

The 2026 MicroTCA/ATCA Workshop for Large Scientific Facility Control

MTCA.4-Based LLRF Control System for S³FEL: Development and Status

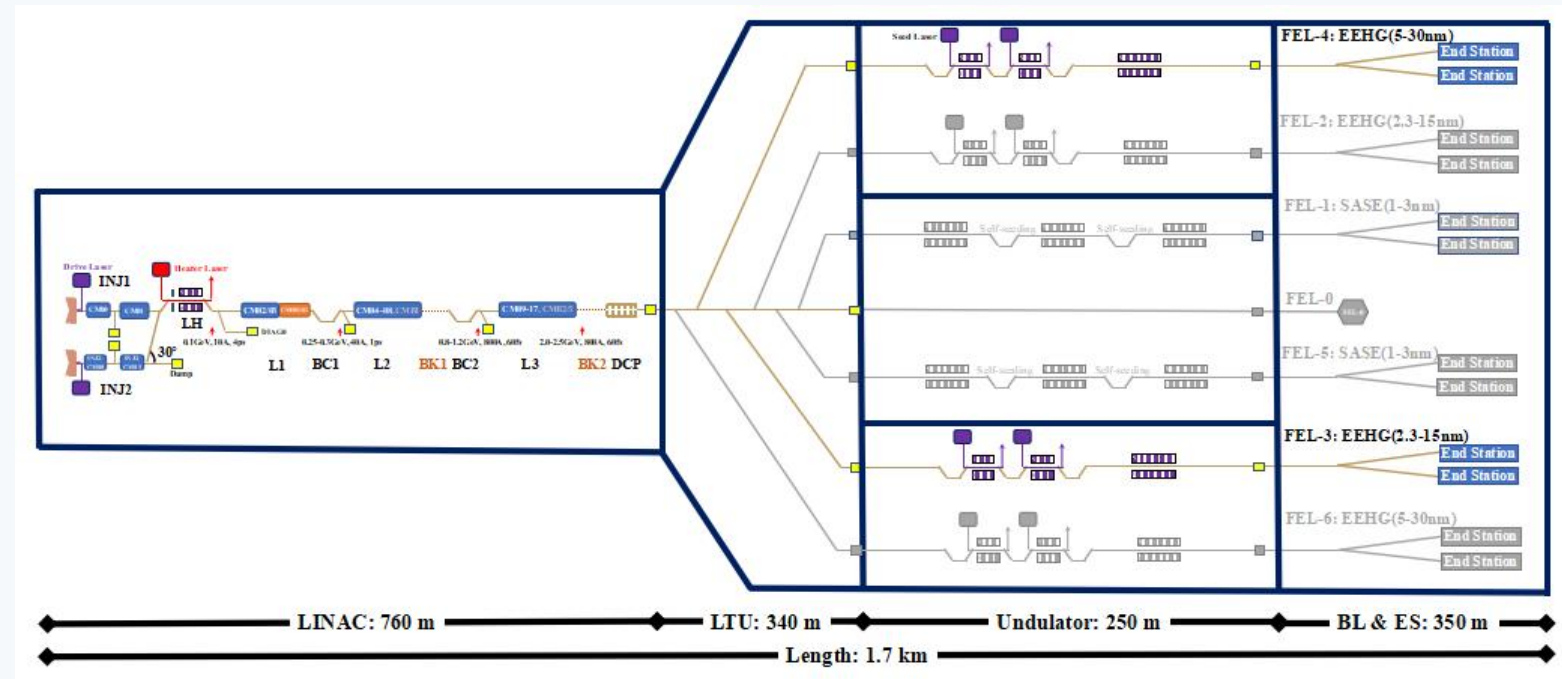
Jinfu Zhu, on behalf of the S³FEL LLRF group

Institute of Advanced Light Source Facilities, Shenzhen

CONTENTS

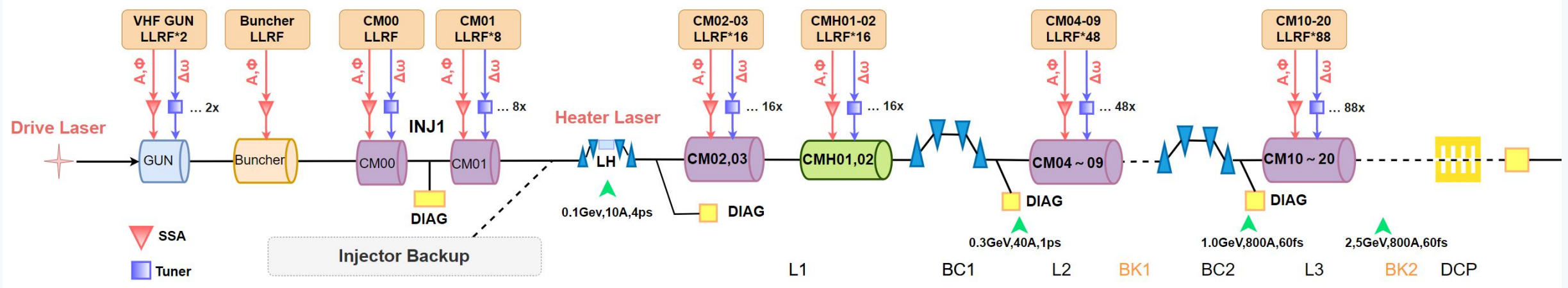
- 1. Introduction and LLRF Requirements for S³FEL**
- 2. MTCA.4 Hardware Platform Development**
- 3. Firmware and Software Development**
- 4. Validation Results at DALSLINAC**
- 5. Summary and Next Steps**

FEL Facility	Length / m	Electron beam energy / GeV	Wavelength range / nm	Repetition rate / Hz	Completion year
Shenzhen Superconducting Soft X-ray Free-Electron Laser, S ³ FEL	1700	2.0-2.5	1-30	1,000,000	FEL expected ~2032



- S³FEL is a 1.7-km superconducting soft X-ray free-electron laser.
- It will provide 1-30 nm radiation with a 1 MHz repetition rate and beam energy of 2.0-2.5 GeV.

