Multiple-Cavity Detector for Axion Search

Workshop on Microwave Cavities and Detectors for Axion Research

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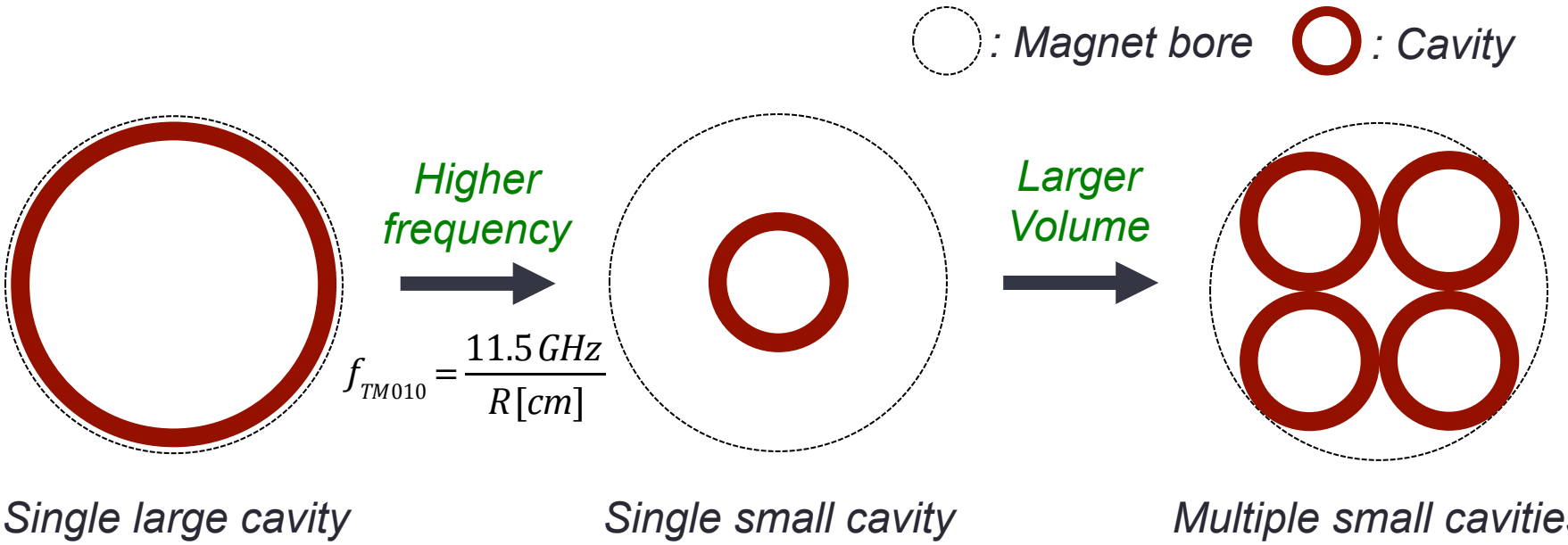
Republic of Korea

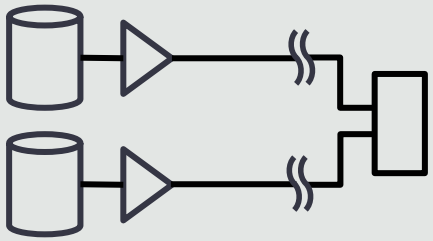
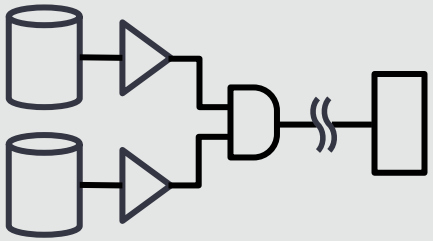
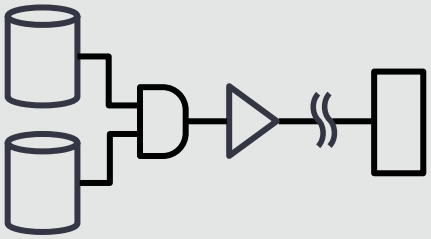
Introduction



$$P_{a\to\gamma\gamma} \sim B^2 V Q C$$

- *Multiple-cavity detector*
  - *Increases experimental sensitivity for axion searches in higher frequency regions*
  - *Requires signal combination in phase: phase-matching*

Configurations

	1	2	3
Schematic			
Characteristic	*N complete readout chains*	*N amplifiers 1 combiner*	*1 amplifier 1 combiner*

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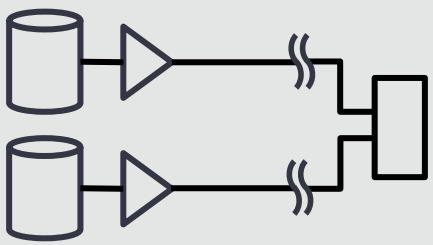
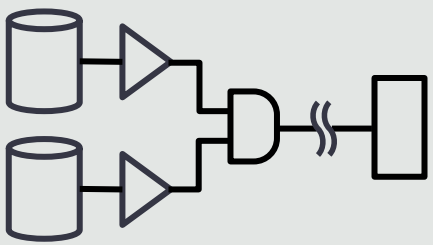
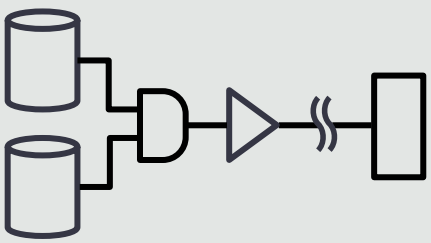
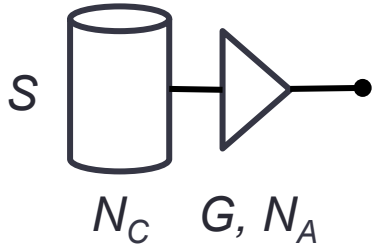
Schematic			
Characteristic	N complete readout chains	N amplifiers 1 combiner	1 amplifier 1 combiner
Sensitivity* (SNR)	$\sqrt{N}\cdot SNR_{sngl}$	$N\cdot SNR_{sngl}$	$N\cdot SNR_{sngl}$ **

SNR_{sngl} = SNR of single cavity



$$V_{out} = G\cdot(S+N_C)+N_A \quad\Rightarrow\quad SNR_{sngl} = \frac{P_S}{P_N} = \frac{(G\cdot S)^2}{(G\cdot N_C+N_A)^2}$$

* Correlated signal and uncorrelated noise

** $N.F._{comb} = 0$

Configurations

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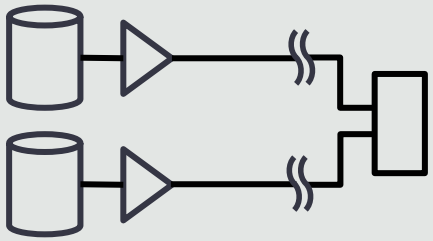
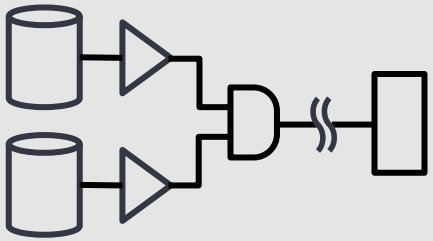
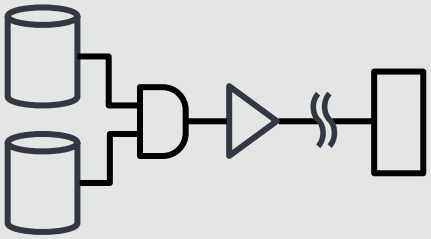
Schematic			
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Sensitivity (SNR)	$\sqrt{N} \cdot SNR_{sngl}$	$N \cdot SNR_{sngl}$	$N \cdot SNR_{sngl}$
Pros.	Individual access	Higher sensitivity	Simpler design
Cons.	Lowest sensitivity N complete readout chains	N amplifiers	$SNR_3 < SNR_2$*

* In reality, $N.F._{comb} \neq 0$

ex) $G=12$, $N.F._{amp}=6$, $N.F._{comb}=0.5$ => SNR_3 is lower than SNR_2 by 10%

Configurations

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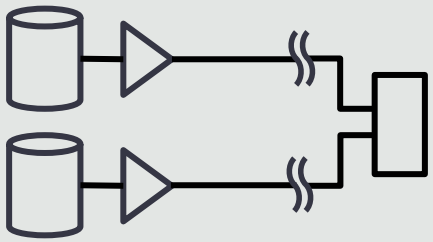
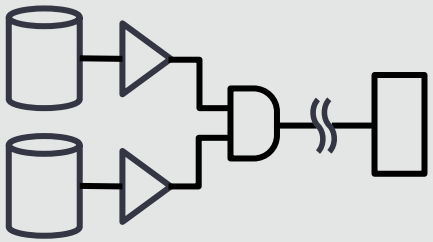
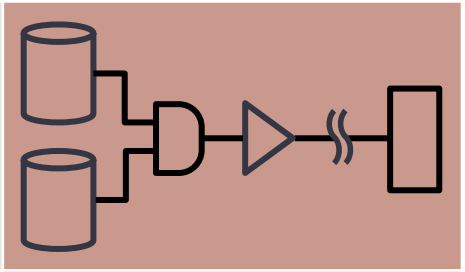
Schematic			
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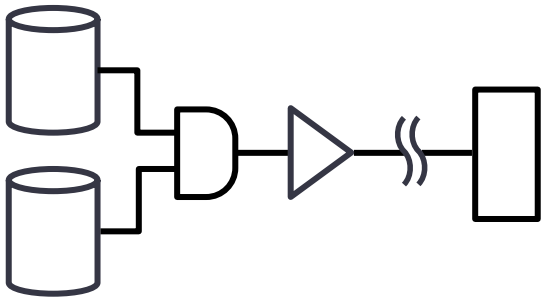
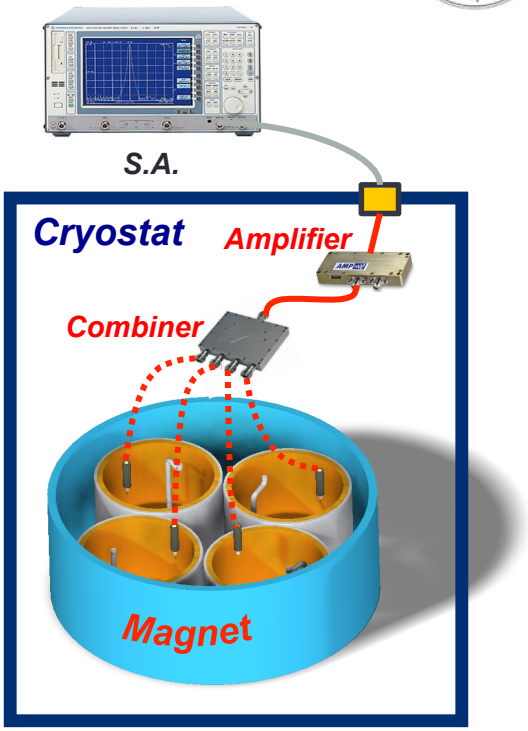
Multiple-Cavity Detector

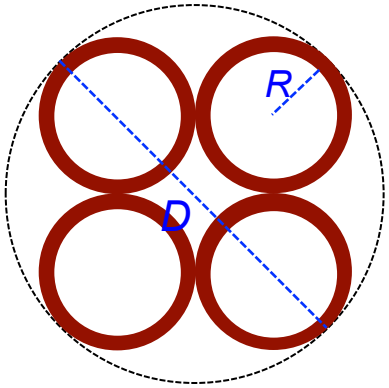


- *Introduced in 1990 and exploited by ADMX*
  - *KSVZ with 3.3639 < m_a [μeV] < 3.3642 excluded with 90% C.L.*
- *Phase-matching mechanism is challenging*
  - *Failure reduces signal power and degrades SNR*
    - *Broadens the bandwidth of power spectrum*
    - *Decreases the cavity quality factor*
- *5 year IBS Young Scientist program is devoted to develop the system at CAPP/IBS*

