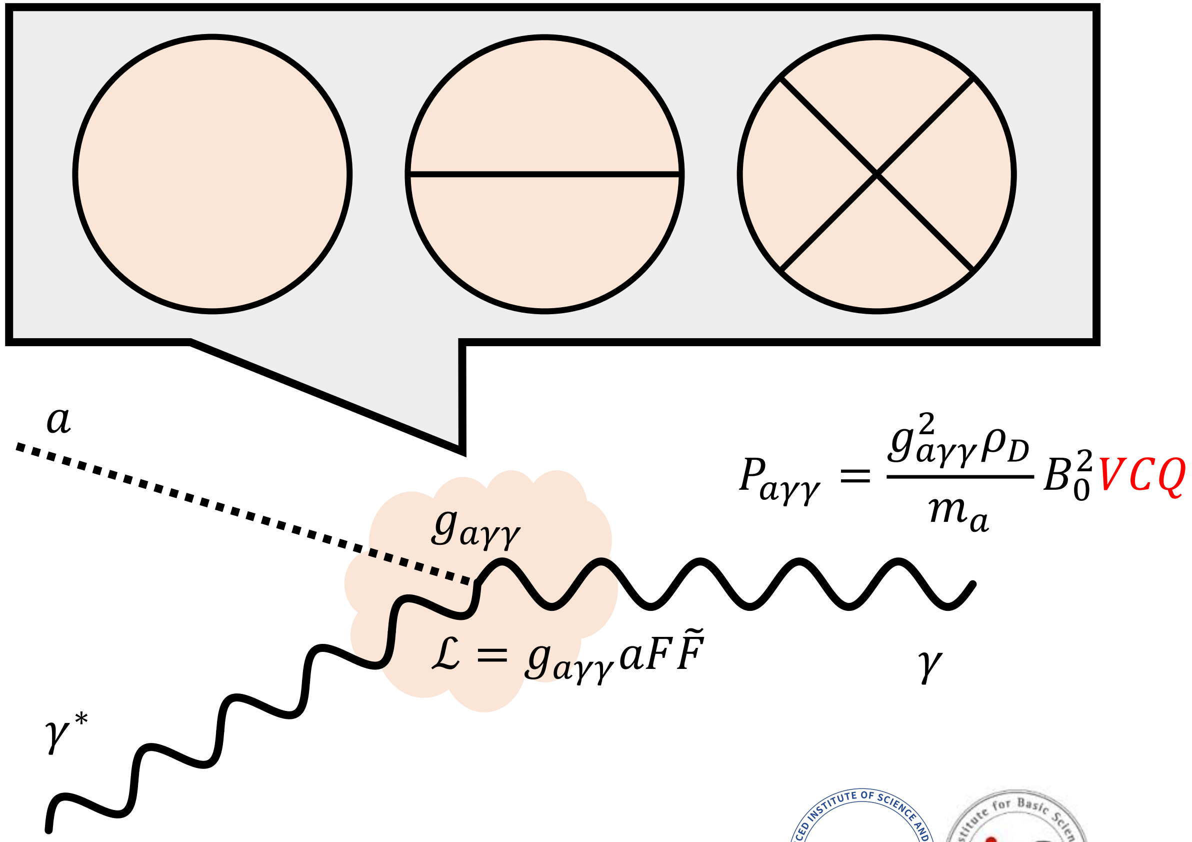
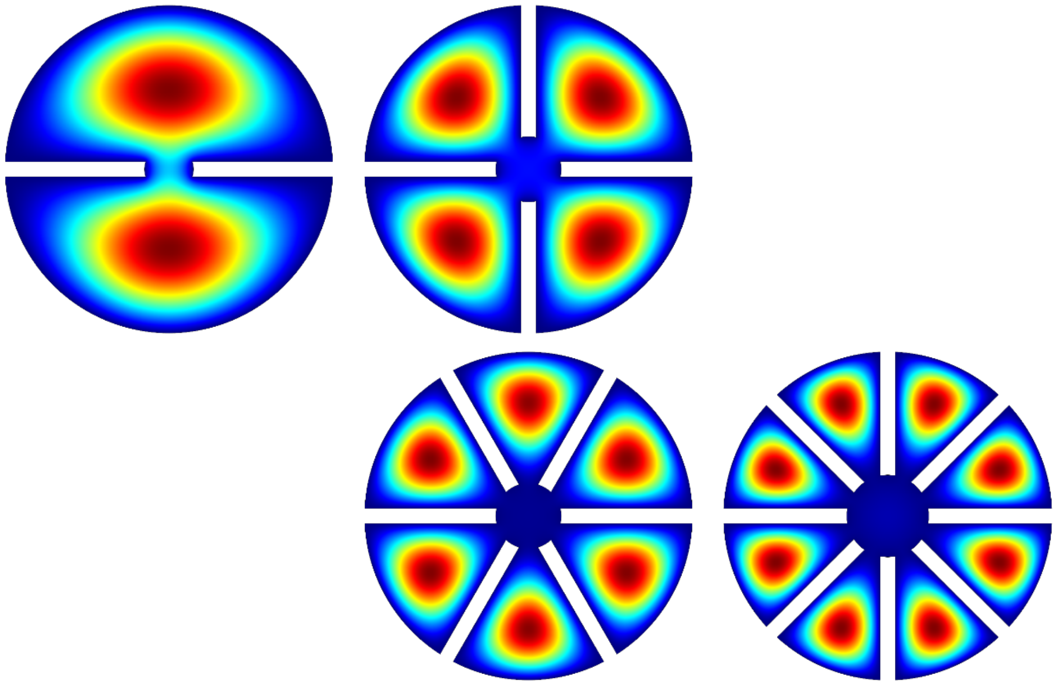
Multiple-cell cavity for high mass axion dark matter search

3rd Workshop on Microwave Cavities and Detectors for Axion Research





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J. Jeong et al, Phys. Lett. B, 777, 412-419 (2018)

Outline

- Motivation of the Multiple-cell cavity
- Frequency tuning mechanism
- Phase-matching of the Multiple-cell cavity
- Demonstration of experimental feasibility
- JANIS He-3 system
- Summary

Motivation of the Multiple-cell cavity

- Axion under a strong magnetic field converts to a RF photon, and resonates in microwave cavities.

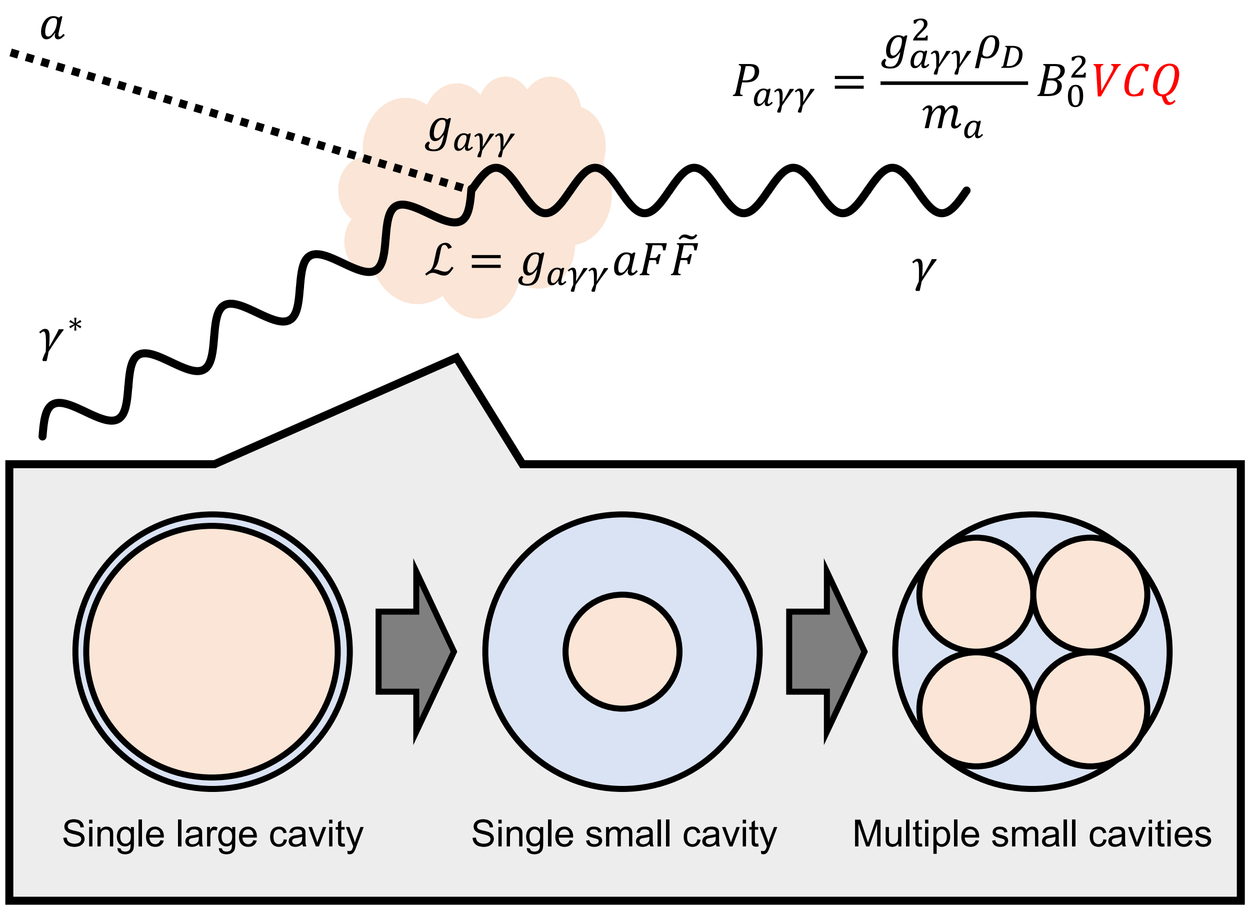
- **Exploring higher frequency regions** requires smaller size of cavities.

$$f_{\mathrm{TM}_{010}} = \frac{c}{2\pi}\frac{2.4048}{\text{cavity radius}}$$

- Multiple cavity system can compensate for the reduced volume.

