Cold Cavity measurements

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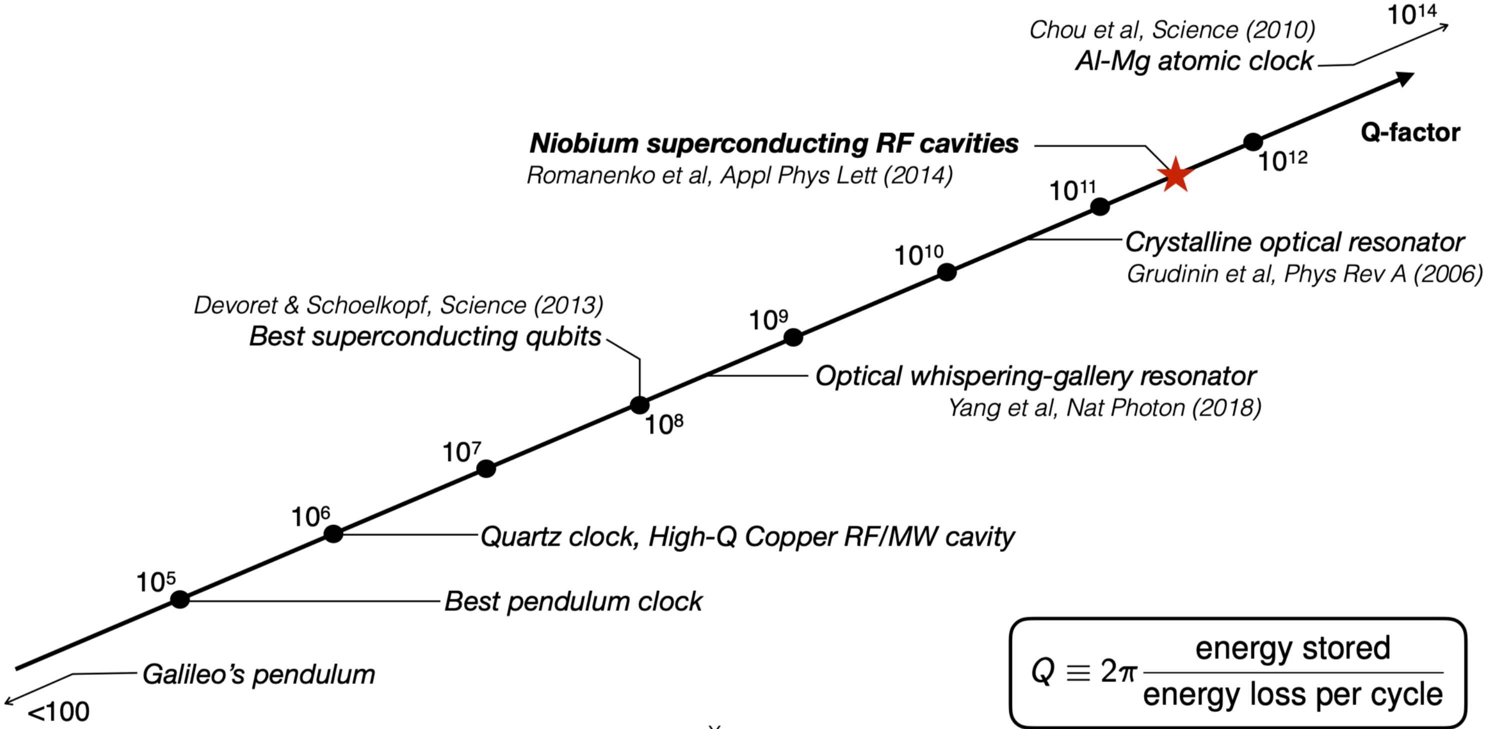
QIS school - August, 2023

Why SRF cavities?

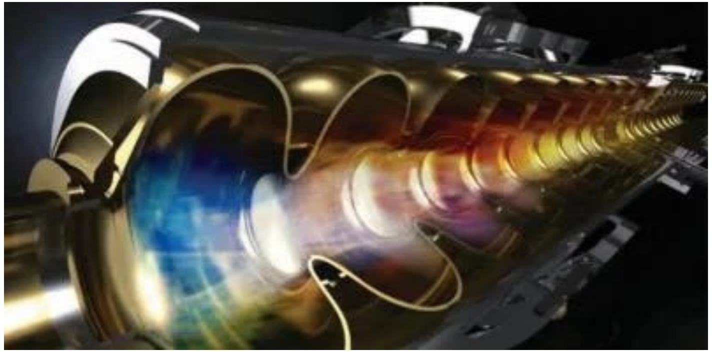
SRF cavities are the most efficient engineered oscillators

