Unleashing the Full Potential of LLRF Algorithms:

Enhancing Stability, Reliability, and Accuracy in RF Systems

—— IQ Award Presentation (LLRF2023)

Feng Qiu, on behalf of LLRF grp of KEK & IMP

Institute of Modern Physics (IMP), Chinese Academy of Science

中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

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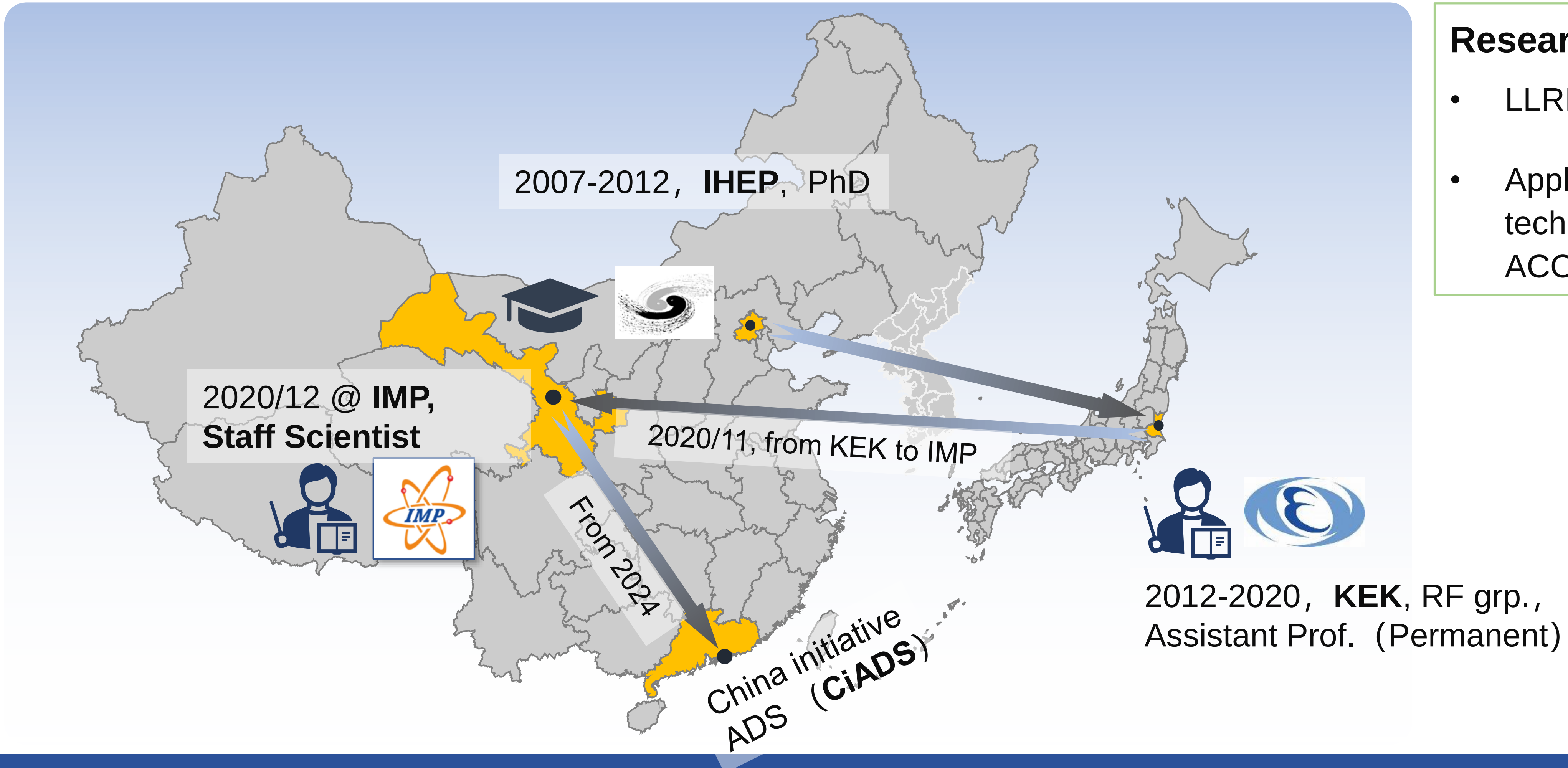
Self Introduction

- **F. Qiu**, Senior Staff Scientist, 1985/07/05, **Affiliation**: Institute of Modern Physics (**IMP**), China
  PhD degree @ **IHEP** (Beijing), Assistant Prof. @ **KEK** (**previous affiliation**)

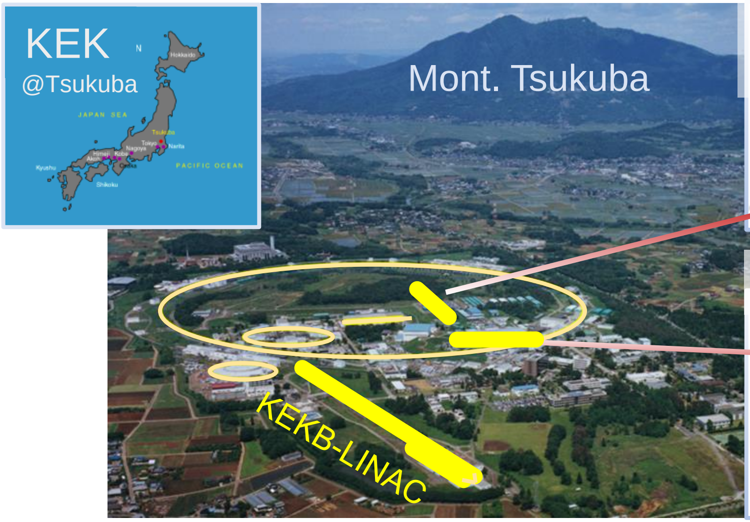


Research Direction

- LLRF algorithm
- Application of AI-technique in ACCLs

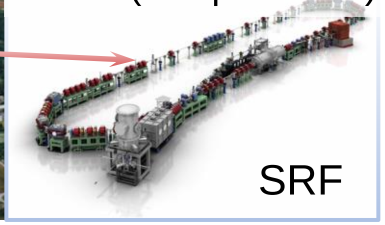
Self Introduction (cont'd)

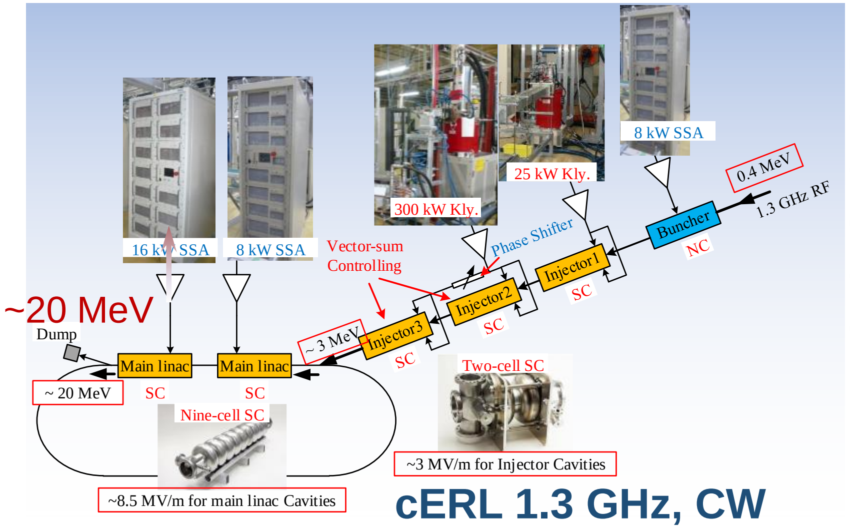
- **Main project involved:** cERL and STF @ KEK; CiADS (& its prototype facility: CAFe) @ IMP



STF （Superconducting test-facility）

cERL (compact ERL)

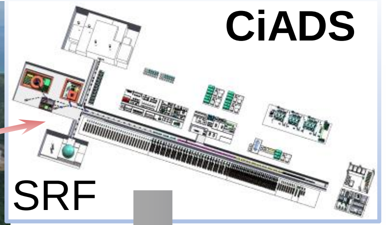




cERL 1.3 GHz, CW

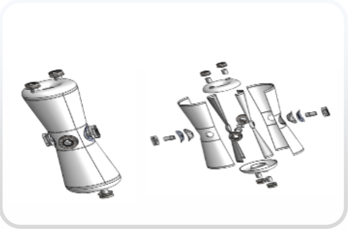
Cav	Q_L	RF Source
Bun	1.1e5	8 kW SSA
Inj_1	1.2e6	25 kW Kly.
Inj_2	5.8e5	300 kW Kly.
Inj_3	4.8e5	
ML_1	1.3e7	8 kW SSA
ML_2	1.0e7	16 kW SSA

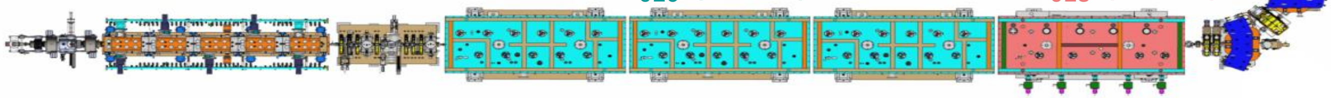
CiADS



Linac Prototype

- ~20 MeV, 10 mA
- 1 RFQ+ 23 SC
- Q_L: 5e5~1e6
- 10 kW SSA

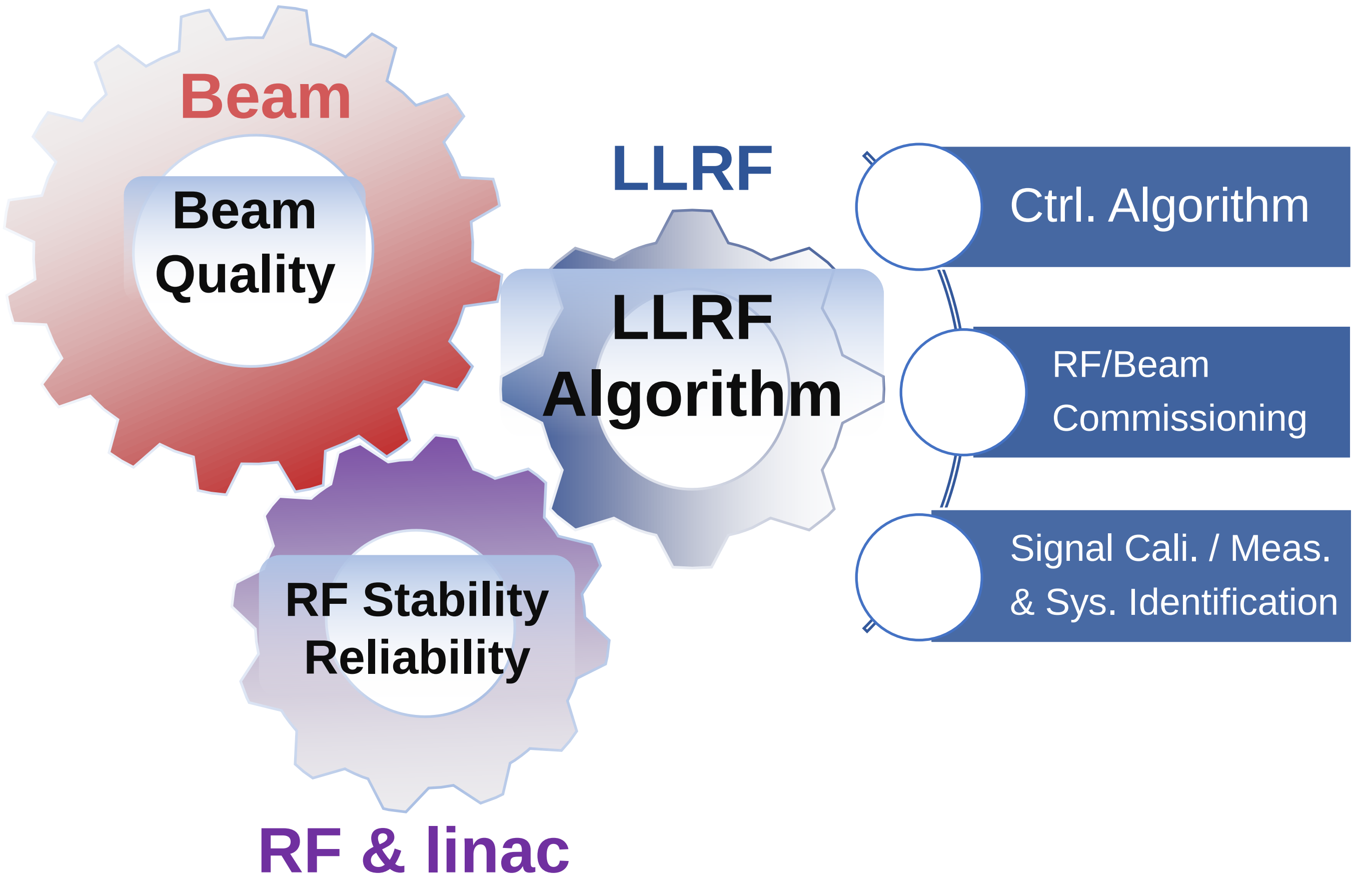




CAFe (Chinese ADS Front-end), 162.5 MHz, CW

LLRF Algorithms (Achievements in the last 3 years)

- Advanced **LLRF** algorithms are crucial for improving the beam quality



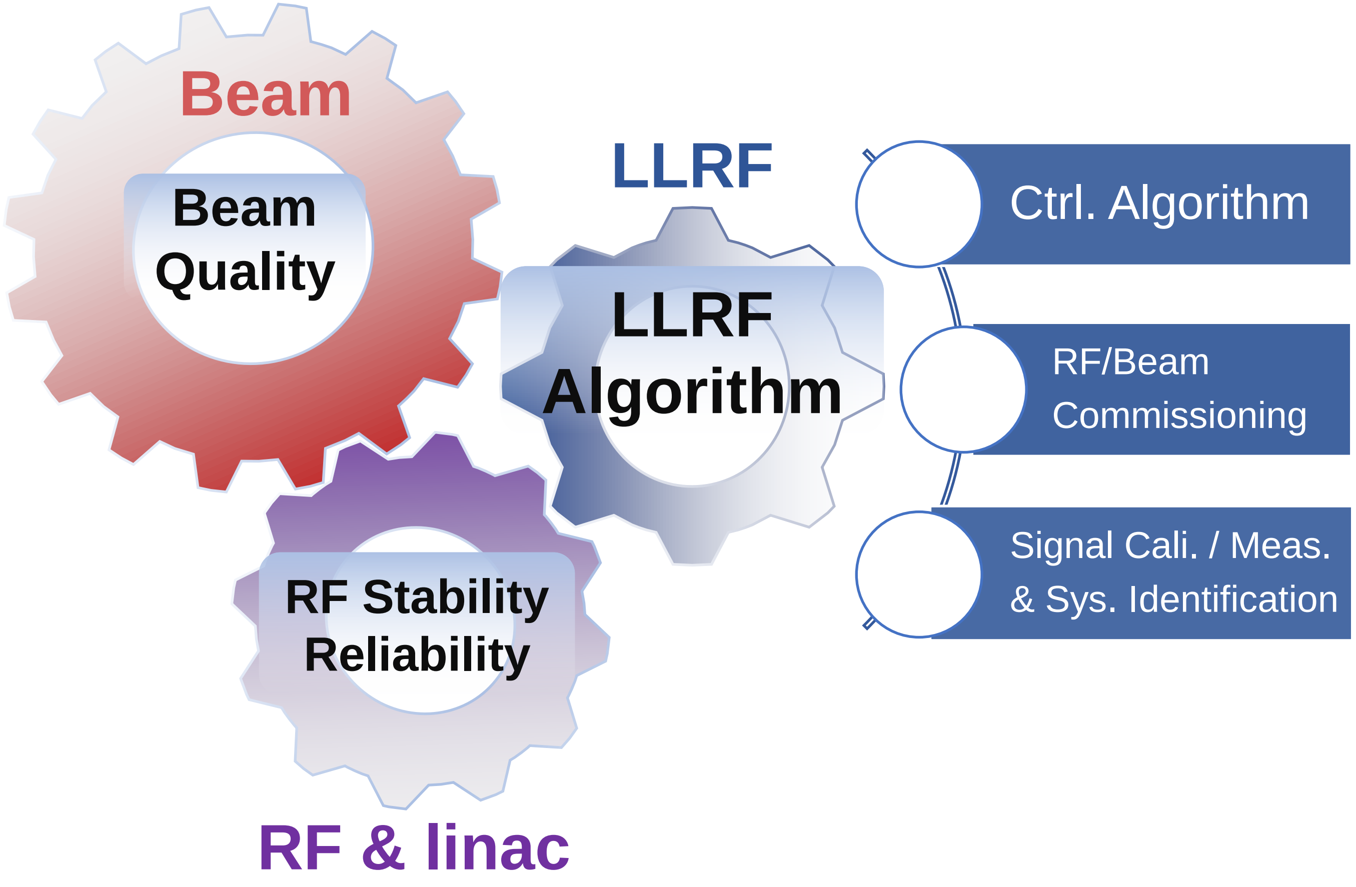
Academic Achievements

Disturbance Observer-based Ctrl.	PRAB, 24:012804, **2021** NST, 32:56, **2021**
Active Noise Control	NIM-A, 955:163820, **2020**
Modified Iterative Learning Ctrl.	NIM-A, 1026: 166237, **2022**
FF-based Rapid Phase Tuning	IEEE-TNS, 70:2, **2023**
Novel RF Pulse Shaping Scheme	NIM-A, 985: 164660, **2021**
Burst-noise Mitigation	NST, 32:140, **2022**
Channel Crosstalk Calibration	NIM-A, 1034: 166769, **2022** NST, 33:4, **2022**
Loaded Q and Detuning Cali.	NST, 34:123, **2023**
LFD Transfer Function Meas.	NIMA, 1012:165633, **2021**