LLRF Requirements for S³FEL



Part	Module No.	Quantity	Temperature	Function & Cavity	RF	RF stability Amplitude/Phase (RMS)	No. of LLRF units
INJ / INJ(Backu p)	GUN	2	NC	Photocathode GUN	VHF-band, 216 MHz	$\leq 0.01\%/\leq 0.02^\circ$	4
	Buncher	2	NC	Buncher, 1×2-cell	L-band, 1.3 GHz	$\leq 0.02\%/\leq 0.02^\circ$	2
	CM00	2	SC	Pre-accelerator, TESLA, 1×9-cell	L-band, 1.3 GHz	$\leq 0.02\%/\leq 0.02^\circ$	2
	CM01	2	SC	Main accelerators, TESLA, 8×9-cell	L-band, 1.3 GHz	$\leq 0.02\%/\leq 0.02^\circ$	16
L1	CM02-03	2	SC	Main accelerators, TESLA, 8×9-cell	L-band, 1.3 GHz	$\leq 0.015\%/\leq 0.03^\circ$	16
	CMH01-02	2	SC	Harmonic, TESLA, 8×9-cell	S-band, 3.9 GHz	$\leq 0.03\%/\leq 0.06^\circ$	16
L2	CM04-09	6	SC	Main accelerators, TESLA, 8×10-cell	L-band, 1.3 GHz	$\leq 0.03\%/\leq 0.06^\circ$	48
L3	CM10-20	11	SC	Main accelerators, TESLA, 8×10-cell	L-band, 1.3 GHz	$\leq 0.03\%/\leq 0.06^\circ$	88
Diagnostic part	Before L2	4	NC	S-band Deflector	S-band, 2997 MHz	$\leq 0.1\%/\leq 0.06^\circ$	4
	After L2	7	NC	X-band Deflector	X-band, 11989 MHz	$\leq 0.2\%/\leq 0.1^\circ$	7

- 2 sets of 216 MHz VHF guns
- 2 sets of 1.3 GHz bunchers
- 21 modules of 1.3 GHz main accelerators: 168 cavities
- 16 units of 3.9 GHz harmonic cavities
- 11 diagnostic deflectors: 4 S-band + 7 X-band
- Requirements: amplitude/phase stability, tuning control, scalability, reliability

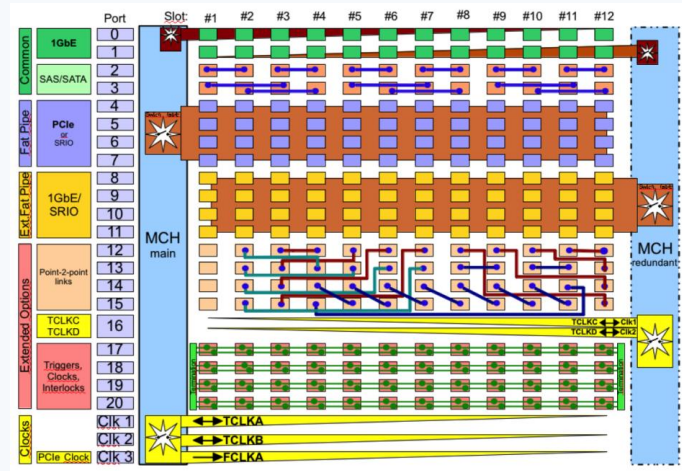
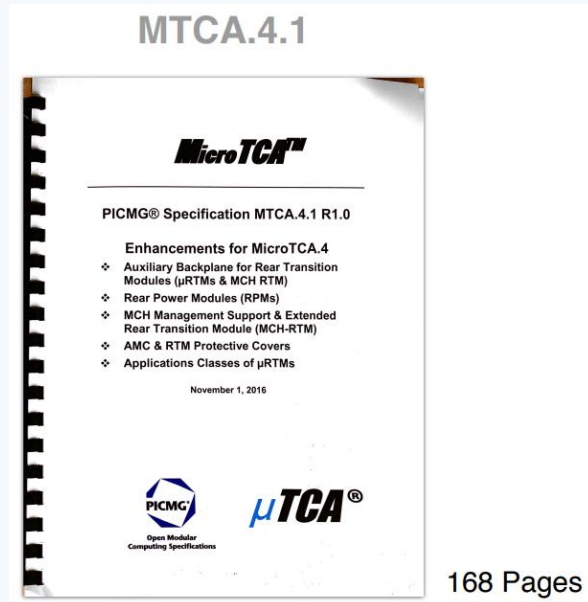
Why MTCA.4 Platform

Requirements:

- More than 200 cavities (>1000 sampling channels)
- Amplitude/Phase stability (mainly $<0.02\%/0.02^\circ$)
- RF/Tuning control
- Reliability
- ...

Advantages of MTCA:

- High channel density
- AMC + RTM decoupling: Digital processing separated from analog I/O
- High backplane bandwidth
- Industrial reliability
- Scalability
- Simplified maintenance and upgrade
- ...



➤ Status of S³FEL LLRF Systems

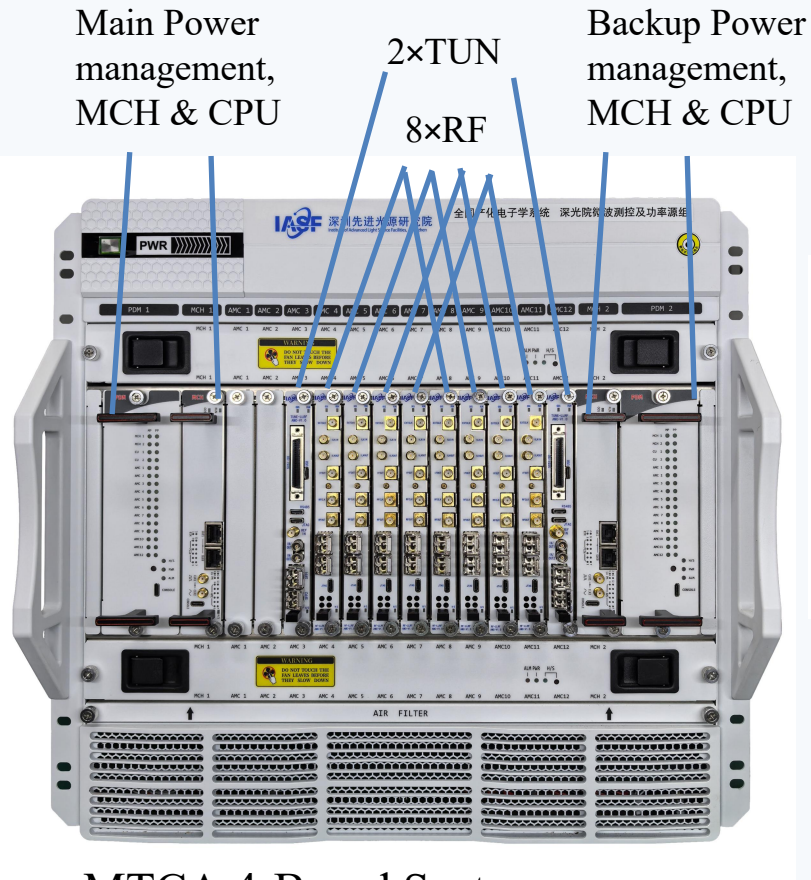
Part	Module No.	Quantity	Temperature	Function & Cavity	RF	RF stability Amplitude/Phase (RMS)	No. of Amplifiers/ LLRF	Status
INJ / INJ(Backup)	GUN	2	NC	Photocathode GUN	VHF-band, 216 MHz	$\leq 0.01\%/\leq 0.02^\circ$	4	Under development
	Buncher	2	NC	Buncher, 1×2-cell	L-band, 1.3 GHz	$\leq 0.02\%/\leq 0.02^\circ$	2	Verified
	CM00	2	SC	Pre-accelerator, TESLA, 1×9-cell	L-band, 1.3 GHz	$\leq 0.02\%/\leq 0.02^\circ$	2	Verified
	CM01	2	SC	Main accelerators, TESLA, 8×9-cell	L-band, 1.3 GHz	$\leq 0.02\%/\leq 0.02^\circ$	16	Verified
L1	CM02, 03	2	SC	Main accelerators, TESLA, 8×9-cell	L-band, 1.3 GHz	$\leq 0.015\%/\leq 0.03^\circ$	16	Verified
	CMH01, 02	2	SC	Harmonic, TESLA, 8×9-cell	S-band, 3.9 GHz	$\leq 0.03\%/\leq 0.06^\circ$	16	Under development
L2	CM04 ~ 09	6	SC	Main accelerators, TESLA, 8×10-cell	L-band, 1.3 GHz	$\leq 0.03\%/\leq 0.06^\circ$	48	Verified
L3	CM10 ~ 20	11	SC	Main accelerators, TESLA, 8×10-cell	L-band, 1.3 GHz	$\leq 0.03\%/\leq 0.06^\circ$	88	Verified
Diagnostic part	Before L2	4	NC	S-band Deflector	S-band, 2997 MHz	$\leq 0.1\%/\leq 0.06^\circ$	4	Under development
	After L2	7	NC	X-band Deflector	X-band, 11989 MHz	$\leq 0.2\%/\leq 0.1^\circ$	7	Under development

