Long Short-Term Memory Models for Online Monitoring of Beam Phase and Current

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Joint effort between IMP and ESS

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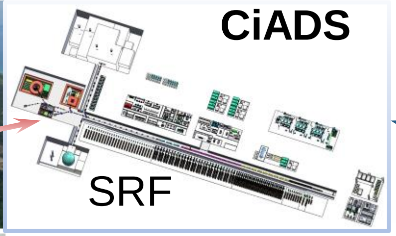
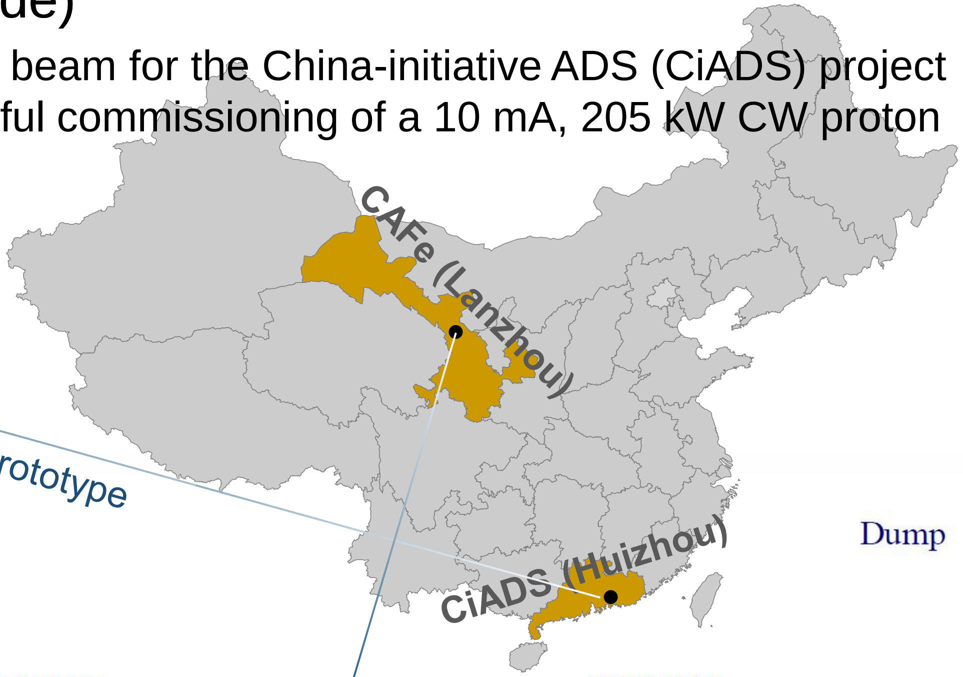
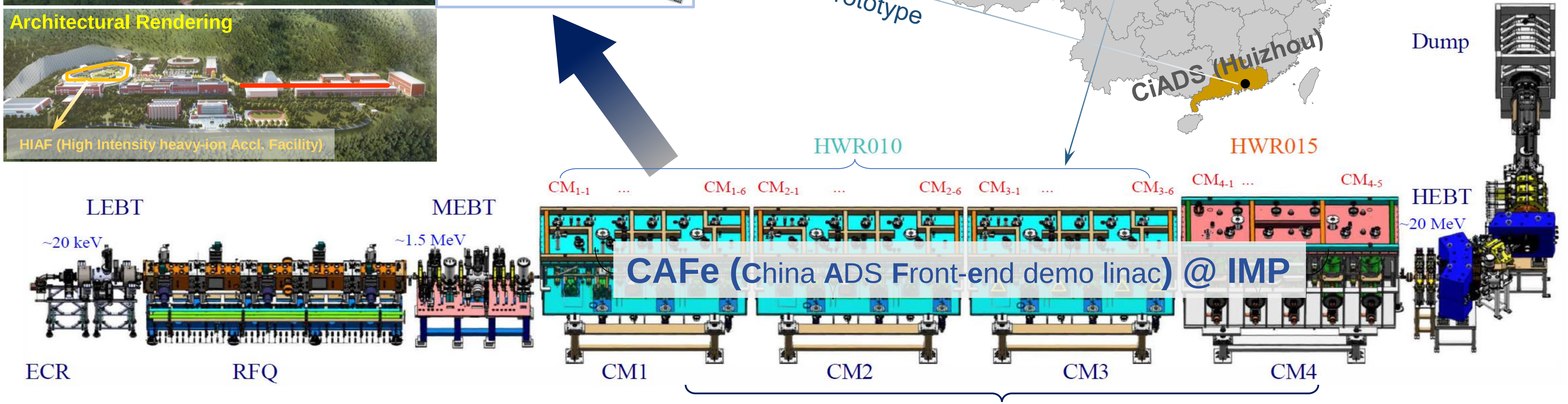
Introduction (CAFe)

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
- In March 2021, CAFe achieved its design goal with the successful commissioning of a 10 mA, 205 kW CW proton beam at an energy of 20 MeV

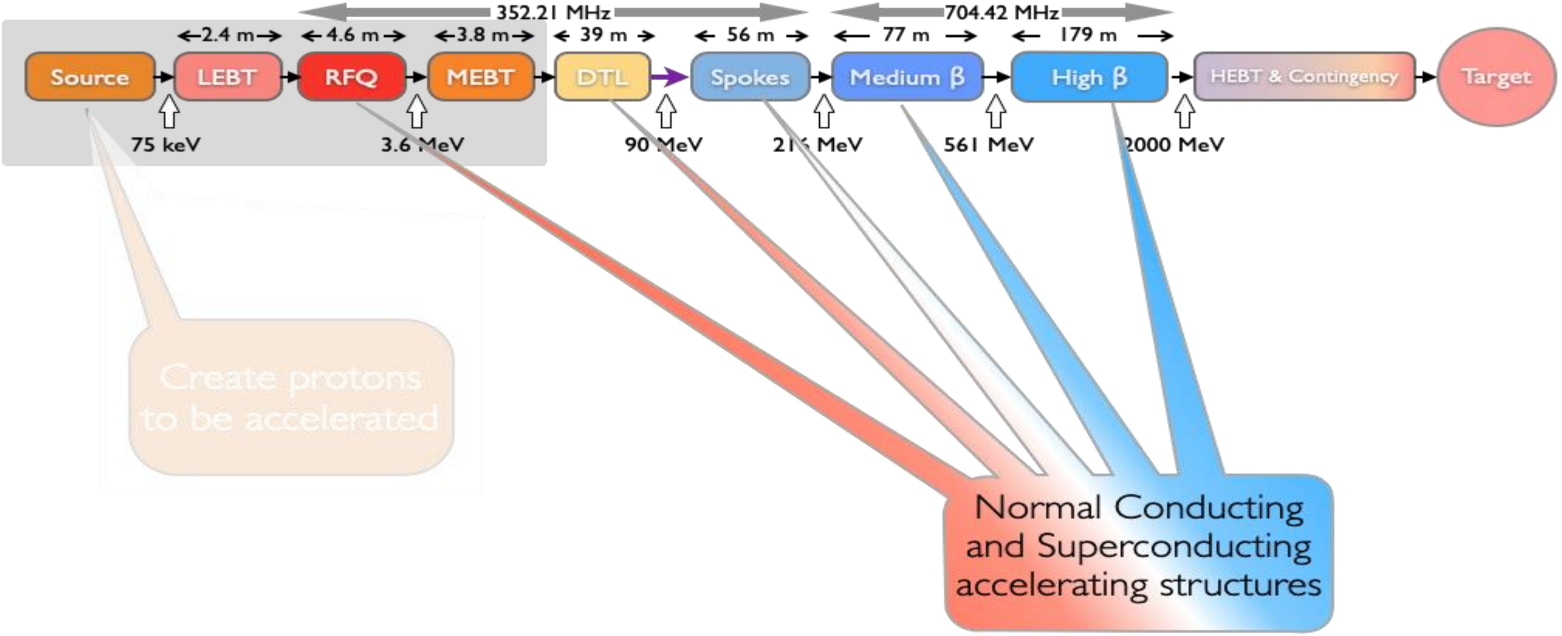






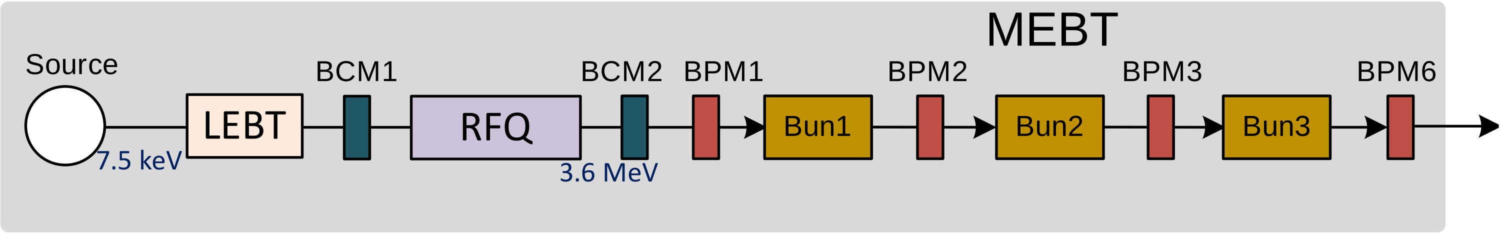
Four Cryomodules, 23 SRF Cavities, Cavity Bandwidth: 80 Hz~200 Hz, HWR$_{010}$+HWR$_{015}$)

