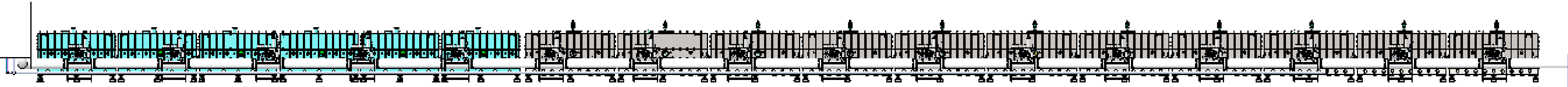
LINAC2026, Aug. 16-21, 2026

Automated Commissioning and Intelligent Operational Strategies for the HIAF-iLinac SRF System

Feng QIU, Rihua ZENG, Shihui Wei, Zhaojie Chen, Yilin MIAO, Lijuan YANG, Zheng GAO, Tiancai JIANG, Lie Peng SUN, Zhijun WANG, Yuan HE



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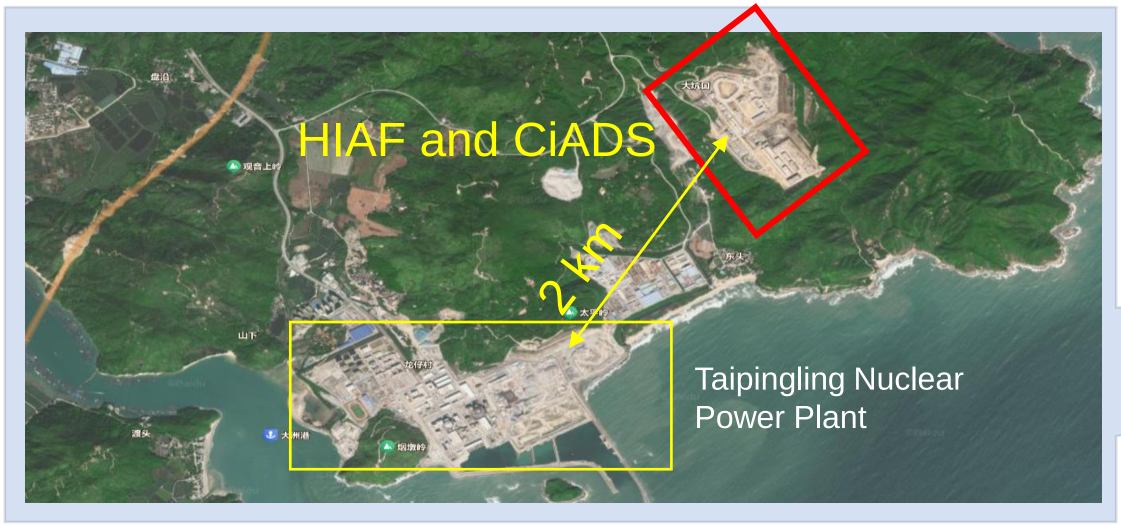
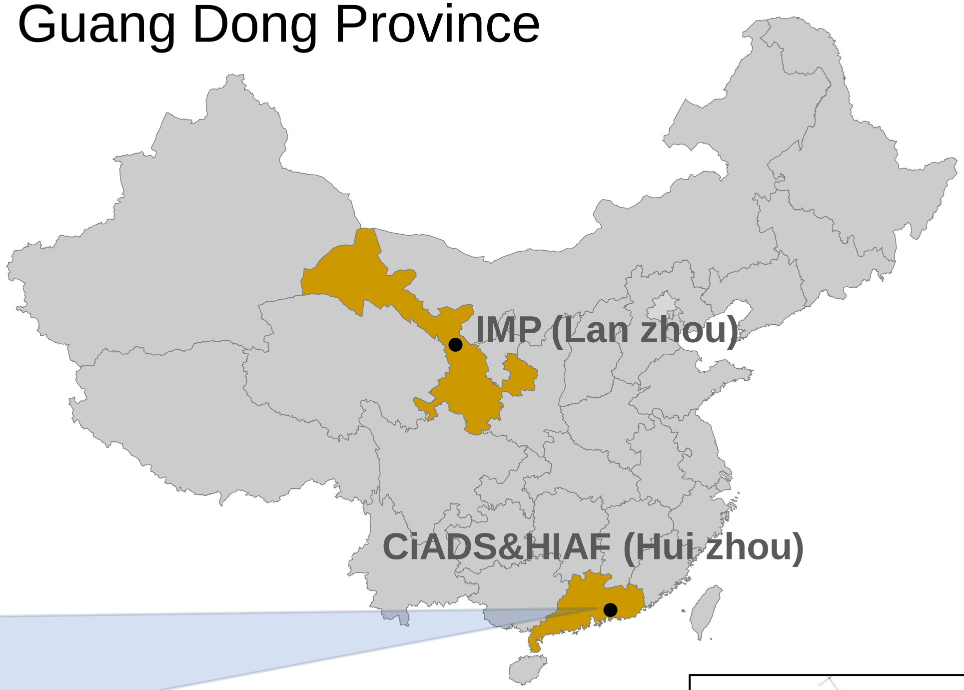
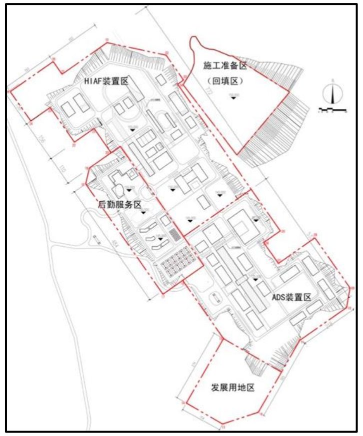
Introduction

- Two new large-scale facilities were built in Hiuzhou, Guang Dong Province
  - HIAF: High Intensity heavy-ion Accelerator Facility
  - CiADS: China Initiative Accelerator Driven System







HIAF Facility

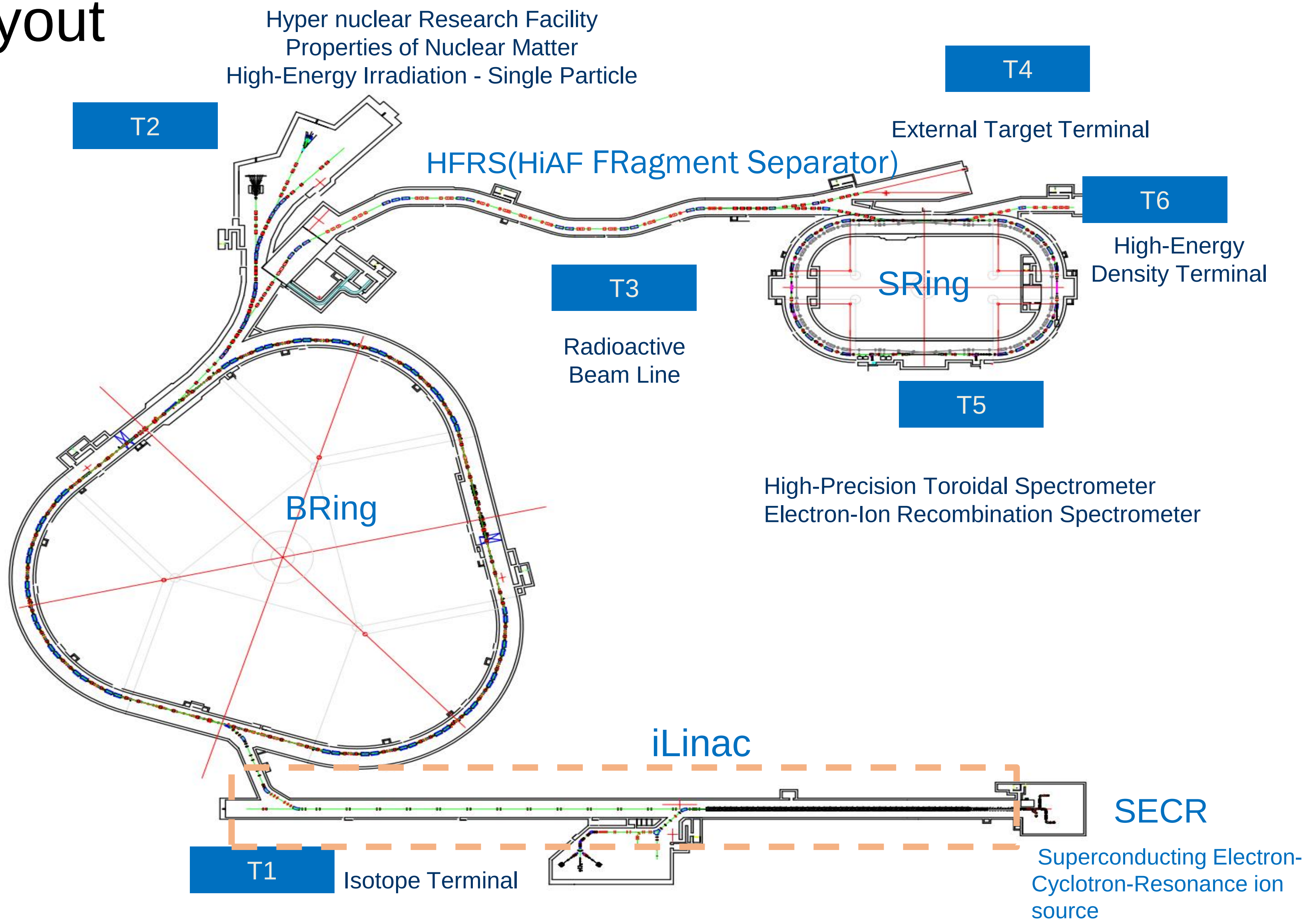
◻Motivation and facility layout

Project Engineering Objectives

- Expanding the Landscape of New Nuclides
- Weakly Bound Nuclear Structure and Reaction Mechanisms
- Precise Measurement of Nuclear Masses

Ions targets：

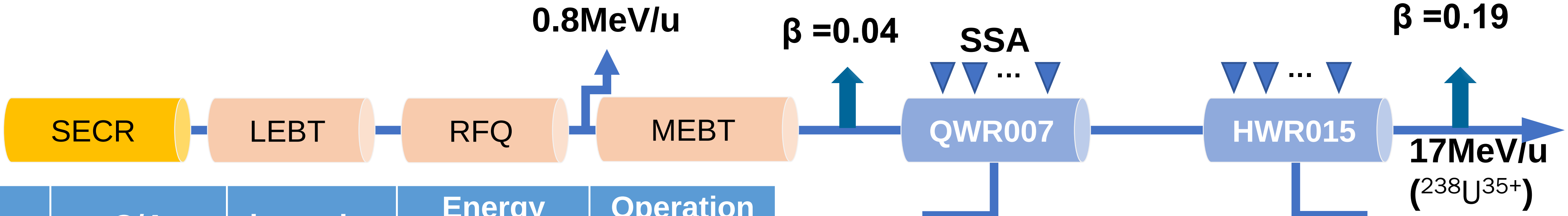
- 5-250 MeV/u CW heavy ions beam
- 35 MeV/u-5.7GeV/u pulse beam



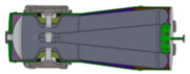
HIAF-iLINAC

iLINAC layout and parameters

- **iLinac Design Specification**: Continuous wave (CW) and pulsed beam
- **Component Structure** : Room temperature front end and Superconduct linac

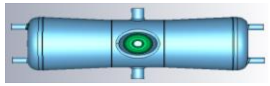


ions	Q/A	intensity	Energy (MeV/u)	Operation mode
$^{238}U^{35+}$	1/7	1.0 emA	17	Pulse
$^{78}Kr^{19+}$	1/4.1	1.0 emA	27	
$^{18}O^{6+}$	1/3	1.0 emA	33	
H_2^+	1/2	0.6 emA	48	
48Ca-70Zn	-	10 pμA	4-8	CW
Xe-U	-	10 pμA	5-22	



