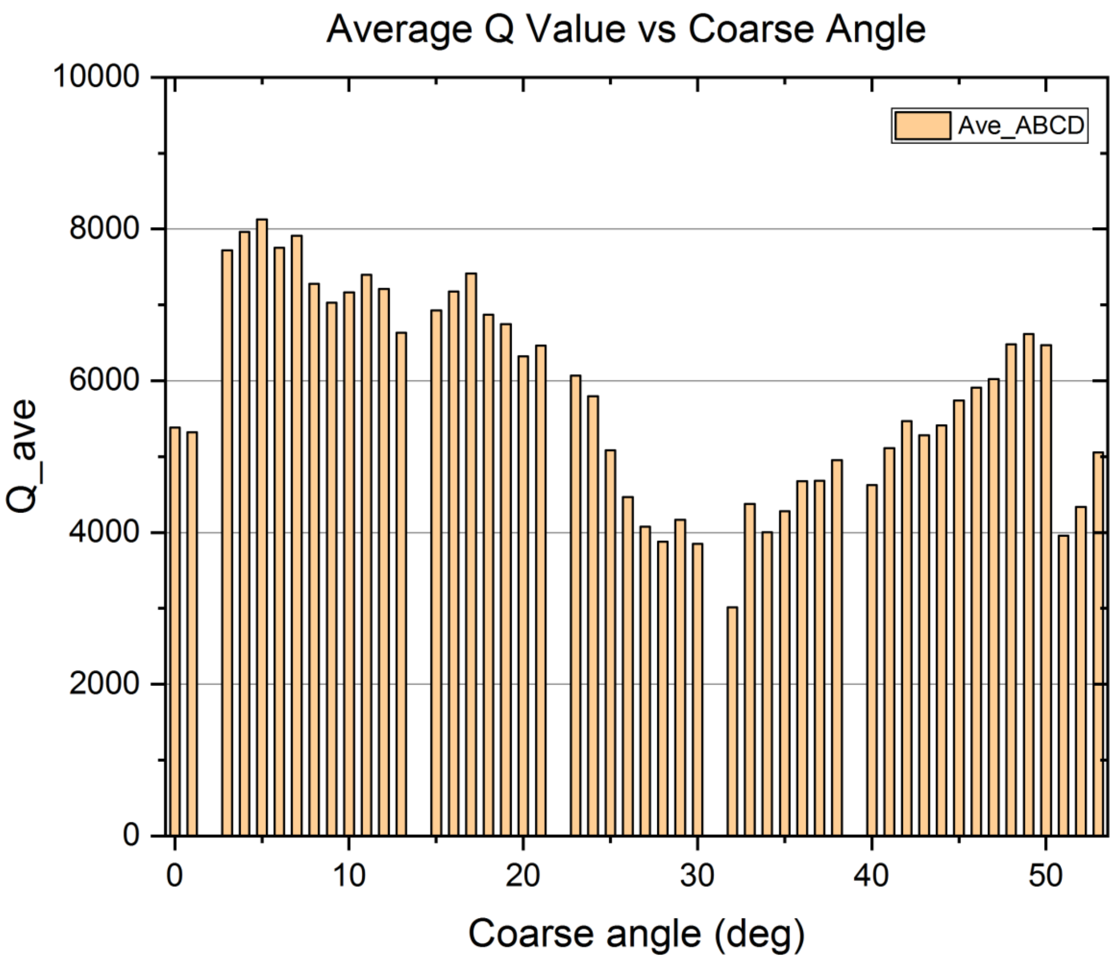
TM010 mode resonant peak (cavity D at 10 deg)



Power Spectrum (Q factor, unloaded)

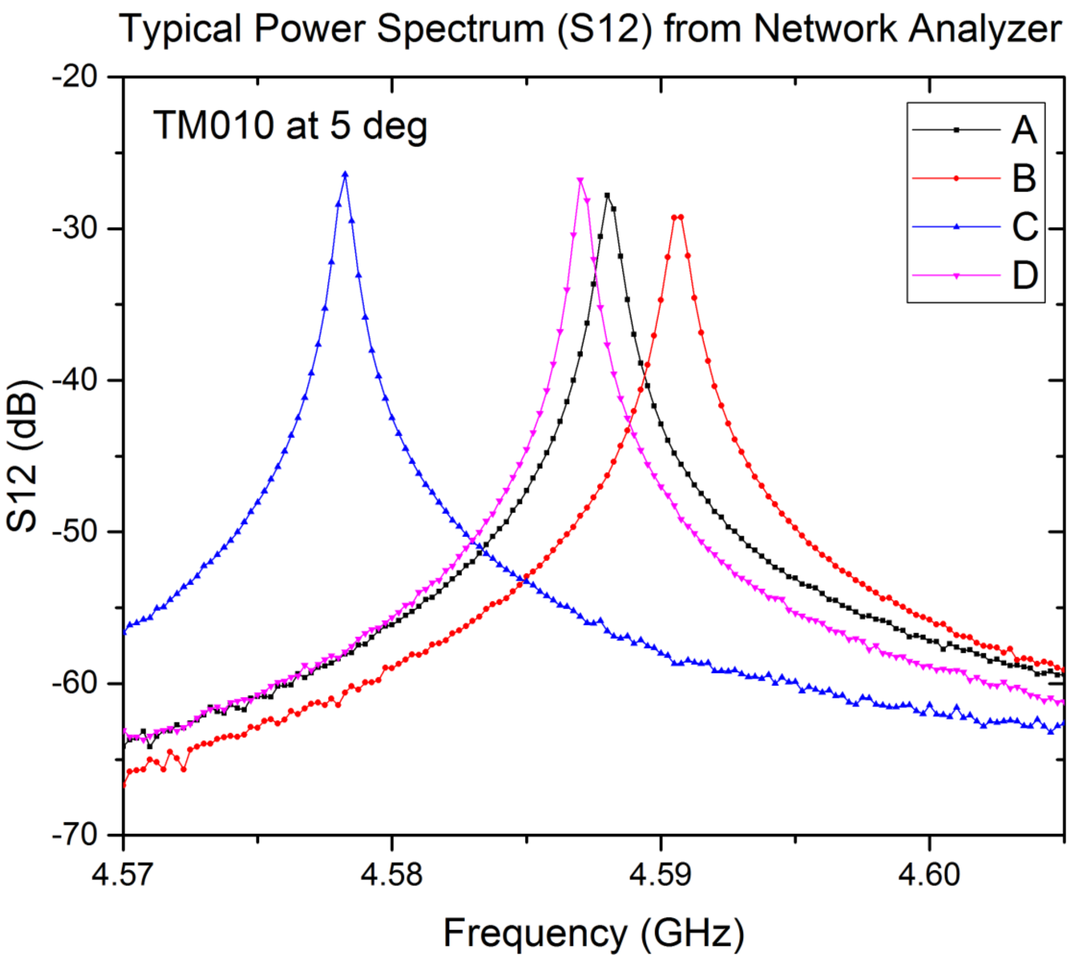


Power Spectrum (Q factor, unloaded)



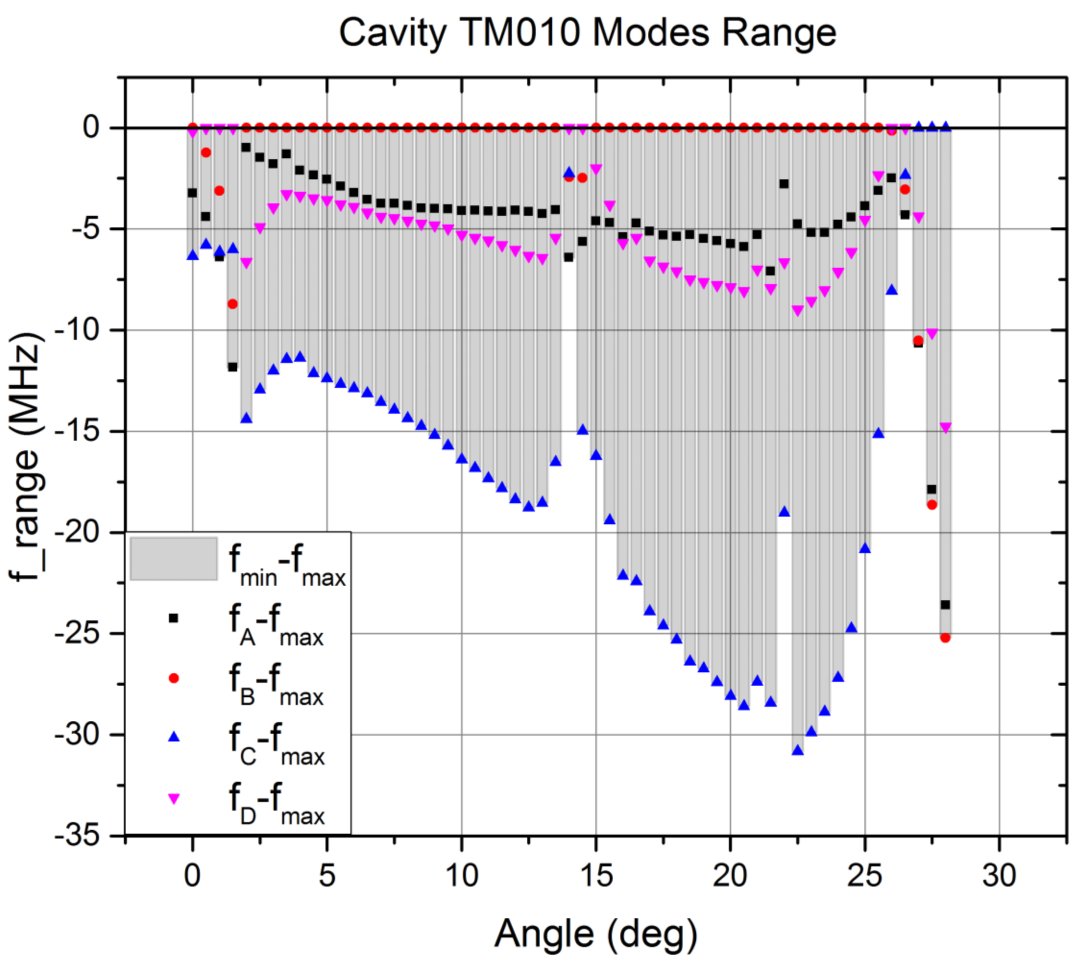
- Overall average Q : 5810 +/- 1340
- Average Q (0-26.5 deg) : 6650
- Q reduction with fine rods : ~37 %

Power Spectrum (cavity freq spread)



- TM010 modes near 4.59 GHz

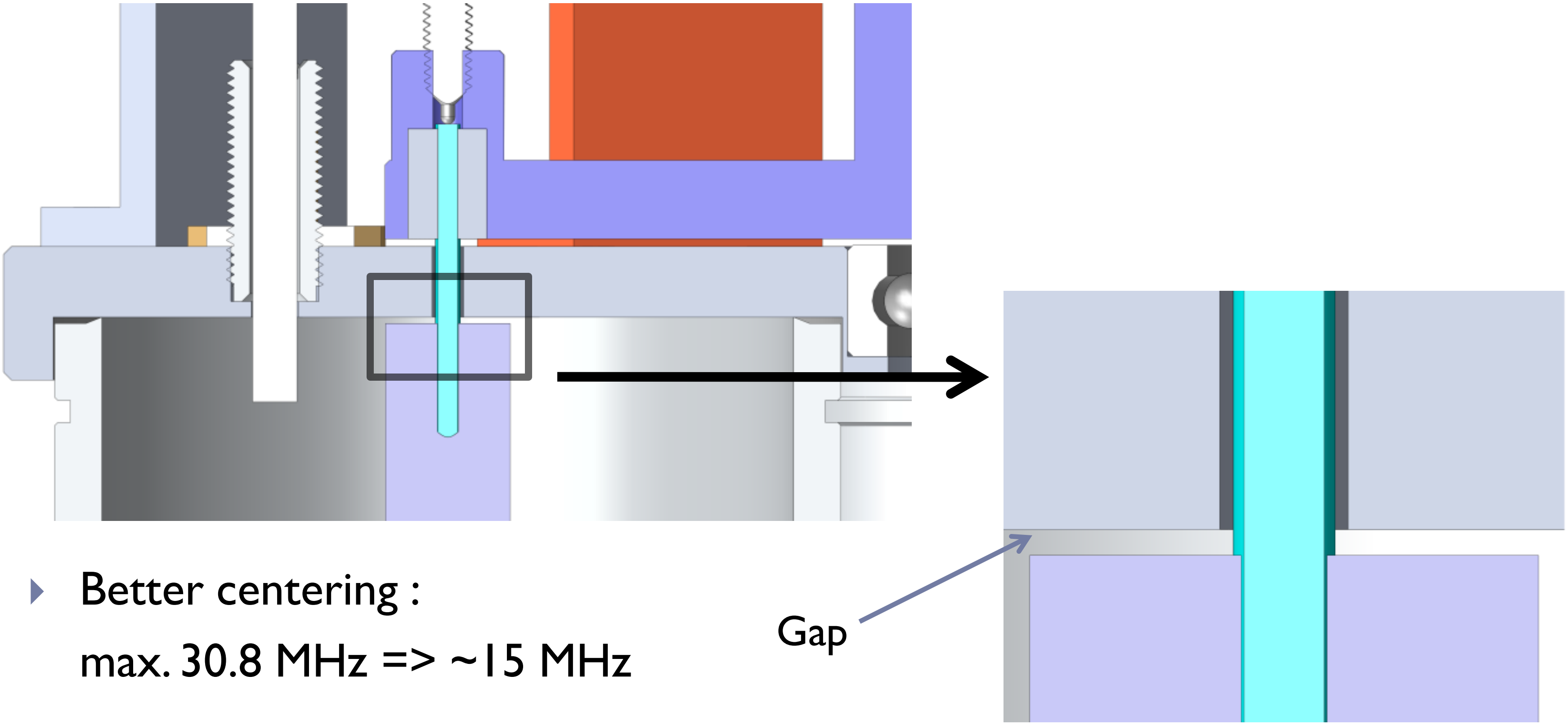
Power Spectrum (cavity freq spread)



- Frequency spread : ave=17.8 MHz max=30.8 MHz

Power Spectrum (cavity freq spread)

- Frequency change
  - Capacitance effect between coarse rod and plates?



