Measurement of Cavity-Loaded Quality Factor and detuning in Superconducting Radio-Frequency Systems with Mismatched Source Impedance

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Joint effort between IMP and ESS

Institute of Modern Physics (IMP)

European Spallation Source (ESS)

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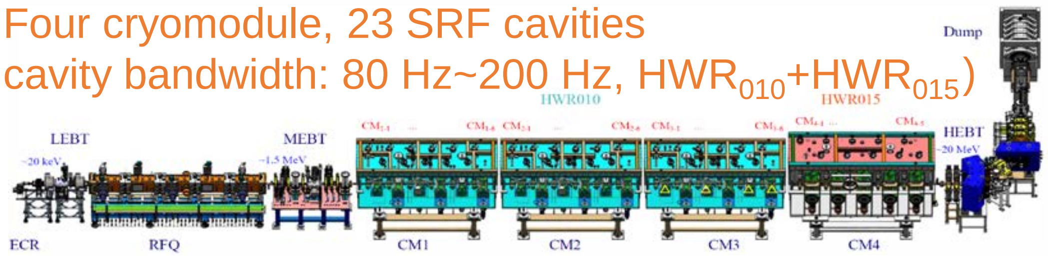
Introduction

CAFe: China ADS Front-end (**SRF** facility, in **CW** mode)

- Demonstrate the feasibility of the 10-mA high-power CW proton beam for the China-initiative ADS (CiADS) project

- 2021.03, stable operation of 10 mA proton beam

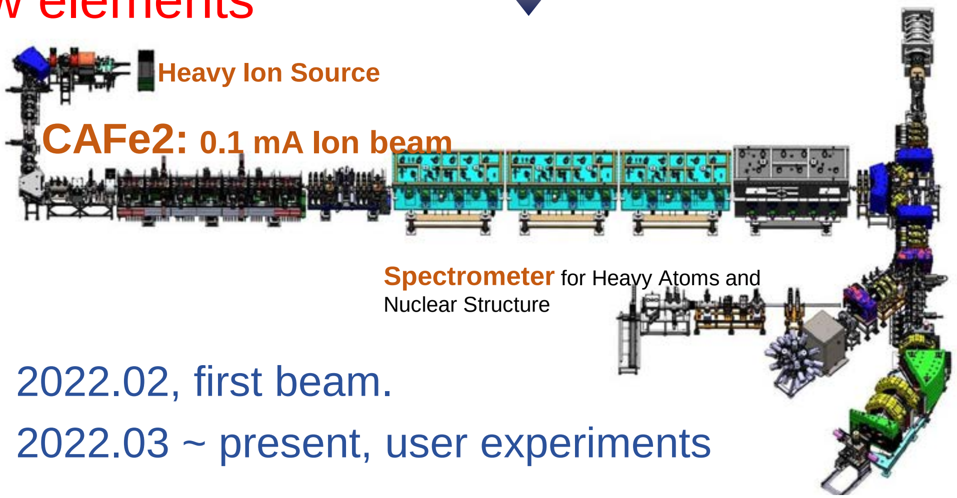
Four cryomodule, 23 SRF cavities
cavity bandwidth: 80 Hz~200 Hz, HWR_{010}+HWR_{015})



CAFe2: China Accelerator Facility for super-heavy new elements

Target:

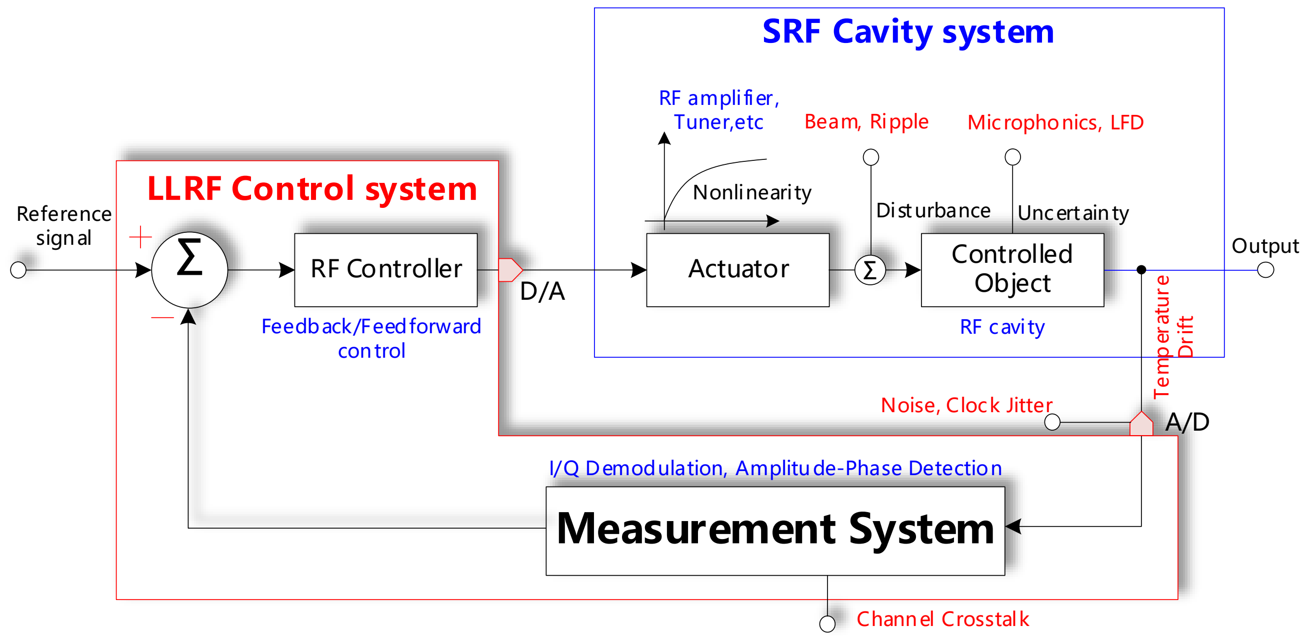
- Highest beam current accelerator for superheavy elements synthesis
- Engaging in research on the synthesis of the 119^{th} and 120^{th} element



- 2022.02, first beam.
- 2022.03 ~ present, user experiments

Introduction（cont'd)

- **Measurement** and **control** are the two core tasks of an RF control system (digital). **RF measurement** serves as the "**eyes**" of the RF system.