$\beta = 0.076$

$f = 81.25$ MHz

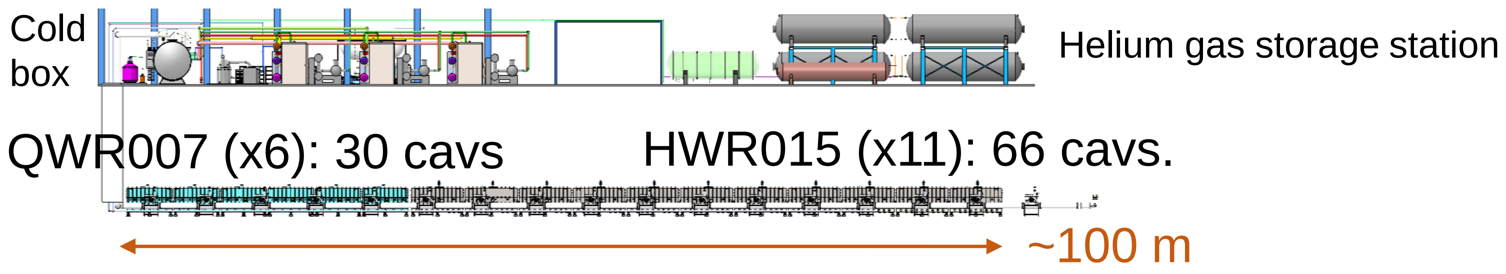


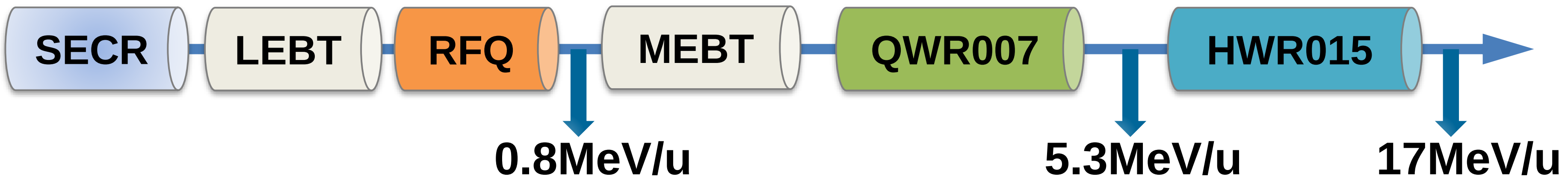
$\beta = 0.15$

$f = 162.5$ MHz

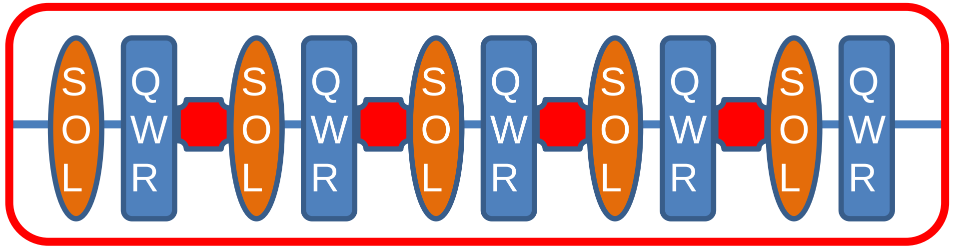
SRF Cavities

- HIAF SRF linac employs 17 cryomodules with 96 SRF cavities

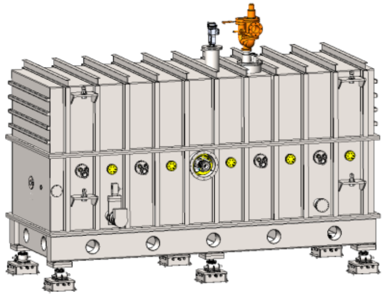


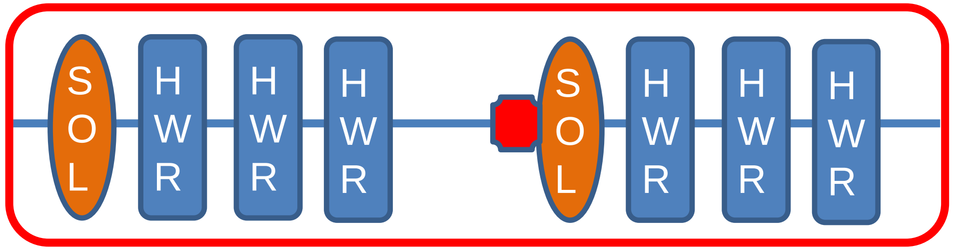


	QWR007	HWR015
CM Quantity	6	11
CM Length [mm]	5073	5836
CM Width [mm]	2000	2000
CM Height [mm]	3800	3800
Cavity Quantity	5	6
Solenoid Quantity	5	2
BPM Quantity	4	1

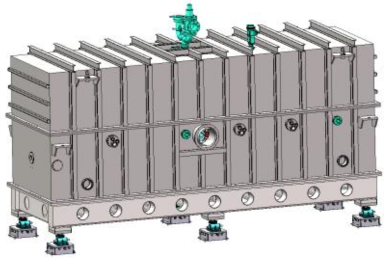


CM-QWR007 (x6)



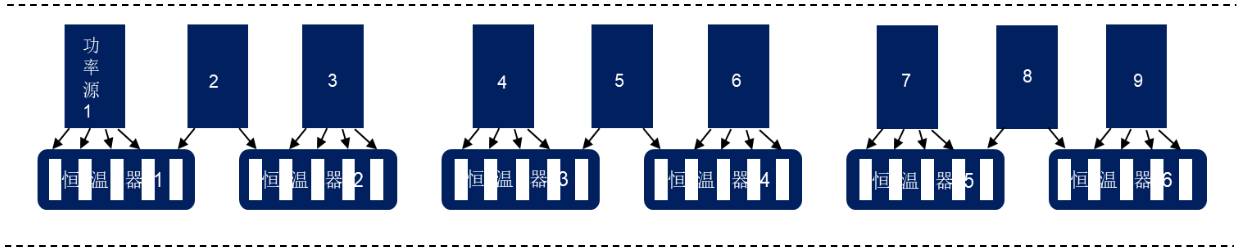


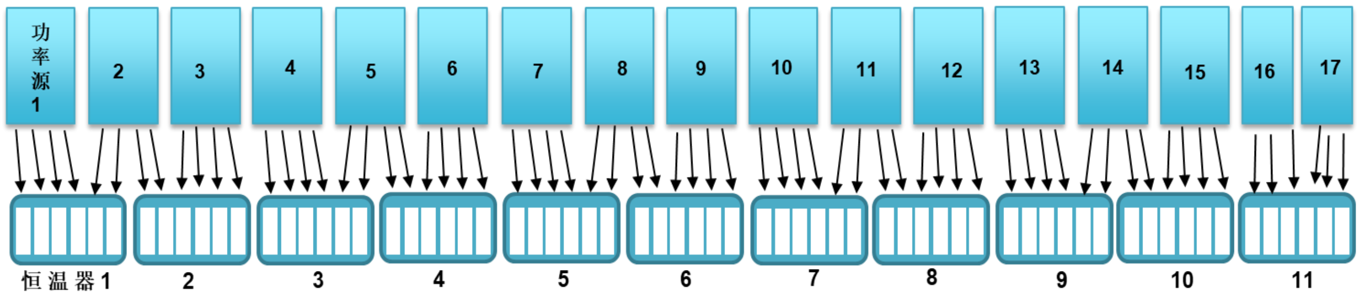
CM-HWR015 (x11)

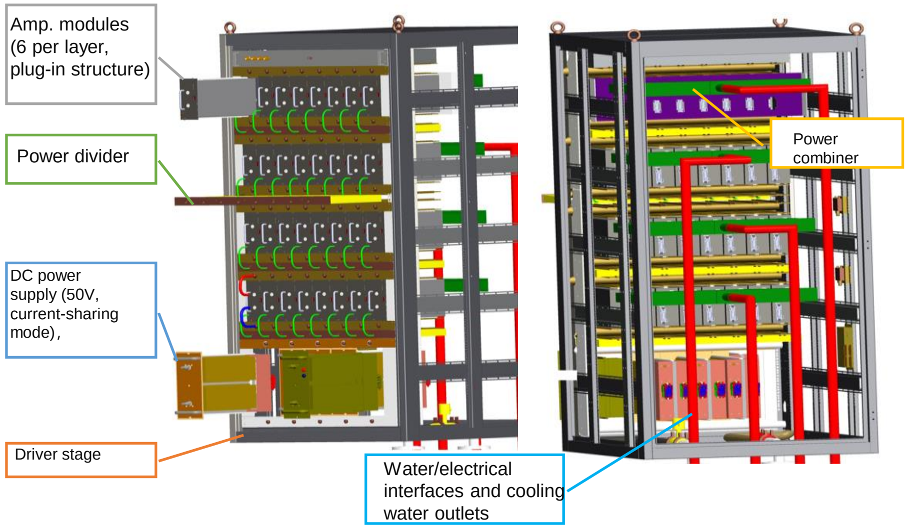


RF Power System

- A total of 36 RF power cabinets, with an output power of 24 kW per cabinet.
- Standardized structural design for the RF power sources.
- Plug-in module design for convenient maintenance.







Cav. Type	Freq (MHz)	Cav. No.	Pf (kW)	Cabinet (kW)	No. of Cabinets	Total (kW)
RFQ	81.25	1	160	24	8	180
Bun.	81.25	3	10	24	2	48
QWR	81.25	30	6	24	9	216
HWR	162.5	66	6	24	17	408

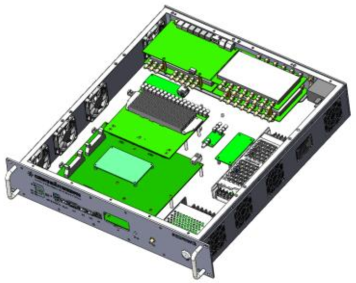
Low Level RF

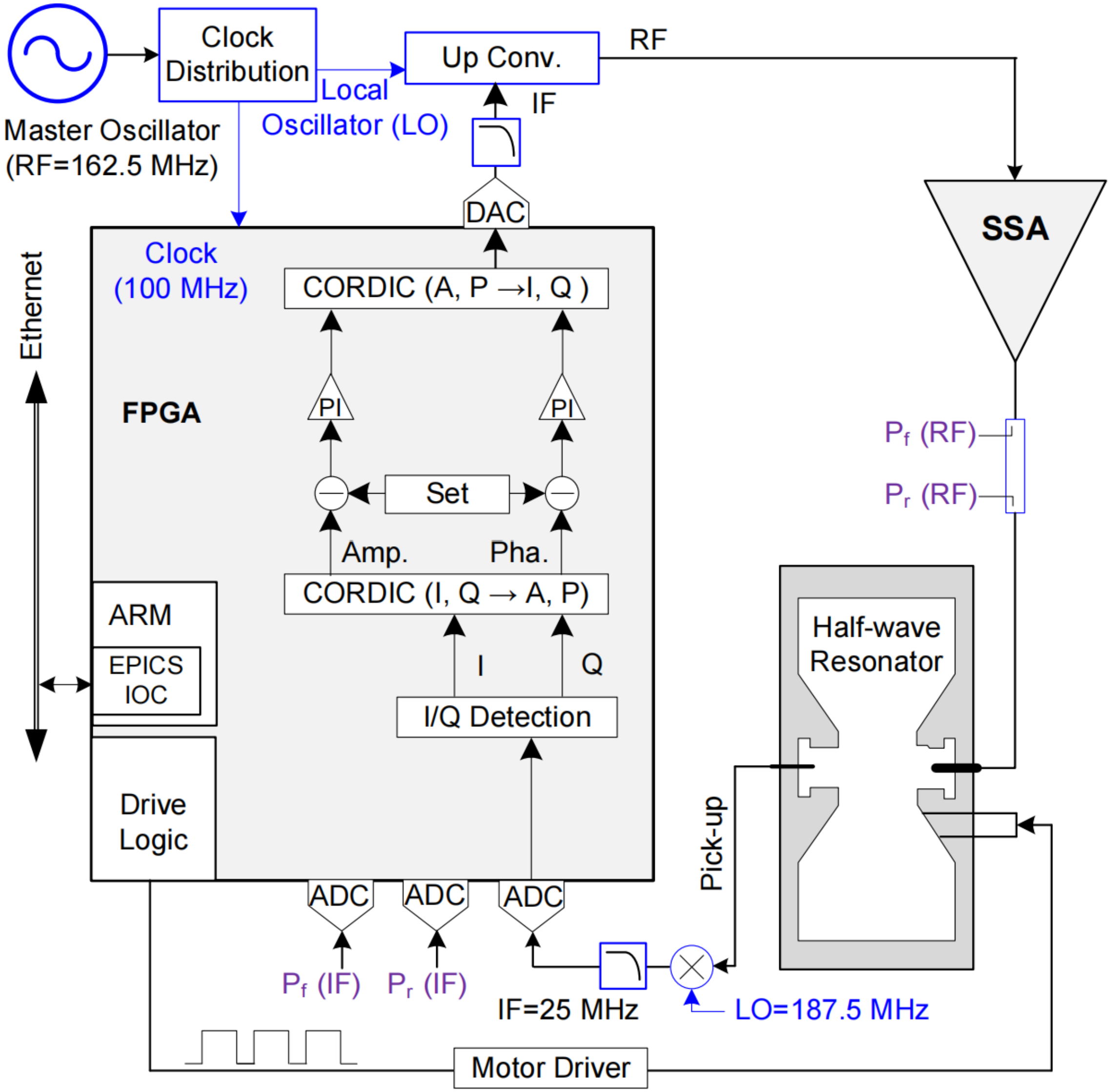
Hardware:

- ADC (×8): ADS42lb69, 16-bits, 250 MHz
- DAC (×2): AD9747, 16-bits, 250 MHz
- FPGA: XCZU19EG
- ARM: 19eg
- Motor Tuner

Algorithm:

- A/P ctrl.
- Individual ctrl.





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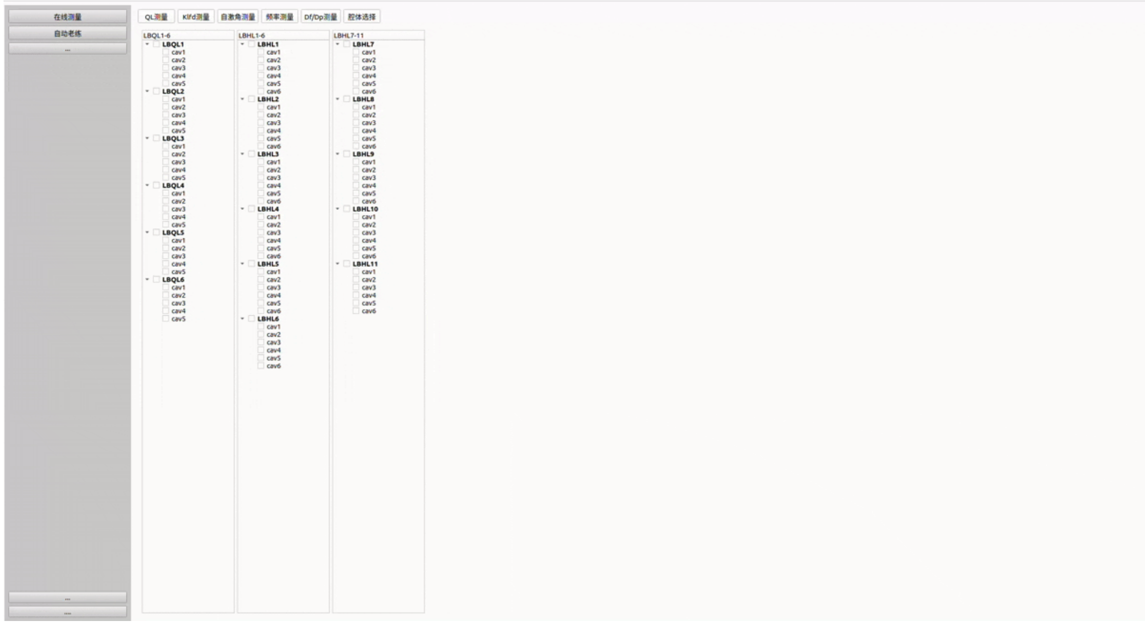
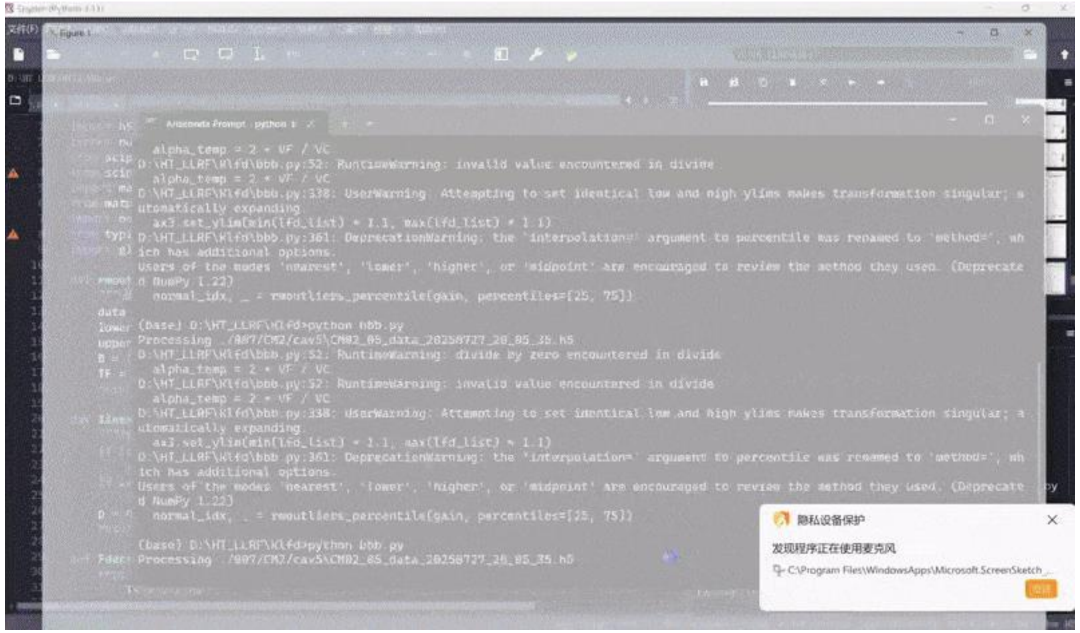
Measurement Automation

- Automated batch measurements of cavity parameters: Q_L,static LFD coefficient (K_{LFD}), and pressure sensitivity (df/fp)

Cavity Loaded Q

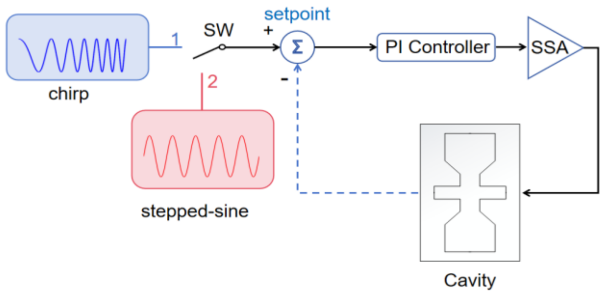


Static LFD Coefficient



Measurement Automation

1. Closed-loop excitation (Method)



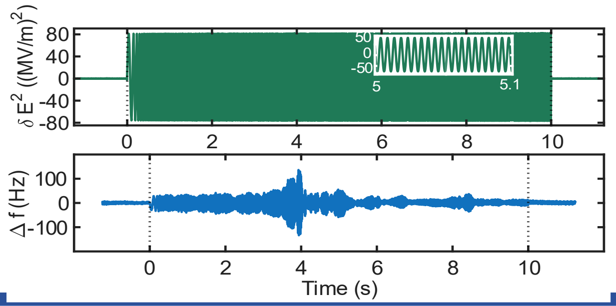
- ✓ Chirp signal is injected into the amplitude setpoint
- ✓ PI amplitude remains closed
- ✓ No external actuator required

Mechanical transfer function

$$K(j\omega) = \frac{\mathcal{F}\{\delta\Delta f(t)\}}{\mathcal{F}\{\delta E^2(t)\}}$$

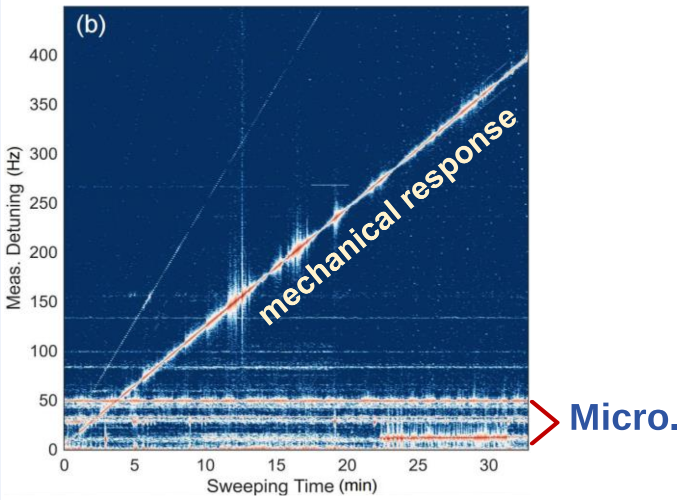
$\delta\Delta f(t)$: detuning response
$\delta E^2(t)$: cavity-field squred pertubation

Typical chirp example (10s)

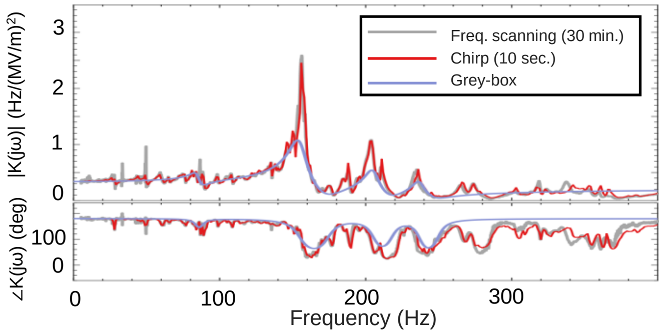


2. Scan reference (Validation)

Scan Time-Frequency map



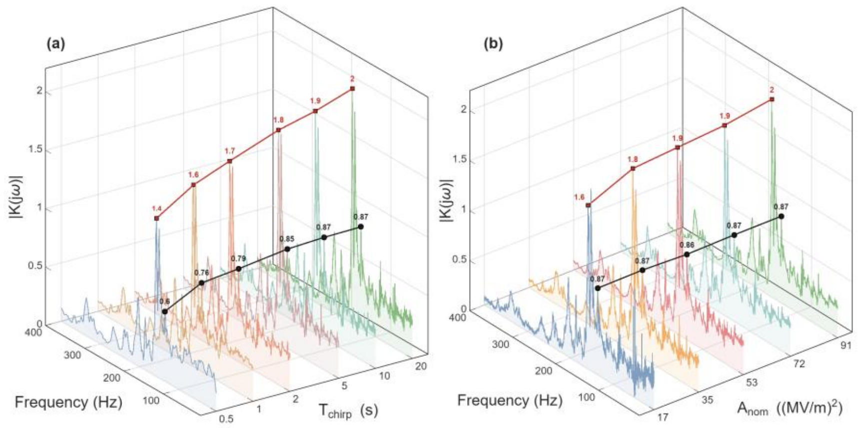
Cross-Validation of Identification Methods



- ✓ Dominant mechanical modes are consistently identified
- ✓ Chirp measurement achieves comparable results to frequency scanning
- ✓ Measurement time is reduced from ~30 min to **10 s (>100x faster)**

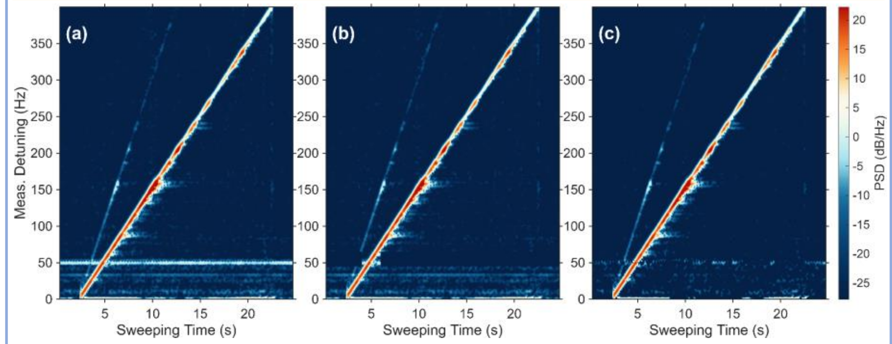
3. Chirp-Measurement Optimization（Results）

Parameter optimization



- ✓ Sufficient excitation amplitude and an appropriate chirp duration improve the signal-to-noise ratio and allow the mechanical modes to be more clearly resolved.