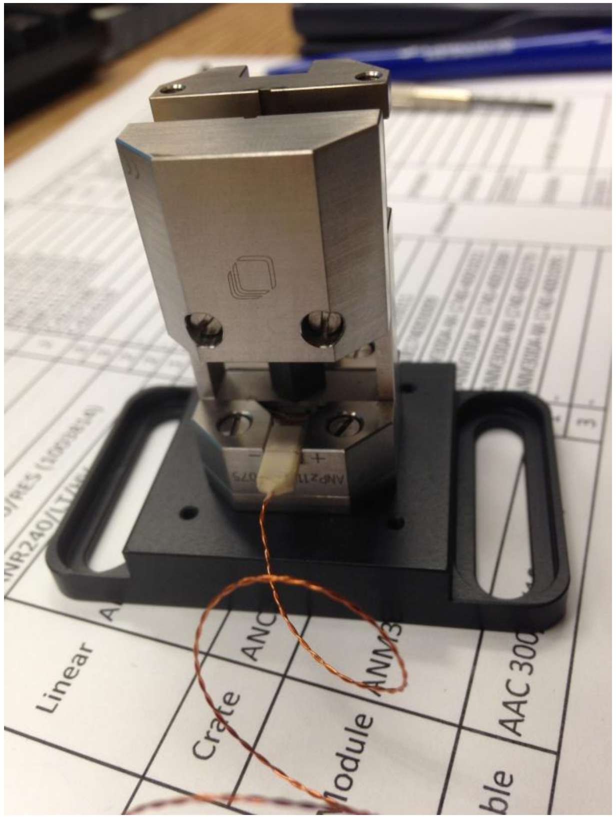
- Better centering :

  max. 30.8 MHz => ~15 MHz

Piezo Actuator Testing

- Actuators required by 4 C system

Experiment Part		Required Electronics	
Coarse Rod	4	Rotary actuator	1
Fine Rod	4	Linear actuator	4
Antenna	4	Linear actuator	4



- Testing at RT, non-vacuum
  - Suboptimal behavior
    - 5 actuators : sporadic stopping
    - 2 actuators : getting stuck

Summary & Future Tests

Lessons learned

Issues revealed

Future tests

Summary : Lessons learned

- RF testing
  - ✓ Q factor : 6650
  - ✓ Cavity f spreads : Max. 31 MHz
  - ✓ Mode map : 3 TE mode-crossings, range of 4.4 – 6.3 GHz

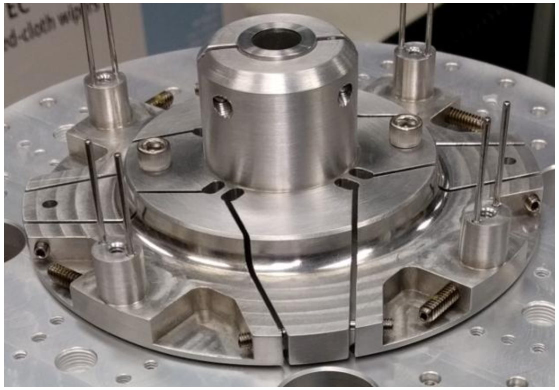
- Cavity tuning
  - ✓ Coarse tuning : 26.5 deg, 70 MHz/deg, (Min.) 70 kHz/step
  - ✓ Fine tuning : 12 mm range -> 10 MHz

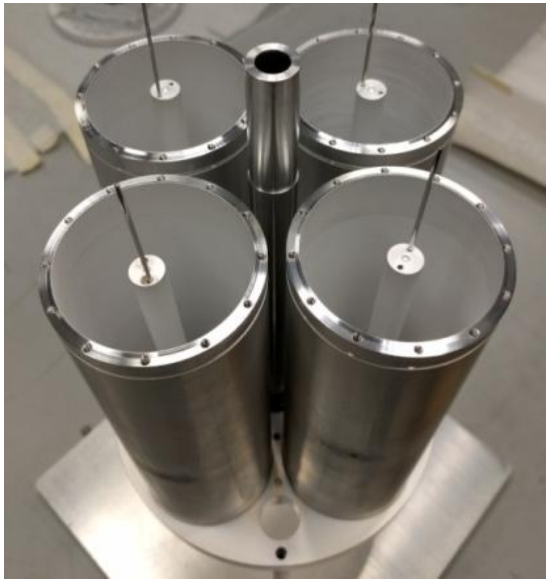
Summary : Issues Revealed

1. Cavity frequency spread
   - Can exceed fine tuning range (x3)
   - ➡ Quality control of cavities, flexure design, lesser gap of coarse rods
2. Mode-crossing regions
   - Cannot be covered by fine tune rod offset (x8)
   - ➡ Different length cavities
3. Piezo actuator performance
   - Some actuators' RT behavior was not satisfactory
   - ➡ Collaborate with Attocube Inc., mock up testing

Future Tests

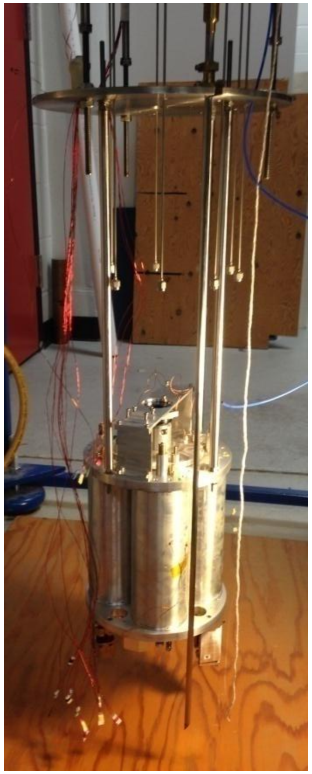
- Prototype v2 test (bench test)
  - Flexure wheel design
  - Lesser gap coarse tuning rods
  - Aluminum plated





Future Tests

- Prototype v2 test (bench test)
  - Flexure wheel design
  - Lesser gap coarse tuning rods
  - Aluminum plated
- LHe (4 K) test
  - RF test
  - Q improvement
  - Mechanical performance




Future Tests

- 2nd prototype test (bench test)
  - Flexure wheel design
  - Lesser gap coarse tuning rods
  - Aluminum plated
- LHe (4 K) test
  - RF test
  - Q improvement
  - Mechanical performance
- B = 7.5 T test

THE END

- Acknowledgments :

This work was supported by the U.S. Department of Energy through Grants No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0010280, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, and No. DE-C03-76SF00098. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.

Why Multi-Cavity Array

- Higher frequency

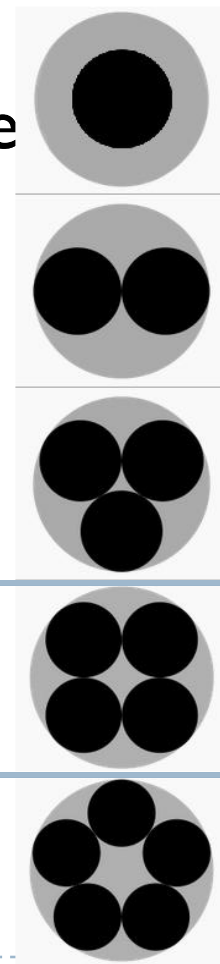
$$f = \frac{c}{2.61r}$$

Axion Mass	4.1 µeV	8.3 µeV
Frequency (f)	1 GHz	2 GHz
Cavity Radius (r)	11.5 cm	5.75 cm

ADMX Site Insert

Requirements for Design

- r = 5.75 ~ 11.5 cm
- Utilize maximum volume
  => Multi cavities
- 4 Cavity Array

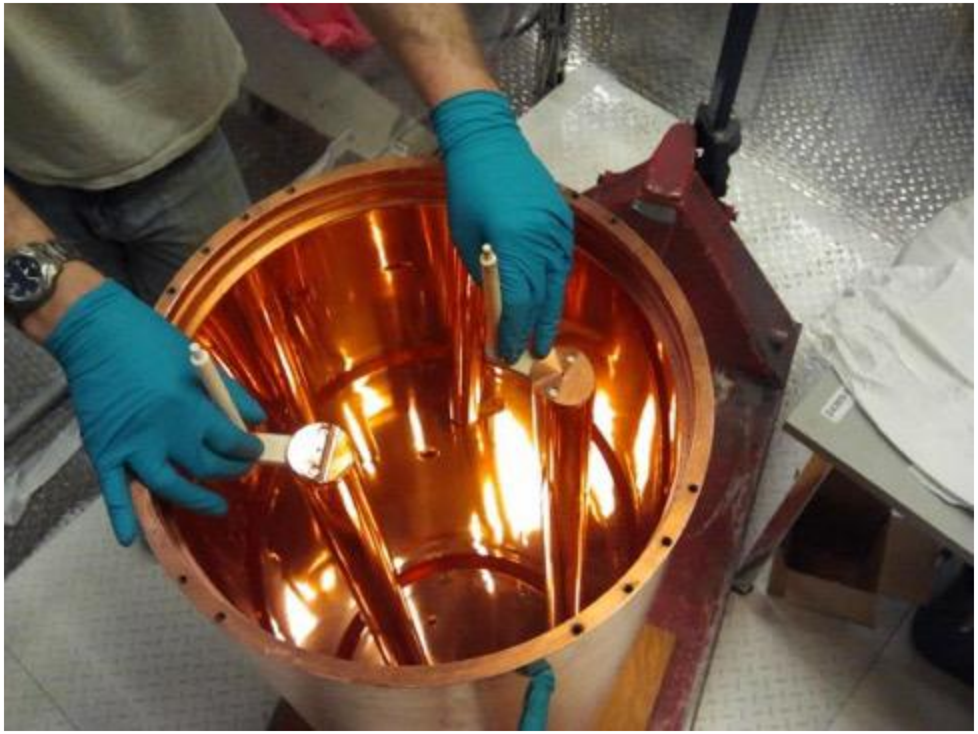


R = 21 cm

Radius (r)	Volume Used
11.5 cm	30.0 %
10.5 cm	50.0 %
9.75 cm	64.7 %
8.70 cm	68.6 %
7.77 cm	68.5 %