- Most main accelerating cavity LLRF systems, including those for the buncher, CM00, CM01, CM02-03, CM04-09, and CM10-20, have been verified.
- The LLRF systems for the GUN, CMH01-02 harmonic cavities, and diagnostic deflectors are still under development.

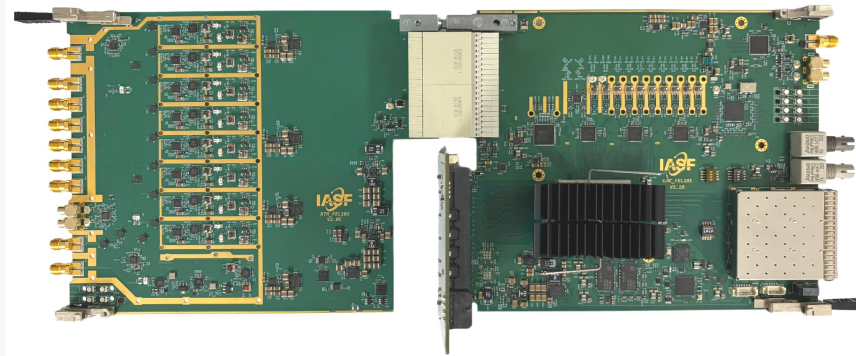
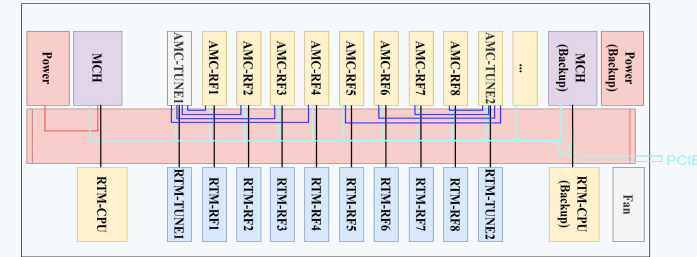
CONTENTS

- 1. Introduction and LLRF Requirements for S³FEL**
- 2. MTCA.4 Hardware Platform Development**
- 3. Firmware and Software Development**
- 4. Validation Results at DALSLINAC**
- 5. Summary and Next Steps**

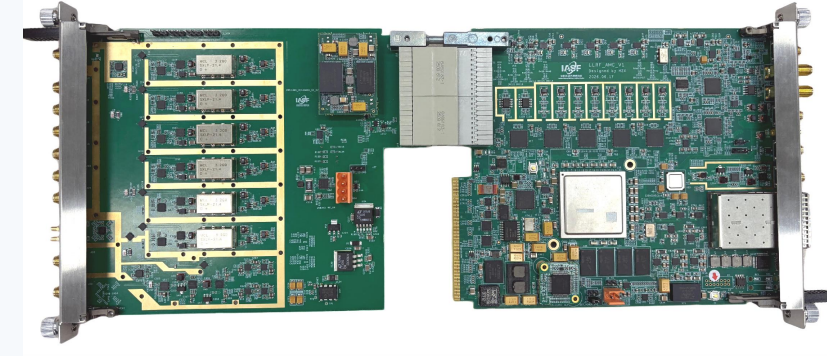
➤ MTCA.4 Hardware Platform



MTCA.4-Based System
(8xRF + 2xTUN boards,
supporting a standard SC module)
[IASF & ZOONENG / YZITECH]



RF Boards [IASF & THU]



RF Boards [IASF & USTC]



Tuning Boards [IASF]

J. Zhu, Y. Li, W. Li, Z. Zhang, H. Ding, J. Yang, W. Zhang. LLRF Prototype Design for the 1.3 GHz Cryomodule of the Shenzhen Superconducting Soft X-ray FEL, 2026 IPAC Conference.

Z. Zhang, J. Han, W. Li, J. Zhu, H. Ding, J. Yang, W. Zhang. Digital LLRF Control System for a High-Repetition-Rate Superconducting Linac, 2026 IPAC Conference.