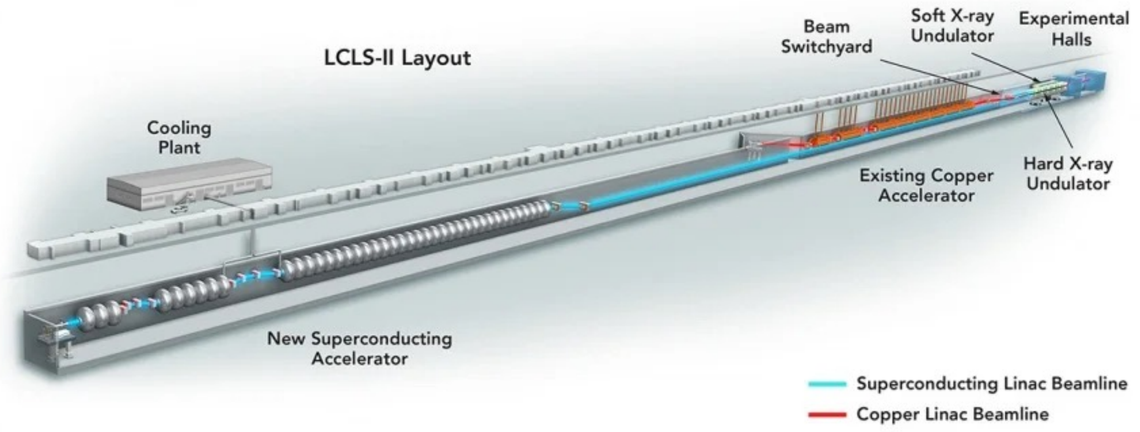


$$Q \equiv 2\pi \frac{\text{energy stored}}{\text{energy loss per cycle}}$$

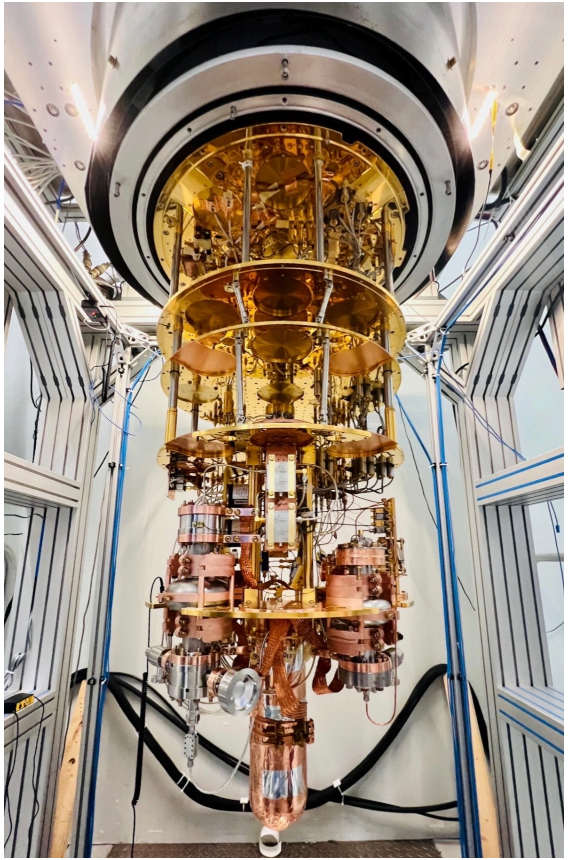
X

SRF cavities in new regimes: from 2K to few mK





https://lcls.slac.stanford.edu/lcls-ii



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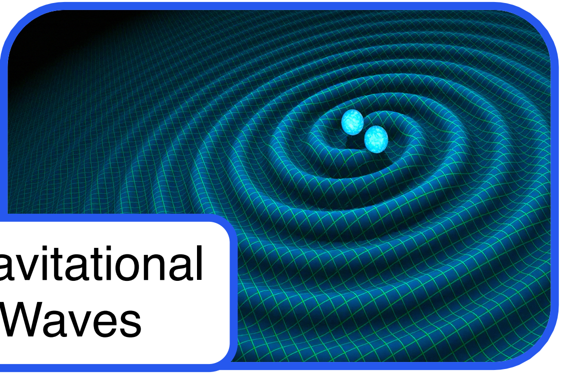
SRF cavities for Quantum Sensing