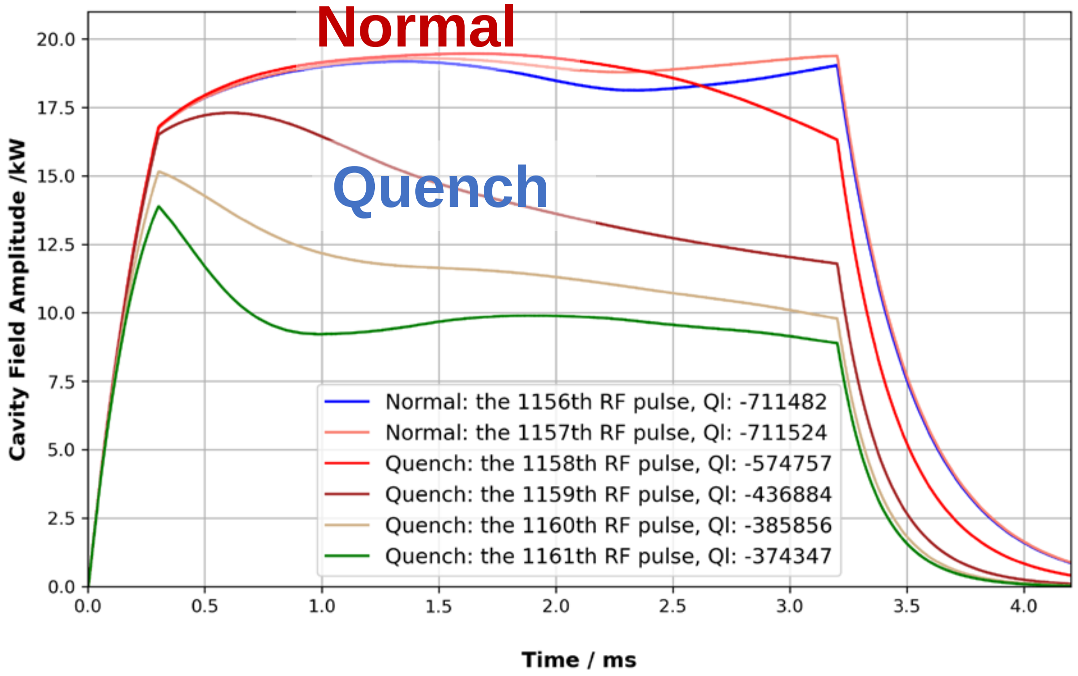
Challenges of RF Measurement

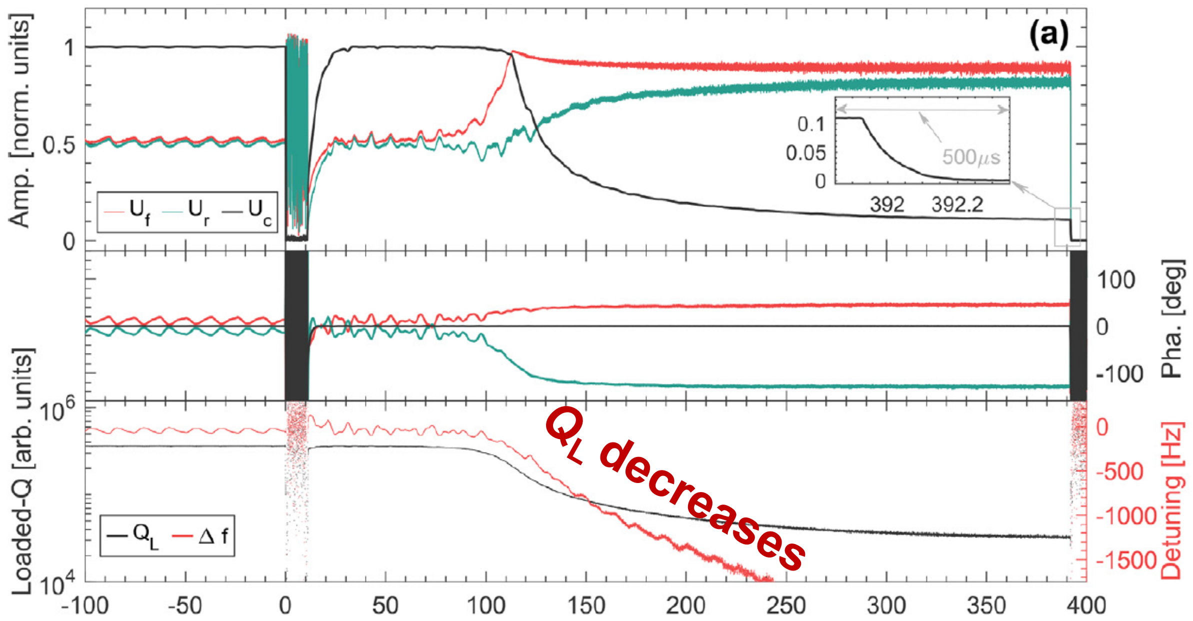
- **Mismatched source impedance:** The source and transmission line impedances are unequal
- **Interference Issues:** Multiple disturbance mechanisms coexisting.
- **Crosstalk Effect:** Coupling between measurement signals.

- Mitigating the impact of these factors is crucial for achieving high precision and accuracy
- RF measurement primarily focus on calibrating key cavity parameters and signals, including **loaded quality factor**, **cavity detuning**, channel crosstalk calibration, and LFD transfer function measurements.

Introduction（motivation）

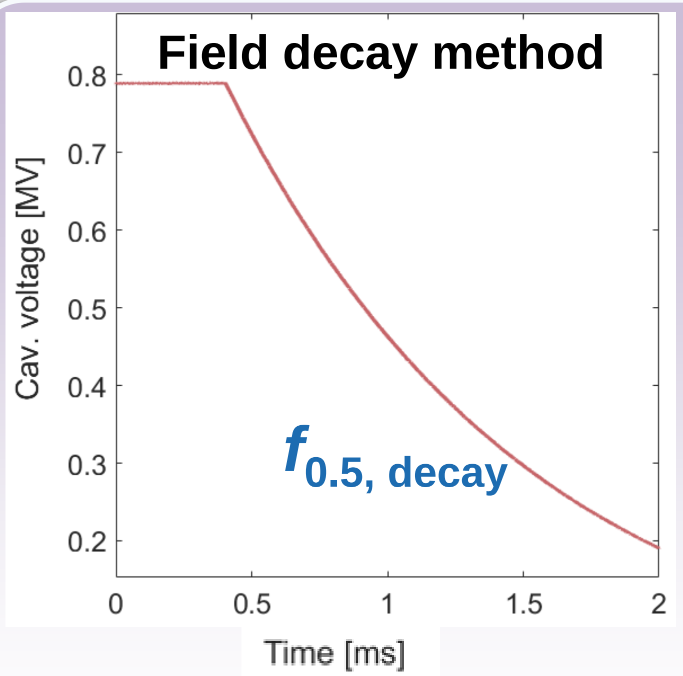
- Accurate measurement of cavity-loaded quality factor (Q_L) and detuning is crucial for monitoring performance of SRF cavities. Its reflects the consumption of the stored electromagnetic energy inside the cavity
  - **Quench** can cause the value of Q_L decreases, making it a key metric for detecting this fault
  - **Dark current loading** can negatively affect Q_L, making it an crucial parameter for identifying such effects
  - Q_L also plays a crucial role in the **design of model-based controllers**

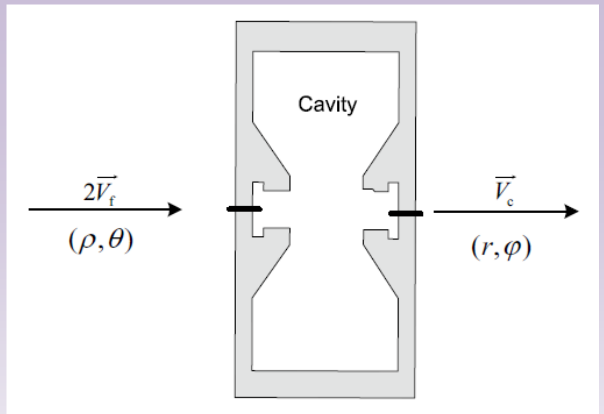




Introduction（motivation）

- **Traditional methods** for measuring Q_L
  - **Field decay method:** The decay curves of the cavity amplitude contains information of $f_{0.5}$
  - **Network analyzer:** Measuring $f_{0.5}$ using the S_{21} parameter

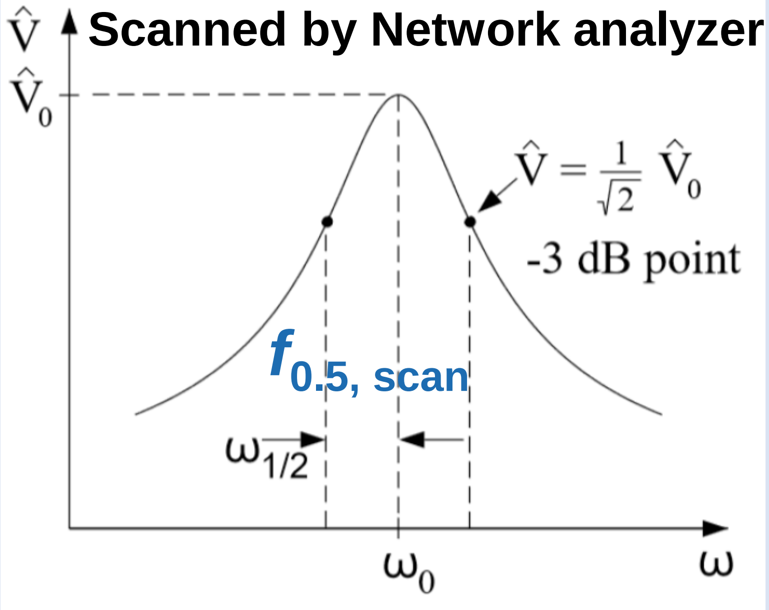




Conventional algorithm to calculate $f_{0.5}$

$$f_{0.5,\mathrm{decay}} = -\left(\frac{r'}{r}\right)\cdot\frac{1}{2\pi}$$

Traditional field decay method requires the cavity to satisfy a “zero-input" condition