Introduction (ESS)



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)

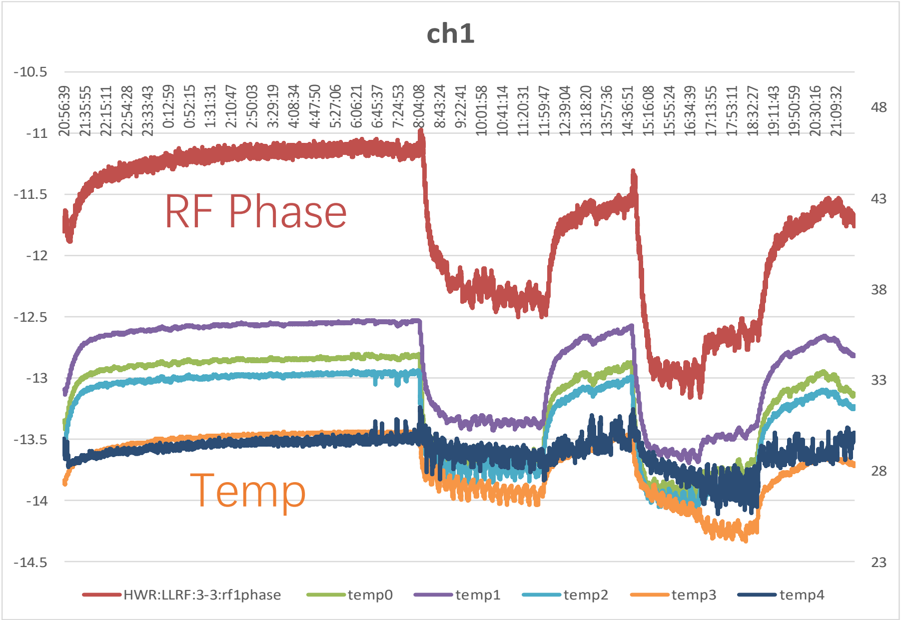
Limitations of Traditional Phase scan Methods

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.



Phase drift caused by temperature changes in CAFe

Limitations

1. **Off-Line**: Takes up machine operation time
2. **Phase Drift:** hard to track phase drift caused by environmental factors
3. **Long Scanning Times**: Inefficient for large accelerators with numerous RF cavities.

Introduction (motivation)

Proposed solution: on-line beam measurement

- It can address the challenges of traditional BPM based phase scan method to determine beam synchronous 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:

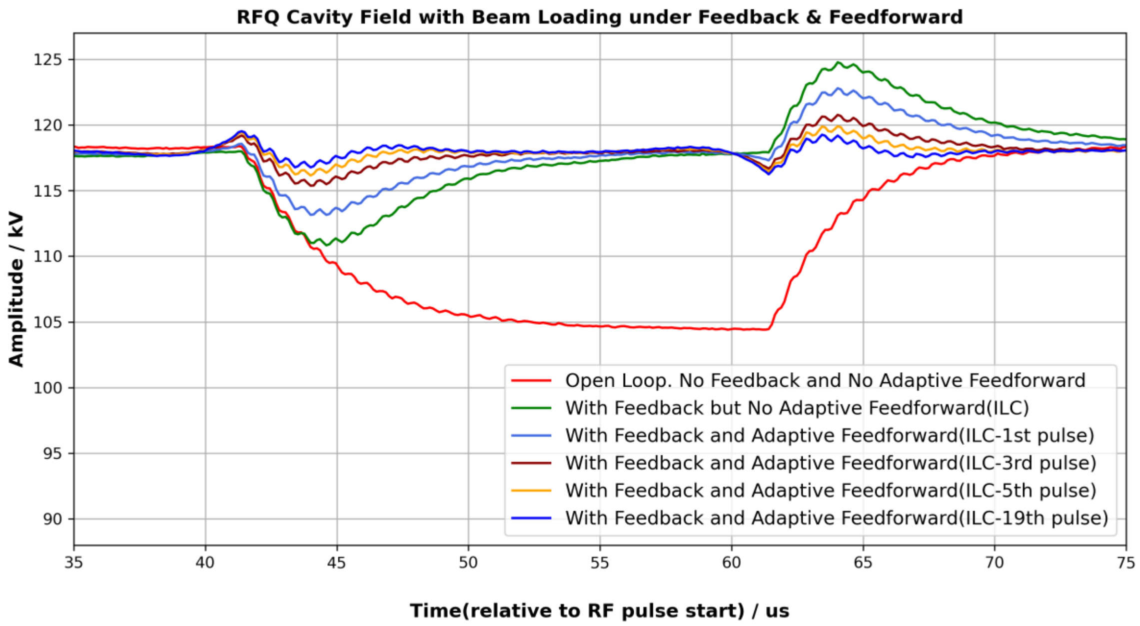
1. Beam Loading and its compensation
2. Beam Trip and Its Recovery

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 adaptive 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

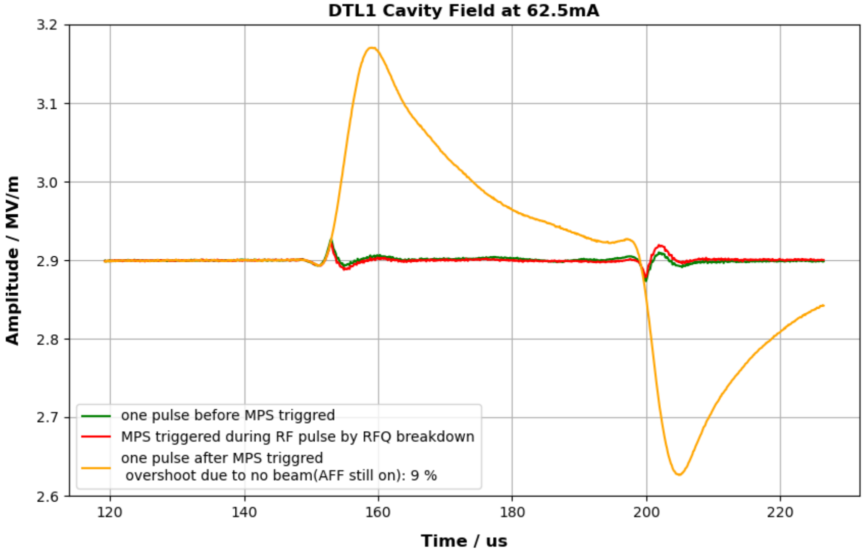
Introduction (motivation)

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 (AFF 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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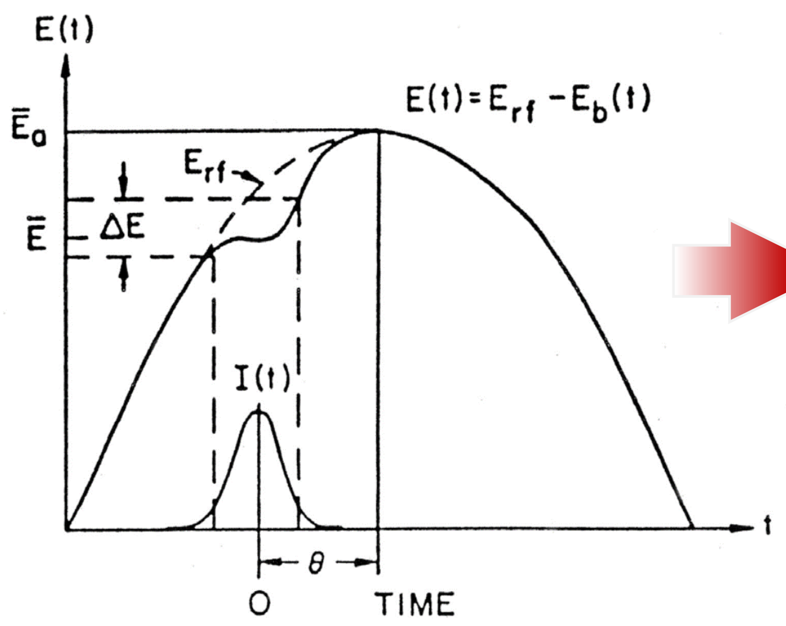
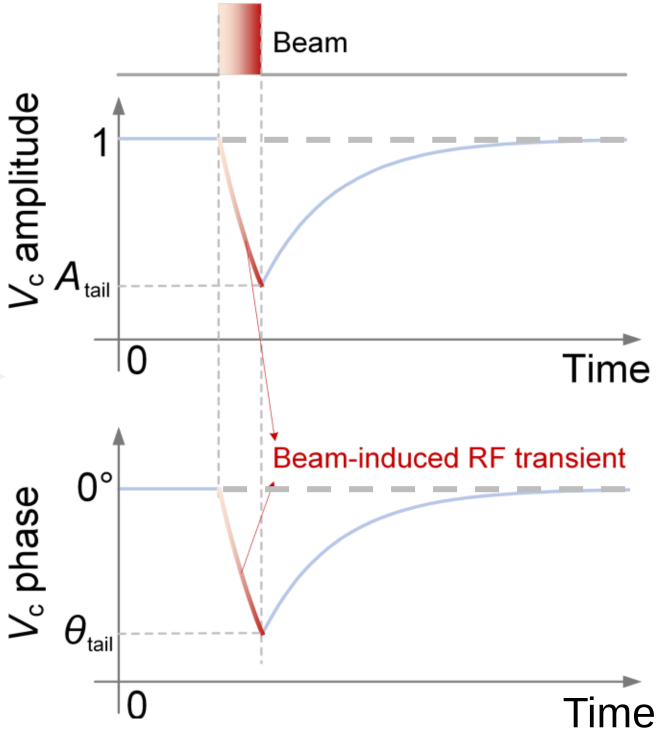
Transient Beam-loading Method

