The 13th International Beam Instrumentation Conference (IBIC2024)

On-line beam synchronous phase calibration using beam-induced RF signals

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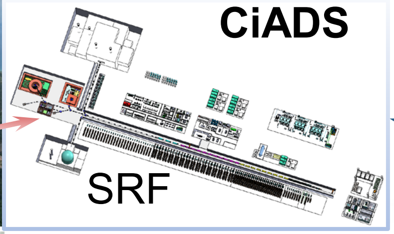
Joint effort between IMP & ESS

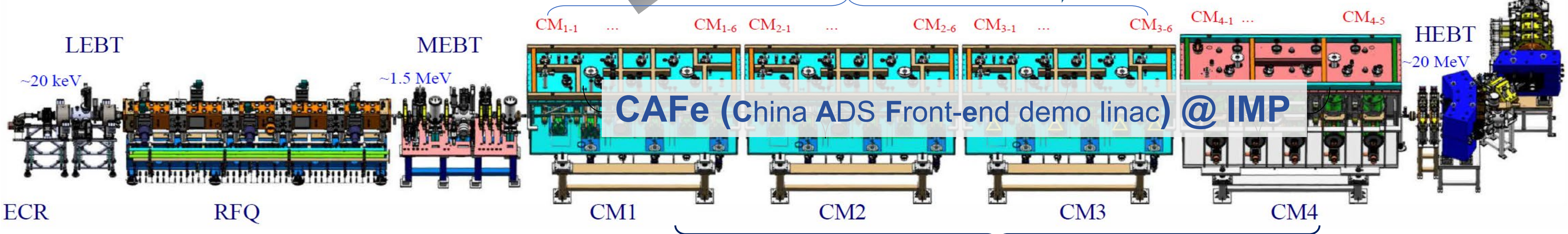
CONTENTS

Introduction (CAFe)

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

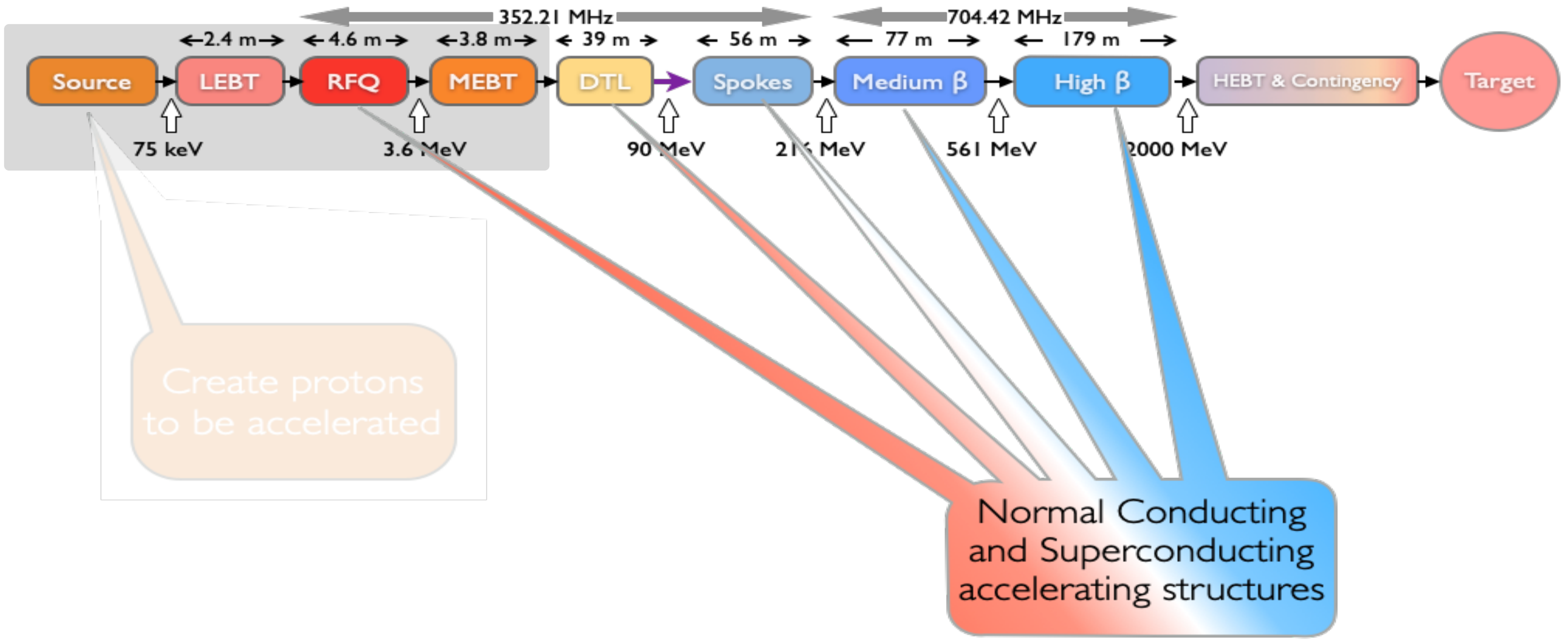




Four Cryomodules, 23 SRF Cavities, Cavity Bandwidth: 80 Hz~200 Hz, HWR_{010}+HWR_{015})

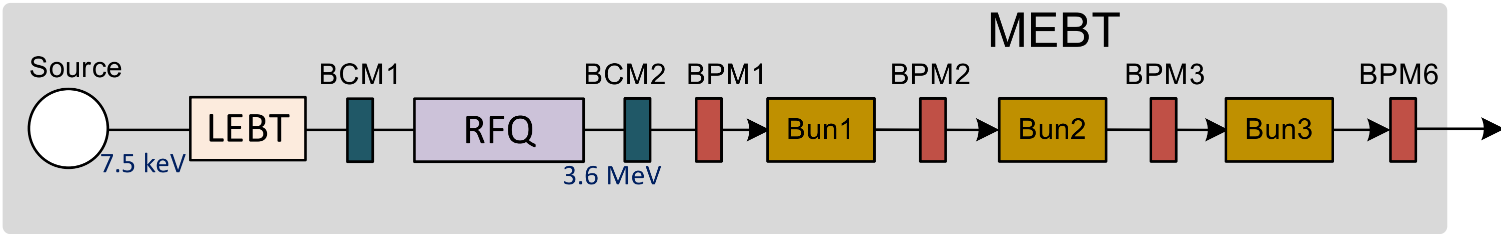
Introduction (ESS)

European Spallation Source (ESS) Layout



Ion Species	Protons	
Output Energy	2	GeV
Frequency	352.21/704.42	MHz
Pulse Length	2.86	Ms
Peak Current	62.5	mA
Protons per Pulse	1.1 x 10^{15}	
Repetition Rate	14	Hz
Duty Cycle	4	%
Average Beam Power	5	MW
Accelerating Structures	RFQ, DTL, SC Spokes/Elliptical	
Accelerator Length	~365	m

The normal-Temperature Front End



	Buncher1	Buncher2	Buncher3
R/Q[Ω]	73.85	76.7	76.9
Q_L[arb.units]	8878	8893	9470
$f_{0.5}$[kHz]	19.83	19.80	18.6
f_{RF}[MHz]	352.21	352.21	352.21
β(v=c) [arb.units]	1.03	1.02	1.06

Introduction (Motivation)

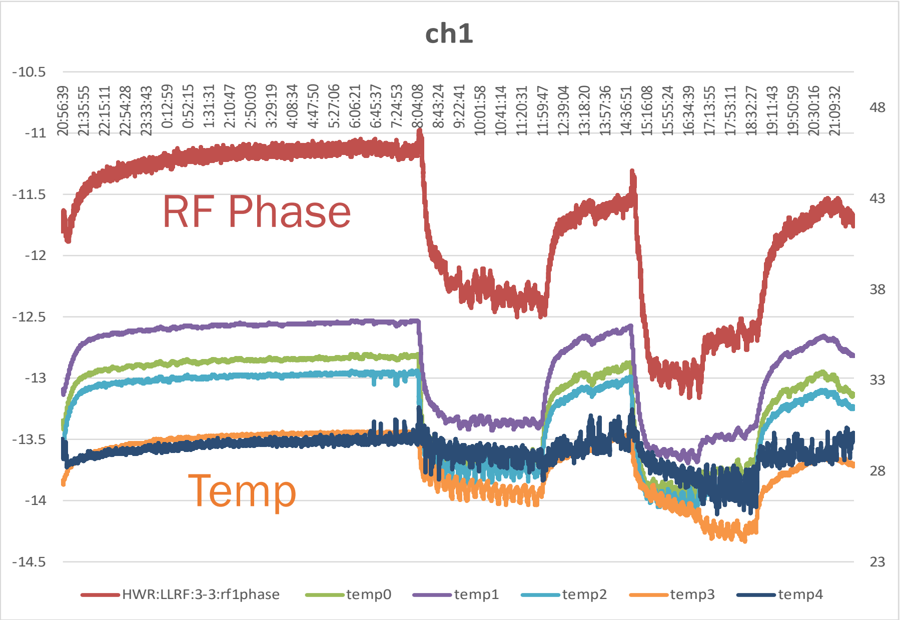
Limitations of Traditional Phase scan Methods

synchronous phase and its measurements

- To maximize the energy gain, the particle must enter the cavity at a specific point in the RF field's oscillation, which corresponds to the synchronous phase (φ_b) .

$$V_{acc} = V_c \cdot \cos(\varphi_b)$$

- The measurement of the synchronous phase is performed by the BPM using the "phase-scan" method.



Phase drift caused by temperature changes @ CAFe

Limitations

1. **Impact on Operations**: Takes up machine operation time due to its off-line nature, usually time-consuming
2. **Phase Drift:** hard to track phase drift caused by environmental factors

Introduction (Motivation)

Our proposed solution: on-line beam measurement

- It can address the challenges of traditional BPM based phase scan method to determine beam phase and beam current.
- It can provide continuous beam phase monitoring and online beam information during accelerator operation. It can solve two major problems in accelerator operation:

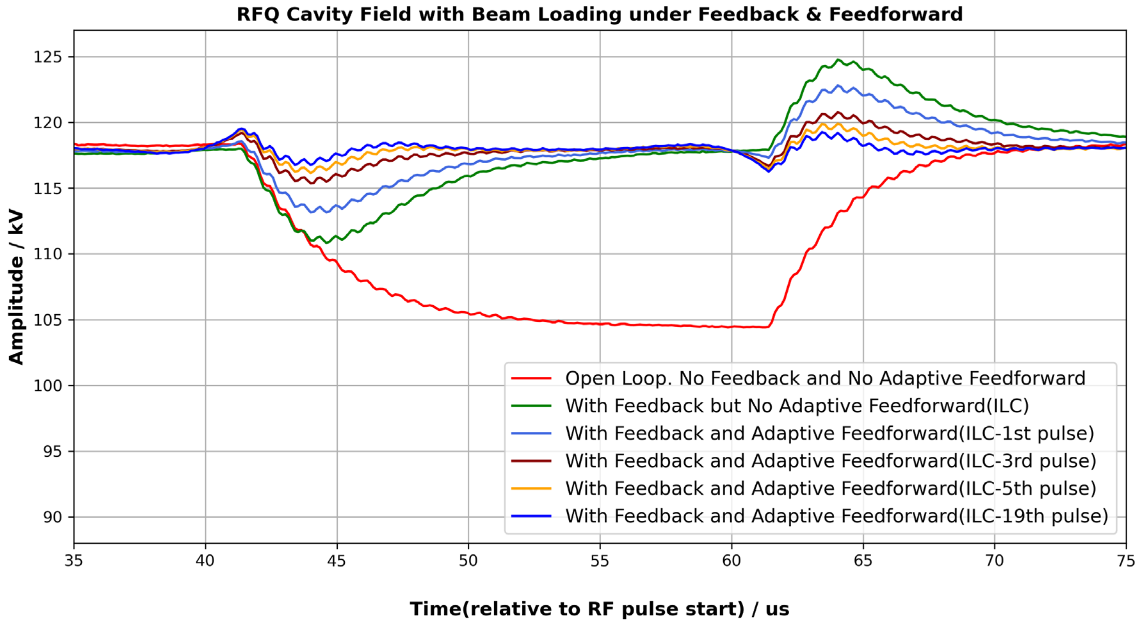
1. Beam Loading and its compensation
2. Beam Trip and Its Recovery

Introduction (Motivation)

On-line measurement during operation:

■ Beam Loading and its compensation

- Beam loading is very hard to fully compensate in normal conducting linac, which affects both beam transmission, and beam phase (more than 10 deg beam phase changes observed when beam compensation feedorward is not on (feedback only) for RFQ)
- Static feedforward is necessary, but knowing beam information in real time (beam current, beam on/off status) is hard