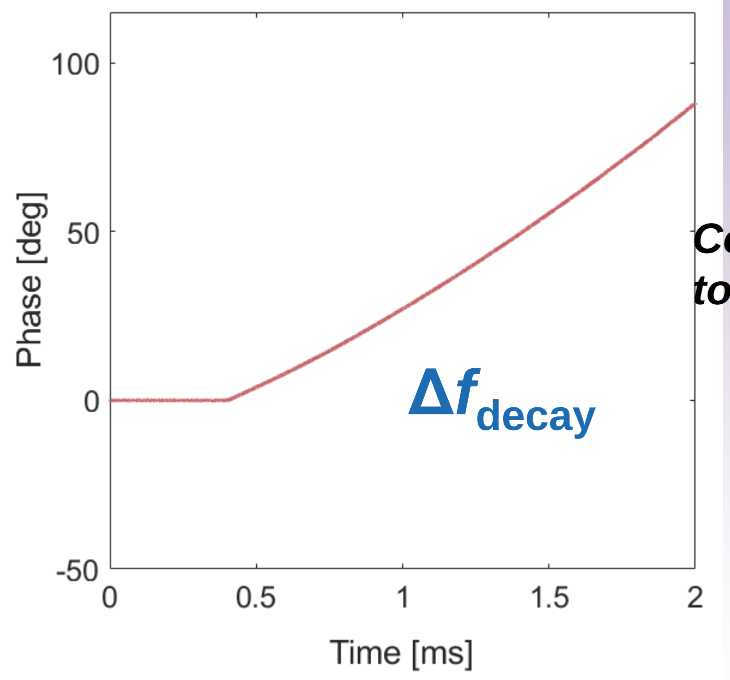


Measurement of the downtime for cavity

Introduction（motivation）

- **Traditional methods** for measuring Δ*f*
  - **Phase decay curve :** The decay curves of the cavity phase contains information of Δ*f*
  - The cavity detuning calculated from **V_c and V_f in the steady state**

Phase curve after power off

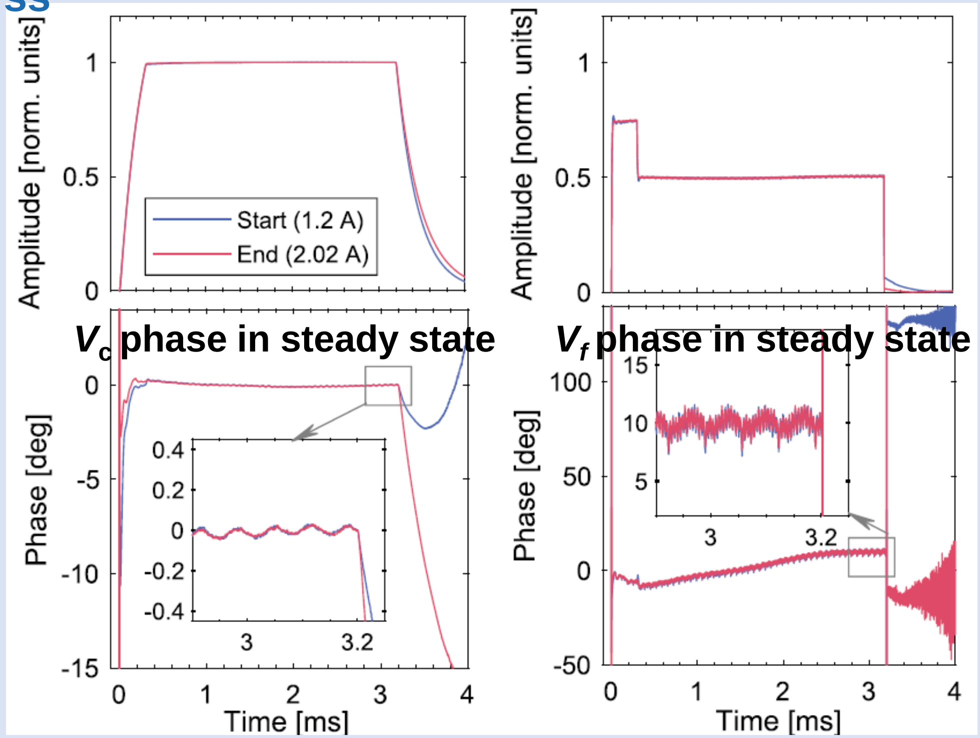


Conventional algorithm to calculate Δf

$$\Delta f_{\text{decay}} = \frac{\varphi'}{2\pi}$$

Need to considering impedance mismatched

Δf_{ss} ***Algorithm*** $\Delta f_{ss} = \tan(\varphi - \theta) \cdot f_{0.5,\text{cali}}$



The signals need to calibration

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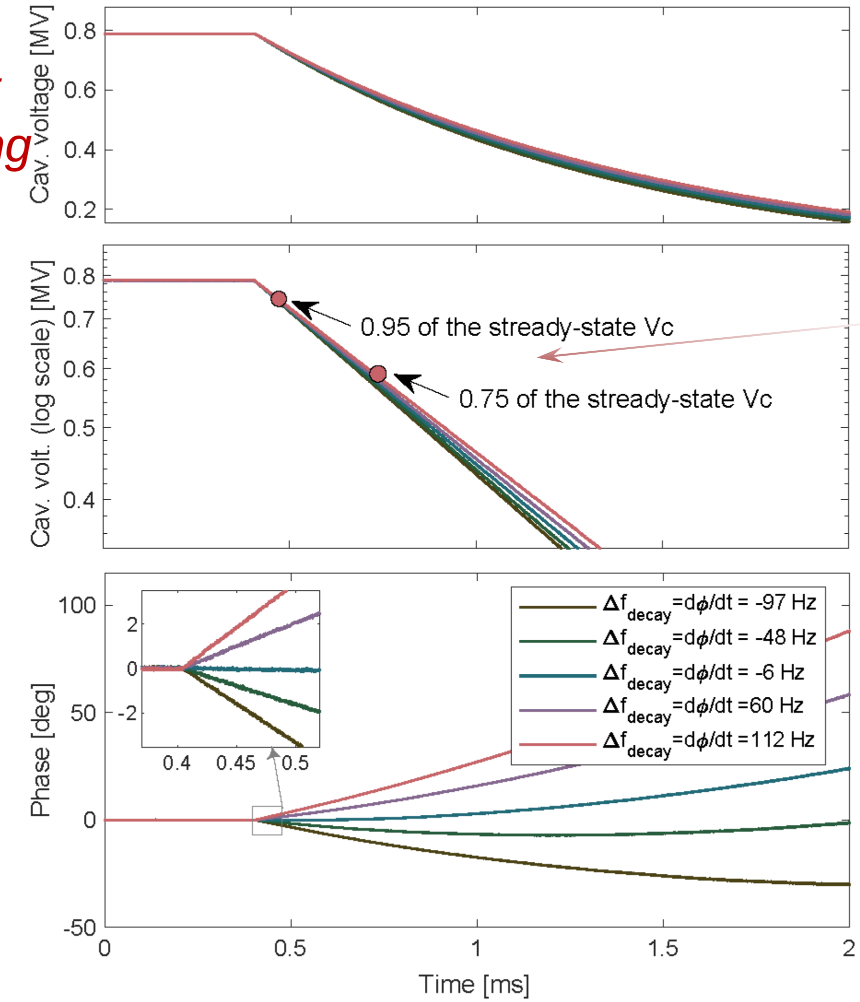
Phenomena and possible interpretation