- However, it is still inefficient in volume.

- **We want to maximize volume usage.**

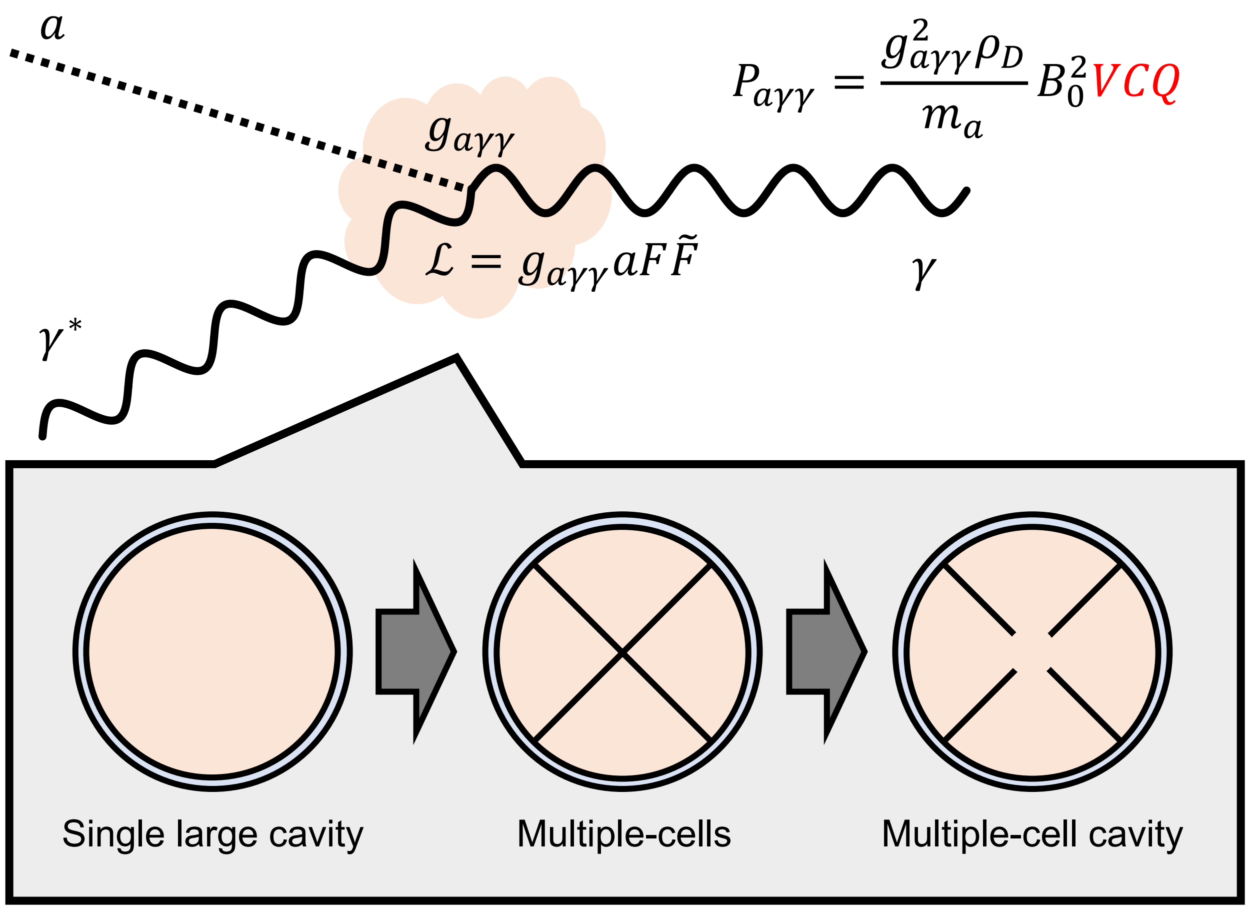


Motivation of the Multiple-cell cavity

How to make Multiple-cell cavity

1. Single cylindrical cavity fitting into the magnet bore
2. Split by metal partitions placed with equidistant intervals
3. Introducing a narrow hole at the center of the cavity

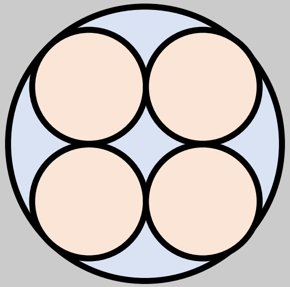
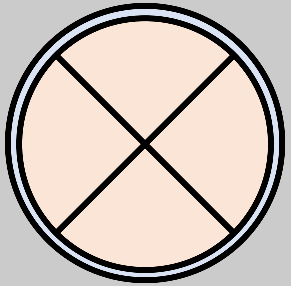
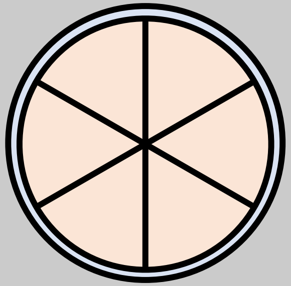
- Multiple-cell cavity provides more effective way to increase volume.
- Resonant frequency increases with the cell multiplicity.
- Same frequency tuning mechanism as multiple cavity system can be employed.
- A single RF antenna extracts the signal out of the cavity.



Motivation of the Multiple-cell cavity

Multiple cavity system vs. Multiple-cell cavity

Magnet bore: 100 mm / cavity height: 200 mm / wall thickness: 5 mm

	Quad-cavity	Quad-cell	Sext-cell
Configuration			
Volume [L]	0.62	1.08	1.02
Frequency [GHz]	7.30	5.89	7.60
Q (room temp.)	19,150	19,100	16,910
Form factor	0.69	0.65	0.63
* Conversion power	1.00	1.65	1.32
* Scan rate	1.00	2.72	**1.98**

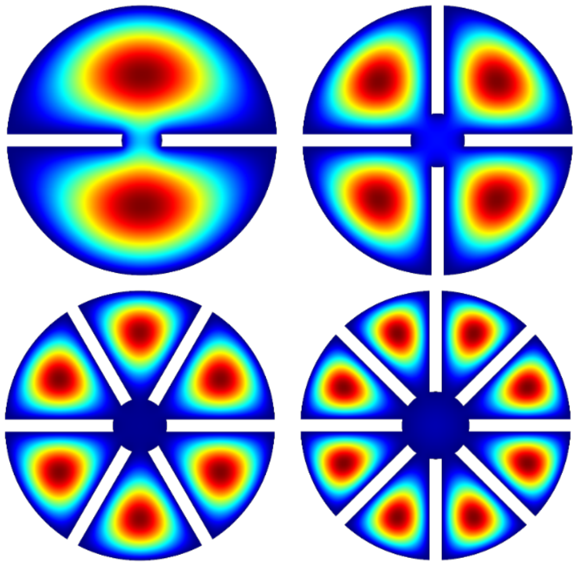
* Conversion power and scan rate is relative value to that of quad-cavity system