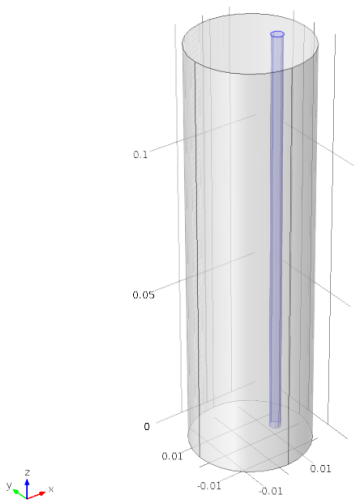
Design of a Multiple-Cavity System

- *Array of N identical cavities*
  - *Same dimension and same tuning mechanism*
- *N-way power combiner*
  - *Before the first stage of amplification*
- *Remaining RF components are identical with a single-cavity experiment*
- *A quadruple-cavity detector*
  - *For a magnet bore (D) of 10 cm*
  - *Maximum cavity radius (R) of 1.7 cm*
    - *Cavity wall thickness of 4 mm*
    - *46% volume usage*
  - *TM_{010} frequency: 6.75 GHz*



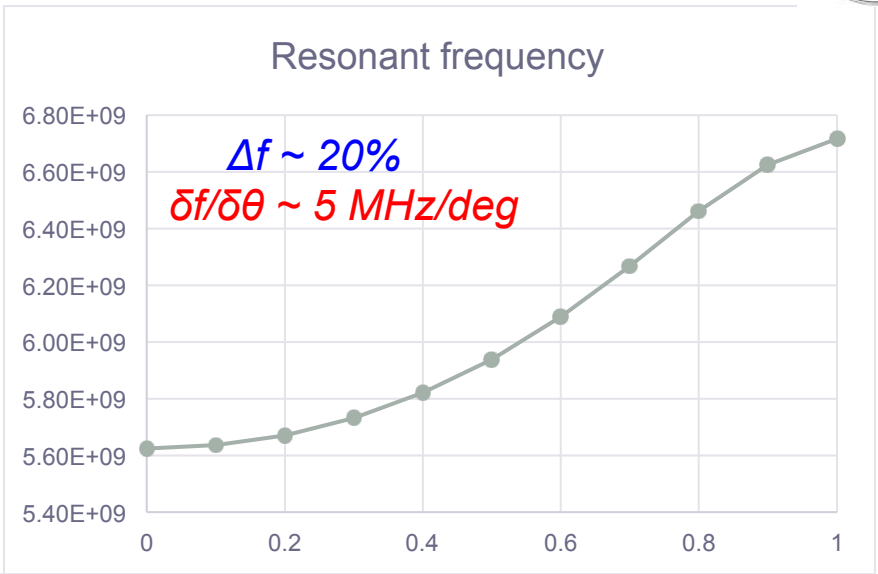


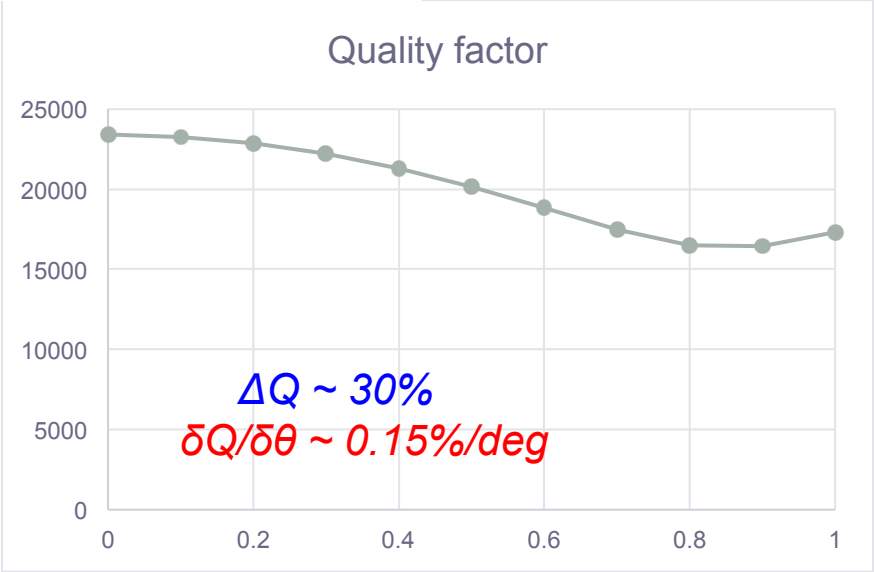
Simulation Study (COMSOL)

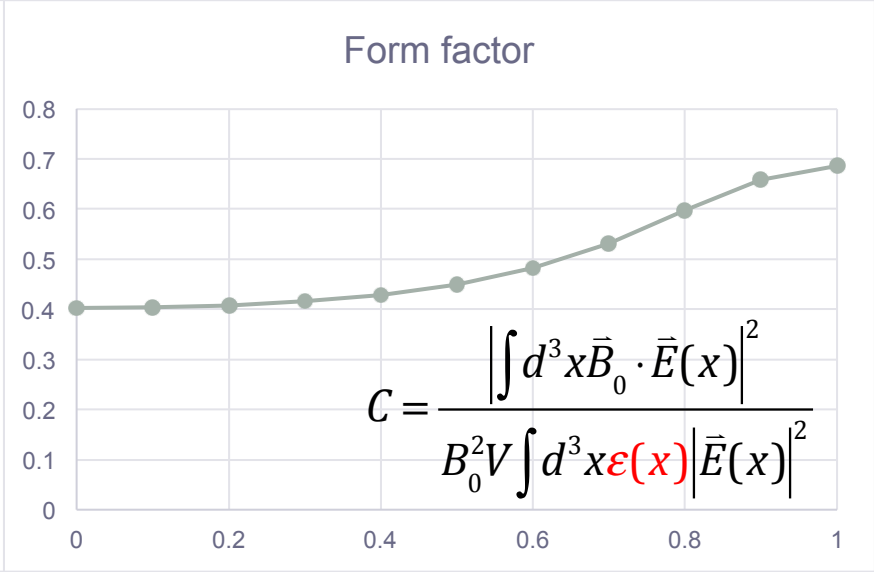


Cu cavity
(R=1.7cm,L=10cm)*

Tuning system
(Dielectric rotational rod)
(ε=10, r/R=0.1)*







$$C = \frac{\left|\int d^3x \vec{B}_0 \cdot \vec{E}(x)\right|^2}{B_0^2 V \int d^3x \varepsilon(x) \left|\vec{E}(x)\right|^2}$$

Conversion Power and Scan Rate

- *A quadruple-cavity system*
  - *4 cavities with R = 1.7 cm and L = 10.0 cm => V = 0.35 L*

- *Conversion power*

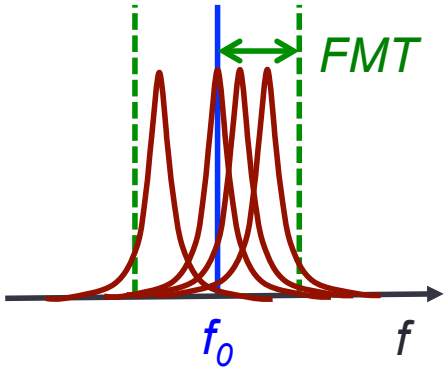
$$P_{a\to\gamma\gamma} = 1.8\times10^{-22}W\left(\frac{g_{a\gamma\gamma}}{0.97}\right)\left(\frac{\rho_a}{0.45GeV/cc}\right)\left(\frac{f_a}{6GHz}\right)$$
$$\times\left(\frac{B_0}{8T}\right)^2\left(\frac{V}{0.35L}\right)\left(\frac{C}{0.5}\right)\left(\frac{Q_l}{Q_a}\right)$$

- *Scan rate*

$$\frac{df}{dt} = \frac{16.3MHz}{year}\left(\frac{4}{SNR}\right)^2\left(\frac{g_{a\gamma\gamma}}{0.97}\right)^4\left(\frac{\rho_a}{0.45GeV/cc}\right)^2\left(\frac{f_a}{6GHz}\right)^2$$
$$\times\left(\frac{B_0}{8T}\right)^4\left(\frac{V}{0.35L}\right)^2\left(\frac{C}{0.5}\right)^2\left(\frac{4.5K}{T_{sys}}\right)^2\left(\frac{Q_l}{Q_a}\right)$$

Phase (Frequency) Matching

- *Source of frequency mismatch*
  - *Machining tolerance in cavity fabrication*
    - *50 μm => 25 MHz for a 6 GHz cavity*
- *Ideal frequency matching is not possible!*
  - *Typical step size ≠ 0°: 0.1 m° => 0.5 kHz*
- *Realistic approach: Frequency mismatch!*
  - *Up to a certain level where a reduction in the "combined" power is not significant*
  - *Frequency Matching Tolerance, FMT*



f_0: target frequency

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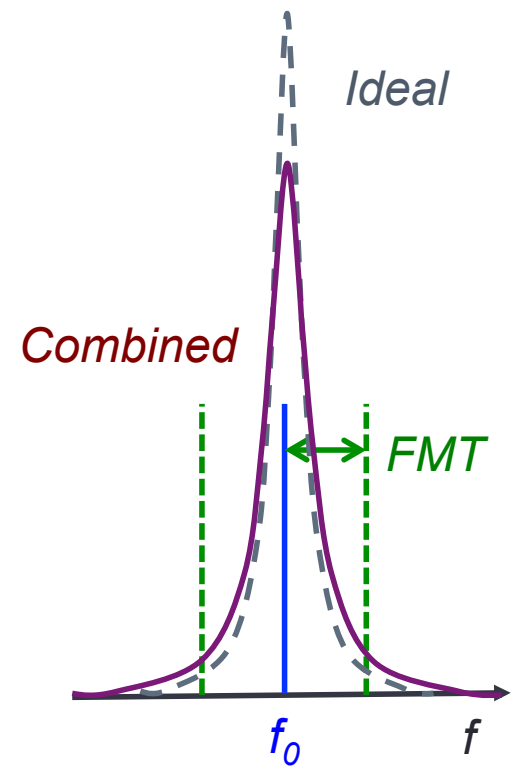
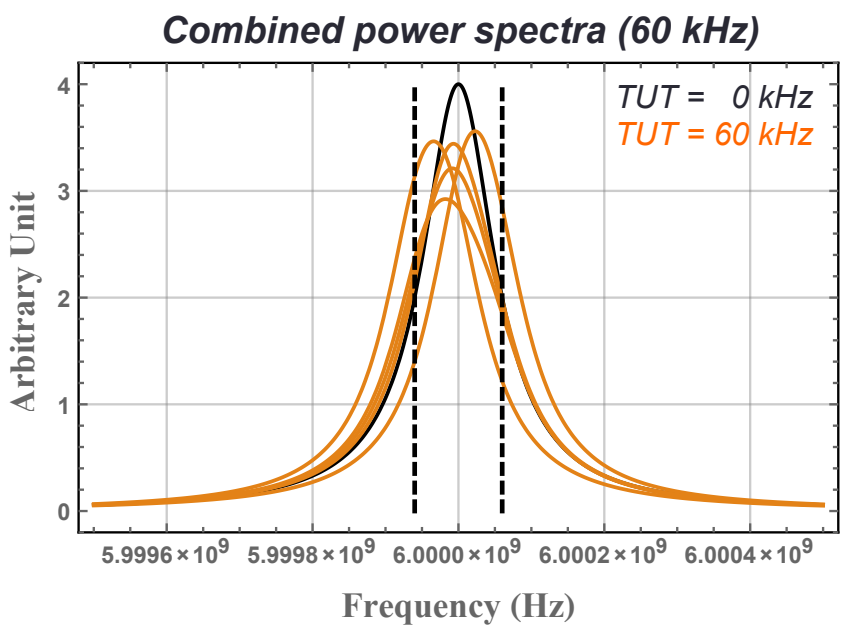
  - *Up to a certain level where a reduction in the "combined" power is not significant*
  - *Frequency Matching Tolerance, FMT*
  - ***Criteria : $P_{comb} > 0.95\ P_{ideal}$***