- The field decay curves for the same cavity should overlap under different detuning conditions; however, they are influenced by the detuning parameter

The field decay curves do not overlap under varying detuning conditions

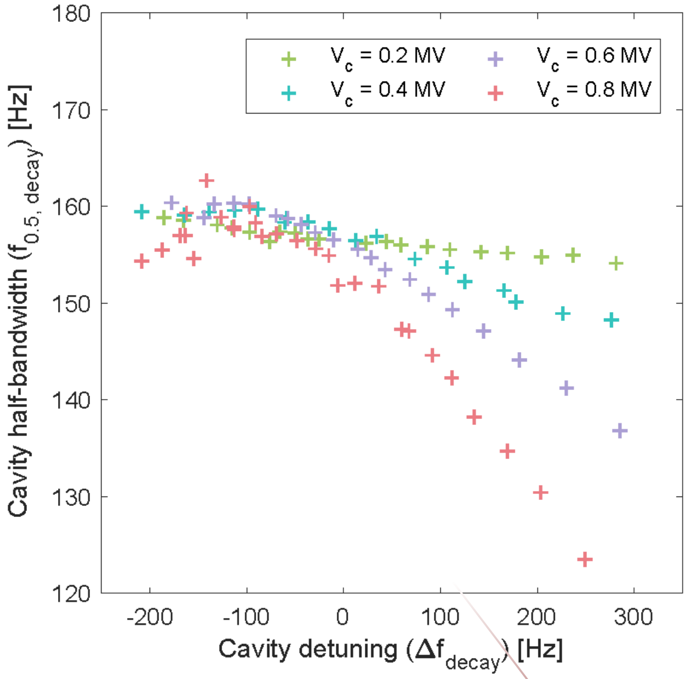


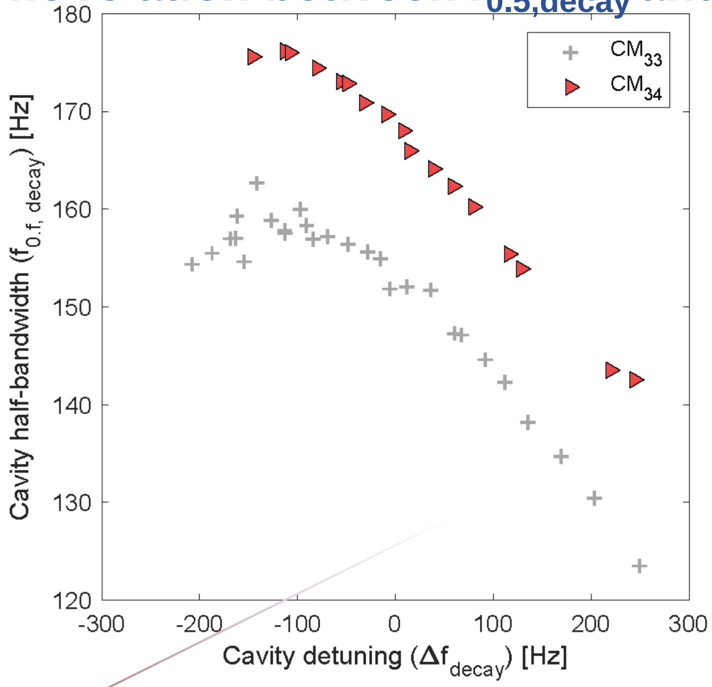
To ensure a sufficient signal-to-noise ratio, we determined $f_{0.5,decay}$ by calculating the slope of the decay curve between 0.95 and 0.75 of the steady-state V_c

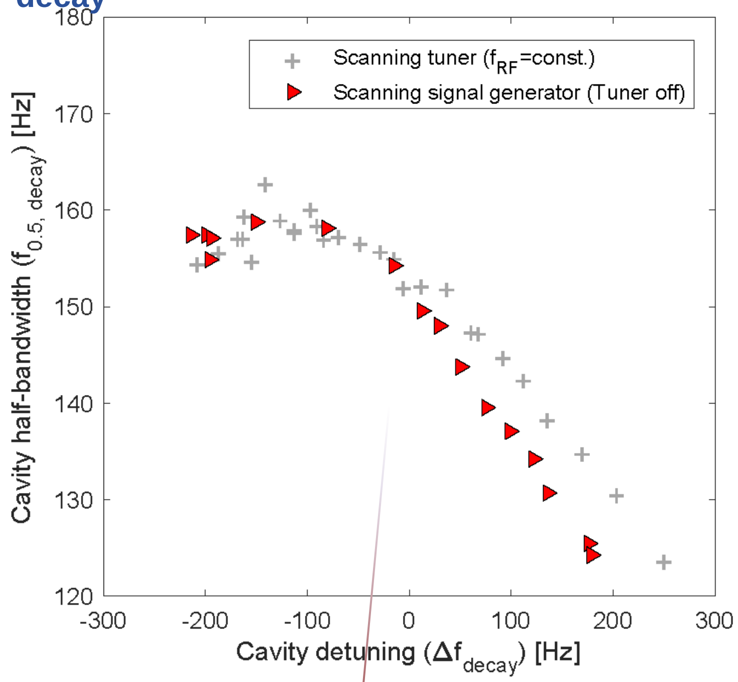
Phenomena and possible interpretation

- Calibrated $f_{0.5,decay}$ and Δf_{decay} with four different V_c values, all curves show ***dependencies*** between $f_{0.5,decay}$ and Δf_{decay}
- To eliminate the effect of tuner, we achieved the cavity detuning by the signal generator

The relation between $f_{0.5,decay}$ and Δf_{decay}





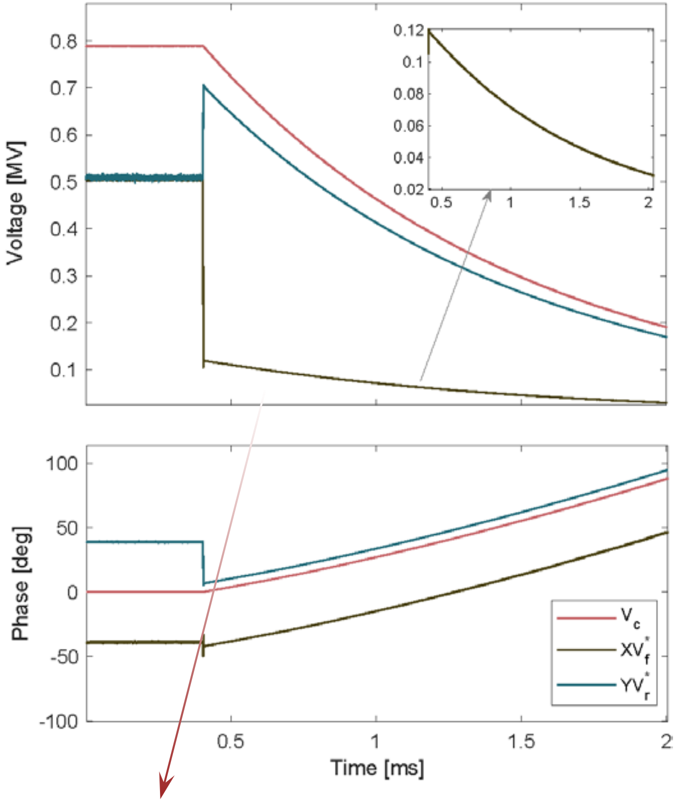


Vc is below the onset gradient of the field emission (approximately 1.2 MV)