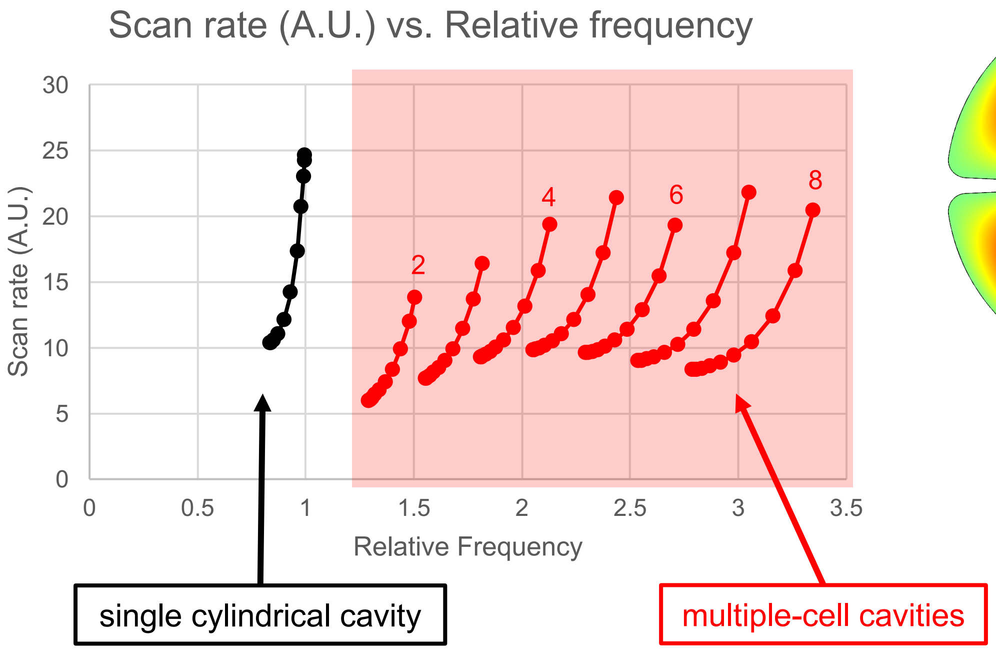
Frequency tuning mechanism

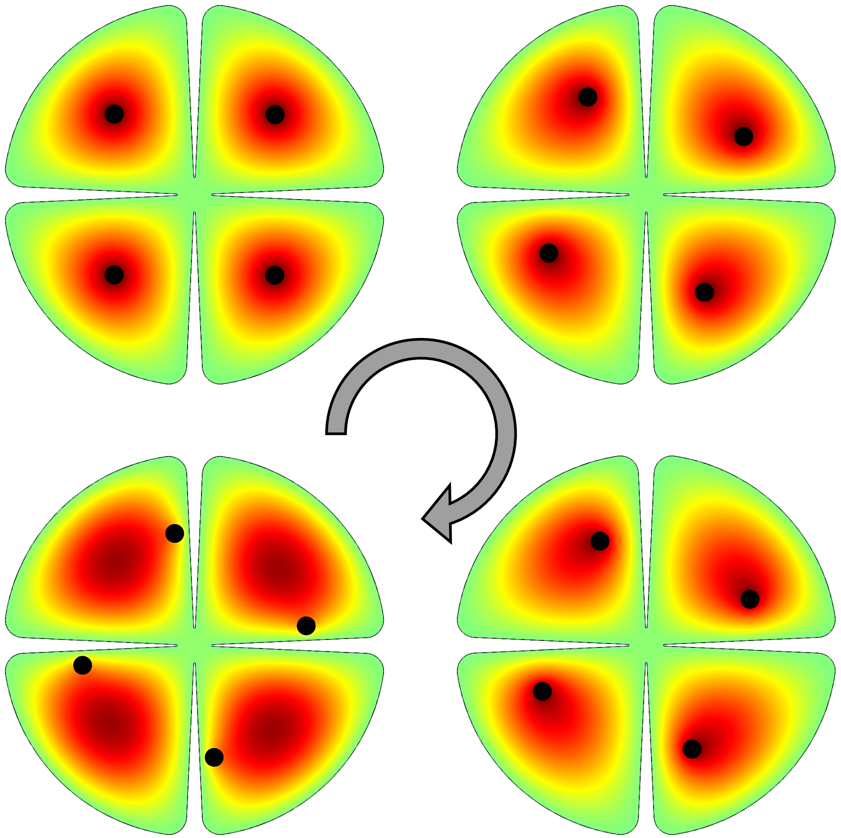
Frequency tuning mechanism employs the same concept as for conventional cylindrical cavity detectors.

- Altering the field distribution of TM_{010}-like mode by moving a dielectric or metal rod, inserted into each cell.

Using a single magnet, we can scan a wide mass range using various multiple-cell cavities, increasing # of cells.







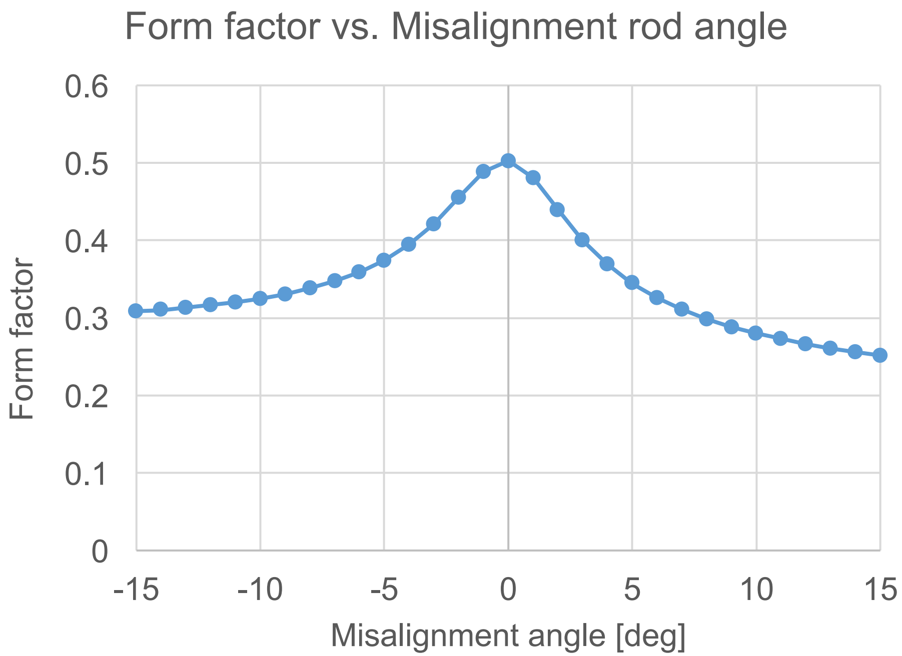
Condition for phase-matching

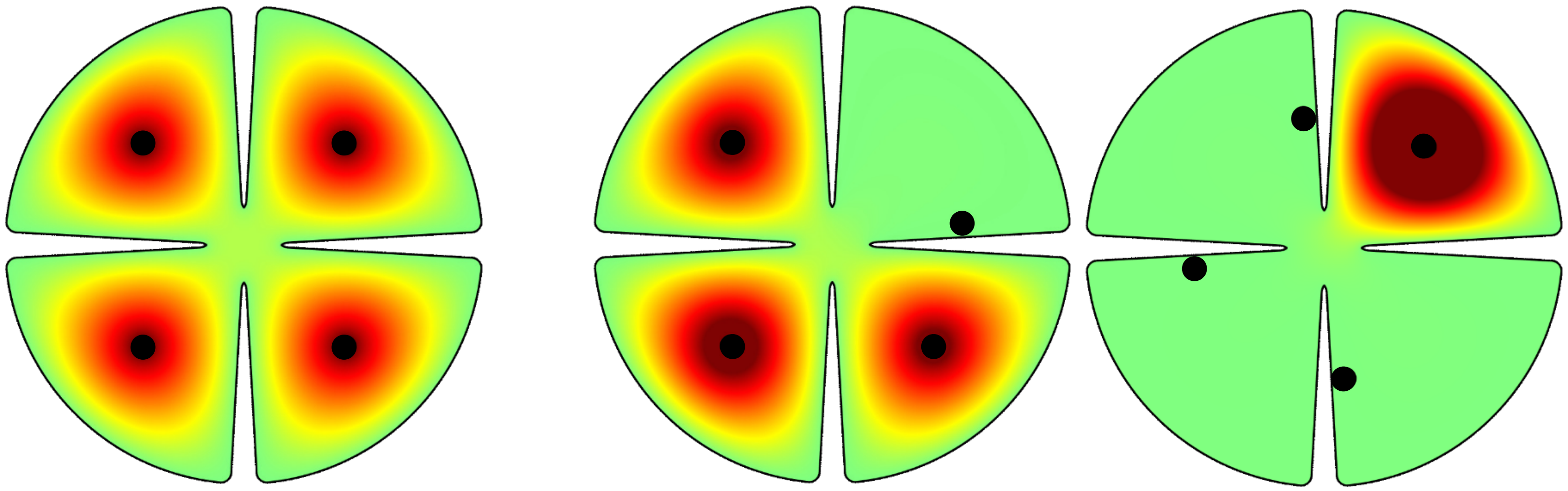
Since the individual cells are spatially connected, the relative rod position in a cell affects the entire field distribution.

- Asymmetric field distribution, localization of the field, generates huge reduction in the form factor.

Frequency tuning mechanism requires that the field distribution in individual cells is identical each other.

- We refer to such condition as **"phase-matching"**





Symmetric
(Phase-matched)

Asymmetric
(Field localized)

Phase-matching of the Multiple-cell cavity

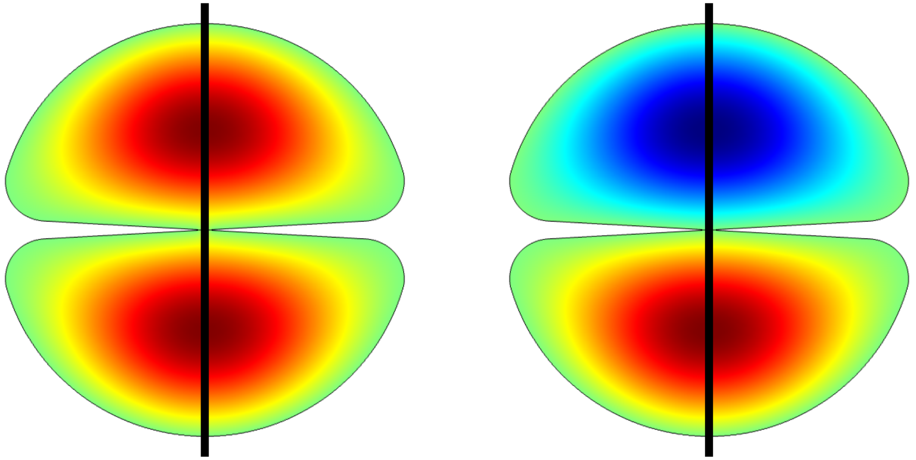
The simplest case, double-cell cavity.

- TM_{010}-like mode = in-phase
- TM_{110}-like mode = 180º out of phase

- When the two rods are aligned symmetrically, the field distributions of modes are also symmetric.
- Once phase-matched, the electric field strength at the center of the cavity becomes zero for the TM_{110}-like mode.