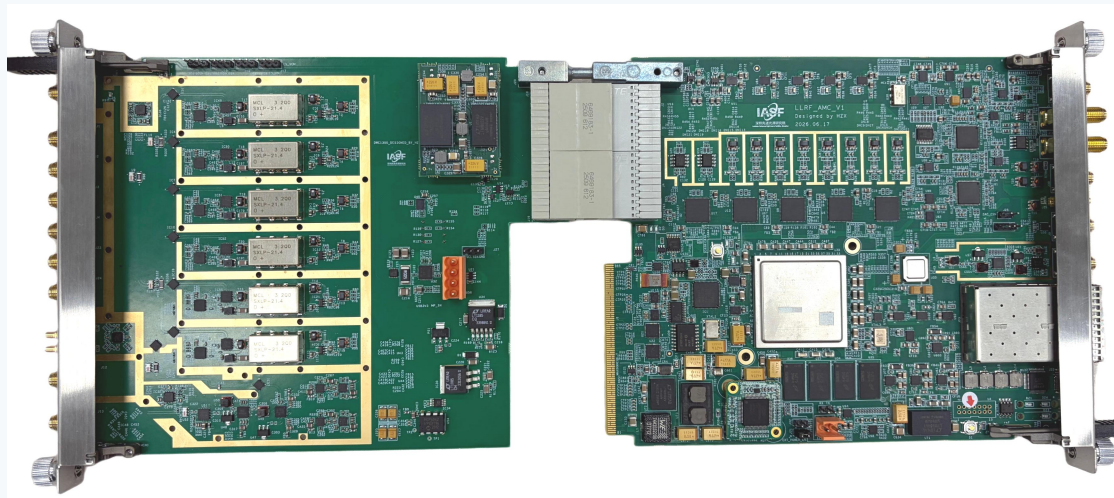
LO (front view)



LO (rear view)

- Receives the REF signal and distributes it to generate LO, REF, and CLK signals.
- LO and REF signals are used for up/down frequency conversion.
- CLK signal is used to drive ADC and FPGA operation.
- Provides eight LO channels and eight clock channels.

REF
LO
Cavity Voltage
Forward Power
Reflect Power
...
SSA Coupling
Power
RF out



RF-RTM

RF-AMC

- High-precision data acquisition.
- Signal down-conversion and up-conversion.
- Ultra-low noise and strong interference suppression.

Tuning Boards

FMC Card 1
(Piezo Control)



Tuning-RTM

Tuning-AMC

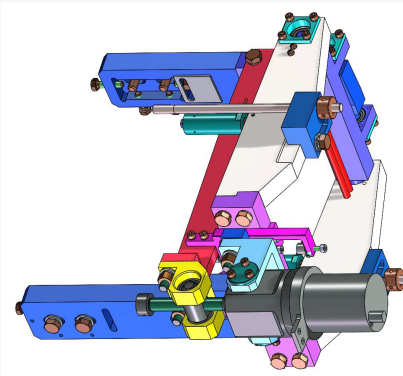
FMC Card 2
(Motor Control)