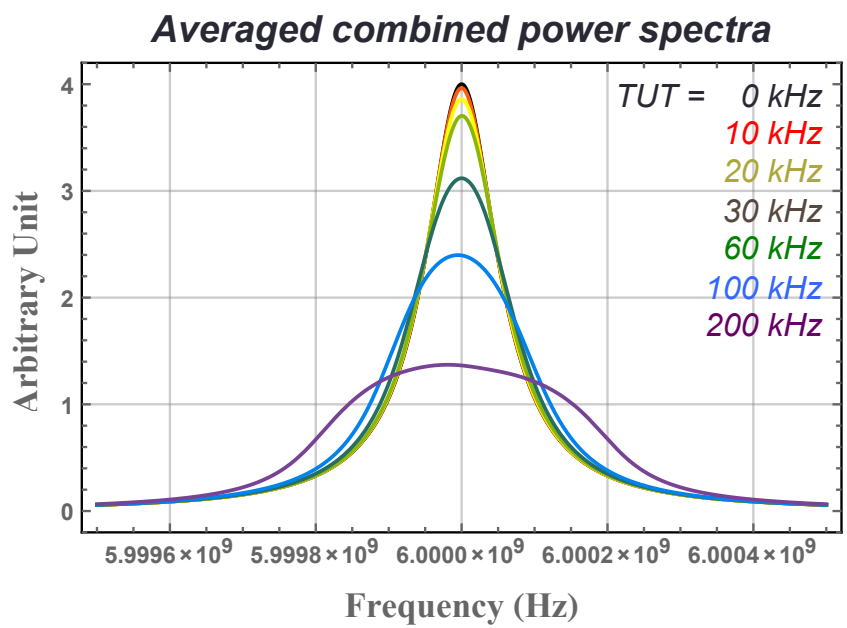


f_0: target frequency

Frequency Matching Tolerance – I

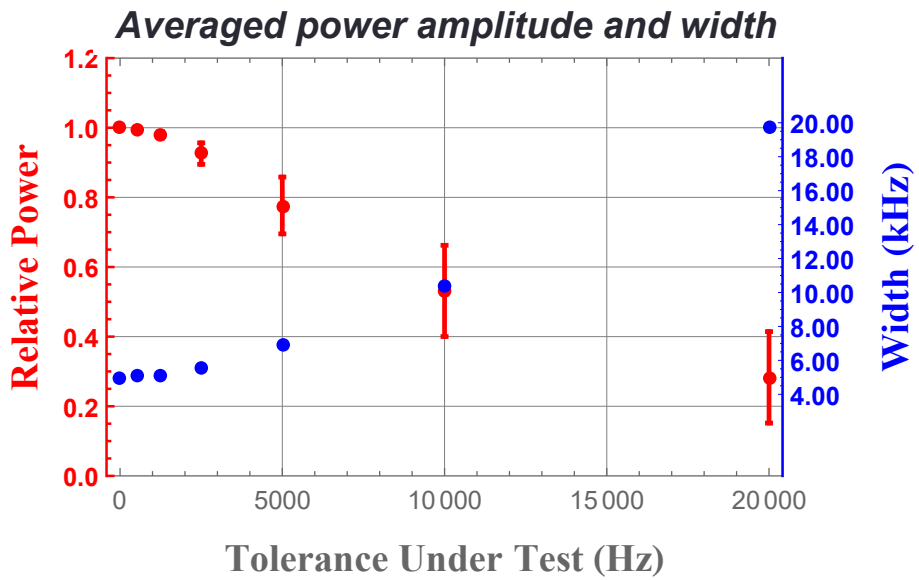
- *Pseudo-experiment study*
  - *4-cavity detector, $Q_u = 10^5$, $f_0 = 6$ GHz*
  - *Tolerance Under Test (TUT) = (0,) 10, 20 ,30, 60, 100, 200 kHz*
  - *Combined power spectra*
  - *1000 pseudo-experiments => averaged power spectra*





Power amplitude from each cavity is normalized to 1.

Frequency Matching Tolerance – II

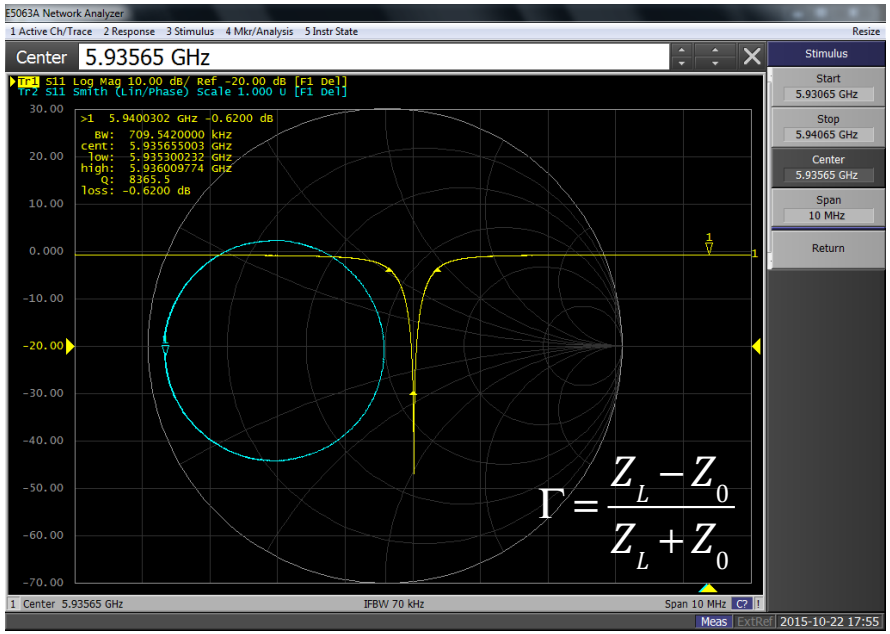


TUT (kHz)	Power Amp.	Q_u	SNR	Scan Rate
0	1.00	1.00	1.00	1.00
10	0.99	0.99	0.99	0.96
20	0.96	0.95	0.94	0.85
30	0.93	0.91	0.88	0.71
60	0.78	0.73	0.67	0.31
100	0.60	0.55	0.45	0.11

- *For 6.0 GHz axion signal, 4-cavity detector with $Q_u=10^5$*
  - *20 kHz is the FMT for the system*
- *In general, FMT = 2 GHz / Q_u*
  - *For $Q_u=10^6$, FMT = 2 kHz*
  - *cf. typical step size of 0.1 m° => frequency step: 0.5 kHz*

Tuning Mechanism – I

- *Basic principle of coupling – critical coupling*
  - *Minimizing the reflection coefficient (Γ) in S parameter spectrum*
  - *Forming a circle passing through the center of the smith chart*

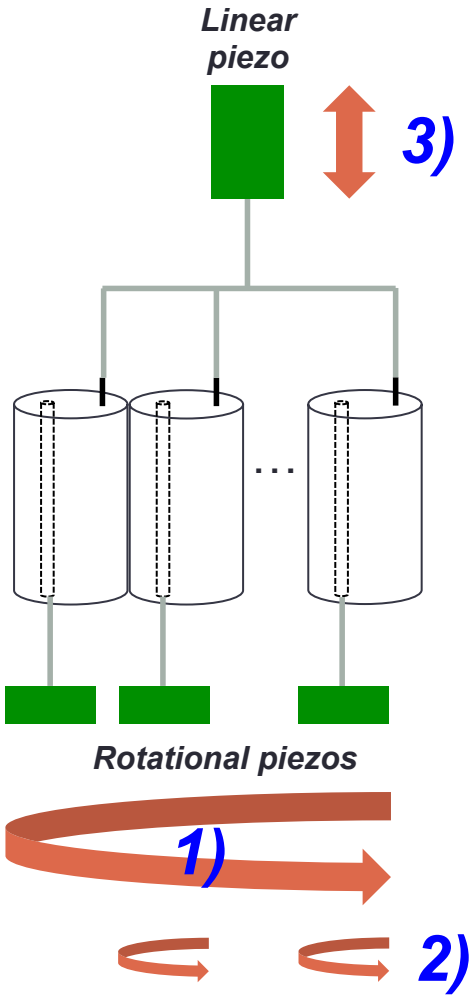


- *For a single cavity*
  - *Γ is minimized when*
    - *System is critically coupled*
- *For a multiple-cavity system*
  - *Combined Γ is minimized when*
    - *Frequency matching is successful*
    - *Entire system is critically coupled*

Tuning Mechanism – II

- *Frequency matching & critical coupling*

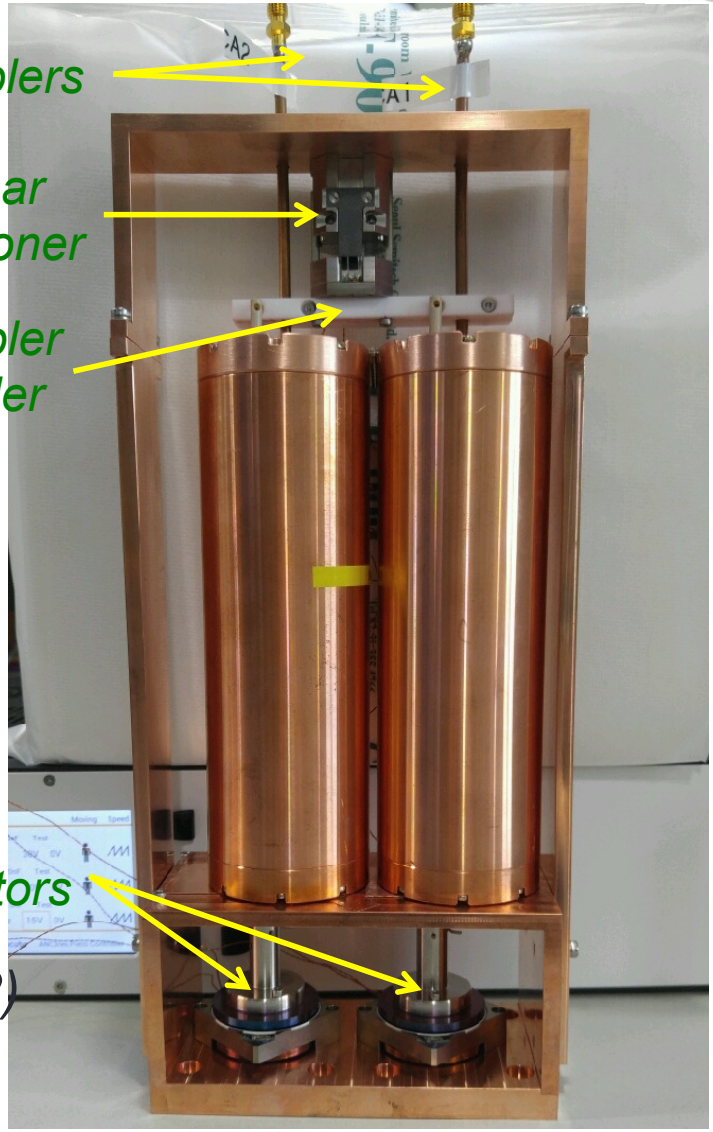
- *Consisting of three steps*
  - *1) simultaneous operation of the tuning systems*
    - *To shift target frequency*
  - *2) finer operation of the individual tuning systems*
    - *To achieve frequency matching*
  - *3) global operation of the couplers*
    - *To achieve critical coupling*
    - *At the sacrifice of sensitivity loss of <0.5%**