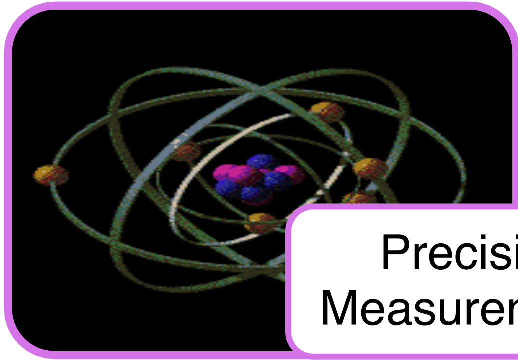
Dark Sector

Dark Matter

“Just” new particles



Gravitational Waves

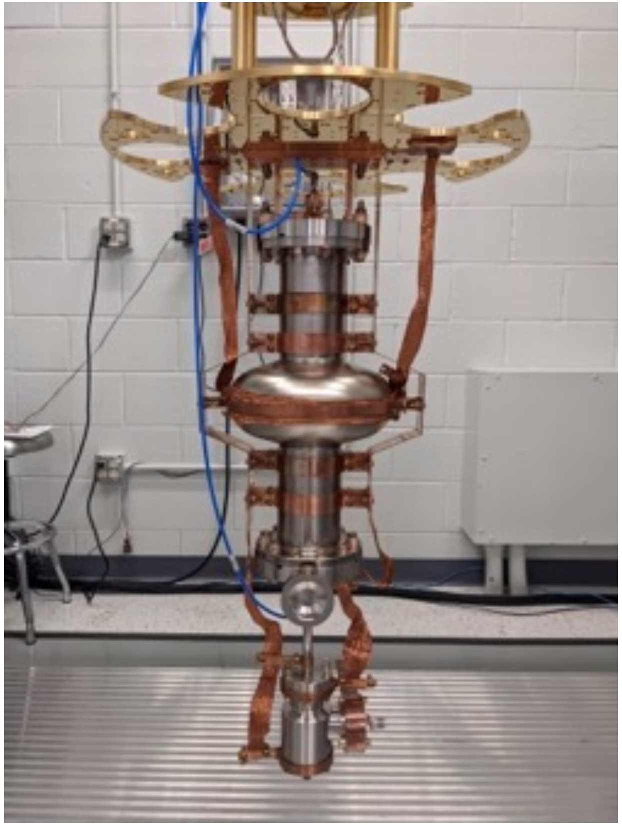


Precision Measurements

Fermilab Dark SRF Experiment

[1] Artwork by Sandbox Studio Chicago with A. Kova symmetrymagazine.org

SRF cavities: Figures of merit



- Energy density in the electromagnetic field:

$$u = \frac{1}{2}\left(\epsilon \mathbf{E^2} + \mu \mathbf{H^2}\right)$$

- Stored energy in a cavity:

$$U = \frac{1}{2}\mu_0 \int_V |\mathbf{H}|^2 \, dv = \frac{1}{2}\epsilon_0 \int_V |\mathbf{E}|^2 \, dv$$

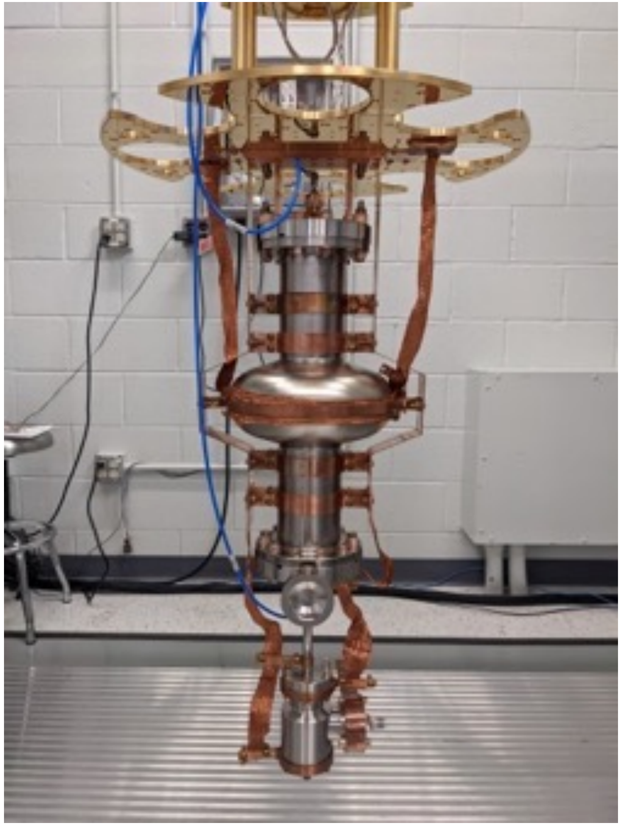
- Quality factor:

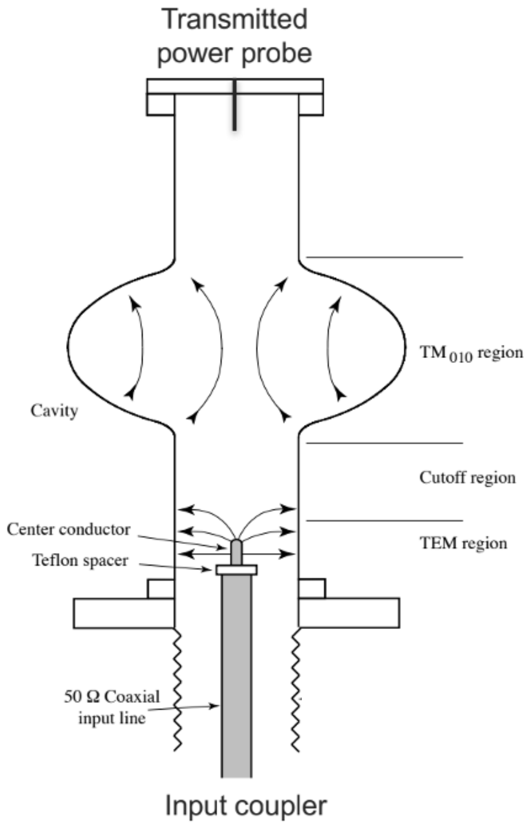
$$Q_0 \equiv \frac{\omega U}{P_c} = \frac{\omega_0 \mu_0 \int_V |\mathbf{H}|^2 \, dv}{R_s \int_S |\mathbf{H}|^2 \, ds} \qquad Q_0 = \frac{\omega}{\Delta\omega}$$