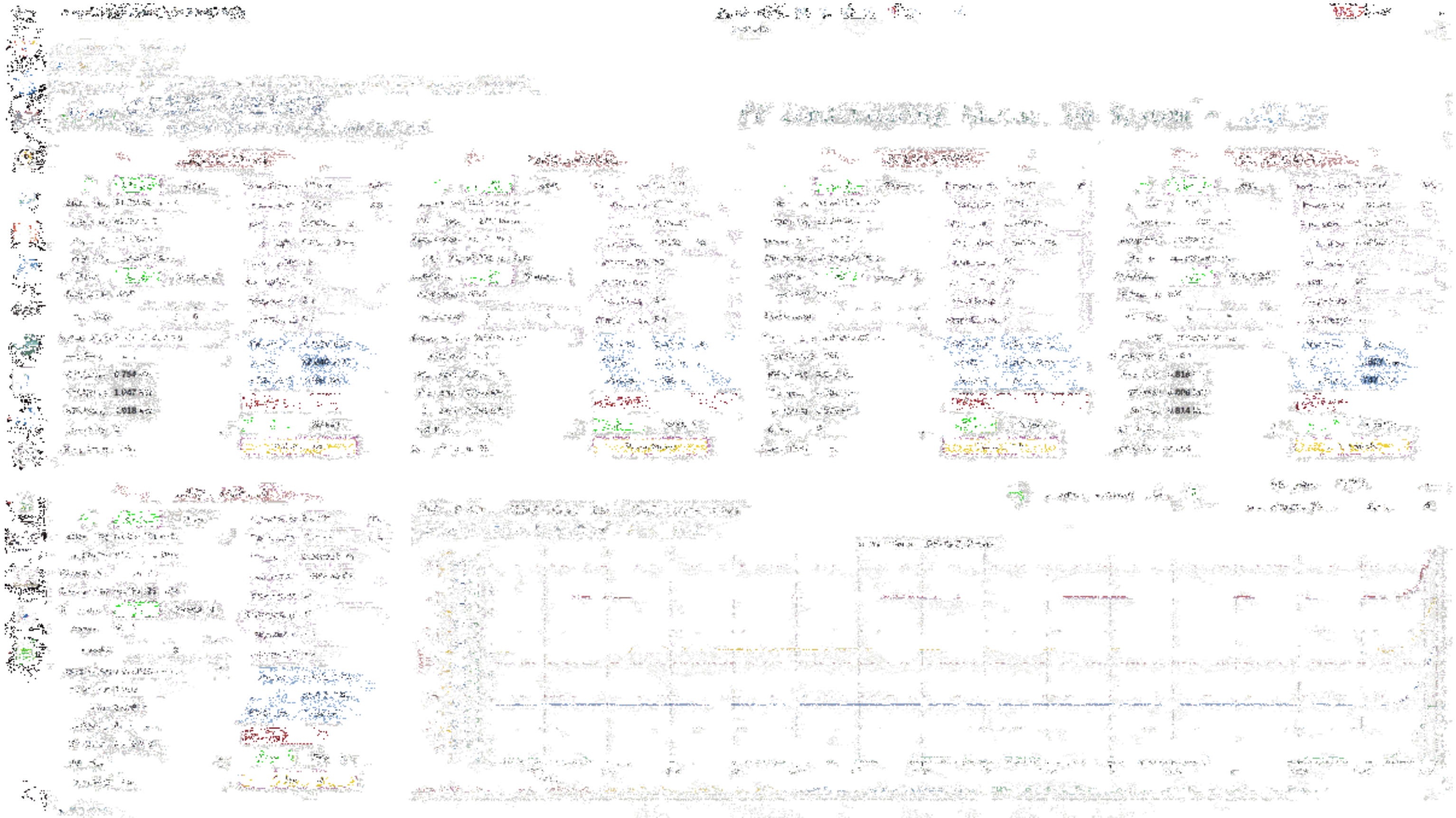
Microphonics suppression

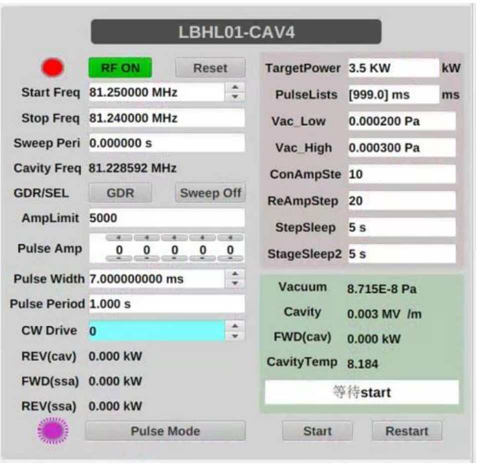


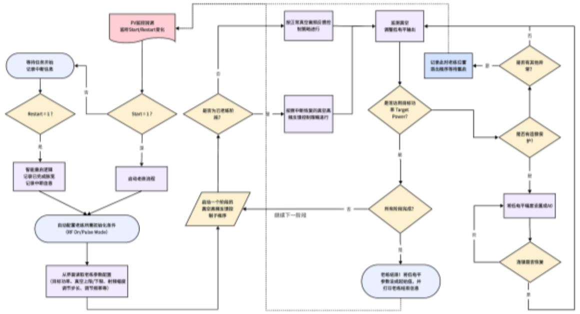
- ✓ The adaptive mask suppresses stationary microphonics background while preserving the chirp-correlated mechanical response

Automated RF Conditioning

- Automated RF conditioning enables adaptive power ramp-up with real-time interlock and vacuum protection, achieving safe, efficient, and unattended cavity processing.
- Key steps: initialization → power ramp-up → interlock/vacuum control → auto recovery → data logging.





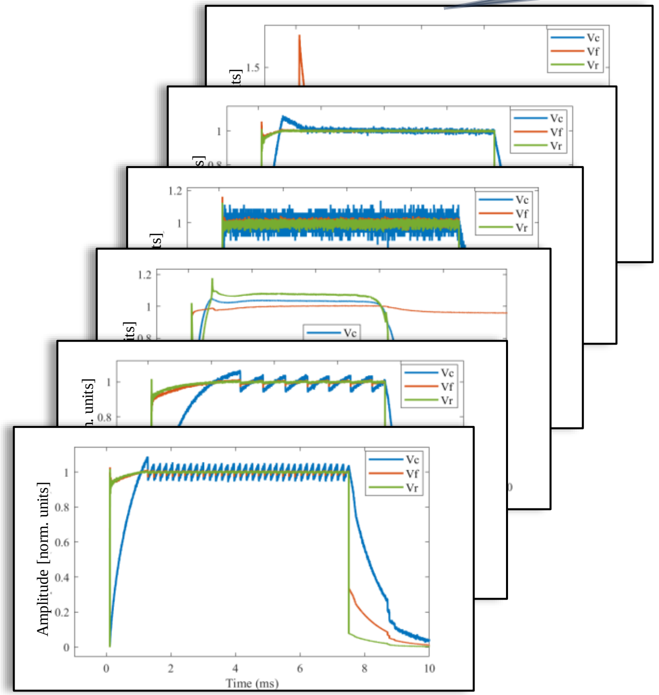


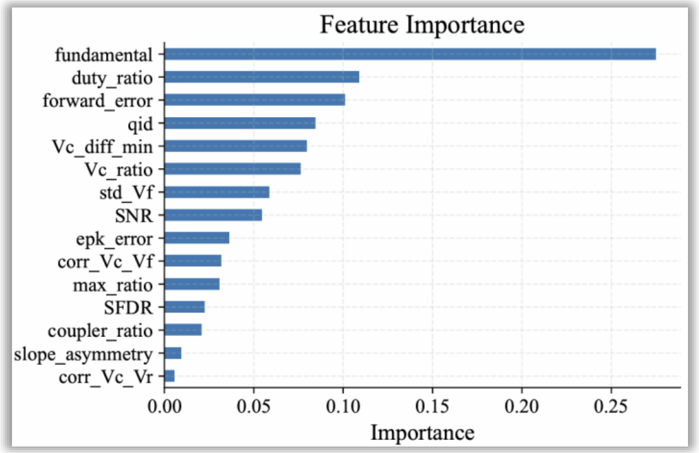
ML-based Abnomal Recognition

- Various abnormal events can occur during automatic RF conditioning.
- Machine learning automatically identifies abnormal events — feed-line faults and multipacting.

Obtaining high-quality, well-labeled event data is the essential first step

Data Pre-processing

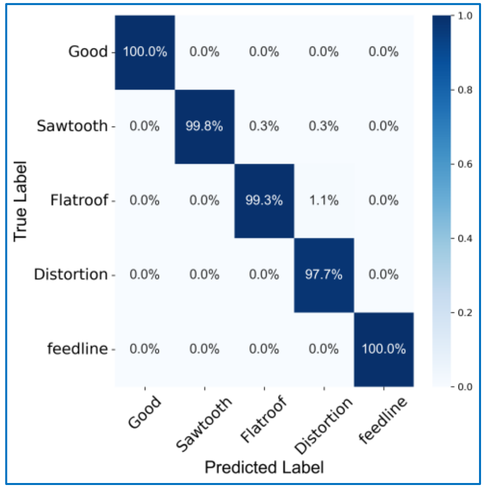


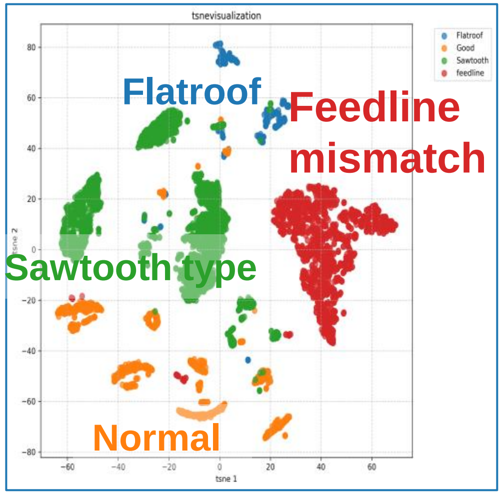


Expert experience-based Feature-Extraction

Experts are required to construct targeted feature engineering based on fault signals and extract time and frequency domains.