** Machining tolerance of 50 μm and uncertainty on surface conductivity of 2%*

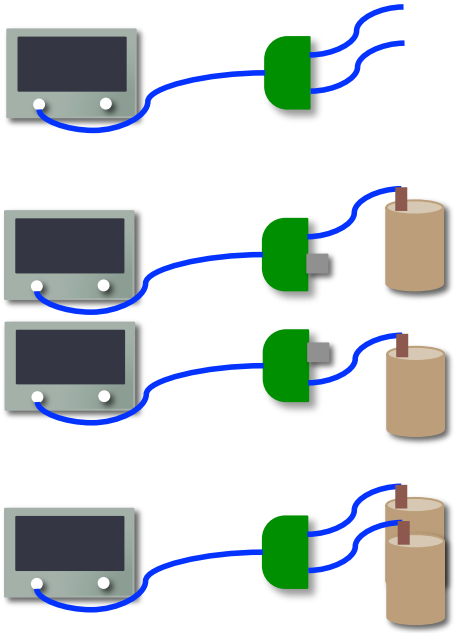
Experimental Demonstration

- *Double-cavity*
  - *O.D.= 5.08 cm*
  - *I.D. = 3.88 cm*
  - f_{TM010} = 5.92 GHz
  - Q_L = 9,000 at RT
- *Tuning system*
  - *Dielectric rods (95% alumina)*
    - f_{TM010} = 4.54 GHz at center
    - Q_L = 2,500 at RT
  - *Two rotators (ANR240)*
    - *Frequency tuning*
  - *One linear positioner (ANPz101eXT12)*
    - *Global operation of two couplers*



Sequence of Demonstration

- *Using a double-cavity system with a combiner*
  - *Calibrate the system up to the two antennas*
- *Critical coupling of each cavity separately at slightly different resonant frequencies*
  - *Measure the initial Q (and S_{11}) values*
- *Assembly of the full system*
  - *Two (small) reflection peaks and double (small) circles*



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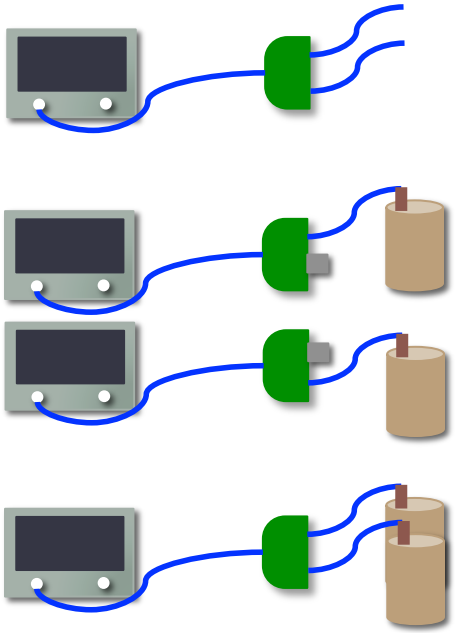

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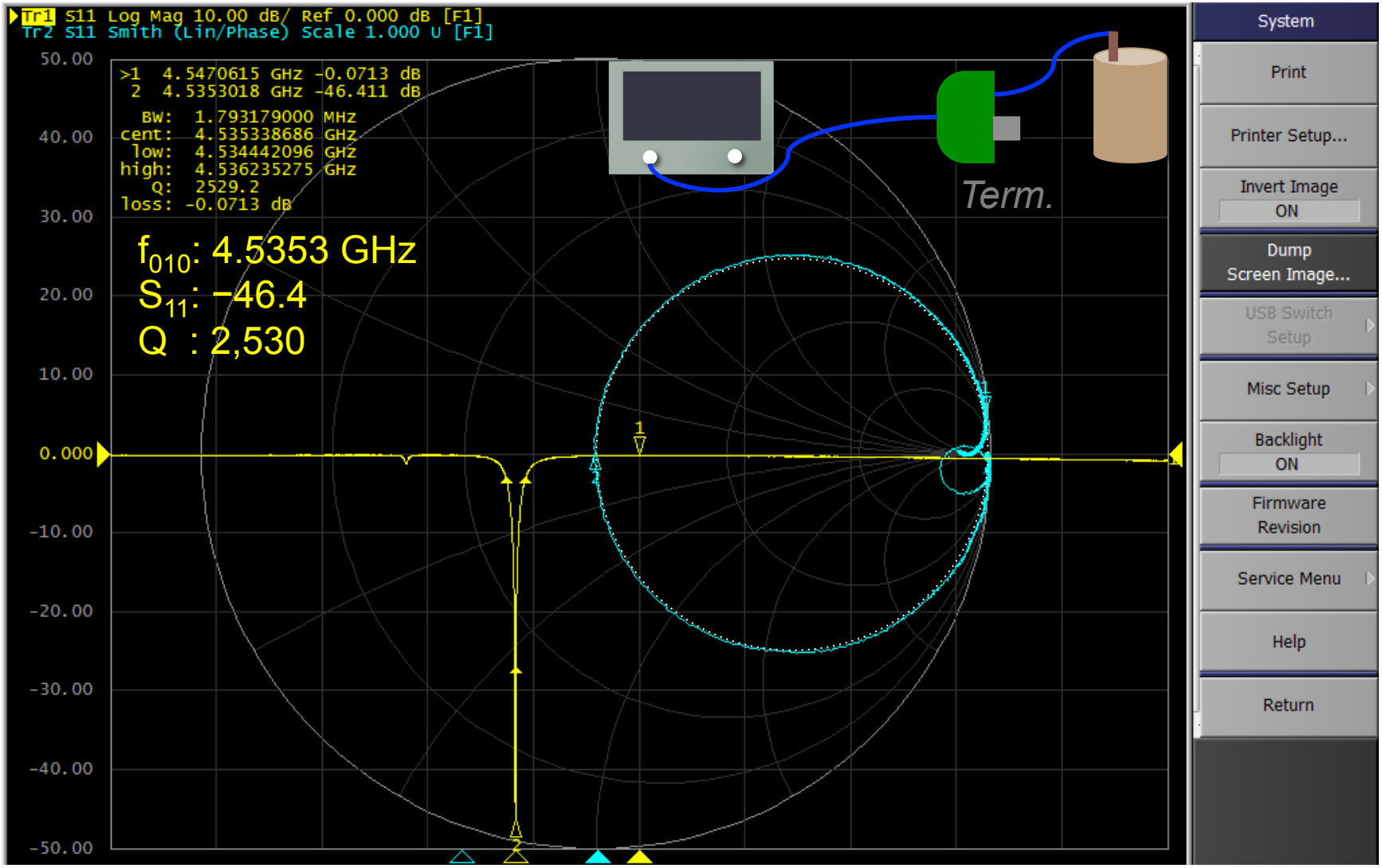
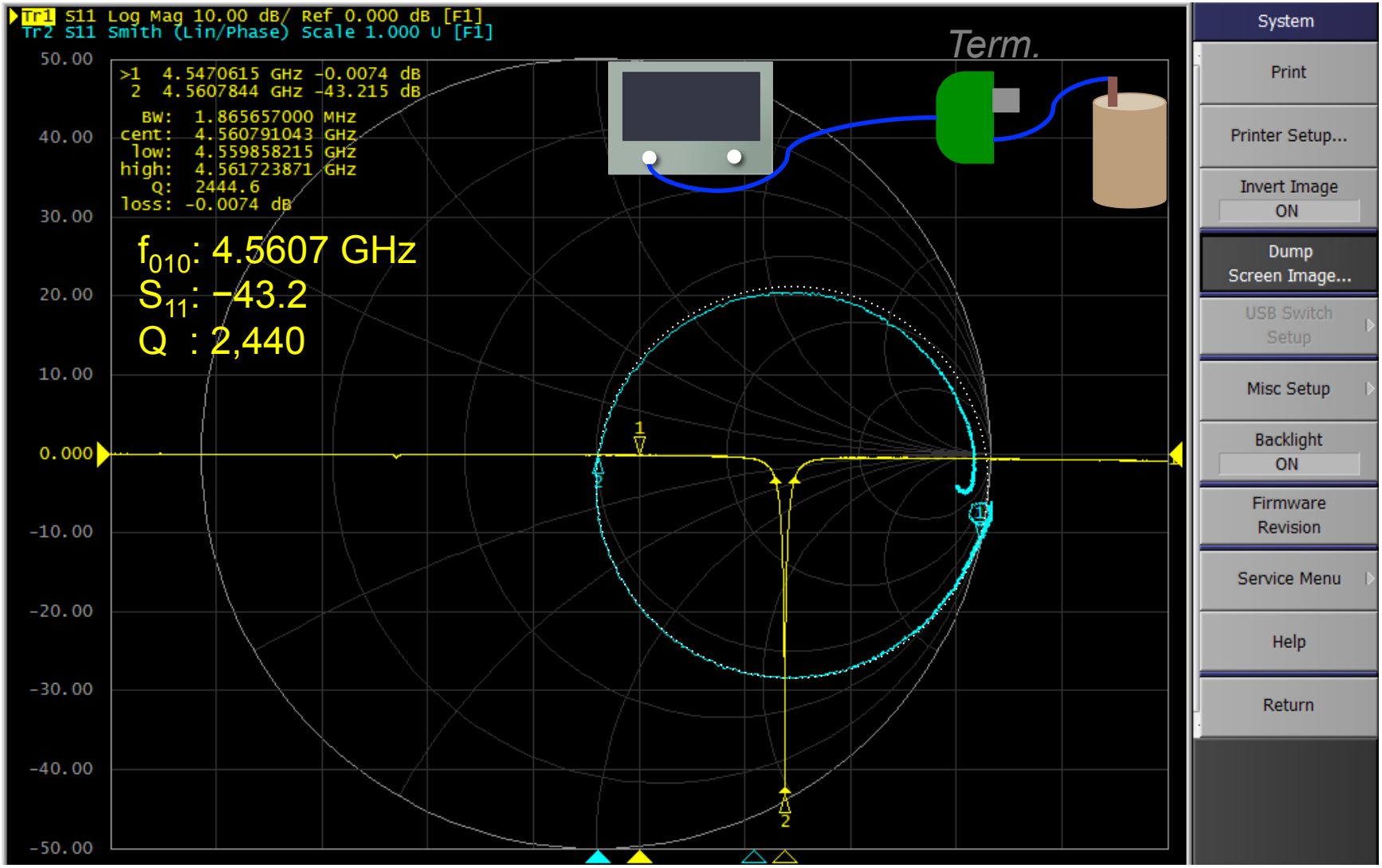
- *Assembly of the full system*
  - *Two (small) reflection peaks and double (small) circles*
- *Operate a rotator*
  - *For frequency matching*
  - *Two peaks become one and minimized / two circles become one and maximized*
- *Operate the linear positioner*
  - *For critical coupling*
  - *Reflection peak becomes further deeper / smith circle passes through the center*
- *Compare the (combined) Q (and S_{11}) value with the initial ones*