with P_c power dissipated in the walls of the cavity

Q_0 is determined both by the material properties and the cavity geometry

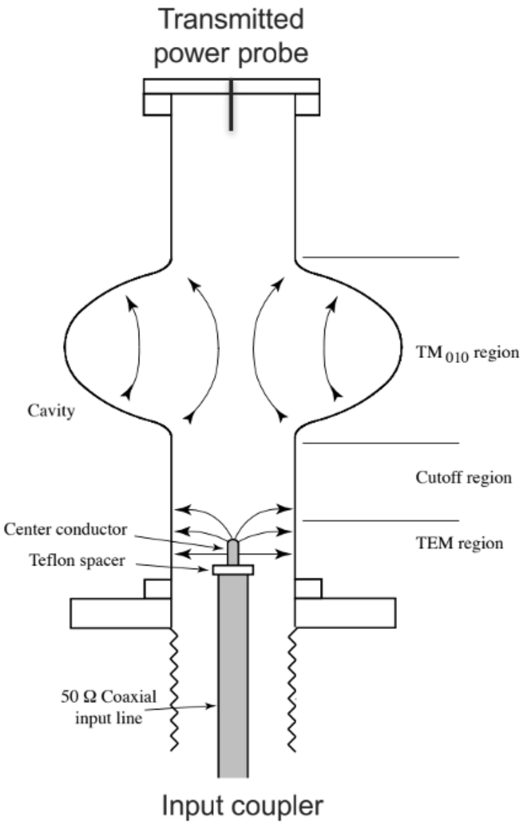
SRF cavities





https://sites.google.com/view/srfuspas17/home

External and loaded quality factors

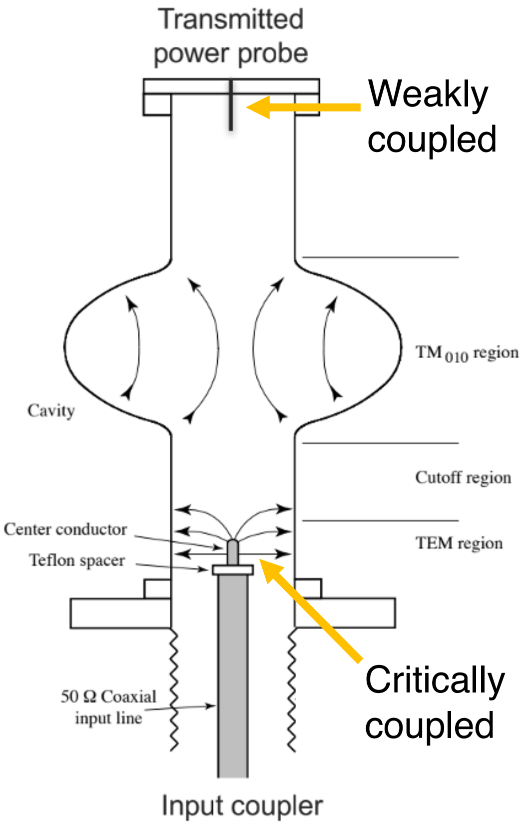


- The cavity is assembled with RF antennas to be able to carry out measurements
- For each coupler there is an associated external quality factor Q_{ext} that quantifies the dissipation through that port.
- The loaded quality factor Q_L is:

$$\frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ext1}} + \frac{1}{Q_{ext2}} + \ldots$$

So $Q_L = \frac{\omega U}{P_{tot}}$ with $P_{tot} = P_c + P_r + P_t$

External and loaded quality factors



- For each port we can define a coupling parameter:

$$\beta \equiv \frac{Q_0}{Q_{ext}}$$

β tells us how strongly the coupler interacts with the cavity

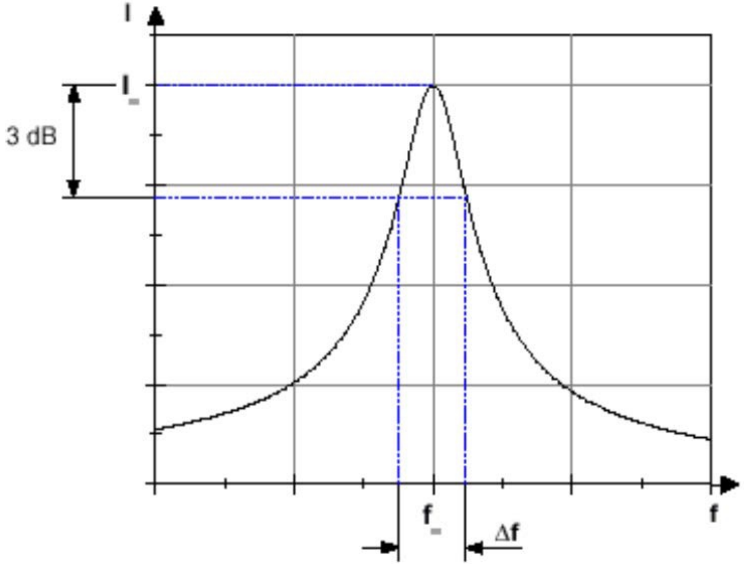
$$Q_0 = \frac{\omega U}{P_c} \Longrightarrow P_{ext1} = \beta_1 P_c$$

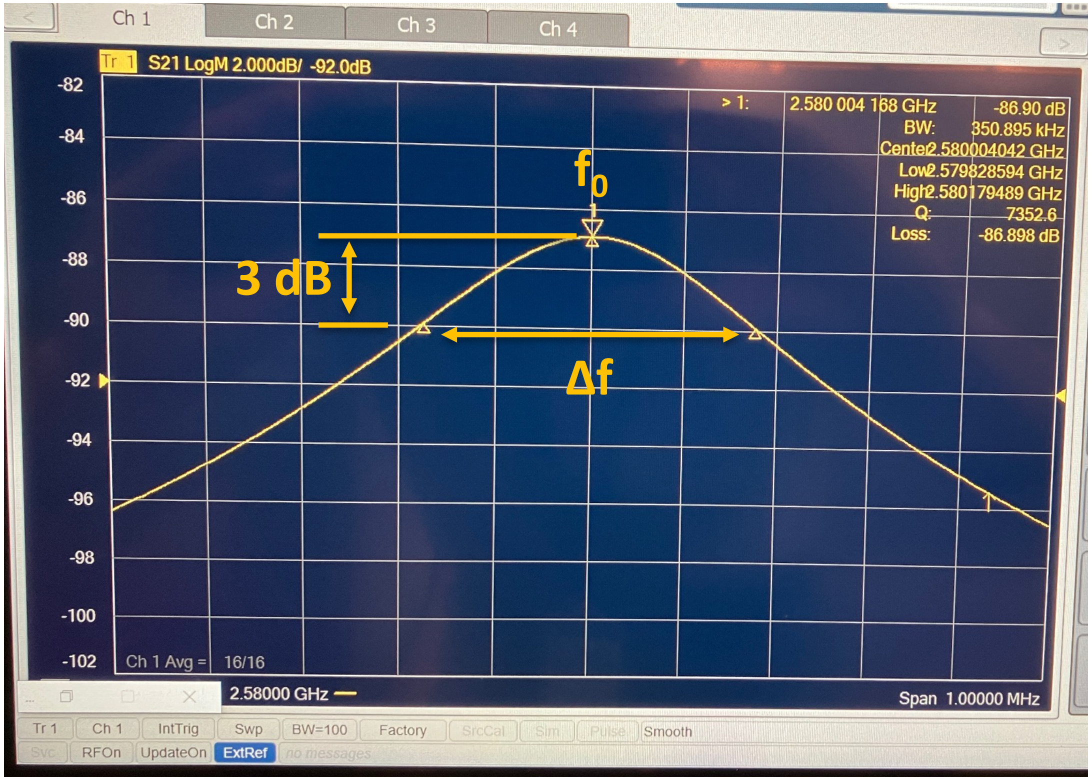
- We refer to critical coupling when $\beta \approx 1$, over coupled when $\beta \gg 1$, under coupled when $\beta \ll 1$
- In the case of a cavity with two antennas: often one coupler is weakly coupled, while the length of the second antenna is chosen to achieve critical coupling