KEK Work (orange: Disturbance Observer-based Ctrl., Active Noise Control, Novel RF Pulse Shaping Scheme) **IMP Work** (blue: others)

LLRF Algorithms (Achievements in the last 3 years)

- Advanced **LLRF** algorithms are crucial for improving the beam quality



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KEK Work   IMP Work

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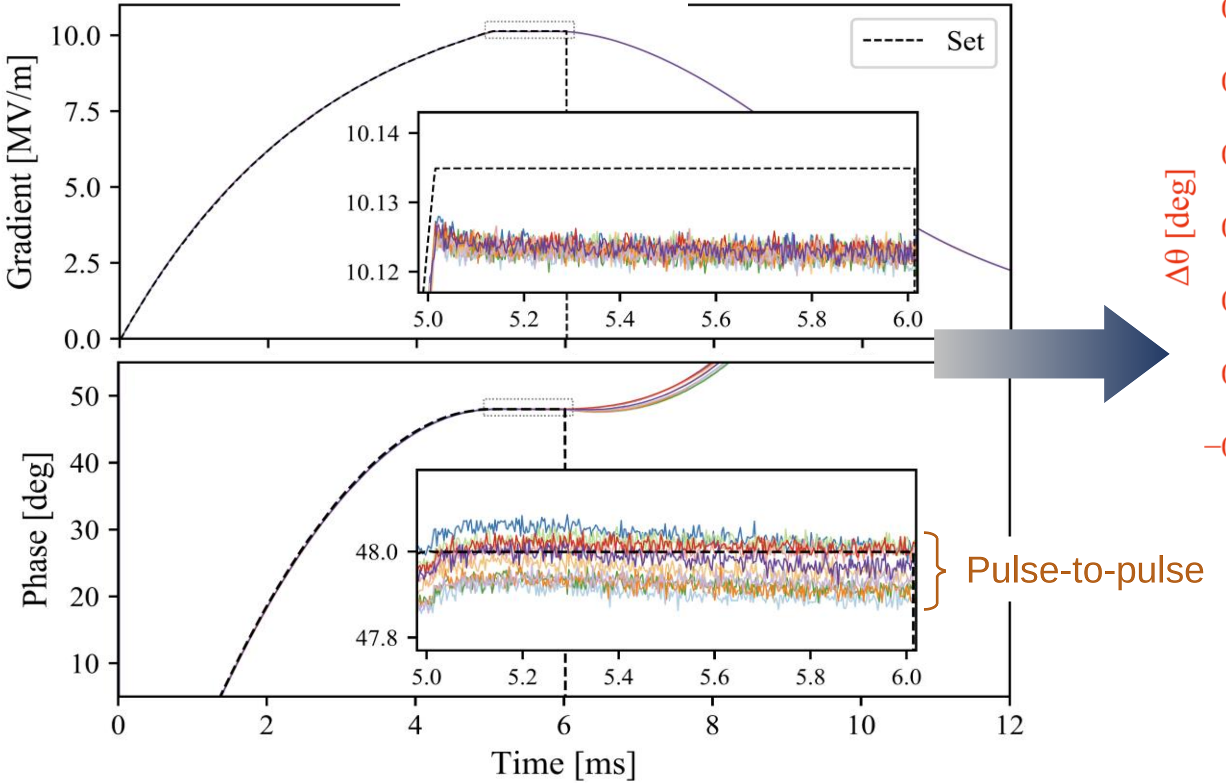
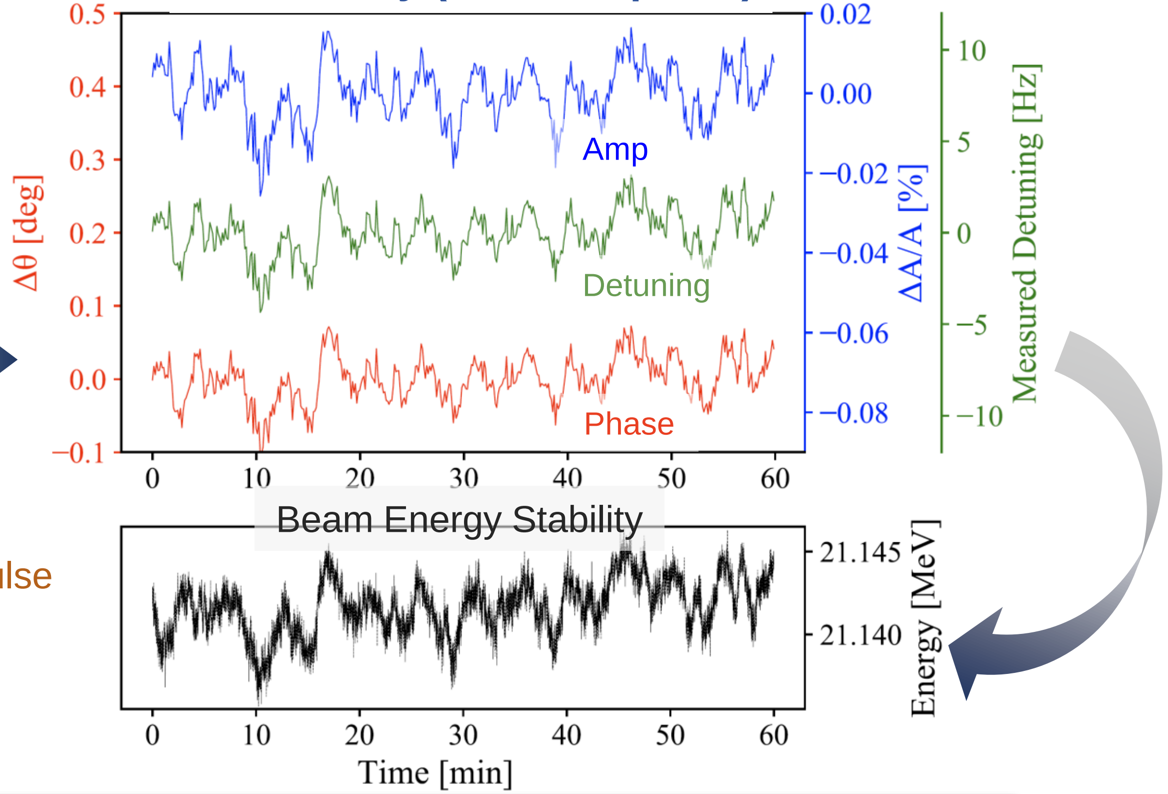
Pulse Mode Operation @ cERL

- Operated cERL in **pulse mode** to increase the beam energy (for isotope production)
- Encountered **poor pulse-to-pulse** stability under **PI ctrl** (Intra-pulse stability looks good)
- Observed fluctuations in the measured beam energy

Pulse shape



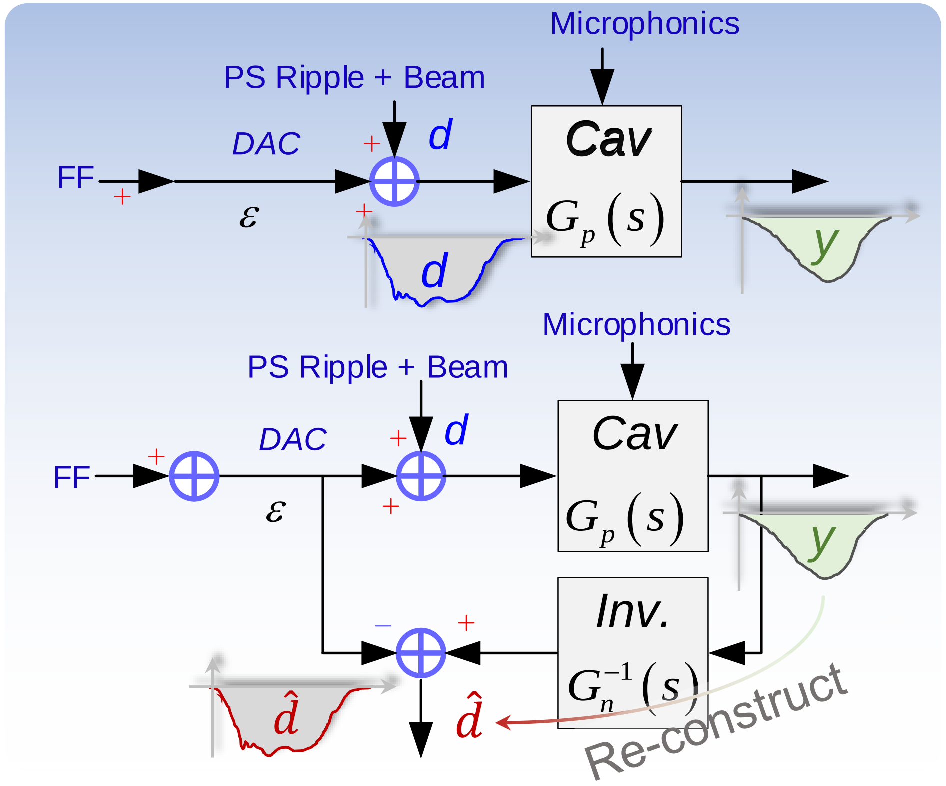
RF Stability (Pulse-to-pulse)



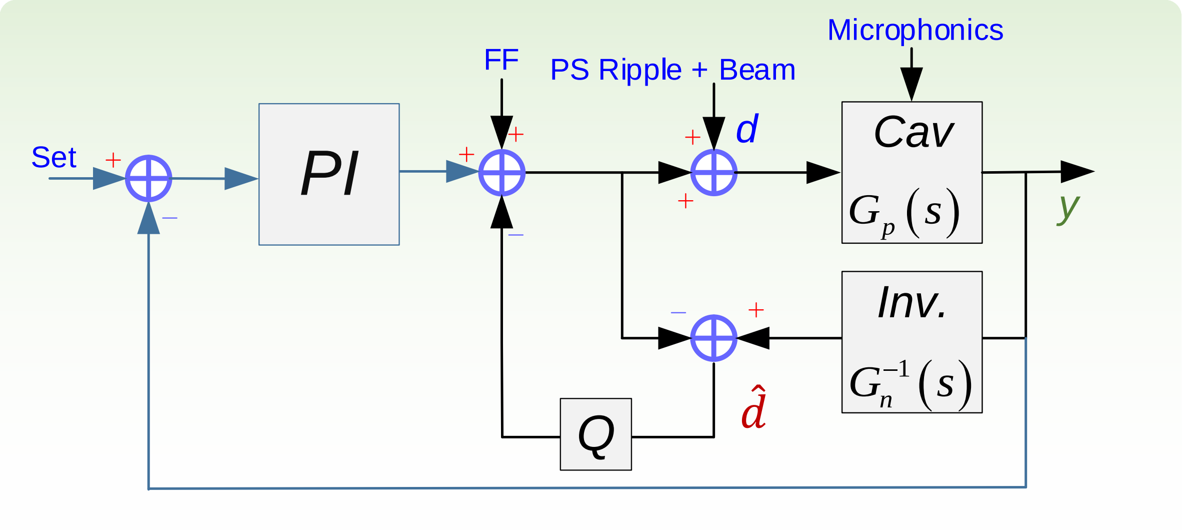
F. Qiu*, et al., Application of disturbance observer-based control on pulsed superconducting radio frequency cavities Phy. Rev. Accel Beam 21, 032003 (2018)

Disturbance Observer-based (DOB) Control

- Disturbance Observer (DOB) ctrl.: Reconstruct **disturbance estimation** ($\hat{d}$), then cancel d with $\hat{d}$ from the LLRF control loop



$$\hat{d} = (\varepsilon + d)G_p(s) \cdot G_n^{-1}(s) - \varepsilon = d$$



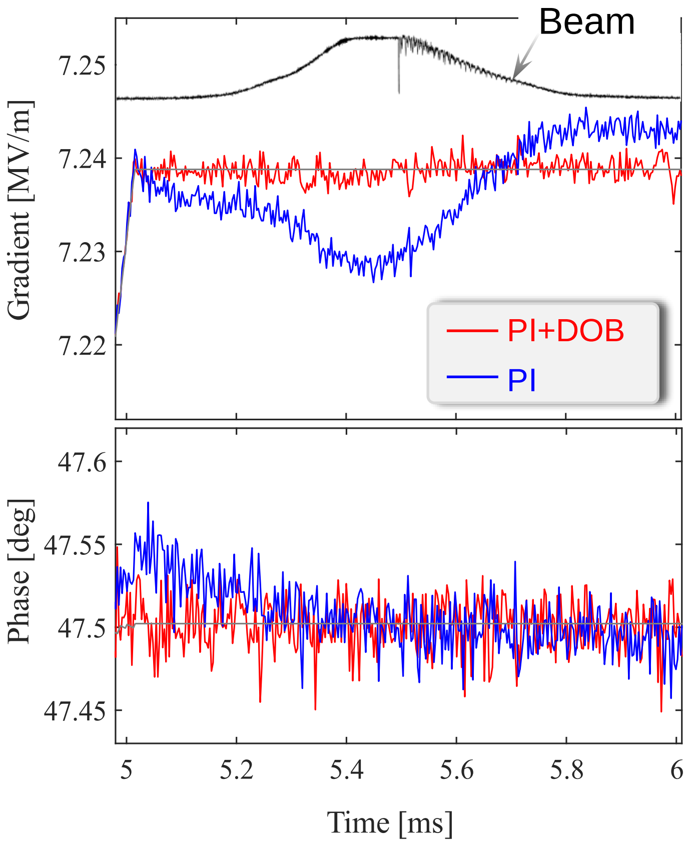
- $H_{PI,d\to y}(s) = \dfrac{G_p(s)}{1 + PI(s)G_p(s)}$
- $H_{PI+DOB,d\to y}(s) \approx [1 - Q(s)] \cdot \dfrac{G_p(s)}{1 + PI(s)G_p(s)}$