Relationship between RF and Beam

- **Beam loading effect**: the influence of the charged particle beam on the accelerating RF field within an RF cavity. When a beam of charged particles (like electrons or protons) passes through the cavity, it induces currents and fields that interact with the existing RF field, which can change the amplitude and phase of the RF field.
- **Mechanism:** The changes measured with respect to the RF field depend on the beam phase, charge and the accelerating field strength.

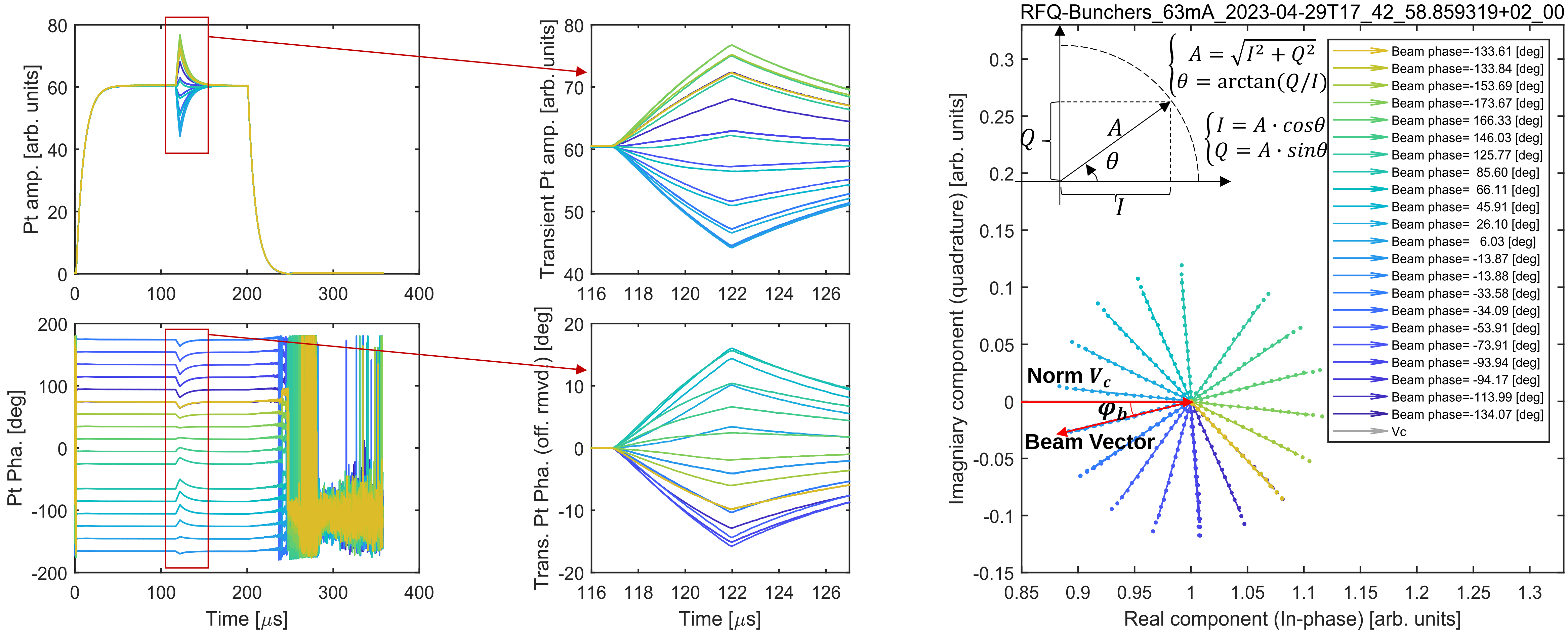




[1] P Pawlik et al, New method for beam induced transient measurement, Meas. Sci. Technol. 2007(18)
[2] Nick Walker, Experience with beam-transient LLRF calibration in XFEL, DESY-TEMF collaboration meeting, 2020

Transient Beam-loading Method

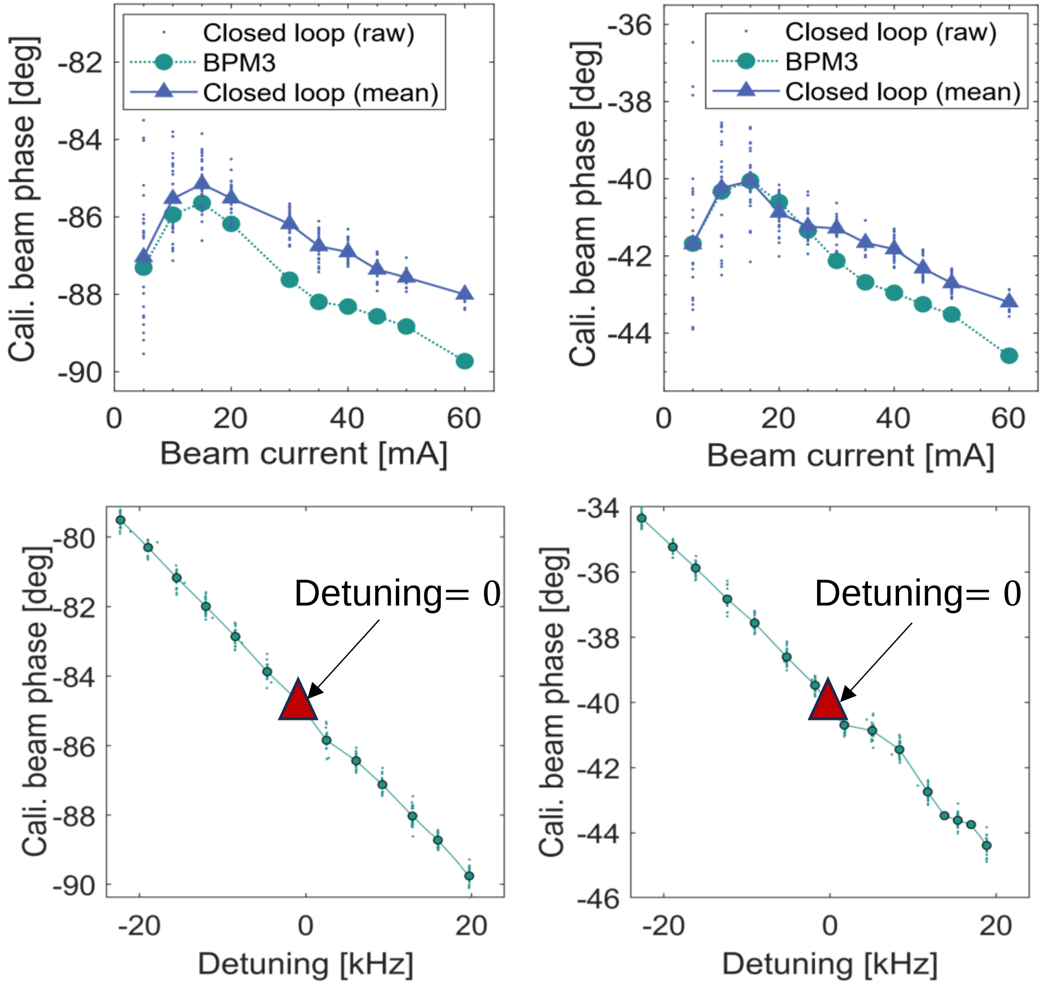
ESS Buncher2 : open loop (this is also used in DESY and KEK)