Δf_{decay} is scanned by the signal source and tuner, respectively

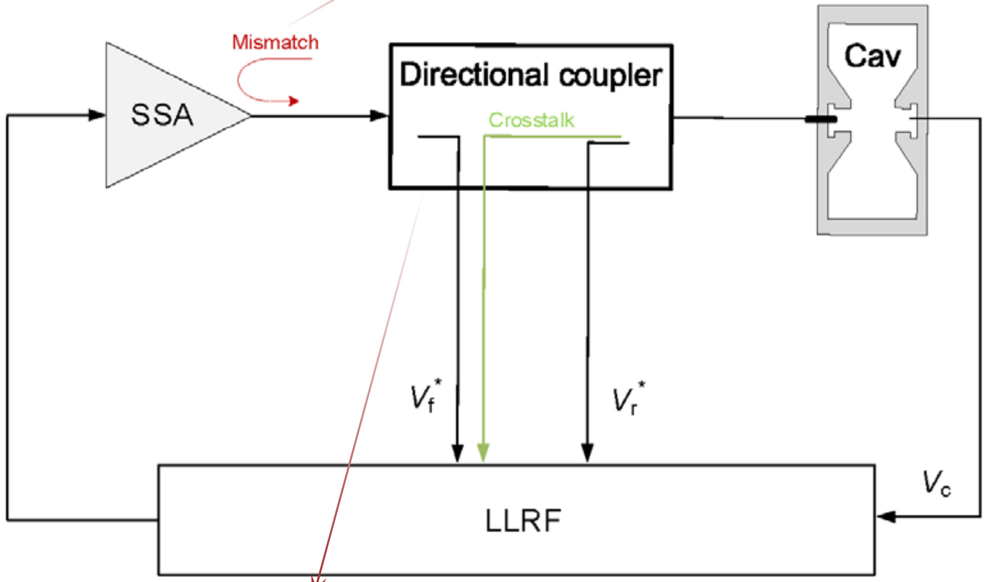
Phenomena and possible interpretation

- Residual attenuation signal of V_f is observed after turning off the RF power.
- Measurement accuracy of V_f signal is mainly affected by two factors:
  - Crosstalk between the meas. channels (e.g., dir. coupler)
  - Impedance mismatch of high-power RF components (RF source or Circulator)



Residual attenuation signal

May impact the field decay process and the measurement of V_f signal

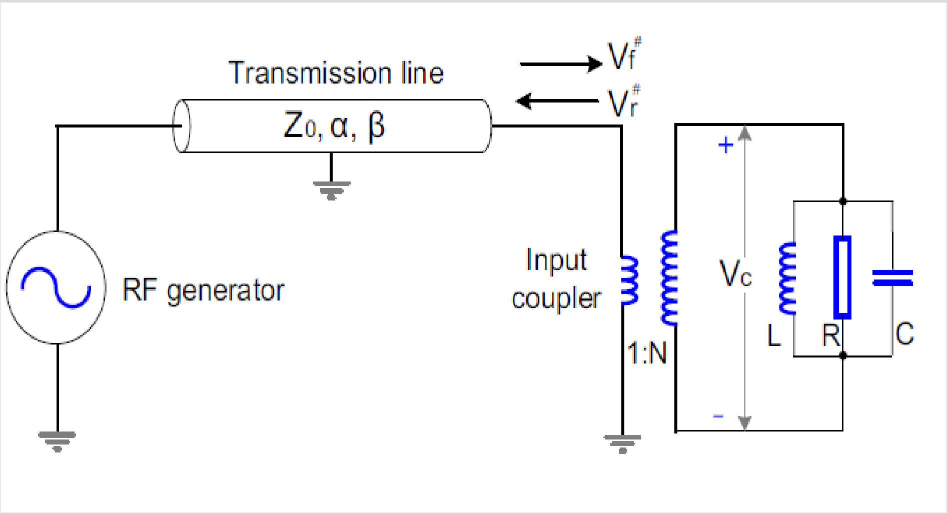


Directional coupler: 40 dB
The forward signal V_f has been calibrated

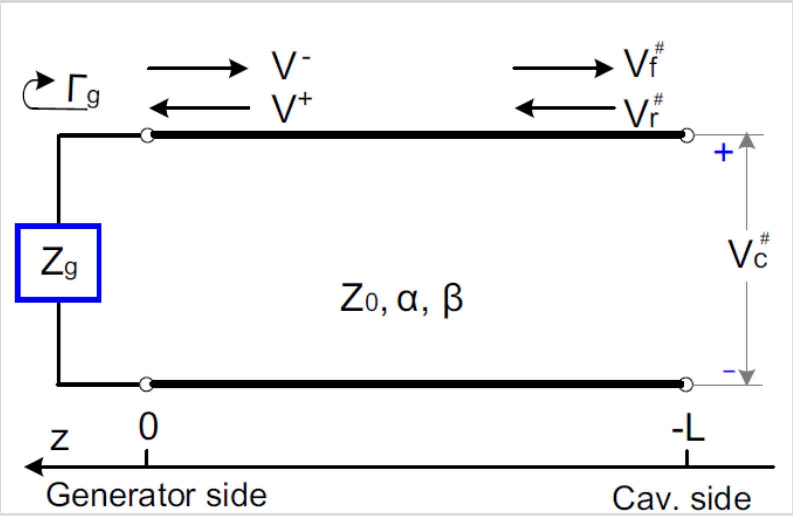
New calibration algorithm

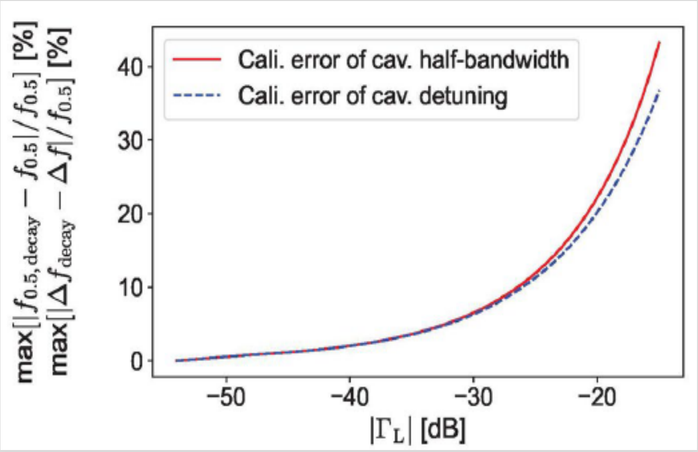
- We established cavity differential equations for mismatched source impedance and derived new formulas to calibrate half-bandwidth and detuning
- calibration error of $f_{0.5,decay}$ and Δf_{decay} increases with the reflection coefficient Γ_L.