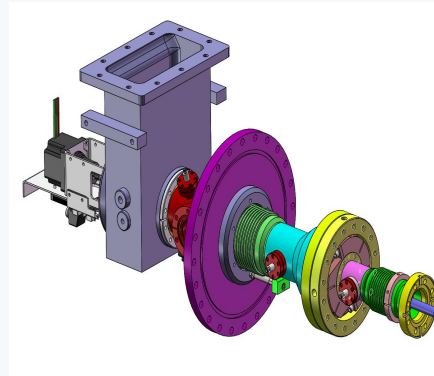
Piezo Driver



Motor Driver



Tuner

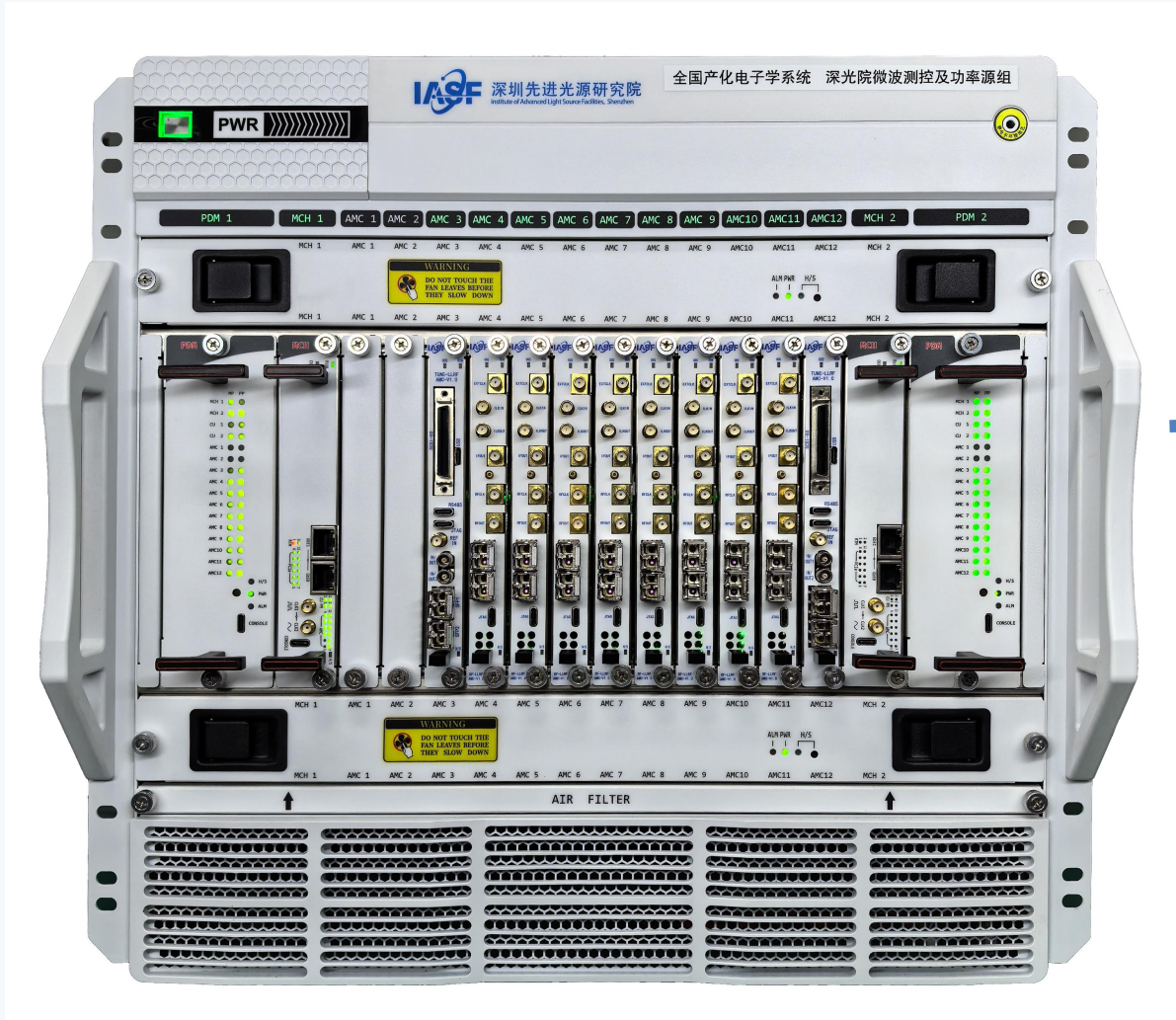


Coupler

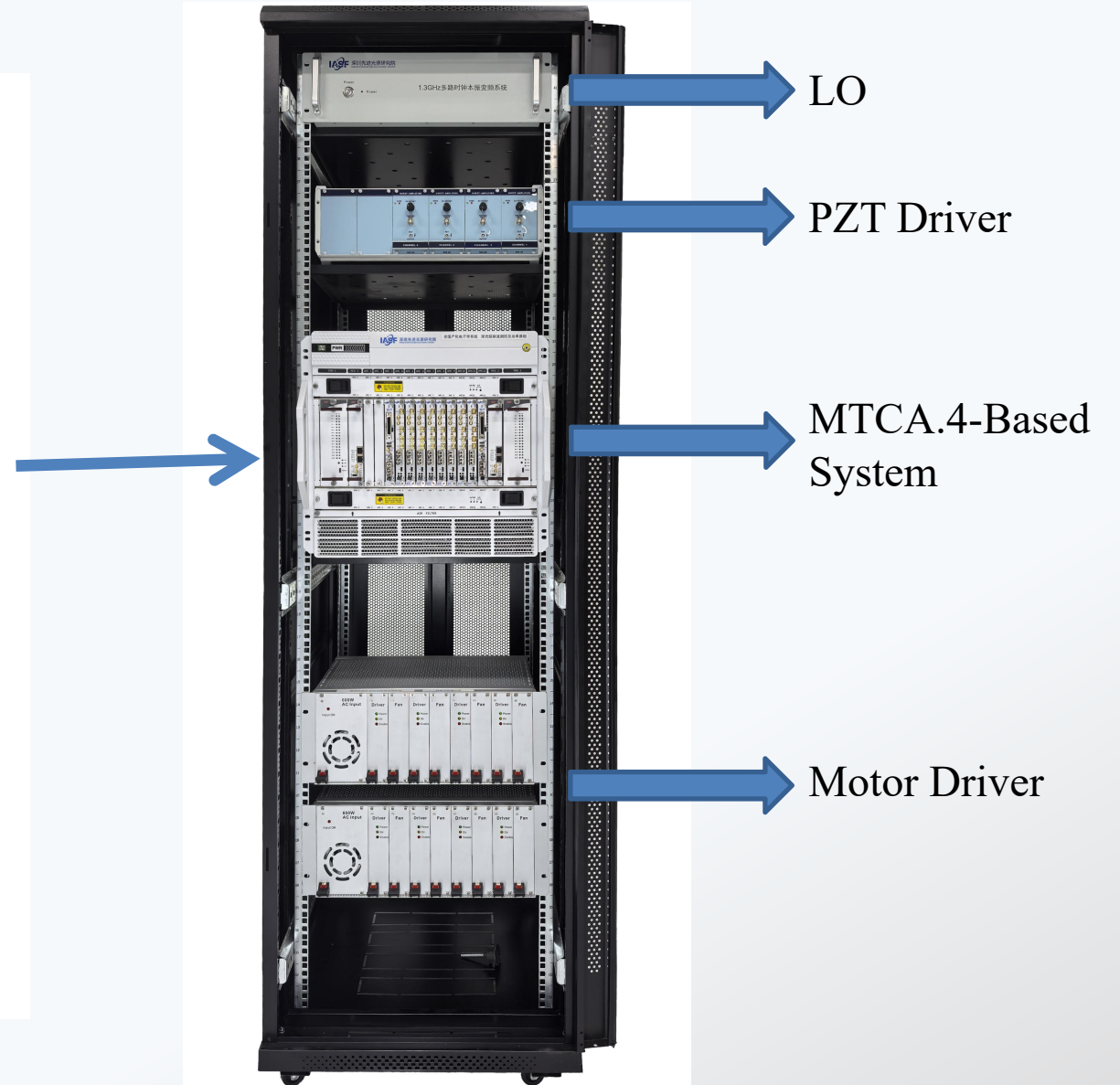
- Precise control of coupling and cavity frequency.
- Greatly expands functionality through FMC cards.

X. Dai, Z. Zhang, J. Zhu, H. Ding, J. Yang, W. Zhang. Preliminary Design of Motor Drivers for the Shenzhen Superconducting Soft X-ray Free Electron Laser, 2026 IPAC Conference.

Jinfu Zhu, Hongli Ding, Zhiyuan Zhang, Gangyang Liu, Weiqing Zhang. Design of an MTCA.4-Based LLRF tuning controller for cryomodules at S3FEL, 2025 SRF Conference.



MTCA.4-Based System (Powered on)