VNA 2-port measurements

Low Q cavities

$$Q_L = \frac{\omega}{\Delta\omega}$$





High Q cavities

For high Q cavities we can't use a peak width meas to extract the Q…
If we power our cavity and then turn off the RF power source, we can use:

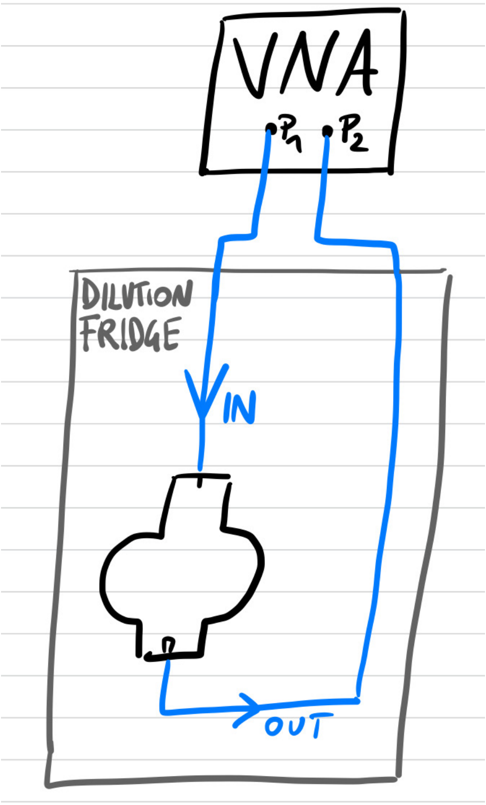
$$P_{tot} = -\frac{dU}{dt} \;, \quad P_{tot} = \frac{\omega U}{Q_L} \;\Rightarrow\; U(t) = U_0 e^{-\frac{\omega t}{Q_L}}$$

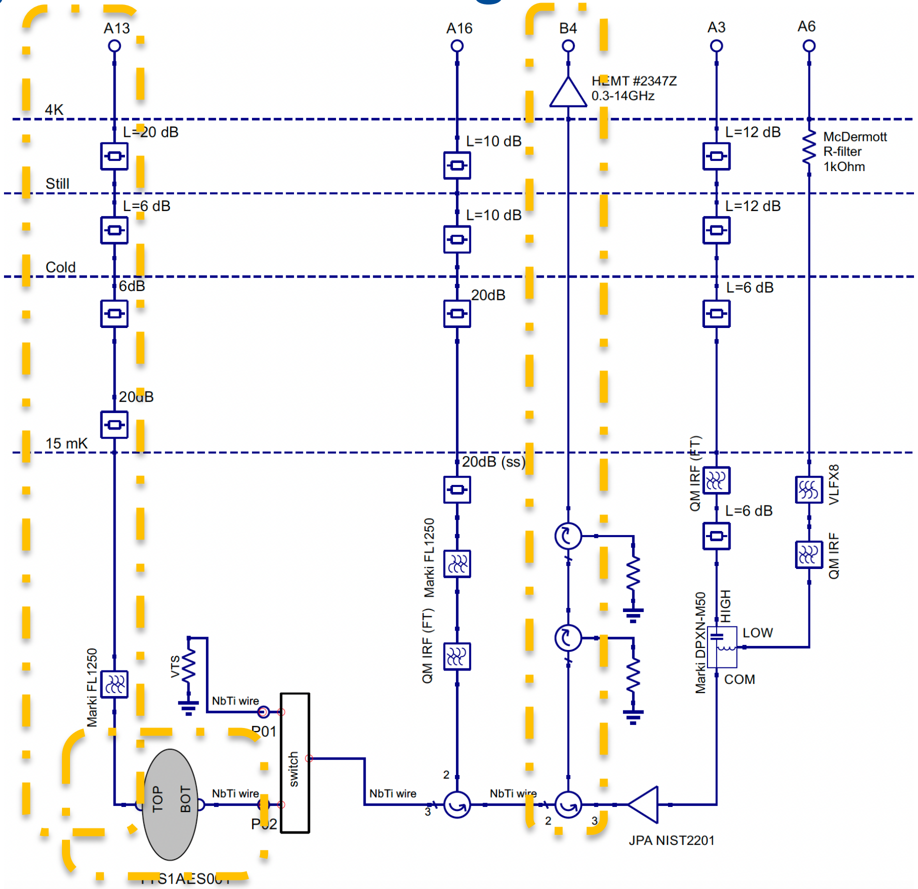
to extract the Q_L.
We define τ the time in which the energy decays by e factor:
which we can easily measure experimentally to extract Q_L