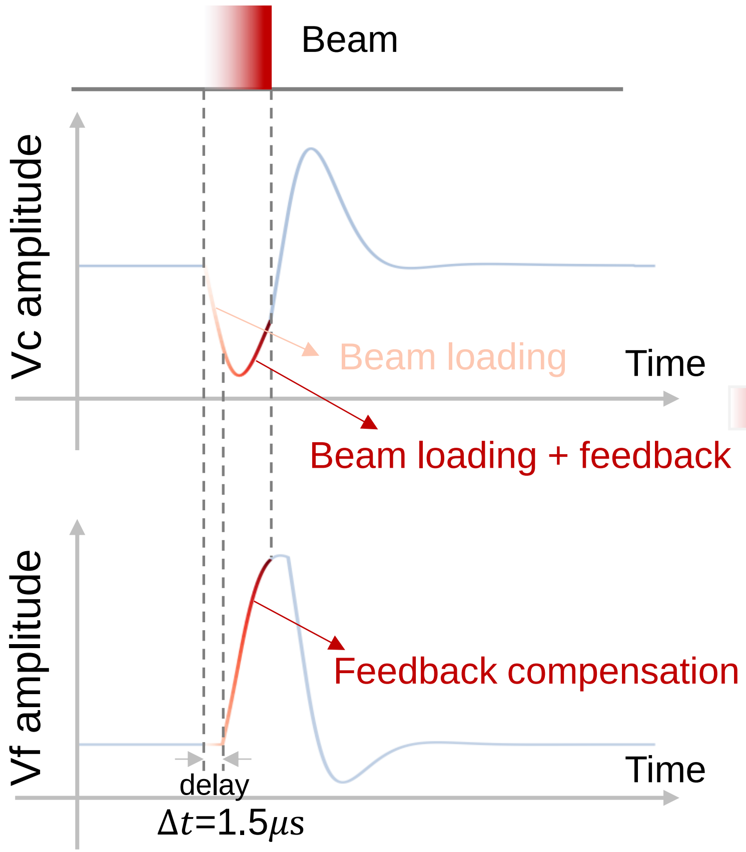


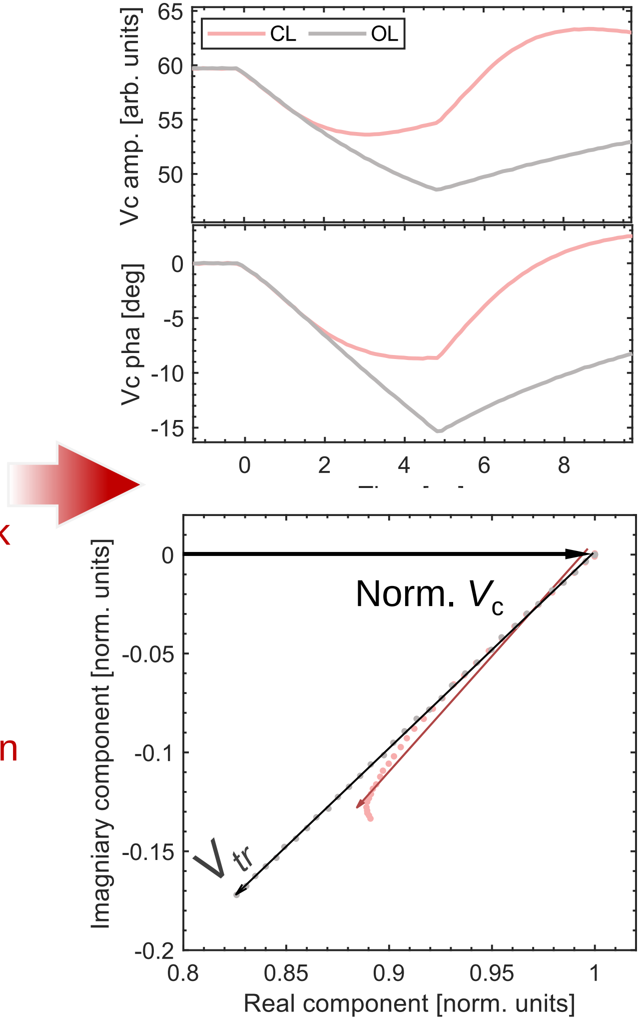
Open loop: I_b =63mA, Beam phase from -180° to 180°, Beam width time=5μs

Transient Beam-loading Method

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





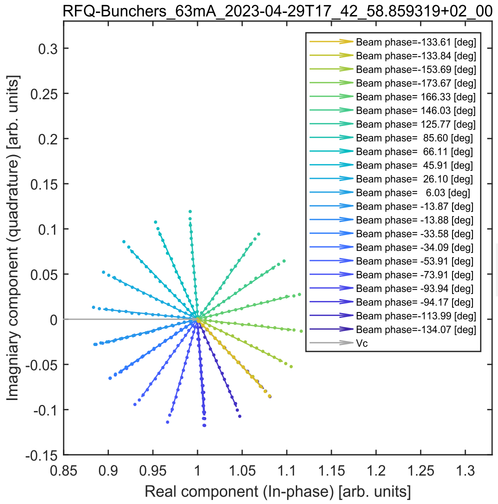


Application Trans. Method at ESS Buncher2 : closed loop

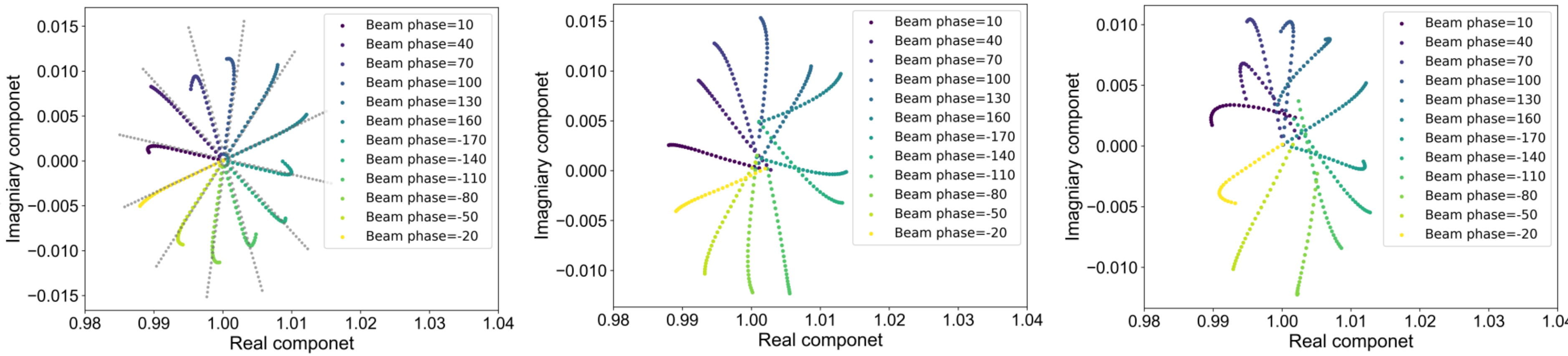
The vector V_{tr} is **NOT** straight under closed-loop operation

Transient Beam-loading Method

Closed-loop vs. Open-loop: Nonlinearity becomes increasingly complex



(a) Open loop



(b) closed loop without detuning

(c) Closed-loop, different detuning, and identical PI parameters.

(d) Closed-loop, different detuning, and various PI parameters.

Challenges faced by the transient beam-loading method when it comes to closed-loop:

1.Generalization Issue: current methods struggle with adapting to different operating conditions:

Open-Loop: when the system is not in a feedback loop.
Closed-Loop: when the system is in a feedback loop.
Detuning: when there are frequency mismatches or detuning.

2.Accuracy Issue: various nonlinear effects greatly increase the complexity of beam behavior, leads to a decrease in the accuracy of the physical methods. (space charge effects, beam emittance, nonlinearity of the accelerating fields).

CONTENTS

AI-based beam measurements

Advantages of AI:

Powerful nonlinear modeling ability; Rich function approximation ability; Automatic feature extraction ability; Adaptability to various complex data types

How can AI technology be applied to beam measurements?