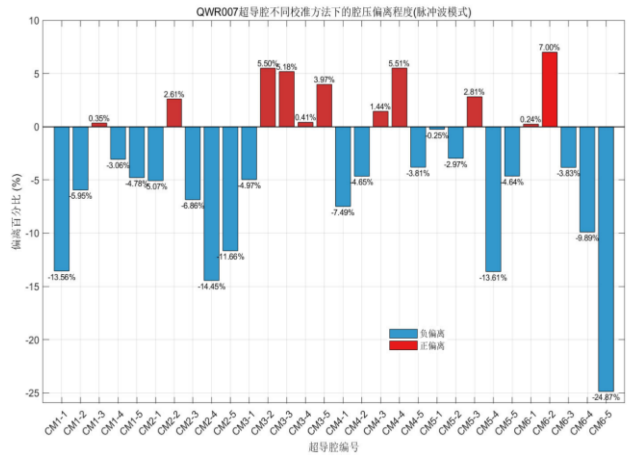
Machine Learning

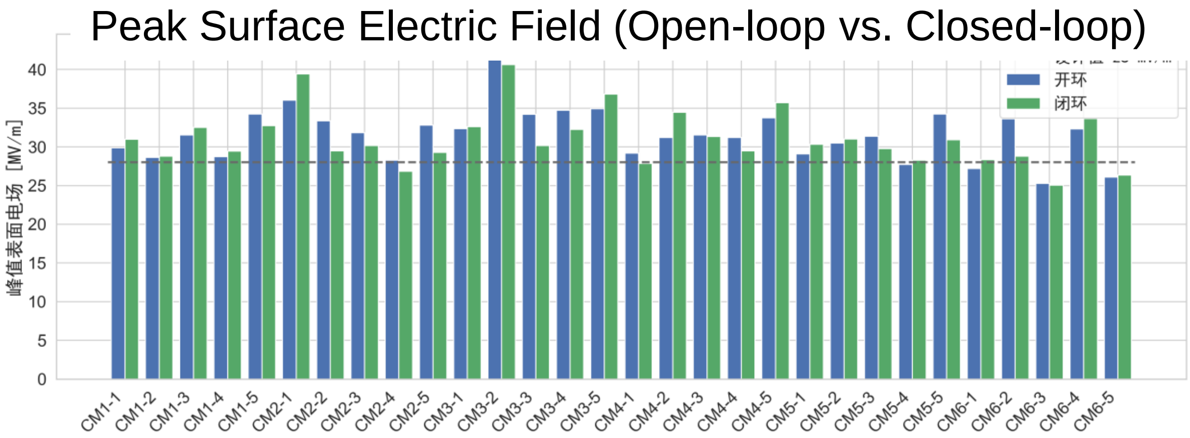


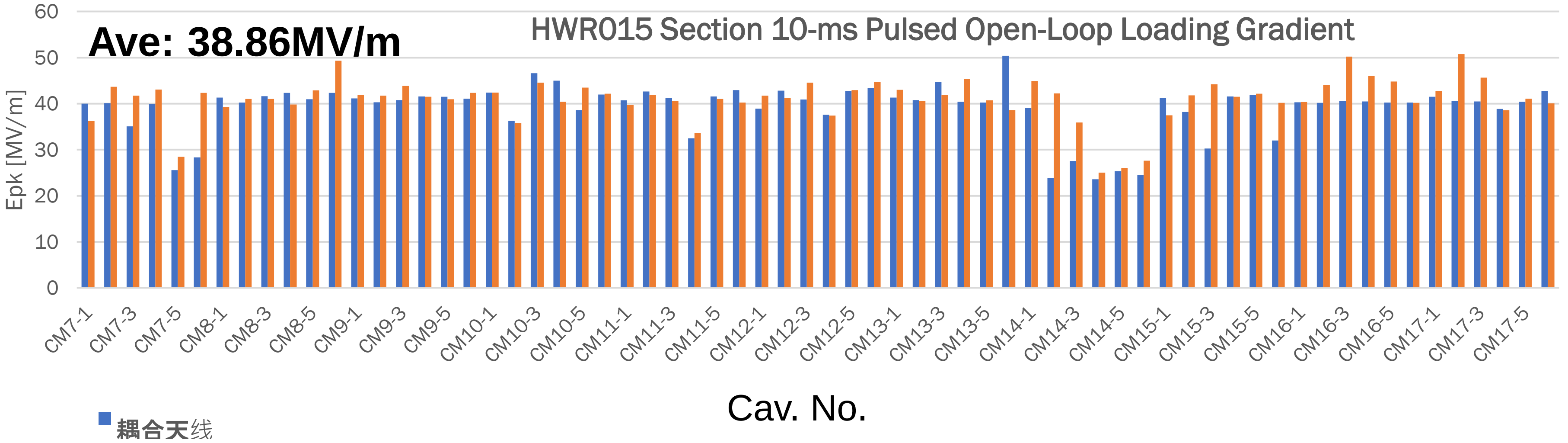


Cavity Gradient Performance

- Post-conditioning gradient test results of 96 SRF cavities with comprehensive digital parameter archiving







	腔号	Q_L	半带宽 FH	XK	YK	测试时间
	5	955223	92	0.42515-0.08844j	0.40044-0.16921j	2025/10/16
	6	1009837	80	0.44706+0.03544j	0.49247-0.02443j	2025/10/16
LBHL03 CM9	1	1035611	78	0.51155+0.13046j	0.50096+0.13601j	2025/10/16
	2	1064784	76	-0.50333+0.15043j	-0.39380+0.32999j	2025/10/16
	3	1171084	69	0.33586-0.40484j	-0.18623-0.98439j	2025/10/16
	4	908004	89	0.39570-0.24972j	0.42994-0.25651j	2025/10/17
	5	917333	89	-0.13958-0.46233j	0.03558-0.44927j	2025/10/17
	6	1092868	74	0.15437+0.57073j	0.13858+0.54713j	2025/10/17
LBHL04 CM10	1	1026345	79	-0.12684+0.01980j	-0.12582+0.05482j	2025/10/17
	2	1067426	76	-0.03020-0.13131j	0.02595-0.14223j	2025/10/17
	3	1144389	71	0.11553+0.08675j	0.08979+0.10761j	2025/10/17
	4	1047510	78	0.31631+0.36905j	-0.38131+0.47869j	2025/10/16
	5	1055832	77	-0.04602-0.31684j	0.00439-0.31421j	2025/10/16
	6	1136529	72	-0.15990+0.47523j	-0.19199+0.53153j	2025/10/16
LBHL05 CM11	1	1044246	78	0.09332+0.50567j	-0.00535+0.42854j	2025/10/16
	2	1028879	79	-0.29343+0.38849j	-0.14334+0.53689j	2025/10/16
	3	998779	81	-0.09967+0.39947j	0.39846+0.24759j	2025/10/16
	4	1073921	76	0.00835+0.42358j	0.15426+0.35415j	2025/10/16
	5	1066276	76	-0.59065+0.07758j	-0.33363+0.41977j	2025/10/16
	6	1003993	81	-0.48690+0.02138j	-0.48788+0.05775j	2025/10/16
LBHL06 CM12	1	979216	83	0.04515-0.30782j	0.16199-0.26937j	2025/10/16
	2	1136094	72	0.09340-0.21590j	0.18400-0.19523j	2025/10/16
	3	1072757	76	-0.09238-0.34274j	0.13771-0.32997j	2025/10/16
	4	1075569	76	0.36007-0.18740j	-0.08474-0.38807j	2025/10/16
	5	998570	81	-0.28449+0.37939j	0.32734+0.28839j	2025/10/16
	6	1045737	78	0.24260+0.08491j	-0.02590+0.09748j	2025/10/16
LBHL07 CM13	1	1047532	78	-0.25182-0.40255j	-0.13664-0.44467j	2025/10/16
	2	1075817	75	0.14594 [illegible]	[illegible]	[illegible]
	3	1174106	69	0.1888 [illegible]	[illegible]	[illegible]
	4	987975	82	-0.0309 [illegible]	[illegible]	[illegible]
	5	877191	93	-0.0352 [illegible]	[illegible]	[illegible]
	6	1062499	76	0.4066 [illegible]	[illegible]	[illegible]
LBHL08 CM14	1	924601	88	-0.2668 [illegible]	[illegible]	[illegible]
	2	824821	99	0.1528 [illegible]	[illegible]	[illegible]
	3	890903	91	-0.3744 [illegible]	[illegible]	[illegible]
	4	853249	95	-0.32307-0.07238j	-0.22375-0.25514j	2025/10/17

LBQL LBHL

Digital Cavity Database

Over 2,000 parameters across all 96 SRF cavities were precisely measured and systematically characterized, establishing a fully traceable digital database to support cavity performance tracking and future intelligent operation.

Automated RF Loading

- The RF control system automatically loads and initializes all superconducting cavities in pulse mode.
- Each cryomodule is sequentially powered and monitored through the automated startup interface.

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01 **Project Overview**
HIAF-iLINAC and its RF system

02 **Automated RF Commissioning**
From automation to intelligent operation

03 **Challenges & Solution**
Lessons from real machine operation

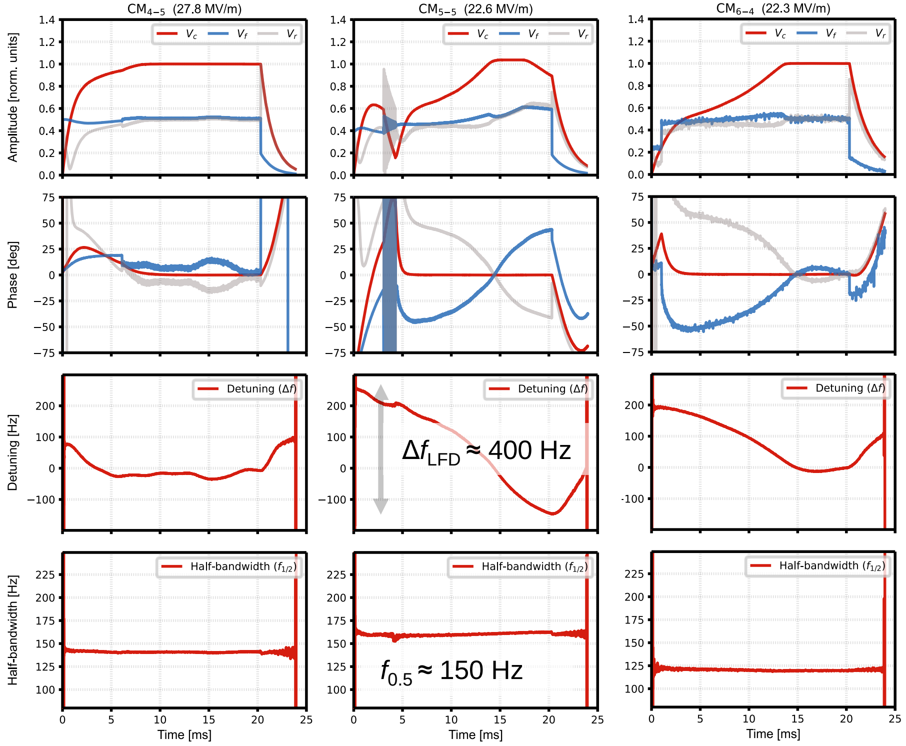
04 **Summary**

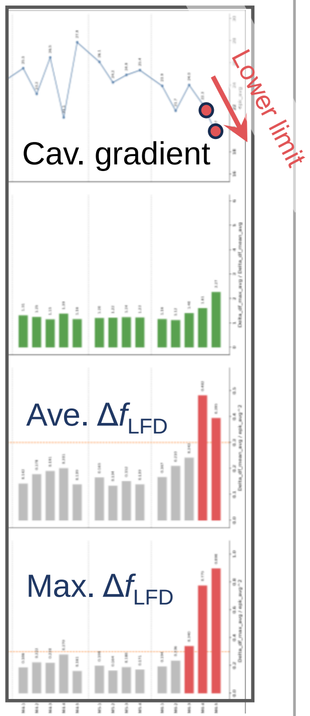
Impact of Mech. Modes on SRF operation

- Mechanical modes in SRF cavities drive large dynamic LFD and resonances, causing difficult closed-loop operation and intermittent abnormal detuning in pulsed mode (**NO** fast tuner).