$$s = j\omega \to 0, Q(s) \approx 1, \to \ 1 - Q(s) \approx 0$$

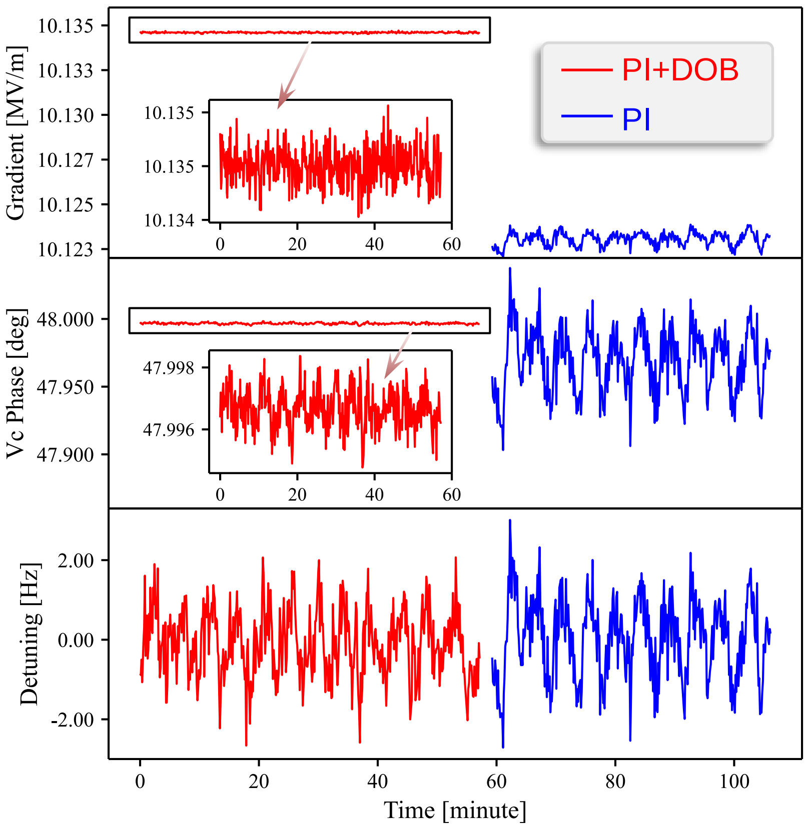
DOB Control (cont'd)

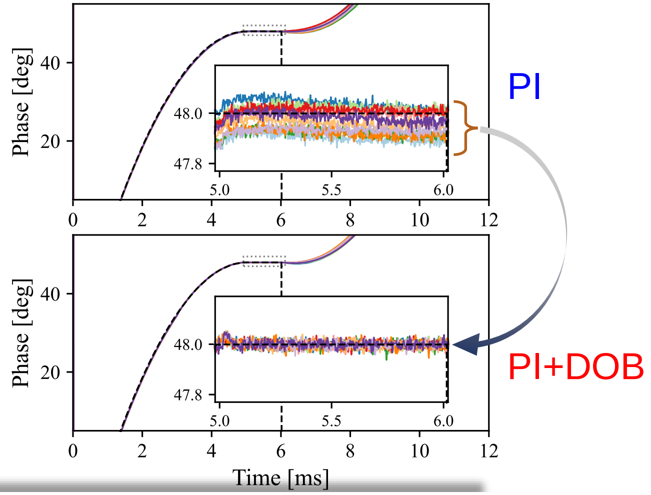
- High RF stabilities and beam energy stability have been achieved

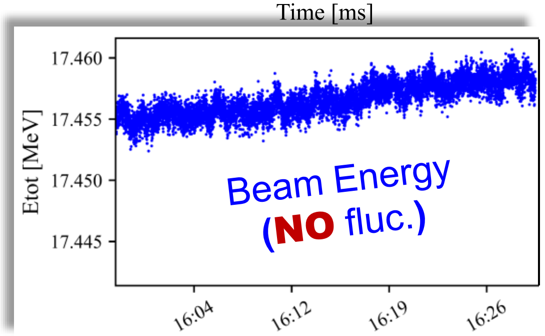
RF stabilities (intra-pulse)



RF stabilities (Pulse-to-pulse)







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F. Qiu*, et al., Combined disturbance-observer-based control and iterative learning control design for pulsed superconducting radio frequency cavities, Nucl. Sci. Tech. 32:56 (2021)

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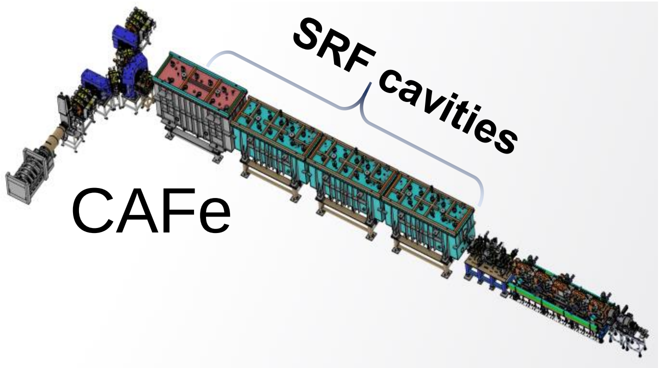
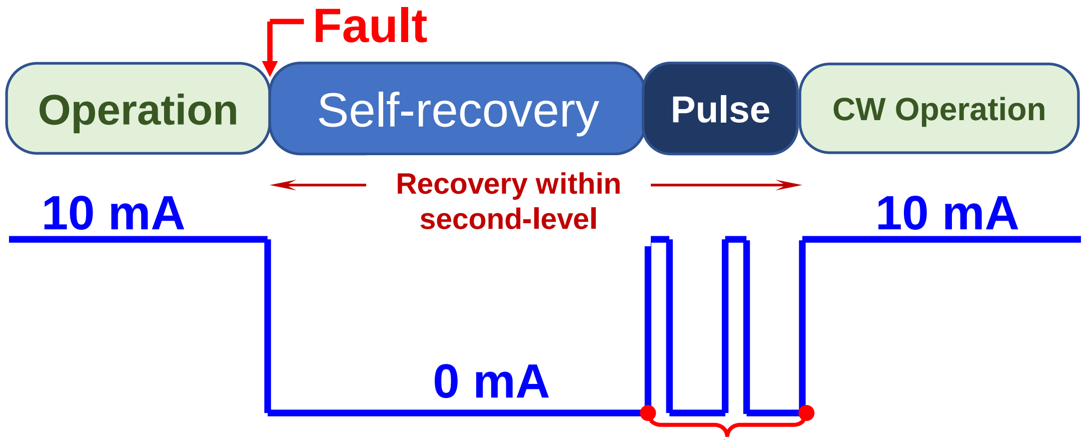
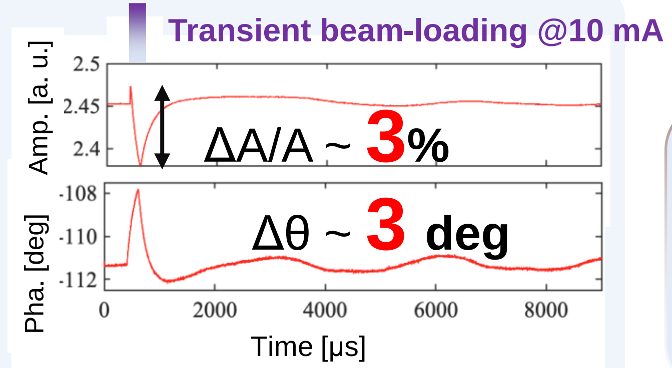
Transient Loading of 10 mA Beam @ CAFe

- **CAFe** → Stable operation of **10 mA** proton beam
  - In March 2021, CAFe achieved stable operation at hundreds of kW for 100 hours, confirming the feasibility 10 mA beam operation. The average beam current set **new world records** for proton linear SRF accelerators





☐ **CERN-COURIER** evaluates this achievement as an outstanding accomplishment and a **milestone breakthrough** in the field of ADS



The **transient loading** of a **10 mA** beam is the most critical technical challenge!!

Iterative Learning Control (ILC)

- **Iterative Learning Control** (ILC) →widely used for beam-loading compensation
  - Step1： Calibrate the error between the reference signal (r) and cavity pick-up signal (y)

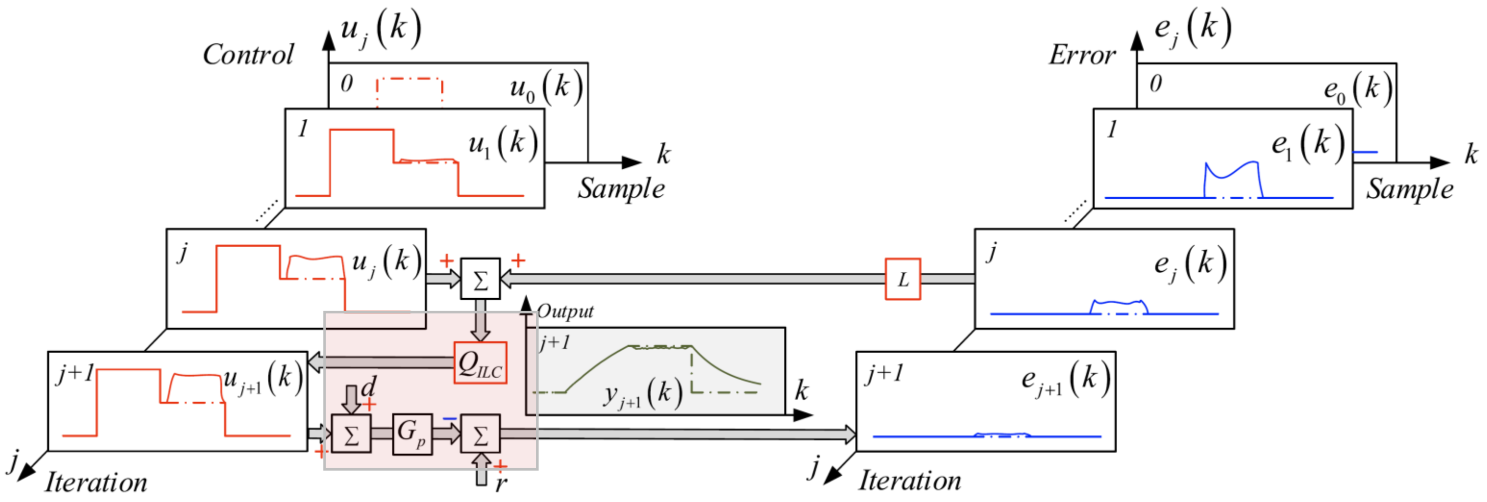
$$e_j(k)=r_j(k)-y_j(k)$$

  - 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

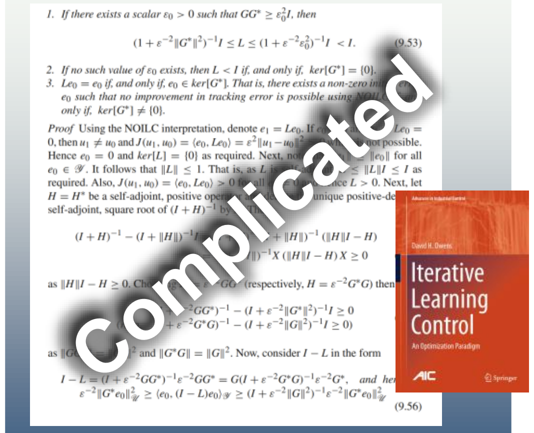
$$u_{j+1}(k)=\mathbf{Q_{ILC}}[u_j+\mathbf{L}(e_j)]$$

A matrix or a plant-inversion-model or PID



The main ILC algorithm is usually implemented outside FPGA

E.g. Norm Optimal ILC

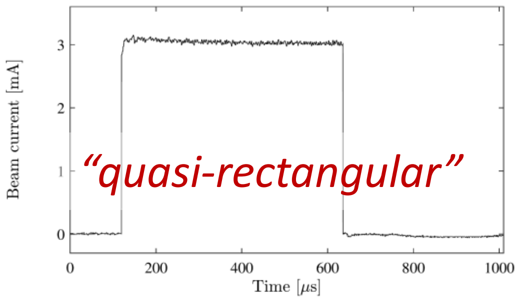


—— D. H. Owens, Springer, 2015

FPGA-based ILC (Basic Idea)

- In most cases, a beam pulse can be considered **quasi-rectangular**, which means the FF could also be rectangular pulse. This assumption may significantly simplify the update law

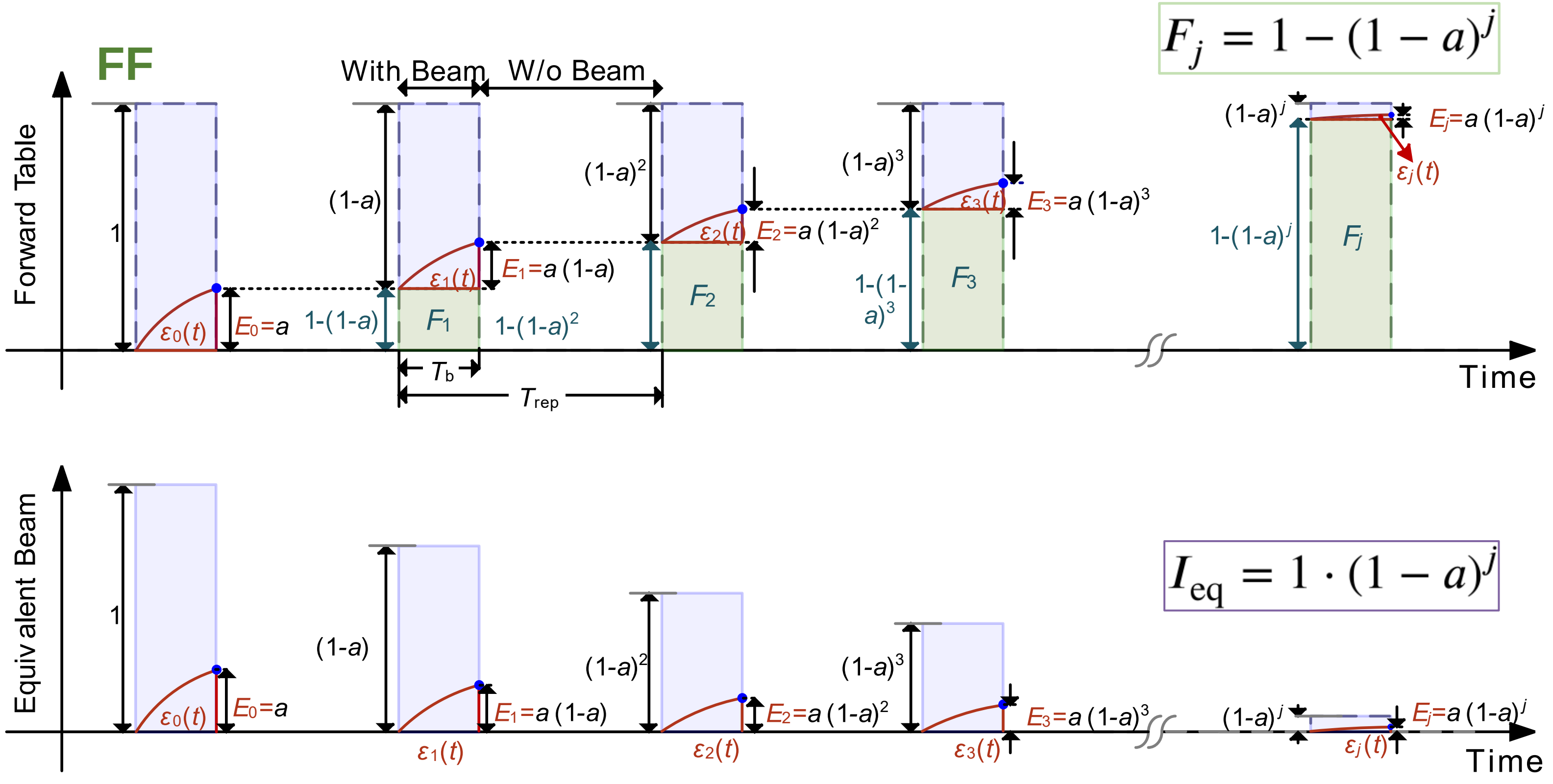
Beam profile @ CAFe



$$u_{j+1}(k) = \mathbf{Q}_{\mathbf{ILC}}[u_j + \mathbf{L}(e_j)]$$

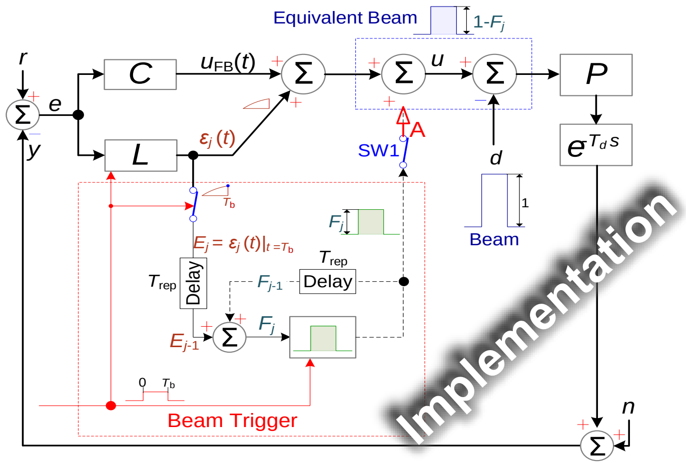
$$\begin{cases} u_{j+1}(k) = \varepsilon_j + F_j,\ \varepsilon_j = L(e_j) \\ \underbrace{F_{j+1} = F_j + E_j}_{} \end{cases}$$

