



Development of intelligent measurement method and automated RF commissioning system for sc linac in IMP

Zheng Gao, Feng QIU, Rihua ZENG, Lijuan YANG, Chengye Xu, Shihui Wei, Zhaojie Chen, Yilin MIAO, Zhenglong Zhu, Jinying Ma, LiePeng SUN, Zhijun WANG, Yuan HE

Institute of Modern Physics, CAS

Content



01

- Introduction

02

- Intelligent measurement method for SRF system

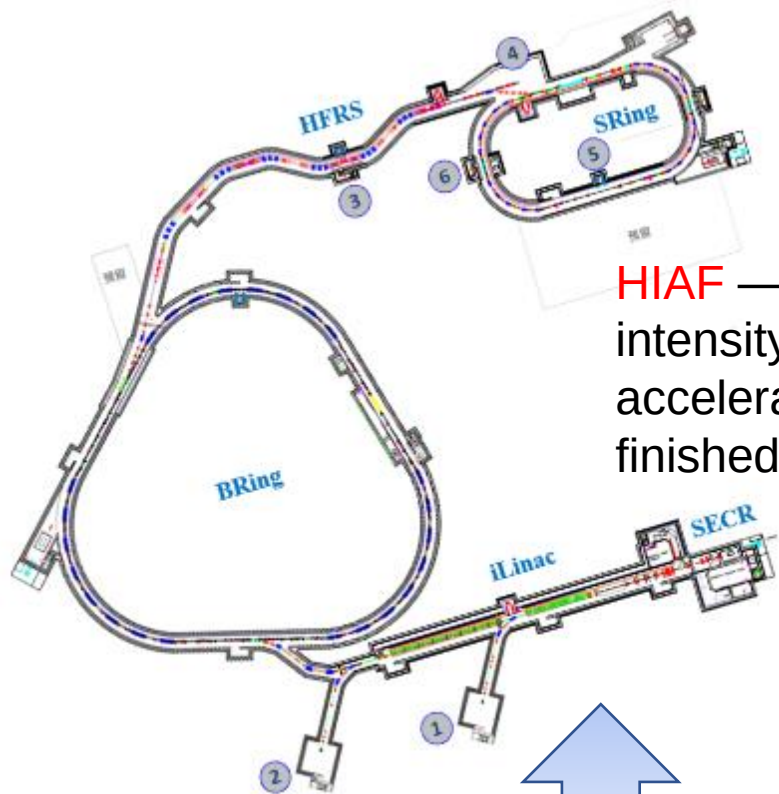
03

- Automated RF Commissioning

04

- Summary

The SC Linac In IMP



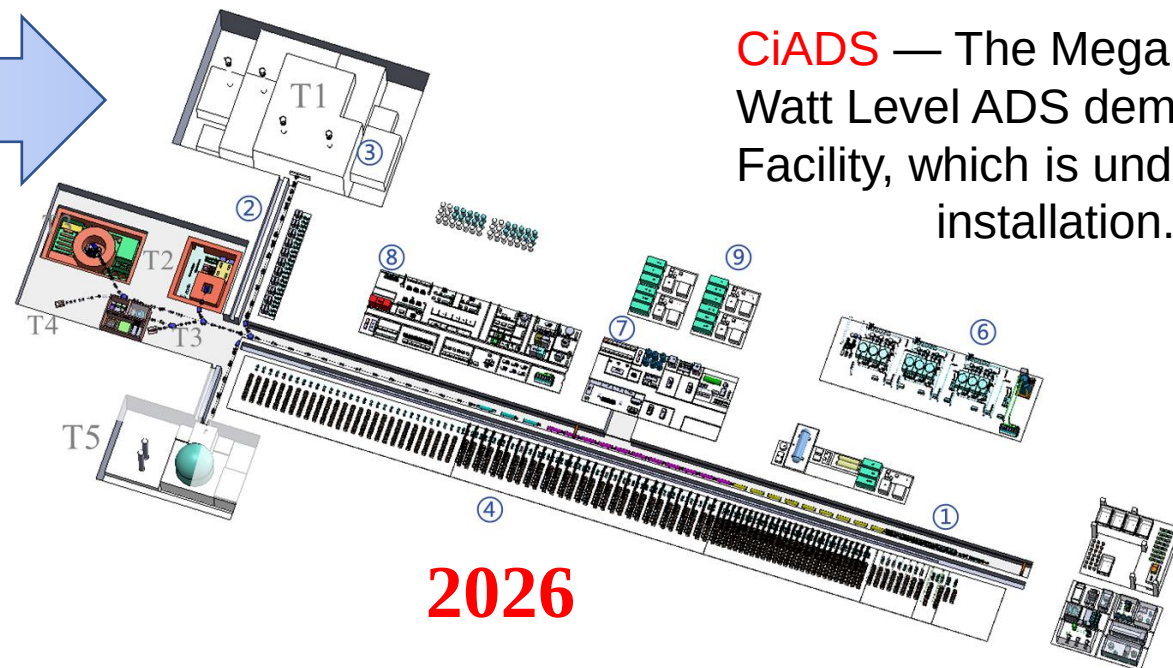
HIAF — The high intensity heavy ion accelerator, it has finished installation.

2025



CAFE2 — China Accelerator Facility for nEw Elements.

2021



CiADS — The Mega Watt Level ADS demo Facility, which is under installation.

2026

Huizhou:

- CiADS – The SC linac of China initiative Accelerator Driven System.
- HIAF -- The superconducting iLinac for heavy ion.

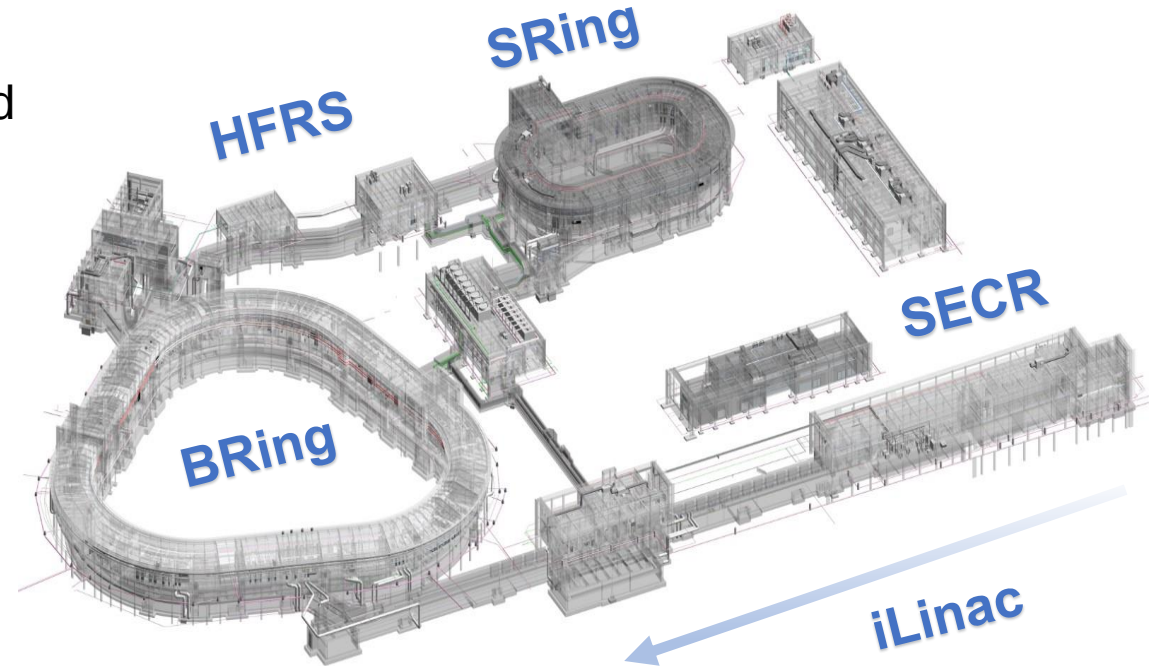
Lanzhou:

- CAFE2 -- China Accelerator Facility for nEw Elements Facility for superheavy element (SHE) and material irradiation.

HIAF Facility

HIAF: High Intensity heavy-ion Accelerator Facility

- Mainly designed to provide high energy ($\sim 800\text{MeV/u}$) and high intensity (10^{11}ppp) heavy ion beams (up to U^{35+})
- Civil construction was started in the end of 2018
- Beam commissioning date is December 2025

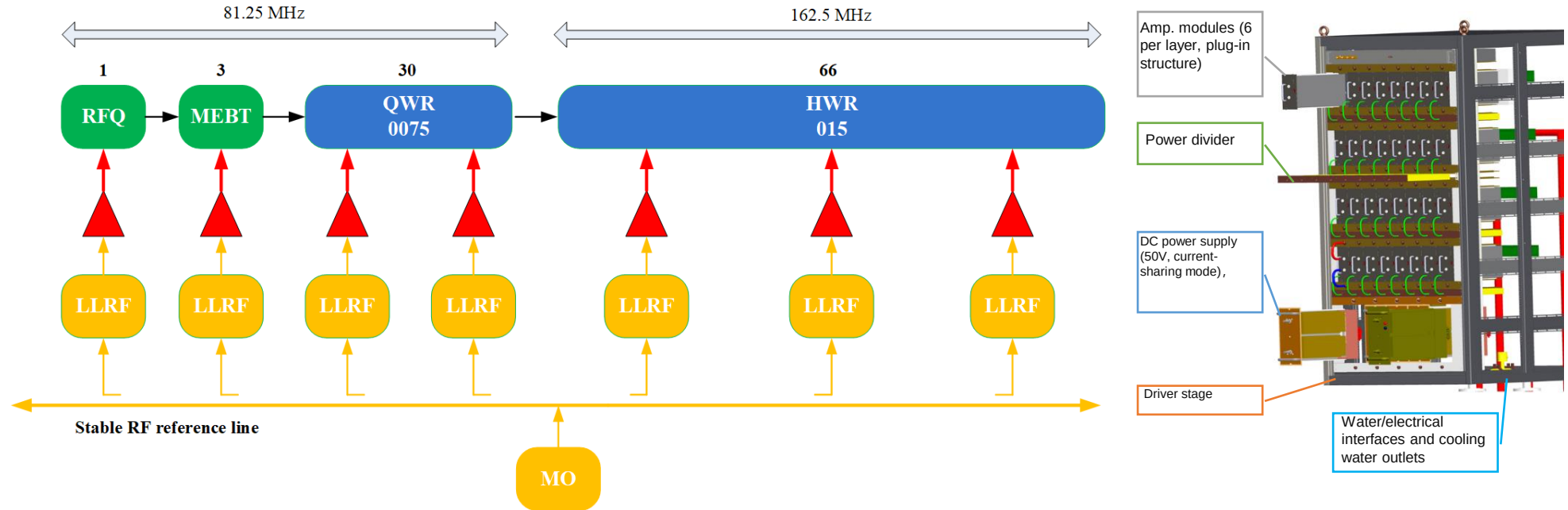


- Approved in Dec. 2015, Ground broke in Aug. 2018, Officially started in July 2021
- Leading institute: IMP
- Location: Huizhou, Guangdong Prov.