The beam loading of 59mA in ESS RFQ

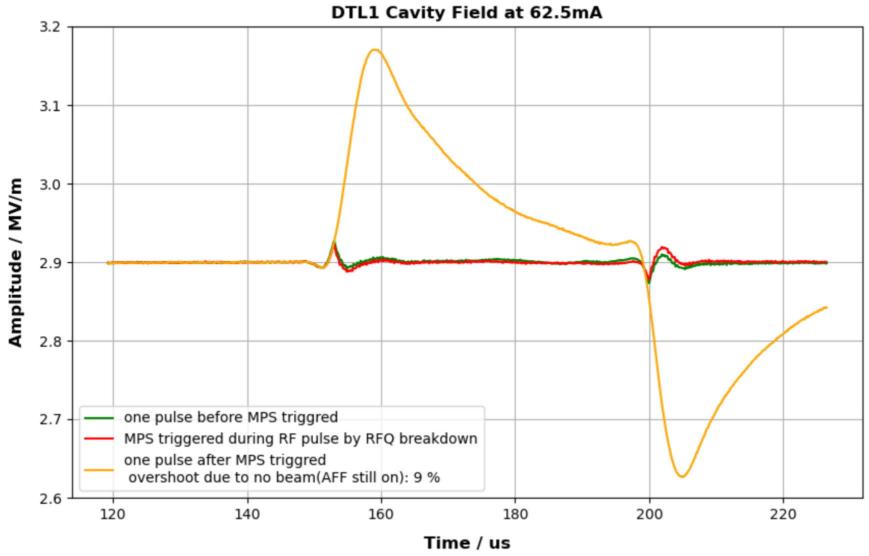
Introduction (Motivation)

On-line measurement during operation:

■ Beam Trip and Its Recovery:

- Detect beam trip, disclose beam information (status, phase, current, energy gain, etc) is essential for preventing overshoot due to no beam (beam compensation feedforward still on).

Overshoot at beam on	62.5mA	63.5mA
RFQ	5%	5%
DTL1	9%	11%
DTL2	8%	8%
DTL3	8%	8%
DTL4	7%	7%



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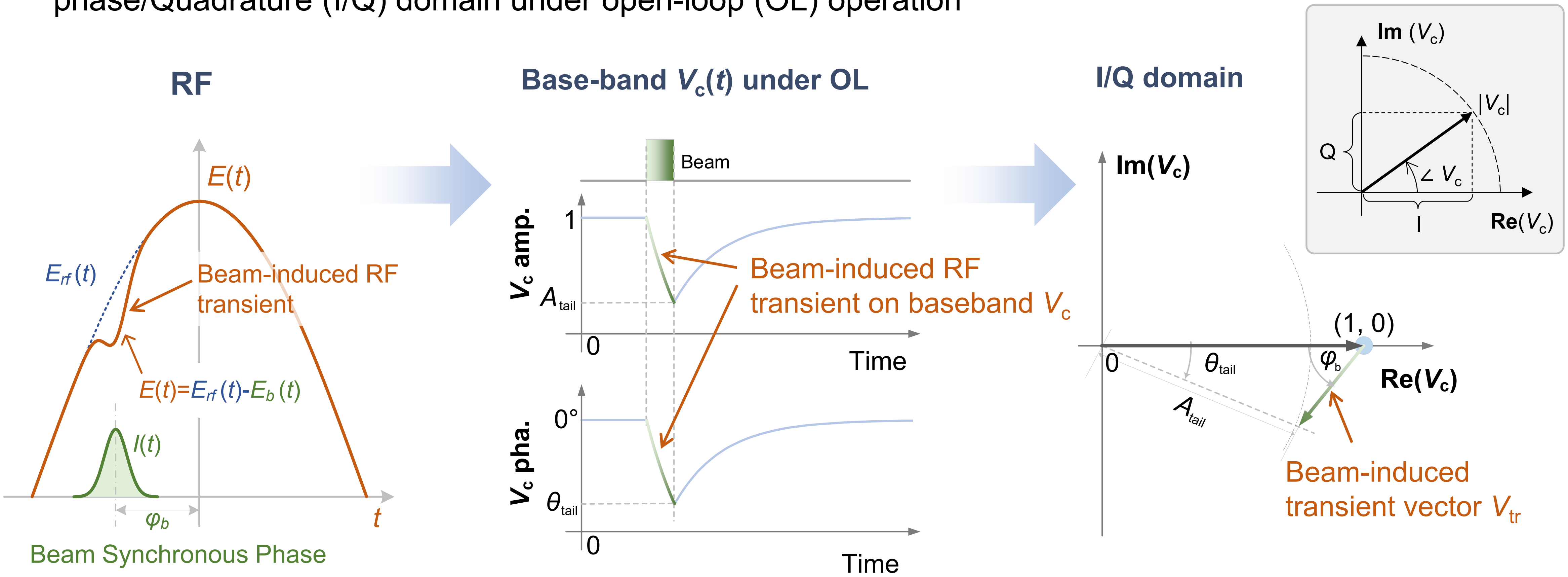
Transient Beam-loading Method (cont'd)

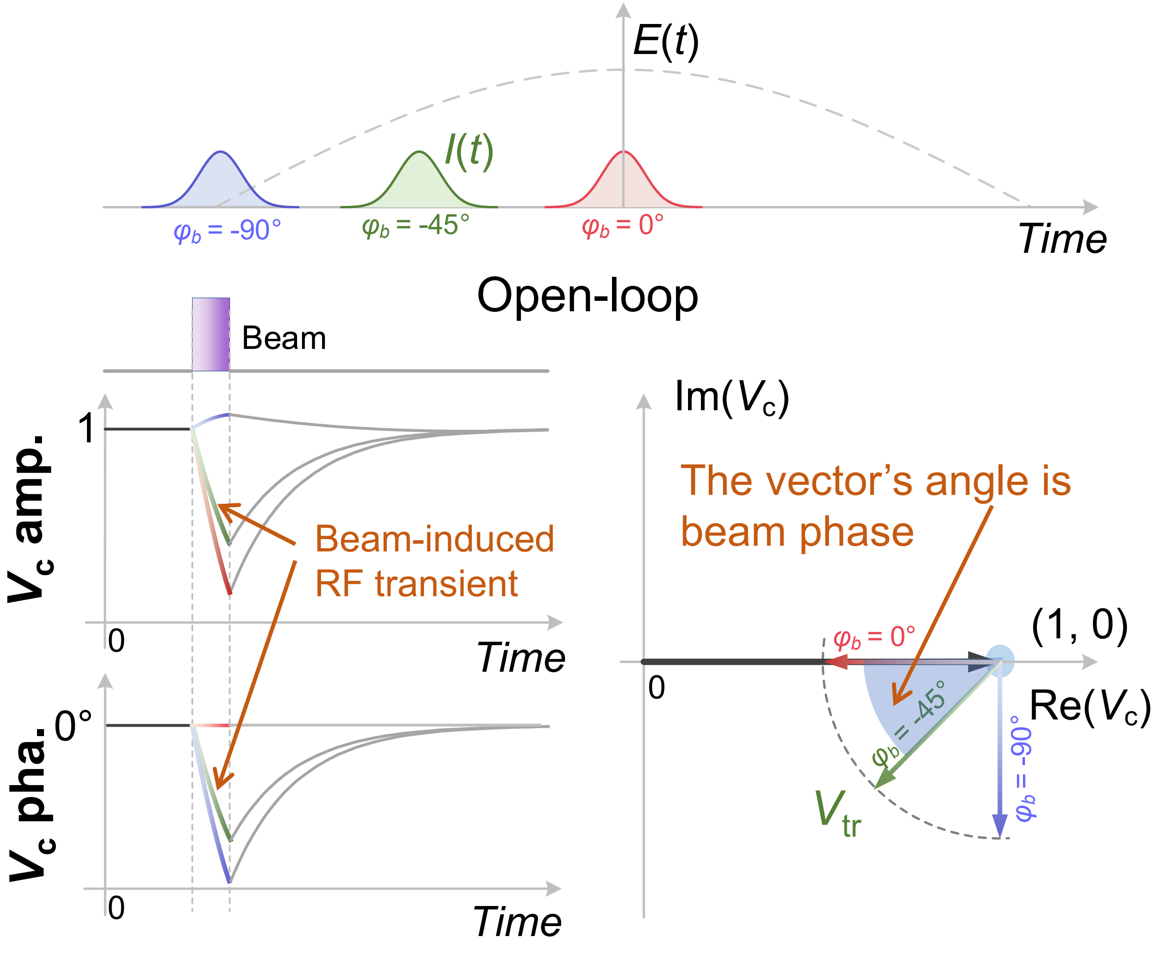
- **Beam-loading effect:** Refers to the influence of charged particle beam on the accelerating RF filed within an RF cavity
- **Beam-induced transient vector:** The transient vector (V_{tr}) induced by the beam in the In-phase/Quadrature (I/Q) domain under open-loop (OL) operation

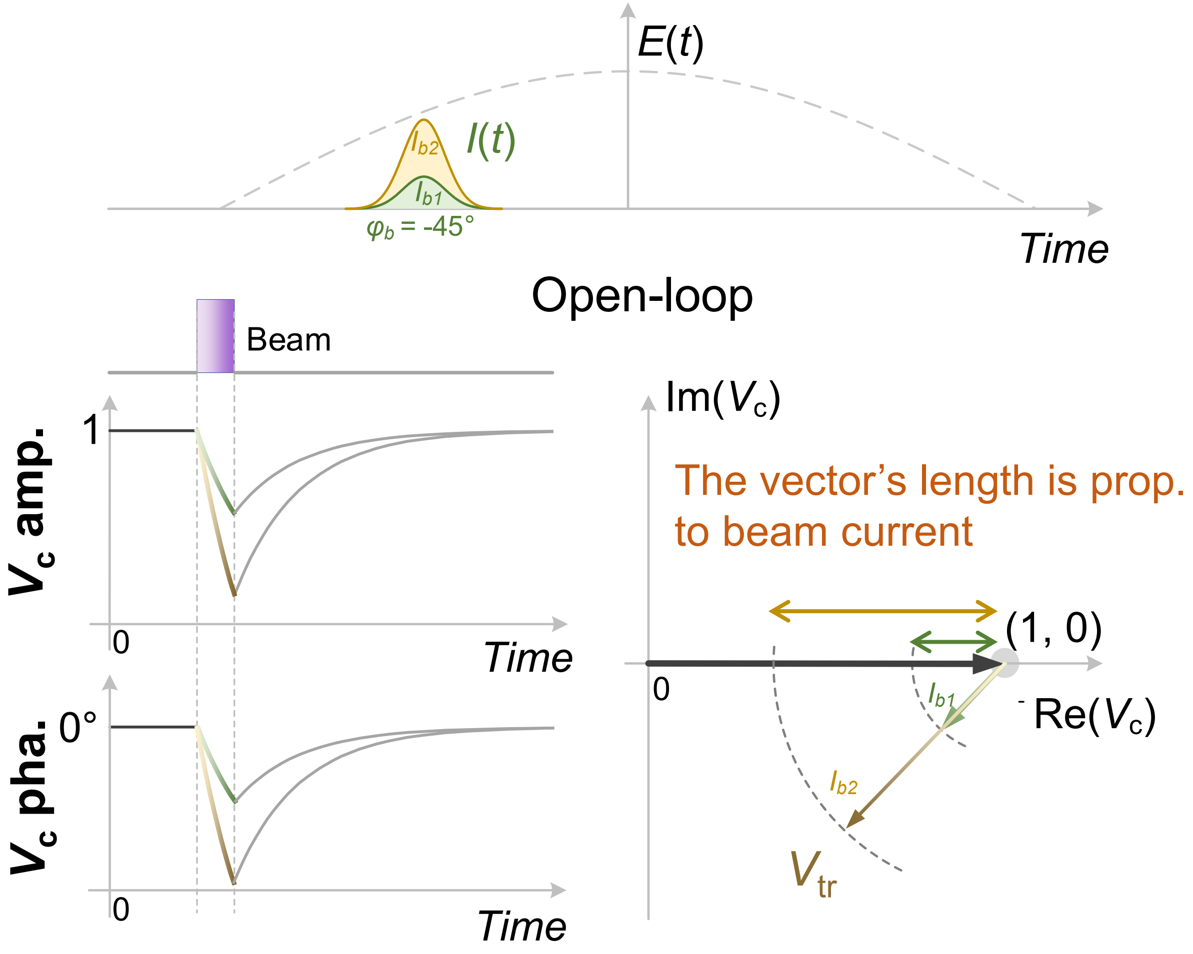


P Pawlik et al.,, New method for beam induced transient measurement, Meas. Sci. Technol. 18 (2007) 2348–2355