After phase-matched, the higher TM_{n10}-like modes have zero electric field at the center of the cavity.

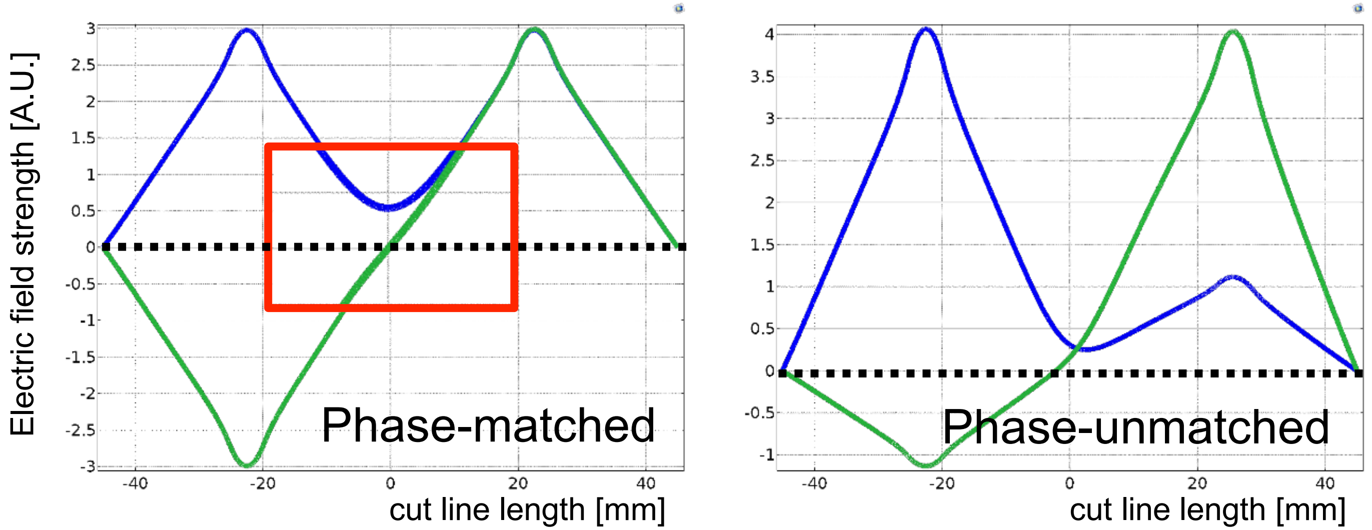
E field distributions



TM_{010}-like TM_{110}-like

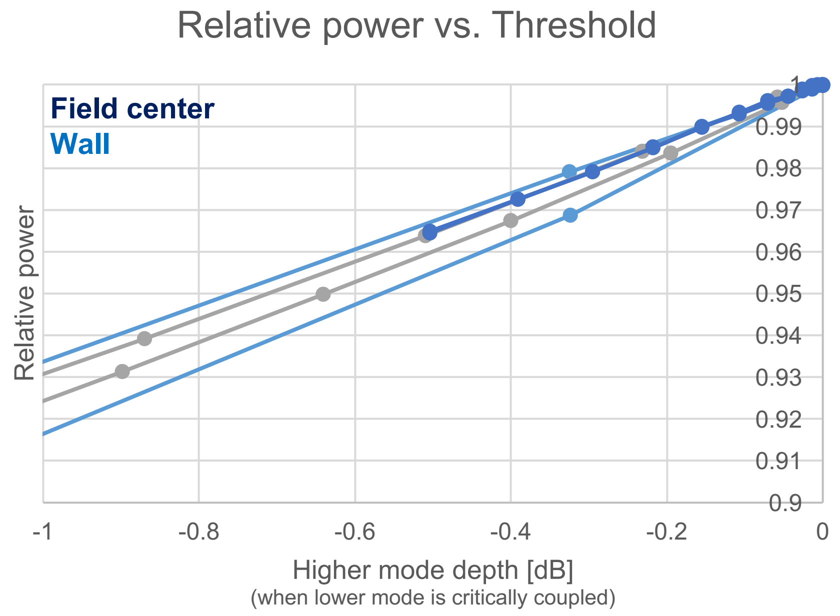
E field profiles

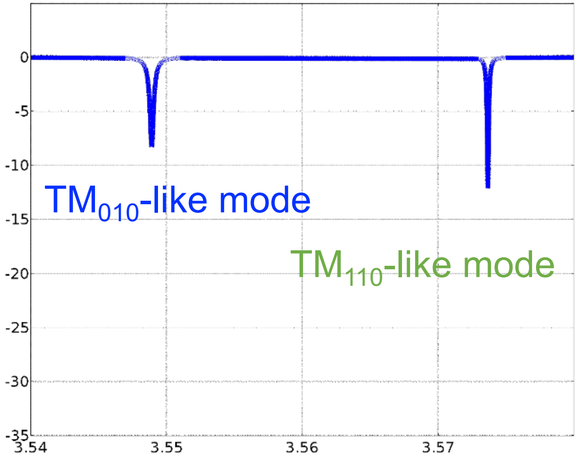
TM_{010}-like
TM_{110}-like



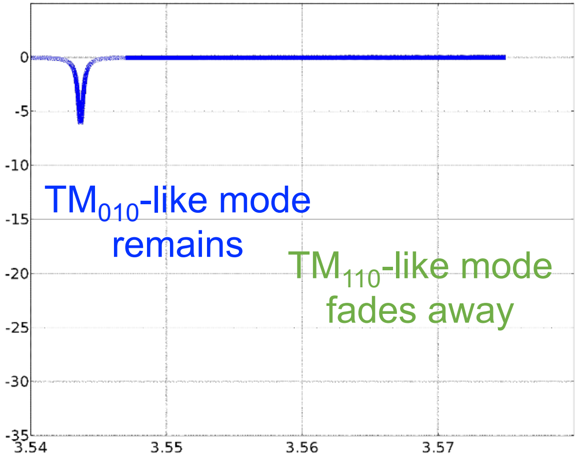
Experimental confirmation of phase-matching

- The center electric field of modes can be measured by monopole antenna located at the center of the cavity.
- When rods are symmetrically aligned, the resonant peak of the higher TM_{n10}-like modes in S-parameter fades away.
- Phase-matching is achieved by aligning the tuning rods until the higher mode peaks vanish.
- The coupling strength for higher modes to be less then 0.05dB at the sacrifice of power loss less than 1%.

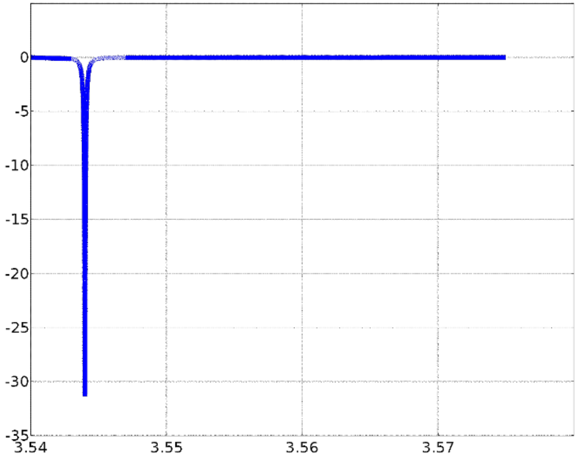




Arbitrary rod configuration and arbitrary coupling



Symmetric rod configuration and arbitrary coupling

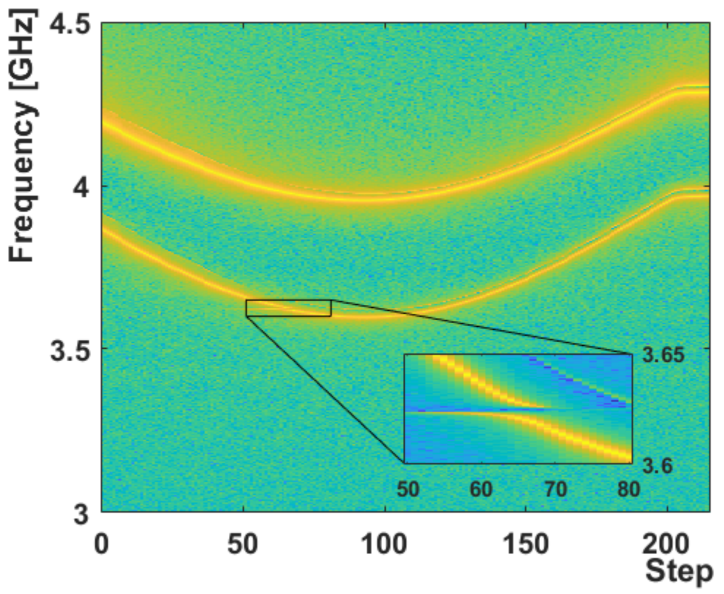


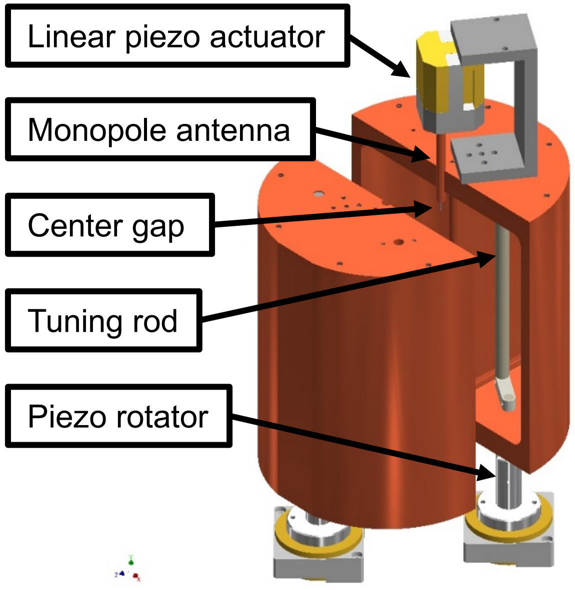
Symmetric rod configuration and critical coupling