The RF System Layout of HIAF iLinac



The RF power transmission line



➤ The RF system of iLinac can be divided into two sections

- The normal conducting section which consist of RFQ and buncher cavity.
- The superconducting section which include QWR and HWR cavities.

• The RF system parameter table

Section	Freq. (MHz)	Qty.	RF Power(kW)	PWR per SSA rack(kW)	SSA Qty.
RFQ	81.25	1	160	24	8
MEBT	81.25	3	10	24	2
QWR007	81.25	30	6	24	9
HWR015	162.5	66	6	24	17

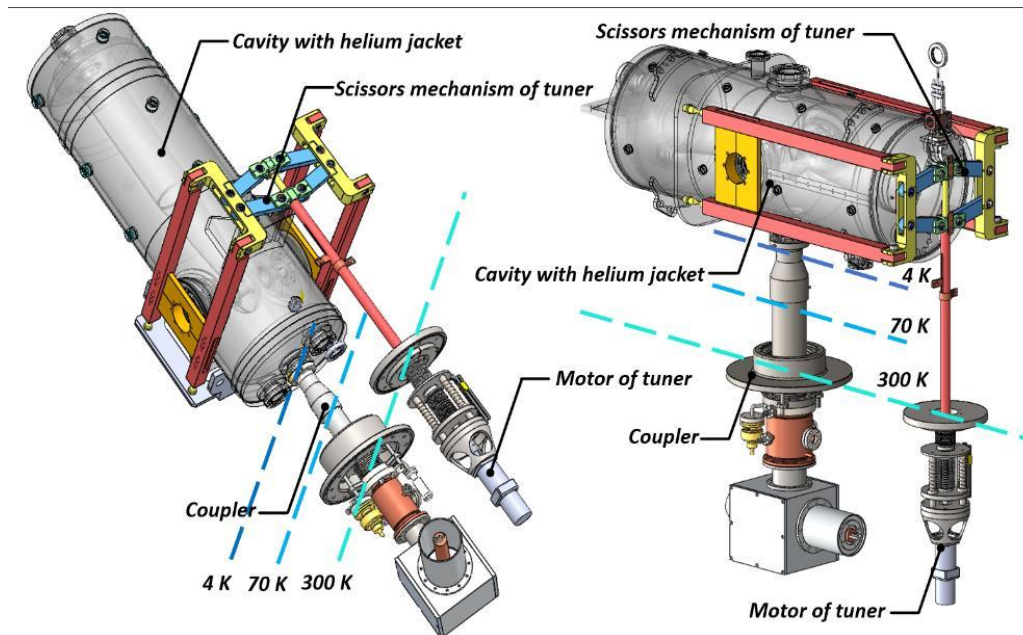
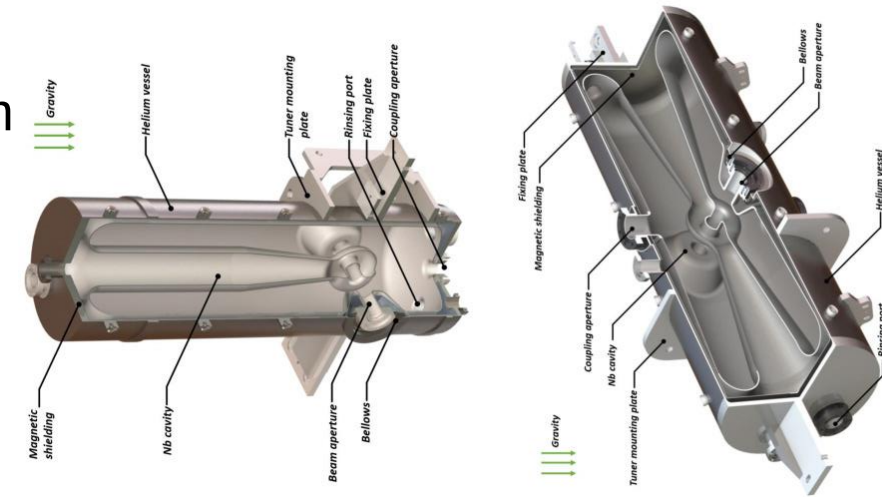
The SRF cavities for iLinac

iLINAC 96 SRF cavities parameters and features:

- ◆ **Design Specification:** Continuous wave (CW) and pulsed beam
- ◆ **Operation Characteristics:** All SC system will operate in CW or Pulse mode, which will result in extreme operation condition and raise sophisticated measurement demand.

QWR007

HWR015

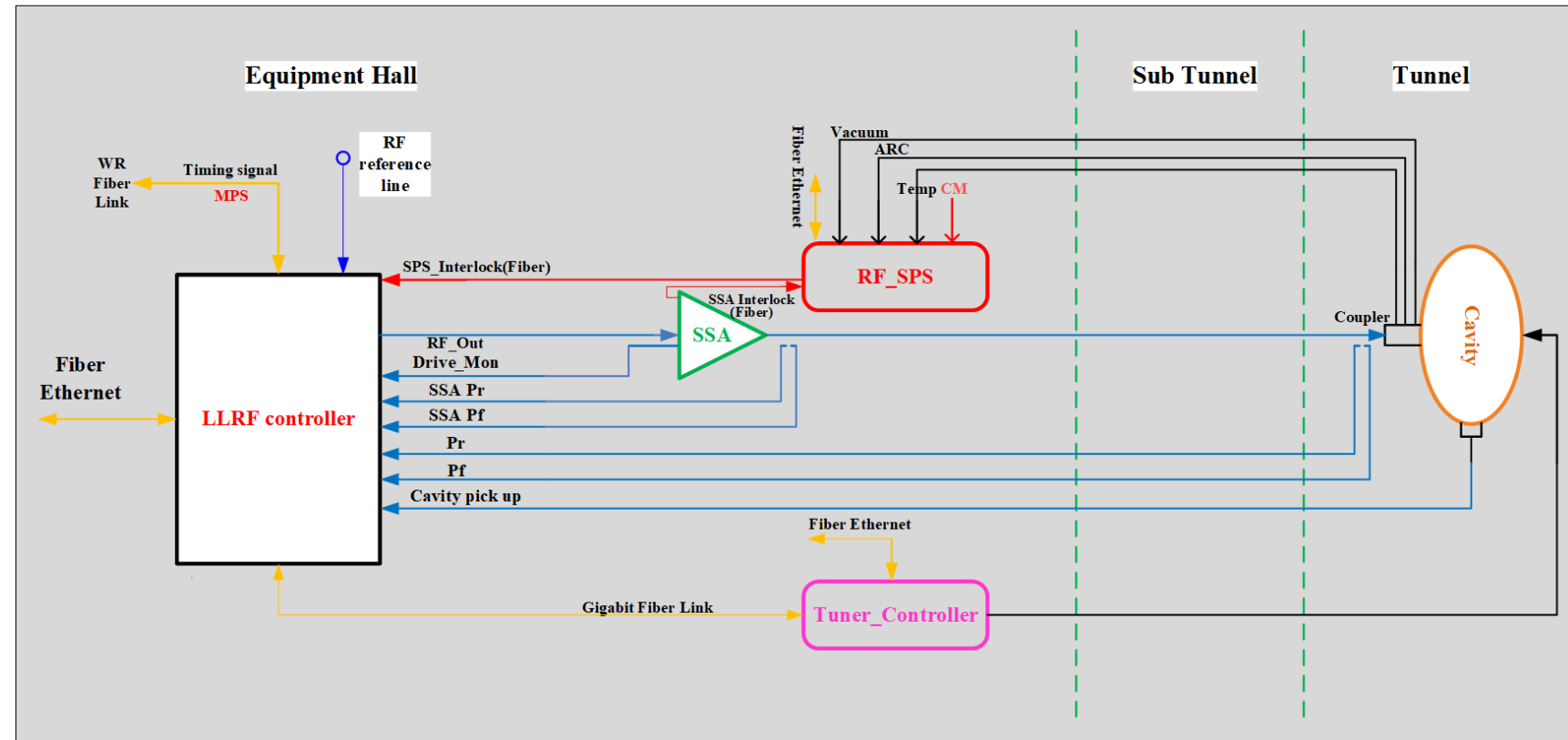


parameters	QWR007	HWR015	Beam intensity	Operation mode
Frequency(M Hz)	81.25	162.5	1.0emA, $^{238}\text{U}^{35+}$	Pulse
β_{opt}	0.07	0.15	1.0 emA, $^{78}\text{Kr}^{19+}$	
$E_{\text{peak}}/E_{\text{acc}}$	4.69	4.7	1.0 emA, $^{18}\text{O}^{6+}$	
$E_{\text{acc}} @ \beta_{\text{opt}}$	5.97	5.96	0.6 emA, H_2^+	
Df/dp(Hz/mbar)	-1.6	-3	10 pμA, ^{48}Ca - ^{70}Zn	CW
LFD Coefficient	-0.8	-1.5	10 pμA, Xe-U	

The LLRF control system for iLinac

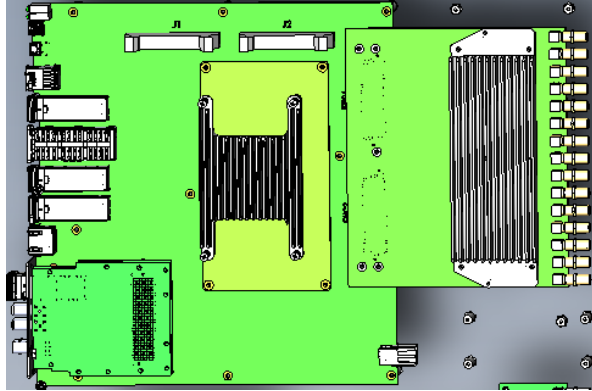


➤ The diagram of LLRF Control for One RF Station



The hardware of LLRF control system:

- The digital control board mainly consist of three parts, SOM core board, carrier board, AD/DA daughter board.
- Design based on the latest embedded FPGA architecture, The baseline design of AD board is 10 channels, cover 8 channels card.