- Model design
- Data prepartion
- Training

1. Design a specialized AI network Specifically for beam measurement : AB-LSTM

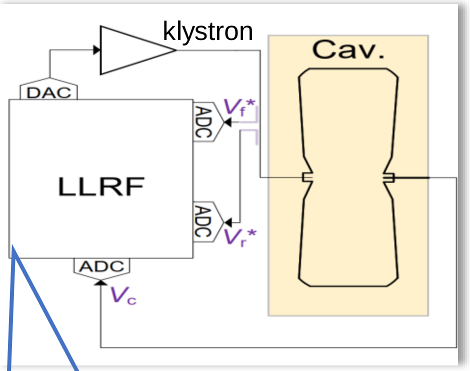
2. Prepare a diverse set of training data: High fidelity simulator

3. Migration of simulated data to real data: Transfer learning techniques

AI-based beam measurements

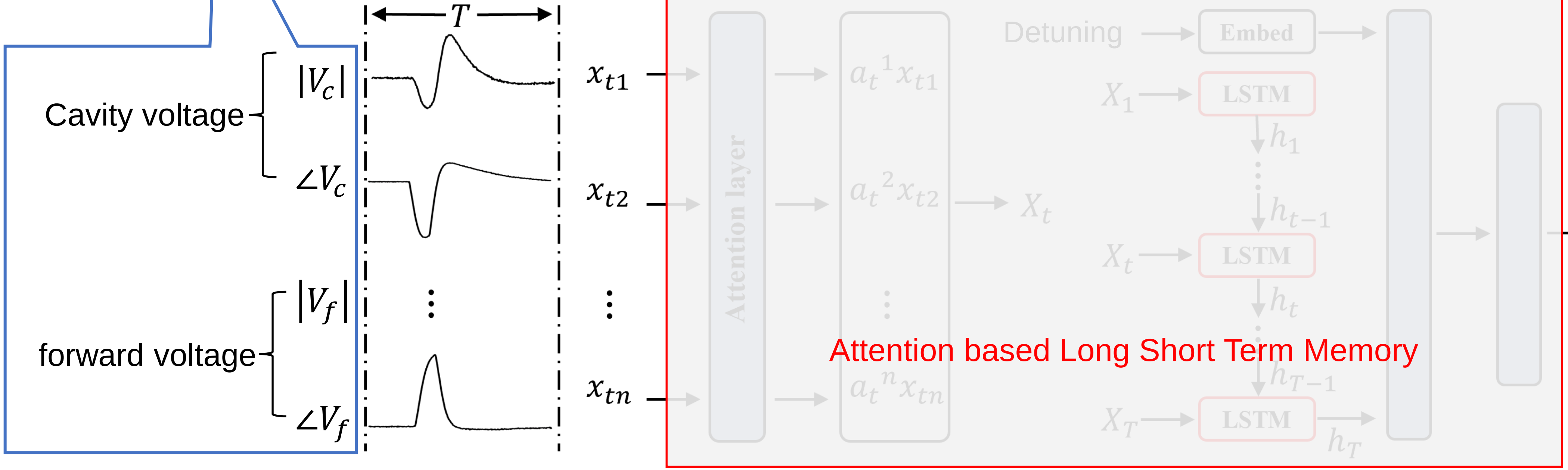
How can AI technology be applied to beam measurements?

- **Model**
- Data
- Training



Goal: Using AI establish a real-time correlation between the beam and RF

$$y_1, y_2 = F\left(V_{c_1}, \cdots, V_{c_T}, V_{f_1} \cdots V_{f_T}\right)$$



Y_1: Beam phase
Y_2: Beam current

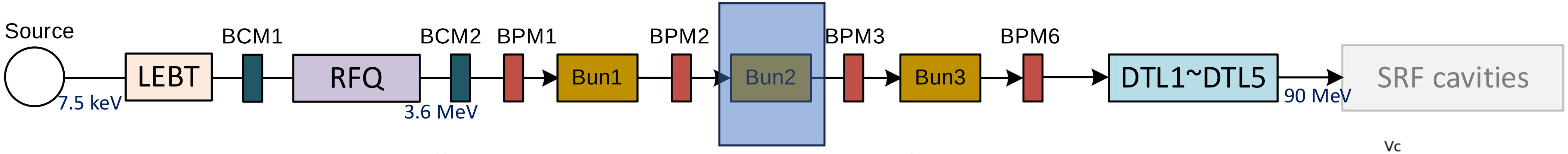
$\rightarrow Y_1, Y_2$

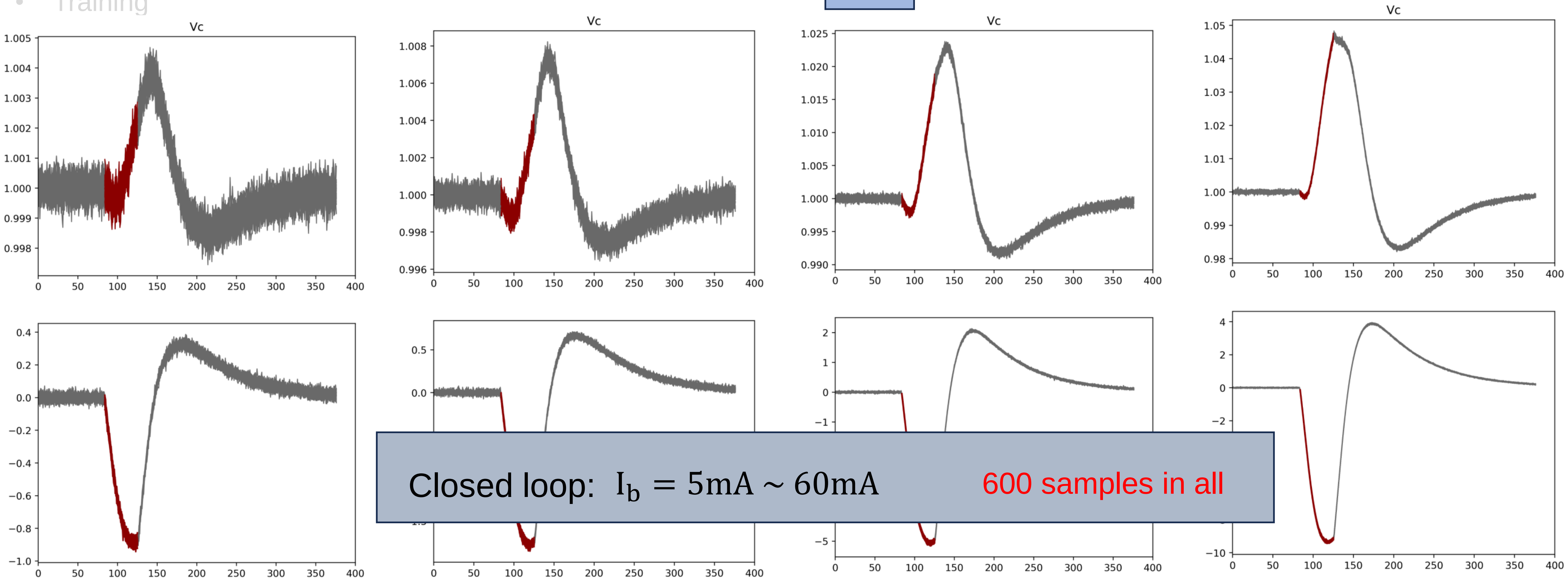
$F \rightarrow$ NN

AI-based beam measurements

How can AI technology be applied to beam measurements?