Dynamic LFD Sets PS-mode limits

- Experience during PS commissioning shows that $\Delta f_{LFD} / f_{0.5} > 1.5$ often indicates difficult closed-loop operation





$\Delta f_{LFD} / f_{0.5} = 0.7$	$\Delta f_{LFD} / f_{0.5} = 2.7$	$\Delta f_{LFD} / f_{0.5} = 1.7$

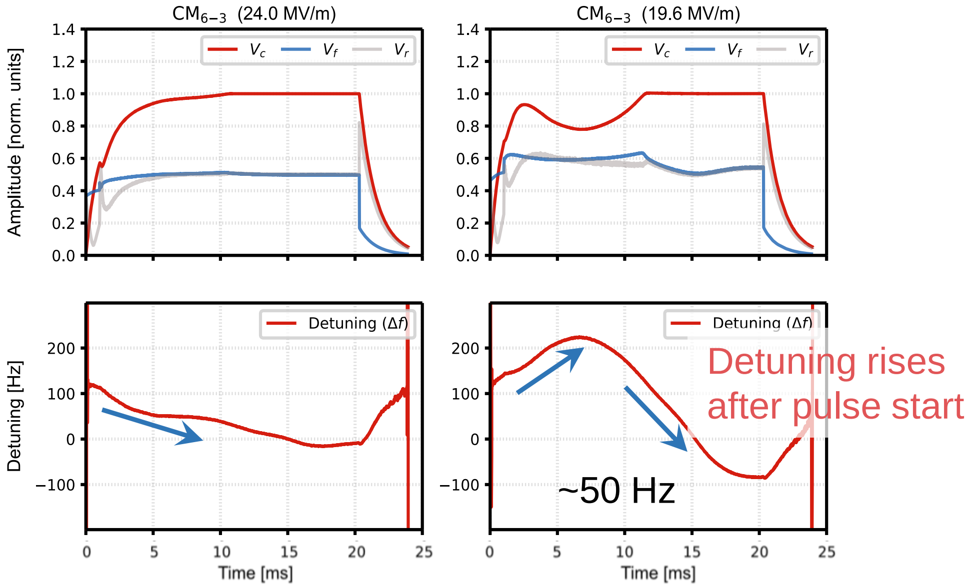
Easy to close loop

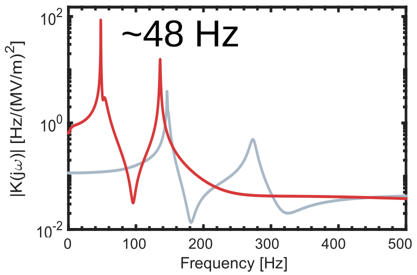
Difficult to close loop

Higher $\Delta f_{LFD} / f_{0.5}$ ratios (red bars) correlate with reduced operational limits

Intermittent Abnormal Detuning

- Detuning sometimes rises after pulse starts——different from normal behavior



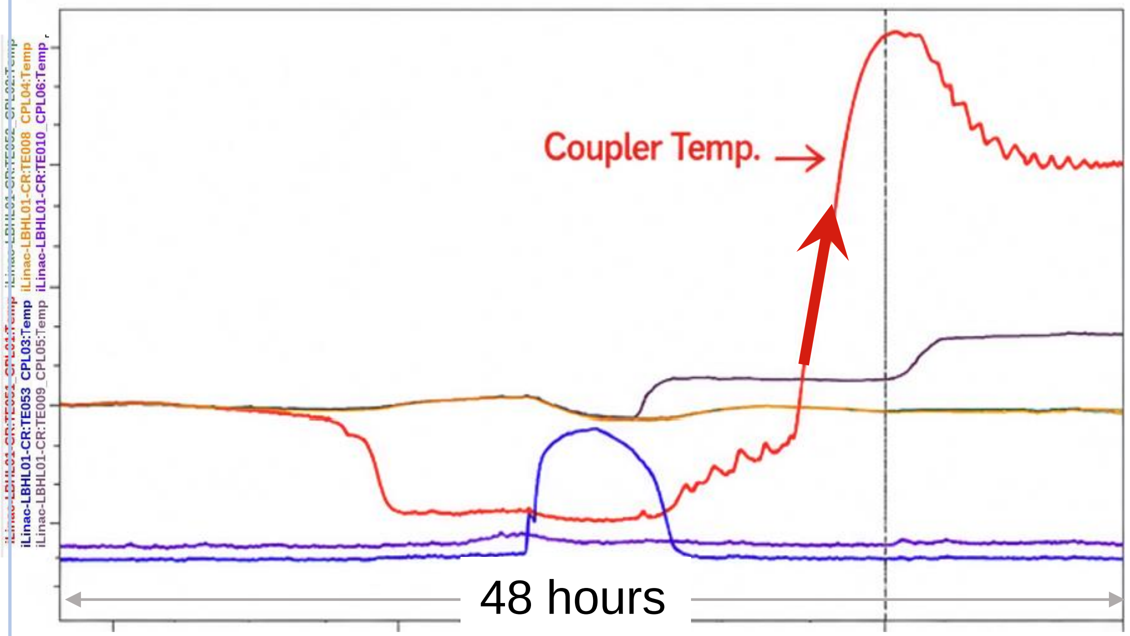


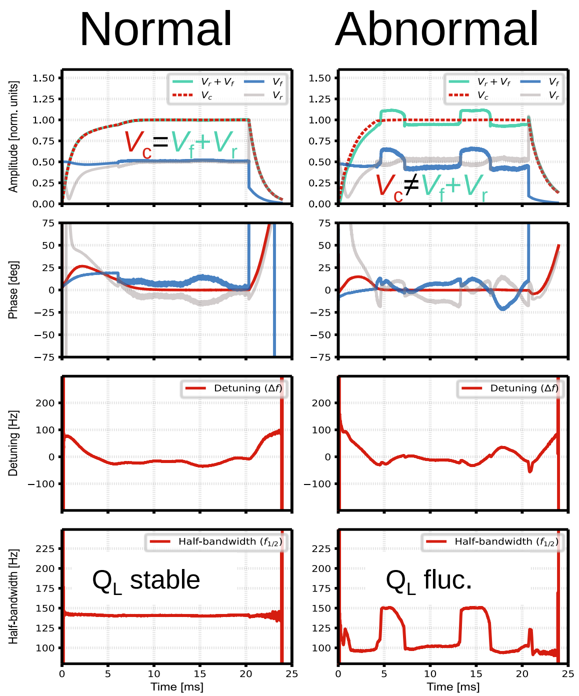
Intermittent ~48 Hz vibrations align with mechanical mode frequencies, but the root cause is still unknown

Coupler-side Temperature Rise

- Coupler-side heating is suspected as another source of cavity performance degradation, but the root cause remains unclear

Experimental Observation





Expected

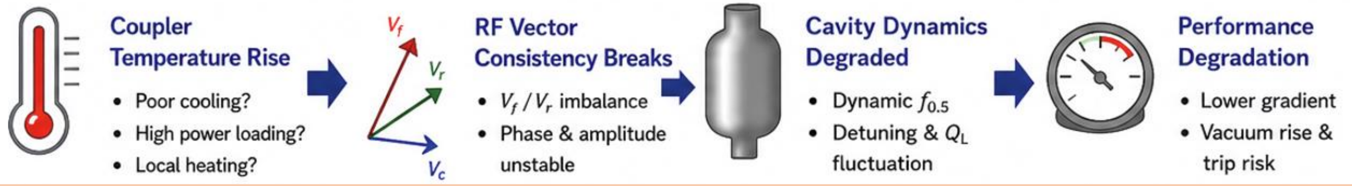
- $V_c=V_f+V_r$
- Flat loaded Q (or bandwidth)

Observed

- $V_c \neq V_f+V_r$
- Fluc. loaded Q (or bandwidth)
- Coupler temp. ↑

Lower gradient & changed loop phase patricianly mitigated

Mechanism & Impact



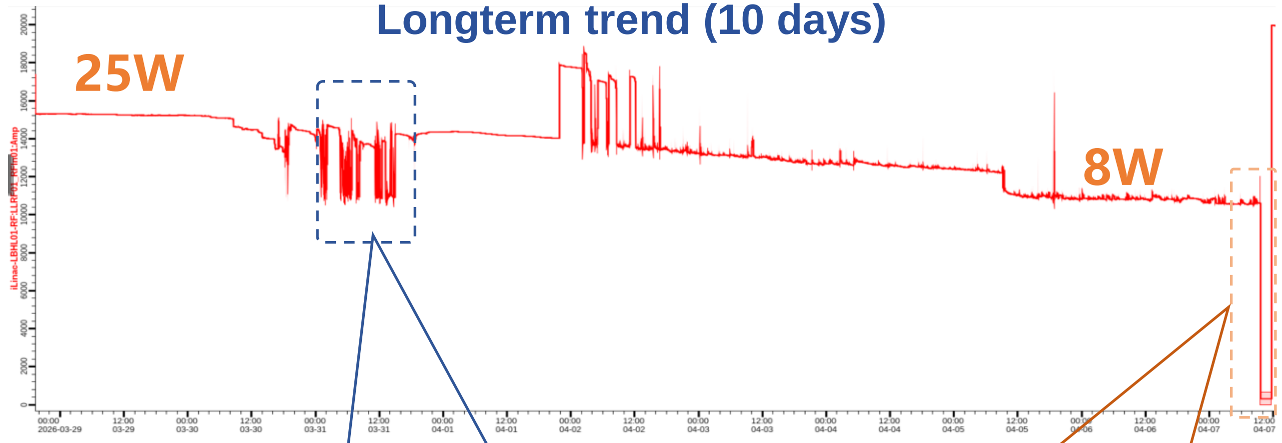
Coupler-side issue suspected; root cause remains unclear, further investigation is needed

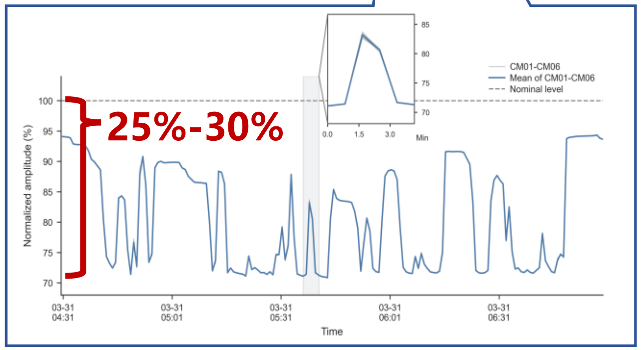
Coupler temperature rise disrupts RF vector balance, induced cavity instability and ultimately limits the cavity performance

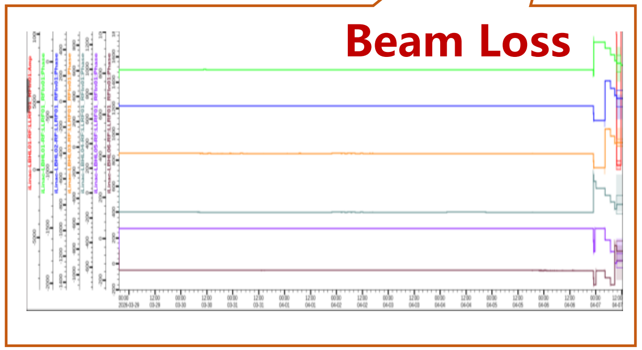
Impact of Master Amplifier

- An amplifier fault in the shared reference path caused a ten-day power degradation from 25 W to 8 W and intermittent beam loss.