➤ Digital LLRF controller board



➤ HIAF iLinac Control Equipment Hall where LLRF chassis located in

Content



01

- Introduction

02

- **Intelligent measurement method for SRF system**

03

- Automated RF Commissioning

04

- Summary

The measurement automation system for large scale SRF



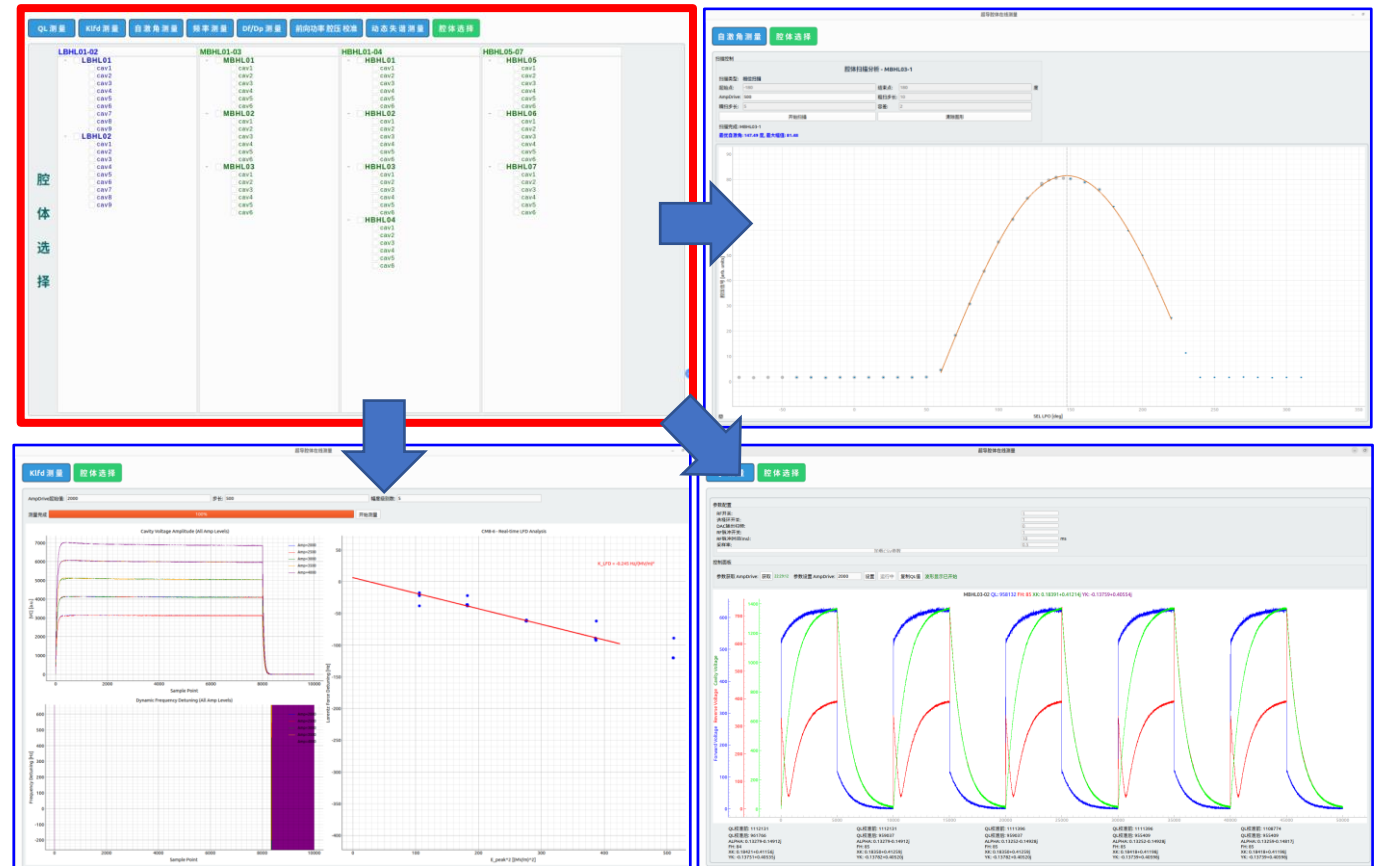
Background

Cavity parameter measurement is essential for:

- Performance evaluation
- Parameter calibration
- Control & anomaly monitoring

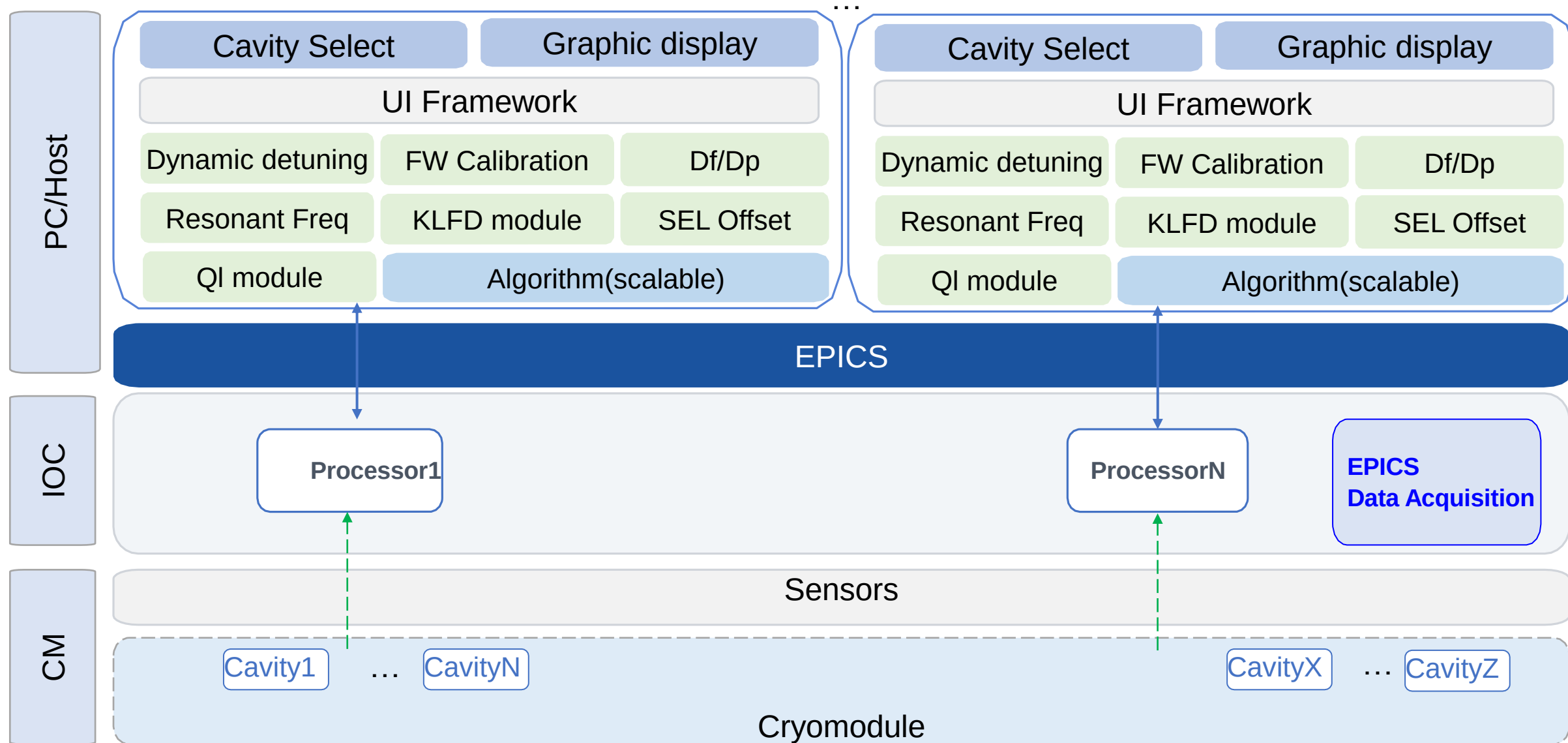
Conventional approach

- Different parameters → different measurement configurations
- Serial measurement: one cavity after another
- Poor consistency among different operators



Standardized measurement procedure and **parallelized measurement architecture** enable fast commissioning of large-scale SRF systems. Demonstrated on **HIAF-iLinac with 96 SRF cavities** for online batch measurement of Q_L , f_h , K_{LFD} , df/dp , and others.