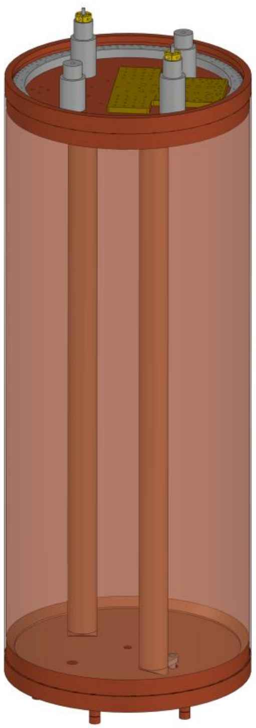
Frequency Tuning

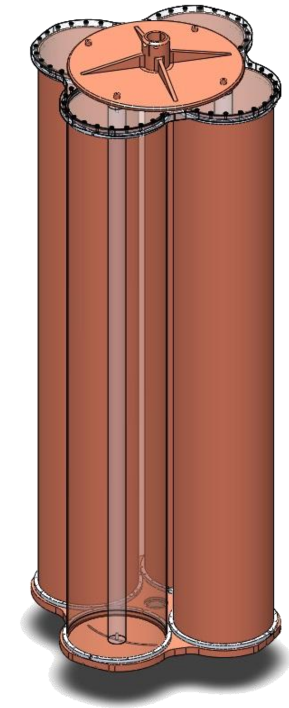
- Tuning rod



ADMX Single Cavity

Multi-cavity Array Concept



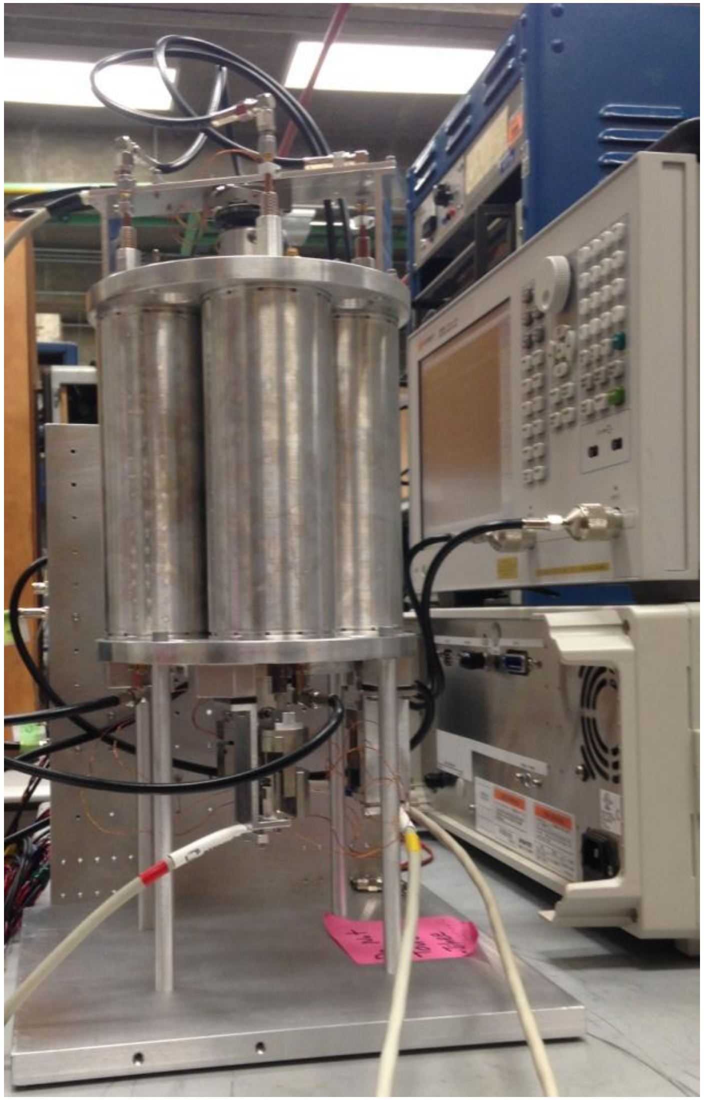


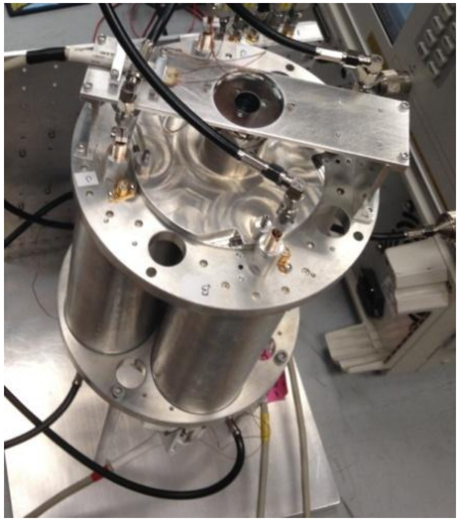
- Why? Higher axion mass range
- Size

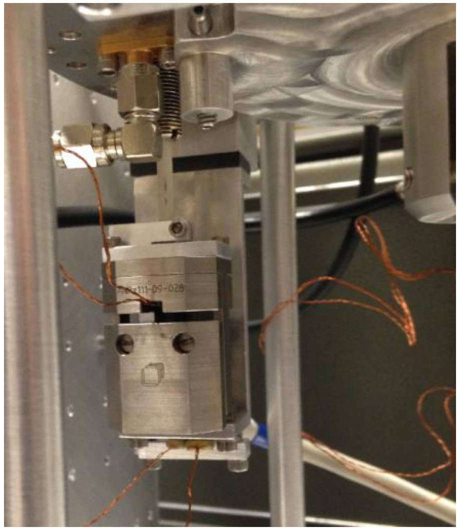
  Ø 42 cm => Ø 16 cm
- Frequency

  600~900 MHz => 1.4~2.1 GHz (metal)
- Prototype first

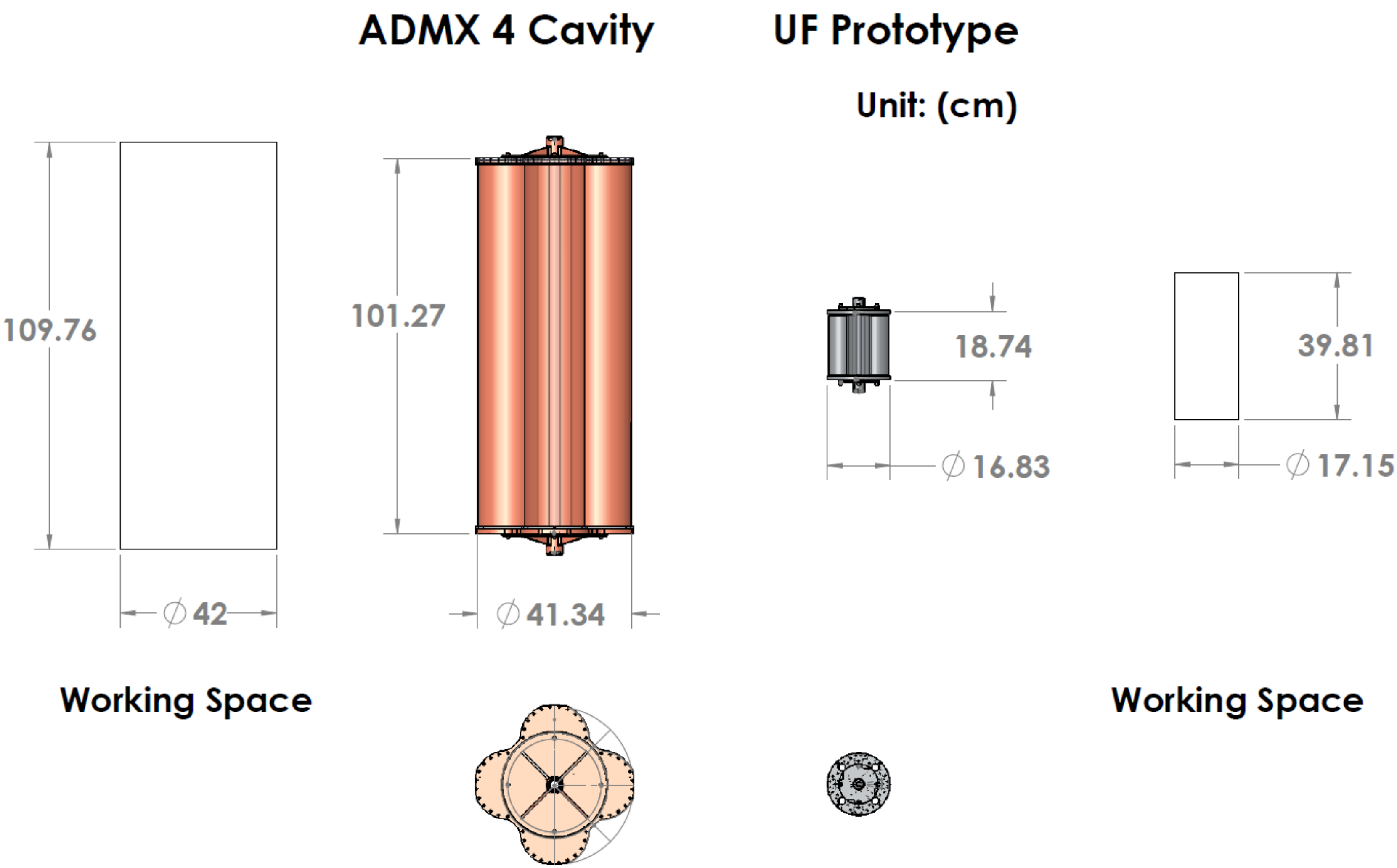
4 Cavity Prototype Pictures



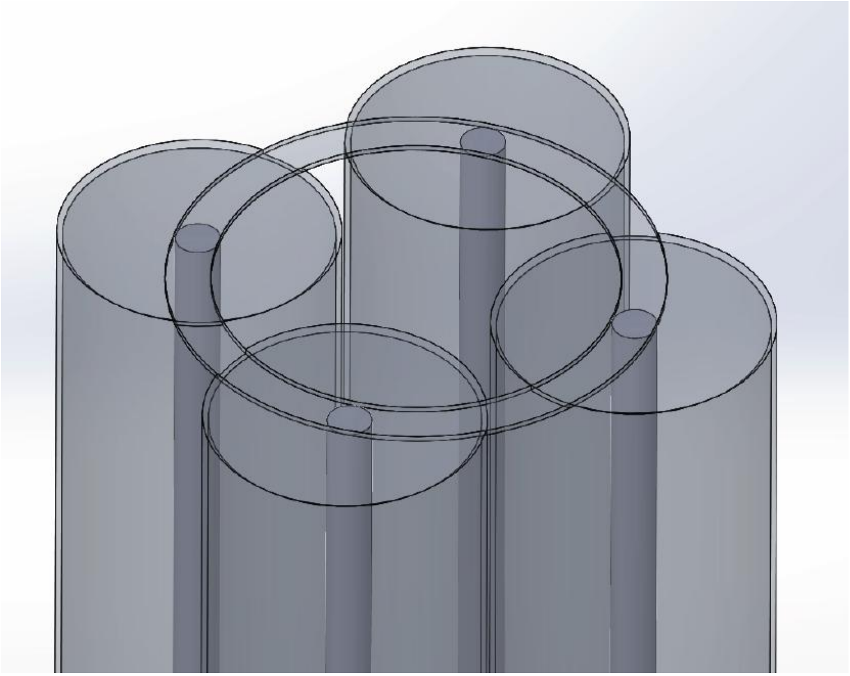




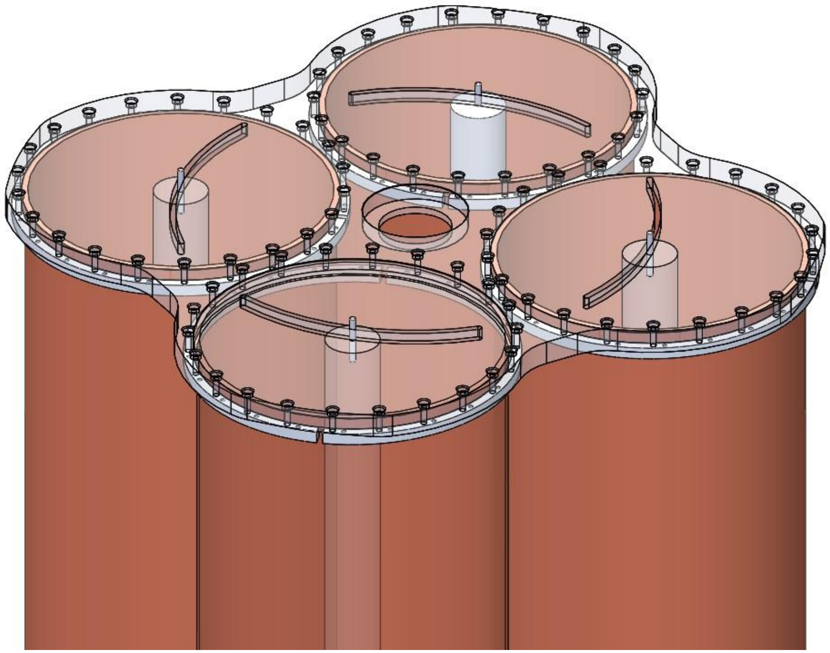
ADMX Working Space



Wheel Concept Modification



Old wheel concept



New wheel concept

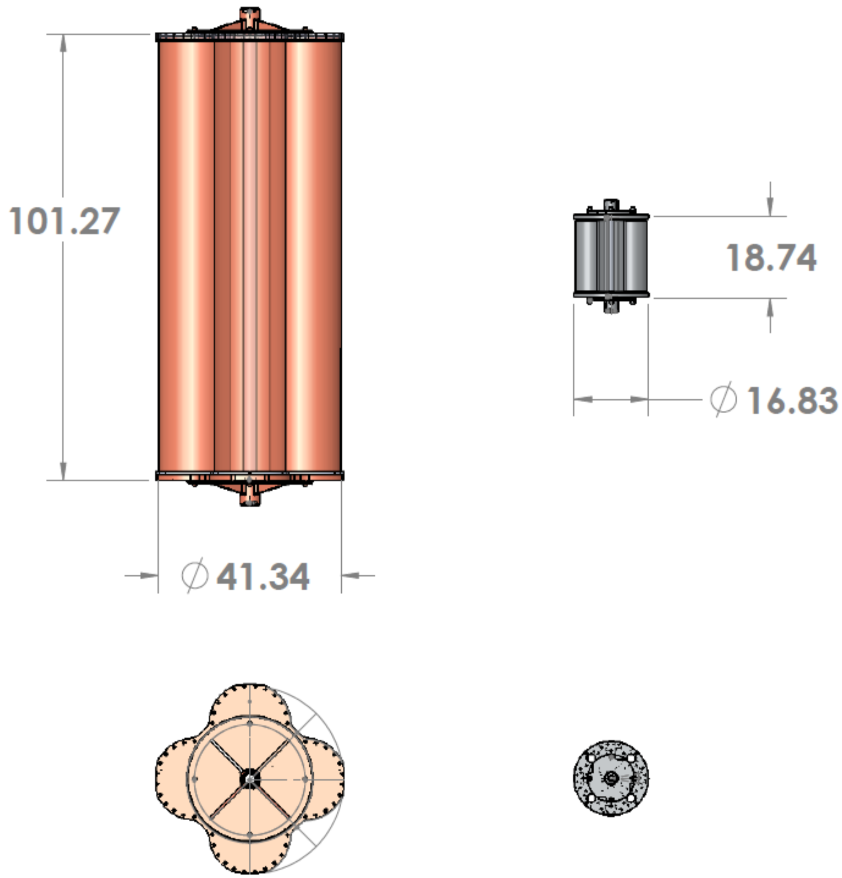
Tuning Range (ADMX 4C)

- r = 7.94 cm
- f_{010} (cyl) = 1.45 GHz
  - Metal Rod: Tune to 2.2 GHz (Dia= 2.88 cm)
  - Dielectric (Al_2O_3) Rod: Tune to 1 GHz