Cavity & RF generator Model



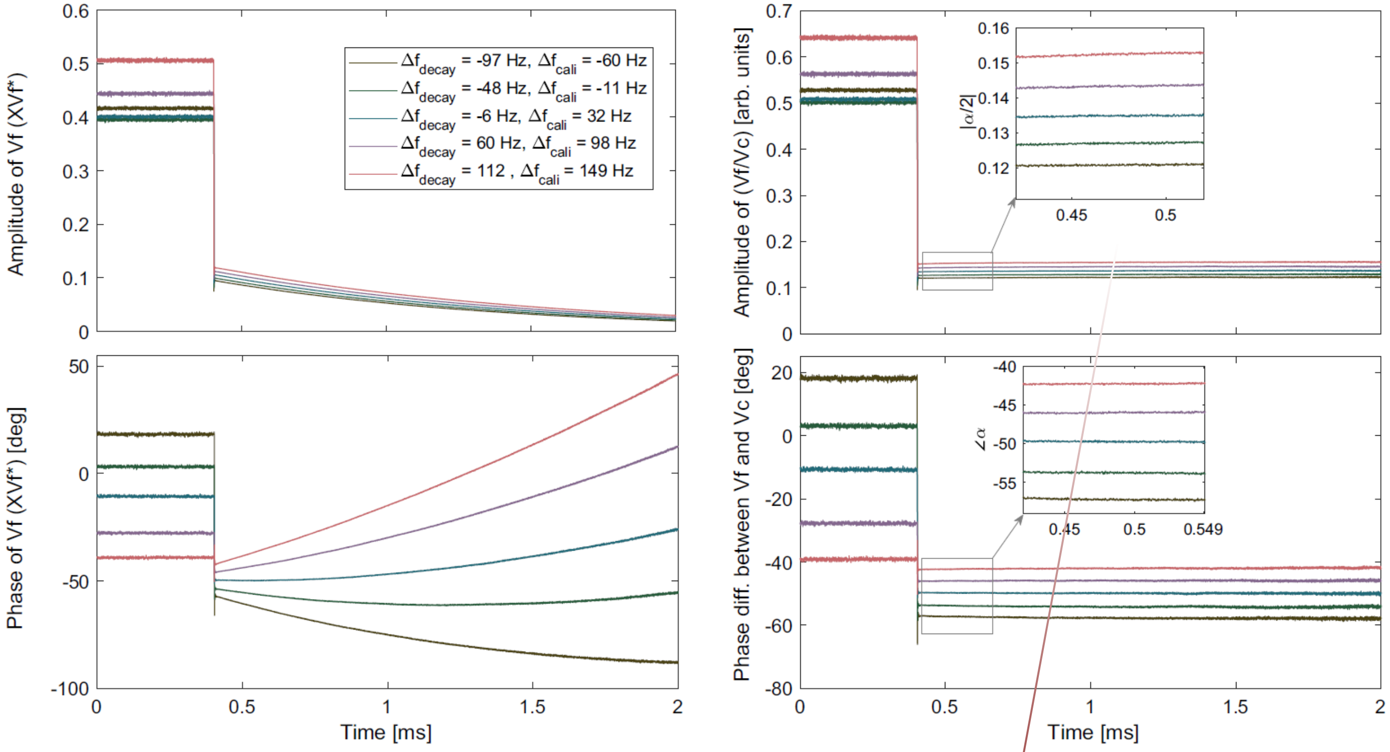
Equivalent circuit





New calibration algorithm

- The coefficient α is the critical factor in the new calibration algorithm;
- α is calculated as twice the ratio of V_f to V_c after turning off the RF power;
- Establish the cavity differential equations for the mismatched source impedance condition



Averaged over a time interval of 50 μs to reduce uncertainty.

Calculate the reflection coefficient Γ_L

$$\begin{cases} V_f = \dfrac{\Gamma_L}{1+\Gamma_L}\cdot V_c \\ \Gamma_L = \dfrac{V_f}{V_r} \end{cases} \quad (t \geq t_{off})$$

Calculate the calibration factor α

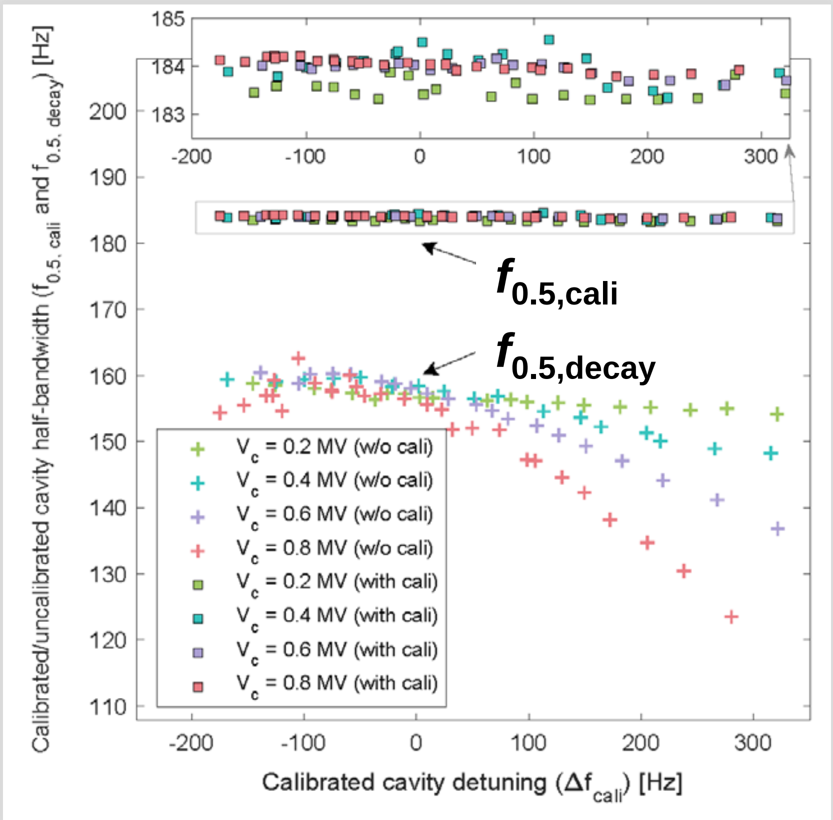
$$\alpha = \frac{2\Gamma_L}{1+\Gamma_L}$$

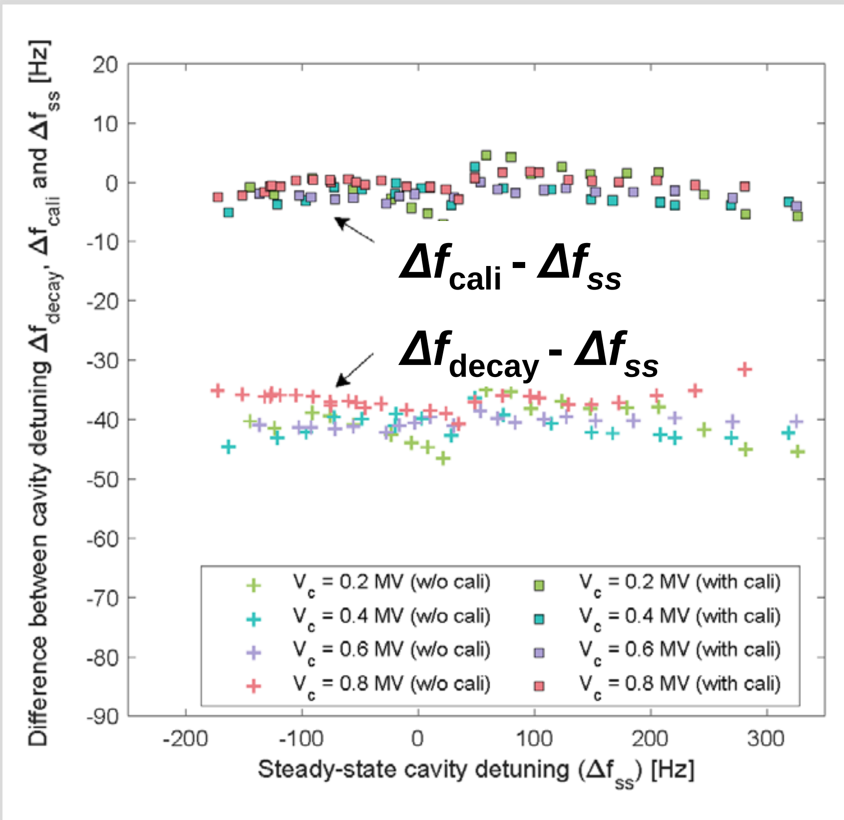
New calibration algorithm

$$\begin{cases} f_{0.5,cali} = \dfrac{f_{0.5,decay}}{1-\alpha_r} = \dfrac{f_{0.5,decay}}{1-\Re\left(\dfrac{2\Gamma_L}{1+\Gamma_L}\right)} \\ \Delta f_{cali} = \Delta f_{decay} - \alpha_i f_{0.5,cali} = \Delta f_{decay} - \Im\left(\dfrac{2\Gamma_L}{1+\Gamma_L}\right)\cdot f_{0.5,cali} \end{cases}$$

Experimental verification-CAFe2

- In contrast to the strong correlation between $f_{0.5,decay}$ and Δf_{decay}, the calibrated $f_{0.5,cali}$ was independent of Δf_{cali} at different V_c values
- The discrepancy between Δf_{cali} and Δf_{ss} is less than ±5 Hz, while there is an offset about 40 Hz between Δf_{decay} and Δf_{ss}.