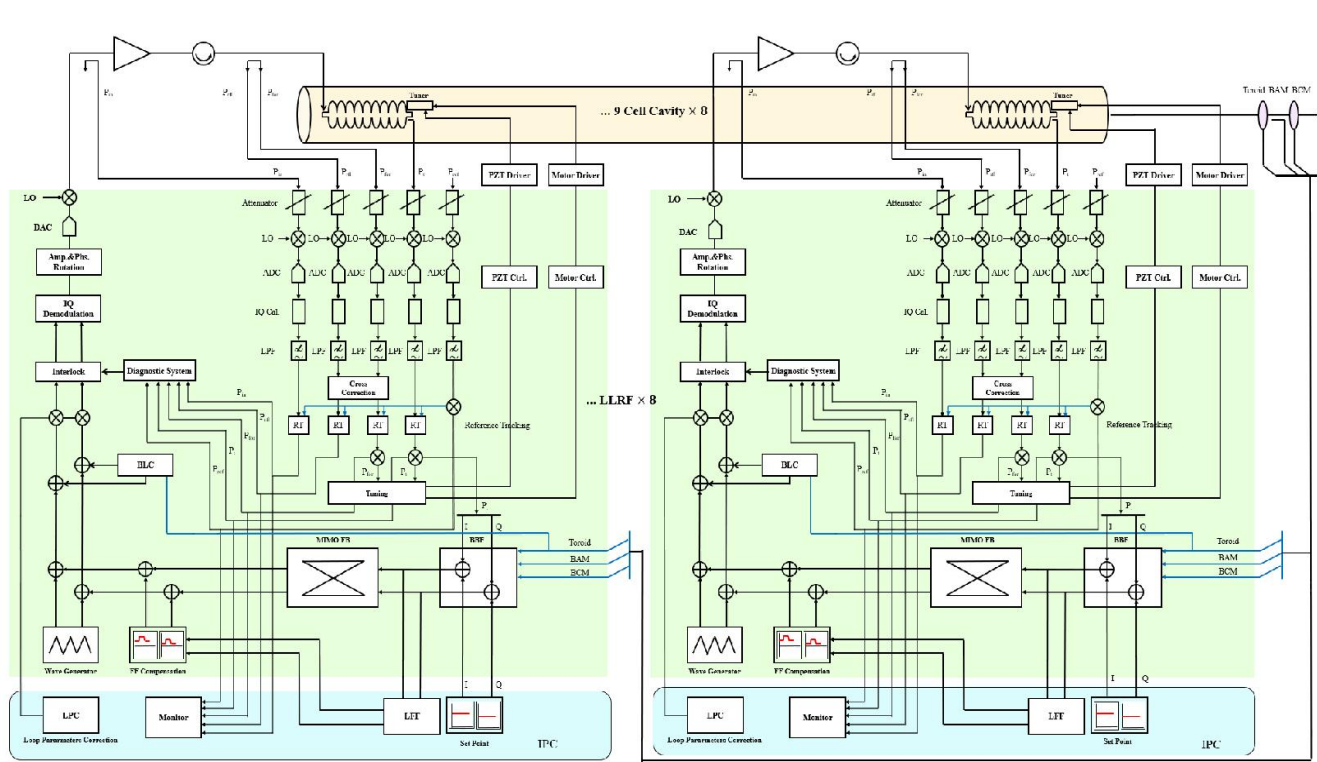


RF station

CONTENTS

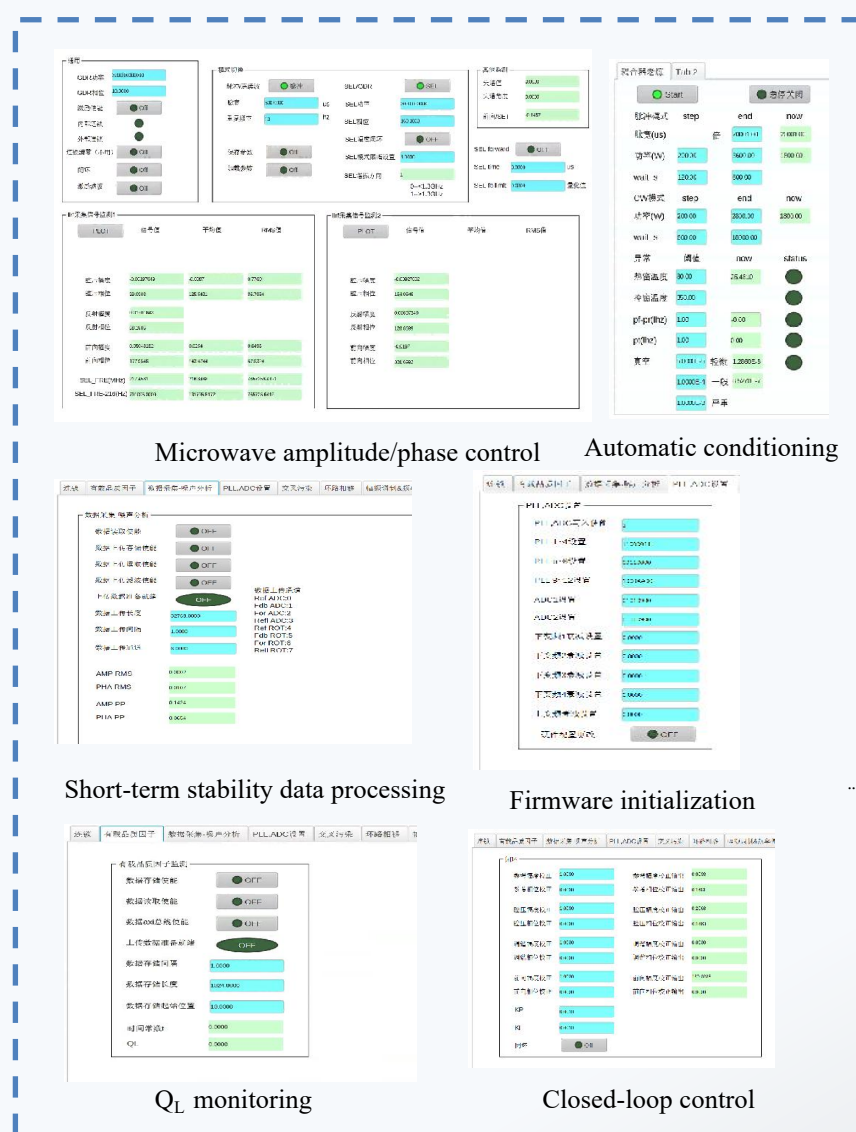
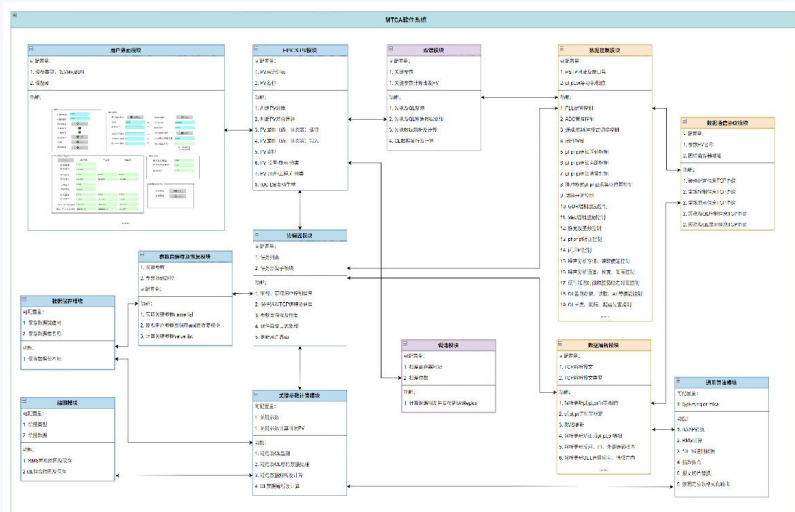
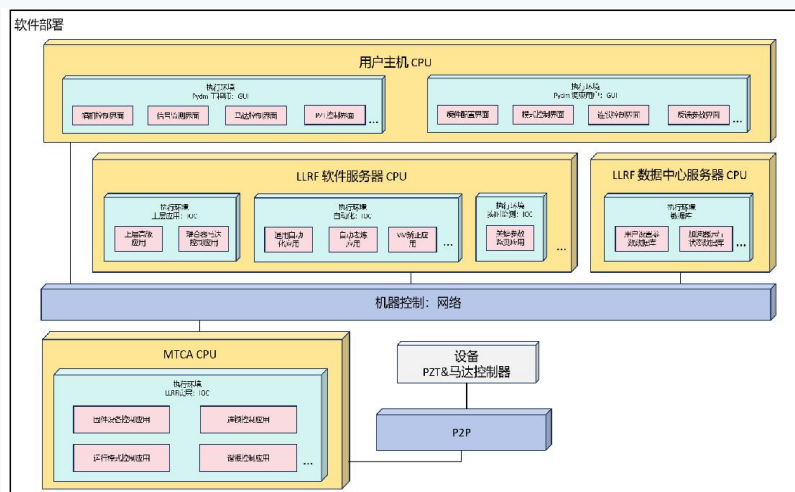
- 1. Introduction and LLRF Requirements for S³FEL**
- 2. MTCA.4 Hardware Platform Development**
- 3. Firmware and Software Development**
- 4. Validation Results at DALSLINAC**
- 5. Summary and Next Steps**

Firmware algorithms mainly consist of an amplitude-phase loop, a tuning loop, and a self-excited loop (SEL).