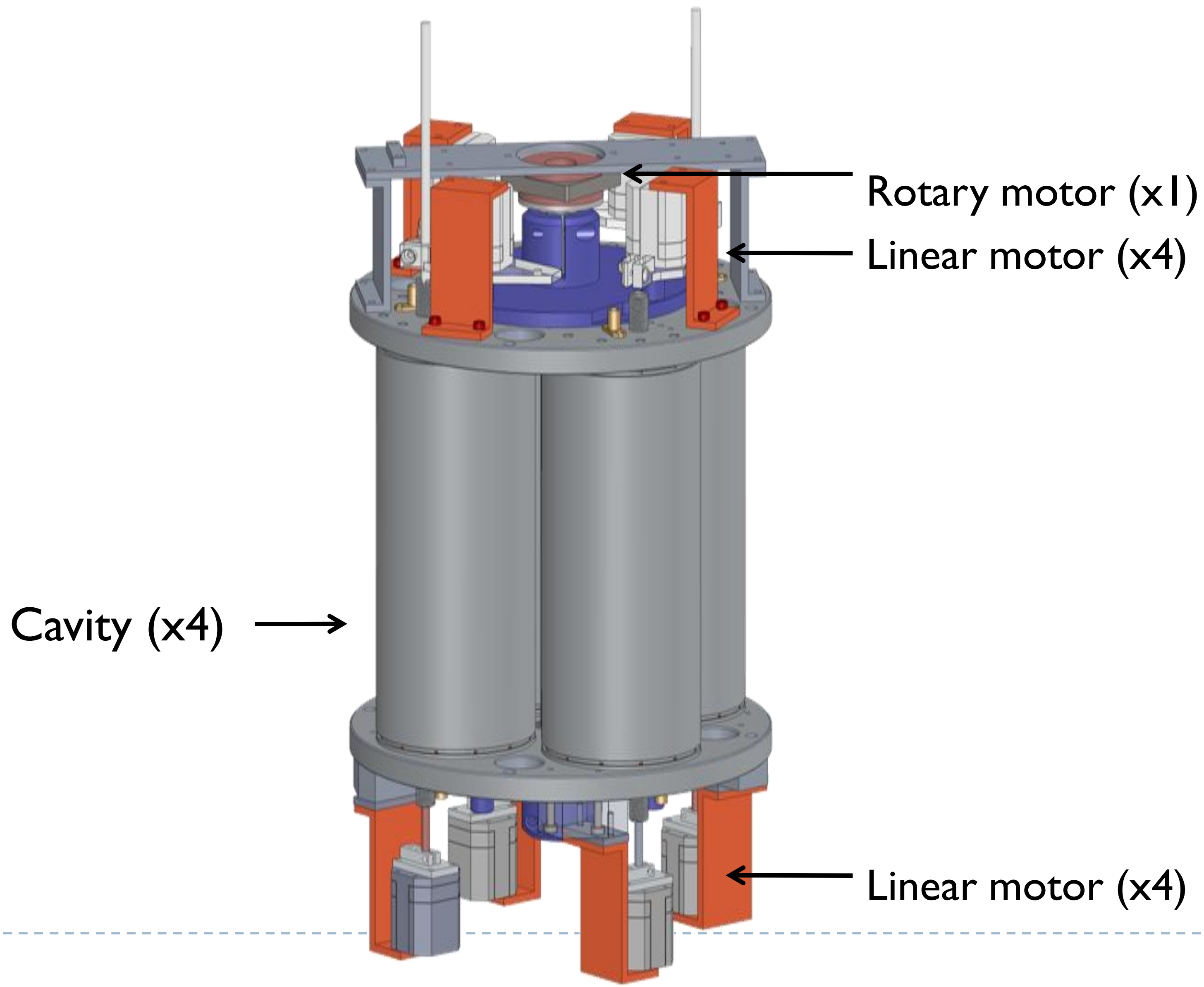
Build ADMX 4 Cavity Array

ADMX 4 Cavity **UF Prototype**

Unit: (cm)

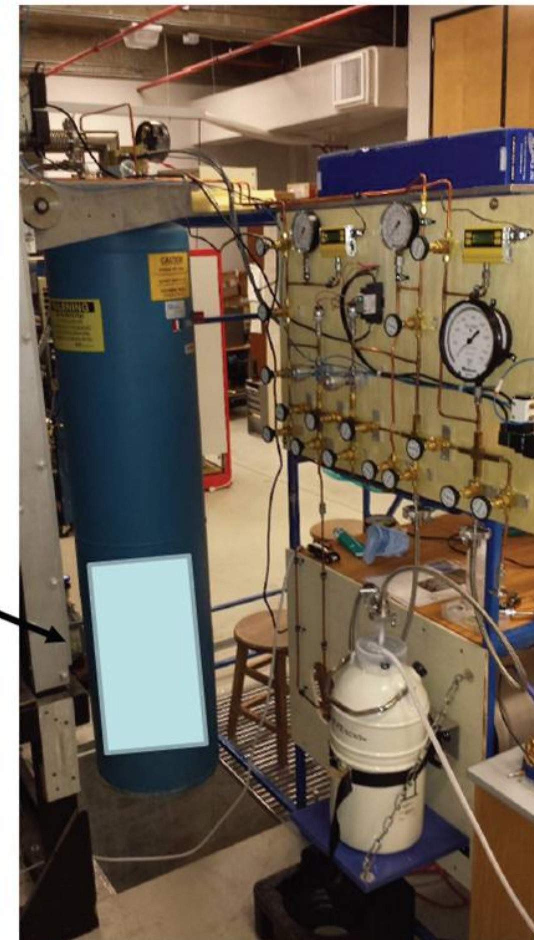


4 Cavity Prototype Design

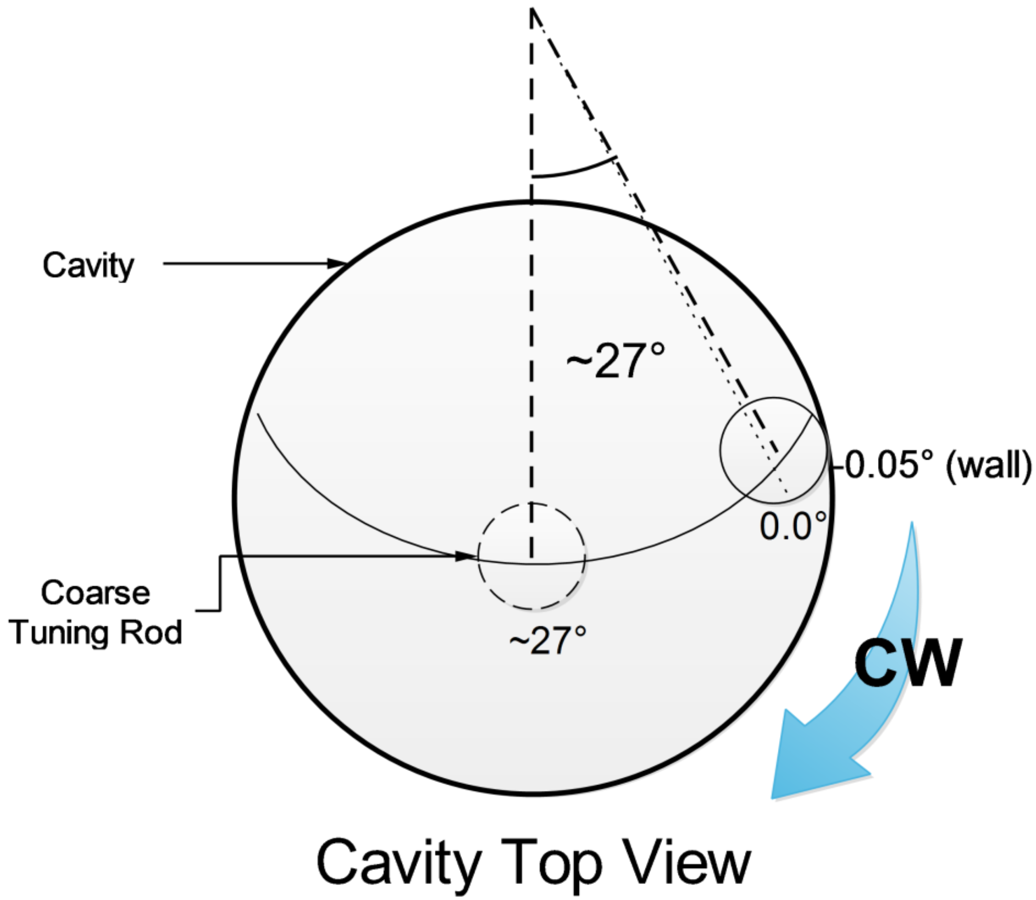


Prototype Array

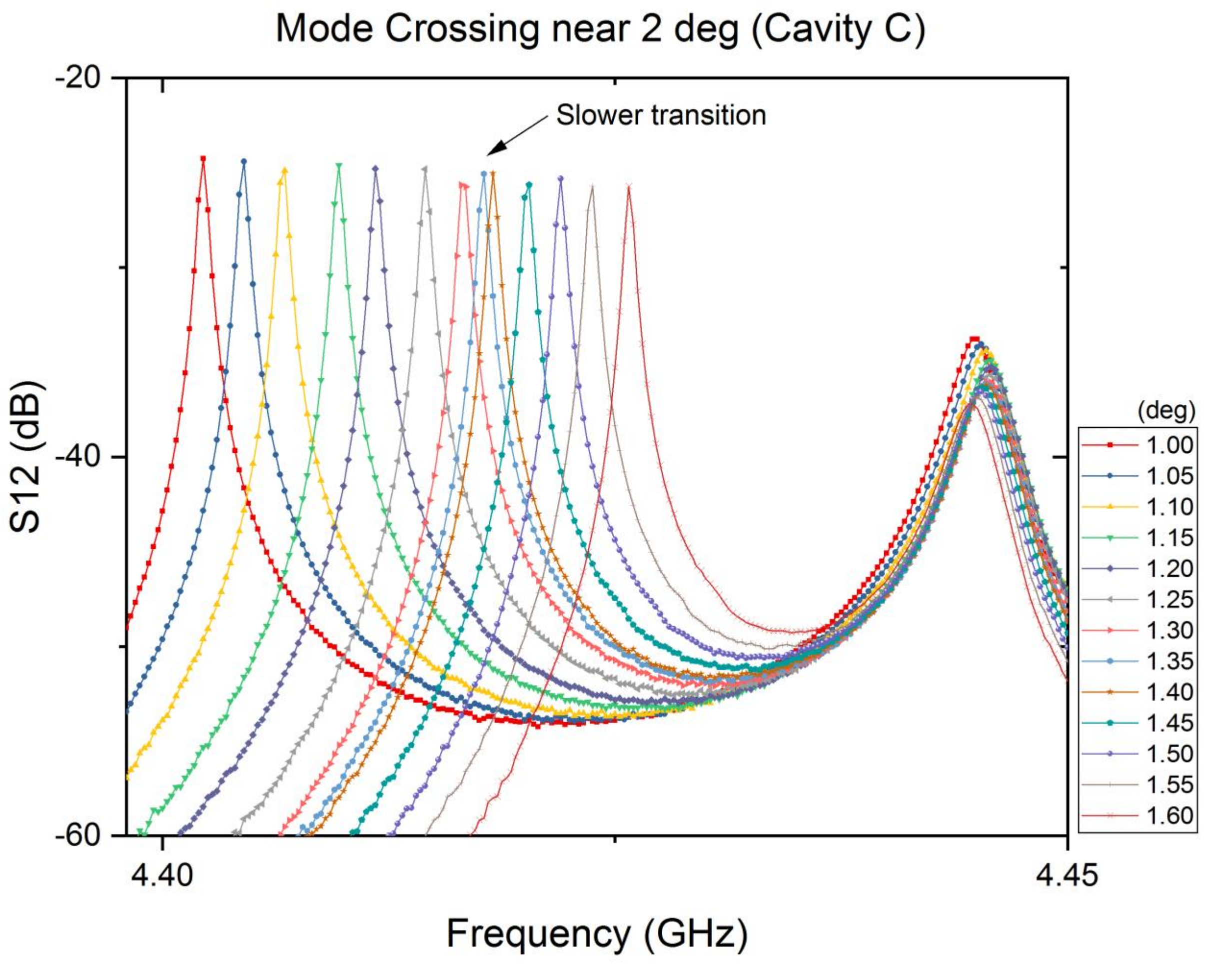
- Finish Assembly
- Testing
  - Rm. Temp. bench test
  - 4 K test
  - Locking test