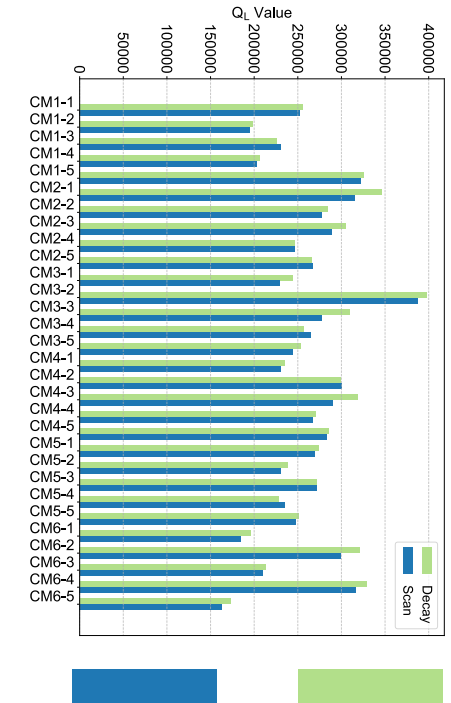
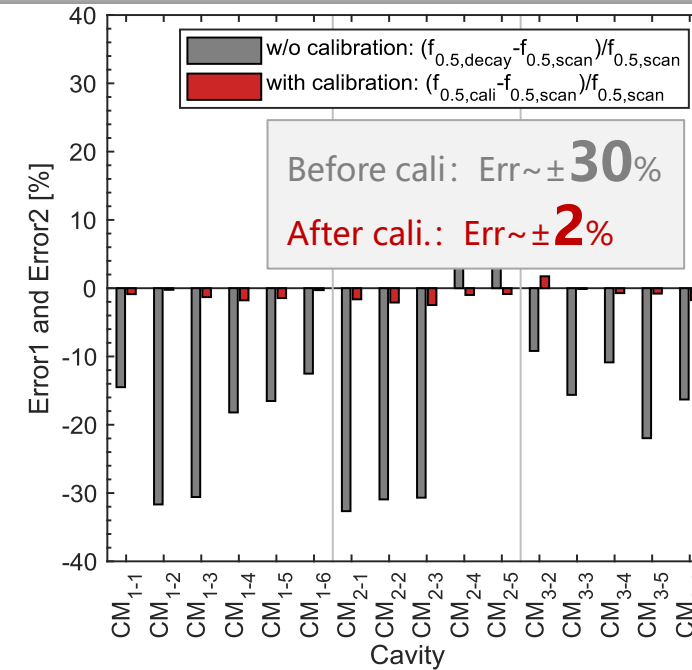
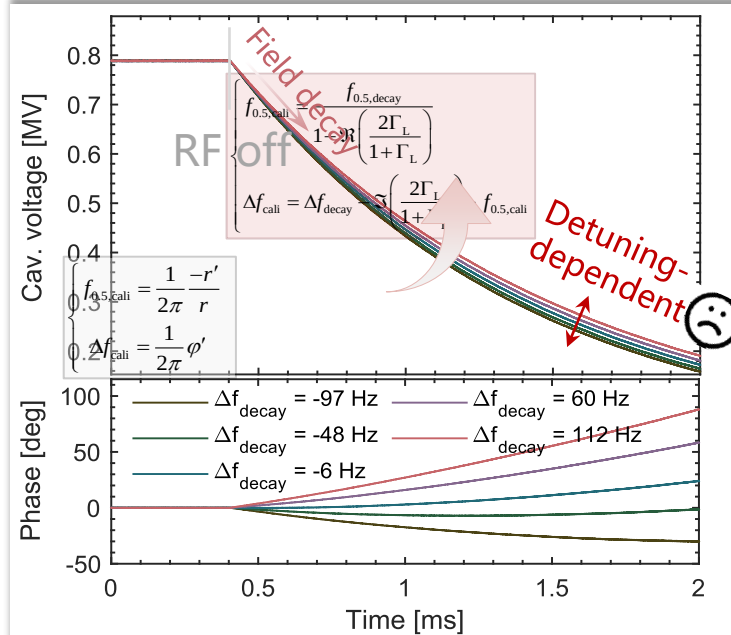
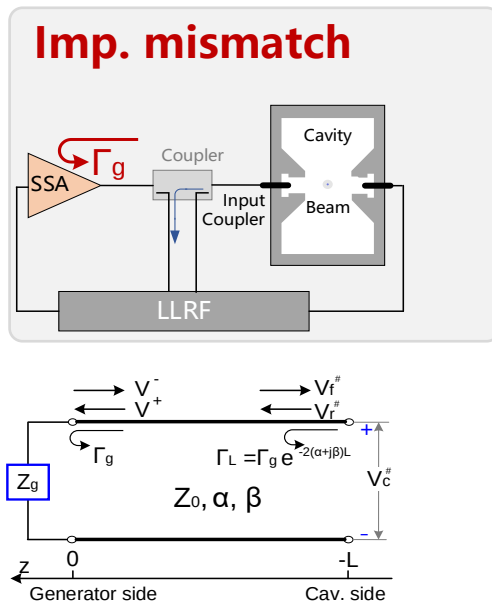
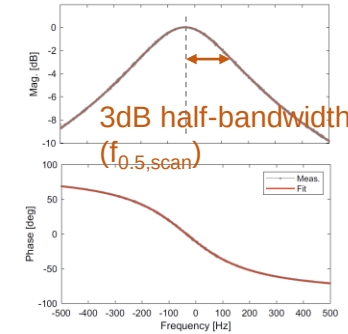
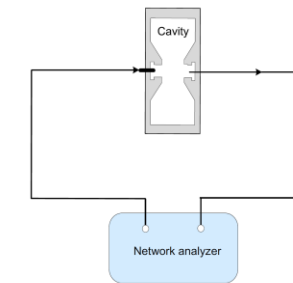
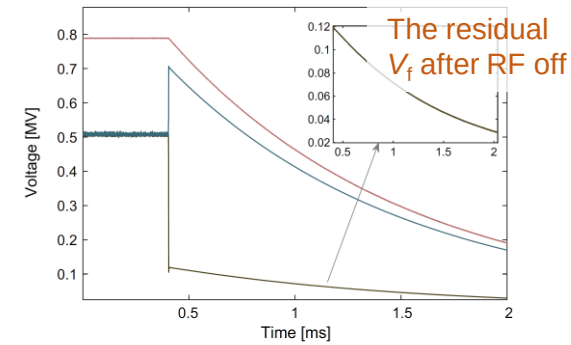
The measurement automation system for large scale SRF



The measurement of QL

Calibration of QL under impedance mismatch

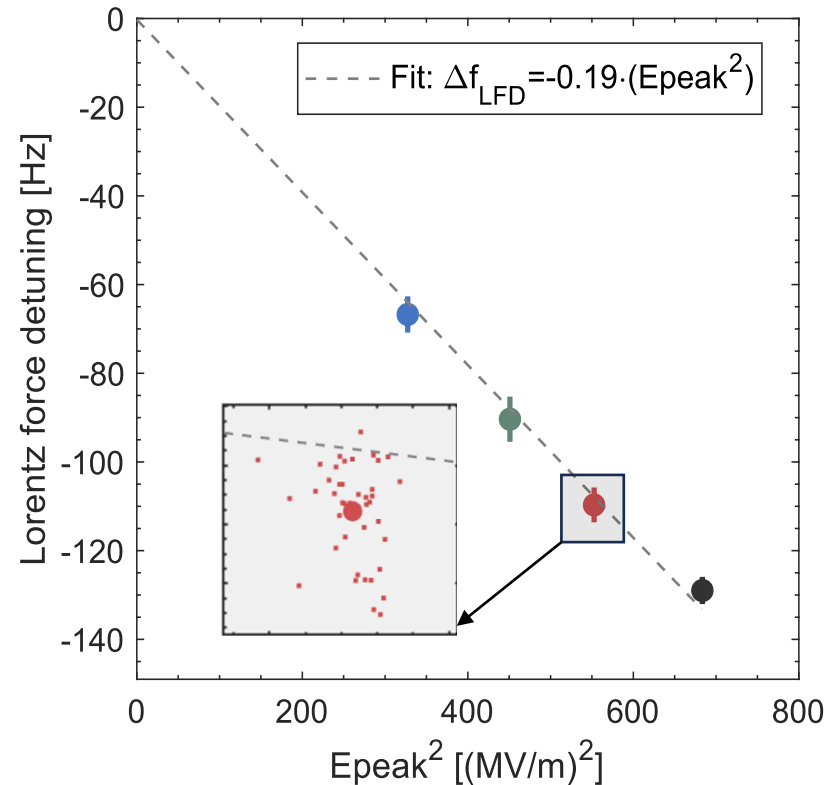
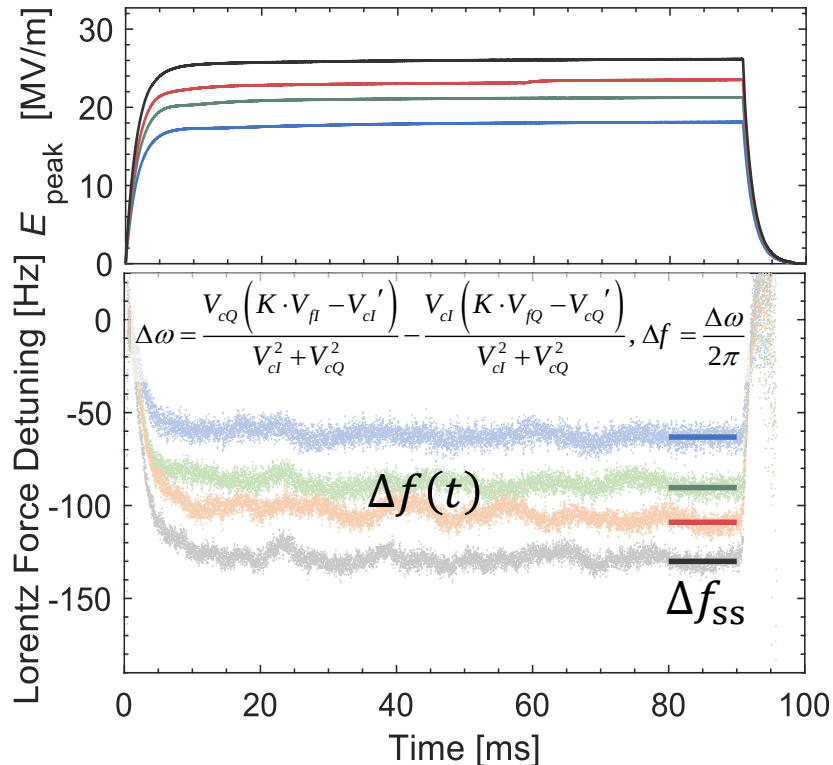
- Error ↓ from $\pm 30\%$ to $\pm 2\%$
- Consistent with network-analyzer scan



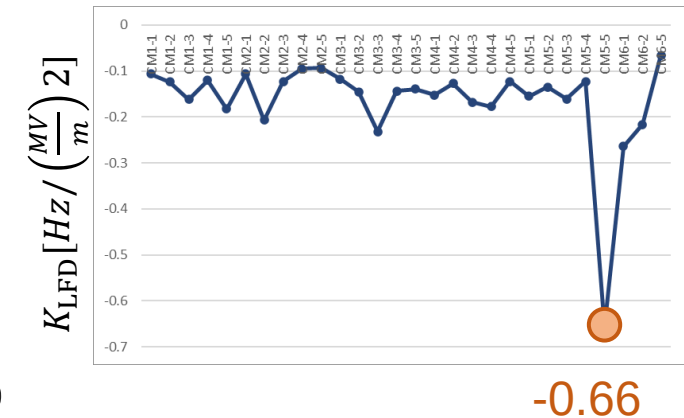
The measurement of static LFD coefficient

Procedure for static LFD measurement:

- Measure dynamic frequency detuning $\Delta f(t)$ during RF pulse.
- Extract steady-state detuning Δf_{ss} at flat-top and record the corresponding E_{peak} .
- Perform a linear fit of Δf_{ss} versus E_{peak}^2 ; the slope gives the static LFD coefficient.



