Measurement of the cavity-loaded quality factor in SC radio-frequency systems with mismatched source impedance

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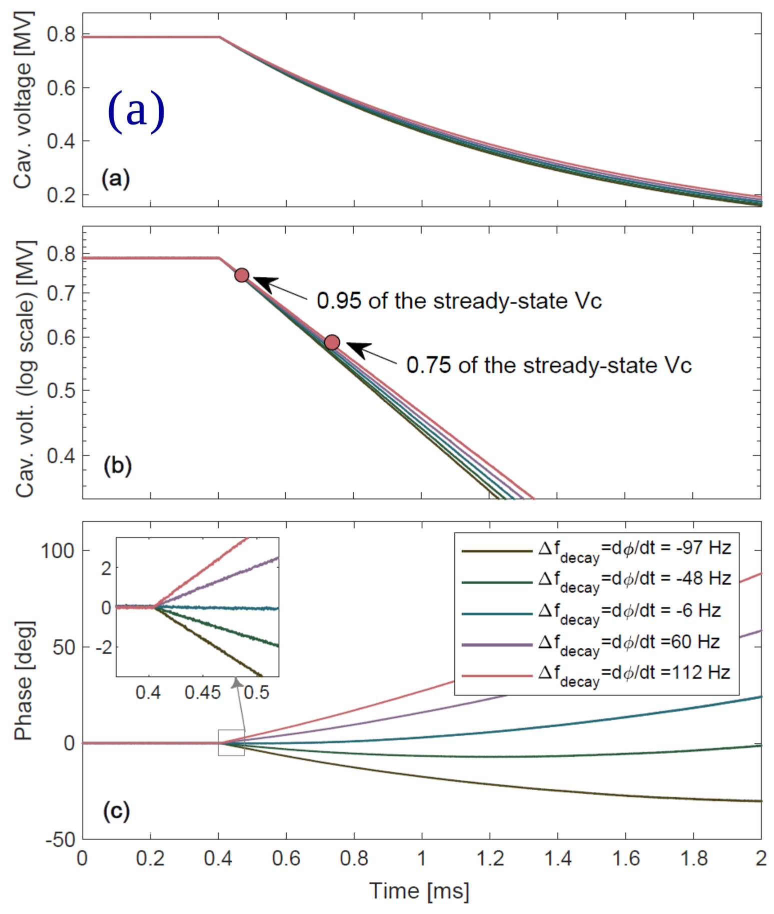
Abstract

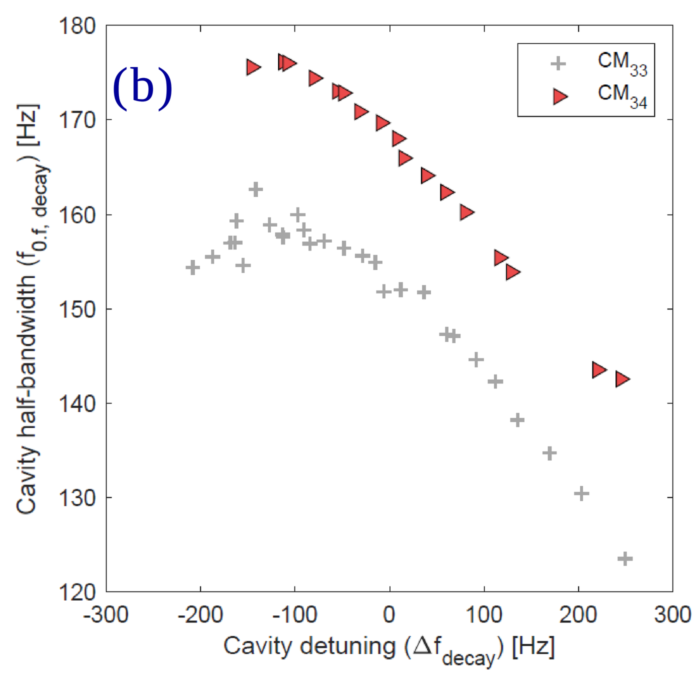
The accurate measurement of parameters such as the cavity-loaded quality factor (Q_L) and half bandwidth ($f_{0.5}$) is essential for monitoring the performance of superconducting radio-frequency cavities. However, the conventional "field decay method" employed to calibrate these values requires the cavity to satisfy a "zero-input" condition. This can be challenging when the source impedance is mismatched and produce nonzero forward signals (V_f) that significantly affect the measurement accuracy. To address this limitation, we developed a modified version of the "field decay method" based on the cavity differential equation. The proposed approach enables the precise calibration of $f_{0.5}$ even under mismatch conditions. We tested the proposed approach on the SRF cavities of the Chinese Accelerator-Driven System Front-End Demo Superconducting Linac and compared the results with those obtained from a network analyzer. The two sets of results were consistent, indicating the usefulness of the proposed approach.