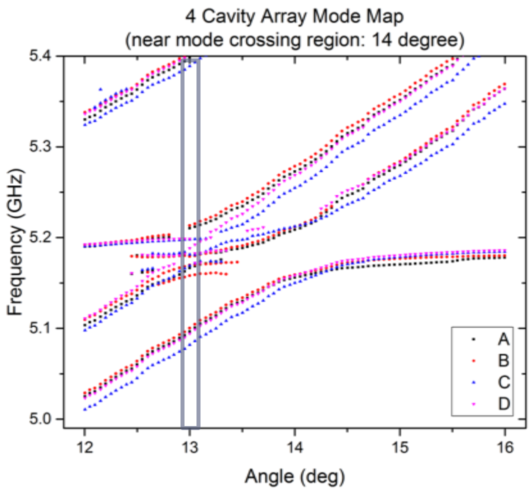
Tuning Rod Range

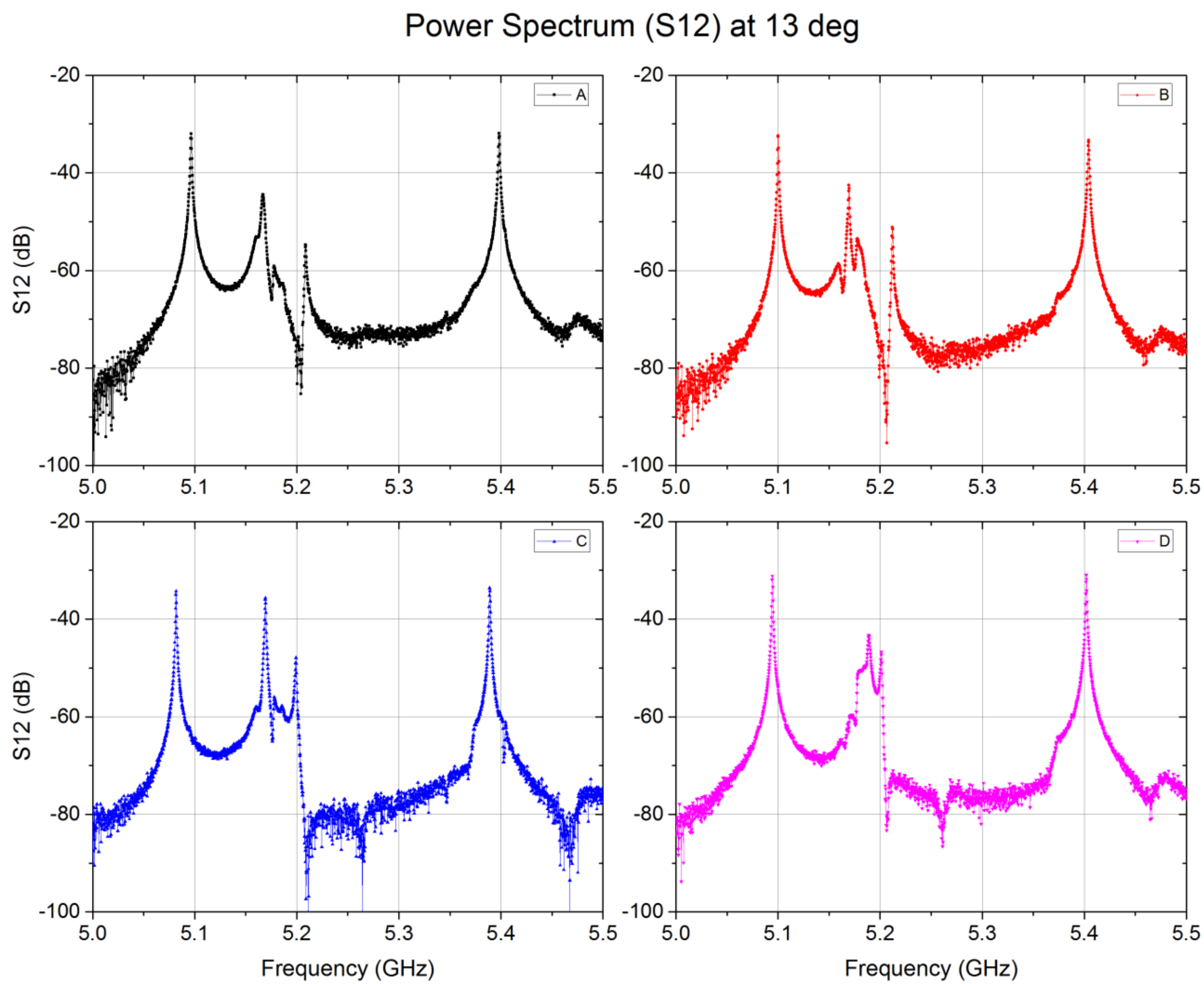


Power Spectrum Near 2 deg Crossing

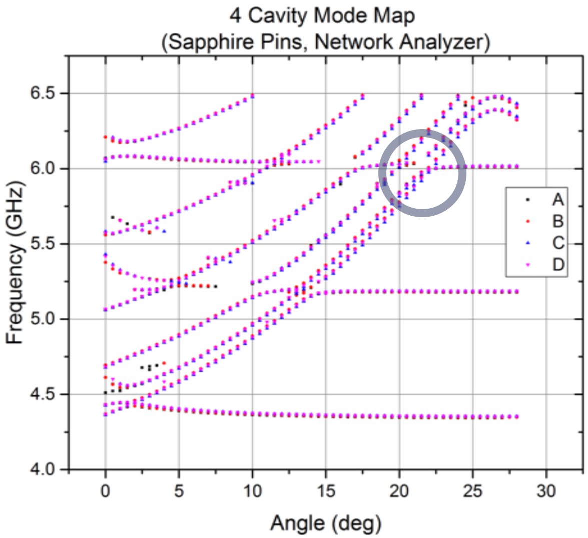


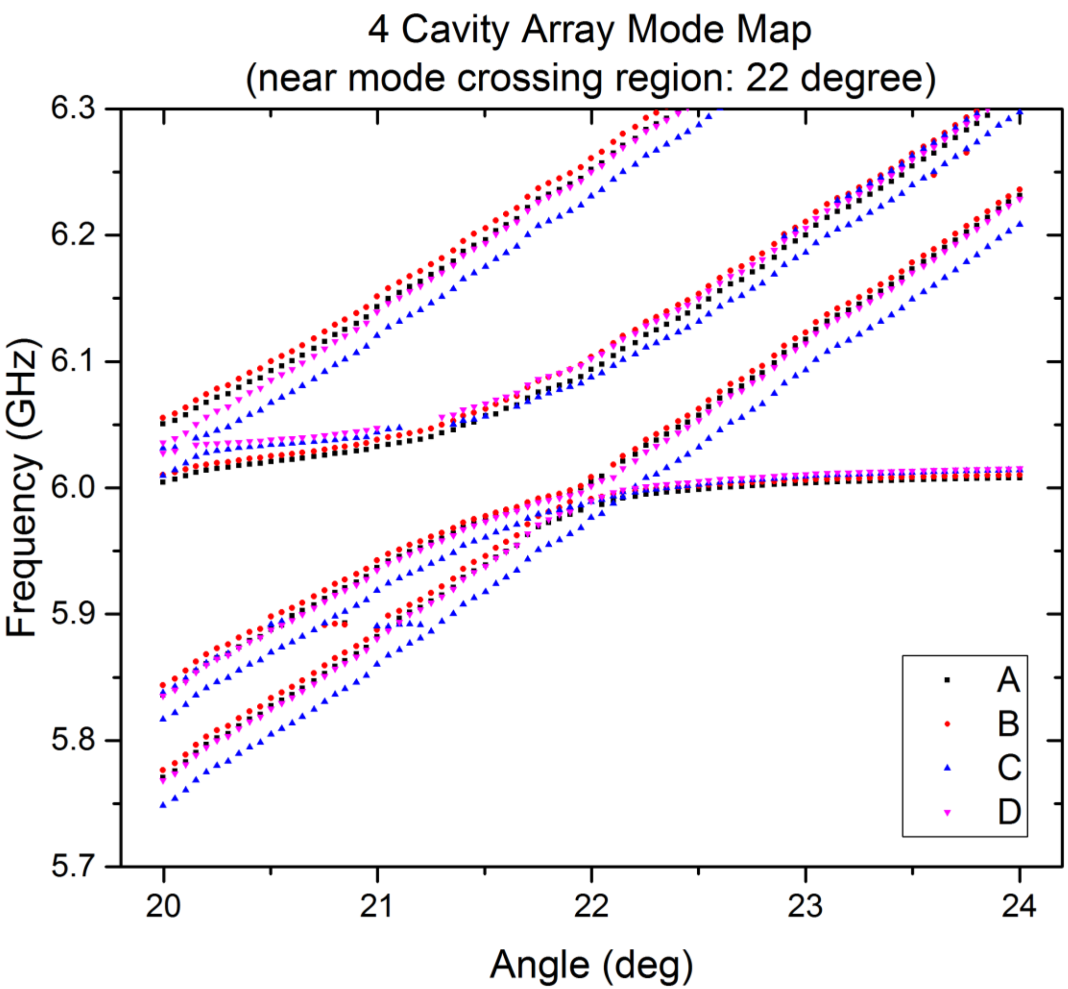
Power Spectrum (~14 deg)



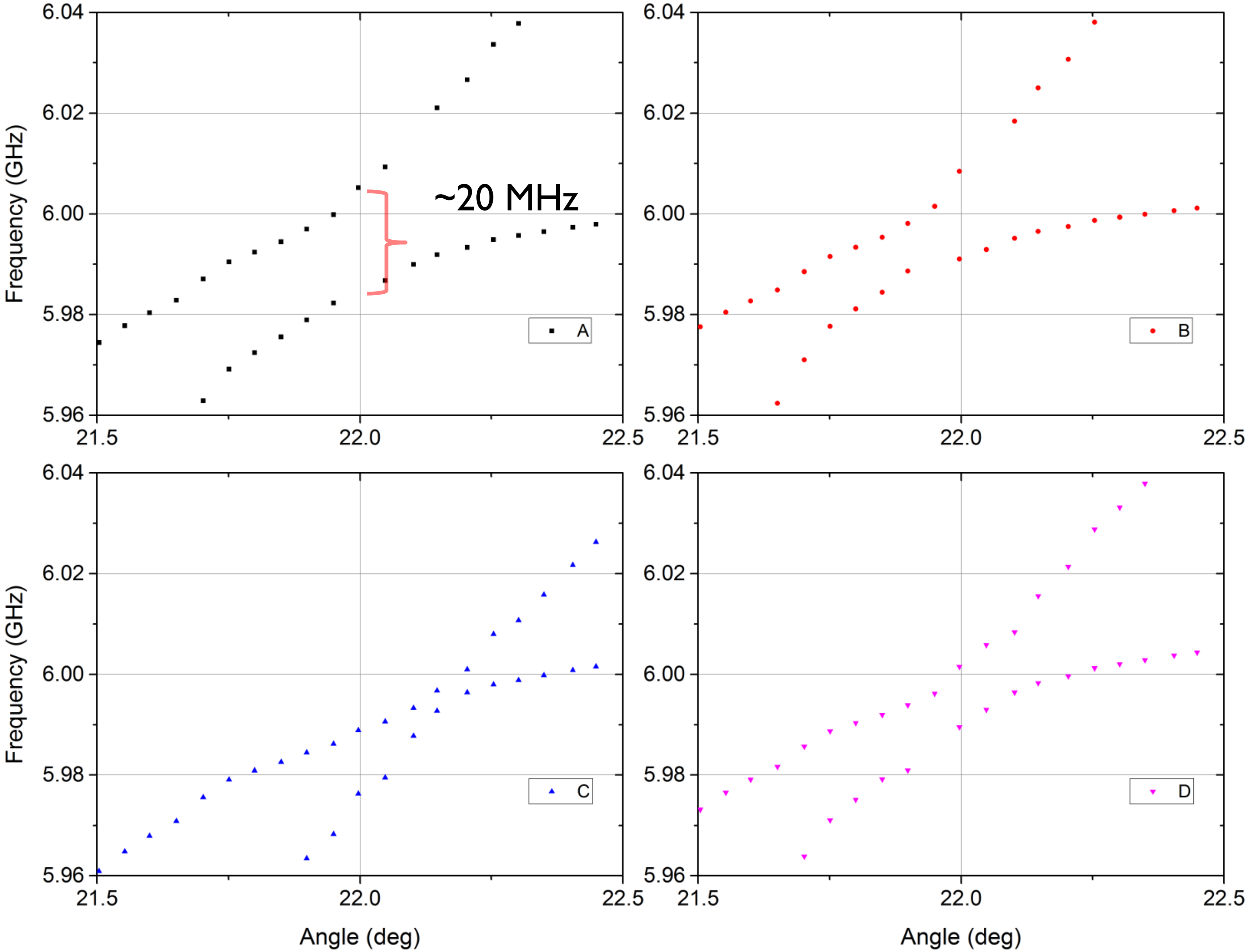


Mode Crossing (~22 deg)