Transient Beam-loading Method (cont'd)

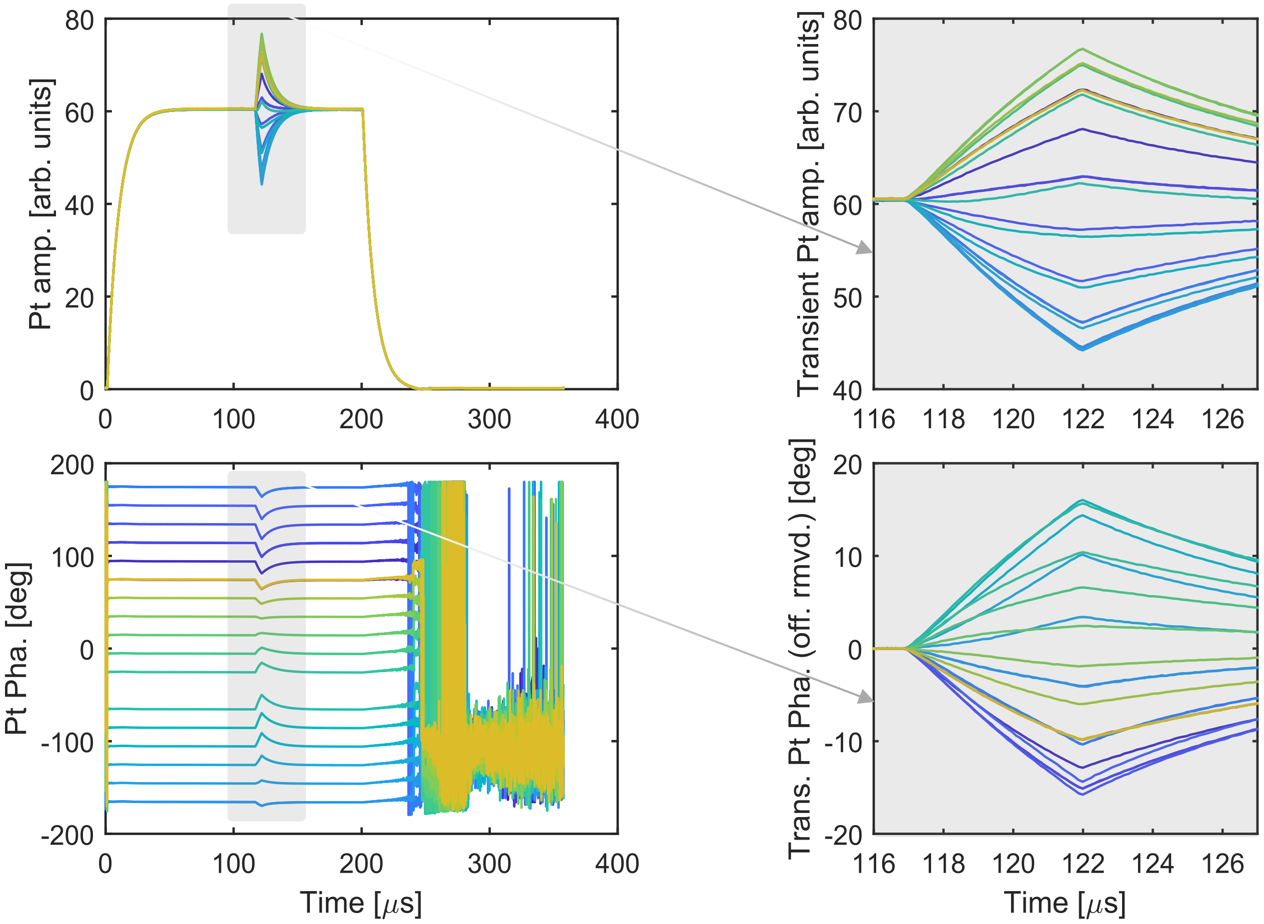
- Beam current and phase can be calibrated using the beam-transient-induced V_c vector V_{tr}

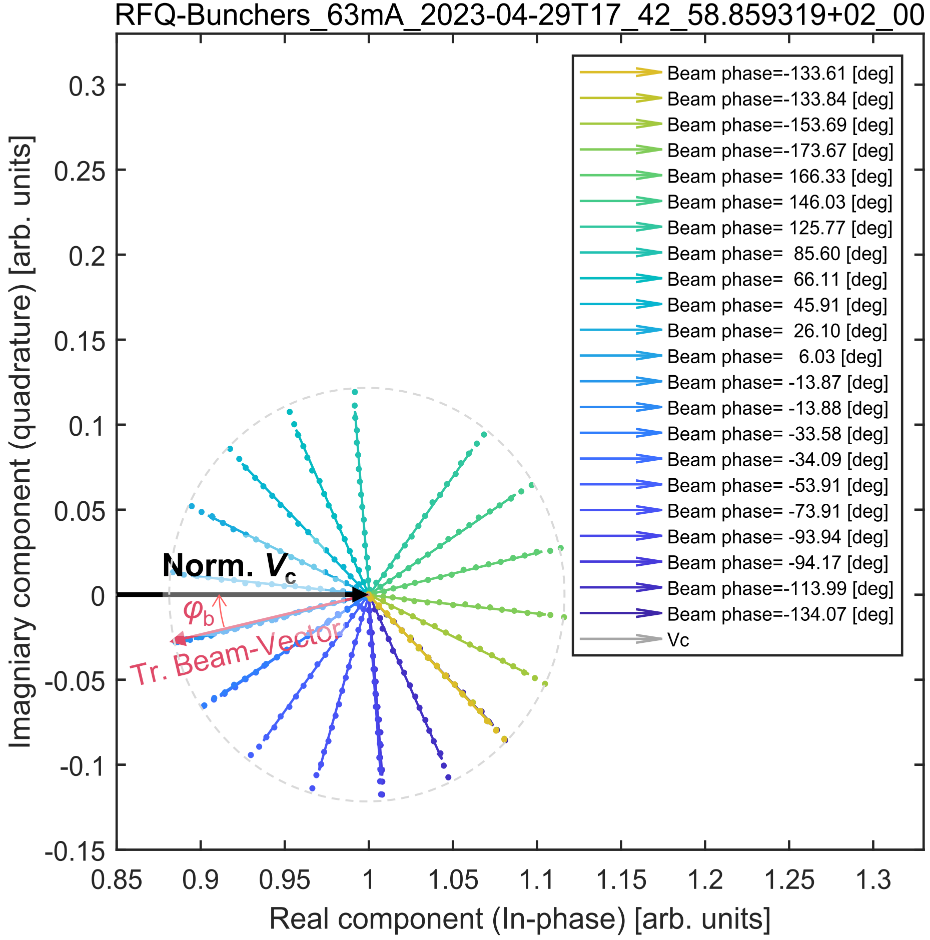




Transient Beam-loading Method (cont'd)

- Method was confirmed at ESS buncher cavity (open-loop, I_b=20 mA, Beam width = 5 μs)

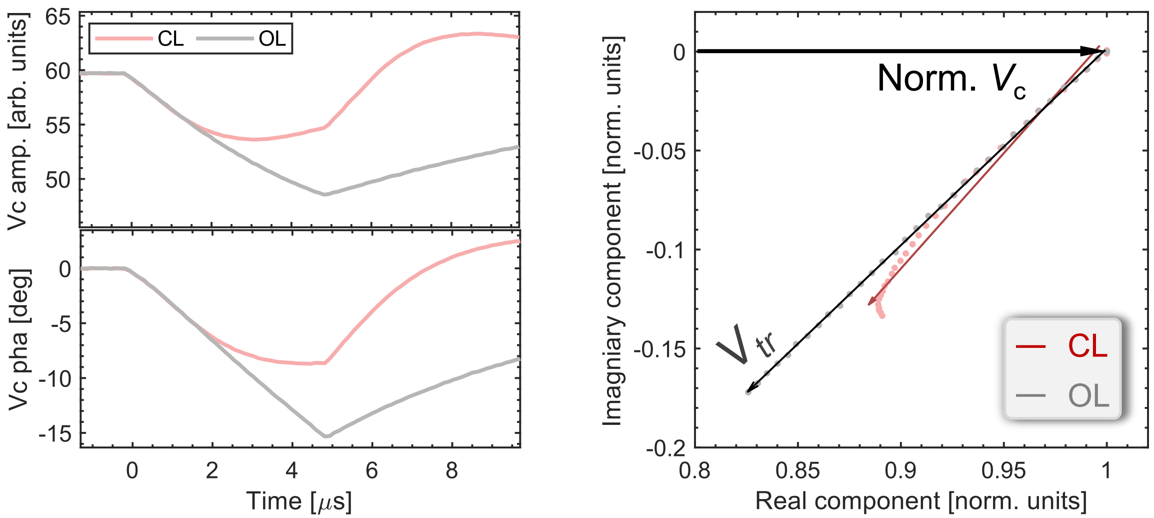




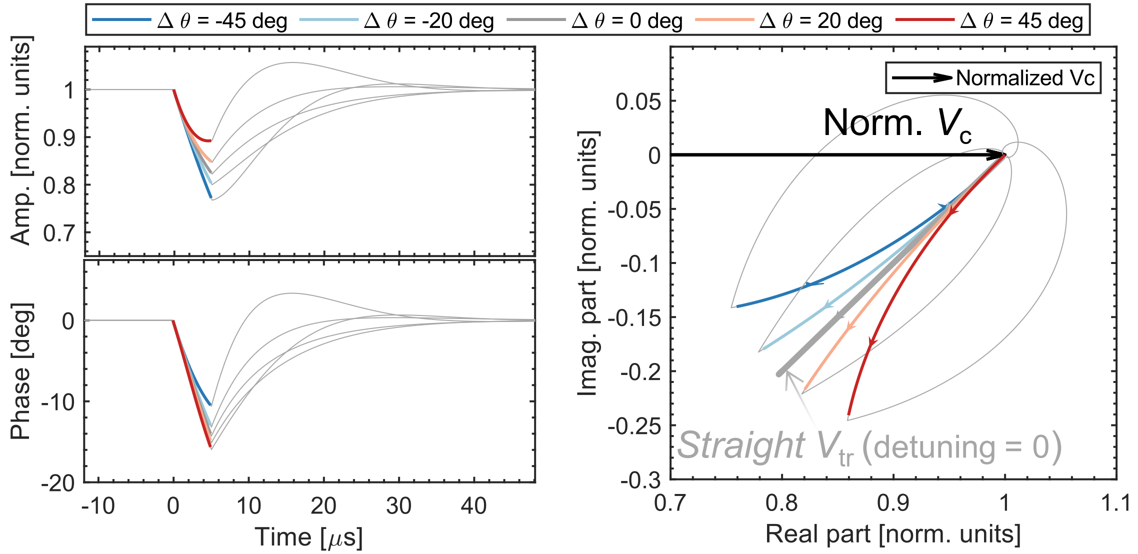
P Pawlik et al.,, New method for beam induced transient measurement, Meas. Sci. Technol. 18 (2007) 2348–2355

Transient Beam-loading Method (Bottlenecks)

- **Bottlenecks:** Requires the cavity to operate w/o detuning (in the case of a normal conducting cavity) and under OL conditions



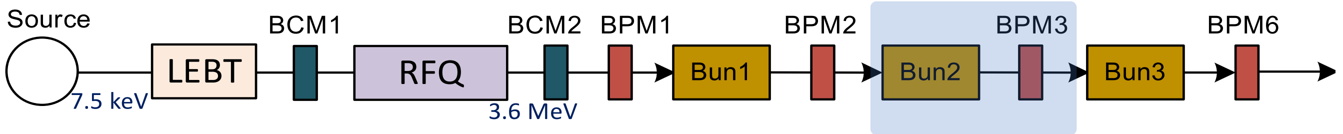
The vector V_{tr} is **NOT** straight under closed-loop operation