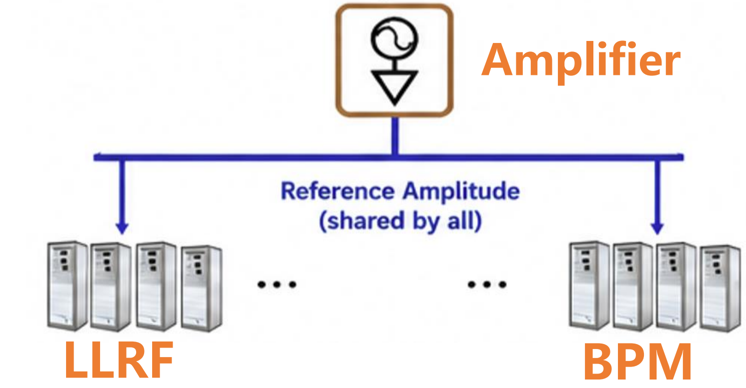
What Happened: Evidence



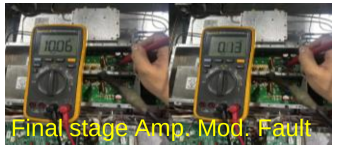




System Architecture



⚠ A fault in the common amplifier reference propagates system-wide, affecting both LLRF and BPM



A hot-standby architecture is under consideration; thermal management and cabinet design are being investigated to ensure reference signal stability

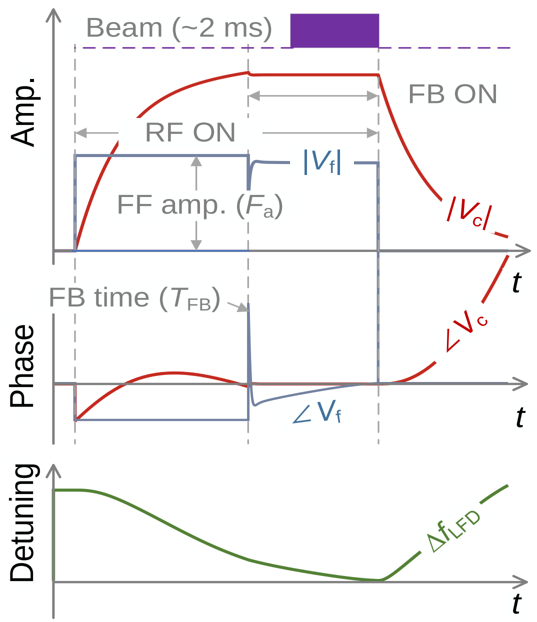
LLRF Parameter Opt. with Bayesian & LLM

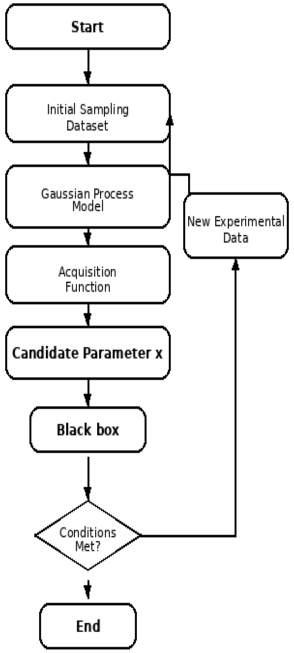
Method 1. Bayesian Optimization

Bayesian optimization tunes six coupled parameters in pulsed SRF operation to improve the RF stability

Six Parameters:

K_{Ap}, K_{Ai}, K_{Pp}, K_{Pi}, F_a, T_{FB}





Objective: Minimize RMS Fluc.

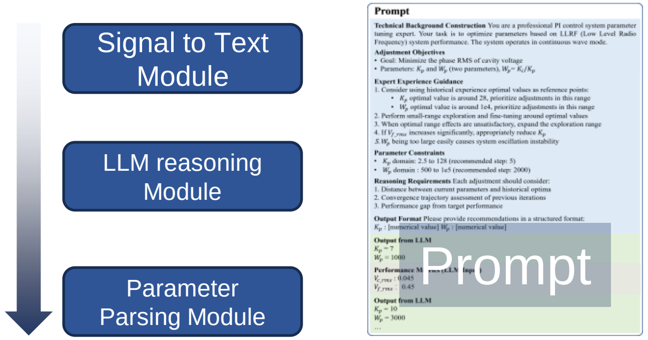
$$J_1 = \sqrt{A_{rms1s} \cdot P_{rms1s}}$$

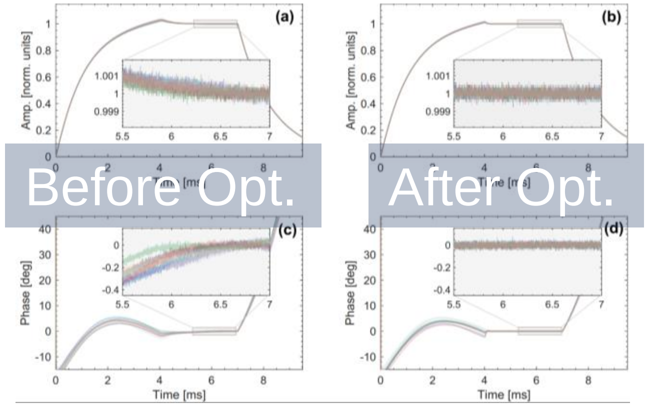
Constraint: Minimize FWD power

$$\begin{aligned} &\text{minimize} && f(\boldsymbol{x}) \\ &\text{subject to} && g(\boldsymbol{x}) \leq Const \\ & && \boldsymbol{x} \in \mathcal{X} \end{aligned}$$

Method 2. LLM-assisted Opt.

An LLM optimizes the six-dimensional parameters by embedding **expert knowledge** into the prompt and exploiting the model's reasoning capability





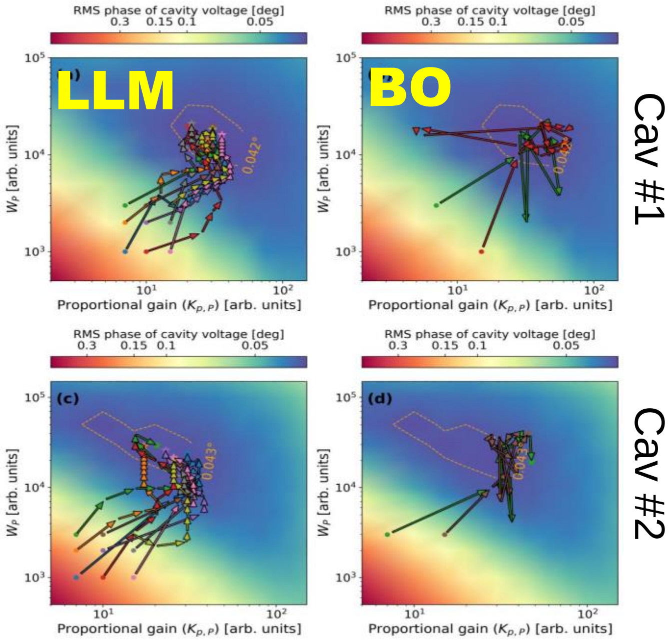
Before Opt. After Opt.

Performance Comparison

LLM optimization: Smooth trajectory, gradual convergence.

BO optimization: Broad exploration early, rapid convergence.

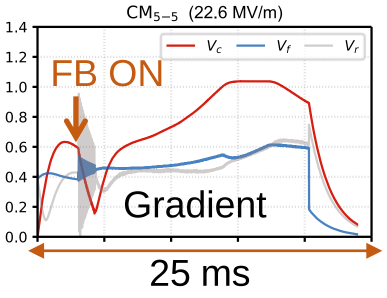
Both methods reach the optimal region within 27 iterations from different initial conditions

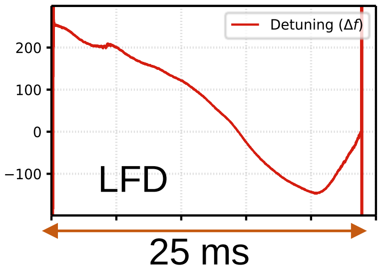


Success Rate Comparison (27 Experiments)

Cavity ID	# of Experiments	BO Success Rate	LLM Success Rate
CM2-5	27	96.3%	100%
CM2-6	27	100%	94.4%
CM3-5	27	100%	96.3%
CM4-3	27	100%	100%

Filling on Resoance





Problem:

Field instability caused by abrupt FB activation in the presence of large dynamic LFD

Objective

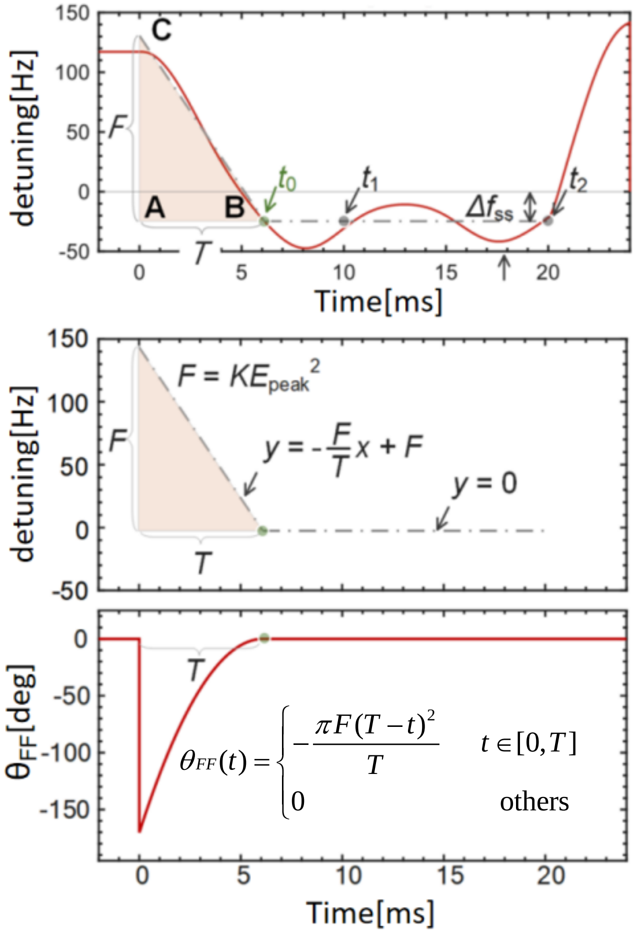
Maintain RF stable during the flat-top

Method

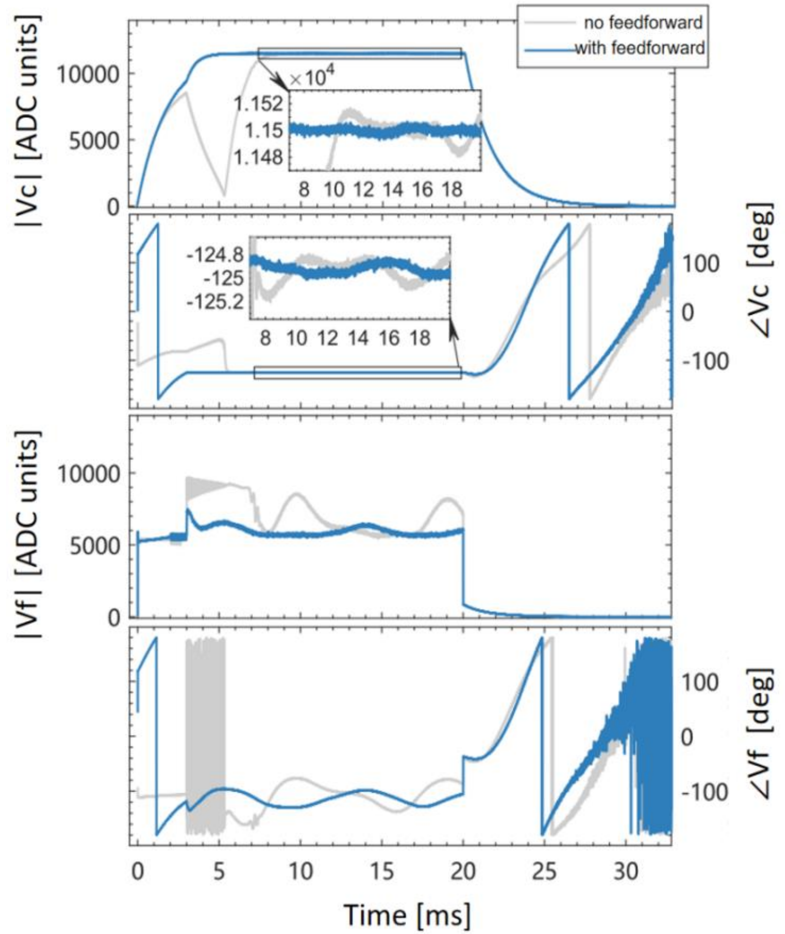
Let the cavity and forward phases actively track the detuning variation during the filling time

$$\Delta\omega = \varphi' \Rightarrow \varphi_{FF} = \int \Delta\omega$$

Detuning & Phase Feedforward



Results

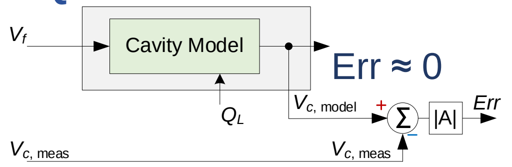


Model-based Real-time Quench Detection

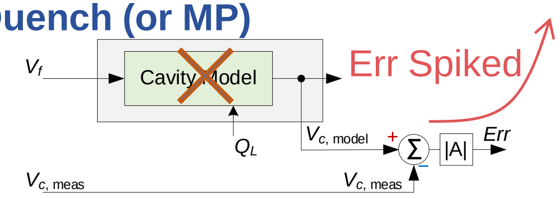
- Real-time model residual accurately identifies true CW quench without dynamic Q_L calculation

Principle & Advantages

Non-Quench event



Quench (or MP)



CW quench discrimination

Residual-based detection reduces false trips associated with transient RF power imbalance.