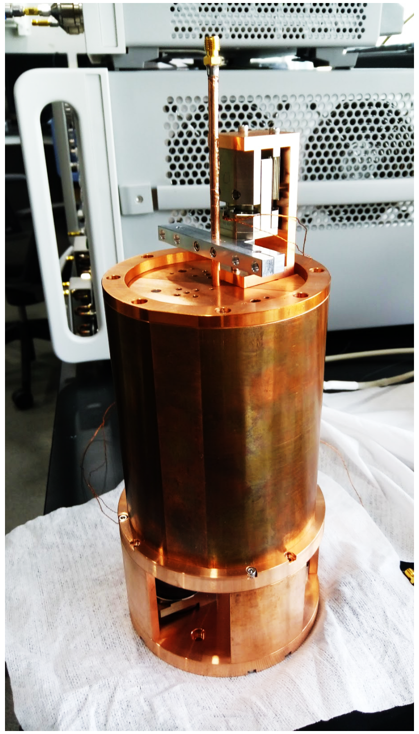
Demonstration of experimental feasibility

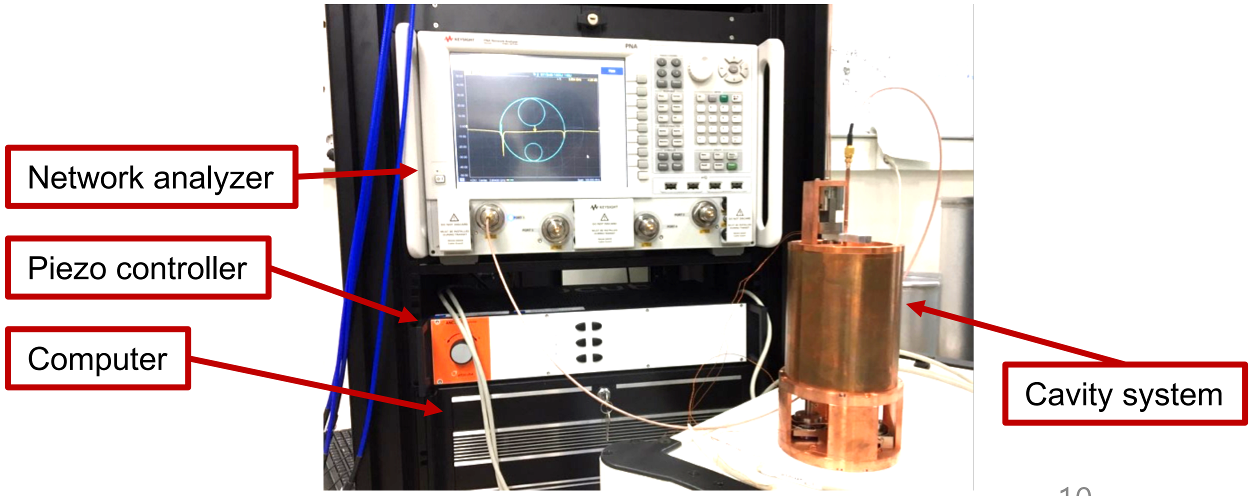
Demonstration was performed using a double-cell cavity at RT.

- Inner diameter = 90mm
- Inner height = 100mm
- Split cavity design
- 99.5% alumina for tuning rods
- Q_L = 2,200 at room temperature





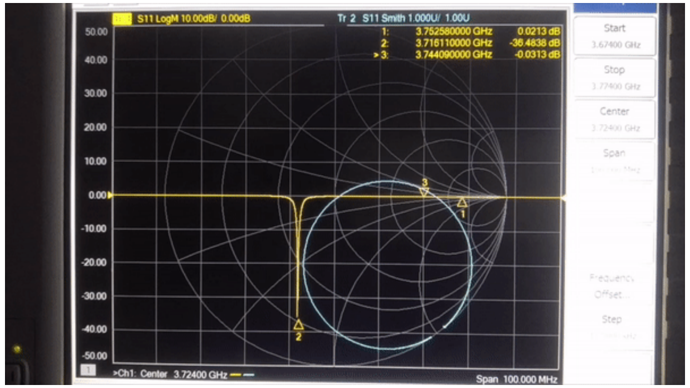


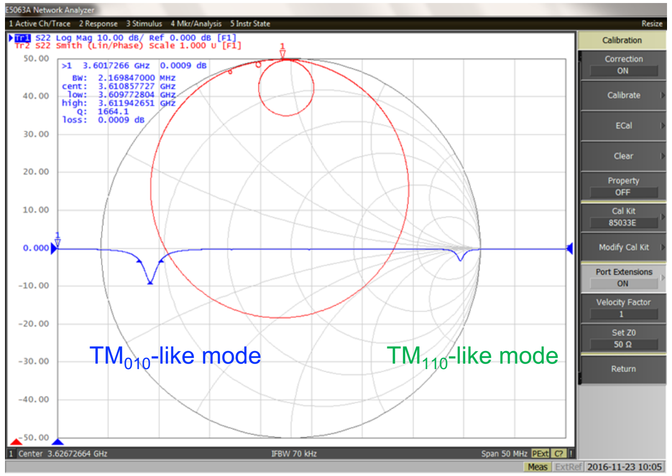


Demonstration of experimental feasibility

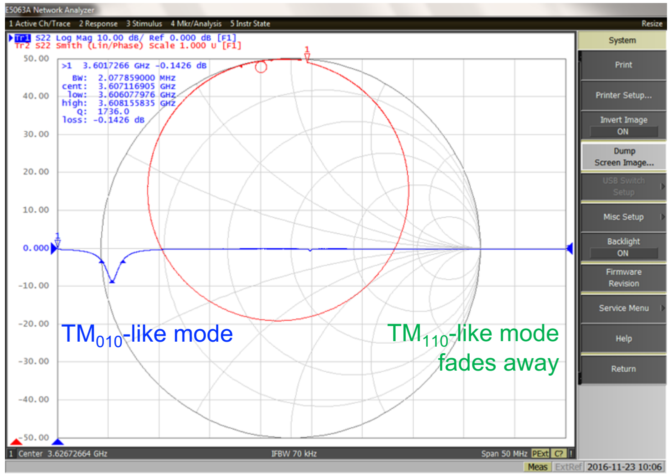
Demonstration of the tuning mechanism using a double-cell cavity

1. Two resonant modes are featured by the two reflection peaks.
2. Phase-matching is assured by vanishing of the higher frequency peak and the corresponding circle.
3. Critical coupling is characterized by the maximum depth of the remaining reflection peak and the corresponding circle passing through the center of the smith chart.