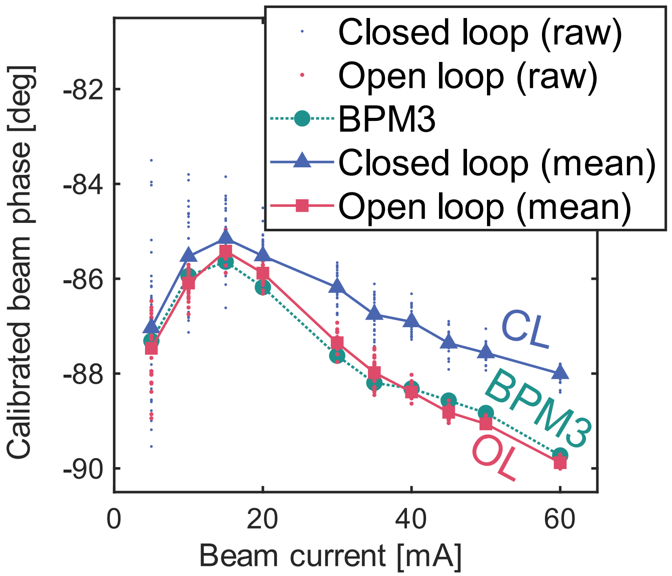


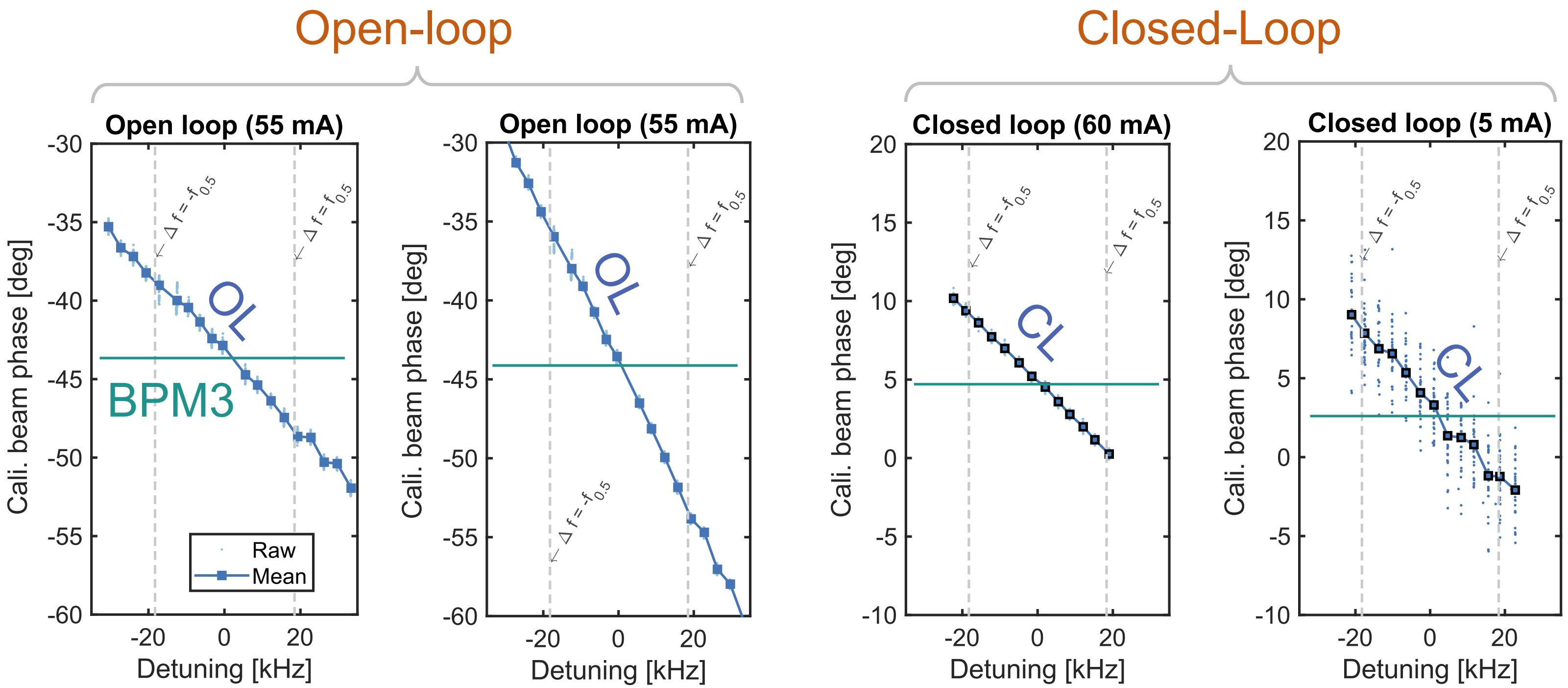
The vector V_{tr} is **NOT** straight if the cavity is detuned (especially for the normal conducting cav. case)

Transient Beam-loading Method (Bottlenecks)

- **Bottlenecks:** Requires the cavity works w/o detuning (for Bun2) and under OL







Hard to calibrate the beam information

⟶ We need a new algorithm that is suitable for both closed-loop operation mode and cases with detuning

CONTENTS

Steady-State V_f Method

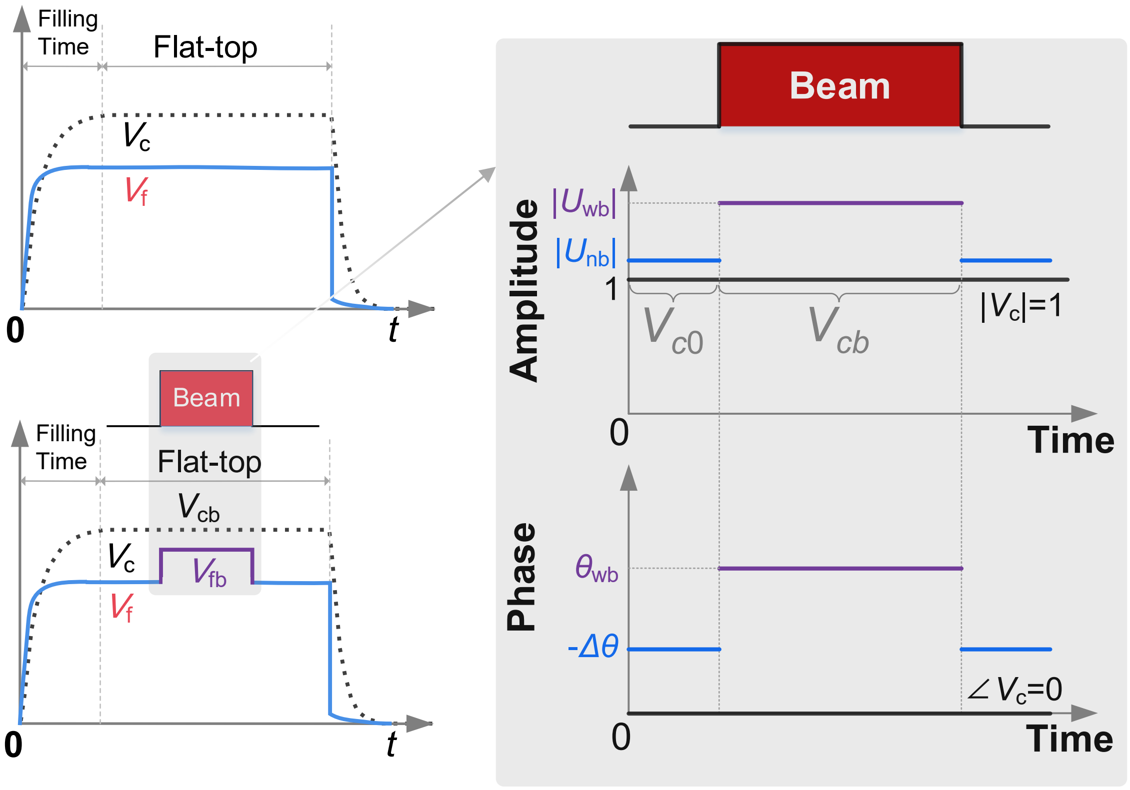
- **Principle:** Compare the steady-state (SS) V_f vectors in case of with (U_{wb}) and w/o beam (U_{nb})

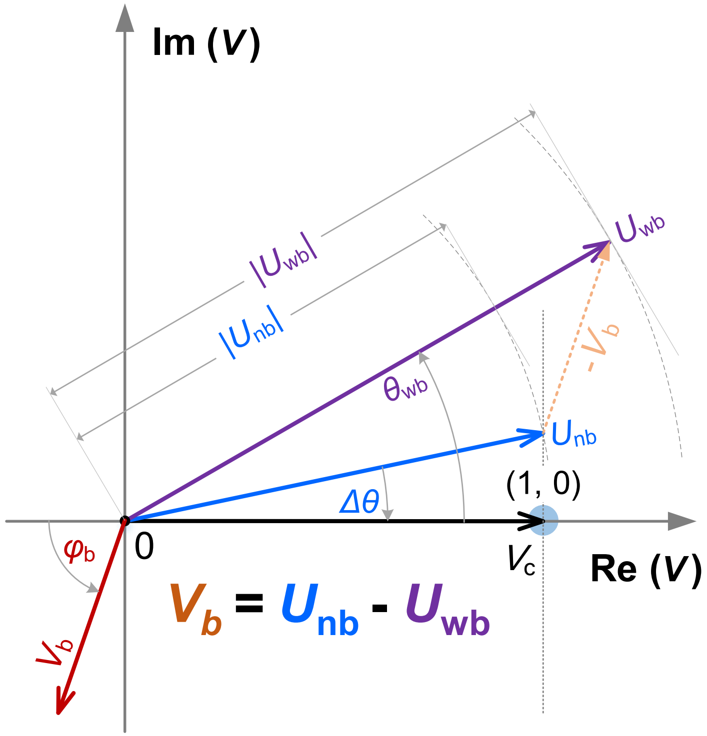
w/o beam
$$\frac{dV_{c0}}{dt}+(\omega_{0.5}-j\Delta\omega)V_{c0}=2\omega_{0.5}\frac{\beta}{1+\beta}V_f$$

with beam
$$\frac{dV_{cb}}{dt}+(\omega_{0.5}-j\Delta\omega)V_{cb}=2\omega_{0.5}\frac{\beta}{1+\beta}V_{fb}+\omega_{0.5}V_b$$

If $V_{c0}=V_{cb}$

$$V_b=\underbrace{2\frac{\beta}{1+\beta}V_f}_{U_{nb}}-\underbrace{2\frac{\beta}{1+\beta}V_{fb}}_{U_{wb}}=U_{nb}-U_{wb}$$





1. Beam-loading must be well compensated (V_{c0}=V_{cb})

→ *FF required*

2. V_f signal must be well calibrated

→ *Cross component in the meas. channels*

Beam-loading Compensation

- Iterative Learning Ctrl (ILC) algorithm usually helps
  - Step1: Calibrate the error between the reference signal (r) and cavity pick-up signal (y)

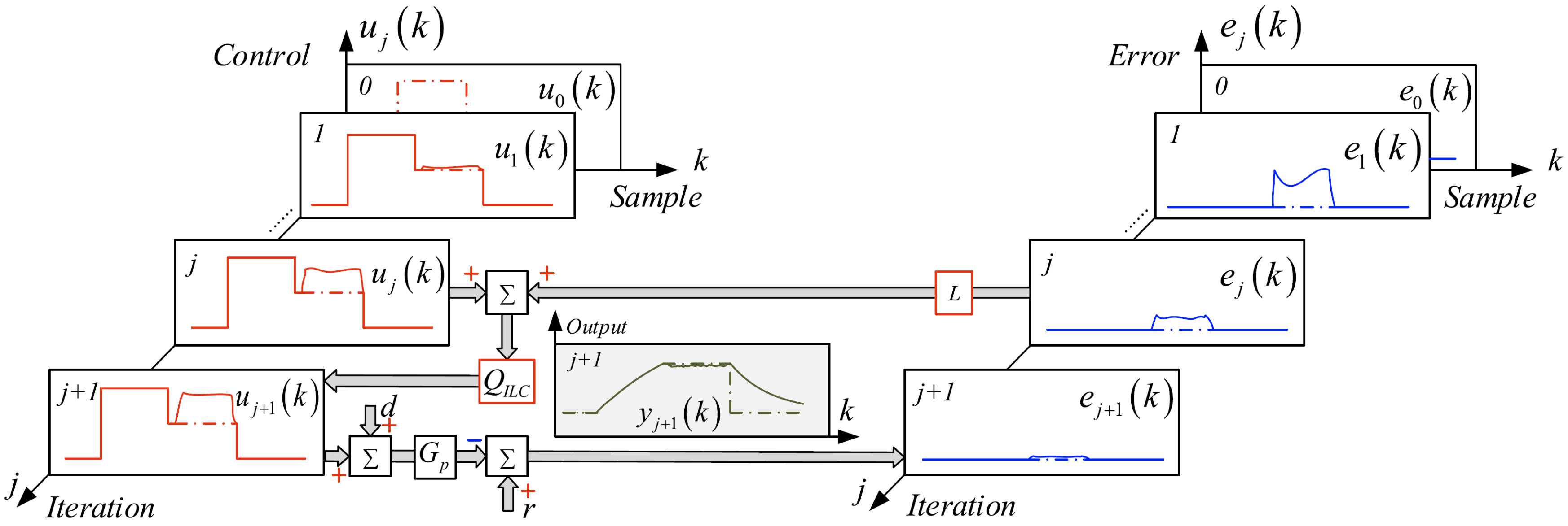
$$e_j(k)=r_j(k)-y_j(k)$$

  - Step2: Update the current feedforward (FF) output (u_{j+1}) using the previous FF (u_j) and error (e_j)