$$\tau = \frac{Q_L}{\omega}$$

Experimentally we can measure the decay of the reverse or transmitted power to extract τ. We will use transmission measurements (S21 on VNA)

Experimental schematic of cavity in Dilution Refrigerator





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Now: cavity decay demo on VNA

Decay measurement

$$U(t) = U_0 e^{-\frac{\omega t}{Q_L}}$$ and $$V(t) = V_0 e^{-\frac{\omega t}{2Q_L}}$$ with $$\tau = \frac{Q_L}{\omega}$$

Remember that

$$P_{dBm} = 10 \cdot log_{10}(1000 \cdot P_W/1W) = 10 \cdot log_{10}(P_W/1W) + 30$$

But when saving the VNA file, the raw data will be in voltage $P = V^2/R$

And for your fit you are interested in the amplitude of the complex signal

TE1AES022 from Vertical Test December 2022:

Q1 = 8.4E9; Q2 = 2.3E11

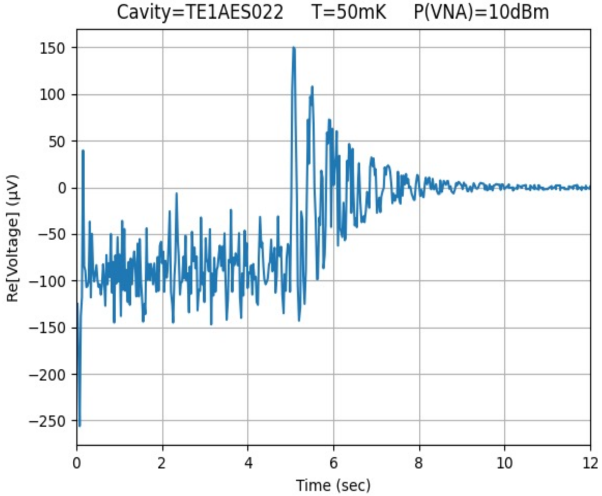
Selected Settings/Parameters for VNA Measurements

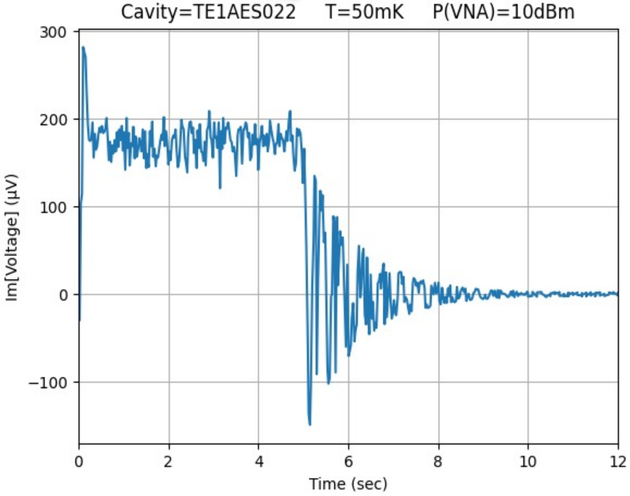
- Finding Cavity Resonance:
  - Measurement Type (e.g. S21, S11)
  - Center Frequency
  - Frequency Span
  - Signal Power
  - Number of Sweep Points
  - Resolution Bandwidth