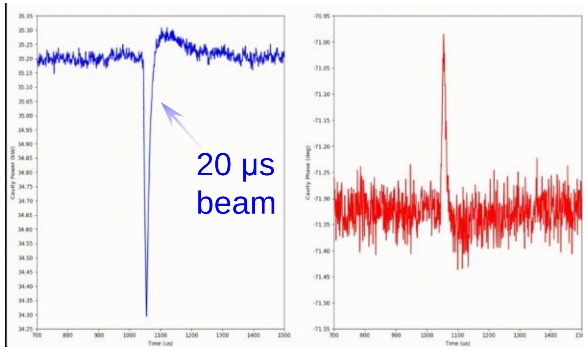
Constant Value (only a register inside FPGA)



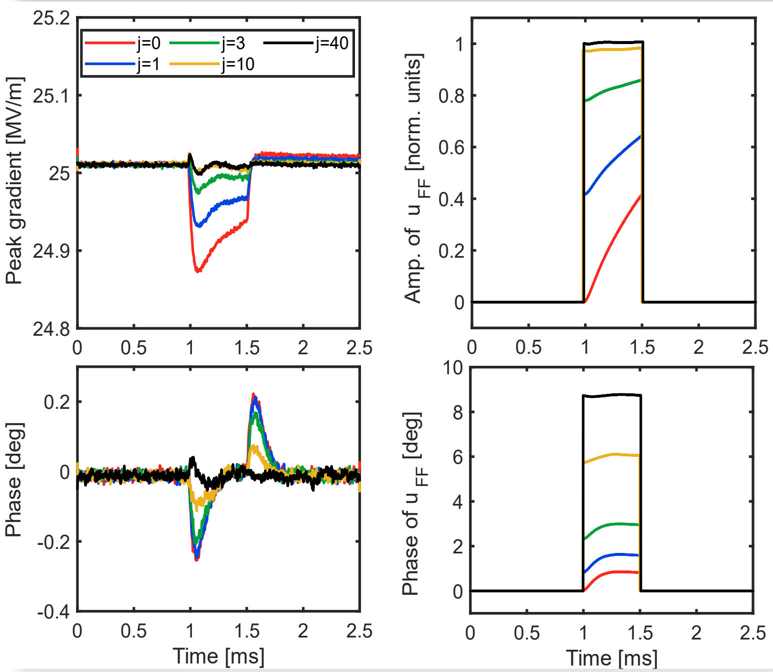
FPGA-based ILC (Confirmation)

- The new ILC algorithm was demonstrated during the CAFe beam-commissioning
  - **High rep. rate:** works in 1 kHz ~ 1 MH; **High bandwidth** (**NO** Q-filter)

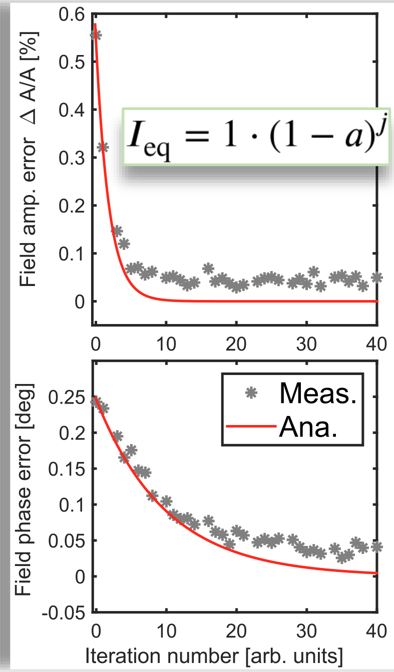


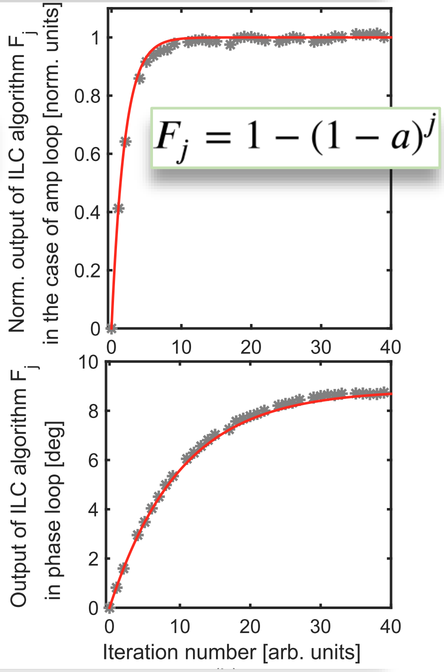


RF waveforms during iter. proc.



Convergence curve





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)

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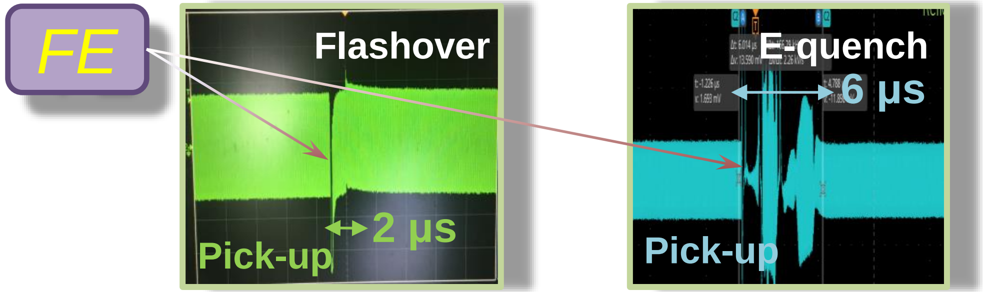
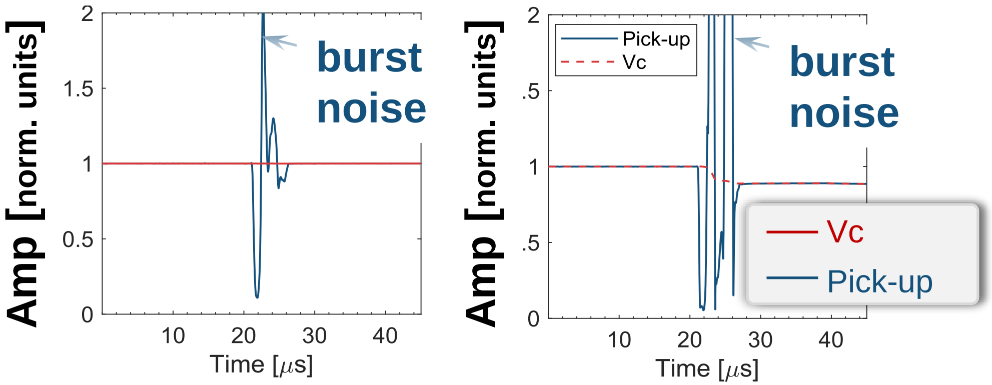
Burst-noise and its implication

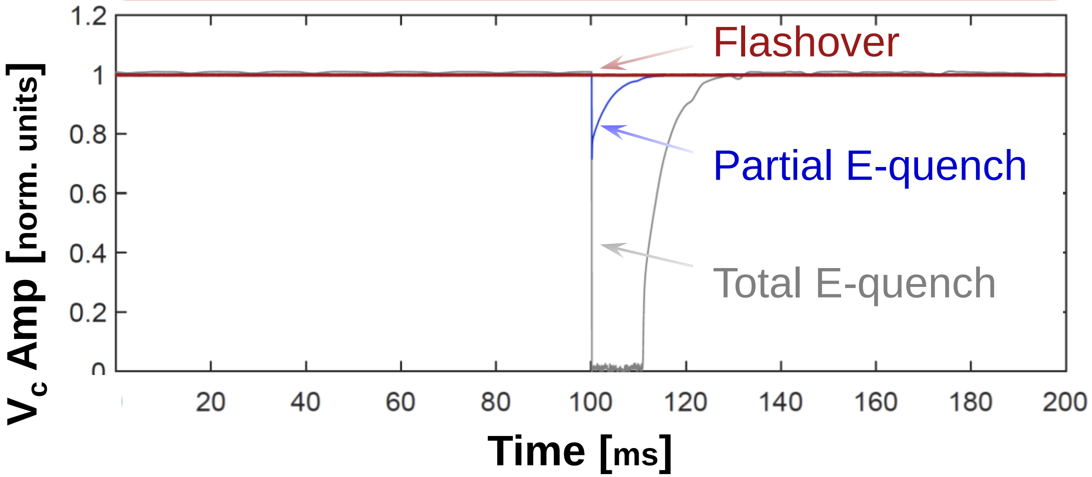
- Two types of burst noise signals induced by field emission
  - Flashover & (Partial) E-quench





- **Flashover**: Discharge at pick-up antenna, the actual field remains unchanged
- **(Partial) E-quench**: Discharge at cavity inner conductor, the actual field rapidly decreases

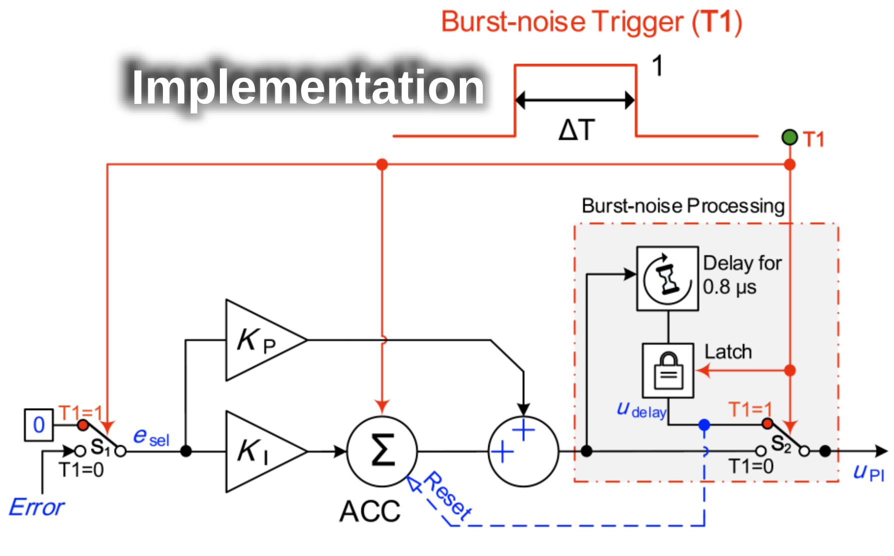
Item	Range	E_{acc} loss	Duration
Flashover	>15 MV/m	None	< 5 μs
Partial E-quench	>25 MV/m	2% ~ 30%	5 ~ 7 μs
Total E-quench	>35 MV/m	100%	~ 1 μs

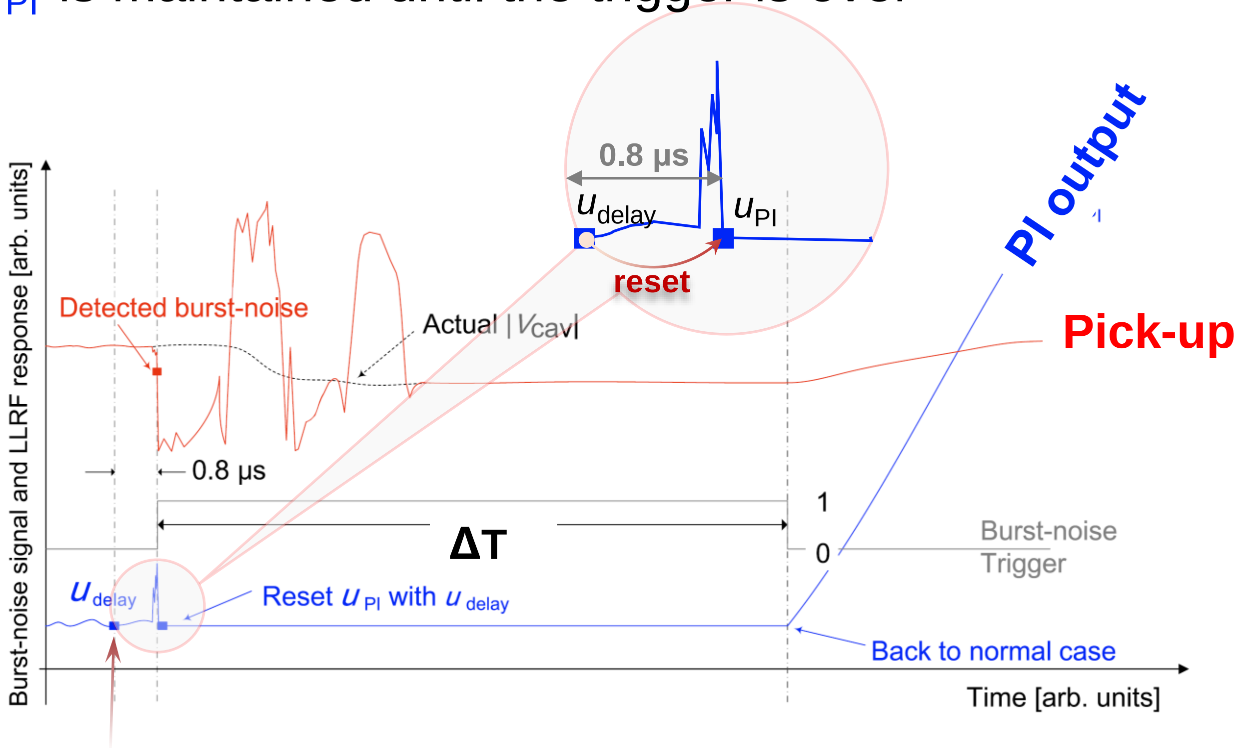


*The burst noise can lead to **an unexpected LLRF response,** eventually causing a cavity fault*

Burst-noise Processing Algorithm (Basic Idea)