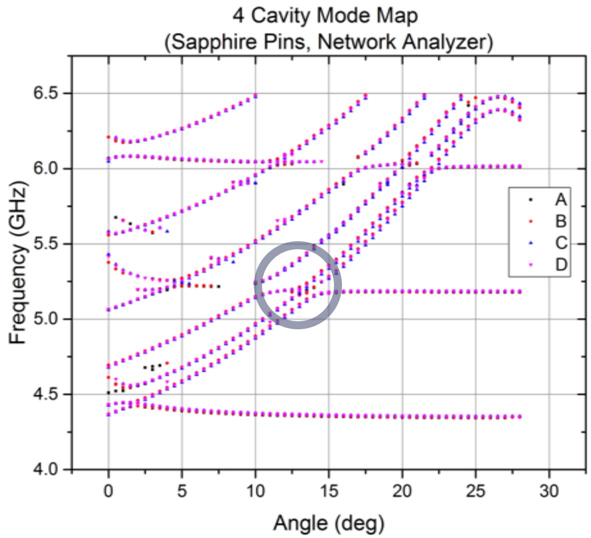


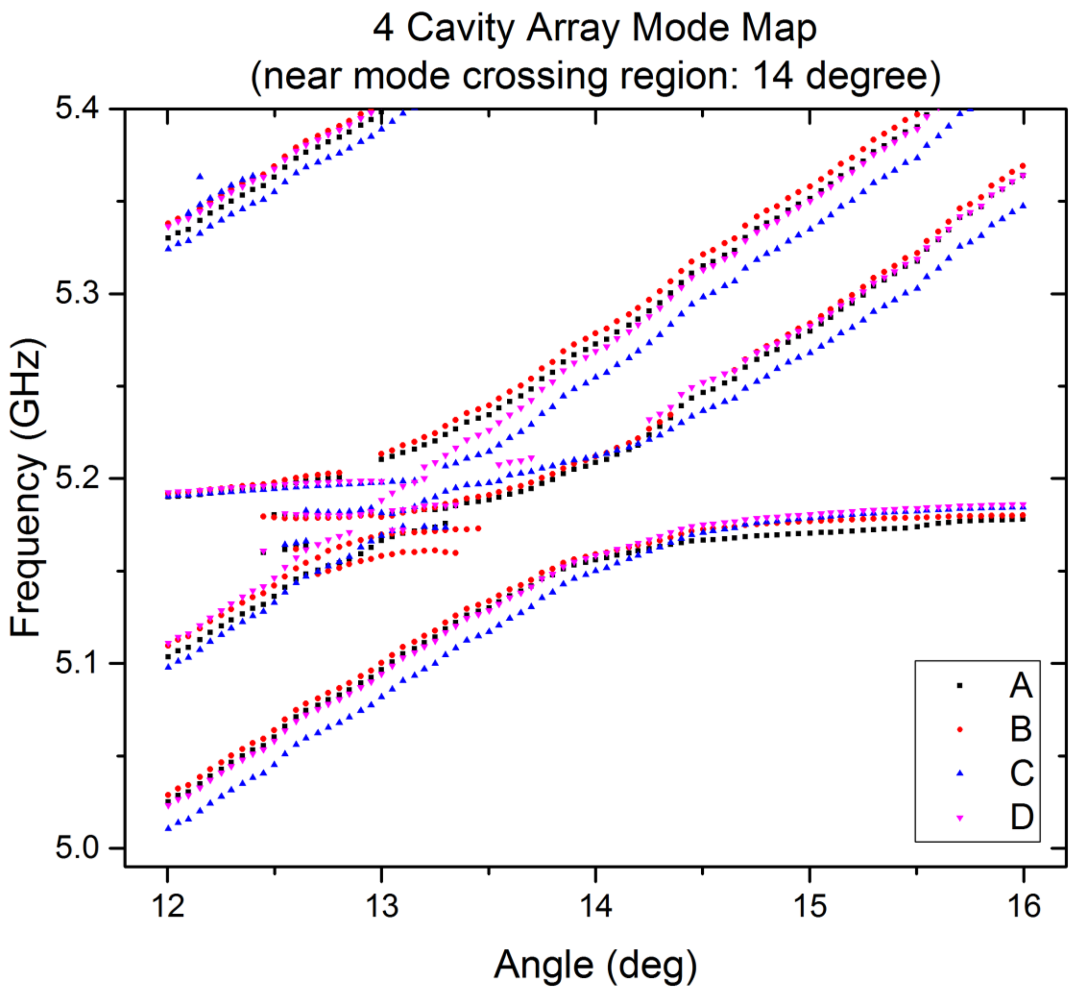


4 Cavity Array Mode Map
(near mode crossing region: 22 degree)

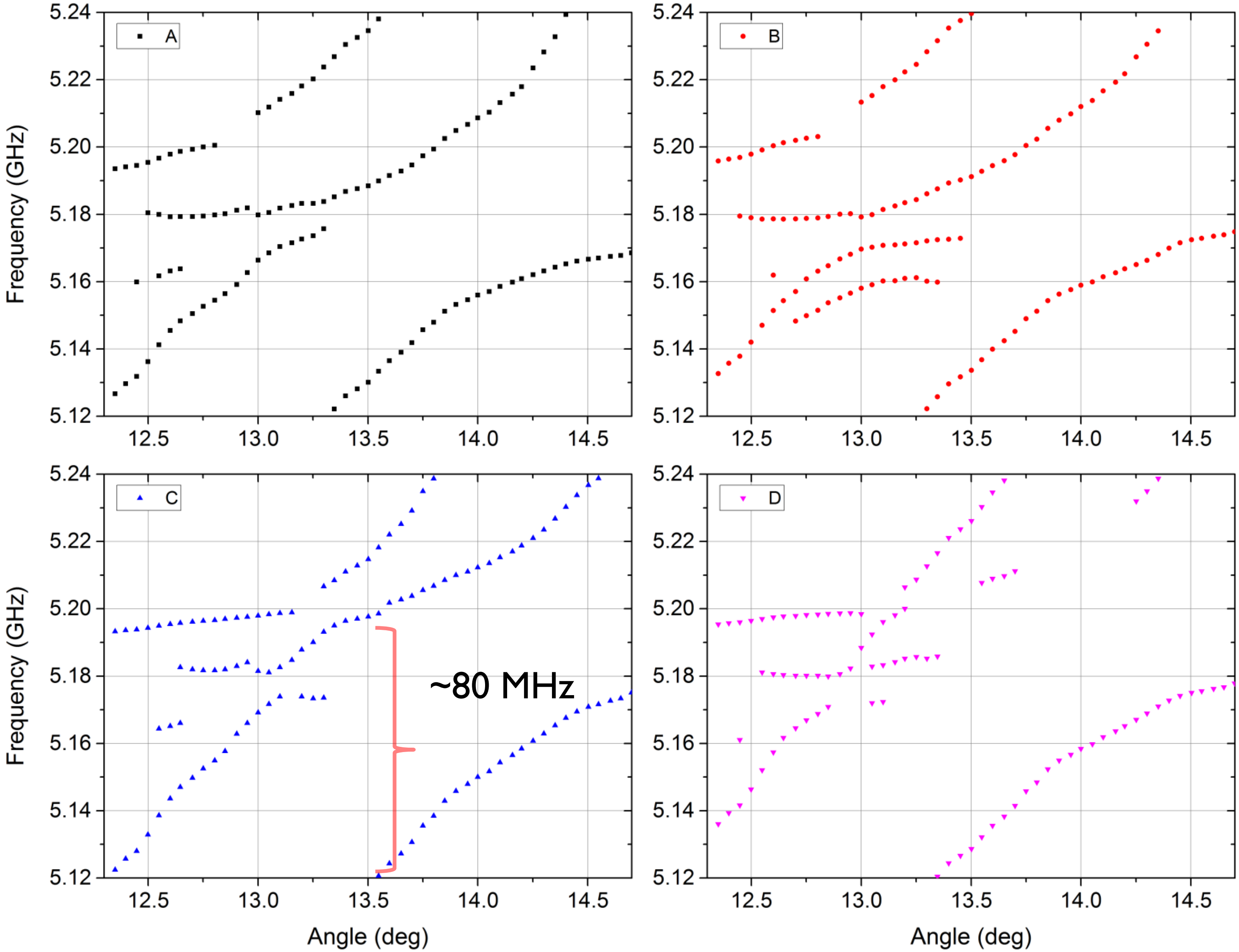


Mode Map (mode-crossing)