Low computational complexity

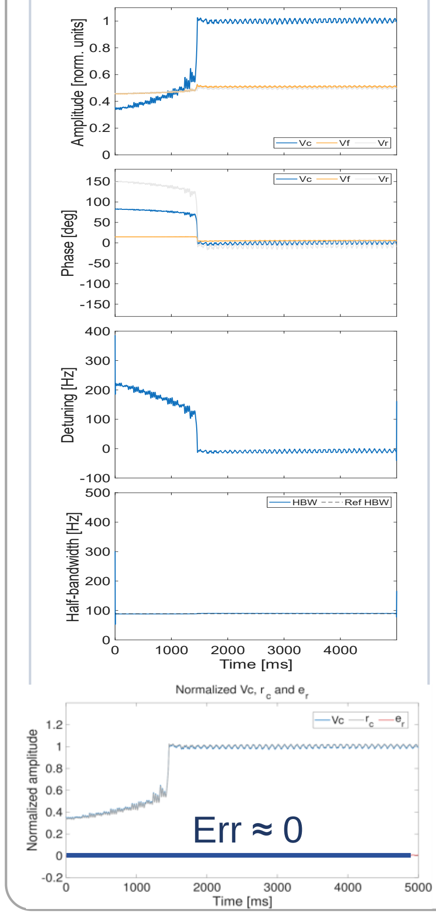
Avoiding detuning estimation and QL reconstruction; suitable for FPGA implementation.

Transient fault discrimination

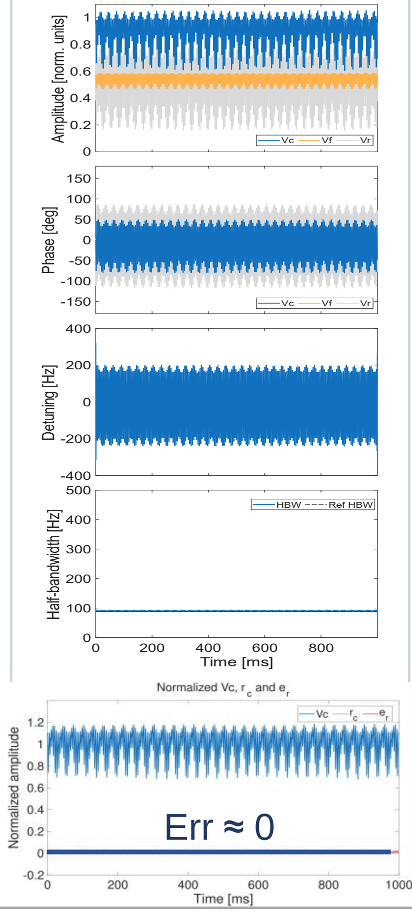
Suppresses short E-quench spikes while retaining sustained thermal-quench residuals.

Measured cases: complete raw signals and residual outputs

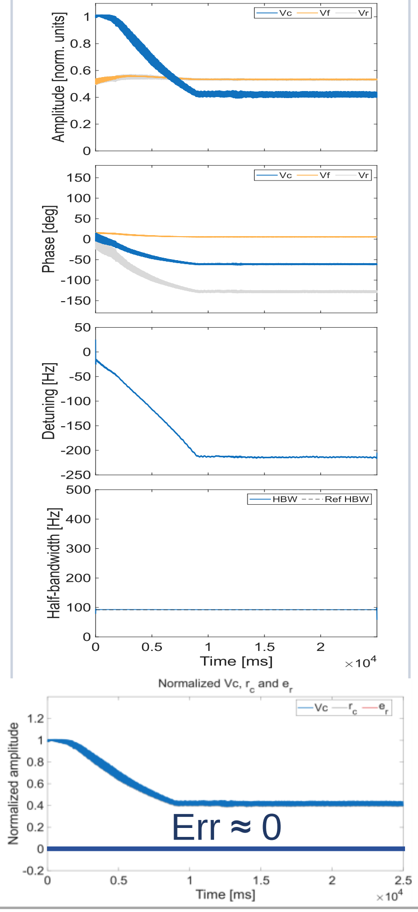
CM2-5 | Ponderomotive I



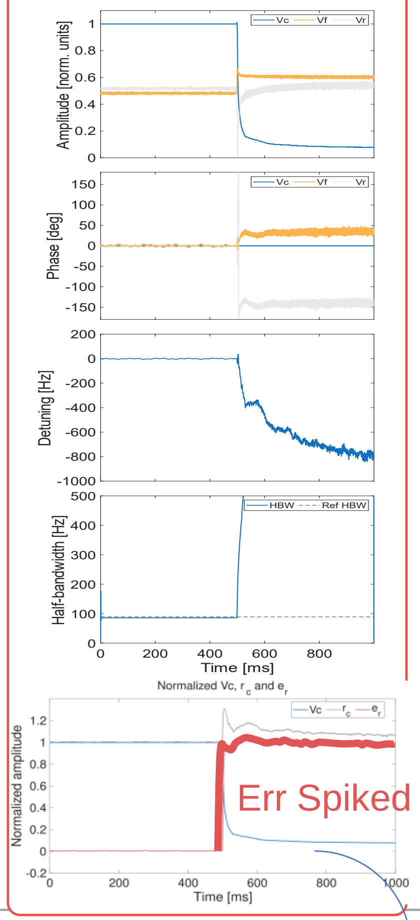
CM2-5 | Ponderomotive II



CM3-1 | Helium Fluc.



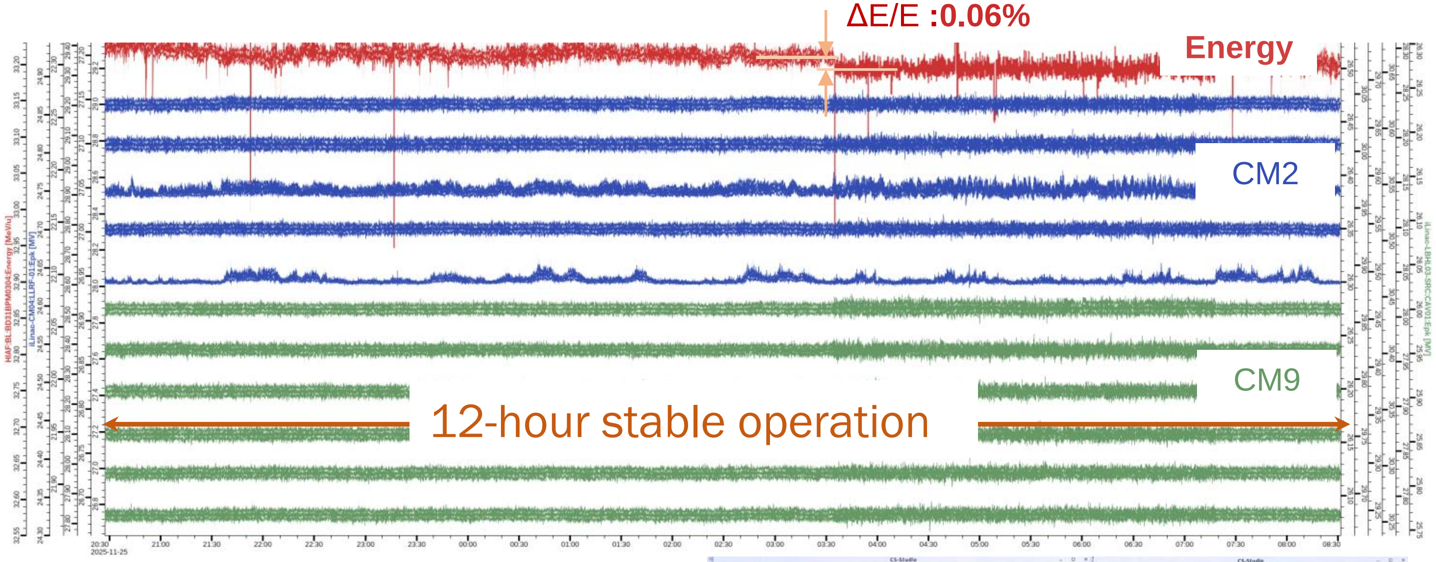
CM2-5 | Thermal quench

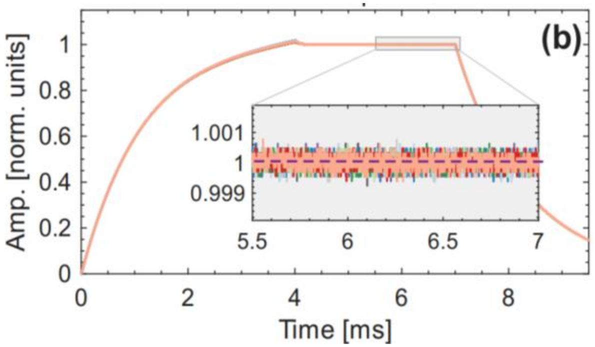


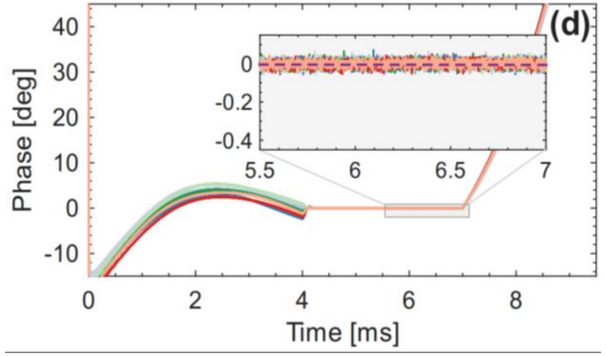
F. Qiu, LINAC2026 (the 33rd Linear Accelerator Conference), Daejeon Convention Center, 16-21 Aug. 2026, Daejeon, Korea

RF Stability and Performance

- Established an instability alarm mechanism (Thresholds: 0.1%, 0.1 deg). The long-term operational stability of the cavities exceeds design specifications, achieving an energy stability of 0.06%







Summary

- **Automation enables efficient commissioning.**
  Automated characterization, conditioning, loading, and anomaly handling have significantly streamlined RF commissioning.

- **Commissioning reveals the real machine.**
  Operational anomalies provide critical insights into SRF dynamics, RF hardware, and system-level limitations.

- **Intelligence drives the next step.**
  Advanced LLRF algorithms and AI-based optimization offer a promising path toward more stable, efficient, and autonomous accelerator operation

Thanks for your attention

Back-up Slides