- Model
- **Data**
- Training



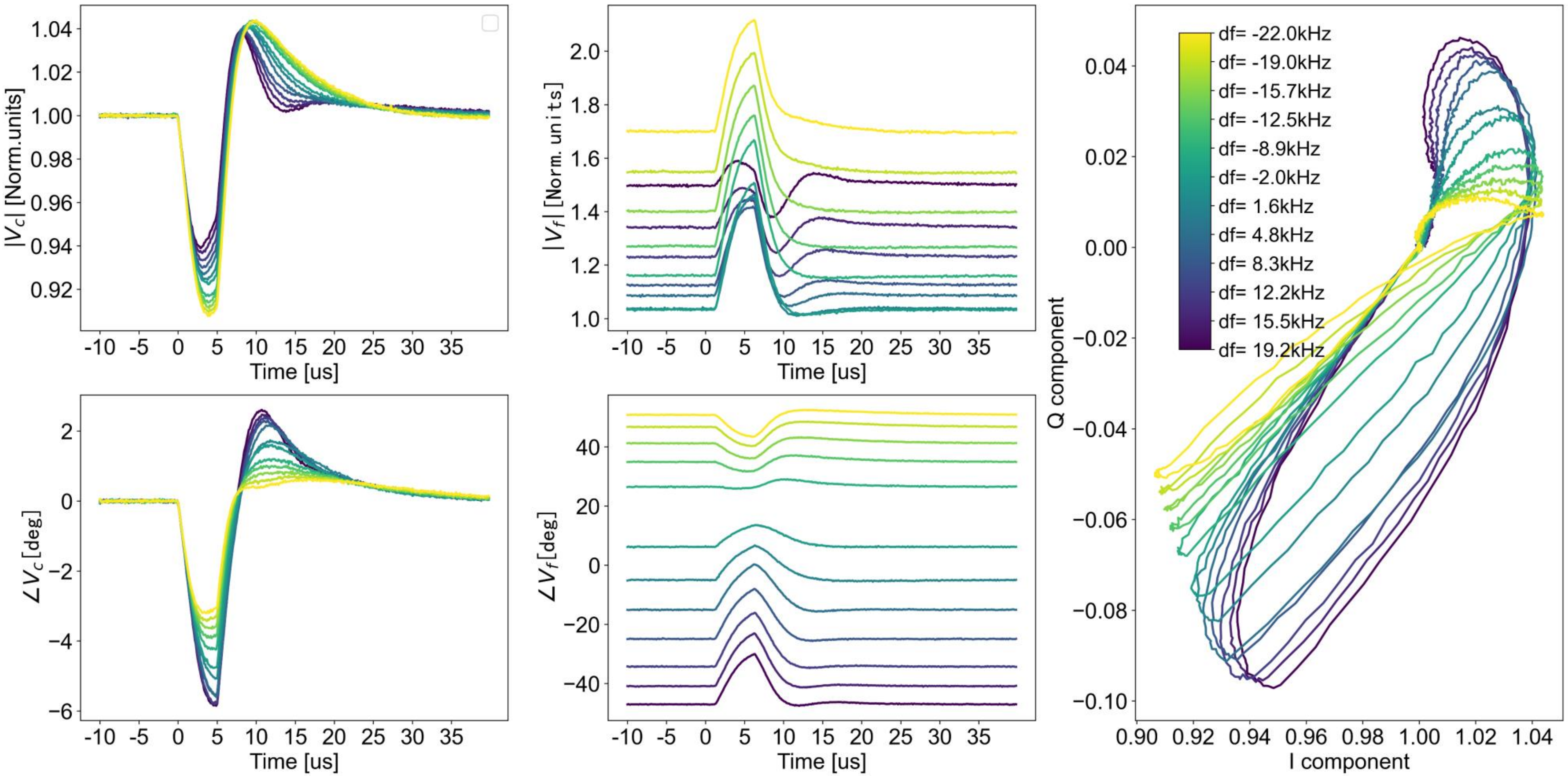


Closed loop: $I_b = 5mA \sim 60mA$ 600 samples in all

AI-based beam measurements

How can AI technology be applied to beam measurements?

- Model
- **Data**
- Training

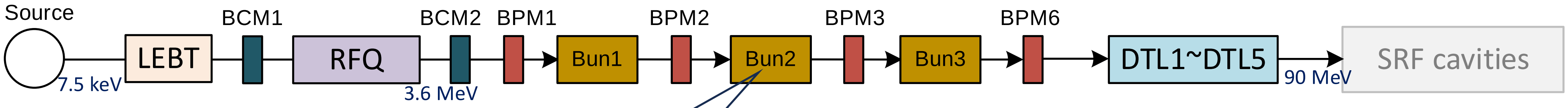


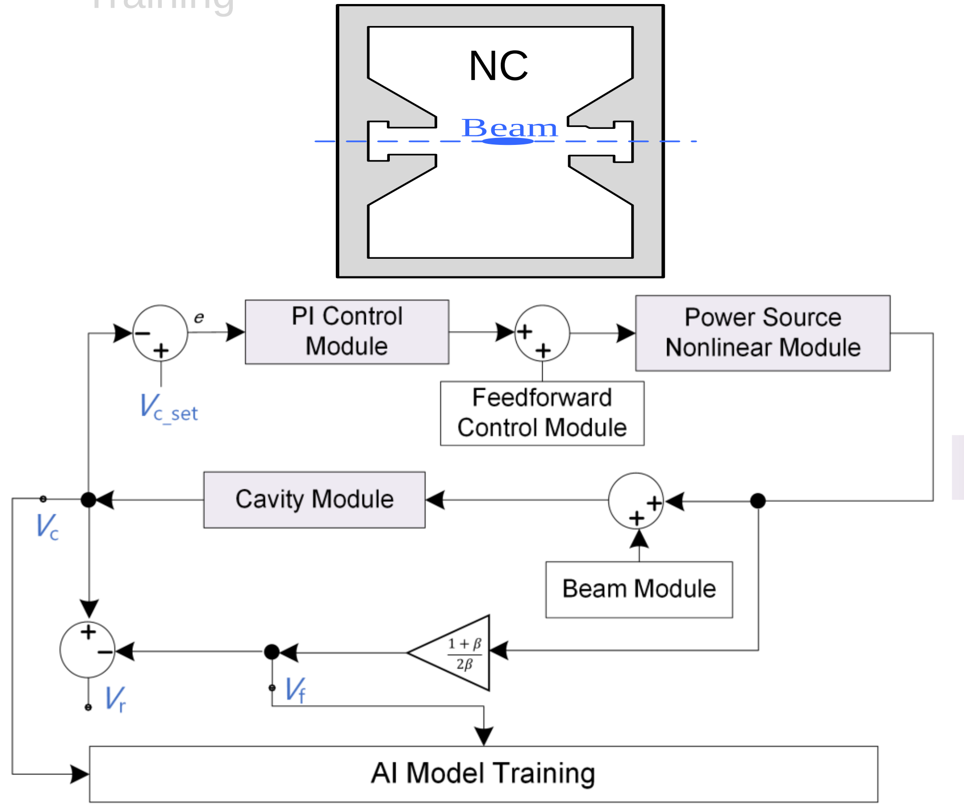
Closed loop: $\text{Detuning} = -22\text{kHz} \sim 22\text{kHz},\ f_{0.5} \approx 20\text{kHz}$ 3513 samples in all

AI-based beam measurements

How can AI technology be applied to beam measurements?

- Model
- **Data**
- Training

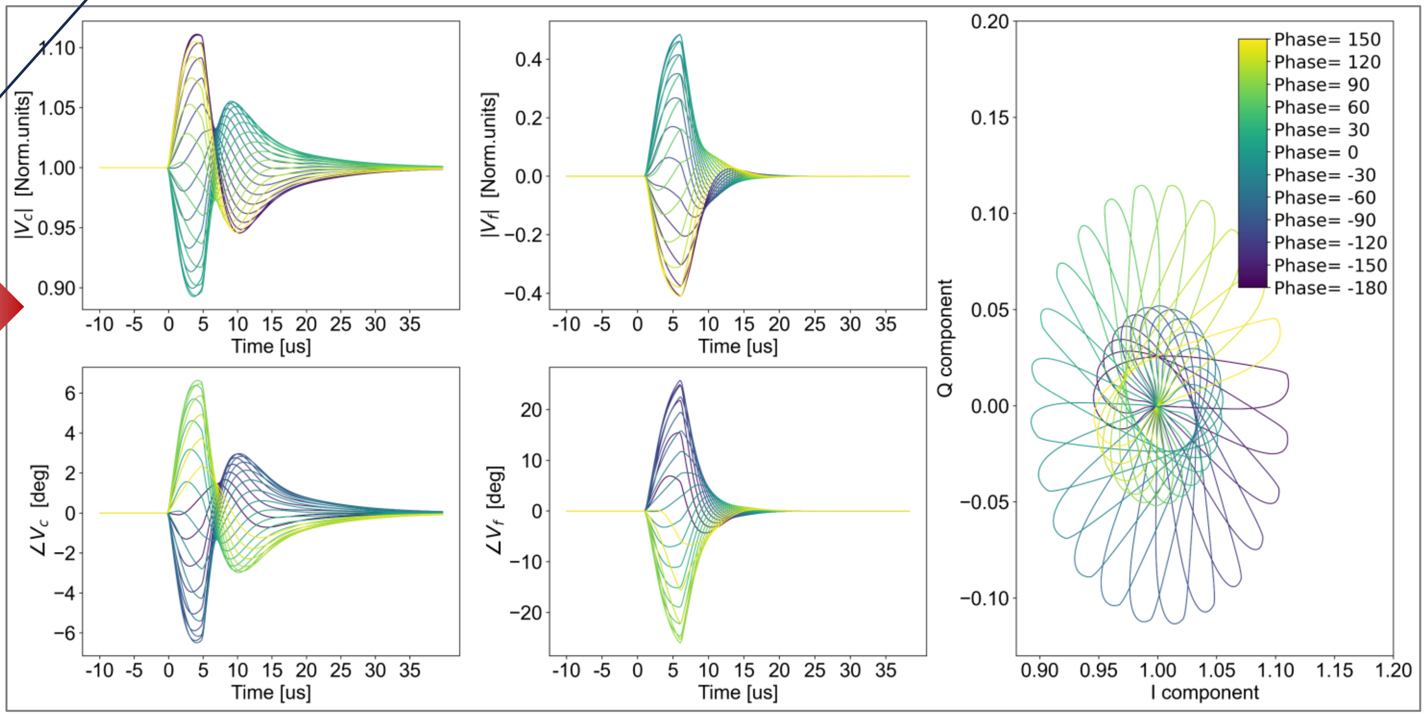




simulation program

Feng Qiu et al., PRAB21, 032003(2018)

Closed loop: $I_b = 5\sim60mA$, $Phase = -180^{\circ}\sim180^{\circ}$, $Detuning = -22\sim22kHz$