- When the LLRF system detects the burst-noise events, a burst-noise trigger is immediately emitted and is held for a time interval of ΔT (>**15 μs**)
- The PI output (u_{PI}) is **overwritten by u_{delay}** which retains the data from u_{PI} **0.8 μs prior** to burst-noise trigger; then the u_{PI} is maintained until the trigger is over

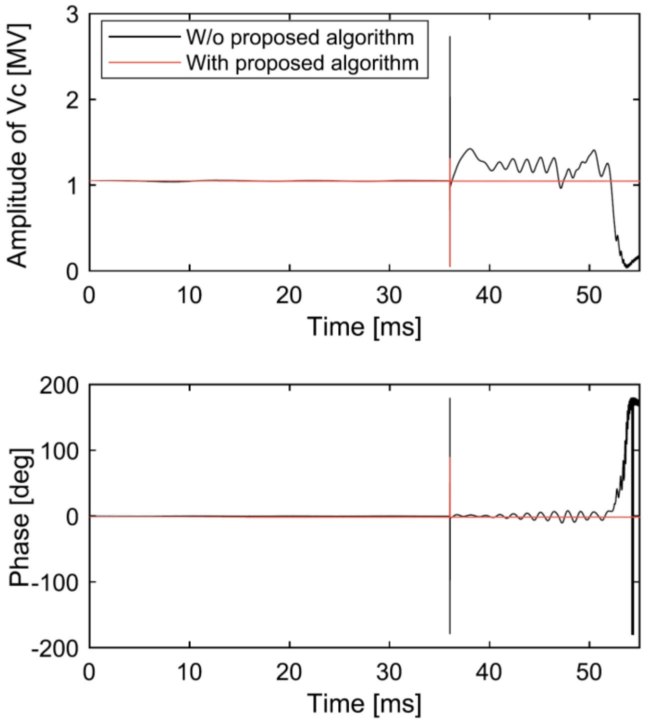


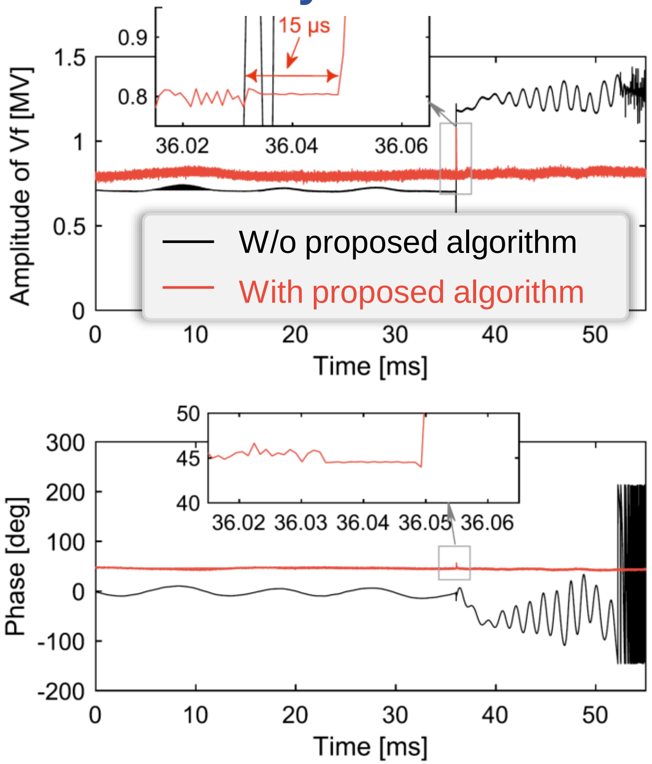


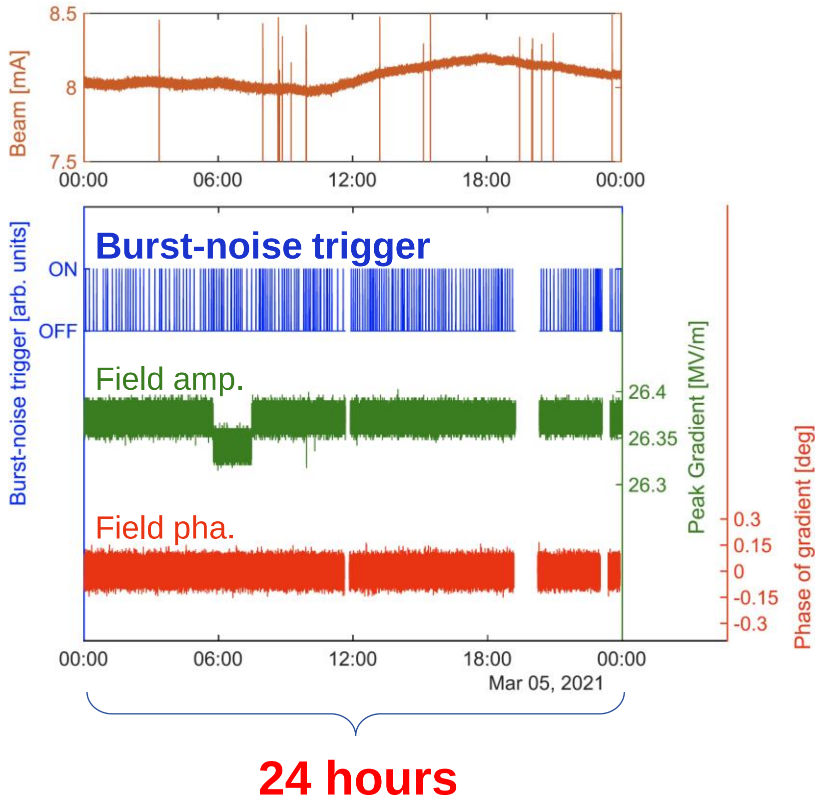
u_{delay} is the reasonable PI output

Burst-noise Processing Algorithm (Results)

- The unexpected LLRF response can be eliminated
- The effectiveness of the proposed algorithm was confirmed during the long-term operation

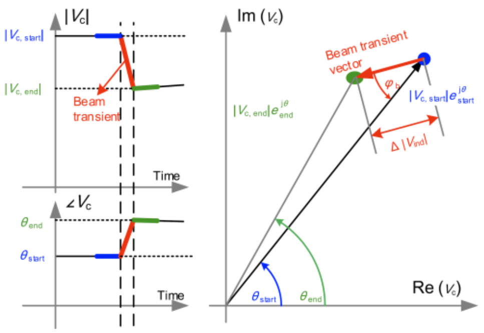




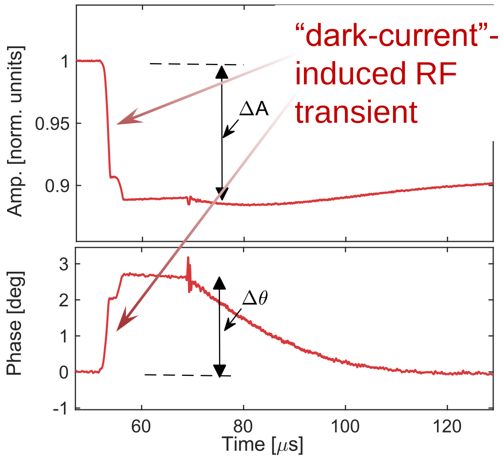


Dark-current Characteristic

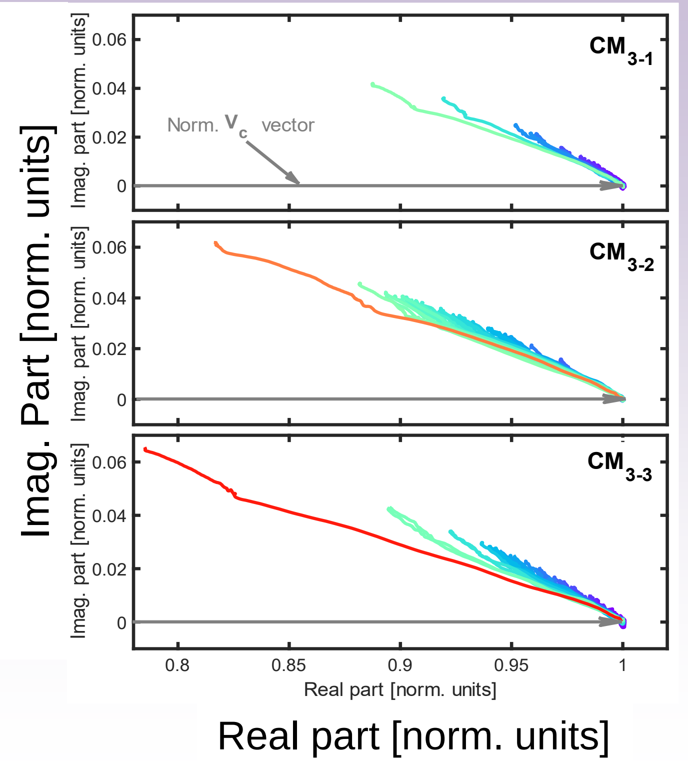
- The "partial E-quench" is accompanied by **dark-current** which can be seen as a kind of beam-loading. It is possible to characterize the dark current using the **"beam induced RF transient"**



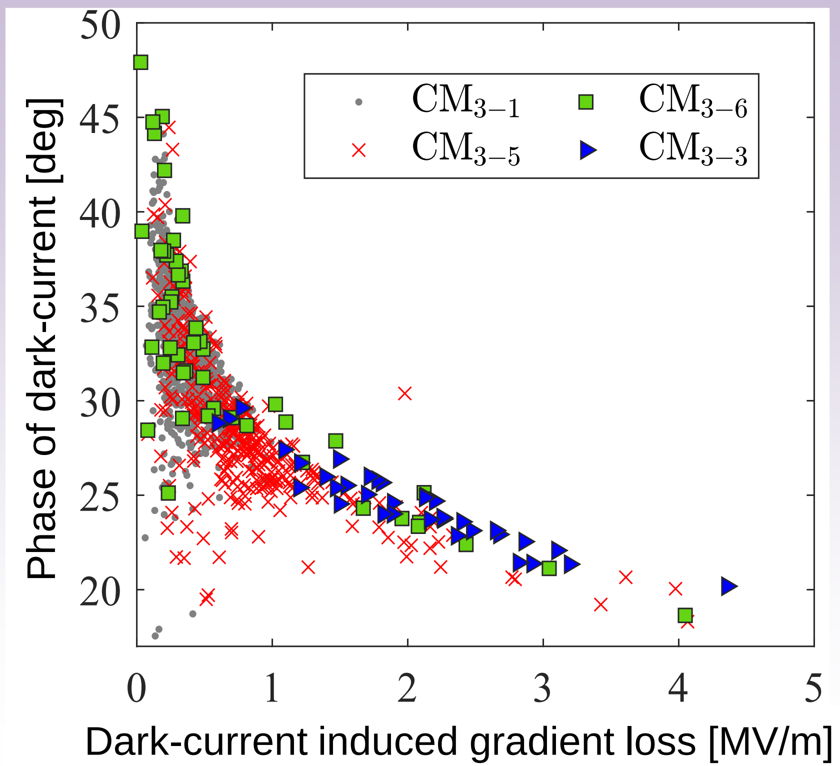
Partial E-quench



"dark-current"-induced transient (I/Q)



Statistical Distribution



F. Qiu* et al., In-situ mitigation strategies of field emission induced cavity fault using low-level radio-frequency system, Nucl. Sci. Tech. 33:140, 2022

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01 Self-Introduction

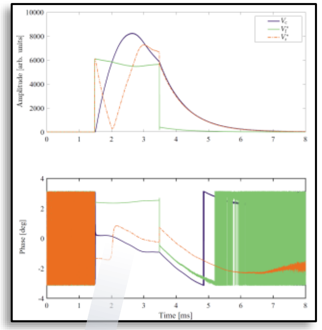
02 Research Activities

- Disturbance Observer-based Ctrl.
- Modified Iterative Learning Ctrl.
- Burst-noise Mitigation
- Channel Crosstalk Calibration

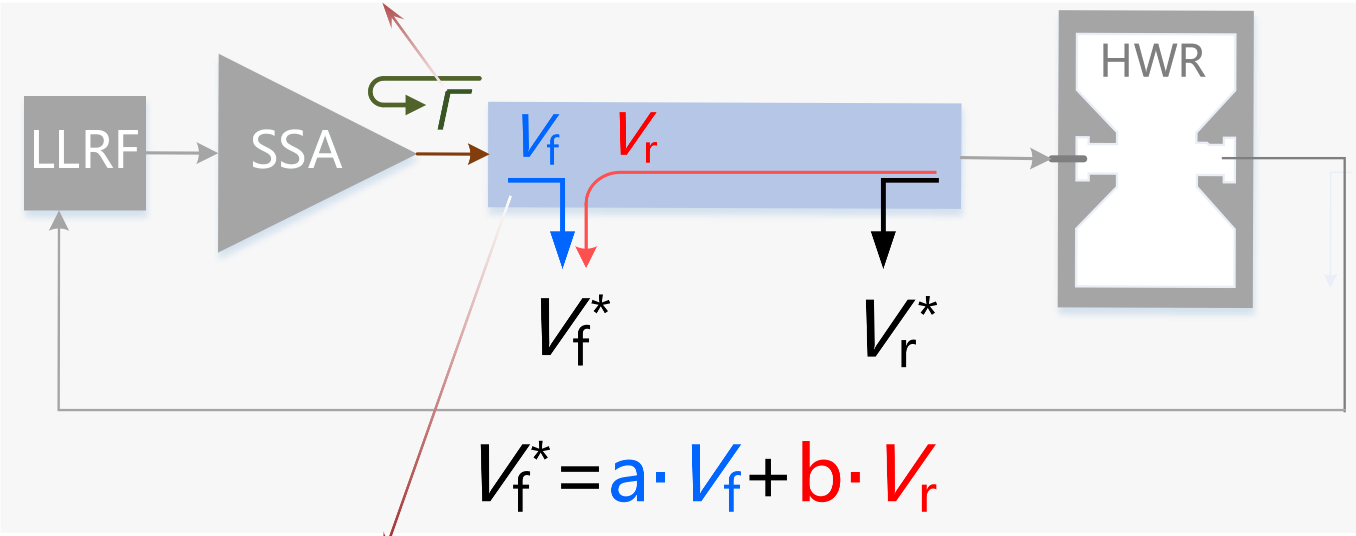
Issues impacting RF Signal Measurements

- Measurement accuracy of RF signals 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) → **See J. Y. Ma's Poster (ID: 09)**

DESY's Method



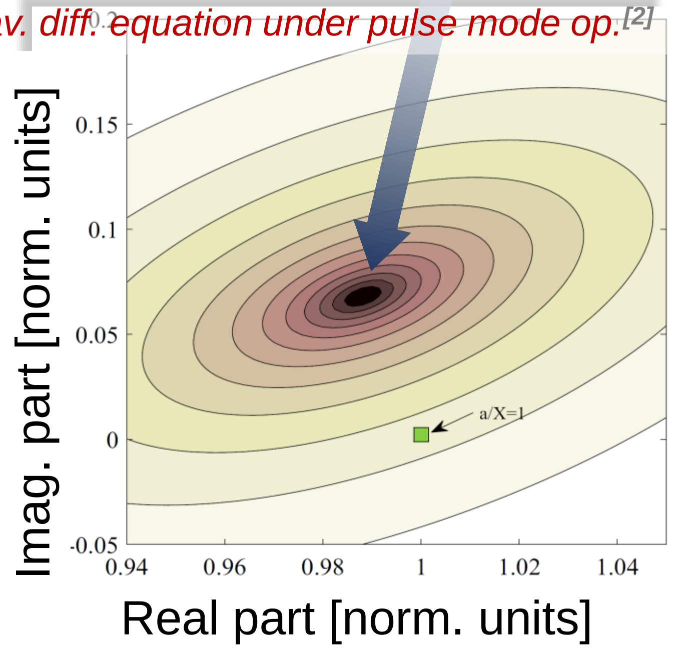
May impact the field decay process and cause the inaccurate meas. of Q_L [1]



$$V_f^* = a \cdot V_f + b \cdot V_r$$

May impact the measurement of V_f signal

The coefficients a b c d can be calibrated using the cav. diff. equation under pulse mode op.[2]