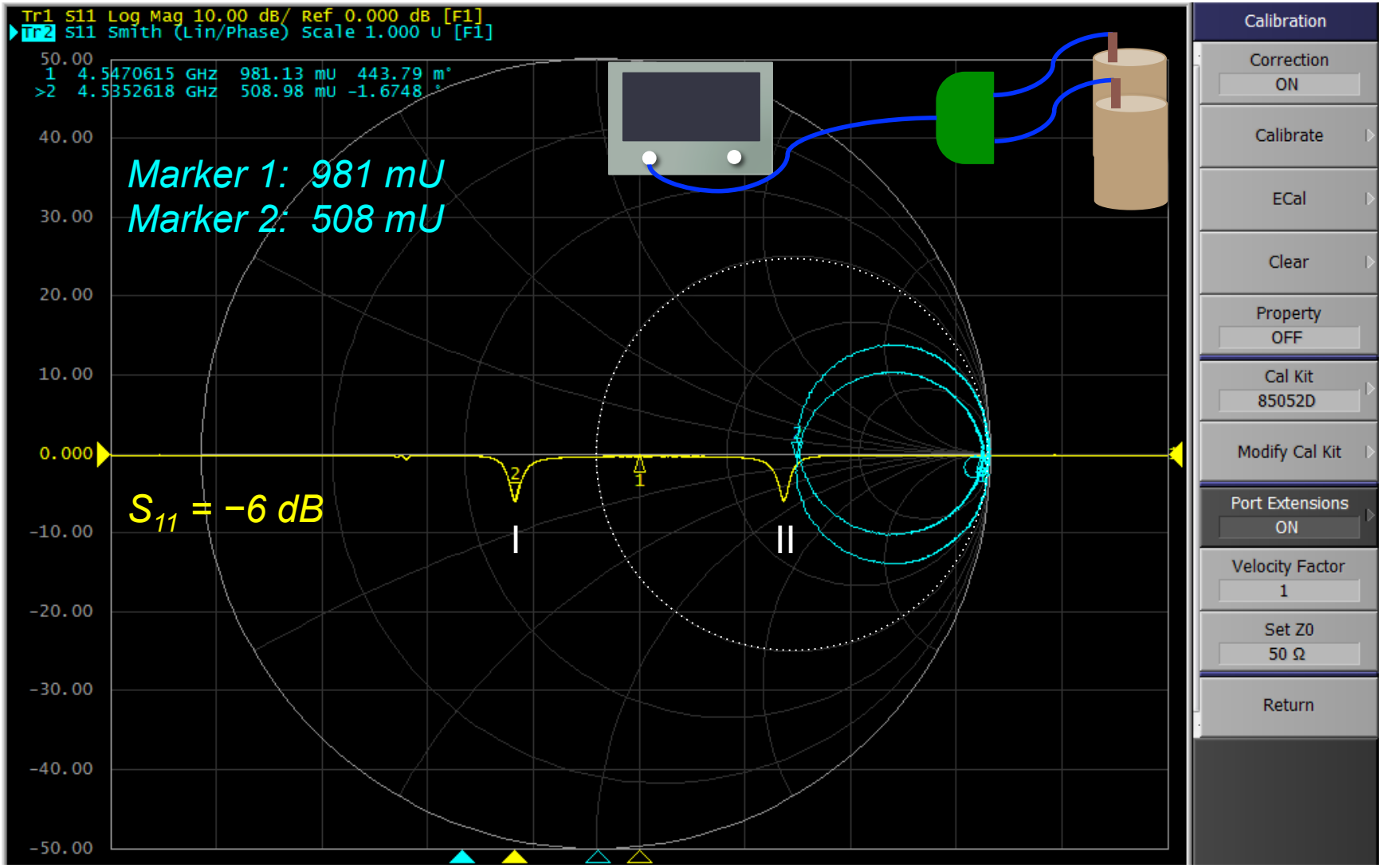
Critical Coupling (Cavity I)



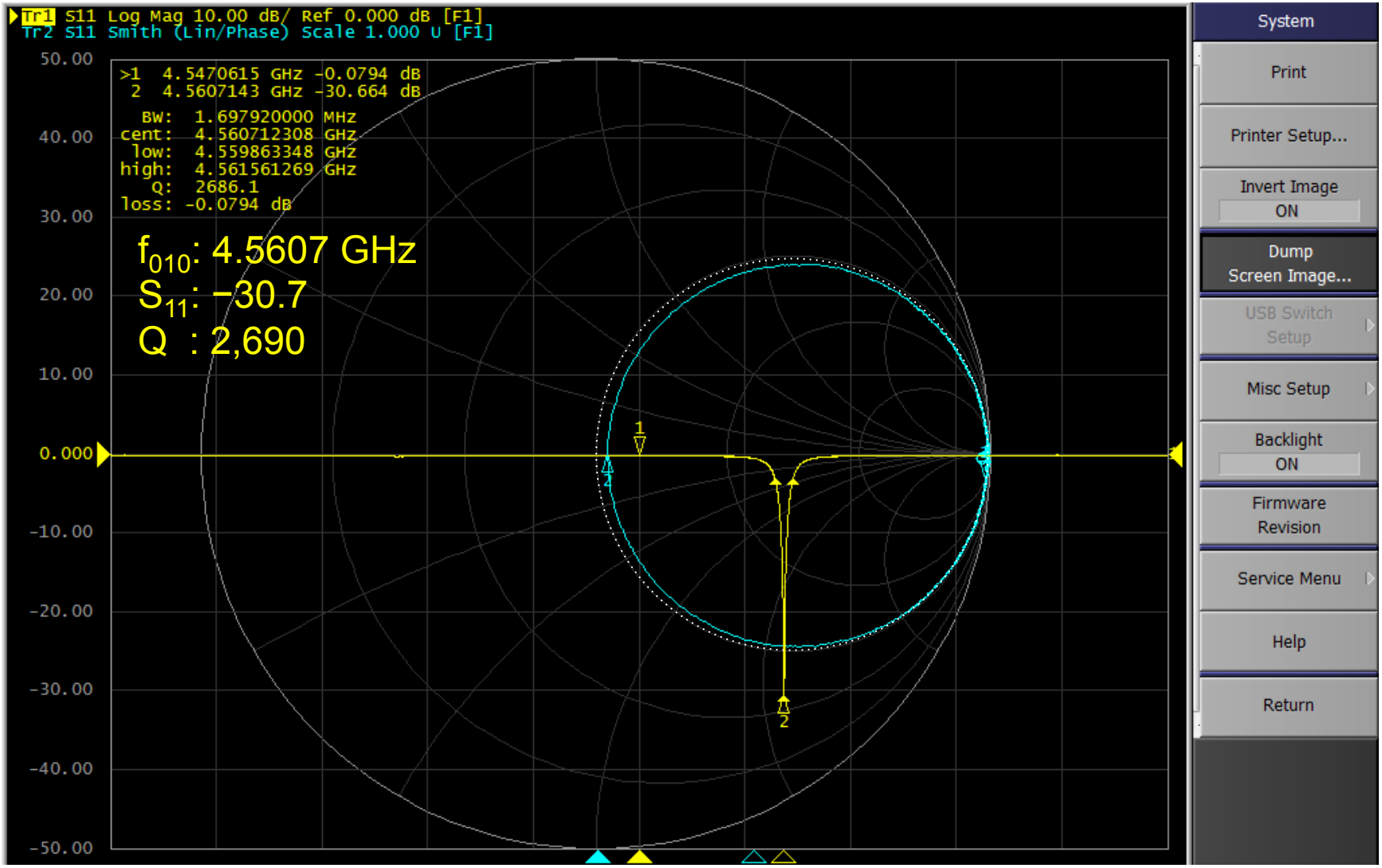
Critical Coupling (Cavity II)