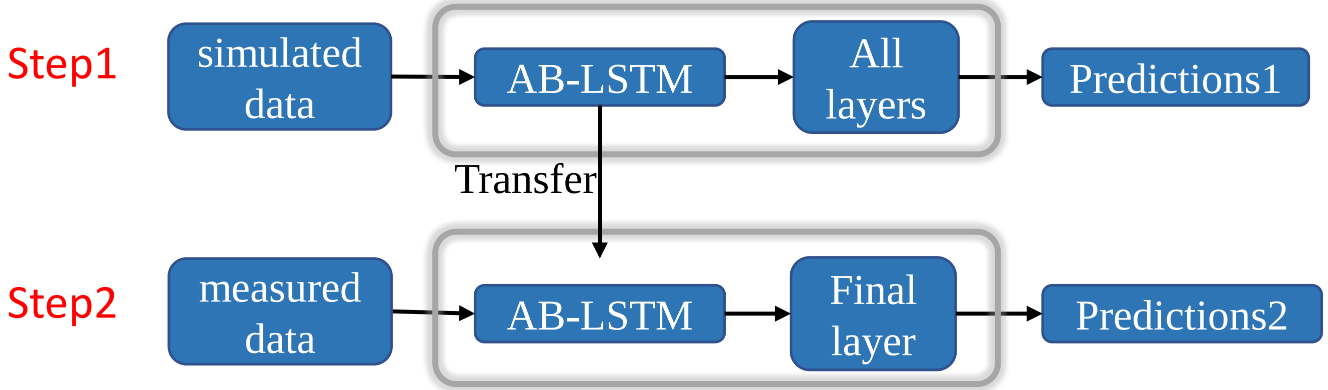


400,000 sample data with different beam current, beam phase and detuning

AI-based beam measurements

How can AI technology be applied to beam measurements?

- Model
- Data
- **Training** { Pretraining: Using simulated data. Fine-tuning: Using real-world data.



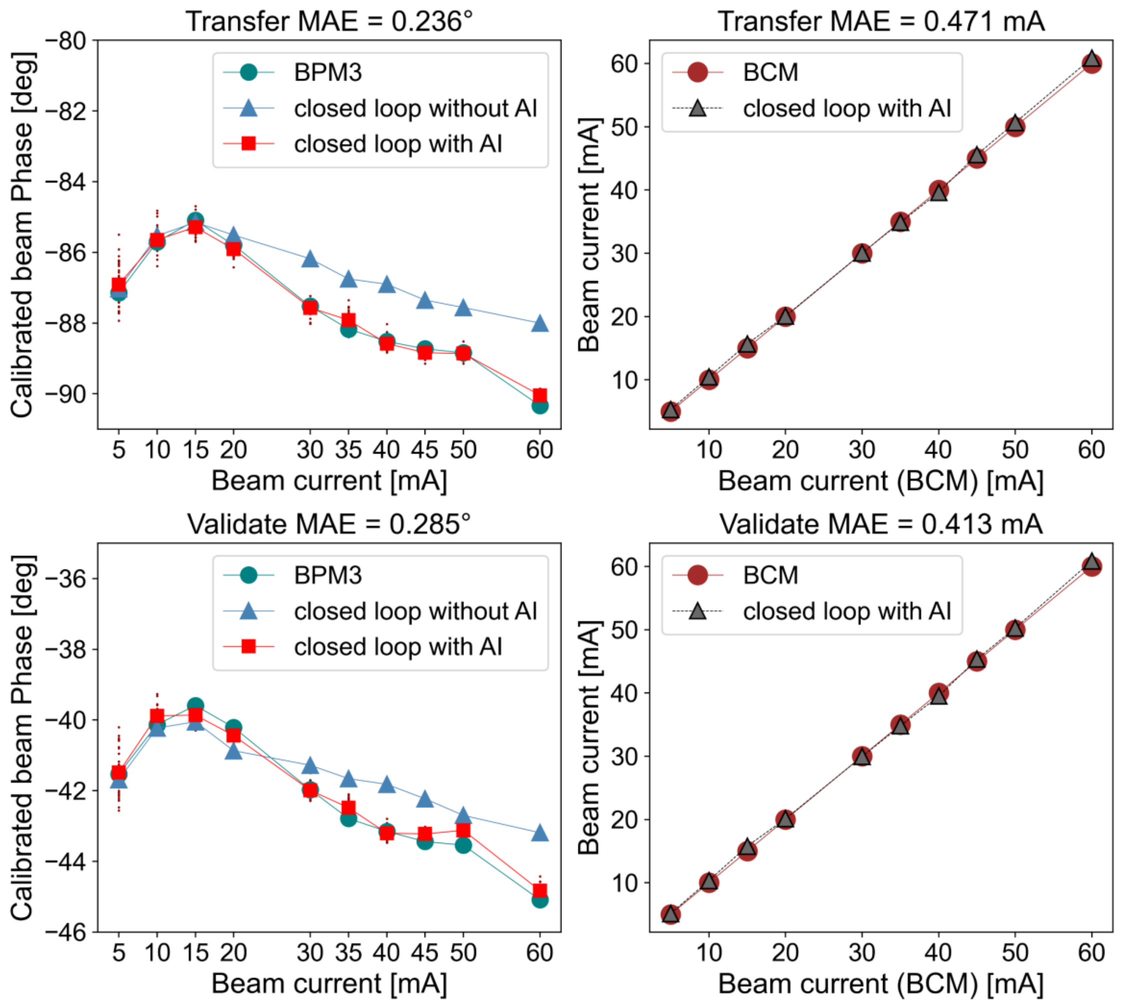
Performance Check

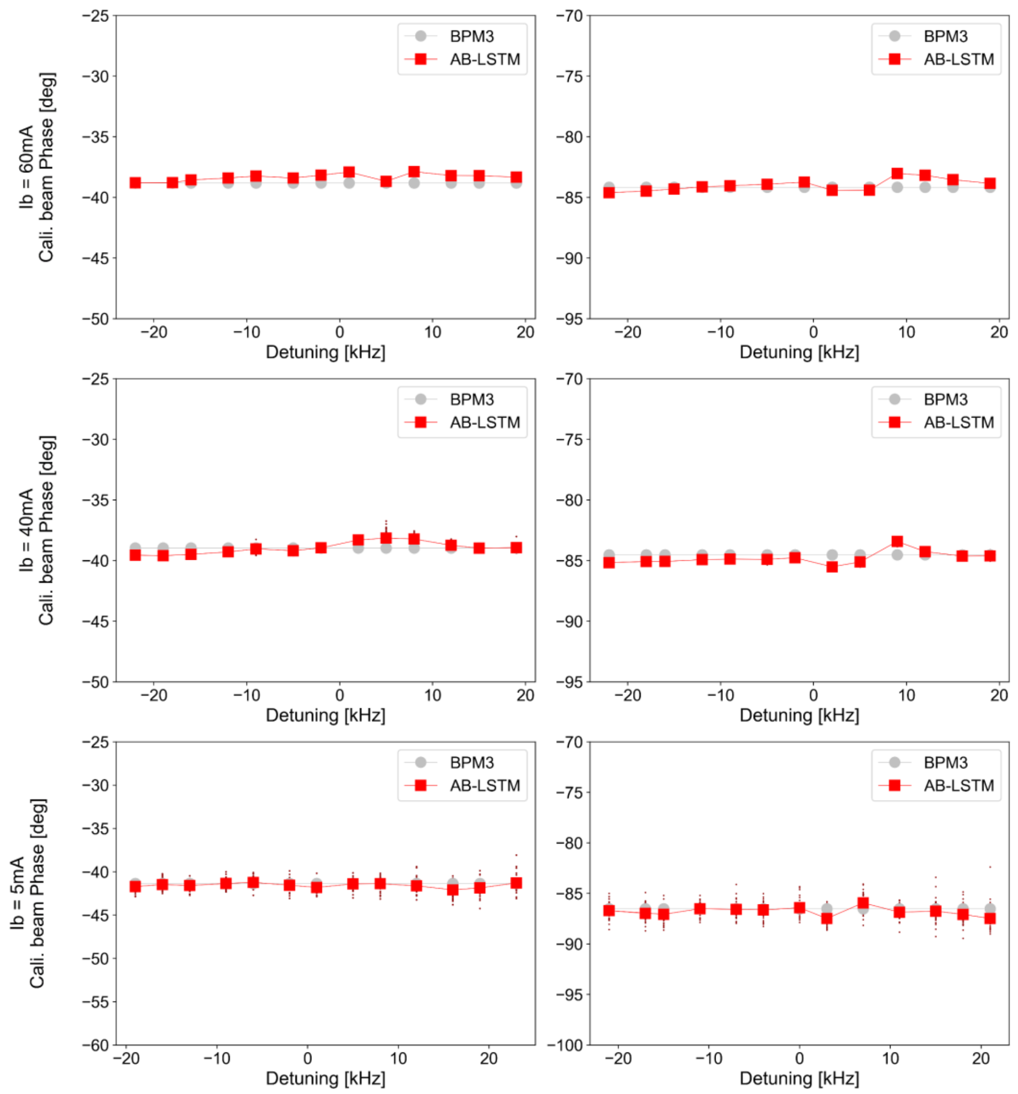
	Model parameters	220,000
Simulated data →	Pretrain dataset	400,000 samples
measured data	Transfer dataset	300 samples
	Validation dataset	300 samples
	Detuning dataset	3513 samples