Phenomena and Possible interpretation

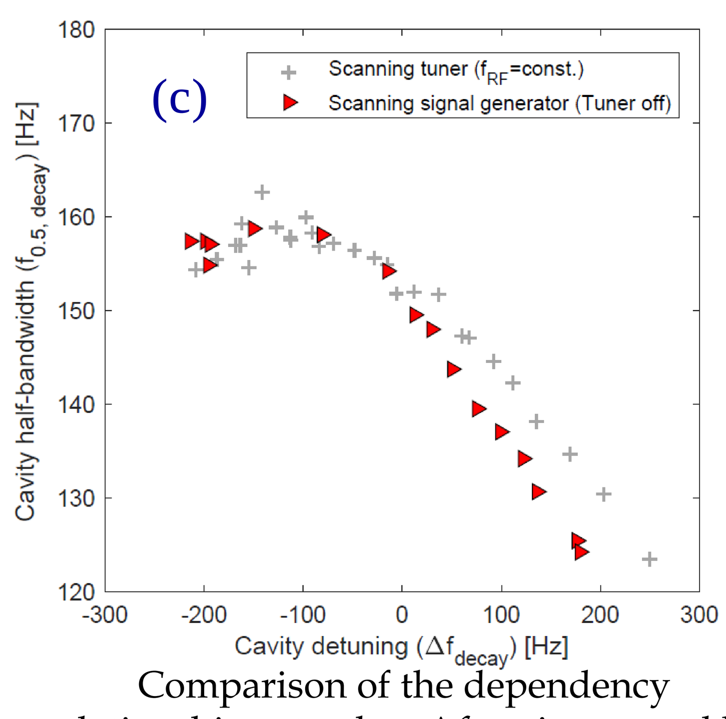
- After the RF power was turned off, the field decay curves did not overlap under different detuning conditions and appeared to be affected by the detuning parameter (see Fig. (a)).
- Cavity half-bandwidth calculated using the amplitude decay curve (i.e., $f_{0.5,decay}$) and the cavity detuning parameter calculated using the phase decay curve (i.e., Δf_{decay}) appeared to be correlated(see Fig. (b)).
- Achieved the cavity detuning by a signal generator instead of the tuner and the same tendency was observed in one cavity (see Fig. (c)).



Cavity amplitude and phase decay curves after the RF power is turned off for various Δf on a cavity