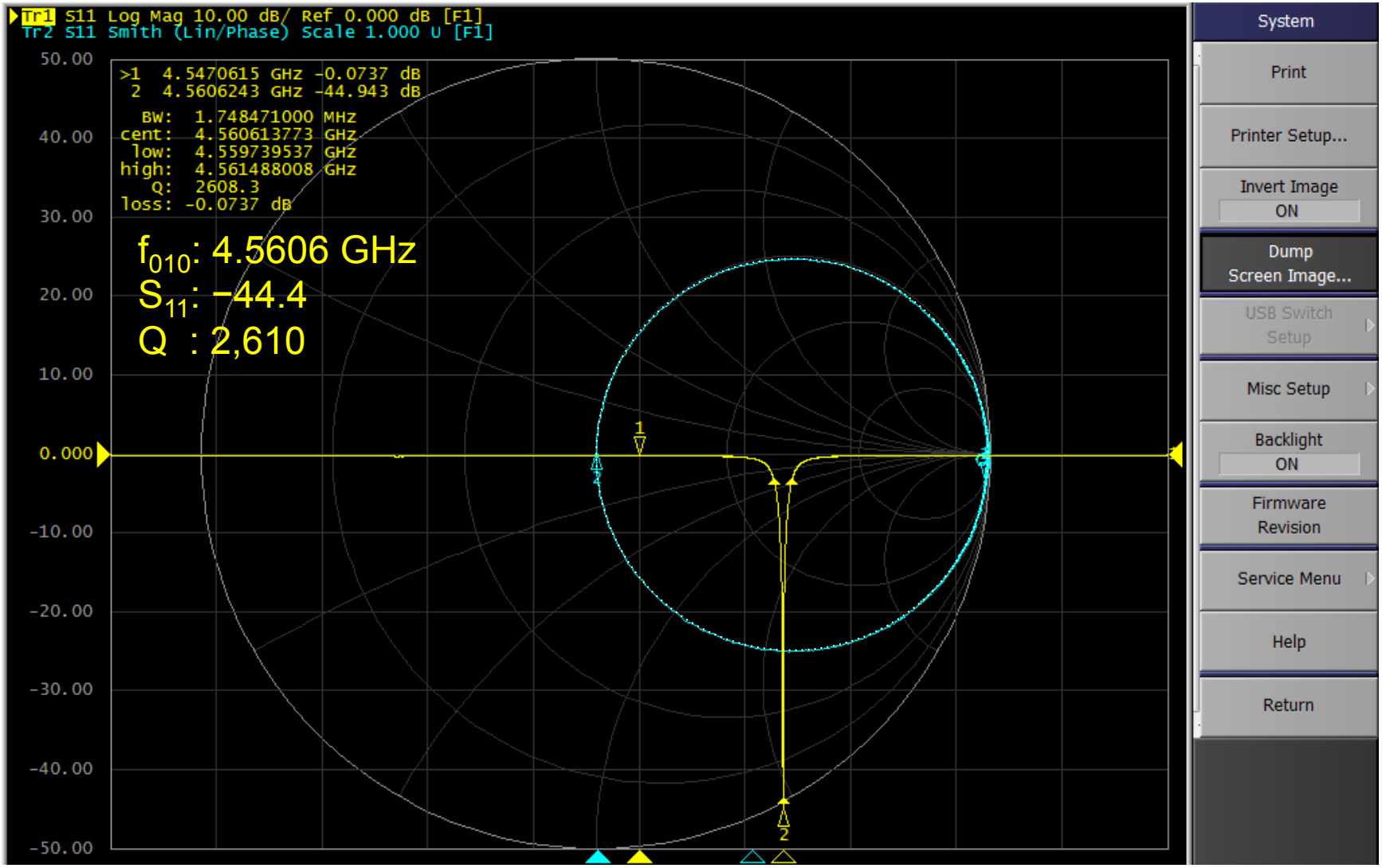
Assembly of Full System



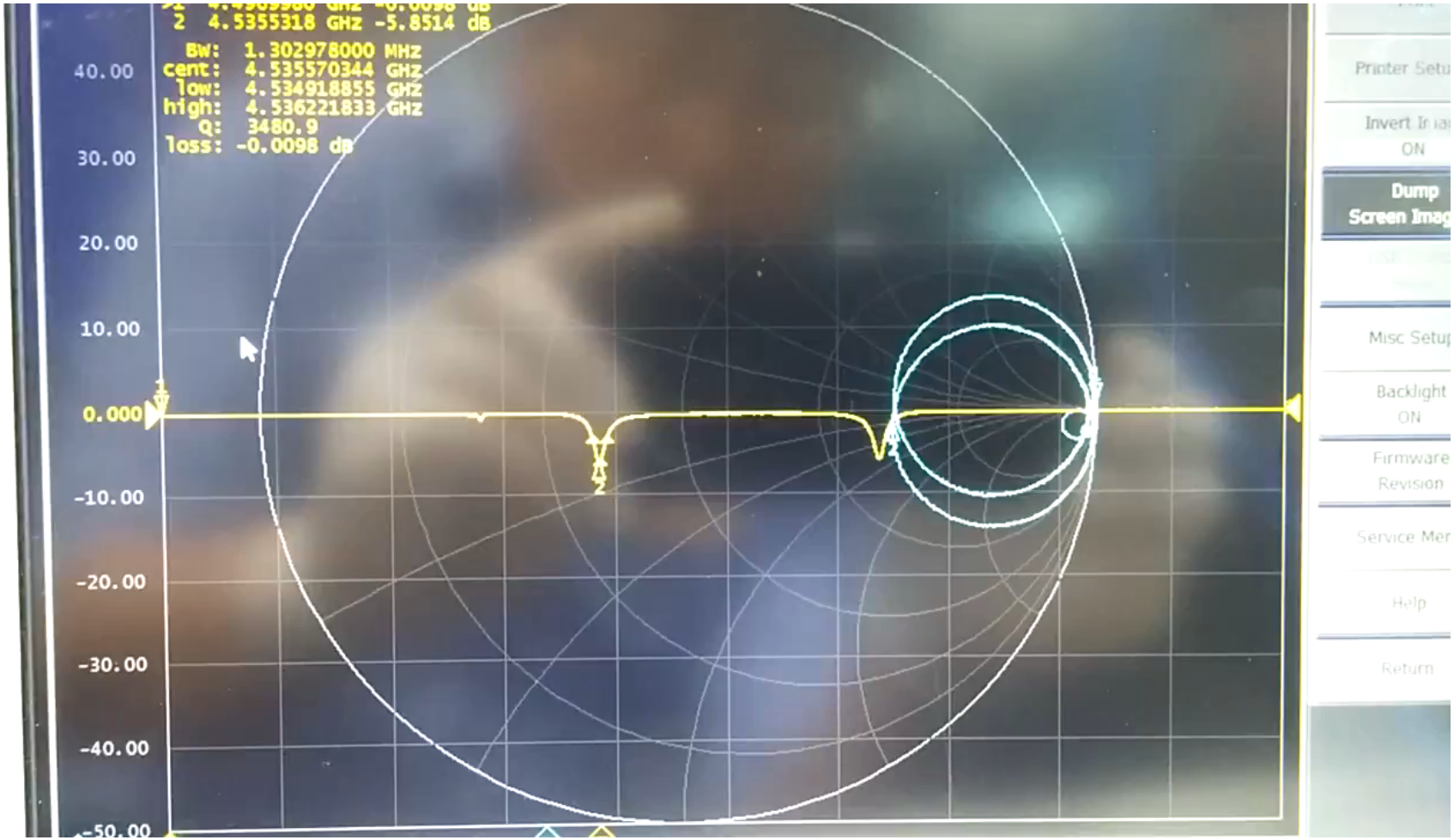
Frequency Matching – Rotator



Critical Coupling – Linear

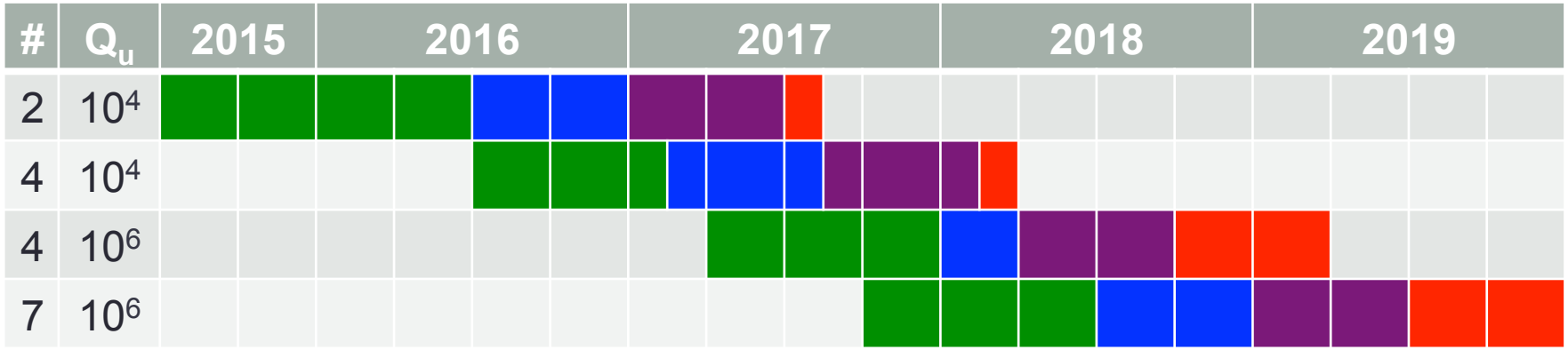


Tuning Mechanism – Movie



Project Plan

- *Multiple stages*
  - *Depending on cavity multiplicity (#) and cavity quality factor*
  - *1st stage: double-cavity with $Q_u=10^4$*
  - *2nd stage: quadruple-cavity with $Q_u=10^4$*
  - *3rd stage: quadruple-cavity with $Q_u=10^6$*
  - *Final stage: septuplet-cavity with $Q_u=10^6$*
    - *R=1.3 cm, $f(TM_{010})$=~9 GHz (with a dielectric tuning rod)*



Design & Procurement

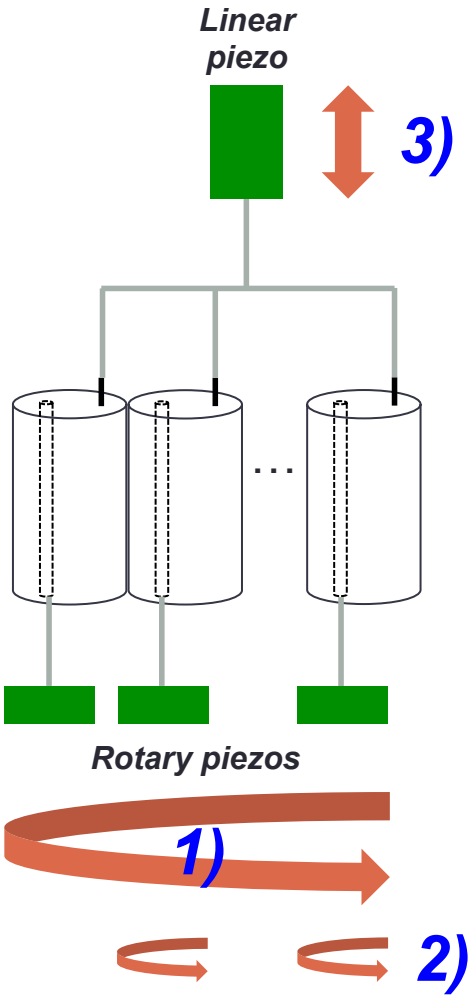
Construction & Test at RT

Commissioning at CR

Operation & Analysis

Summary

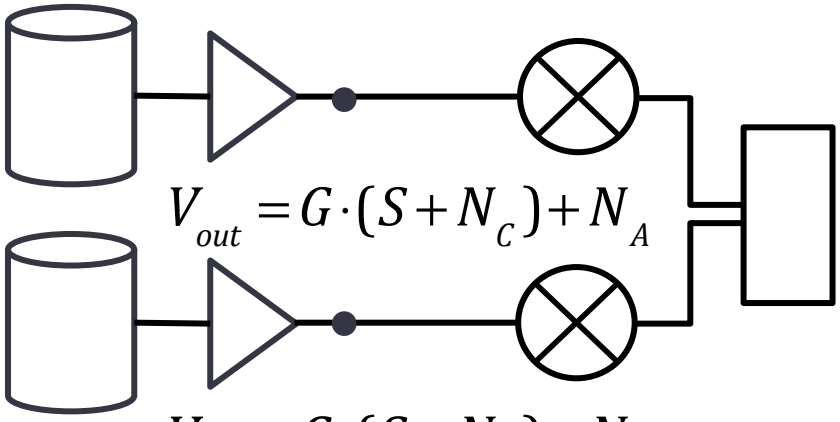
- *Multiple-cavity detector*
  - *Increases the sensitivity for axion search in higher frequency region*
- *Basic design: signal combination preceding amplification*
  - *Simpler setup with minimal sensitivity degradation*
- *Realistic approach for phase (frequency) matching*
  - *Frequency mismatch within FMT ($P_{comb} > 0.95\ P_{ideal}$)*
  - *FMT = 2 GHz / Q_u for 6 GHz axion*
- *Tuning mechanism*
  - *To achieve frequency matching and critical coupling*
- *Experimental demonstration*



Backups

SNR – Configuration 1

- *Multiple chains*



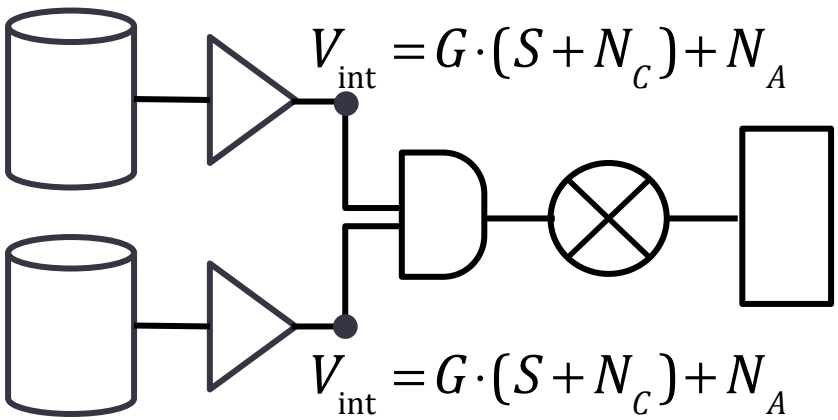
$$SNR_{ind} = SNR_{sngl}$$

$$SNR_1 = \sqrt{2} \cdot SNR_{sngl}$$

S : signal voltage
N_C: cavity noise voltage
G : amplifier gain
N_A : amplifier noise voltage

SNR – Configuration 2

- *Amplification + combination*



$$V_{out} = \frac{1}{\sqrt{2}}\cdot\left[2\cdot G\cdot S+\sqrt{2}\cdot\left(G\cdot N_C+N_A\right)\right]$$

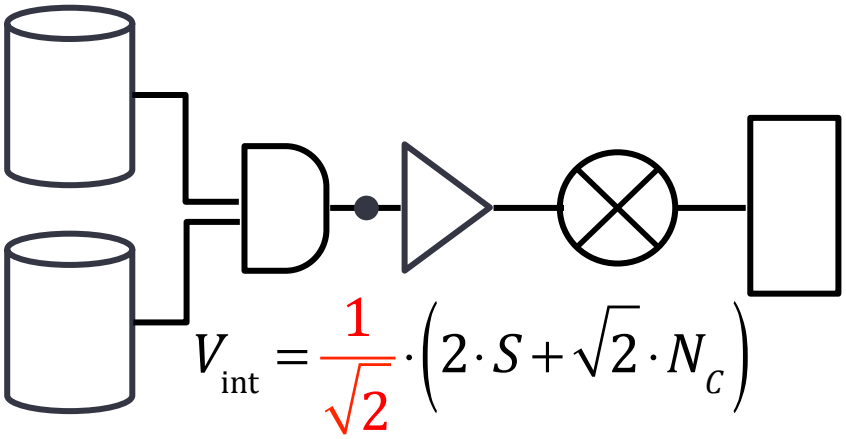
$$SNR_2 = \frac{\left(\sqrt{2}\cdot G\cdot S\right)^2}{\left(G\cdot N_C+N_A\right)^2} = 2\cdot SNR_{sngl}$$

S : signal voltage
N_C: cavity noise voltage
G : amplifier gain
N_A : amplifier noise voltage

Noise from the combiner is assumed to be negligible.
Signal is correlated while noise is uncorrelated.
Voltage adds in sqrt.