A matrix or a zero-phase filter

$$u_{j+1}(k)=Q_{ILC}[u_j+L(e_j)]$$

A matrix or a plant-inversion-model or PID



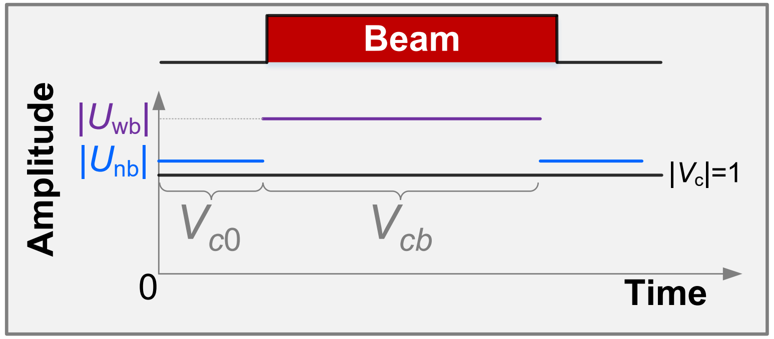
1. Beam-loading must be well compensated ($V_{c0}=V_{cb}$)
→ *FF required*

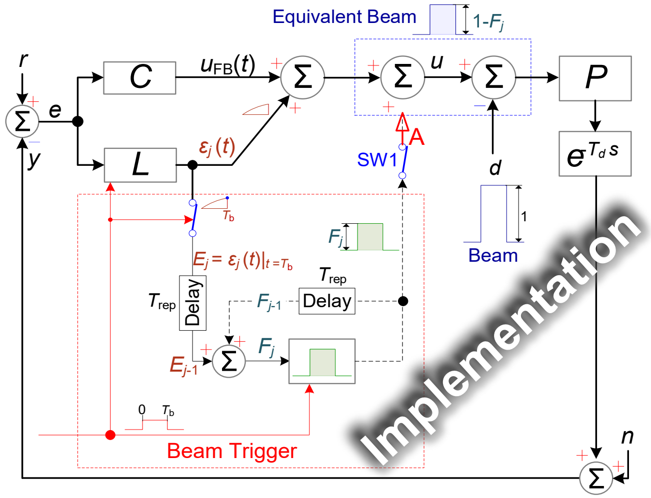
2. V_f signal must be well calibrated
→ *Cross component in the meas. channels*

Beam-loading Compensation

- After several times of iteration, we can obtain the condition

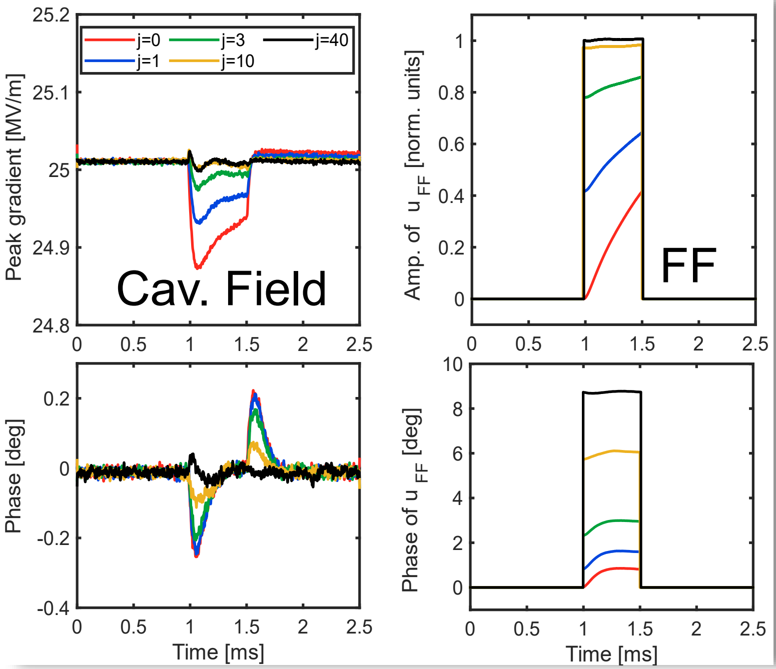
$V_{c0}=V_{cb}$

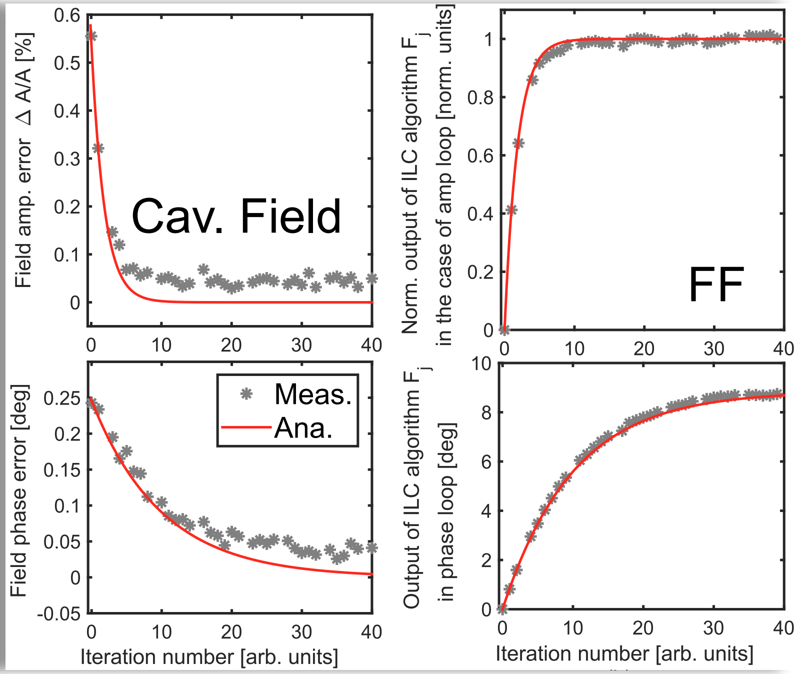




RF waveforms during iter. proc.

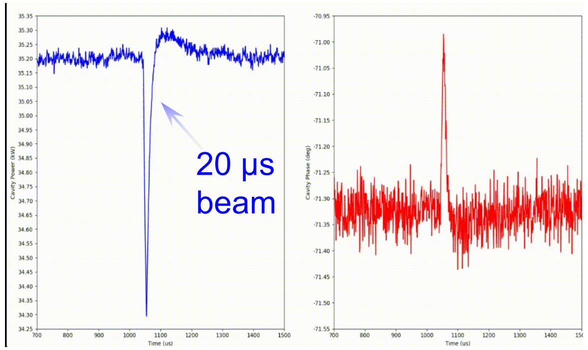
Convergence curve





Field Amp.

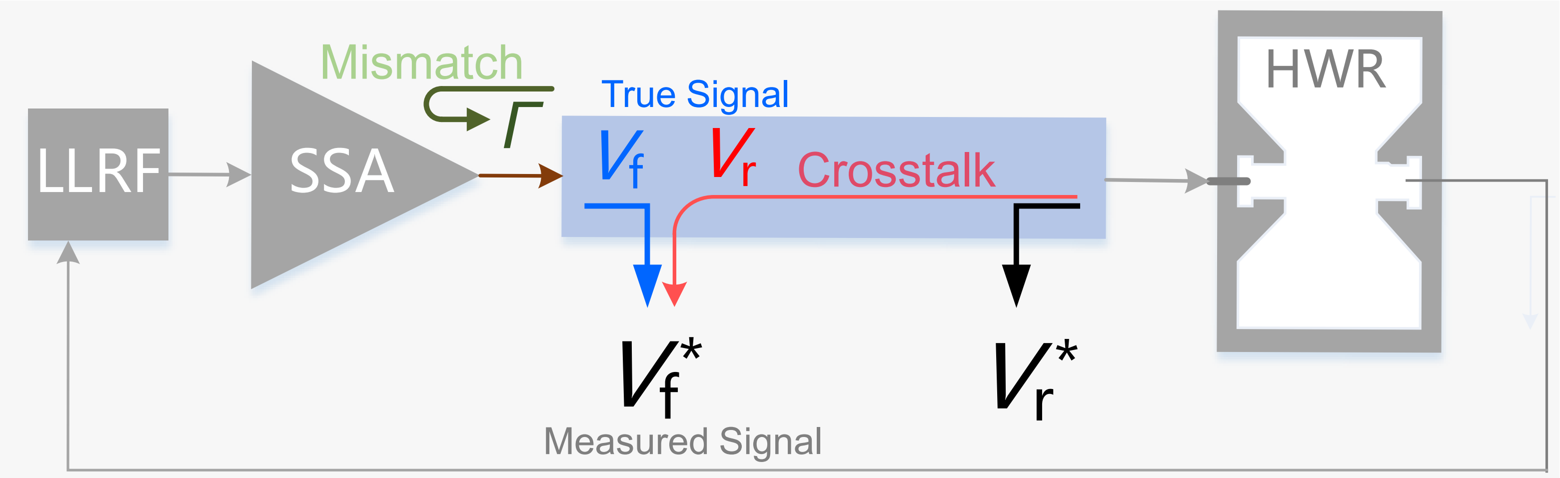
Field Pha.



C. Xu, Z. Zhu, F. Qiu* et al., Application of a modified iterative learning control algorithm for superconducting radio-frequency cavities, Nucl. Instrum. Methods. A . 955,166237 (2022)

Signal Calibration

- The accuracy of RF signals measurement is primarily affected by the following factors:
  - Crosstalk between the measurement channels (e.g., directional coupler)
  - Impedance mismatch of RF source (which can be mitigated by a well-designed circulator)



1. Beam-loading must be well compensated ($V_{c0}=V_{cb}$)
→ *FF required*

2. V_f signal must be well calibrated
→ *Cross component in the meas. channels*

$$\begin{cases} V_f^* = c_1 V_f + c_2 V_r \\ V_r^* = c_3 V_f + c_4 V_r \end{cases} \Rightarrow \begin{cases} V_f = aV_f^* + bV_r^* \\ V_r = cV_f^* + dV_r^* \end{cases}$$

The key issue is configuring the four COMPLEX calibration coefficients ***a b c d***

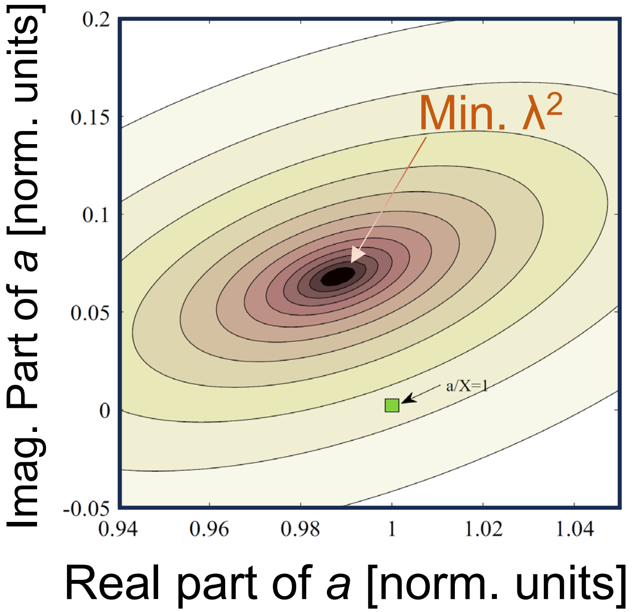
e.g., $\mathbf{a} = |\mathbf{a}| \cdot e^{j\angle \mathbf{a}}$