For nearly 80% of the cavities, $|K_{LFD}|$ lies in **0.1–0.2**, with just one cavity above **0.6**

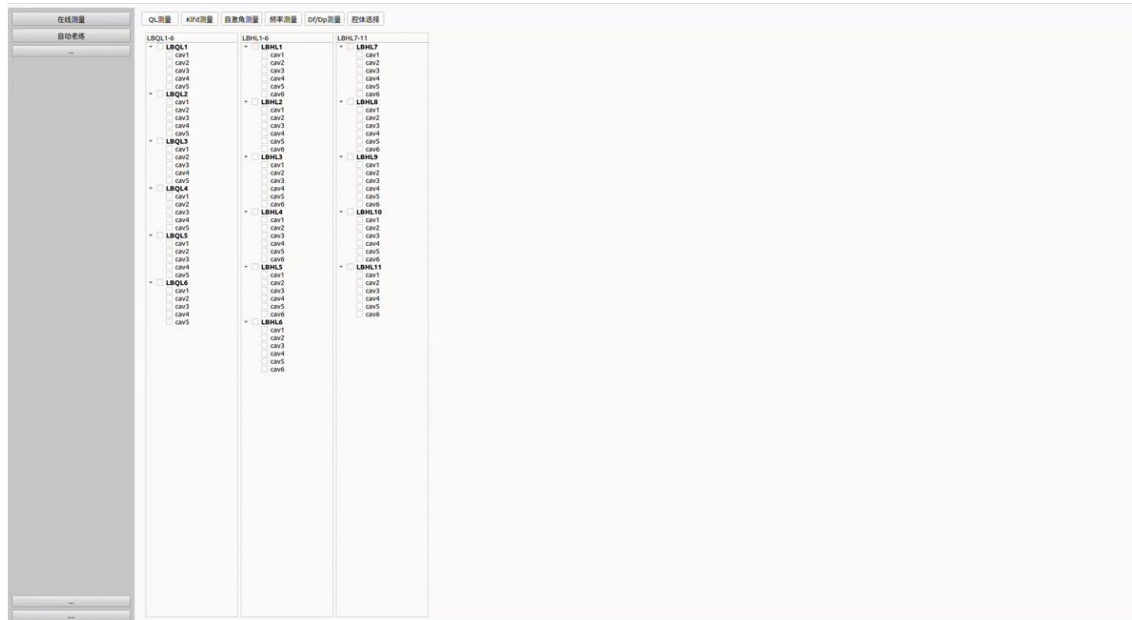


The demonstration of Measurement Automation

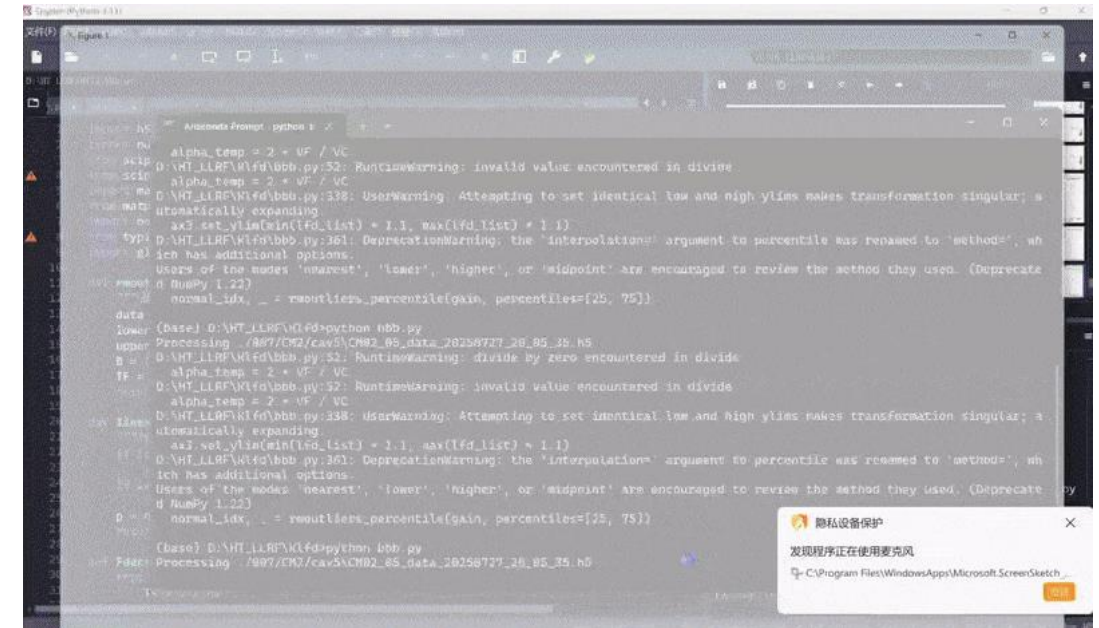


- Automated batch measurements of cavity parameters: Q_L , static LFD coefficient (K_{LFD})

Cavity Loaded Q



Static LFD Coefficient

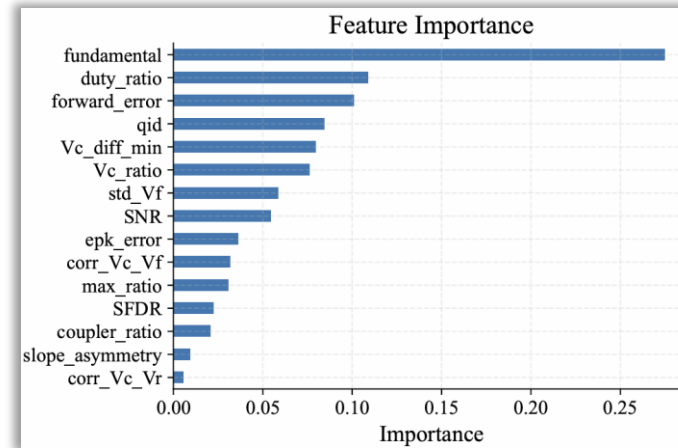
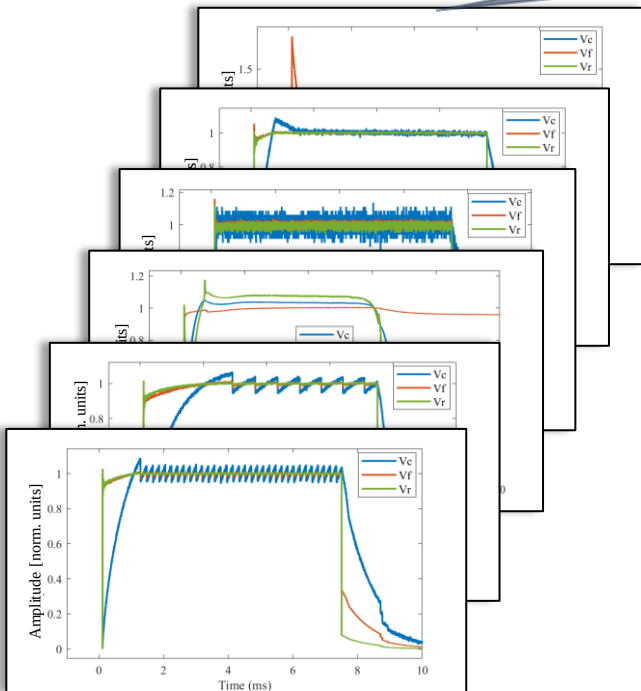


ML-based Abnormal Detection Online

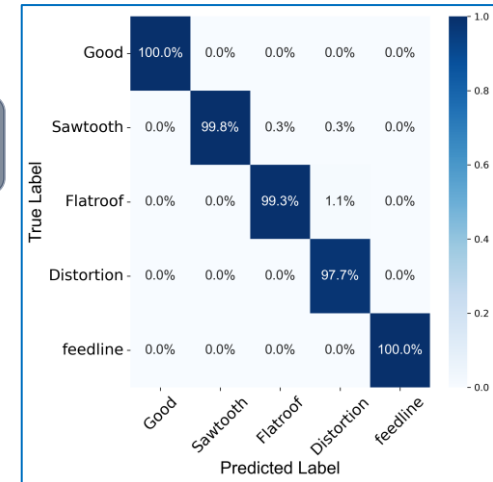
- Various abnormal events can occur during automatic RF conditioning.
- Machine learning automatically identifies abnormal events — feed-line faults and multipacting.

Data Pre-processing

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

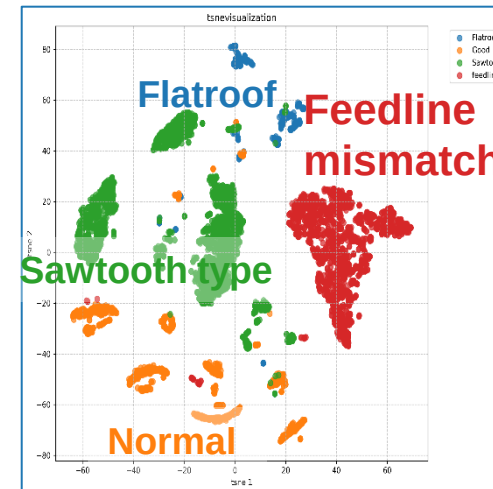


Machine Learning



Expert experience-based Feature-Extraction

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



Content



01

- Introduction

02

- Intelligent measurement method for SRF system

03

- **Automated RF Commissioning**

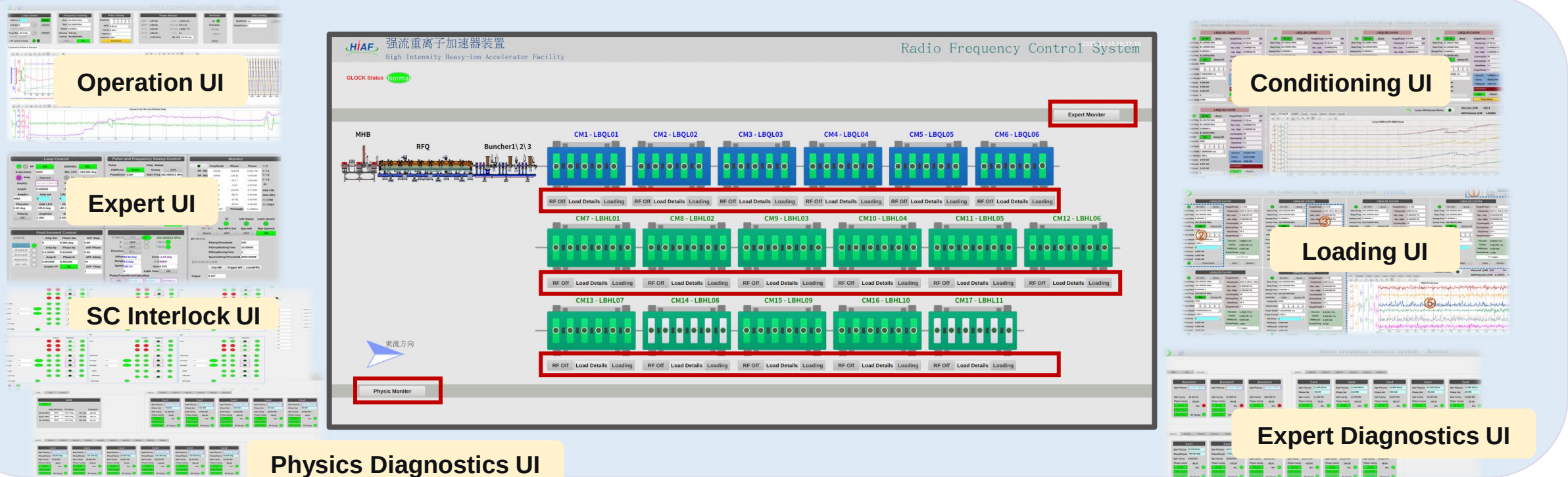
04

- Summary

The automated RF commissioning system – Top layer UIs



- **Designed & developed independently** for HIAF's complex conditions
- **>10 iterations | 240+ functional modules** refactored
- **From engineering black box → visualized workflow**
- **Key outcomes:** ✓ Lower Operation & maintenance threshold ✓ Reduced misoperation risks