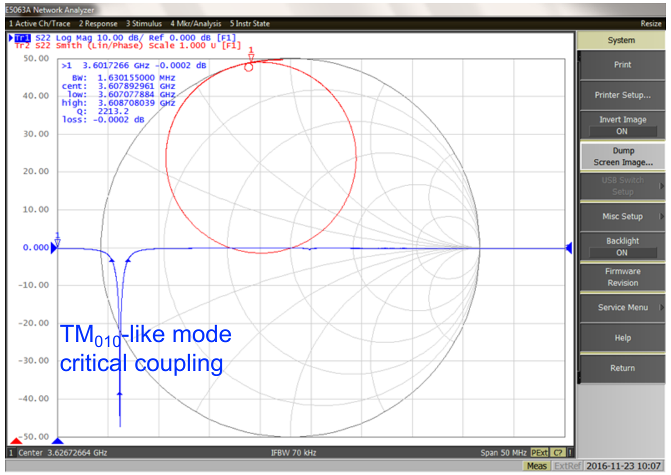




1. Phase unmatched, arbitrary coupled



2. Phase matched, arbitrary coupled

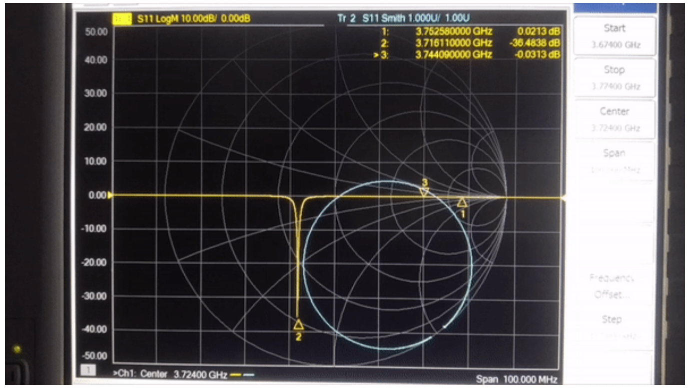


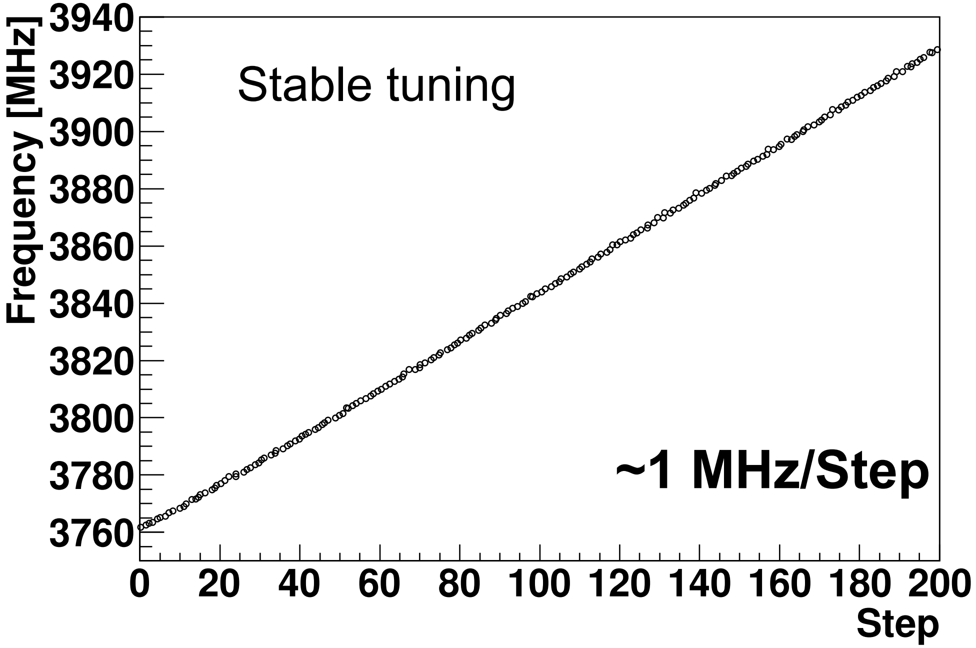
3. Phase matched, critical coupled

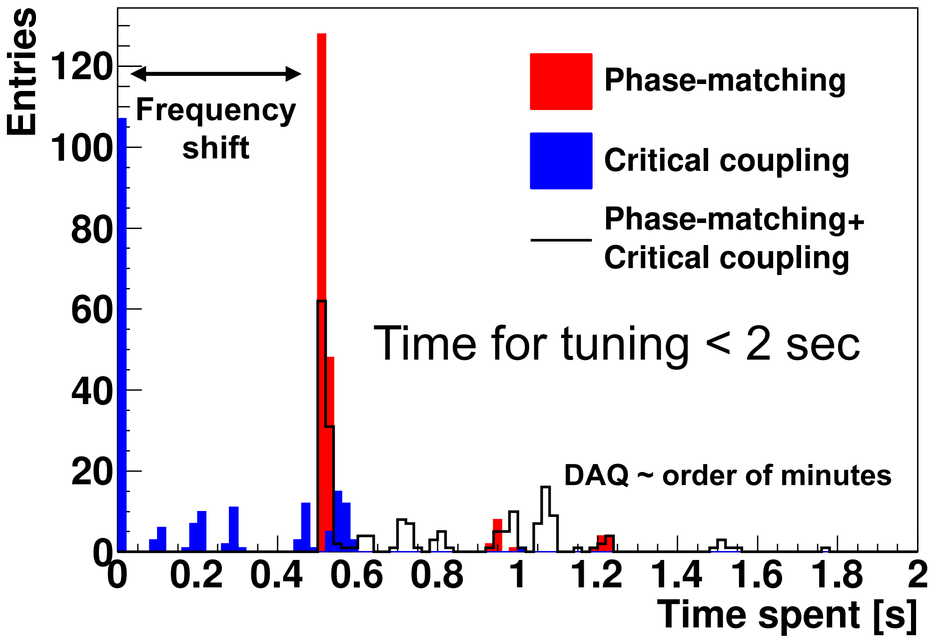
Demonstration of experimental feasibility

Repeated 200 times with large frequency shift

- Good linear behavior of the target frequency with step
- Phase-matching (critical coupling) are already satisfied more than 90% (50%) of the time after tuning.
- Less than 2 seconds are required to complete the tuning process.
    - Frequency shift + Phase-matching + Critical coupling