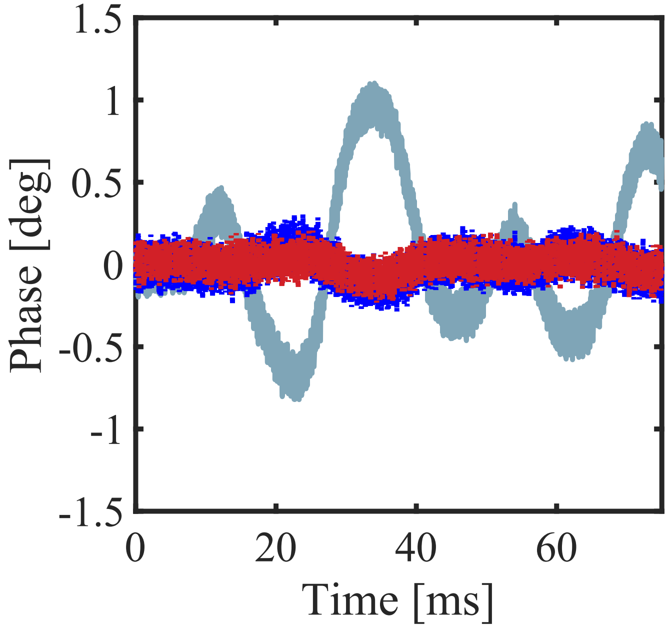
Signal Calibration

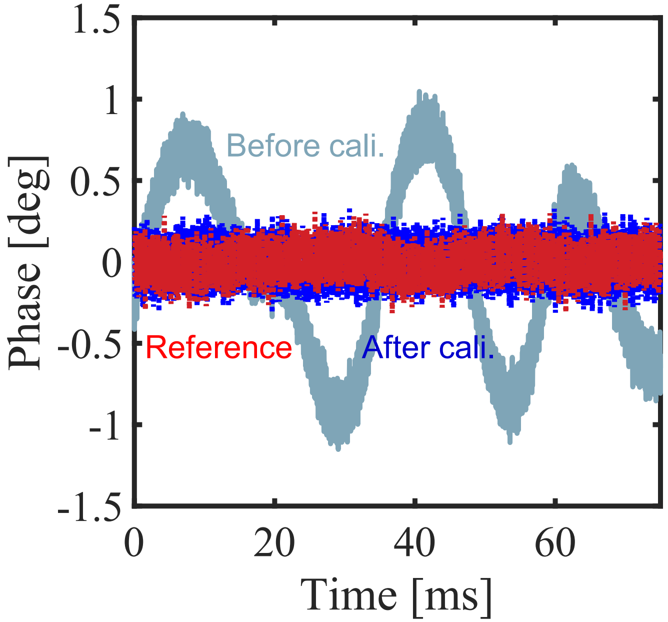
- The optimal calibration factors can be determined by minimizing the error between cavity model output $y(a, t)$ and actual measurement $|V_c|'$

$$\frac{dV_c}{dt} + (\omega_{0.5} - j\Delta\omega)V_c = 2\omega_{0.5}\frac{\beta}{1+\beta}V_f \Rightarrow \frac{d|V_c|}{dt} = \omega_{0.5}\left[2\frac{\beta}{1+\beta}|V_f|\cos(\angle V_c - \angle V_f) - |V_c|\right],\ V_f = f(V_f^*, V_r^*, a) \Rightarrow \lambda^2(a) = \sum_t \left[\frac{d|V_c|}{dt} - y(a)\right]$$

$|V_c|'(t)$ $y(a, t)$ Must be minimized



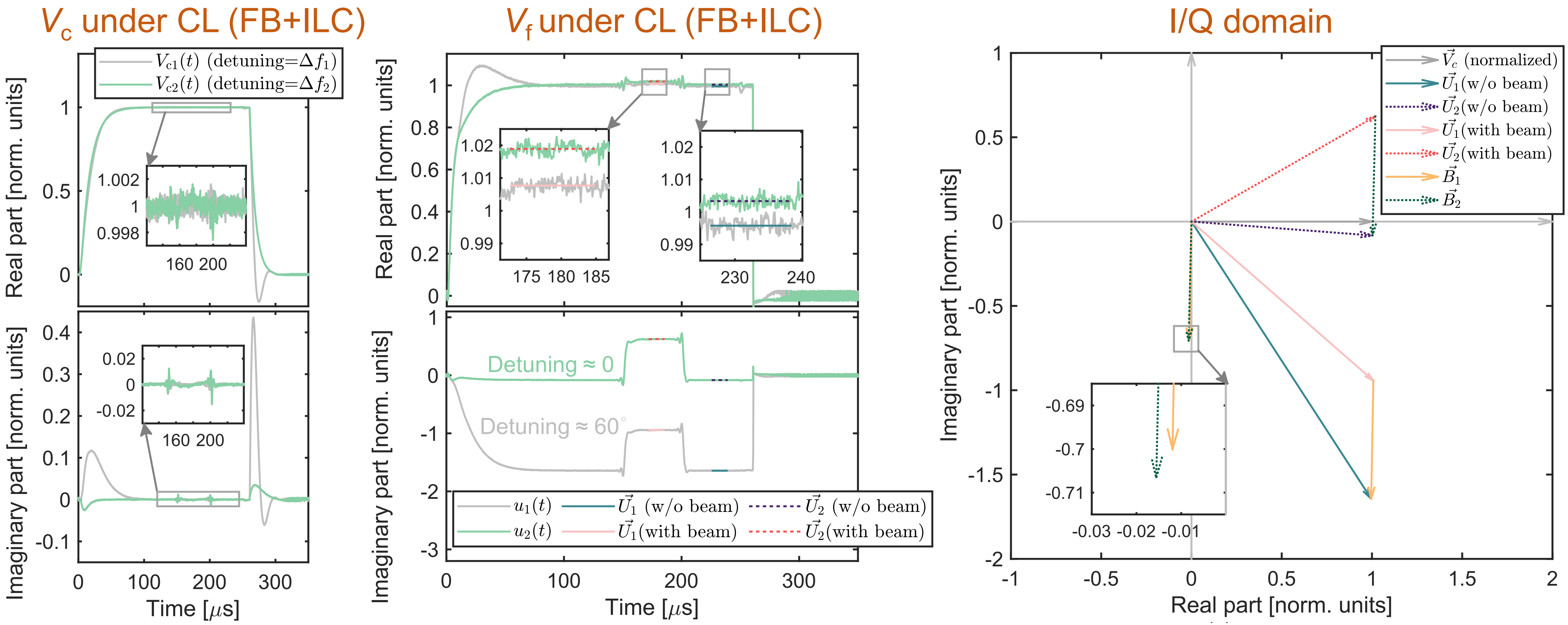




A. Brandt, PhD thesis, Universitt Hamburg, 2007
J. Y. Ma, F. Qiu* et al., Precise calibration of cavity forward and reflected signal using low-level radio-frequency system, Nucl. Sci. Tech. 33:4, 2022

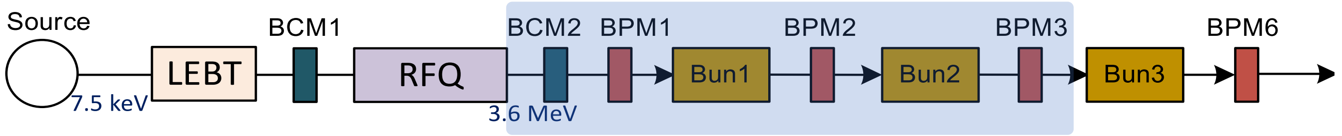
Steady-State Method

- The Steady-State (SS) method performs effectively with FB+ILC (which is the CL case)
- Results are not affected by cavity detuning

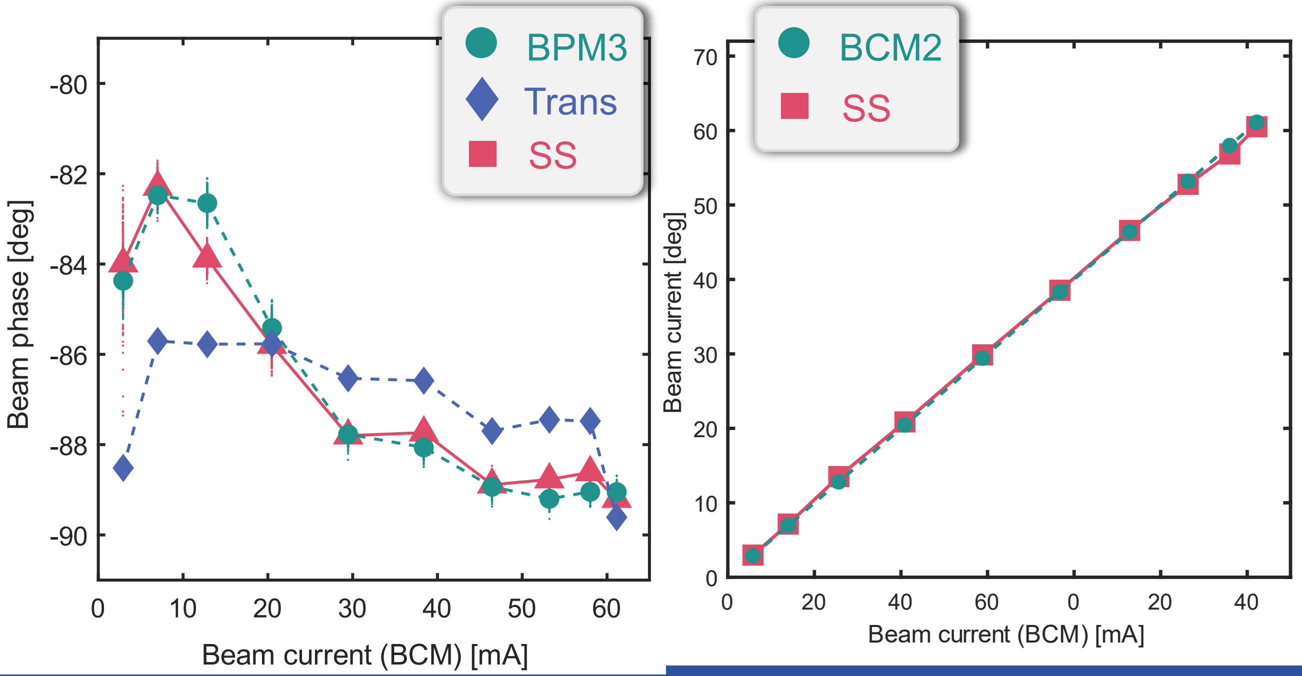


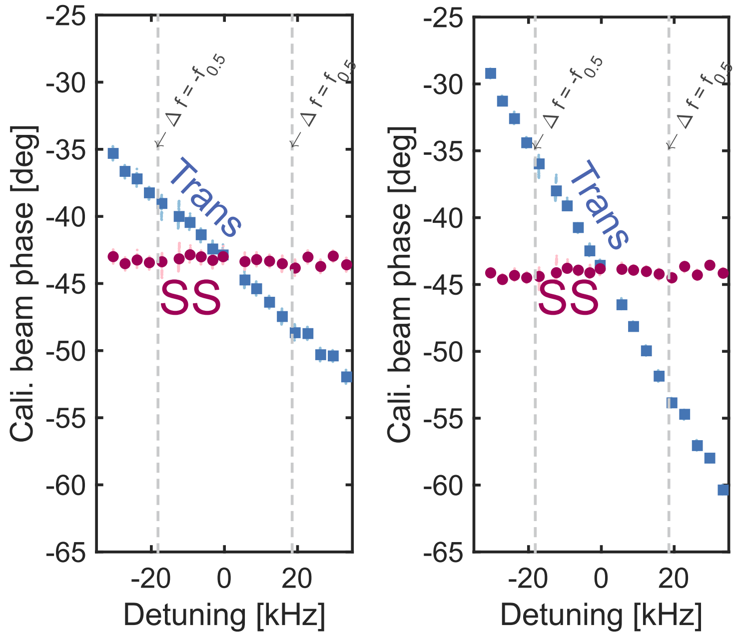
Results (SS Method)

- The identified beam phase and current in the SS (Steady-State) method are consistent with the BPM (Beam Position Monitor) and BCM (Beam Current Monitor) measurements
- Calibration results are not impacted by the cavity detuning