The automated RF commissioning system – Key Design Features



Multi-process architecture

- Each cavity operates independently in a separate process
- Mutual isolation between processes
- The failure of a single cavity does not affect other cavities
- Managing with multiprocessing.Process

Thread cooperation mechanism

- threading.Event Implement inter-thread communication
- mStartEvent: Control task start/stop
- mNonLowTempExceptionEvent: Low temperature anomaly signal
- mNonNormExceptionEvent: Other abnormal signals

PV callback mechanism

- epics.camonitor Monitor PV changes
- Real-time response to GUI commands
- threading.Lock Concurrency Conflict Prevention
- Asynchronous event-driven architecture

Exception handling strategy

- Low-temperature anomalies and normal-temperature anomalies should be handled separately
- Abnormality triggers automatic shutdown of RF and amplitude
- Supports automatic and manual recovery
- Reset frequency detection to prevent frequent resets

Configuration-driven

- All PV names are defined through CSV
- Supports both default configuration and cavity-specific configuration
- Configure hot loading (takes effect after restart)
- Decoupling of parameters and code

log management

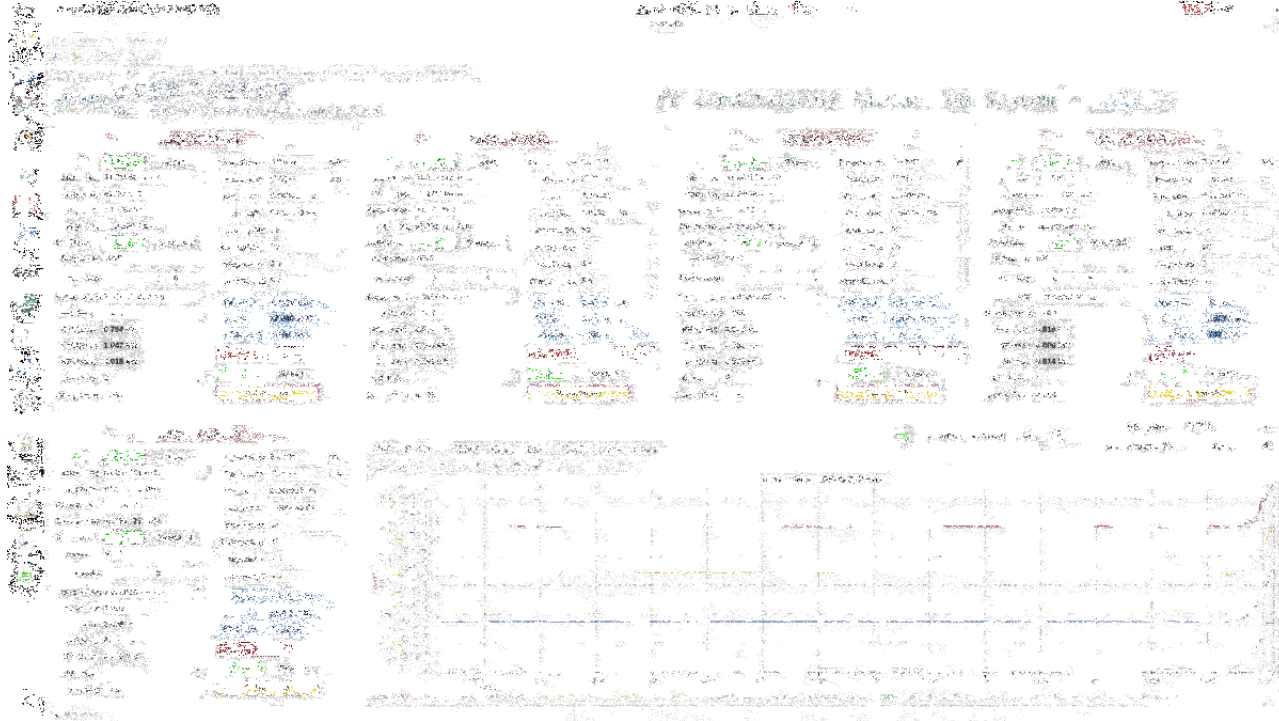
- unified management
- All core modules share logs
- Output to the logs/ directory
- Support operation status tracking

The demonstration of automated RF commissioning



The goal of conditioning is to gradually increase the RF power to the design value, eliminate field emission sources, and reduce the risk of sudden breakdown during cavity operation.

- **Automated conditioning + intelligent abnormal waveform recognition**
- Fully automatic conditioning with real-time smart monitoring
- Enables **large-scale 24/7 non-stop conditioning**



Epk	Before / MV/m	After / MV/m
CM8-3	31.073	41.62
CM8-4	17.373	23.722
CM8-6	21.366	42.347
CM9-4	39.351	41.579
CM9-5	23.6	41.357
CM9-6	13.468	18.675
CM10-6	15.01	24.86

- ✓ both **warm-conditioning** and **cold** conditioning for all **96 SRF cavities** of HIAF-iLinac
- ✓ Significantly accelerated commissioning progress
- ✓ Developed a **standardized, portable intelligent conditioning framework**
- ✓ Ready for direct reuse in **other** superconducting cavity conditioning

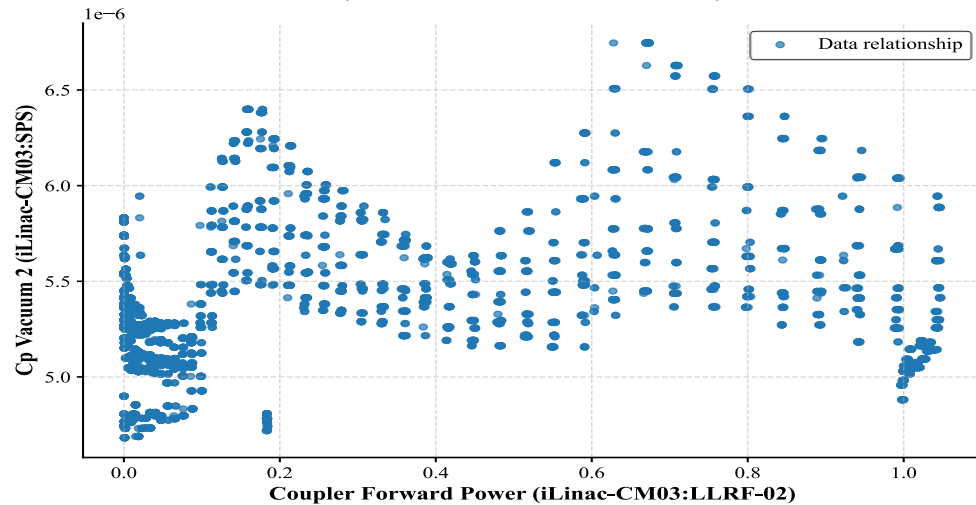
The RF commissioning result at room temperature