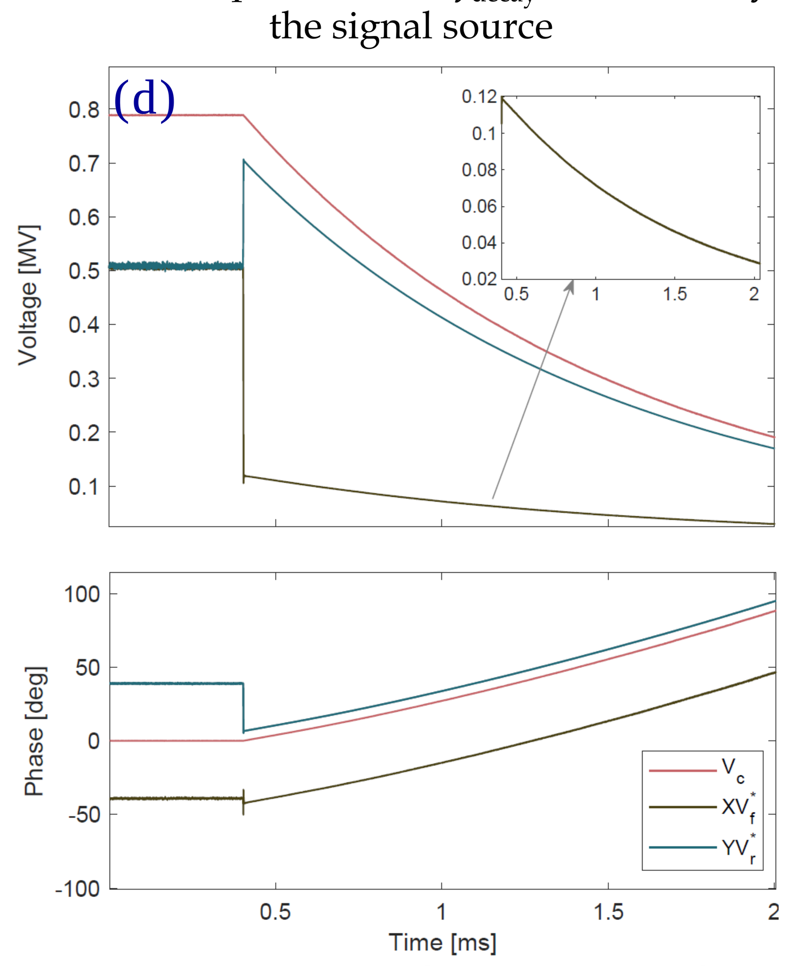


$f_{0.5,decay}$ and Δf_{decay} have dependency relations on cavity CM_{3-3} and CM_{3-4}



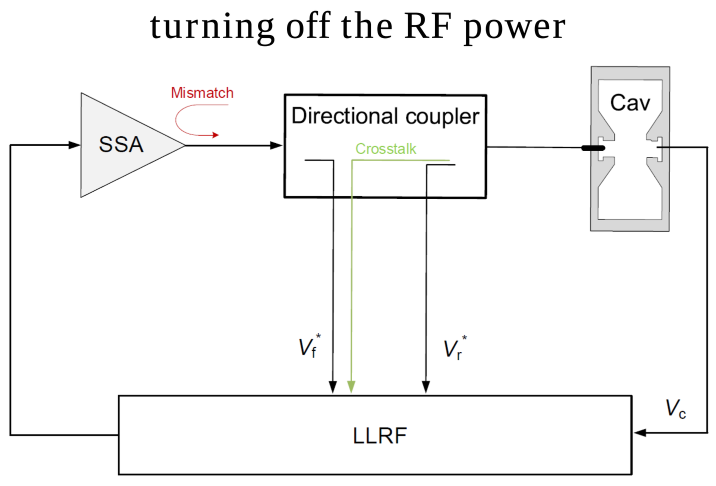
Comparison of the dependency relationships at when Δf_{decay} is scanned by the signal source

- A residual attenuation signal of V_f is observed after turning off the RF power (see Fig. (d)). Two possible reasons for this:
  - I. The crosstalk between the measurement channels, that is, the residual signal of V_f is coupled with the signal V_r.
  - II. The second reason is: source impedance mismatch, where the V_r signal is reflected from the generator side and mixed with the V_f signal.