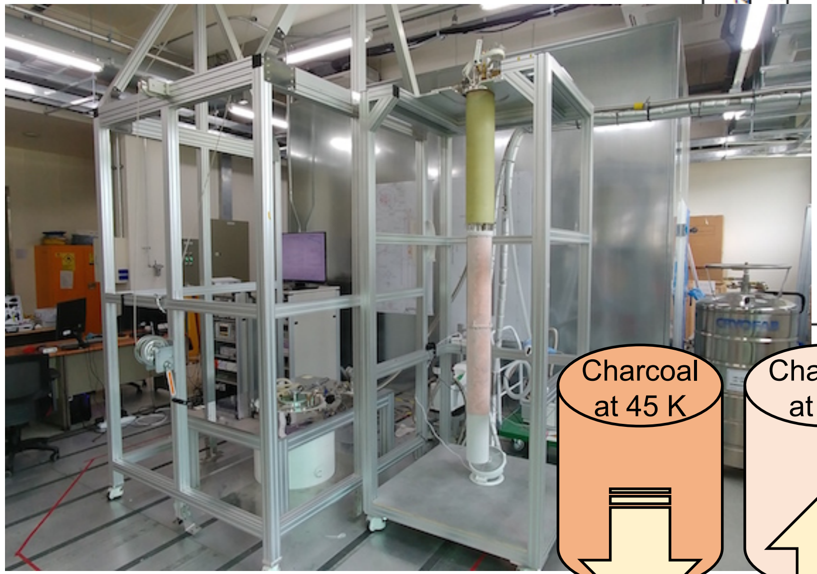


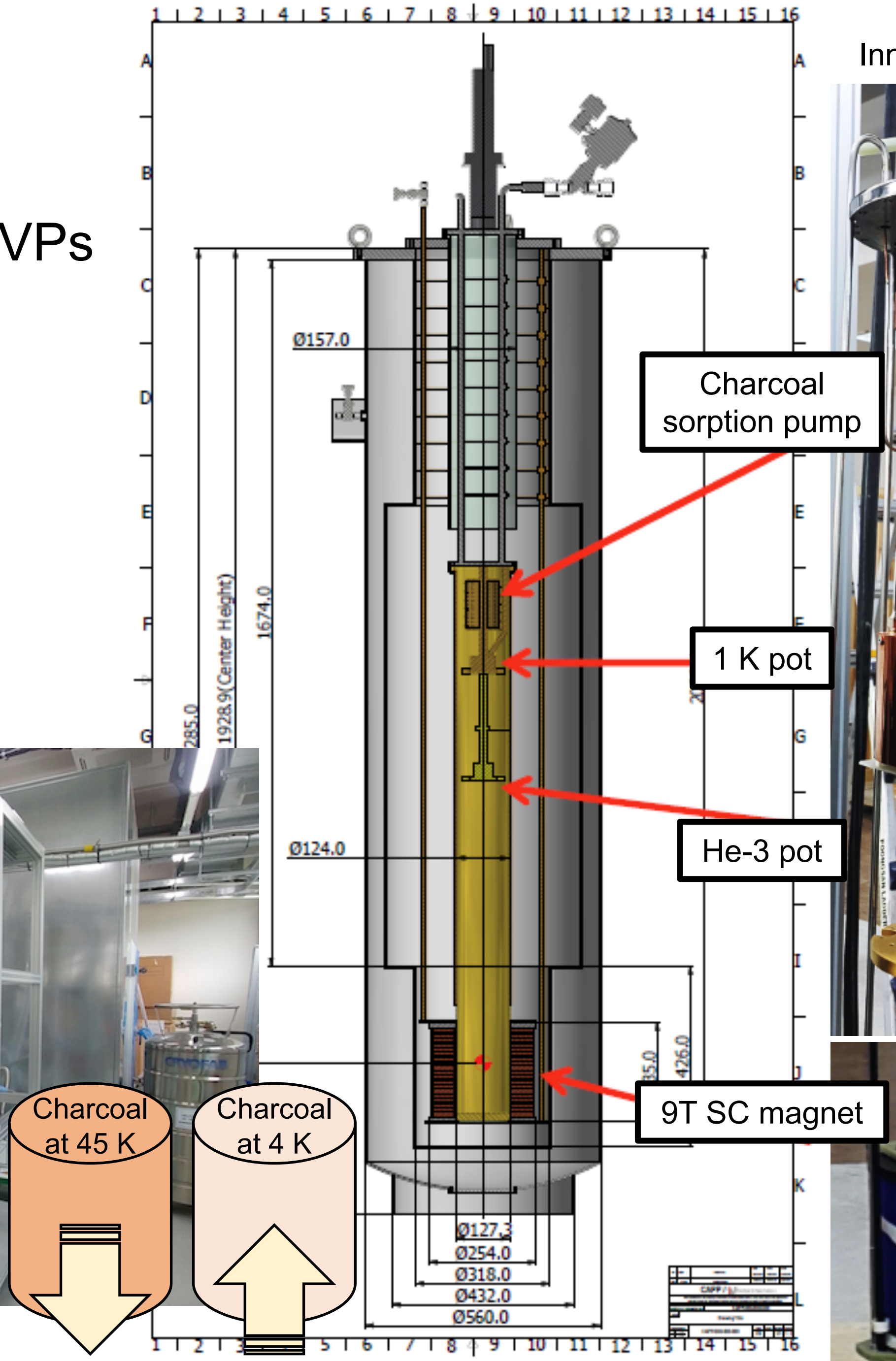


JANIS He-3 system

JANIS system w/ 9T SC magnet was installed at one of LVPs at CAPP

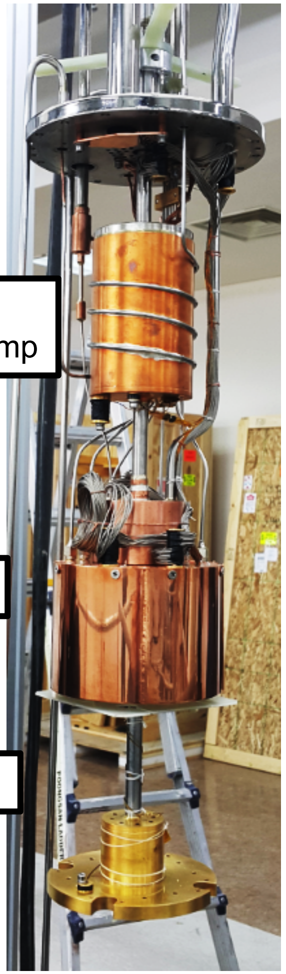
- Cryogenic and SC magnet system utilizing charcoal sorption pump
- 1K pot lowers the temperature by pumping LHe-4 to condense the He-3 into the He-3 pot
- He-3 pot evaporatively cooled to maintain the base temperature at 300mK

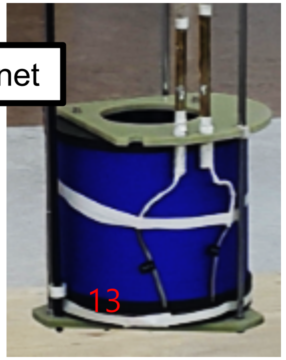




release He-3 absorb He-3

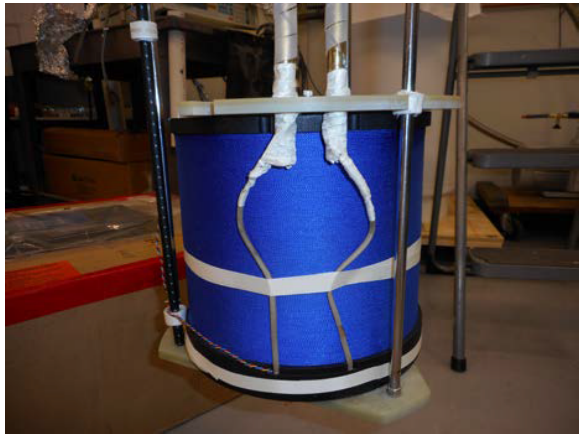
Inner vacuum can



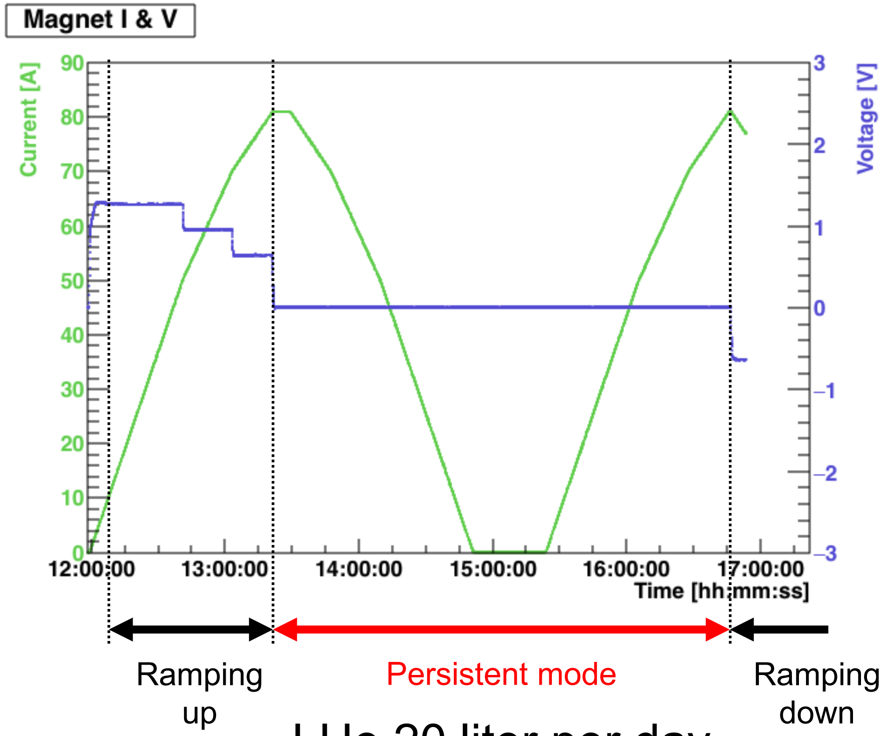


JANIS He-3 system: SC Magnet

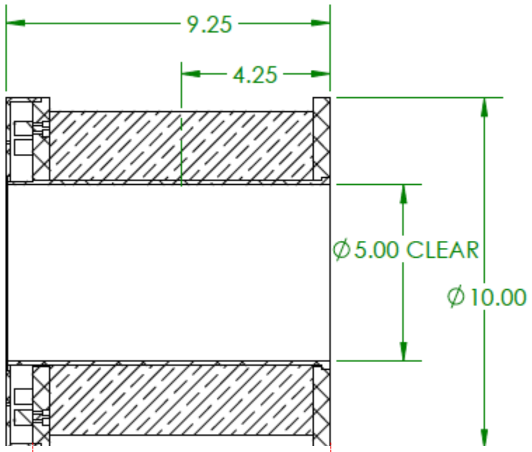
- SC magnet generates 9T magnetic field in persistent mode
- Field distribution was well modeled with FEM (finite element method) simulation in CAPP.
- The test operation of 9T SC Magnet was performed and confirmed operating in persistent mode without quench.

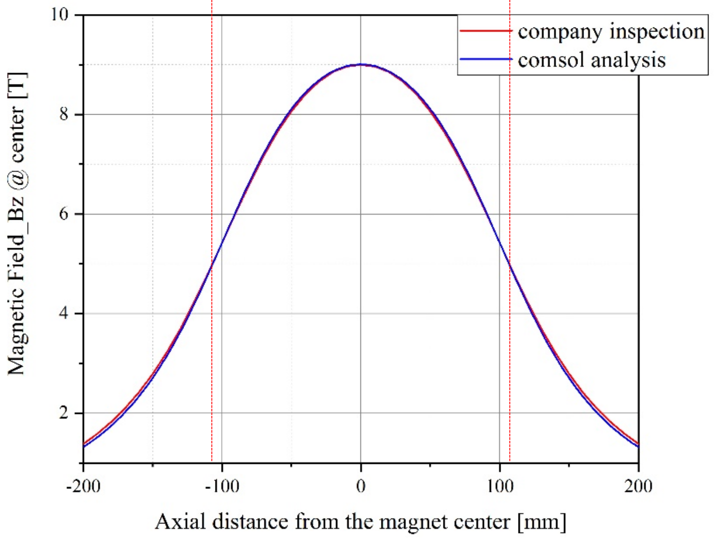


Property	Specification
Manufacturer	Cryomagnetics
Superconductor	NbTi
B_{max}	9 T (4.2 K)
Inner bore	125 mm
Height	235 mm
Operating current	81 A
Operation mode	Persistent