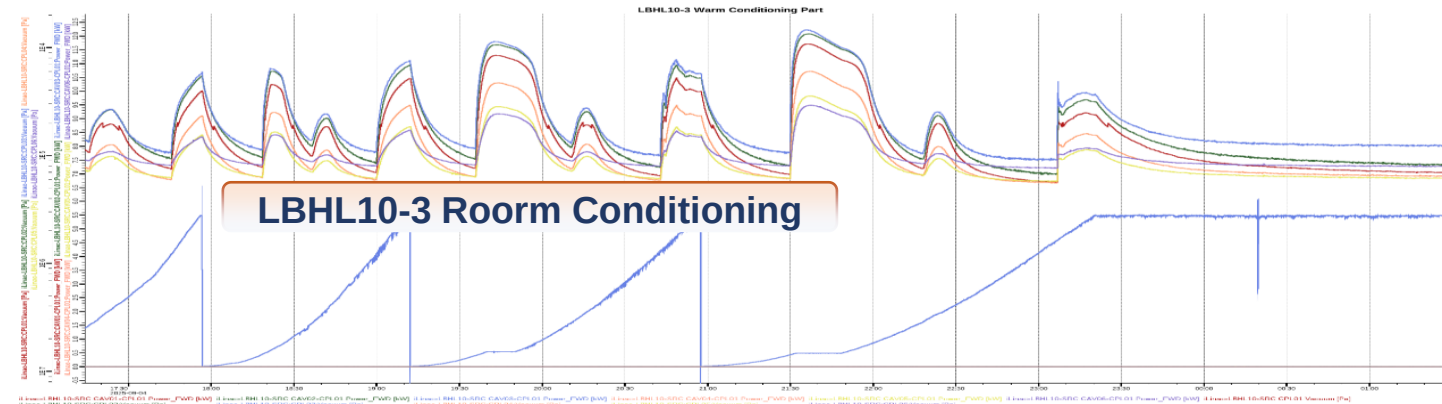
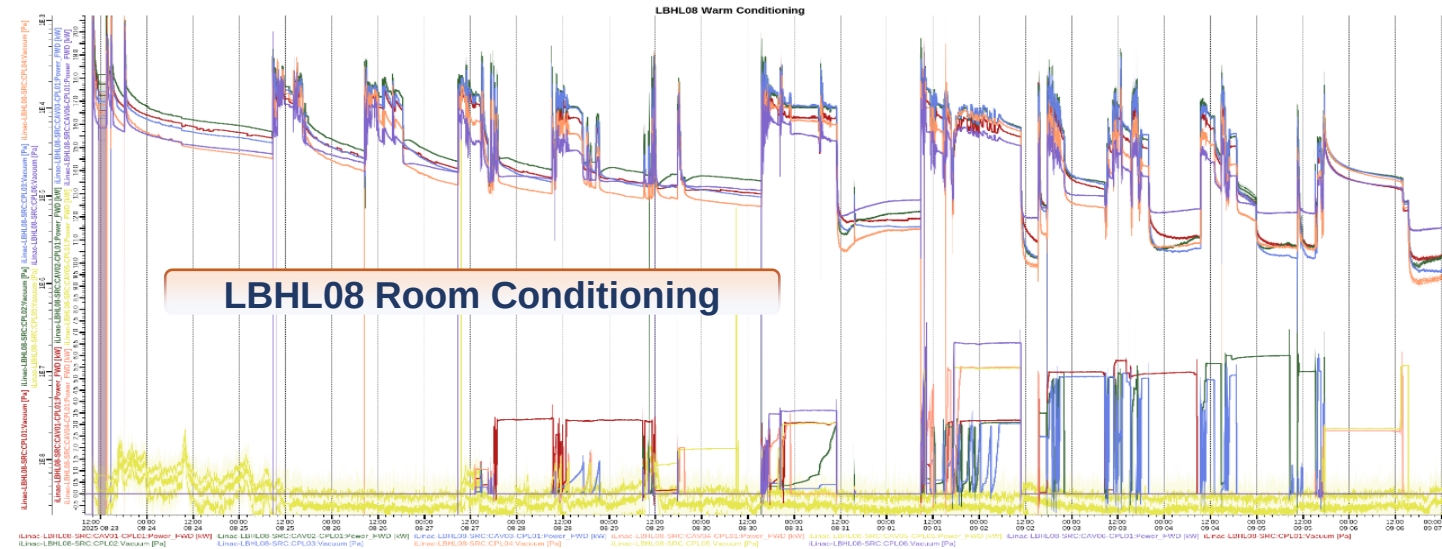
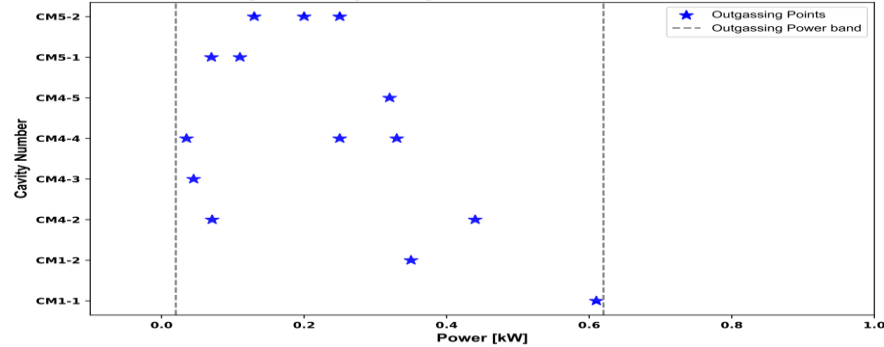
HWR015
Room
Conditioning

	LBHL01	LBHL02	LBHL03	LBHL04	LBHL05	LBHL06	LBHL07	LBHL08	LBHL09	LBHL10	LBHL11	Average
Conditioning Time/day	18	12	8	10	10	12	9	9	6	9	10	10.27
P_Cav_FWD/Kw	3	2	2.5	2.5	5	5	5	5.5	5	5	4	4.05

Vacuum Level vs. Coupler Forward Power
(2025-06-02 10:00:00 - 10:30:00)



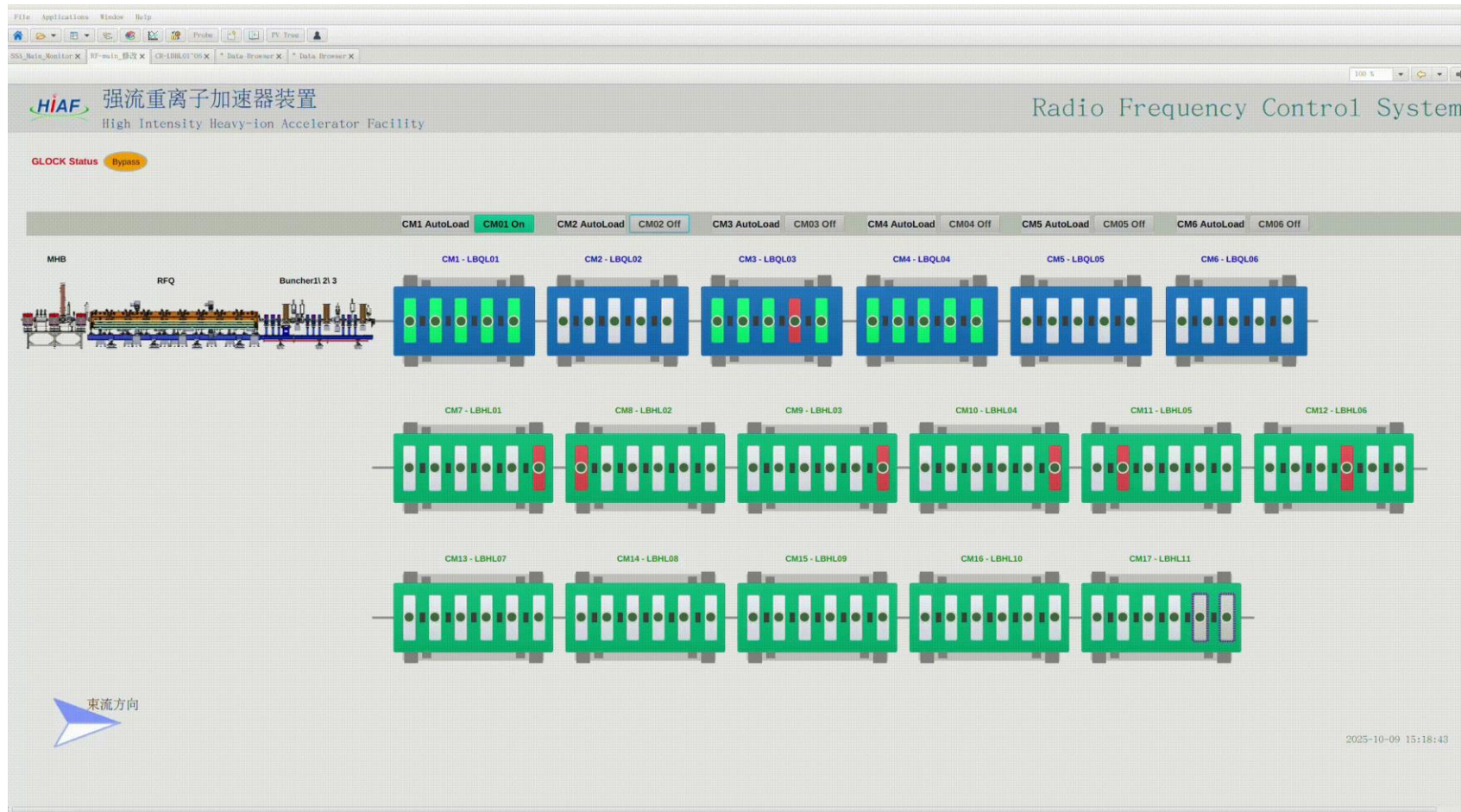
Residual Multipacting and Outgassing Points Distribution in Post Warm Conditioning



Automated turn on RF for Close Loop Operation



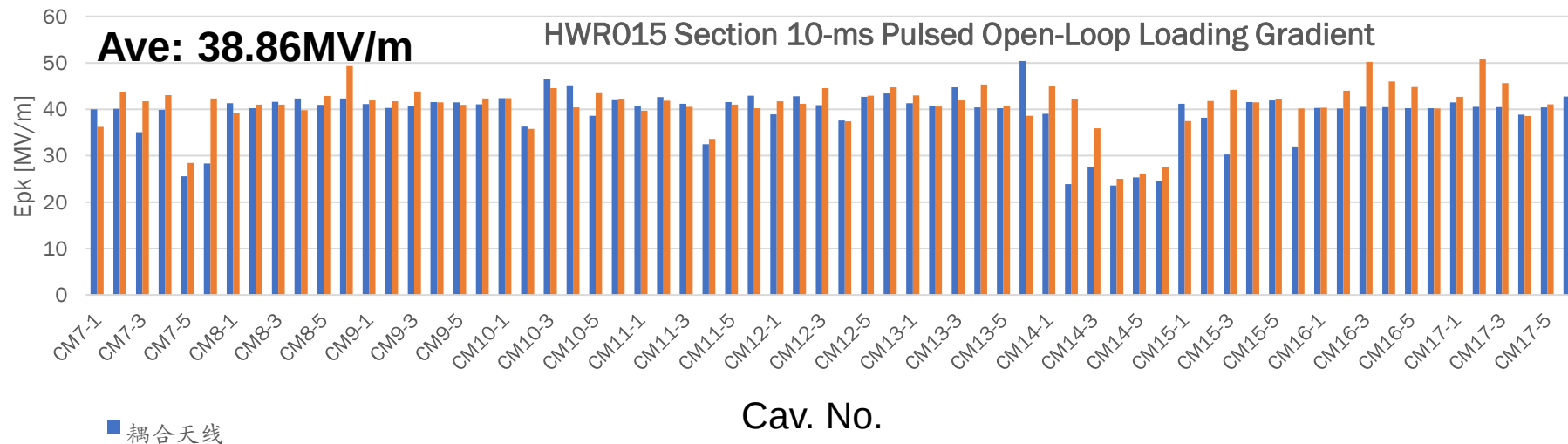
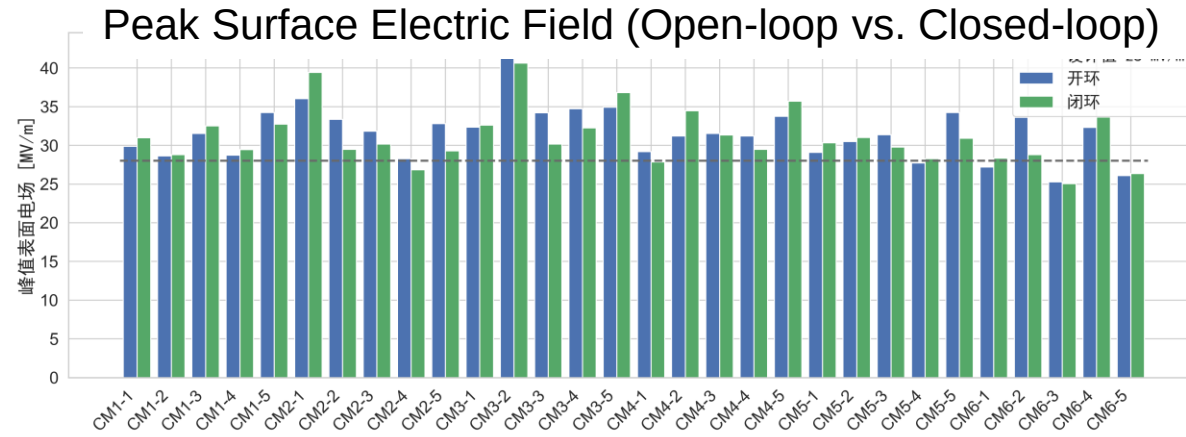
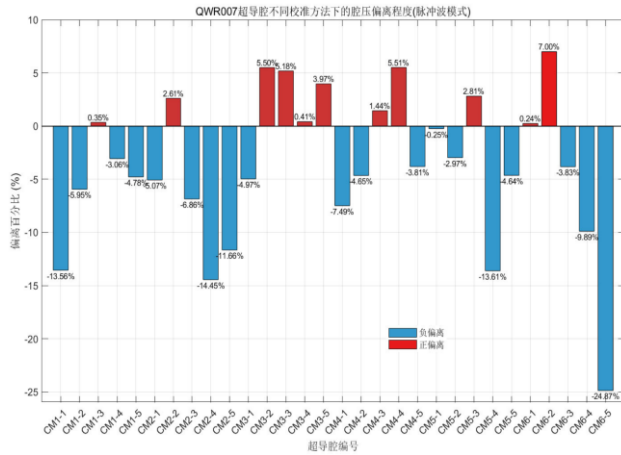
- The RF control system automatically turn on and load all superconducting cavities in pulse mode.
- Each cryomodule is sequentially powered and monitored through the automated startup interface.