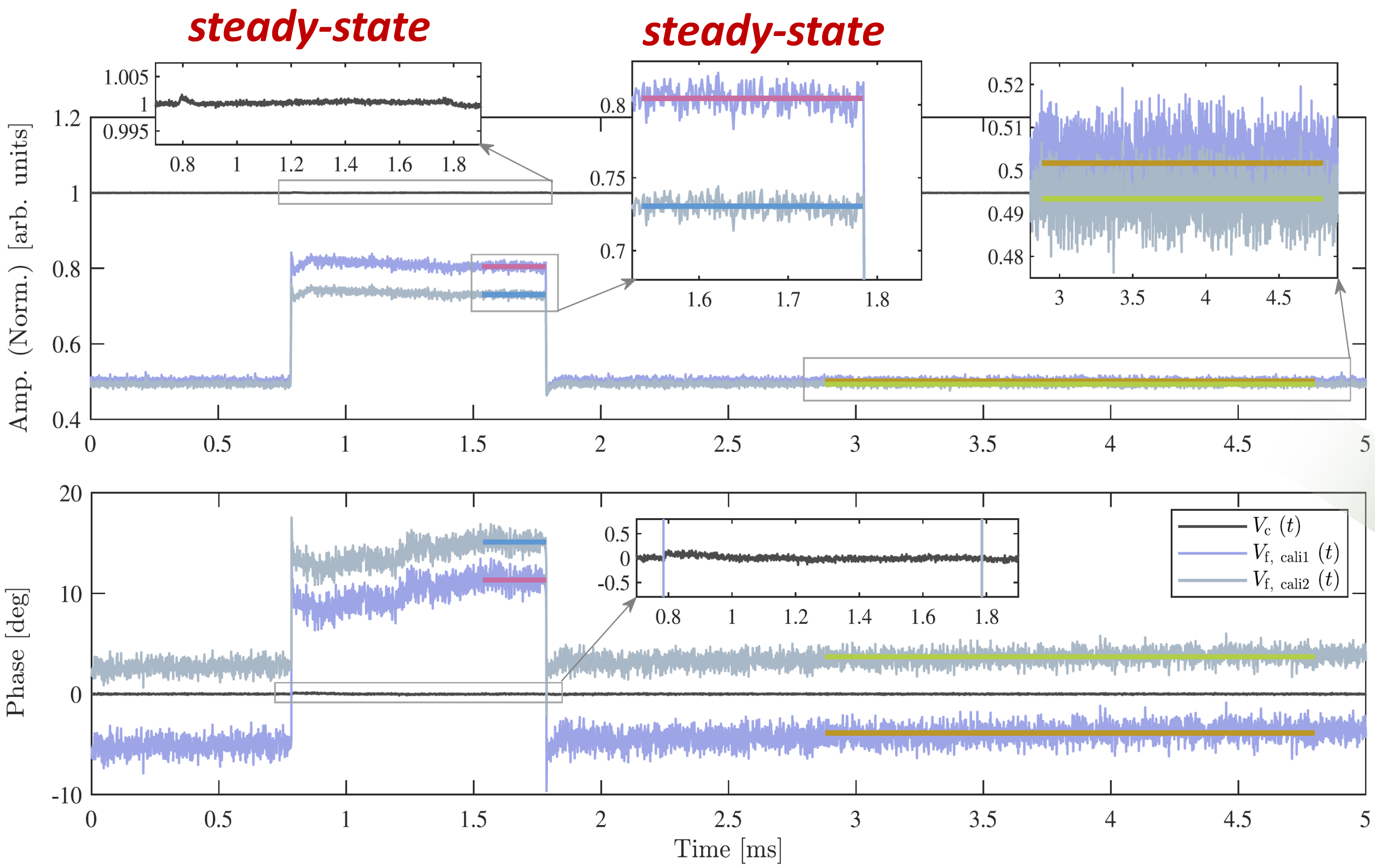
CL operation





Impact of Signal Calibration (@IMP)

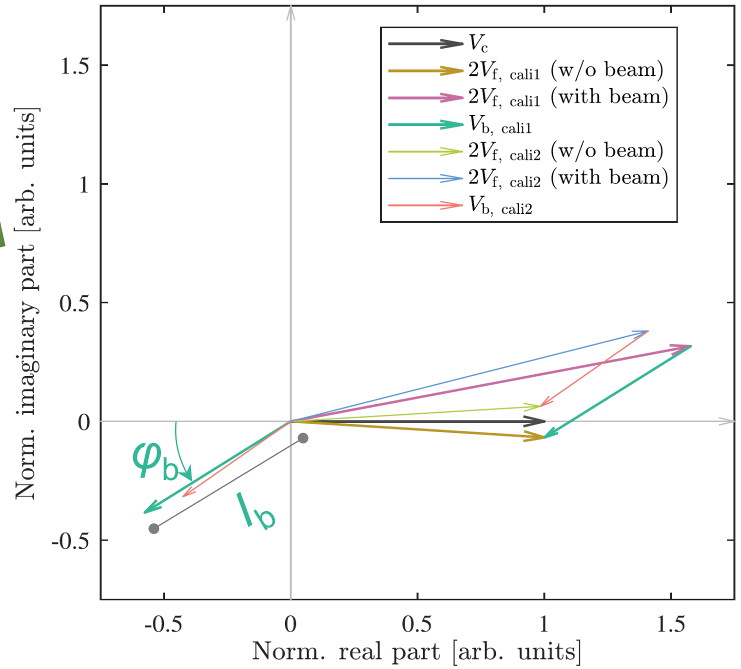
- Accurate calibration of the V_f signal is the key issue



F. Qiu* et al., Approach to calibrate actual cavity forward and reflected signals for continuous wave-operated cavities, Nucl. Instrum. Methods. A . 955,166237 (2022)

BPM	Proposed Method	
	With cali.	W/o cali.
(I_b, φ_b)	$V_{f,\ cail1} = aV_f^* + bV_r^*$	$V_{f,\ cail2} = XV_f^*$
	$(I_{b,\ cail1}, \varphi_{b,\ cail})$	$(I_{b,\ cail1}, \varphi_{b,\ cail\ 2})$
(8.3 mA, −34°)	(8.2 mA, −33°)	(6.3 mA, −36°)
(5.6 mA, −34°)	(5.6 mA, −33°)	(4.3 mA, −36°)
(3 mA, −34°)	(2.9 mA, −36°)	(2.2 mA, −39°)

Cross-talk was considered



CONTENTS

Differential Eq.-based Method

- **Principle:** Calibrating beam information based on the cavity differential equation with (Eq. ①) and without (Eq. ②) beam presence.

$$\begin{cases} V_{c0}'(t)+(\omega_{0.5}-j\Delta\omega)V_{c0}(t)=\omega_{0.5}\dfrac{2\beta}{1+\beta}V_{f0}(t), & ① \\ V_{c1}'(t)+(\omega_{0.5}-j\Delta\omega)V_{c1}(t)=\omega_{0.5}\dfrac{2\beta}{1+\beta}V_{f1}(t)+\omega_{0.5}V_{b}(t), & ② \end{cases}$$

$$\begin{cases} V_{cb}(t)=V_{c1}(t)-V_{c0}(t) \\ V_{fb}(t)=V_{f1}(t)-V_{f0}(t) \end{cases}$$

V_{cb}: Variation of V_c with and w/o beam

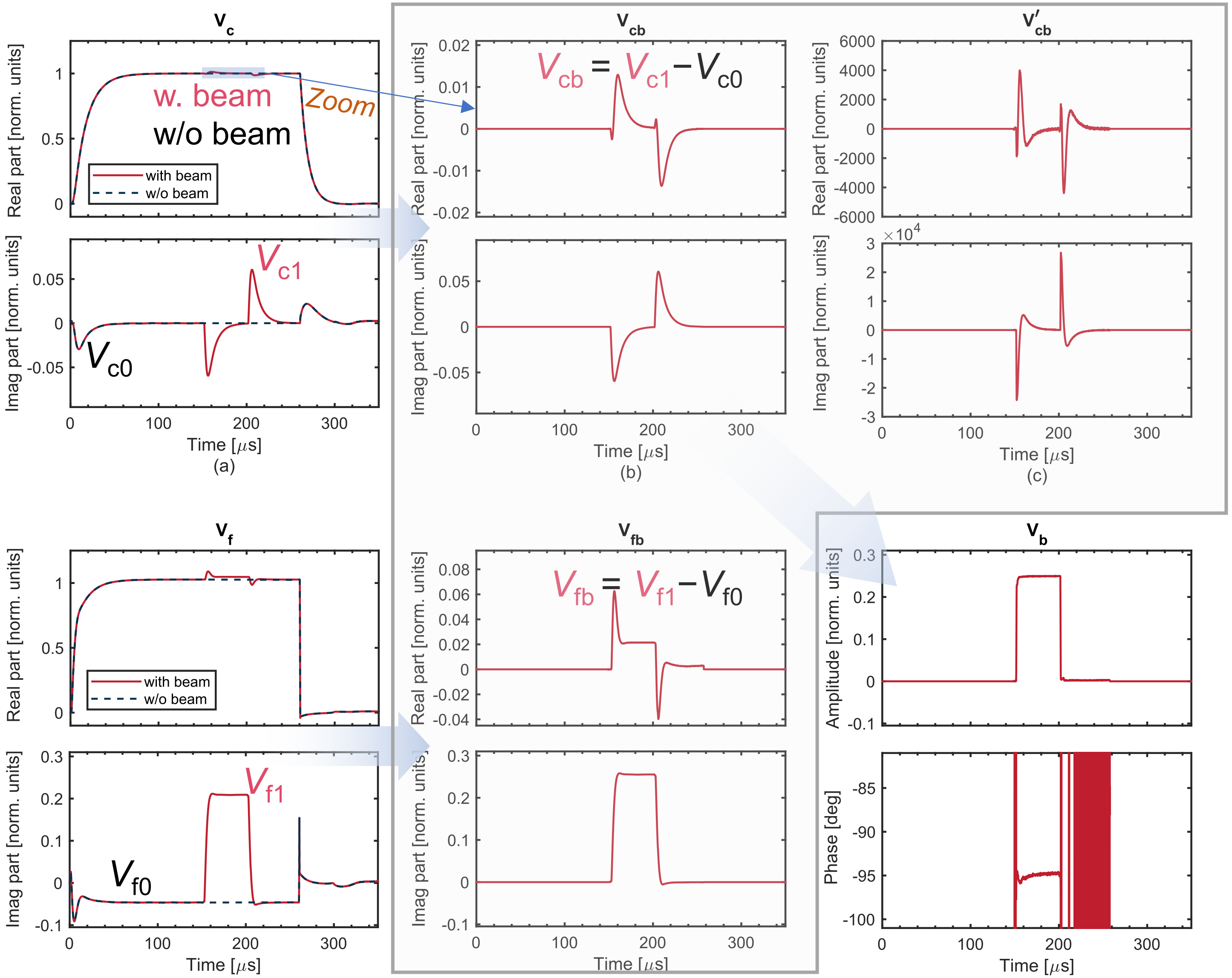
V_{fb}: Variation of V_f with and w/o beam

② – ① yield

$$V_b(t)=\frac{1}{\omega_{0.5}}V_{cb}'(t)+\left(1-j\frac{\Delta\omega}{\omega_{0.5}}\right)V_{cb}(t)-\frac{2\beta}{1+\beta}V_{fb}(t)$$

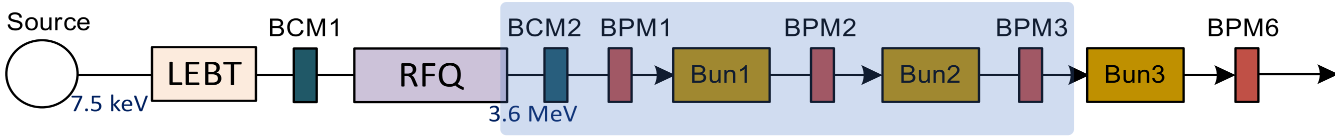
$$\begin{cases} I_b=\dfrac{G|V_b|}{(r/Q)Q_L} \\ \varphi_b=-180^\circ-\angle V_b \end{cases}$$