SNR – Configuration 3

- *Combination + amplification*



$$V_{out} = G \cdot \frac{1}{\sqrt{2}} \cdot \left(2 \cdot S + \sqrt{2} N_C\right) + N_A$$

$$SNR_2 = \frac{\left(\sqrt{2} \cdot G \cdot S\right)^2}{\left(G \cdot N_C + N_A\right)^2} = 2 \cdot SNR_{sngl}$$

S : signal voltage
N_C: cavity noise voltage
G : amplifier gain
N_A : amplifier noise voltage

Noise from the combiner is assumed to be negligible.
Signal is correlated while noise is uncorrelated.
Voltage adds in sqrt.

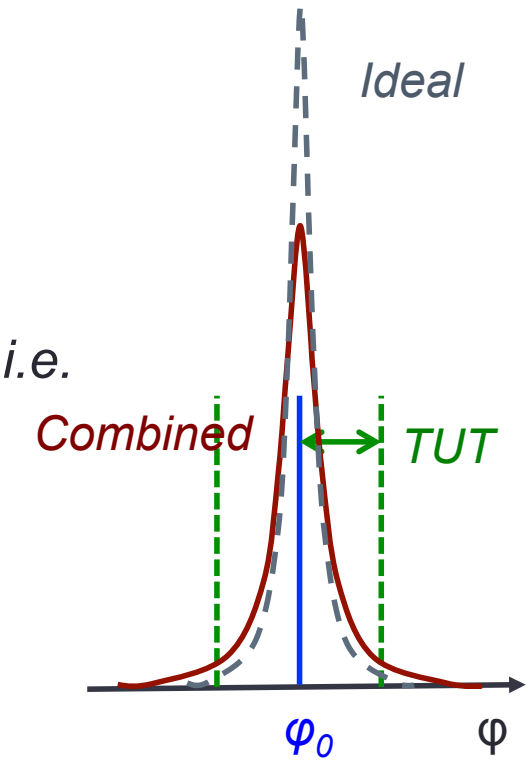
Phase-locking (Time)

- *Source of phase mismatch at the combiner*
  - *Different cable lengths between individual cavities and the combiner*

- *NOTE: Ideal phase matching is difficult!*
  - *Exactly same length of cables*
  - *More realistic to keep the phases within a certain range*
    - *Phase Matching Tolerance, PMT*
    - *Acceptable as long as the reduction in combined power (or SNR) is not significant*

Phase-locking (Time)

- *Determining the PMT*
  - *Consider a tolerance (tolerance under test, TUT)*
  - *Assume that individual signals have phases (φ_i) within the tolerance, i.e. $|\varphi_i - \varphi_0| < TUT$ when arriving at the combiner*
  - *If the combined power is >95% of the ideal case, i.e. $\varphi_i = \varphi_0$ or TUT=0, then take the TUT as the PMT*

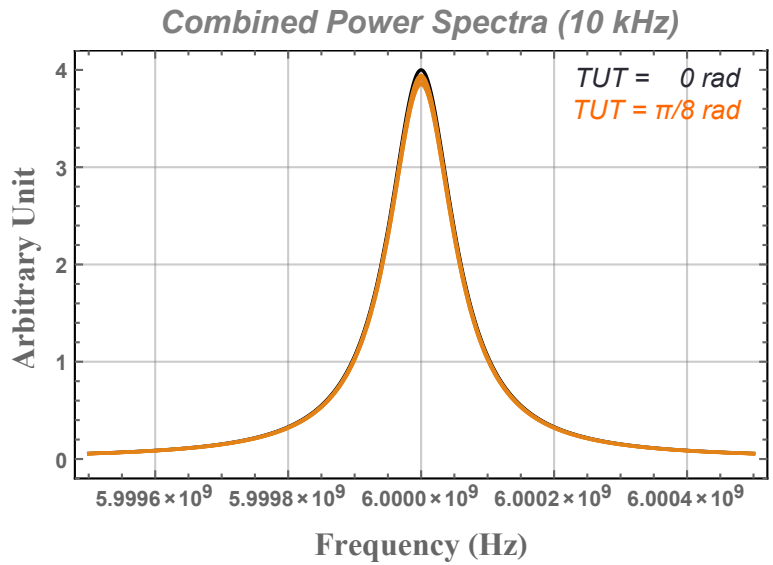


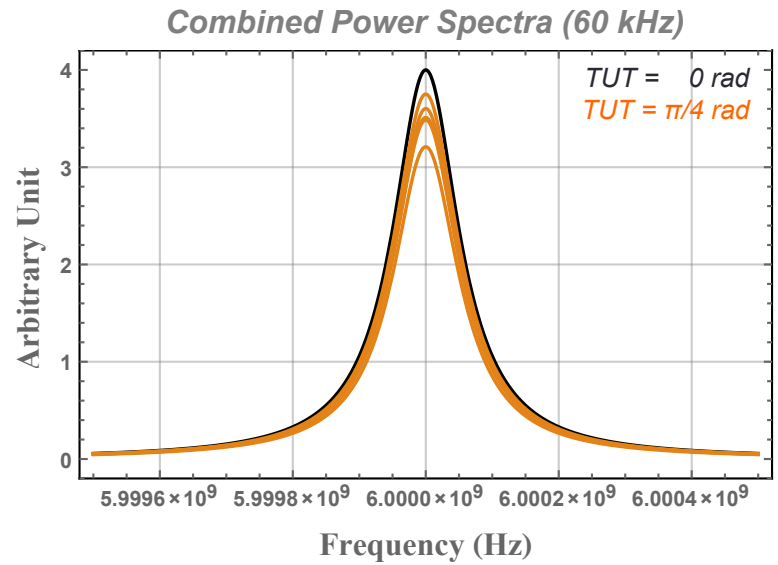
φ_0: leading frequency

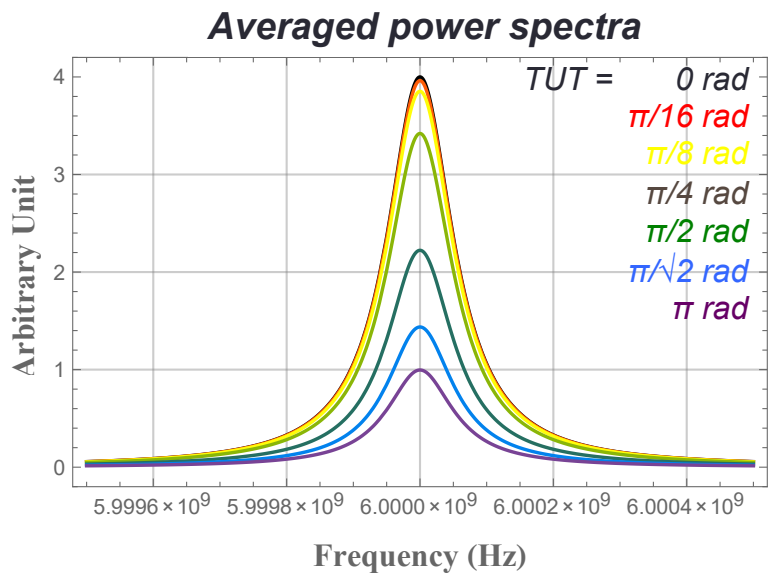
- *Pseudo-experiment study*
  - *4-cavity detector, f_0=6 GHz, $Q_u=10^5$*
  - *TUT = (0,) π/16, π/8, π/4, π/2, π/√2, π*
  - *1000 pseudo-experiments*

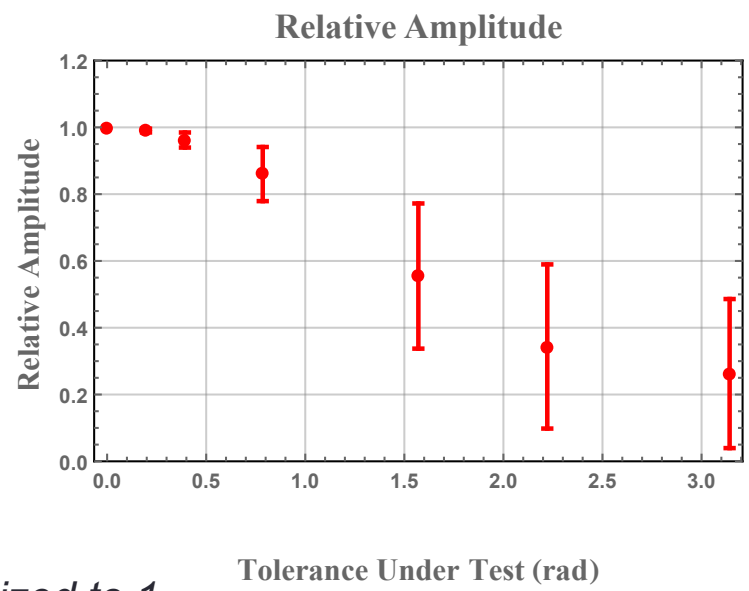
Pseudo-experiment Study

Junu Jeong



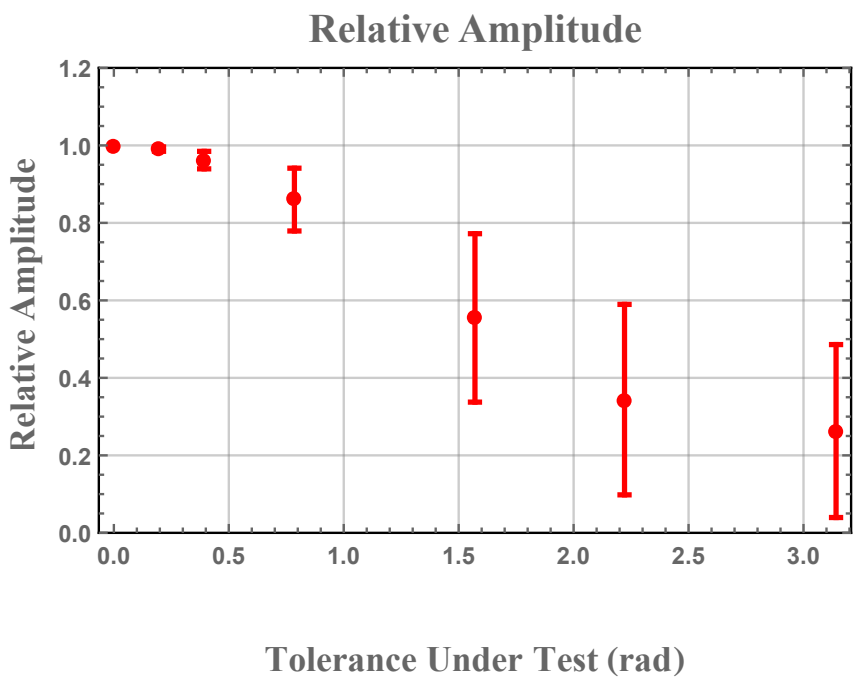






Power amplitude from each cavity is normalized to 1.