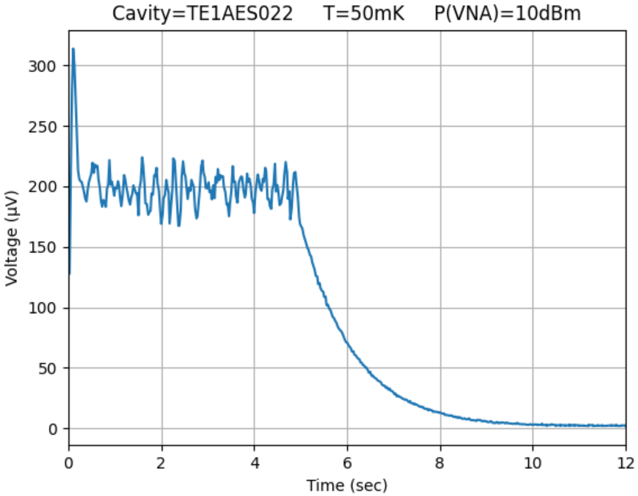
- Decay Measurement:
  - Measurement Type (Pulse)
  - Pulse parameters (e.g. duration)

Data Analysis (Voltage: Re, Im, Magnitude)

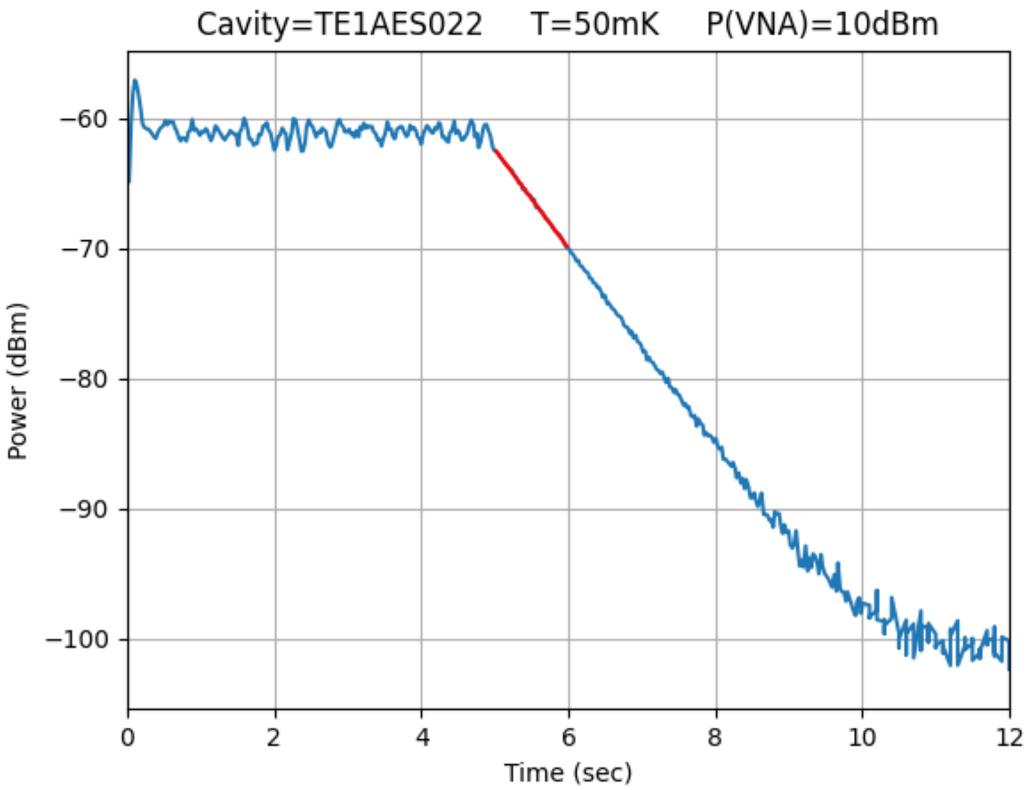
	time[s]	re:Trc1_b2d1sam[V]	im:Trc1_b2d1sam[V]	Magnitude[V]
3	time[s]	re:Trc1_b2d1sam[V]	im:Trc1_b2d1sam[V]	Magnitude[V]
4	0.00E+00	-3.93E-05	-2.34E-05	4.57801E-05
5	2.60E-02	-1.25E-04	-2.95E-05	0.00012806







Data Analysis (Power, Decay Fit)



Slope = −7.60
Offset = −24.34

tau = 0.571 sec

QL = 4.64 x 1E+09

Q_0 = ~ 1.0E10