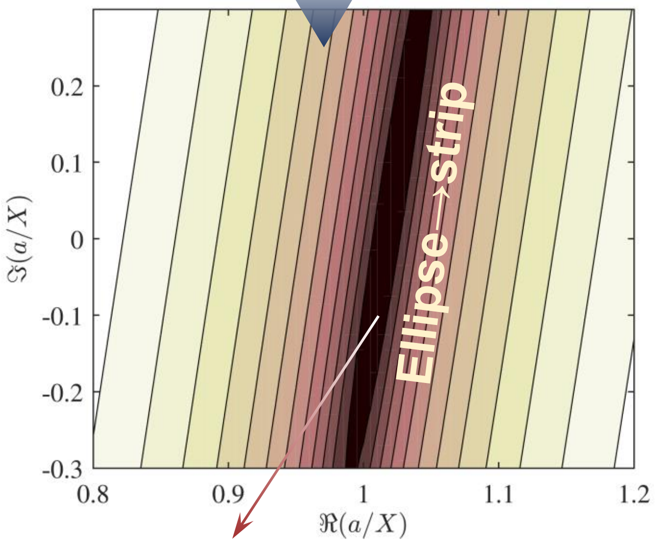
[1] J. Y. Ma, …F. Qiu* et al., Measurement of the cavity-loaded quality factor in superconducting radio-frequency systems with mismatched source impedance, Nucl. Sci. Tech. 33:123, 2023
[2] A. Brandt, PhD thesis, Universitt Hamburg, 2007

Novel Signal Calibration Algorithm

- We proposed a novel signal calibration algorithm more suitable for CW mode machine

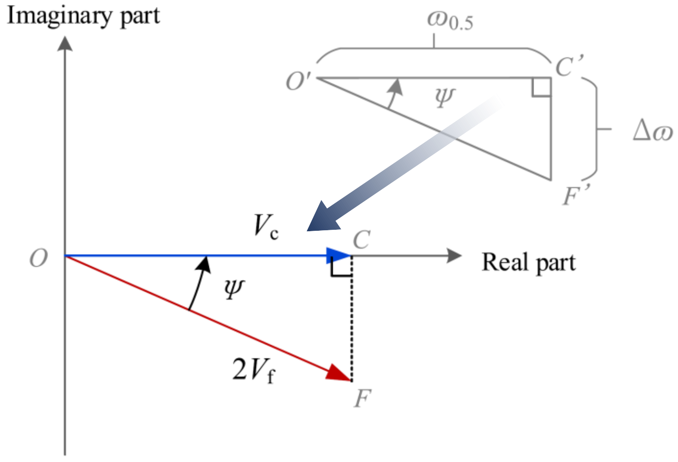
For CW machine, we have:

$$\frac{\mathrm{d}V_c}{\mathrm{d}t} \approx 0$$



We can't locate the opt. coef. (using DESY's method)

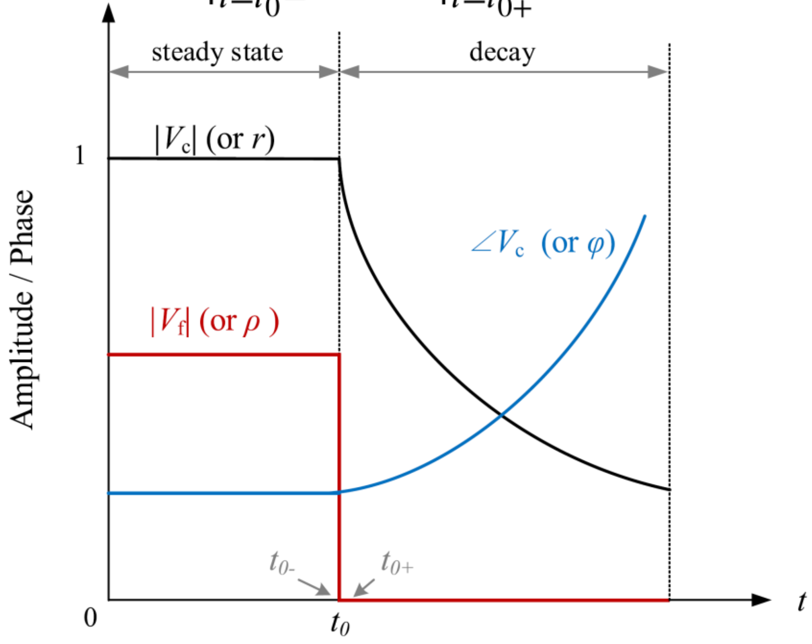
Condition 1: Vectors Identity



$$\mathrm{Re}\left[\left(\frac{V_f}{V_c}\right)\right] = 0.5 \quad \text{(Condition I)}$$

Condition 2: Detuning Continuity

$$\Delta\omega|_{t=t_0-} = \Delta\omega|_{t=t_0+}$$

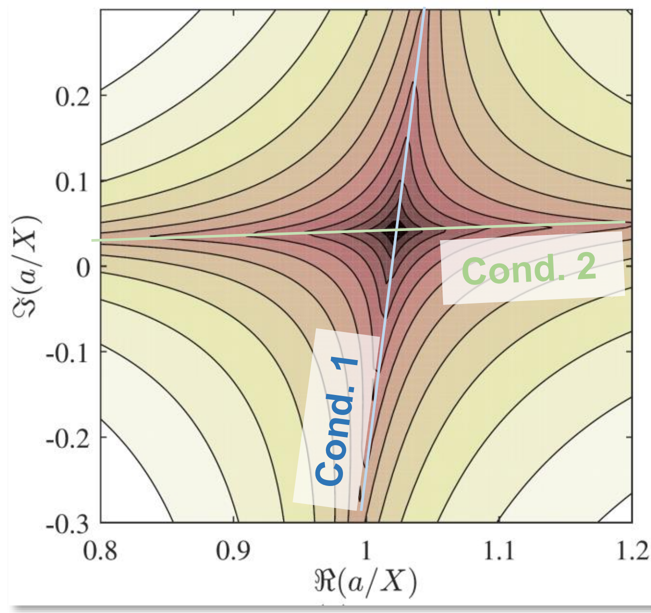


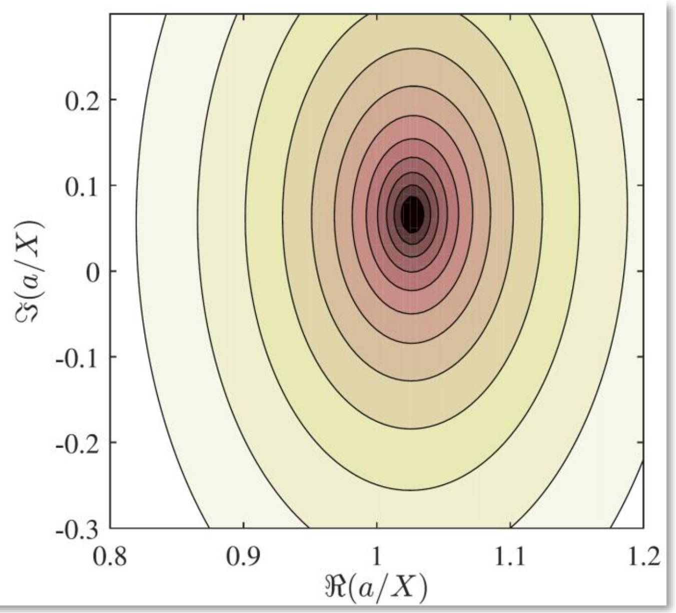
$$\tan[\varphi - \theta(a)]\omega_{0.5}|_{t=t_0-} = \dot{\varphi}|_{t=t_0+} \quad \text{(Condition II)}.$$

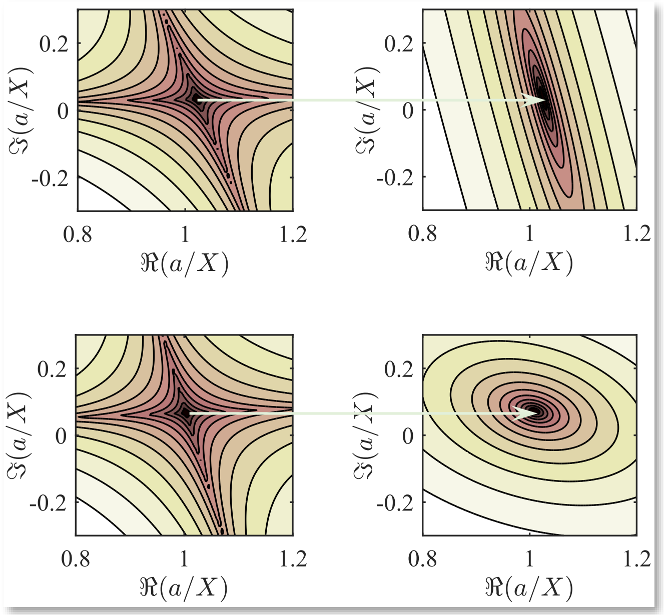
Novel Signal Calibration Algorithm (Results)

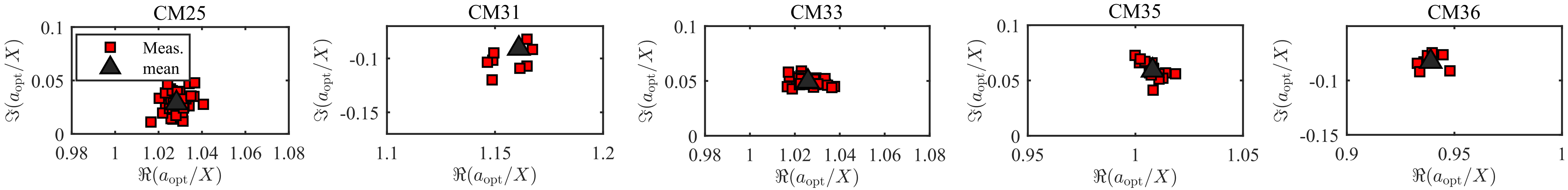
- The proposed algorithm was confirmed at CAFe

Proposed Algorithm (CW) **DESY's Algorithm (Pulse)**









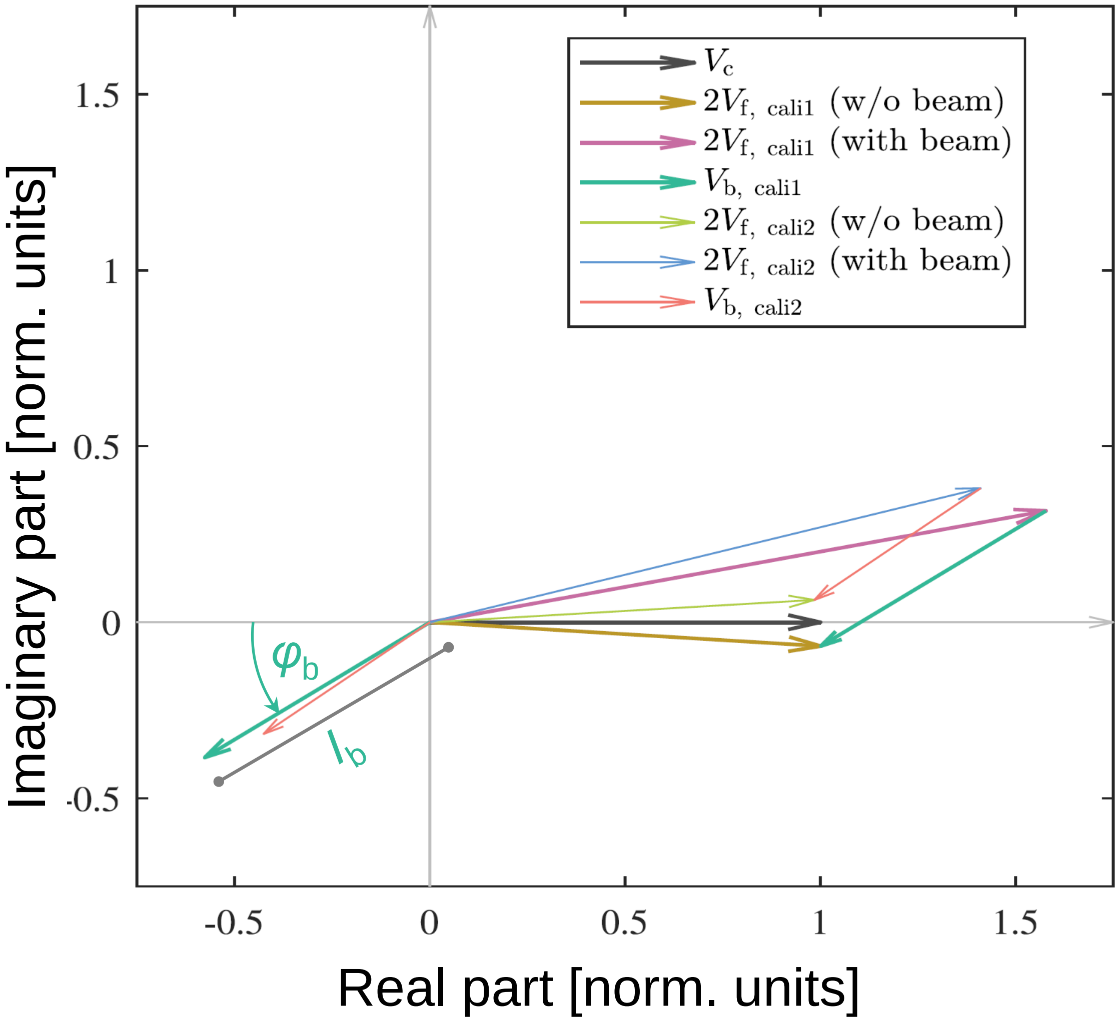
J. Y. Ma, **F. Qiu*** et al., Precise calibration of cavity forward and reflected signal using low-level radio-frequency system, Nucl. Sci. Tech. 33:4, 2022
F. Qiu* et al., Approach to calibrate actual cavity forward and reflected signals for continuous wave-operated cavities, Nucl. Instrum. Methods. A . 955,166237 (2022)

Beam Phase Calibration (application)

- Within the calibrated optimal coefficients, it is possible to accurately calculate the RF vectors, as well as the beam phase

BPM Meas.	Beam Phase using RF	
	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°) (5.6 mA, –34°) (3 mA, –34°)	(8.2 mA, –33°) (5.6 mA, –33°) (2.9 mA, –36°)	(6.3 mA, –36°) (4.3 mA, –36°) (2.2 mA, –39°)

Cross-talk was considered



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KEK

CONTENTS

Summary

- Innovatively applying **DOB control** in the LLRF community, achieving precise beam energy spread control with remarkable results at cERL

- Leveraging prior knowledge of the beam profile to develop a **FPGA-based real-time ILC control**, successfully suppressing RF transient instabilities caused by the10 mA CW proton beam at CAFe

- Developing **a real-time digital filter** with robustness to FE-induced burst noise, resolving RF instability and improving machine reliability of CAFe

- Proposing a novel **cross-talk calibration** algorithm for SRF cavities operated in CW mode

Acknowledgments

- I would like to express my gratitude to LLRF **SPC & LOC** for this incredible honor. I would also like to thank the members of the **Selection Committee** for their diligence and hard work in choosing me for this award. Special thanks to generous **Dimtel Inc.** for their invaluable support