Pseudo-experiment Study – Summary



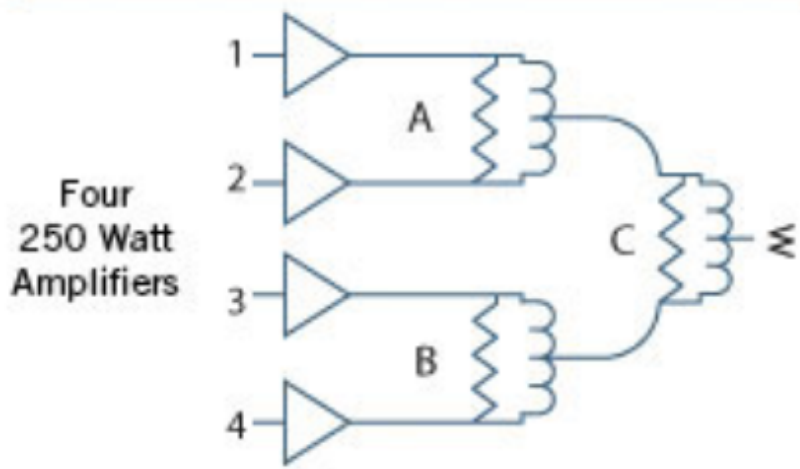
TUT (rad)	Power Amp.	Q_u	SNR	Sensi-tivity
0	1.00	1.00	1.00	1.00
π/16	0.99	1.00	0.99	0.98
π/8	0.96	1.00	0.96	0.93
π/4	0.86	1.00	0.86	0.75
π/2	0.54	1.00	0.54	0.29
π	0.25	1.00	0.25	0.06

- *For 6.0 GHz axion signal, 4-cavity detector with $Q_u=10^5$*
  - *π/8 rad is the PMT for this system*
  - *This corresponds to Δl = ~3 mm (λ = 5 cm)*
- *In general, Δl = 1/16*c/f*
  - *For 10 GHz, Δl = ~2 mm*
  - *Can be under good control*

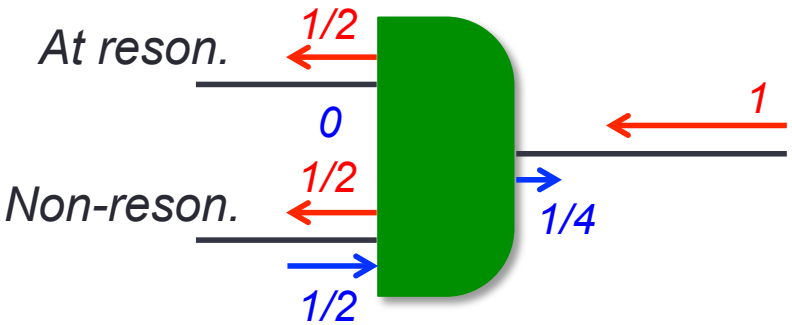
Isolating Termination Dissipation

- *Isolating terminations enable the dissipation of power due to various unbalances and possible input failures*

Input Failure(s) vs Power Output

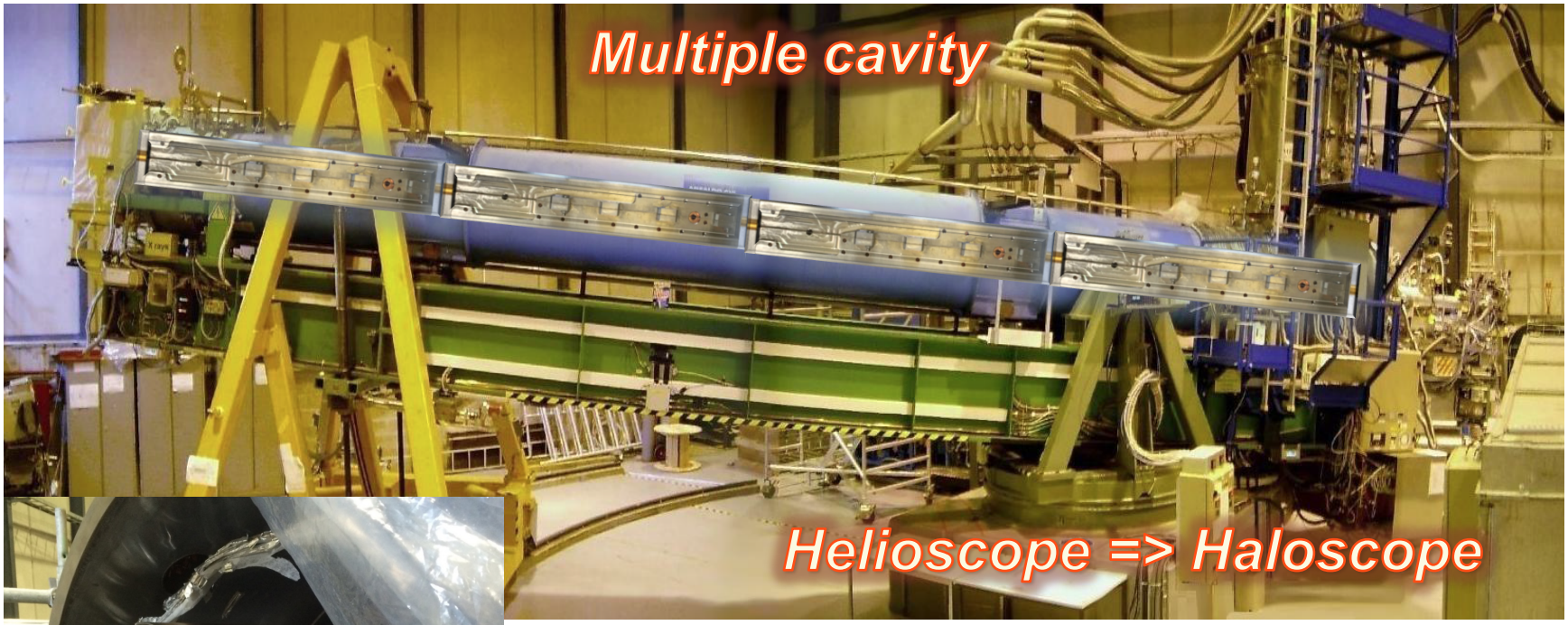


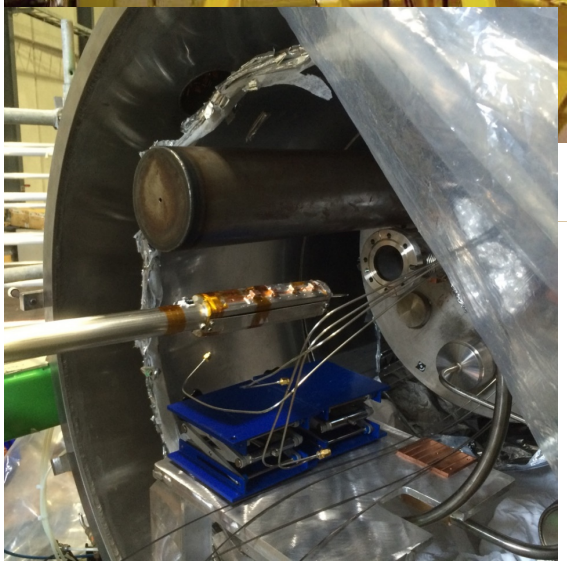
Input Failure(s)	Watts P-Out	Dissipated Power (Watts) A	B	C
0	1000	0	0	0
1	562.5	125	0	62.5
1 & 2	250	0	0	250
1 & 3	250	125	125	0
1, 2 & 3	62.5	0	125	62.5



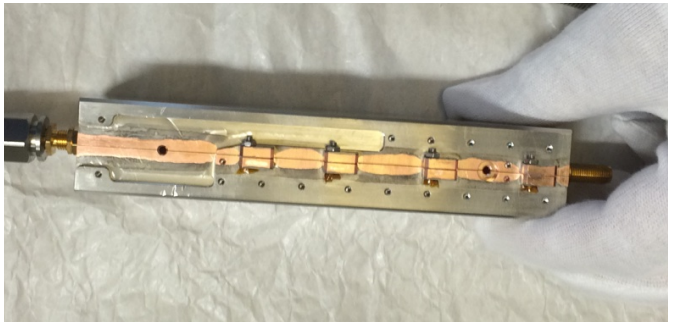
- *Schematic representation of four 250 W amplifiers feeding a 4-way combiner*
- *Power output and power dissipation associated with various input failure scenarios*

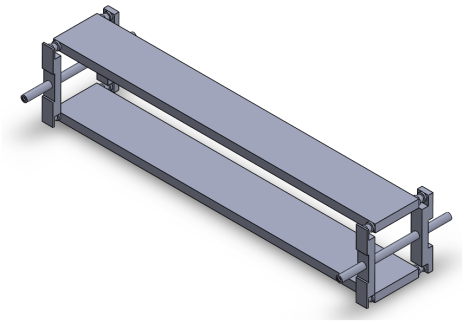
CAST-CAPP/IBS





Magnet: 9 T & 9.25 m / Bore: 43 mm / Temp.: 1.8 K



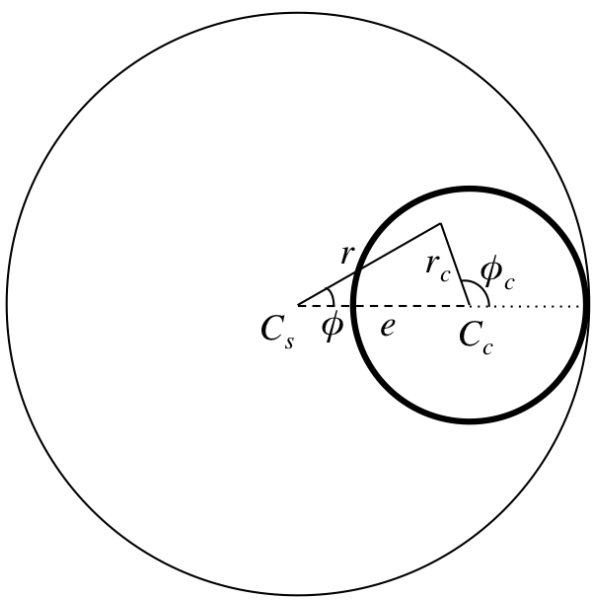


Tuning Mechanism – Movie

Comment on Magnetic Form Factor C_B

- *"Axion Dark Matter Coupling to Resonant Photons via Magnetic Field"*
  - *B. T. McAllister et al. (PRL 116, 161804)*
  - *Magnetic coupling (form factor) is not constant: $C_B = C_B(e)$*

$$C_B = \frac{\frac{w_a^2}{c^2}\left|\int dV_c \frac{r}{2}\vec{B}_c \cdot \hat{\phi}\right|^2}{V\int dV_c |B_c|^2}, \quad \vec{B}_c = \vec{B}_c(r_c)\hat{\phi}_c \equiv B_{c,\phi_c}\hat{\phi}_c$$



$$\hat{\phi}_c \cdot \hat{\phi} = \cos(\phi_c - \phi) = \frac{1}{r}[r_c + e\cos\phi_c] \quad vs. \quad \hat{\phi}_c \cdot \hat{\phi} = \frac{1}{r}[r + e\cos\phi]$$

$$\Rightarrow C_B = \frac{\frac{w_a^2}{c^2}\left|\int dV_c \vec{B}_{c,\phi_c} \frac{r_c + e\cos\phi_c}{2}\right|^2}{V\int dV_c |B_c|^2} \quad vs. \quad C_B = \frac{\frac{w_a^2}{c^2}\left|\int dV_c \vec{B}_{c,\phi_c} \frac{r + e\cos\phi}{2}\right|^2}{V\int dV_c |B_c|^2}$$

CB is constant with offset for all TM0n0 modes!

Comment: S. L et al. (arXiv:1606.09504)
Erratum: B. T. McAllister et al. (PRL 117, 159901)