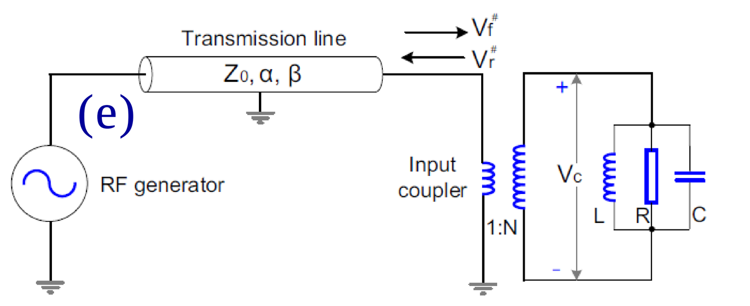
Voltage and phase of cavity signals after turning off the RF power

- The residual V_f signal could be attributed to impedance mismatch (CAFe directional coupler with high directivity (40 dB) while not installing a high-power circulator).

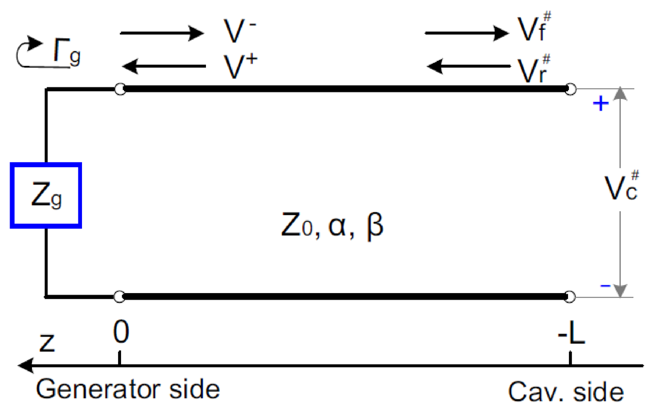


Two causes of $V_f \neq 0$ (RF off): crosstalk between the measurement channels and source impedance mismatch

Theory and algorthim



Simplified model of a cavity coupled to an RF generator by a rigid coaxial line and an RF input power coupler.



Equivalent circuit diagram of (e) after the RF power is turned off.

Before calibration, $f_{0.5}$ and Δf can be expressed as:

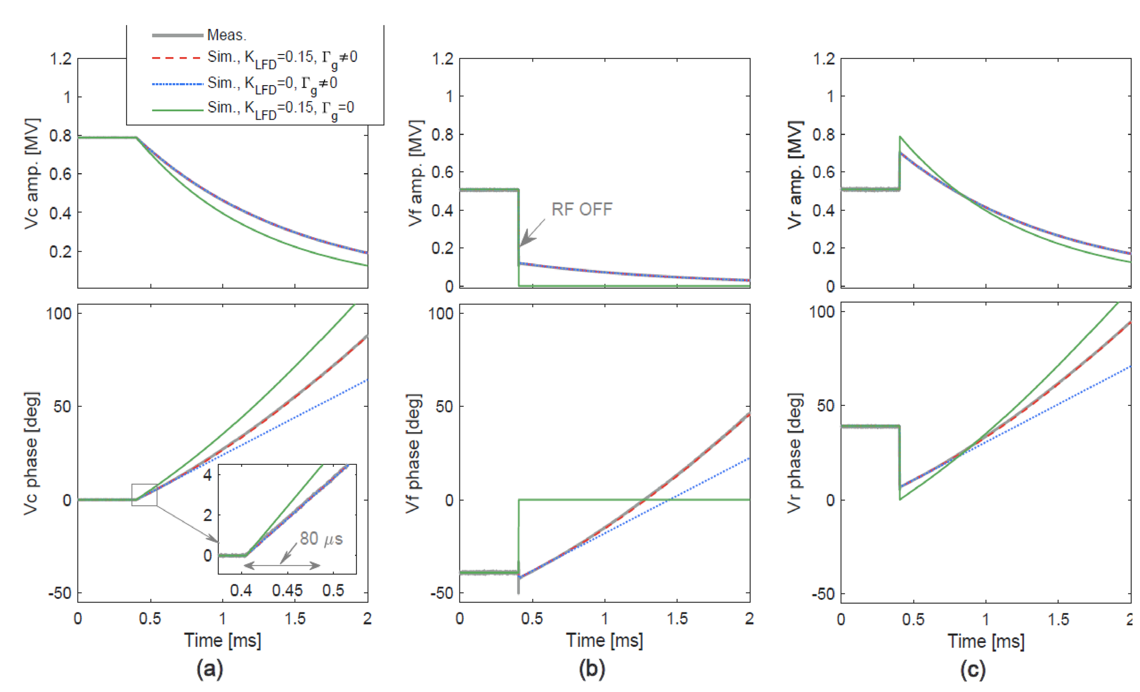
$$\begin{cases} f_{0.5,decay} = -\left(\frac{r'}{r}\right)\cdot\frac{1}{2\pi} \\ \Delta f_{decay} = \frac{\varphi'}{2\pi} \end{cases}$$