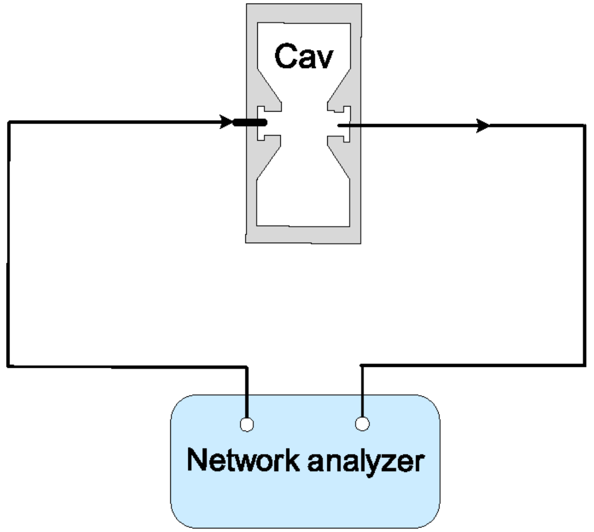


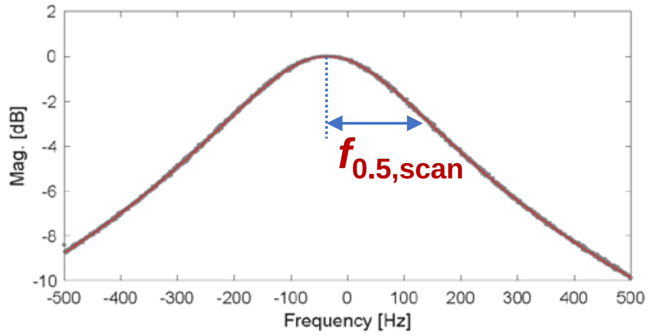


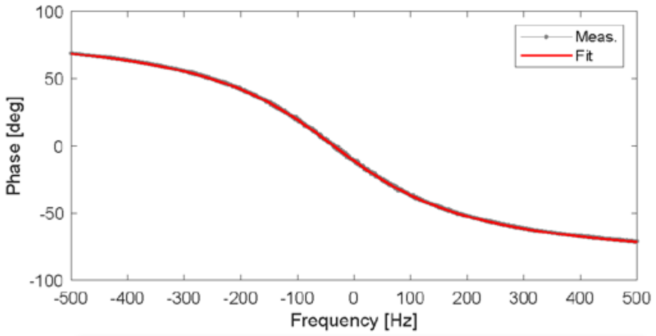
Experimental verification-CAFe2

- We utilized a network analyzer to scan the cavities in CAFe2 and estimated $f_{0.5,scan}$ by curve fitting
- The deviation between $f_{0.5,scan}$ and $f_{0.5,cali}$ was maintained roughly within ±2% → ***Further validated***

Measurement block diagram based on the network analyzer



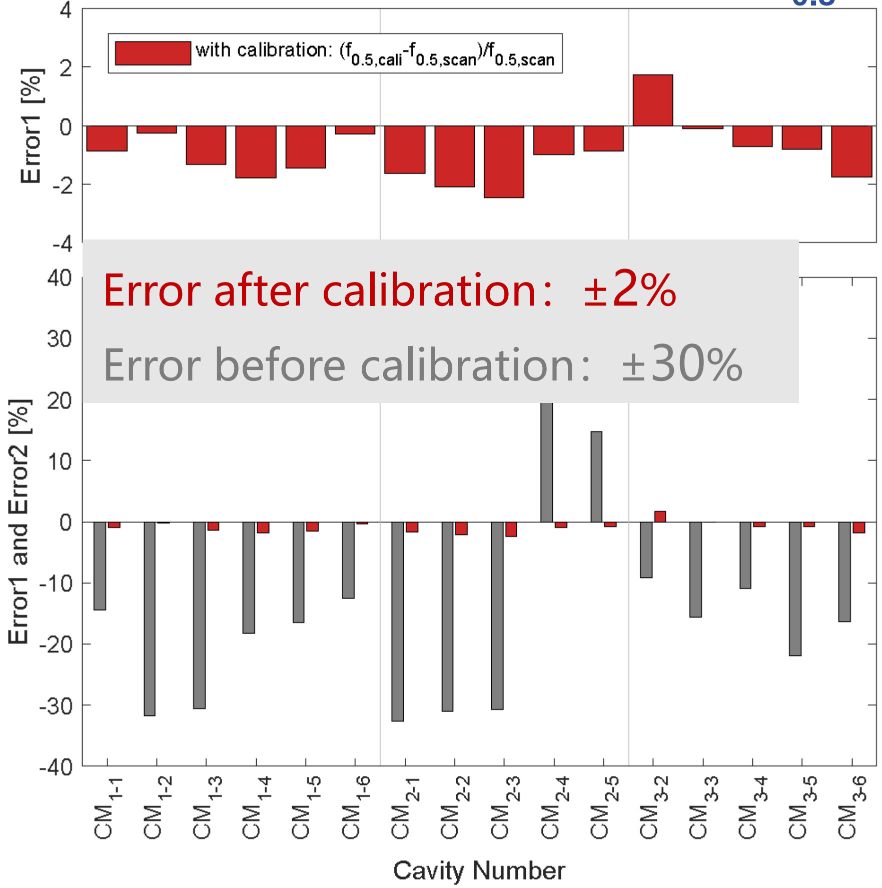




Fitted formula

$$A_{fit} = \frac{A_{max} \cdot f_{0.5}}{\sqrt{(f - f_{offset})^2 + f_{0.5}^2}}$$