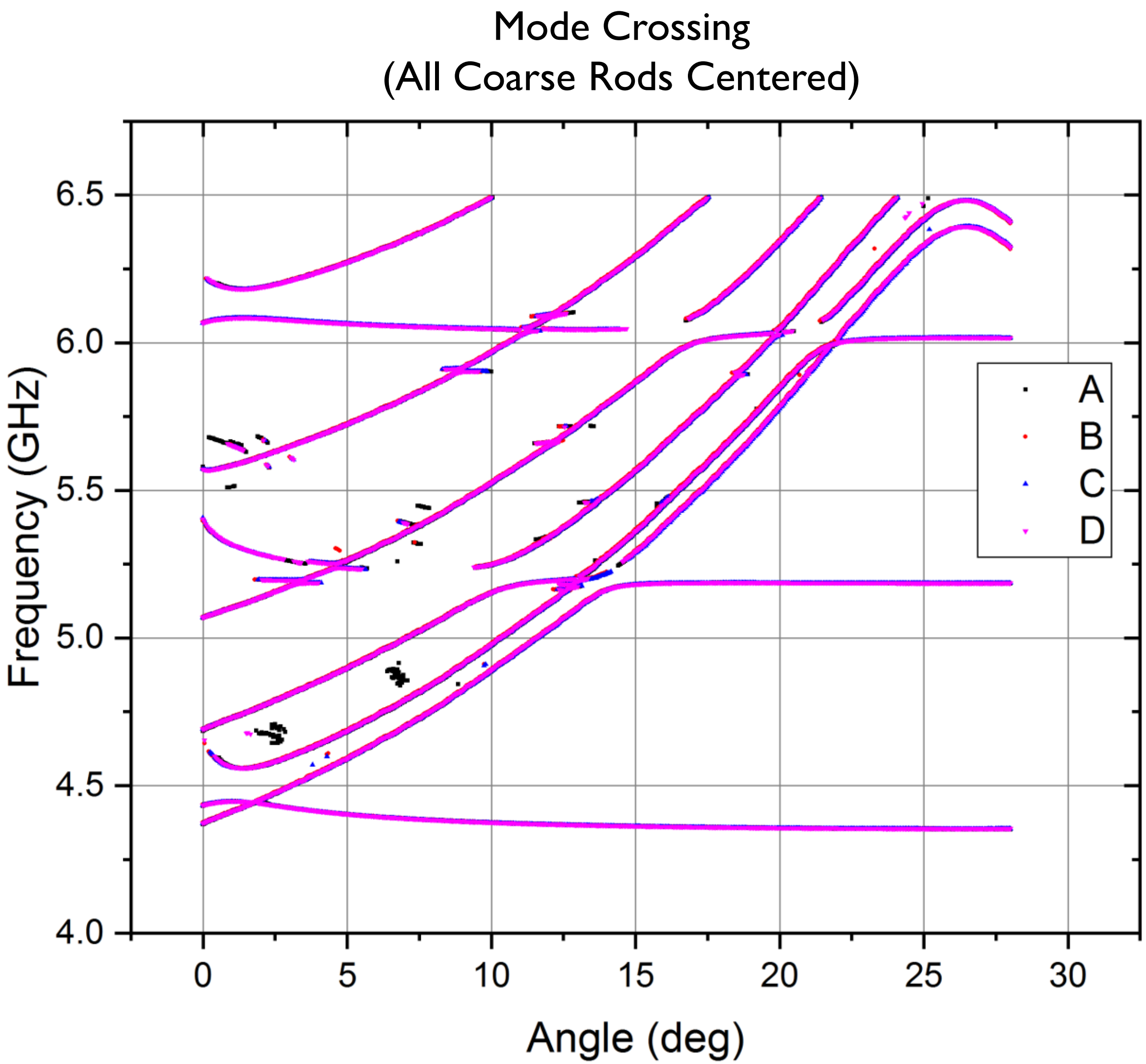




4 Cavity Array Mode Map
(near mode crossing region: 14 degree)

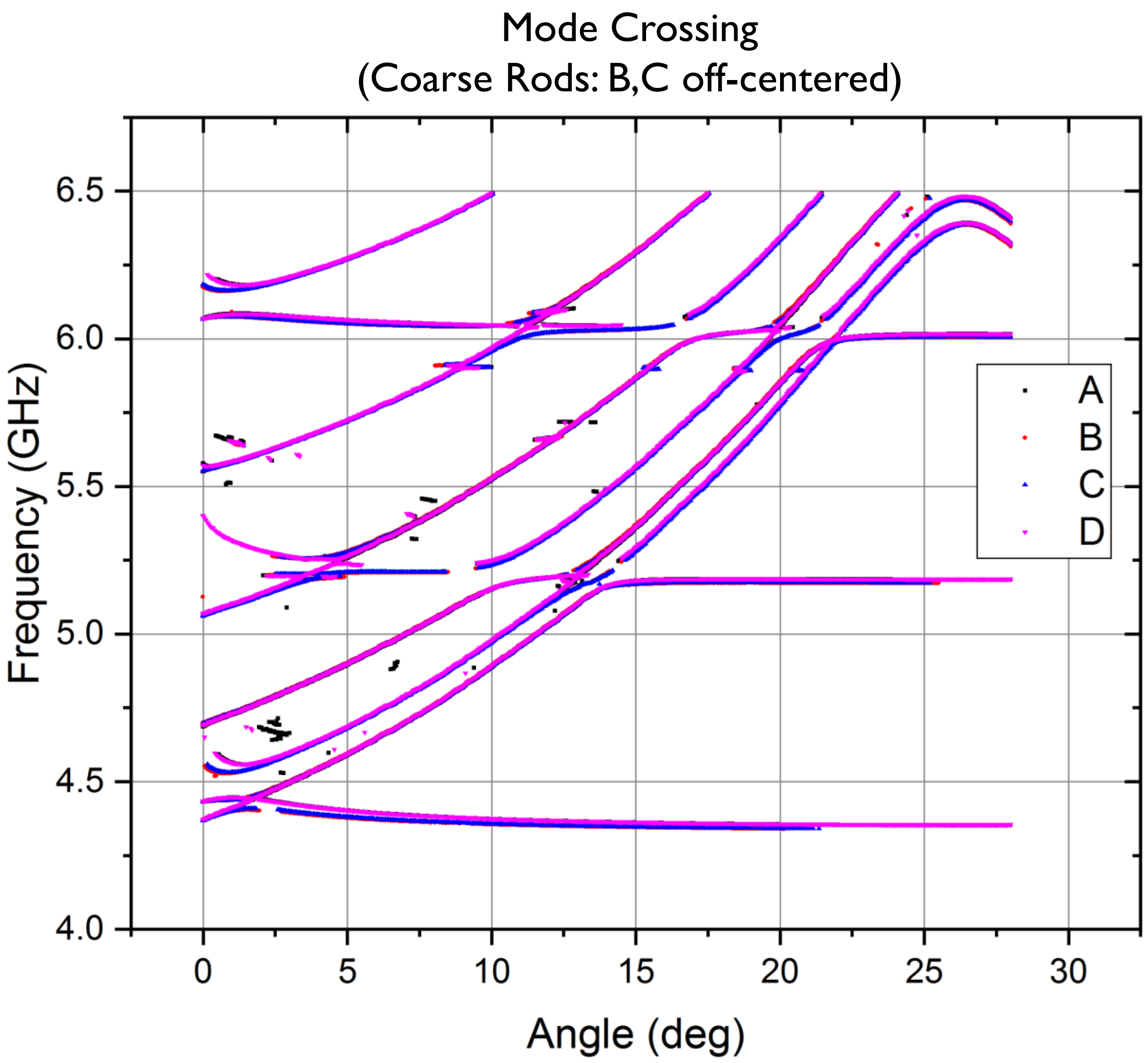


Mode Map



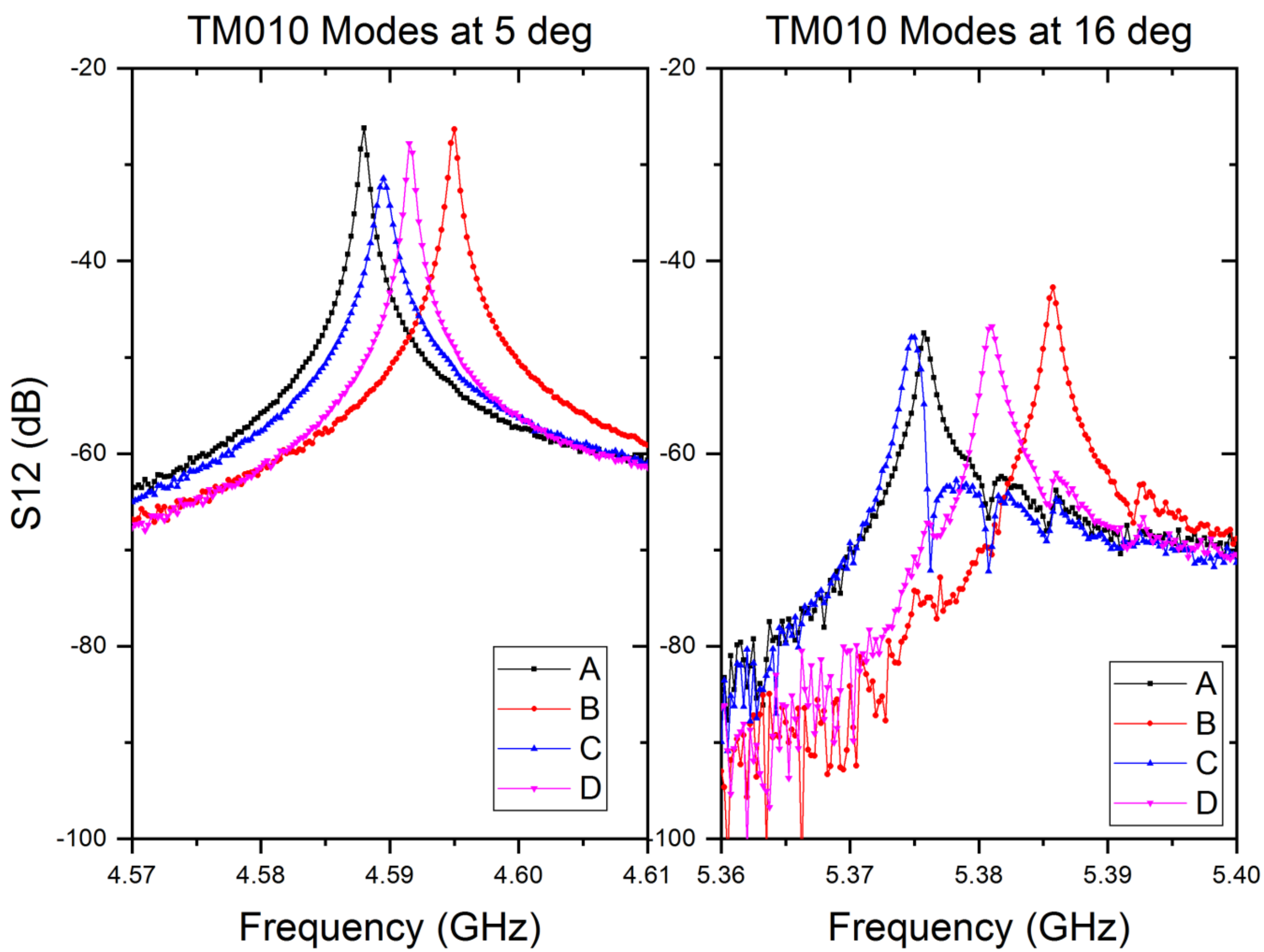
Mode Crossing
(All Coarse Rods Centered)
Frequency (GHz)
Angle (deg)
6.5
6.0
5.5
5.0
4.5
4.0
0
5
10
15
20
25
30
A
B
C
D

Mode Map



Mode Crossing
(Coarse Rods: B,C off-centered)
6.5
6.0
5.5
5.0
4.5
4.0
Frequency (GHz)
0
5
10
15
20
25
30
Angle (deg)
A
B
C
D

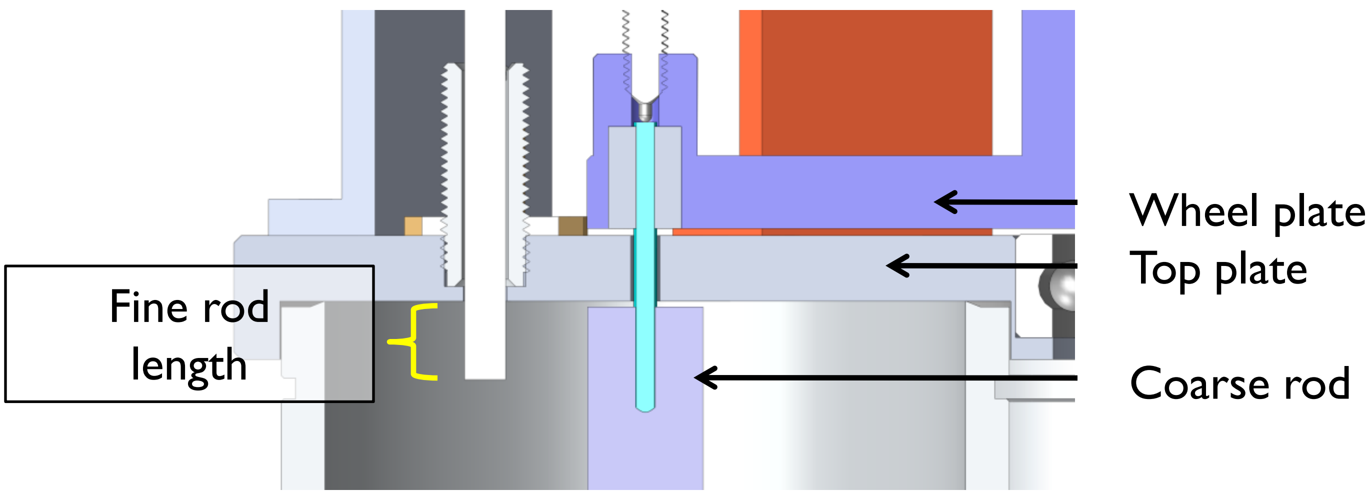
Power Spectrum (cross-talk)



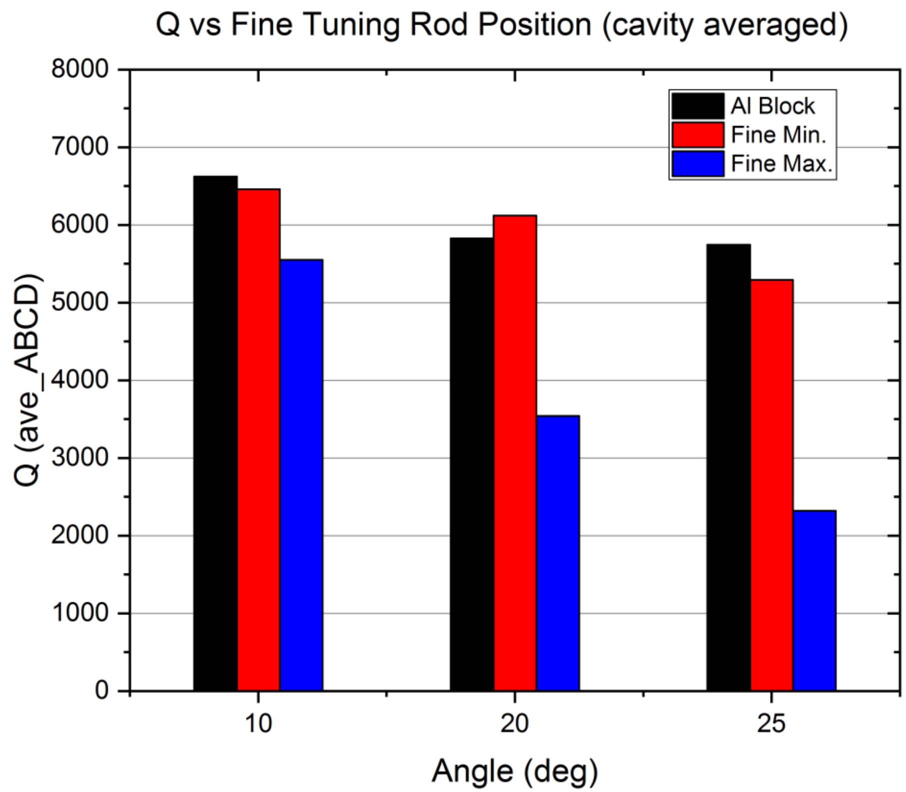
- More cross-talk with lower power
- Problem with low temp case?

Power Spectrum (Q factor)

- Fine rod positions
  1. No fine rods : Al block flushing with top plate
  2. Min. length : 3 mm
  3. Max. length : 15 mm



Power Spectrum (Q factor)



- Q reduction :

	Al Block	Fine Min.	Fine Max.
Average Q Factor	6070 +/- 610	5960 +/- 470	3810 +/- 750
Q Reduction Rate	-	1.81 %	37.23 %

Gap Change Measurement

- **Original**

  (wheel index swapped) :

Cavity	Coarse Rod Vertical Position
A	~Center
B	~Center
C	~Center
D	~Center

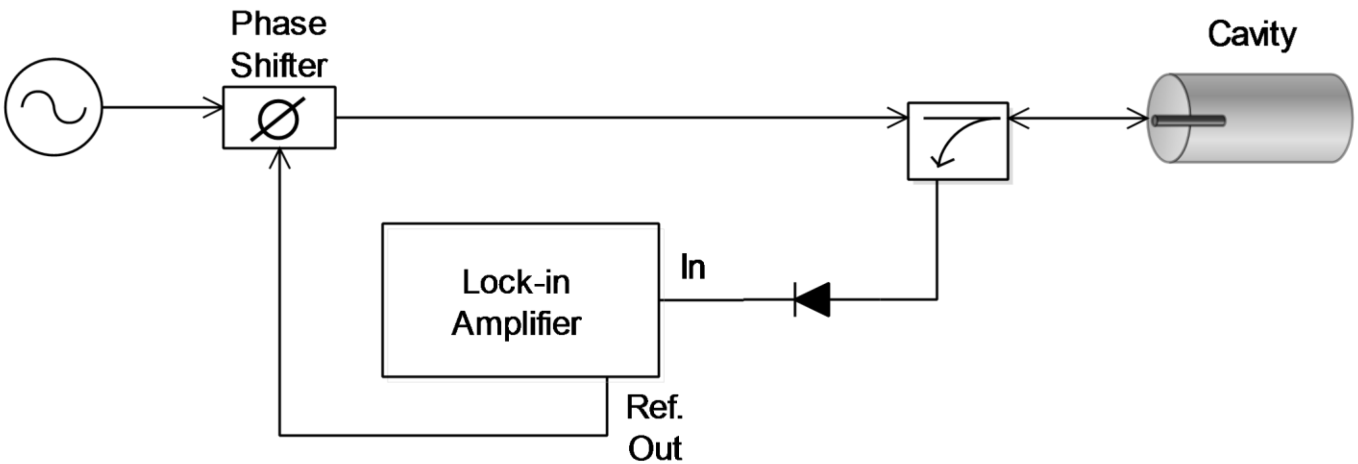
- **Coarse Rod Adjusted:**

Cavity	Coarse Rod Vertical Position	Gaps btw Rod & End Plate
A	~Center (no change)	Top gap ~ btm gap
B	**~closer to bottom plate**	Top gap > btm gap
C	**~closer to bottom plate**	Top gap > btm gap
D	~Center (no change)	Top gap ~ btm gap

Note: Adjusting the coarse rod (vertical) position was done by observing (TM010) frequency response (S12). At the center position, frequency seemed to be highest. When rod gets closer to end plates, frequency got lower. Rods in cavity **B and C** were lowered to a position closer to the bottom plate.