After calibration, $f_{0.5}$ and Δf can be expressed as:

$$\begin{cases} f_{0.5,cali} = \frac{1}{2\pi}\cdot\frac{-r'/r}{1-\alpha_r} = \frac{f_{0.5,decay}}{1-\alpha_r} \\ \Delta f_{cali} = \frac{1}{2\pi}\varphi' - \alpha_i f_{0.5,cali} = \Delta f_{decay} - \alpha_i f_{0.5,cali} \\ \Gamma_L = \Gamma_g e^{-2(\alpha+i\beta)L} \\ \alpha = \frac{2\Gamma_L}{1+\Gamma_L} \end{cases}$$

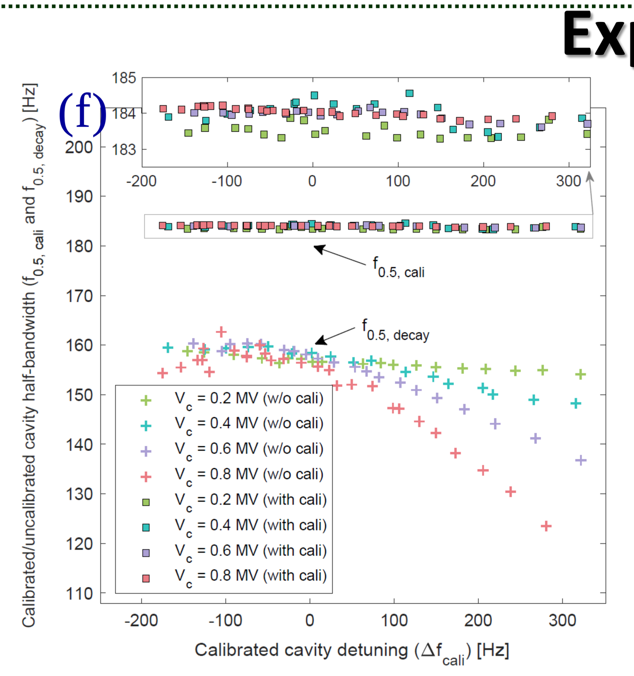
Modeling and simulation

- The simulation and measurement results are coincident when considering LFD and impedance mismatch.
- Cavity phase curves overlap in the first 80 µs after the RF power is turned off, thus, we fit the 80 µs cavity phase data to obtain Δf.