The Commissioning Status



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

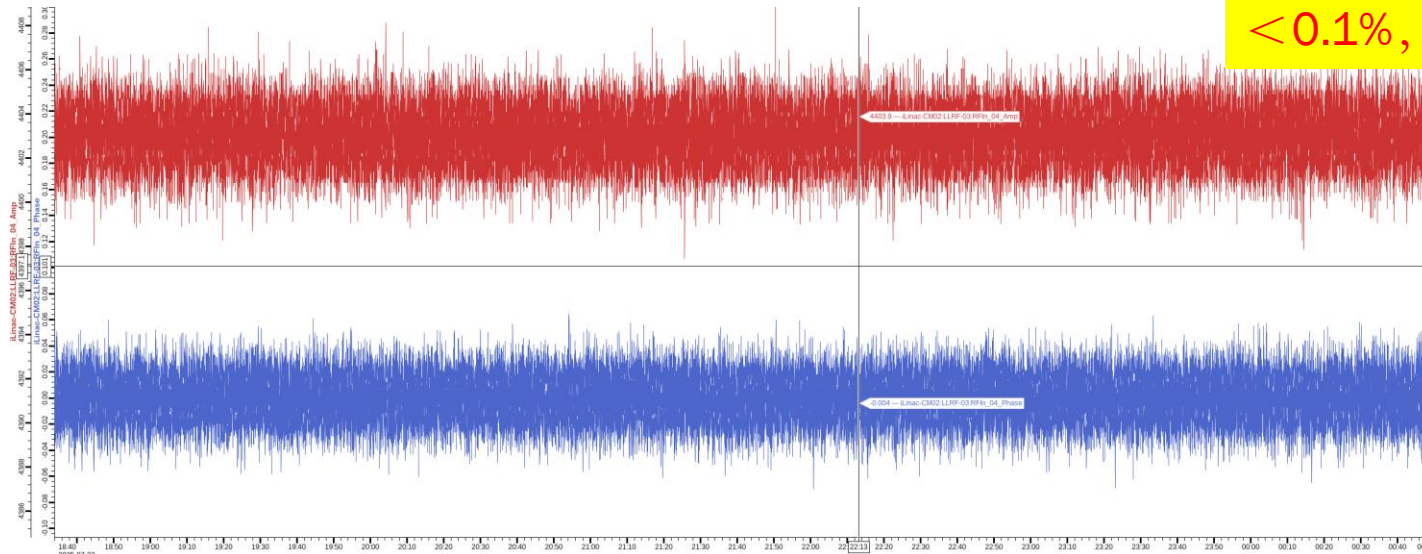


	腔号	Q.L	半带宽 FH	XK	YK	测试时间
LBHL03 CM9	5	955223	92	0.42515+0.08844j	0.40044-0.16921j	2025/10/16
	6	1009837	80	0.44706+0.03544j	0.49247-0.02443j	2025/10/16
	1	1035611	78	0.51155+0.13046j	0.50096-0.13601j	2025/10/16
	2	1064784	76	-0.50333+0.15043j	-0.39380+0.32999j	2025/10/16
	3	1171084	69	0.33586+0.40484j	-0.18623-0.98439j	2025/10/16
LBHL04 CM10	4	908004	89	0.39570-0.24972j	0.42994-0.25651j	2025/10/17
	5	917333	89	-0.13858+0.46233j	0.03558+0.44927j	2025/10/17
	6	1082868	74	0.15437+0.57073j	0.13858+0.54713j	2025/10/17
	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
LBHL05 CM11	3	1144389	71	0.11553+0.08675j	0.08979+0.10761j	2025/10/17
	4	1047510	78	0.31631+0.36955j	-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
	1	1044246	78	0.09332+0.50567j	-0.00535+0.42854j	2025/10/16
LBHL06 CM12	2	1029879	79	-0.25343+0.38849j	-0.14334+0.53669j	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
LBHL07 CM13	1	979216	83	0.04515-0.30782j	0.16199-0.28937j	2025/10/16
	2	1136094	72	0.09340-0.21590j	0.18400-0.19523j	2025/10/16
	3	1072767	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	0.32754+0.28839j	2025/10/16
LBHL08 CM14	6	1045737	78	0.24260+0.08491j	-0.02590+0.09748j	2025/10/16
	1	1047532	78	-0.25182+0.40255j	-0.13664+0.44467j	2025/10/16
	2	1075817	75	0.14589		2025/10/16
	3	1174100	69	0.18858		2025/10/16
	4	987975	82	-0.03035		2025/10/16
LBHL09 CM15	5	877191	93	-0.03352		2025/10/16
	6	1062499	76	0.40666		2025/10/16
	1	924013	88	-0.20952		2025/10/16
	2	824821	92	0.15528		2025/10/16
	3	890903	91	-0.37444		2025/10/16
LBHL09 LBHL09	4	8512346	96	0.52307+0.07238j	0.22378+0.26541j	2025/10/17

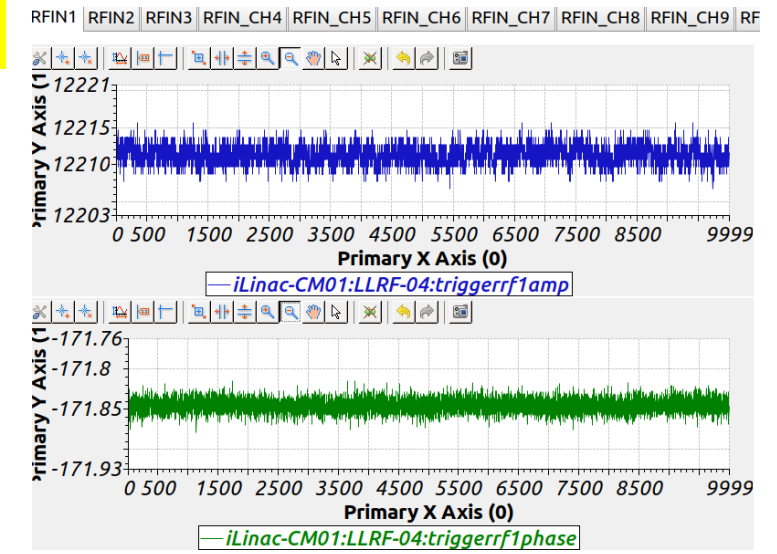
Digital Cavity Database

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.

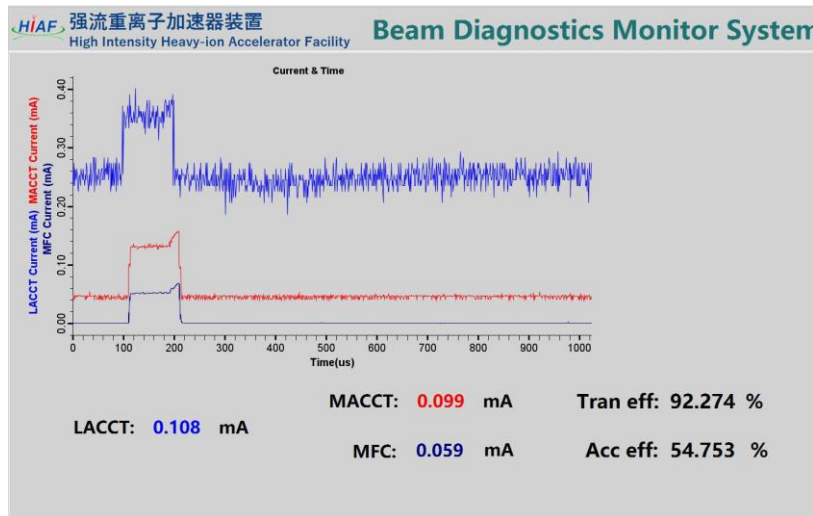
The Commissioning Status(cont.)



✓ The long-term stability test record of QWR under pulse close loop operation



✓ The short-term stability



➤ The pulse beam signal

The beam commissioning result

- ◆ Beam commissioning of RFQ
 - Designed Energy: 0.8 MeV/u
 - Length: ~9.8 m
 - Pulsed: ~98 kW for M/Q=7
 - CW: ~56 kW for M/Q=5
 - Transmission efficiency: 83%(Design value)
- ◆ First beam of iLinac: Oct. 2025.

Summary



- ❑ An integrated LLRF automation framework was developed, enabling automatic measurement of key cavity parameters — loaded Q, Lorentz-force detuning coefficient, and system characterization.
- ❑ Automated characterization, conditioning, loading, and anomaly handling have significantly streamlined RF commissioning.
- ❑ Real-time batch operation was achieved for automated RF conditioning and pulse-mode loading across multiple superconducting cavities

Thanks