- I want to acknowledge the unwavering support **of RF group and Beam-commissioning team** in **KEK** and **IMP**
  - **KEK: S. Michizono** (**Supervisor, Division Head**), T. Matsumoto, T. Miura, K. Furukawa, Z. Fang, H. Sakai, M. Omet, D. Arakawa, S. Matsumoto, E. Kako, K. Umemori, H. Katagiri, S. Fukuda, T. Furuya, T. Miyajima, T. Obina…
  - **IMP: Y. He** (**Division Head**), Z. J. Wang, G. R. Huang, L. P. Sun, Z. Gao, T. C. Jiang, Z. L. Zhu, Q. Chen, L. B. Xu, Z. H. Xue, J. Y. Ma, L. J. Yang, C. Y. Xu, Z. L. Zhang, T. Tan, M. X. Xu, Z. Q. Yang, A. D. Wu, C. Y. J. Wong, D. D. Luo…

- I owe a debt of gratitude to my family, colleagues, and friends

- Finally, thanks again for this incredible honor. I am deeply moved and inspired to continue my work with renewed passion and dedication

Thanks for your attention

감사합니다

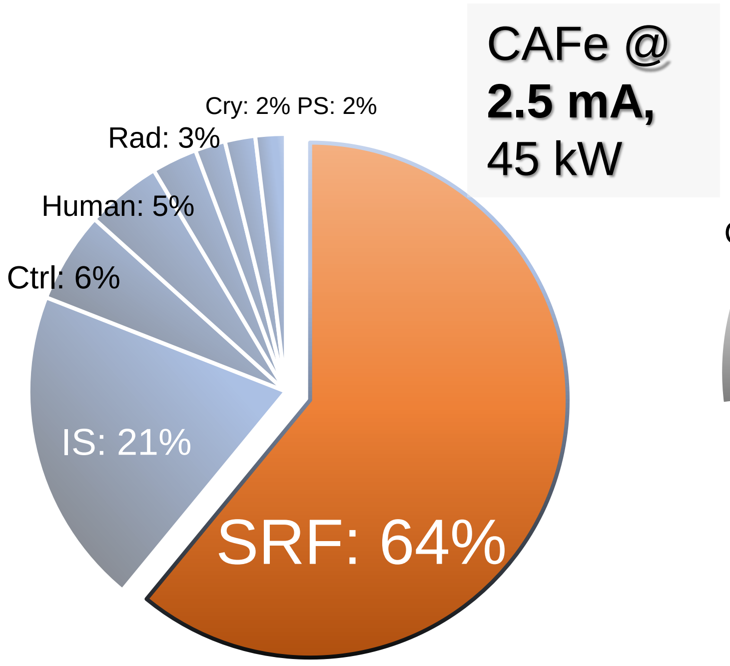
Back-up Slides

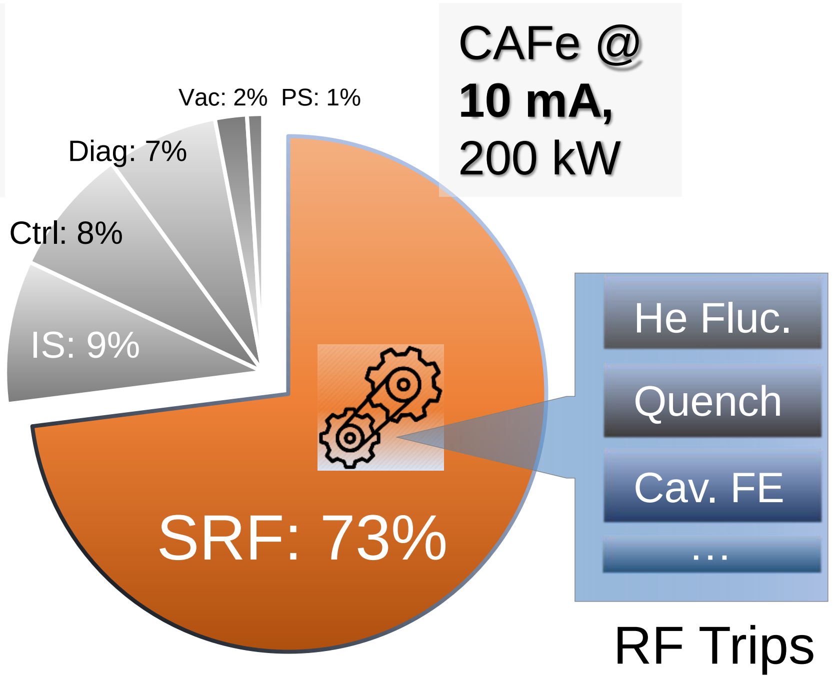
SRF faults at CAFe

SRF faults account for most beam trips (Eu-XFEL/CEBAF/ELBE/CAFe)

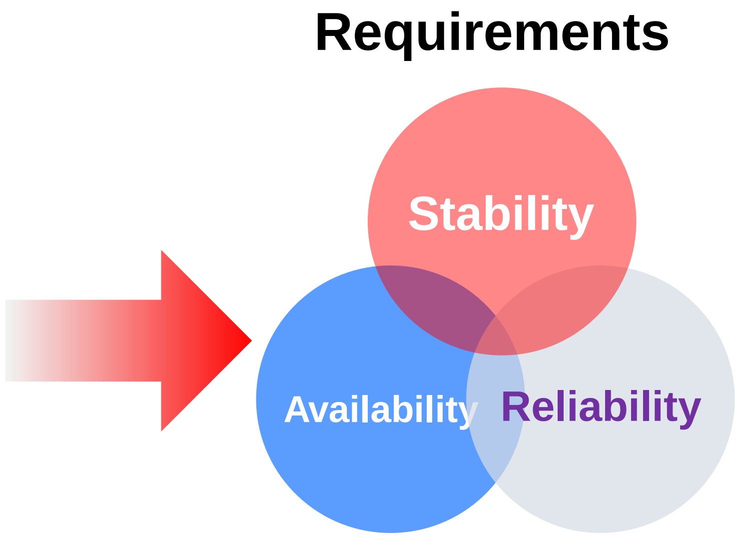
Problem: Minimize cavity faults to enhance beam availability, reliability, and stability

Solution: Gain a deep understanding of the unstable mechanisms behind cavity faults





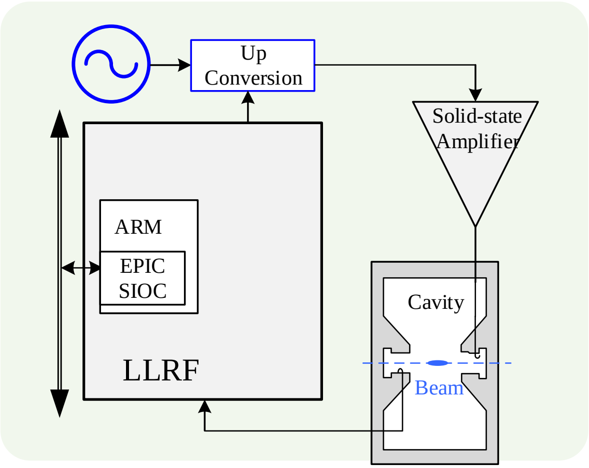
SRF faults contribute to the dominant beam trips



SRF faults at CAFe (cont'd)

Digtial low-level RF

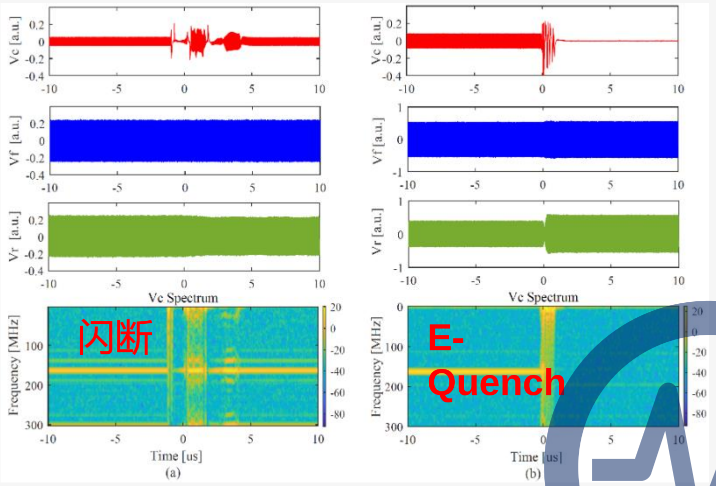
- Capture fault waveform
- Analyze fault patterns & mechanisms



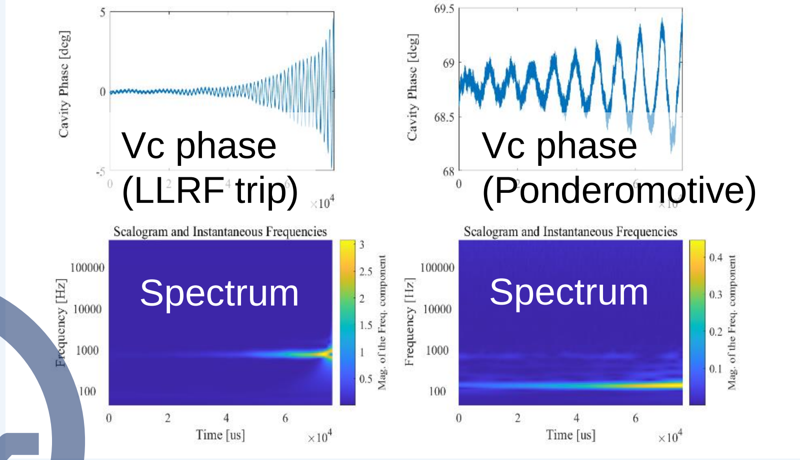
Features of the DAQ：

- 10 kHz ~ 100 kHz rates
- 0.5 s ~ 5 s waveforms
- 8 ADC channels

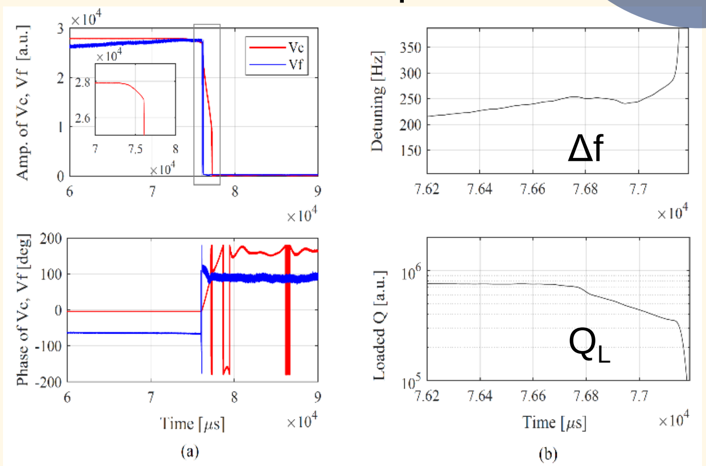
Flashover & E-quench



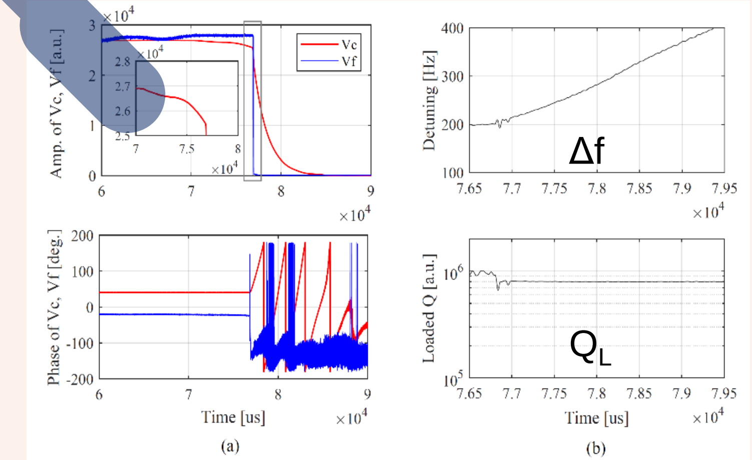
LLRF trip & Ponderomotive



Thermal quench

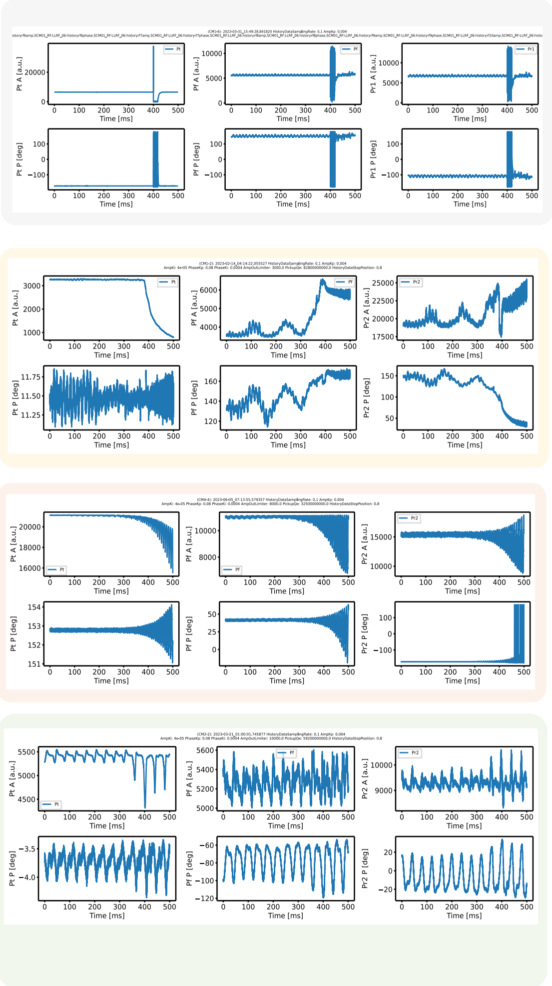


Helium fluc.