From simulation to real accelerator with Transfer learning: robust and reliable

AI-based beam measurements

Improvement with AI





Compared to BPM and BCM, the mean absolute error of AI is less than 0.5

AI-based beam measurements

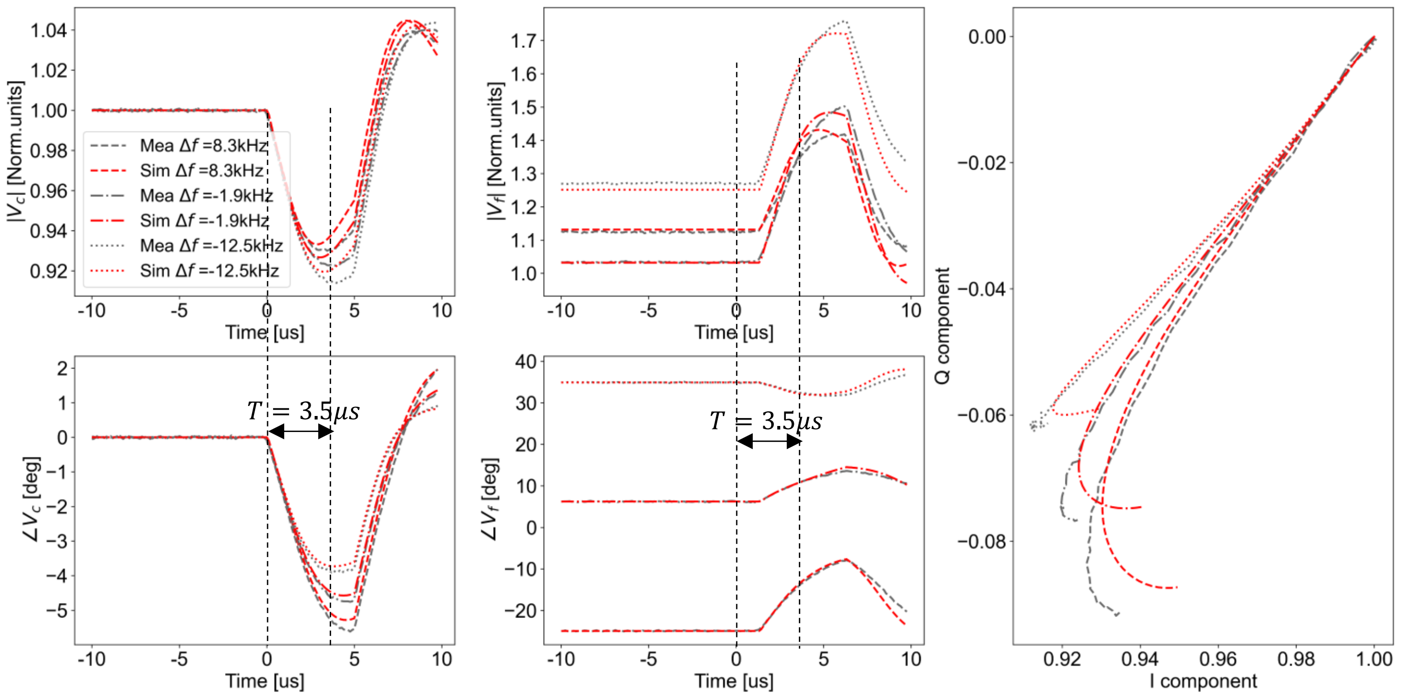
Challenges

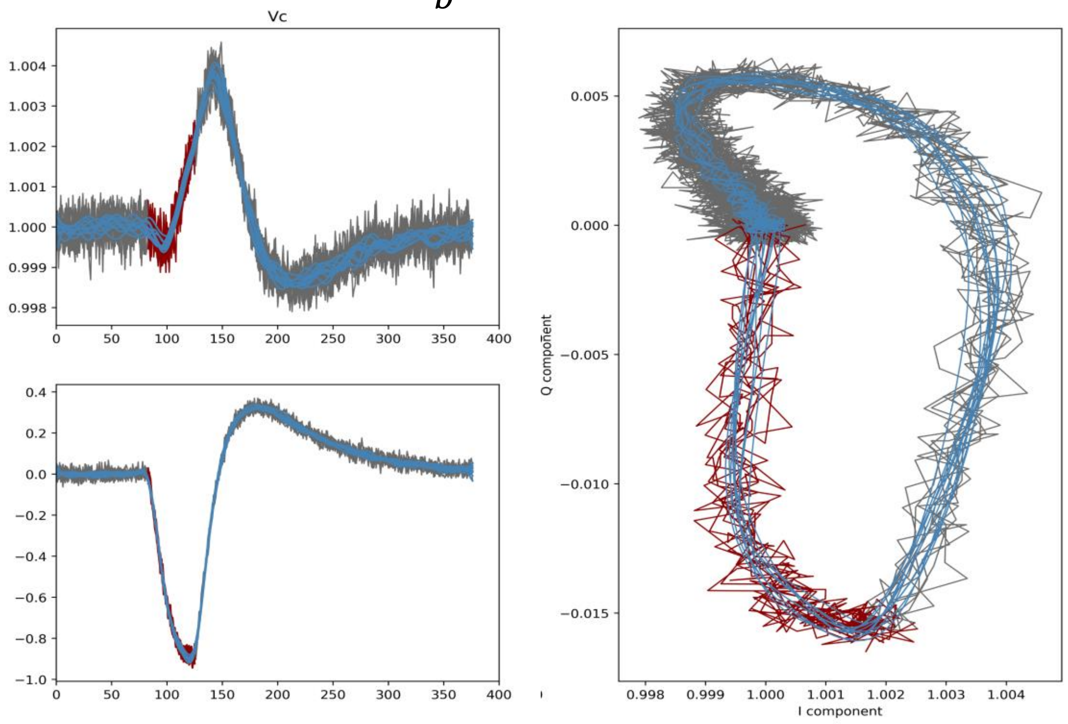
Quantity and Quality of Data

- **Simulation error:** Using simulated data in the absence of experimental data, but the simulated data has biases.
- **Signal-to-noise ratio in measured data:** data noise, when the beam current is low, the noise heavily impacts calculation reliability

errors gradually increase after $3.5\mu s$

$I_b = 5mA$



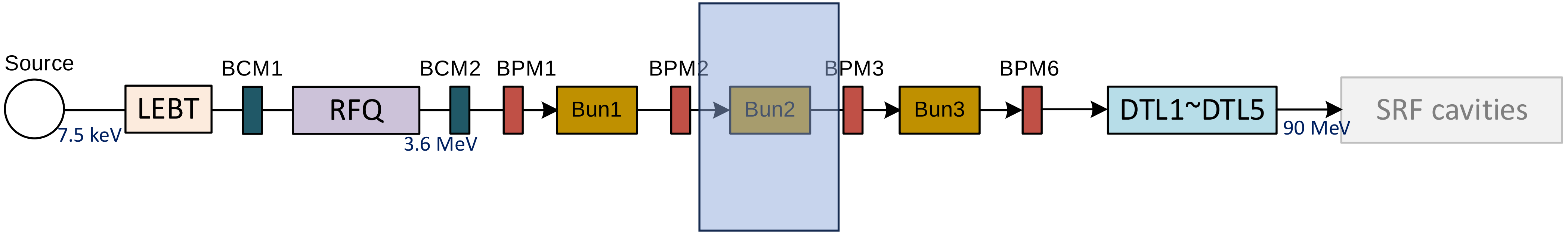


AI-based beam measurements

Challenges

Model Generalization

- AI models may struggle to generalize in new cavities or conditions, necessitating continuous updates and validation to ensure reliability under varying operational conditions.



Model Interpretability

- “black box” nature of AI models, makes it difficult to understand their decision-making processes, which may affect their credibility in high-risk applications.

Summary

Benefits of AI Online Measurement

1. **High Accuracy:** Provides precise measurements and strong generalization ability.
2. **Non-Intrusive:** Measures beam information without disturbing accelerator operations.
3. **Continuous Monitoring:** Ensures stable and reliable performance. Real-time updates on beam status, phase, current, and energy gain.
4. **Data-Driven**: It can be applied to other accelerators to enhance their operation.
5. ……

Challenges of AI algorithm

1. **Data Scarcity :** requires large amount of high quality experimental data. Data scarcity limits the accuracy and applicability of the models.
2. **Generalization Ability :** AI models may struggle to generalize in new environments or conditions.
3. **Model Interpretability:** "black box" nature of AI models, makes it difficult to understand their decision-making processes.
4. **Integration of Interdisciplinary Knowledge**: requires the integration of knowledge from physics, engineering, and data science.
5. ……

Thanks for your attention

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