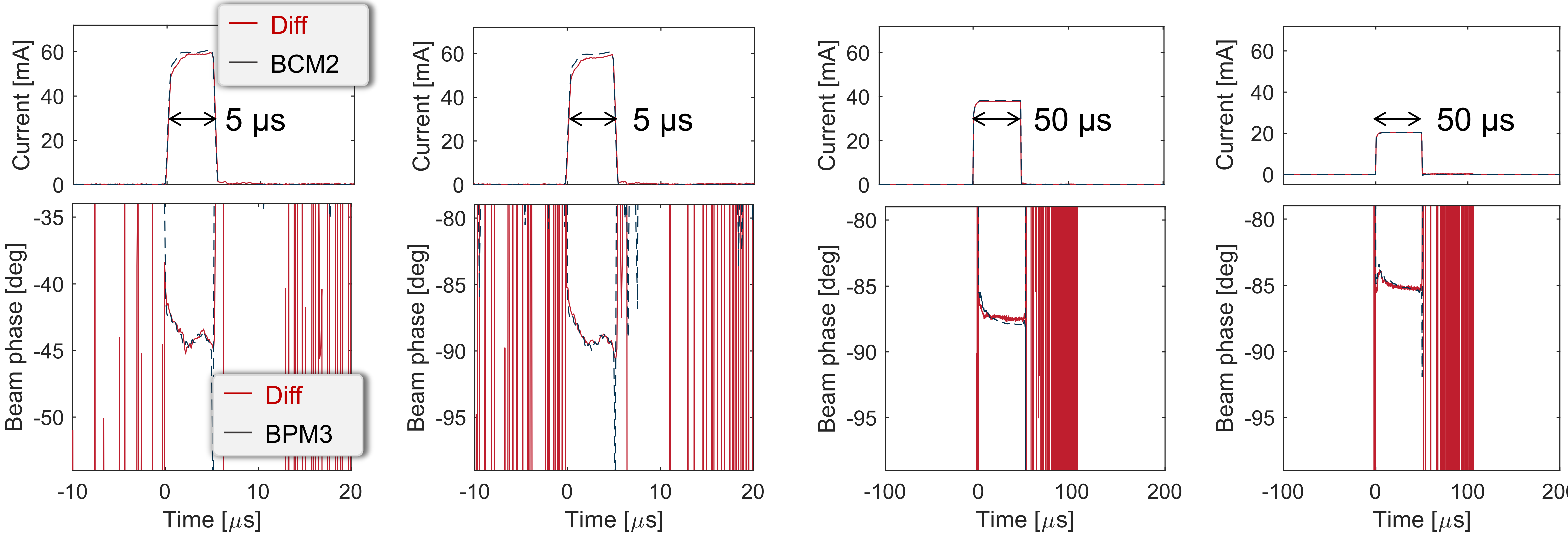
We finally obtain the beam information



Differential Eq.-based Method

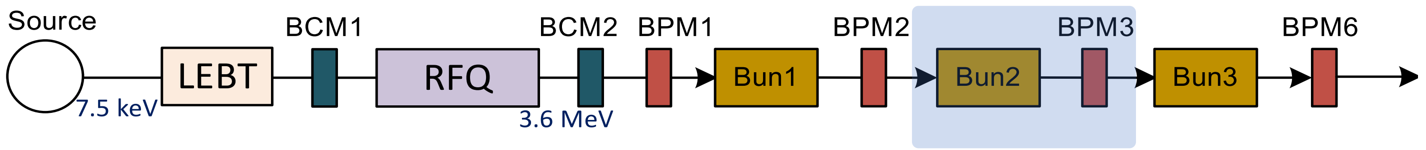
- The calibrated beam current and beam phase on Bun2 are consistent with the BPM3 and BCM2 result.

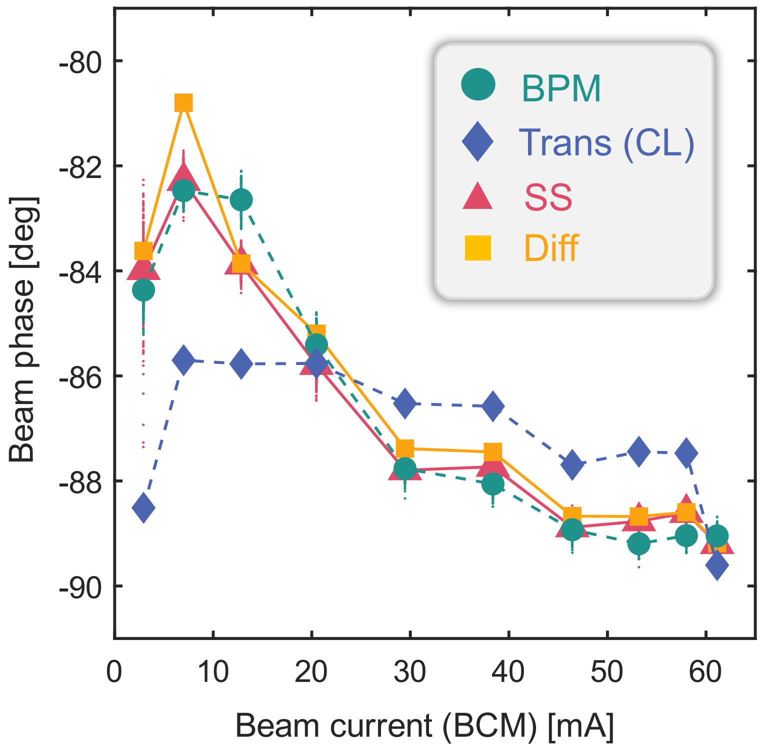


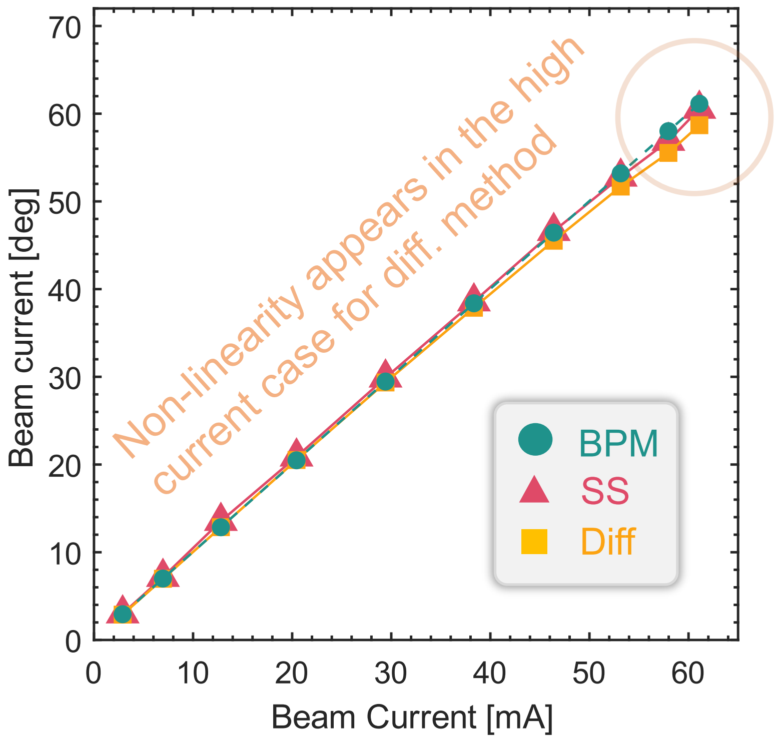


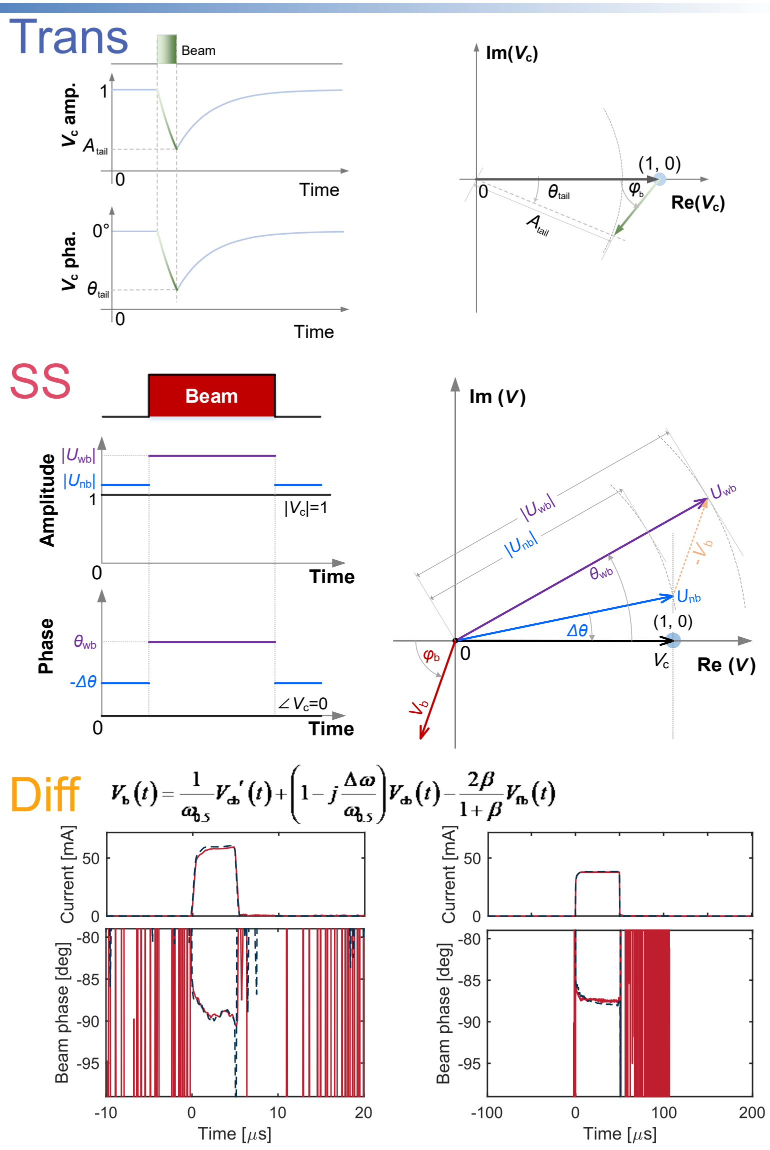
Differential Eq.-based Method

- Basically, the results are same with BPM or BCM









$$V_b(t) = \frac{1}{\omega_{0.5}} V_{cb}'(t) + \left(1 - j\frac{\Delta\omega}{\omega_{0.5}}\right) V_{cb}(t) - \frac{2\beta}{1+\beta} V_{fb}(t)$$

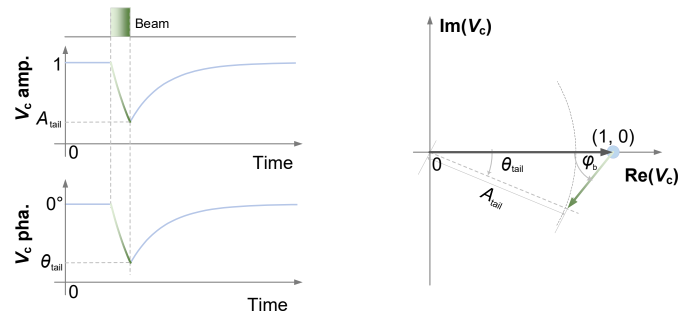
Differential Eq.-based Method

- The calibrated beam current and beam phase is consistent with the BPM and BCM result.

Method	Operation Mode	Detuning Requirement	Beam Width Requirement
Trans. Beam Loading Method	Basically OL	On-resonance state needed	Basically, Short Pulse (e.g. 5 μs)
Steady-State V_f Method	Basically CL (FB+ILC)	None	Basically, Long Pulse (e.g. 50 μs)
Diff. Eq.-based Method	OL or CL (FB)	None	None

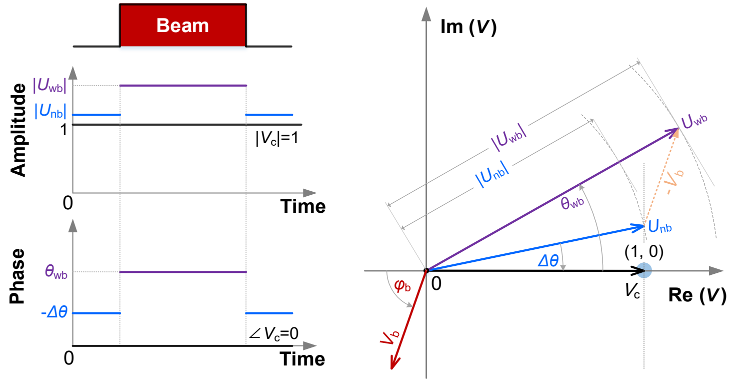
Short Pulse

Trans.



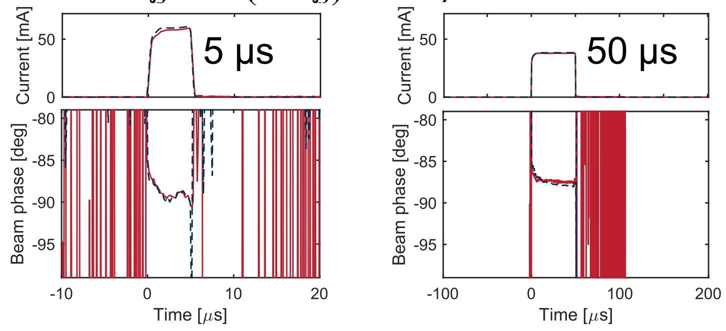
Long Pulse

SS



Diff.

$$V_b(t)=\frac{1}{\omega_{0.5}}V_{cb}'(t)+\left(1-j\frac{\Delta\omega}{\omega_{0.5}}\right)V_{cb}(t)-\frac{2\beta}{1+\beta}V_{fb}(t)$$



Summary

- Testing results from the ESS room-temperature cavity indicate that using RF online measurements for beam current information is feasible
- The transient beam-loading method requires the cavity to operate on resonance and in open-loop mode
- A high-accuracy signal calibration method is crucial for the steady-state measurement approach.
- By using the cavity's differential equations, the waveform of the entire beam pulse can be obtained, but it is prone to nonlinear effects at high current intensities.

Thanks for your attention

Back-up Slides