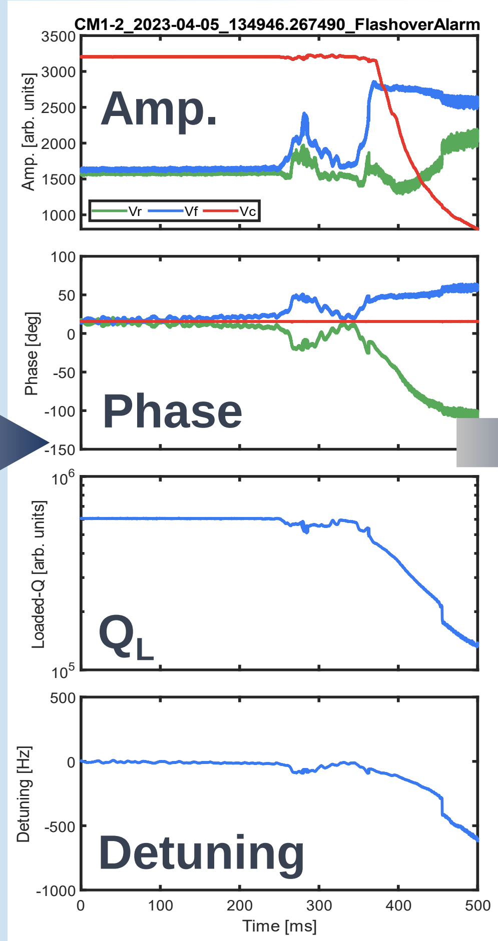


ML-based SRF faults Classification

Raw fault signals



Signal Preprocessing



Feature Extraction

- Q_{id}
- E_{id}

Model-based

- F_{max}
- E_{fmax}

FFT & Wavelet

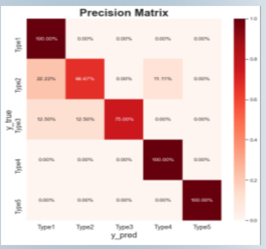
- Std_A_1
- Std_A_2
- $Mean\_P_{diff}$
- $Max\_ P_{diff}$
- $Diff\_P_f$
- …

Statistical Features

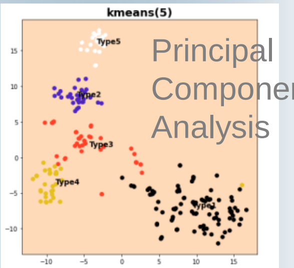
ML classification

- SVM (support vector machine)
- Radom Forest
- K-means
- …

Confusion matrix

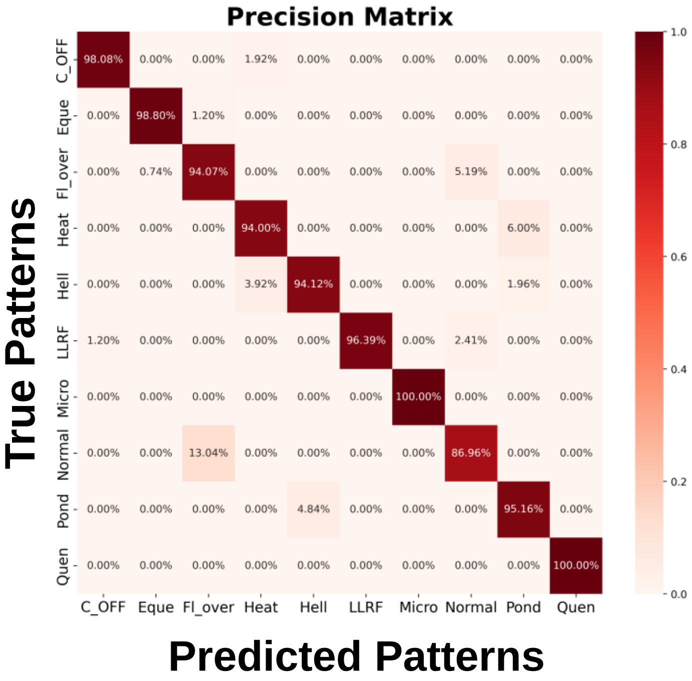


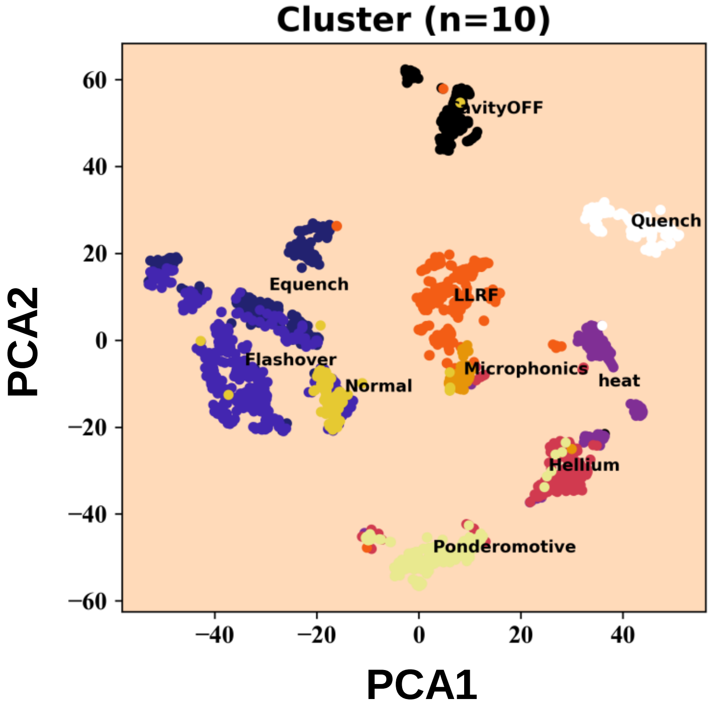
PCA plot

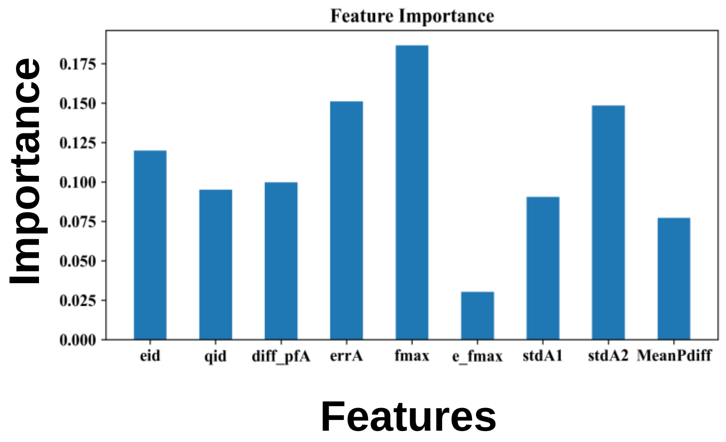


ML-based SRF faults Classification (cont'd)

- **Precision:** Roughly > **90**% (compared with expert predictions), seems promising
- **PCA analysis:** Which patterns are prone to confusion?
- **Feature importance analysis:** Which features have the greatest impact on the results?



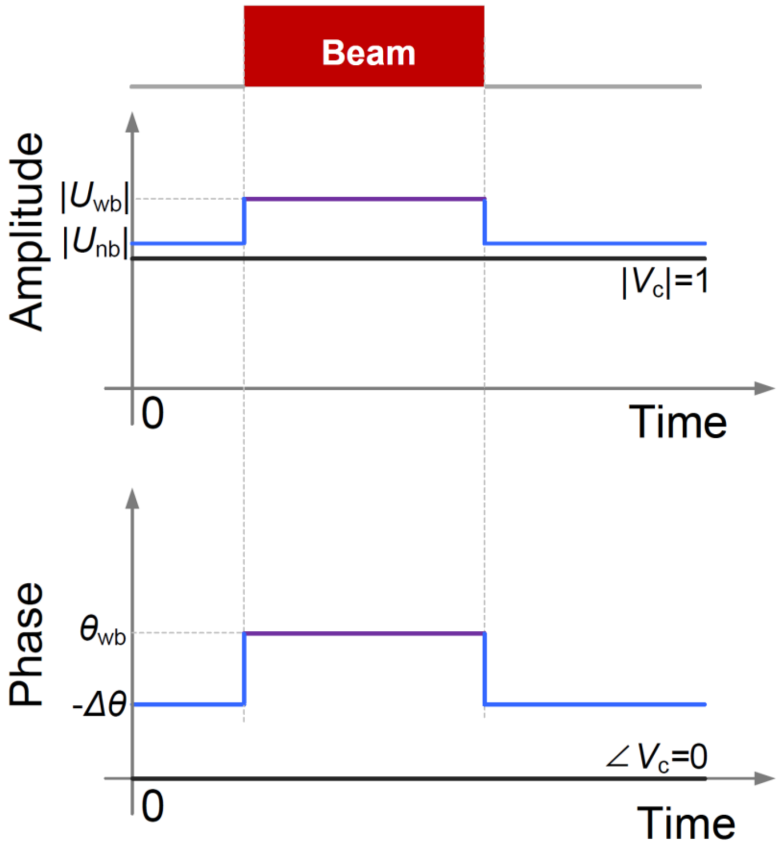




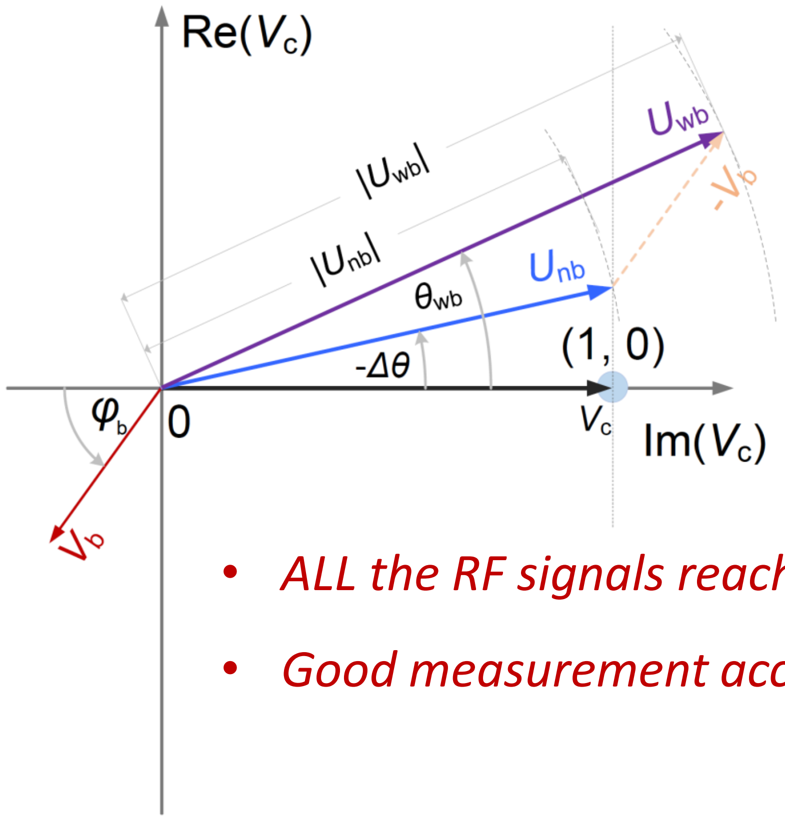
Beam Phase Calibration

- The cavity forward power would be different in the case of with and w/o beam
- Characterize the beam vectors $\boldsymbol{V}_b$ using $\boldsymbol{V}_f$ signal with beam ($\boldsymbol{U}_{wb}$) and w/o beam ($\boldsymbol{U}_{nb}$)

Waveform Plots



Vector Plots (in steady-state)



$\boldsymbol{V}_b = \boldsymbol{U}_{nb} - \boldsymbol{U}_{wb}$

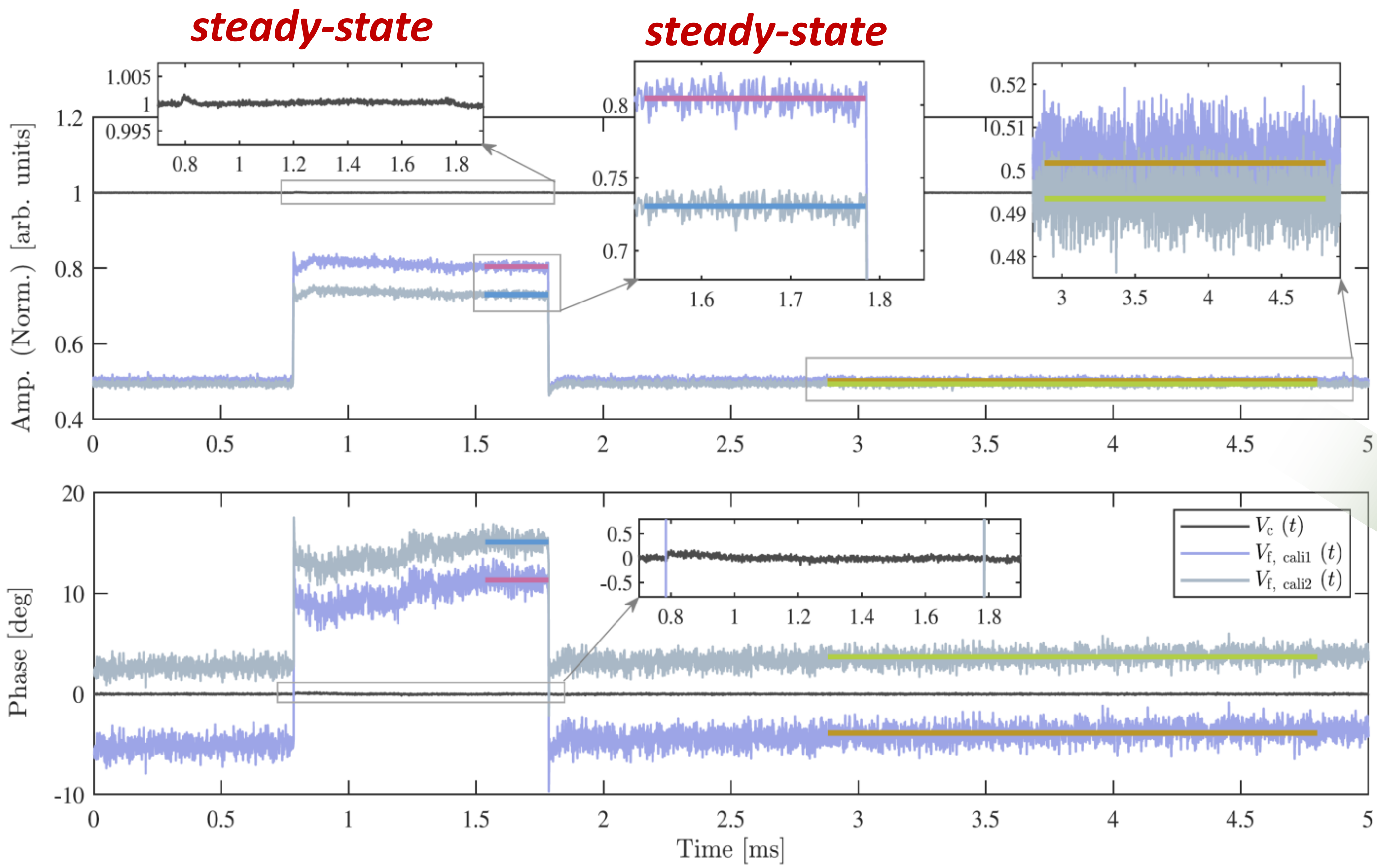
$\varphi_b = \angle \boldsymbol{V}_b$

$I_b = |\boldsymbol{V}_b|$

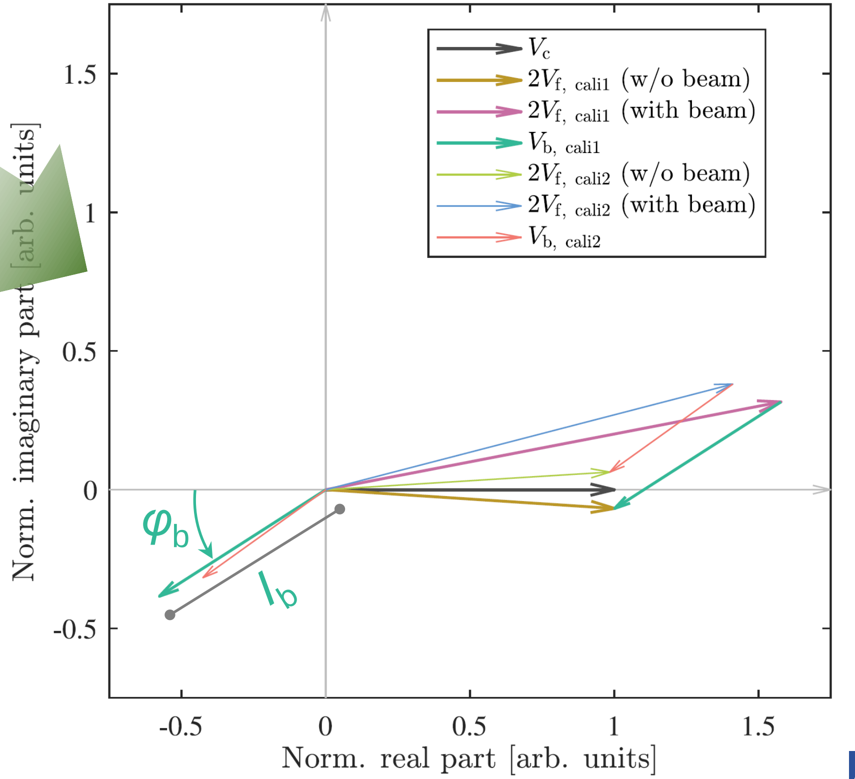
- *ALL the RF signals reaches **steady-state** (I_b, V_c, V_f)*
- *Good measurement accuracy (**cross-talk cali.**)*

Beam Phase Calibration (@ IMP-CAFe)

- The preliminary experiment was confirmed at IMP



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°)



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)