LLRF Firmware Diagram

- A phase/amplitude loop algorithm to achieve stable control of the accelerating voltage and phase.
- A PZT feedback-loop control algorithm to achieve stable control of the superconducting cavity resonance frequency.
- A self-excited loop (SEL) to implement a cavity frequency tracking mode.
- An active noise control (ANC) algorithm to suppress microphonic noise.
- Monitoring reference and reflected signals for software-level functions like over-limit protection.



- EPICS-based low-level control and IOC design
- Automated debugging and conditioning application design
- Data acquisition and analysis modules
- Remote configuration and monitoring functions



Software Design



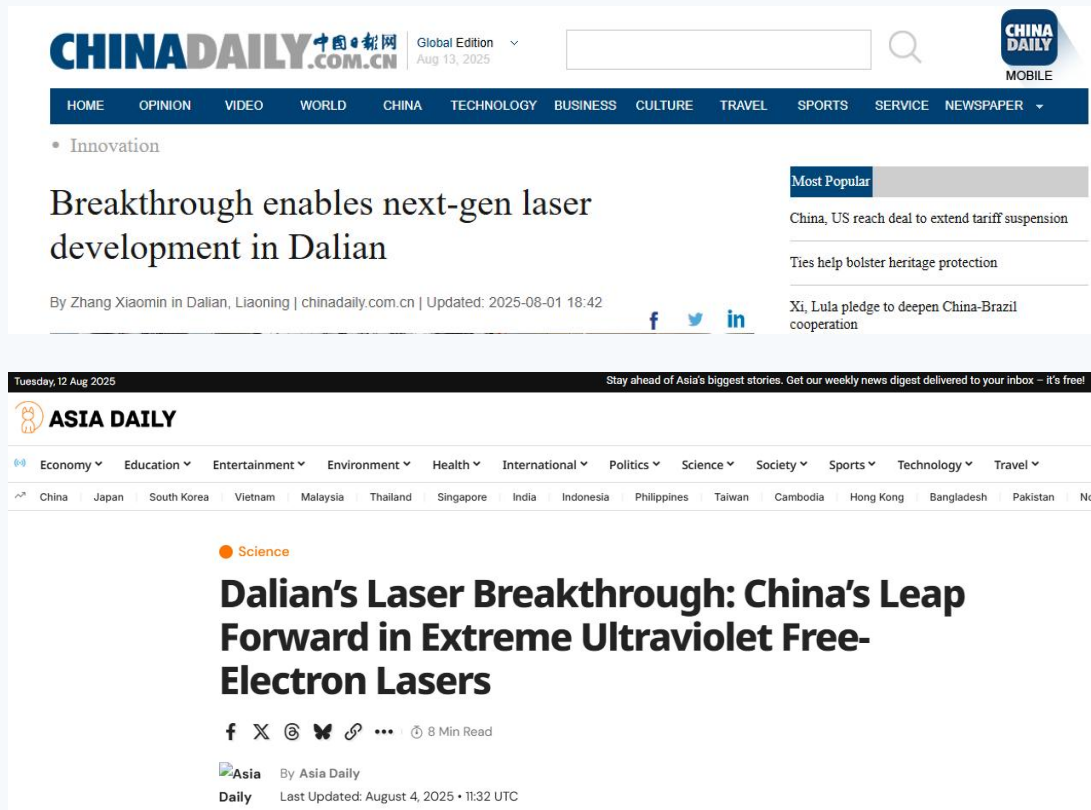
深圳先进光源研究院
Institute of Advanced Light Source Facilities, Shenzhen



CONTENTS

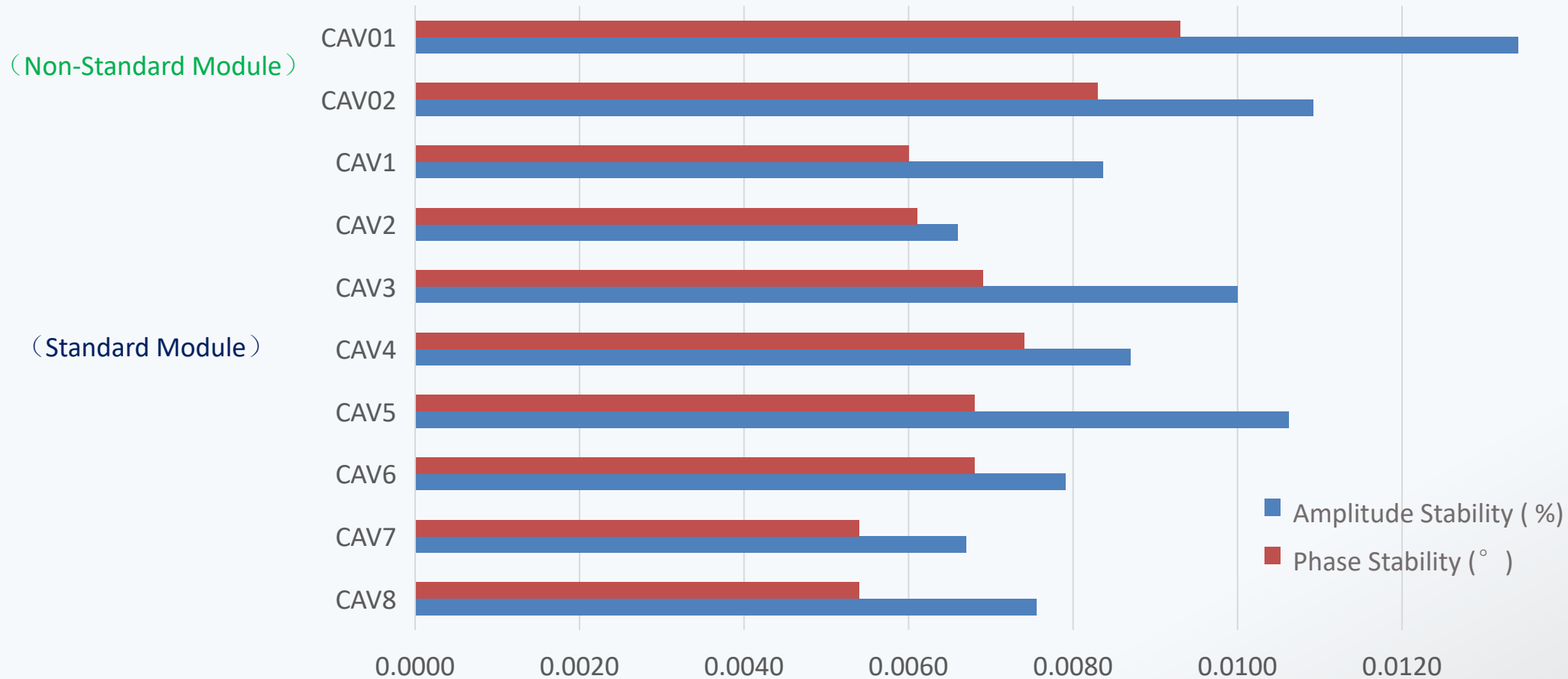
- 1. Introduction and LLRF Requirements for S³FEL**
- 2. MTCA.4 Hardware Platform Development**
- 3. Firmware and Software Development**
- 4. Validation Results at DALSLINAC**
- 5. Summary and Next Steps**