LHe 20 liter per day

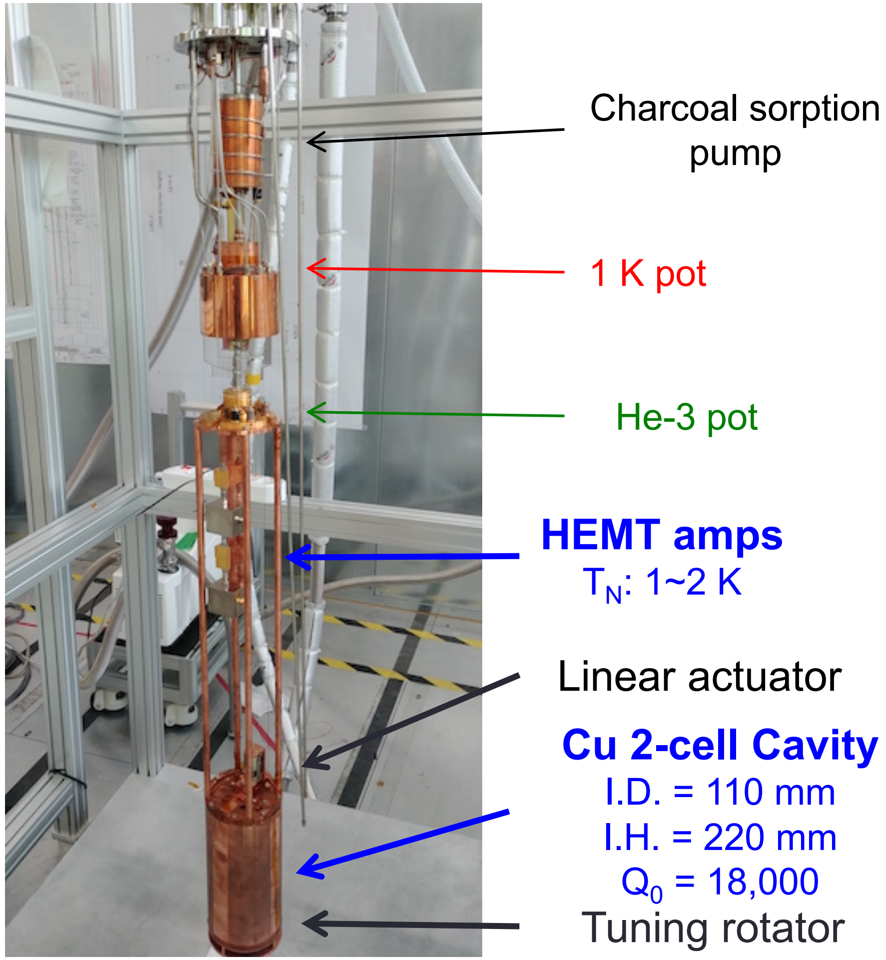


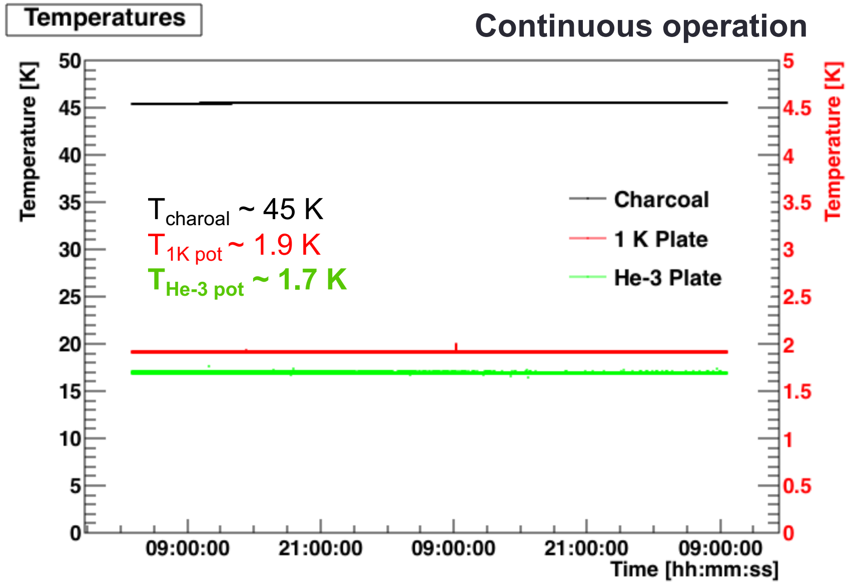


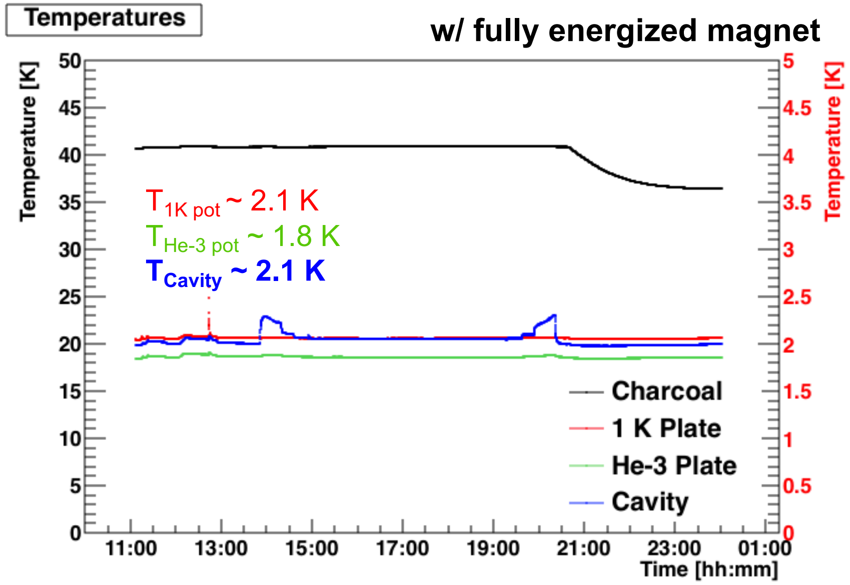
Magnetic field distribution

JANIS He-3 system: Cryogenic system

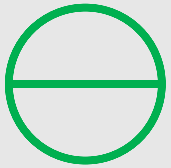
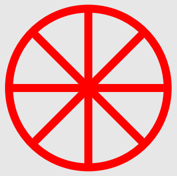
- Test operation confirmed the desired specifications.
- Cavity temperature is maintained at 2K while continuous operation with fully energized magnet.

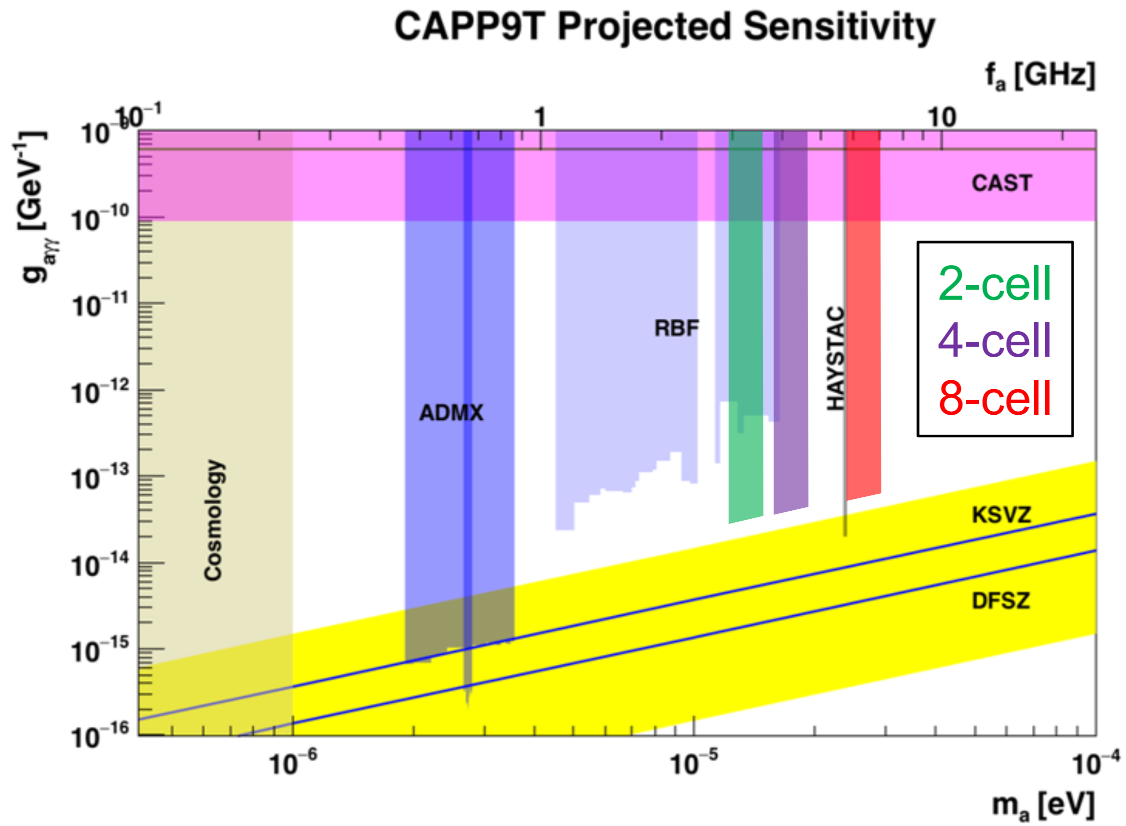






Target sensitivity (10 KSVZ)

	2-cell	4-cell	8-cell
Average magnetic field [T]		7.8	
Frequency [GHz] ($f_{max} - f_{min}$ [GHz])	2.8 ~ 3.3 (0.5)	3.8 ~ 4.5 (0.7)	5.8 ~ 7.0 (1.2)
Q_0 (RRR=9)	60,000	51,000	51,000
Form factor	0.45	0.45	0.40
Volume [L]	2.0	1.9	1.7
DAQ efficiency		0.5	
T_{sys} [K]	2.1+2.0	2.1+3.0	2.1+4.0
Scan rate [GHz/year] for 10 KSVZ	5.4	4.8	5.0
Geometry			



Year	2018				2019				2020
Quarter	1	2	3	4	1	2	3	4	1
Double-cell									
Quadruple-cell									
Octuple-cell									

Summary

1. New design of cavity, multiple-cell cavity, is introduced.
   - Multiple-cell cavity provides more effective way to increase volume.
   - A single RF antenna extracts the signal out of the cavity.
2. Frequency tuning mechanism and criteria for the phase-matching is introduced.
   - Frequency tuning mechanism employs the same concept as for conventional cylindrical cavity detectors.
   - After phase-matched, the higher TM_{n10}-like modes have zero electric field at the center of the cavity.
   - Phase-matching is achieved by aligning the tuning rods until the higher mode peaks vanish.
3. Demonstration of experimental feasibility was performed.
   - There is a good linear behavior of the target frequency with step.
   - Less than 2 seconds are required to complete the tuning process.
4. JANIS He-3 system installation in CAPP has been completed.
   - JANIS system with 9T SC magnet was installed at one of LVPs at CAPP.
   - We are targeting 10 KSVZ sensitivity of high mass axion using the multiple-cell cavities at IBS/CAPP for the next two years.