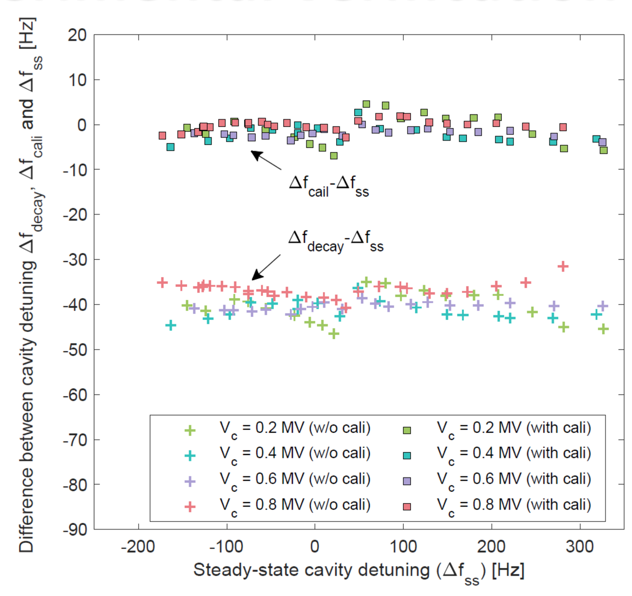


Comparison of the cavity voltage (a), cavity forward (b), and reflected signal (c) measurements based on the cavity model (red) and real SC cavity (gray)

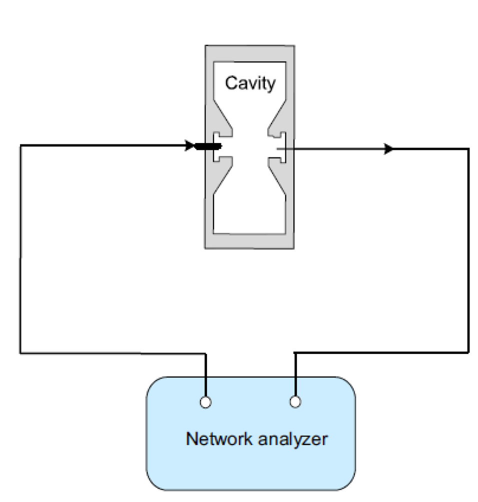
Experimental verification



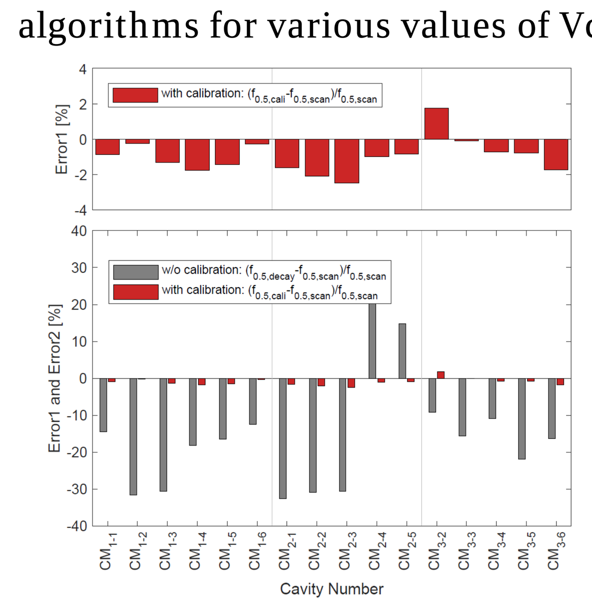
Relationship between the cavity half bandwidth and cavity detuning parameter in the calibrated and uncalibrated algorithms for various values of Vc .



Comparison of the results of Δf_{decay} and Δf_{cali} measurements with the cavity detuning value obtained in the steady state. Measurement block diagram based on the network analyzer.



Measurement block diagram based on the network analyzer.



Comparison of the deviation between $f_{0.5,decay}$ and $f_{0.5,cali}$ for the 16 cavities and the network analyzer measurement results, $f_{0.5,scan}$

- the new calibrated value of $f_{0.5,cali}$ was not independent of Δf_{cali} at different V_c levels (see Fig. (f)).
- The deviation between $f_{0.5,scan}$ and $f_{0.5,cali}$ was maintained roughly within ±2% , indicating that the proposed calibration algorithm accurately estimated the values of $f_{0.5}$