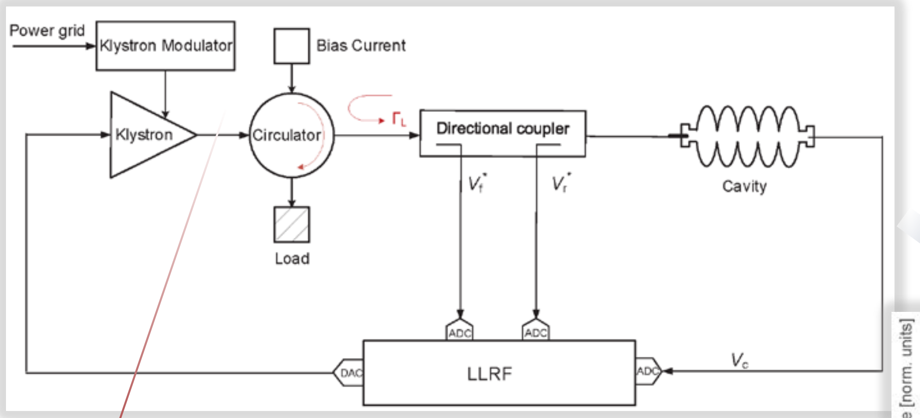
Pre-calibrated vs. calibrated $f_{0.5}$

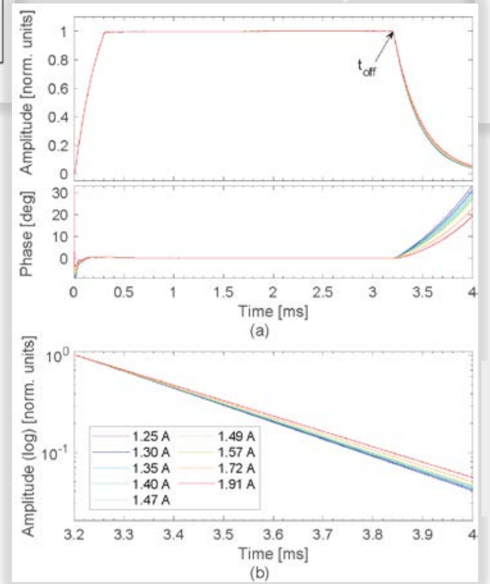


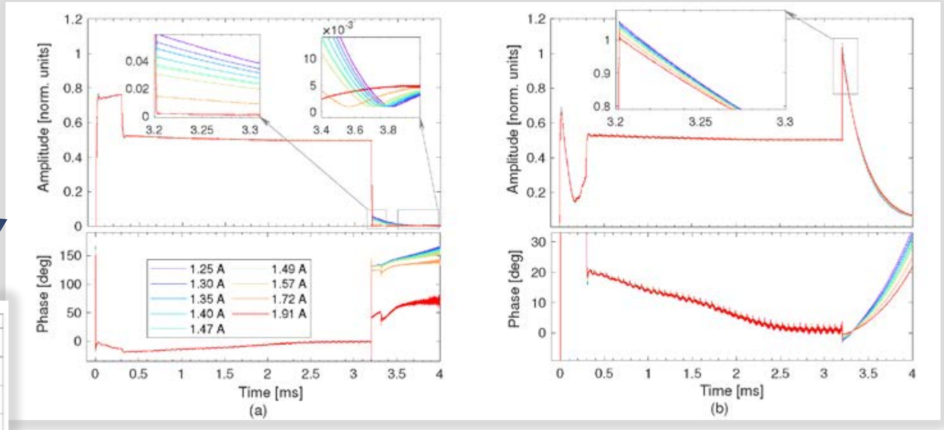
Experimental verification-TS2

- We applied the proposed algorithm to measure Q_L at the ESS TS2 facility
- The ESS TS2 facility is equipped with a high-power circulator, for which Γ_L is adjustable, providing flexibility in designing experiments to confirm the algorithm.

Impedance mismatch results in a residual V_f signal for various bias currents





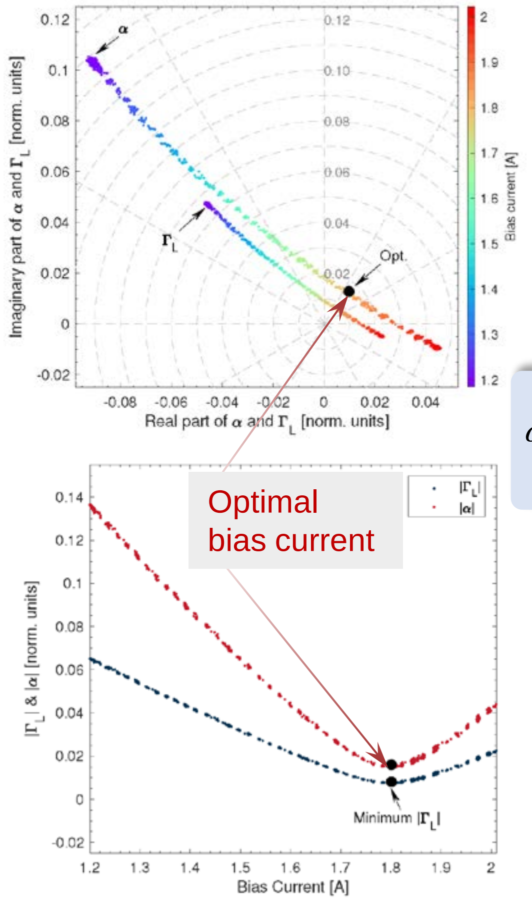


Adjusting the bias current modulates the circulator's electromagnetic response, resulting in impedance mismatched

The field-decay curves for different values of the bias currents (or Γ_L) did not overlap after the RF power was turned off

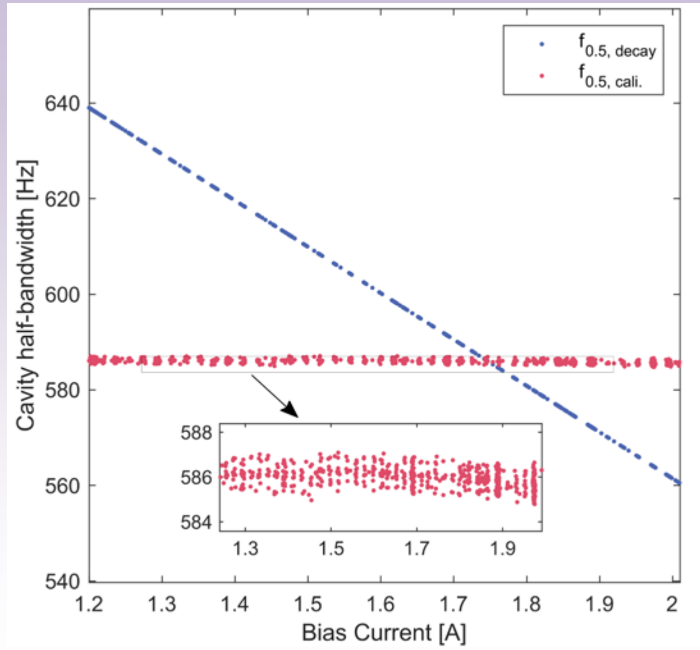
Experimental verification-TS2

- Operating the circulator at optimal bias current, the impedance mismatch effect becomes negligible. Under this conditions, the original field-decay method can be employed to calculate Q_L
- The calibrated value $f_{0.5,cali}$ and Δf_{cali} no longer depends on Γ_L $\rightarrow$ ***Further validated***

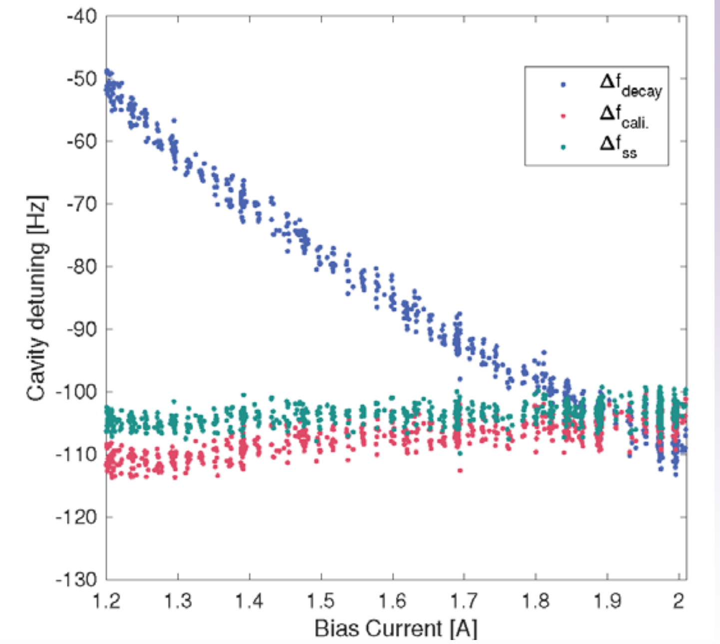


$$\alpha = \frac{2\Gamma_L}{1+\Gamma_L}$$

Pre-calibrated vs. calibrated $f_{0.5}$



Pre-calibrated vs. calibrated Δf



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Summary

- After the RF power was turned off, the residual signal (V_f) caused by source impedance mismatch could affect the field decay process, causing measurement errors for $f_{0.5}$ and Δf
- We proposed approach enables the precise calibration of these two parameters under mismatch conditions.
  1. Calibrating the actual forward and reflected signals
  2. Determining the calibrating factor
  3. Calibrating $f_{0.5}$ and Δf using the traditional field decay method
  4. Calibrating $f_{0.5}$ and Δf using the proposed formula
- The accuracy of the calibration algorithm has been validated on the cavities of CAFe2 and TS2 facilities.

Thanks for your attention

Backup

- Comparison of V_c, V_f and V_r signals demonstrates good consistency between the cavity model and the real SC cavity.
- Reflected the reflection coefficient is not zero

The cavity phase curves ***overlap*** in the first 80 μs after the RF power is turned off, regardless of whether the LFD is included. Consequently, we use the 80 μs cavity phase data to obtain the cavity detuning.