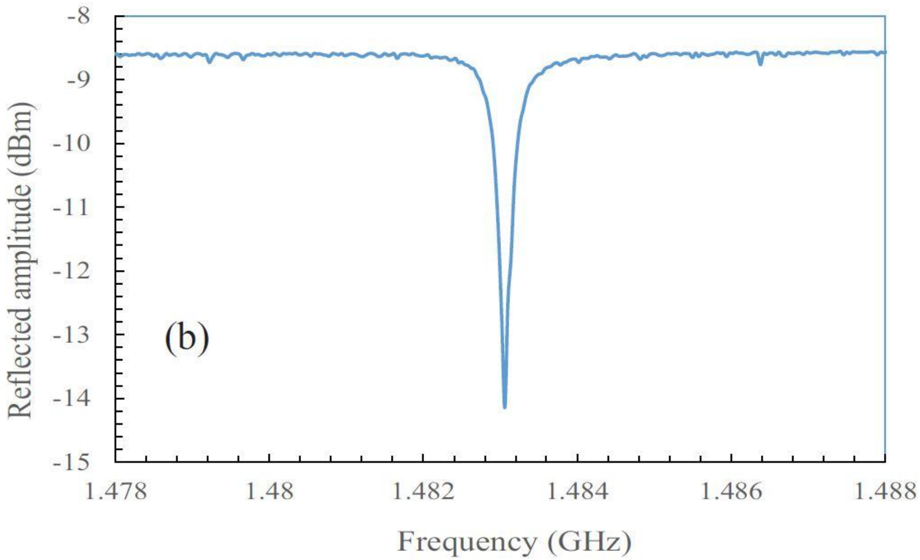
Near wheel plate angle of 17 deg, cavity B frequency was lowered ~9 MHz, cavity C frequency was lowered ~5 MHz. (see plot on page 4)

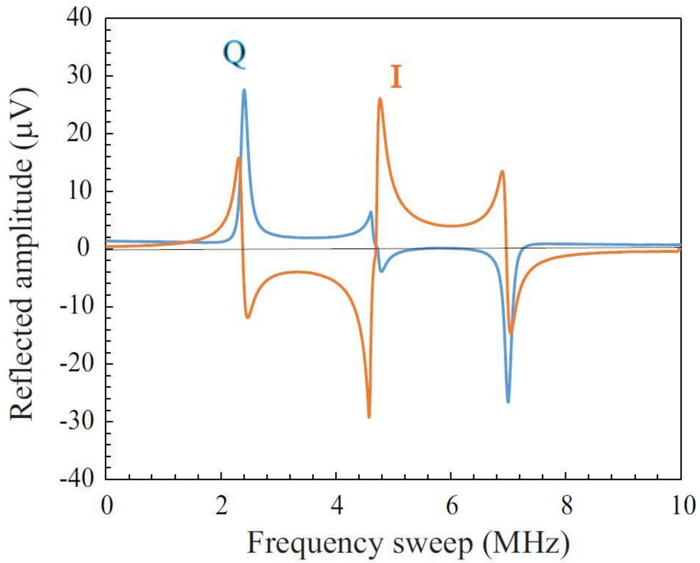
Cavity Locking (Pound Lock)



A **phase modulated** RF signal (modulation frequency: 2.5 MHz) is fed to the cavity and the **reflected signal** is detected and used to synchronize multi cavity resonant frequencies.

Cavity Locking (Pound Lock)

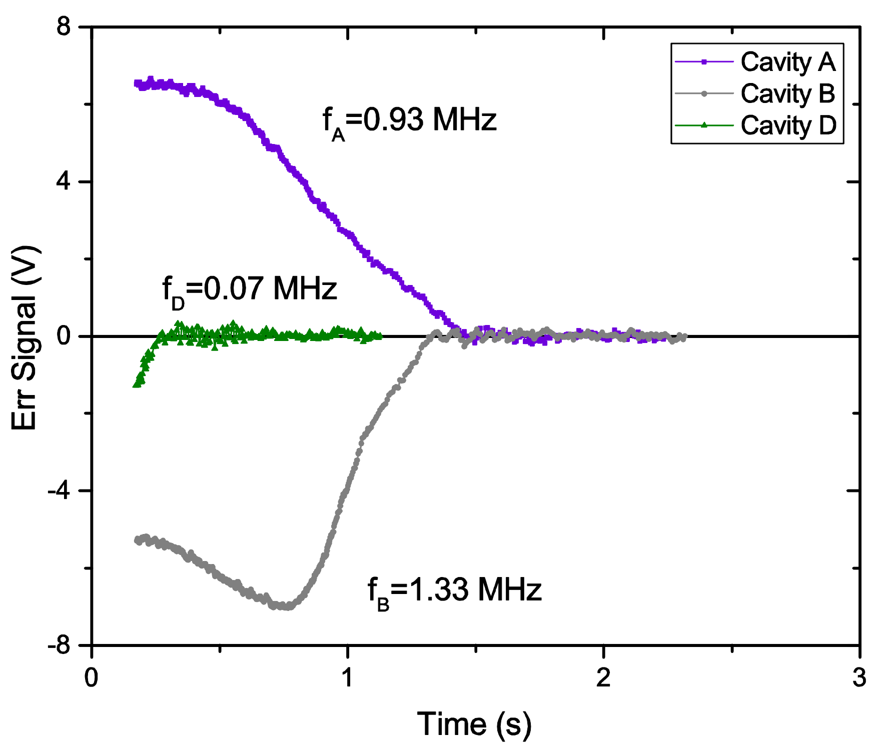




A **phase modulated** RF signal (modulation frequency: 2.5 MHz) is fed to the cavity and the **reflected signal** is detected and used to synchronize multi cavity resonant frequencies.

Cavity Locking (Pound Lock)

- Typical locking error signal



- Cavity A, B, D are locked consecutively
- Tested throughout tuning range (0~27 deg)
- Result :

Accuracy	6.44 % of linewidth
Total Time (x4)	8.4 s
Est. dissipated power	1.67 mW

Cavity Locking (Pound Lock)

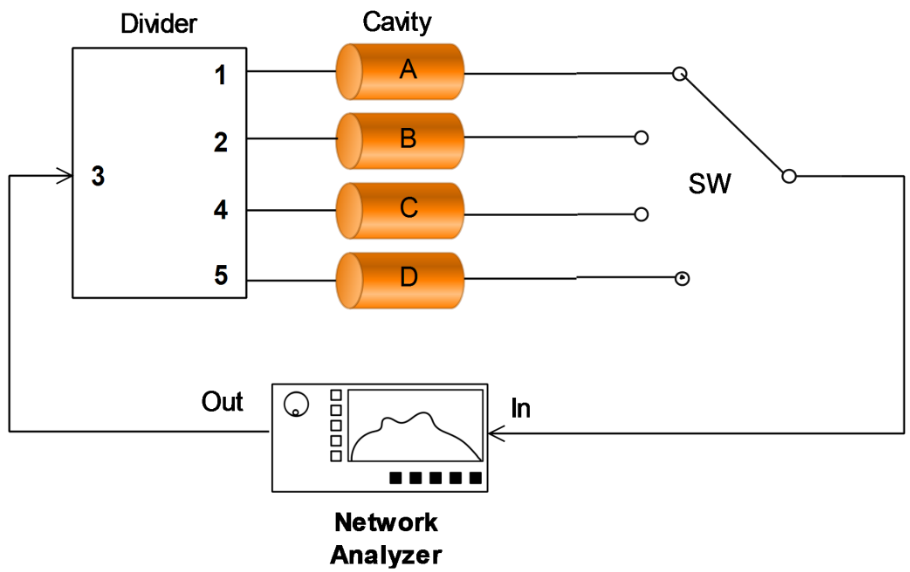
- Results (Heat)

$$E_{dissipated} = CV^2 tan(\delta)$$

$E_{dissipated}$: Energy dissipated
C : Motor capacitance
V : Motor drive voltage
tan(δ) : Loss tangent

	Unavoidable	Avoidable	Total
Steps	321	140	**462**
Heating (mJ)	45.3	4.8	**50.1**
Power (uW) (per cycle : ~ 120 sec)	377	40	**417**

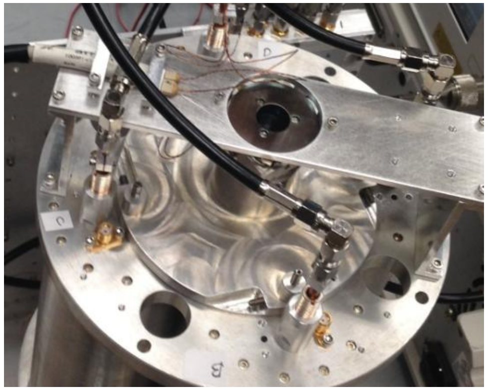
Mode Map Test Setup

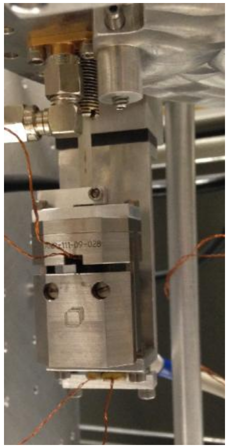


- Electronics :
  - Network analyzer (Keysight E5063A), motor controller (Attocube ANC350), rotary motor actuator (Attocube ANR240/RES)
- Stimulus (input) Power :
  - Output of NA : 0 dBm
- All others kept same with previous setup :
  - configuration and coupling of antennas, coarse tuning path, step size etc.

Piezo Actuator Testing

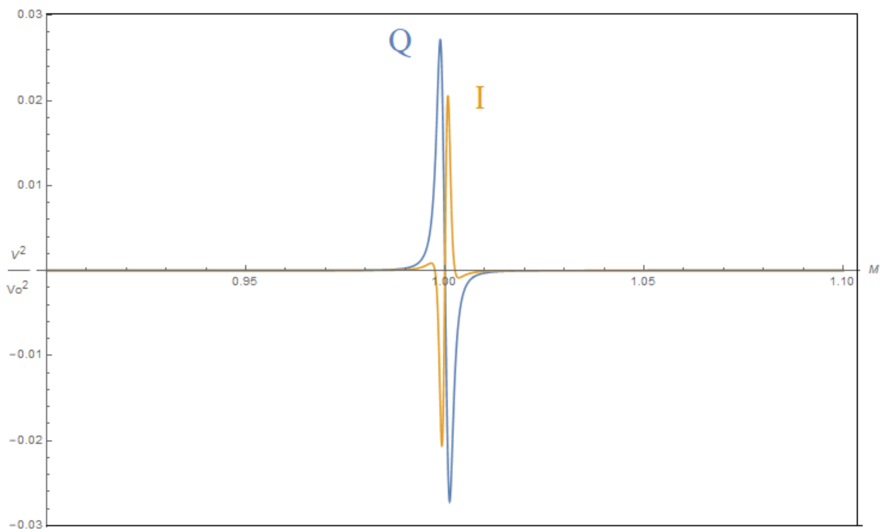
- Specifications
  - Rotary actuator
    - Max. load : 2 N
    - Max. dynamic torque around axis : 2 Ncm
  - Linear actuator
    - Max. load : 2 N
    - Max dynamic force along the axis : 5 N
- Tests
  - Antenna (RG402, dia = .140”)
    - Weight : 0.06 N
    - Friction : 5.88 N
  - Fine tuning rod (dia = .125”)
    - Weight : 0.01 N
    - Friction : 1.08 N



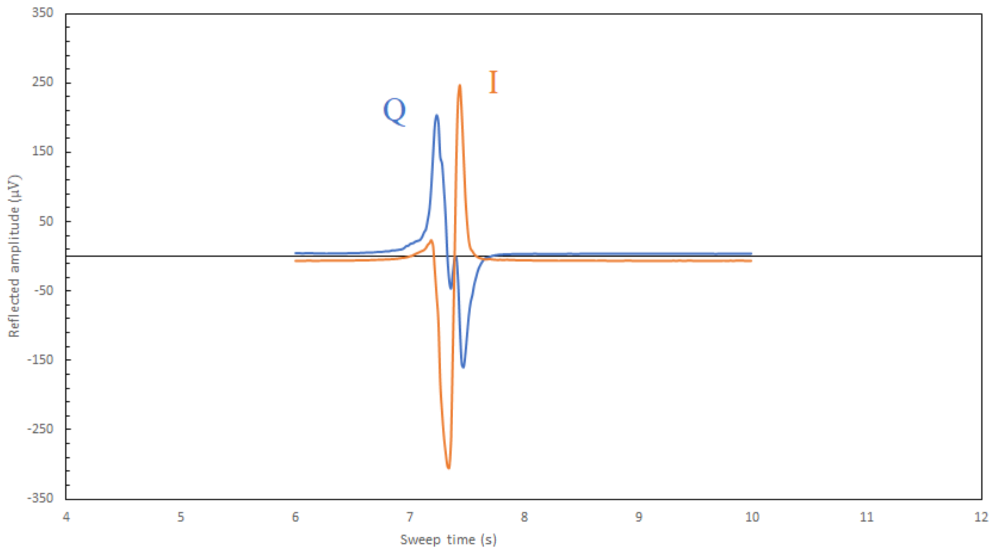


What's Next?

- Antenna coupling with Pound lock



Simulated plot



Observed plot

- Electroplated cavity (pure Al)
- Low temperature test (@ 4 K)
- B field test (~7.5 T)