- The system was validated at the DALS superconducting linac by DICP and IASF in the summer of 2025.
- 1 MHz repetition rate, 0.1 mA beam current, and a total cavity voltage of 130 MV were realized.
- The system operated continuously for 24 hours.



➤ Amplitude/Phase Stability

- LLRF control technology has been developed to achieve stable control of 10 superconducting cavities.
- Each cavity achieves a closed-loop amplitude/phase stability of better than 0.02%/0.02° .



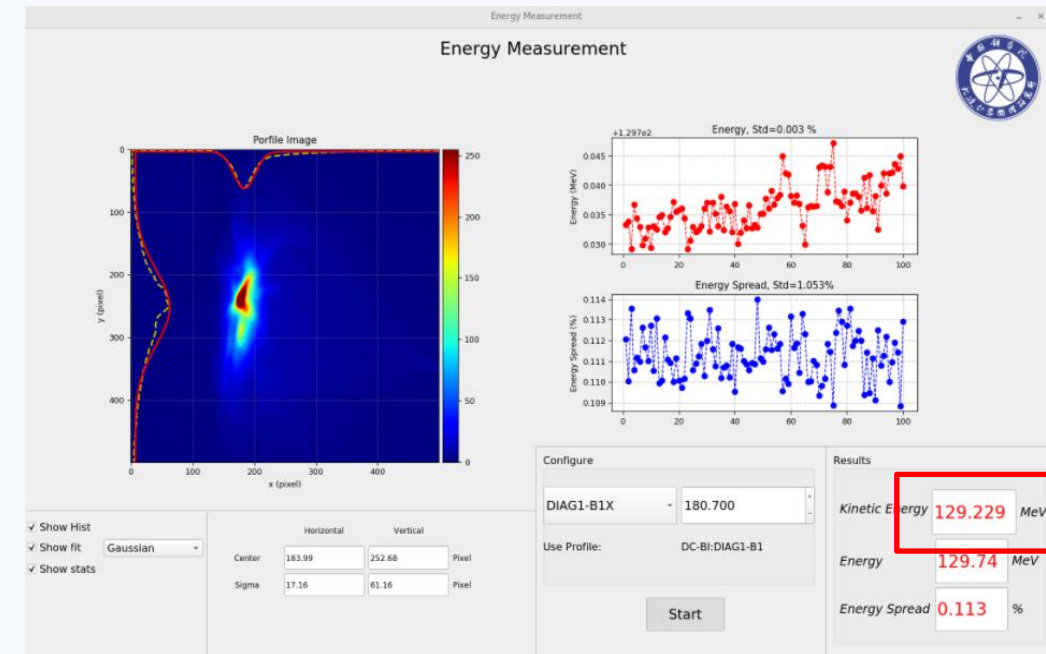
GDR Amplitude and Phase Stability

➤ $Q_L \approx 6E7$, Total Cavity $\approx 130MV$

- Q_L is approximately $6e7$ for the standard module.
- Stable operation has been achieved at a total cavity voltage of 130 MV.

Cavity	Q_L	Q_t	Amplitude stability	Phase stability(°)
Cavity1	6.06E+07	3.09E+11	0.0114%	0.0071
Cavity2	6.36E+07	2.31E+11	0.0073%	0.0060
Cavity3	6.36E+07	3.26E+11	0.0093%	0.0061
Cavity4	6.08E+07	3.69E+11	0.0074%	0.0051
Cavity5	6.09E+07	3.48E+11	0.0075%	0.0054
Cavity6	6.28E+07	2.18E+11	0.0088%	0.0068
Cavity7	6.09E+07	3.42E+11	0.0071%	0.0053
Cavity8	6.21E+07	2.67E+11	0.0072%	0.0053

$$Q_L \approx 6E7$$

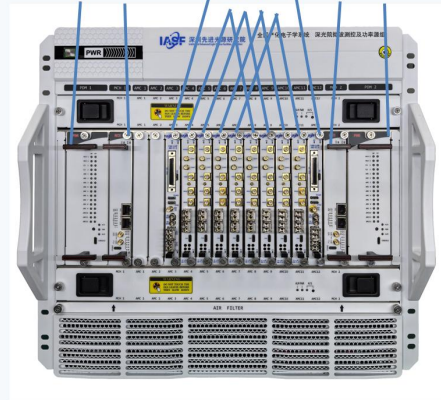


Total cavity voltage ≈ 130 MV

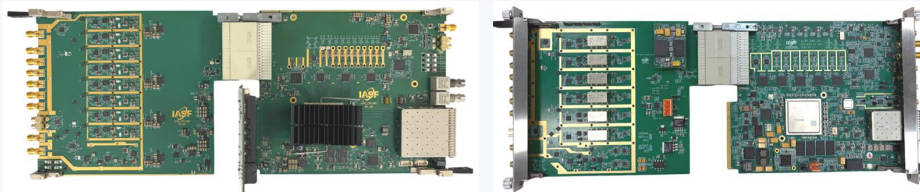
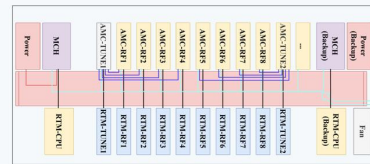
CONTENTS

- 1. Introduction and LLRF Requirements for S³FEL**
- 2. MTCA.4 Hardware Platform Development**
- 3. Firmware and Software Development**
- 4. Validation Results at DALS LINAC**
- 5. Summary and Next Steps**

- **Stable operation has been achieved at a total cavity voltage of 130 MV.**



MTCA.4-Based System
(8*RF + 2*TUN boards,
support for a standard SC module)
[IASF & ZOONENG / YZITECH]



RF Boards [IASF & THU]

RF Boards [IASF & USTC]



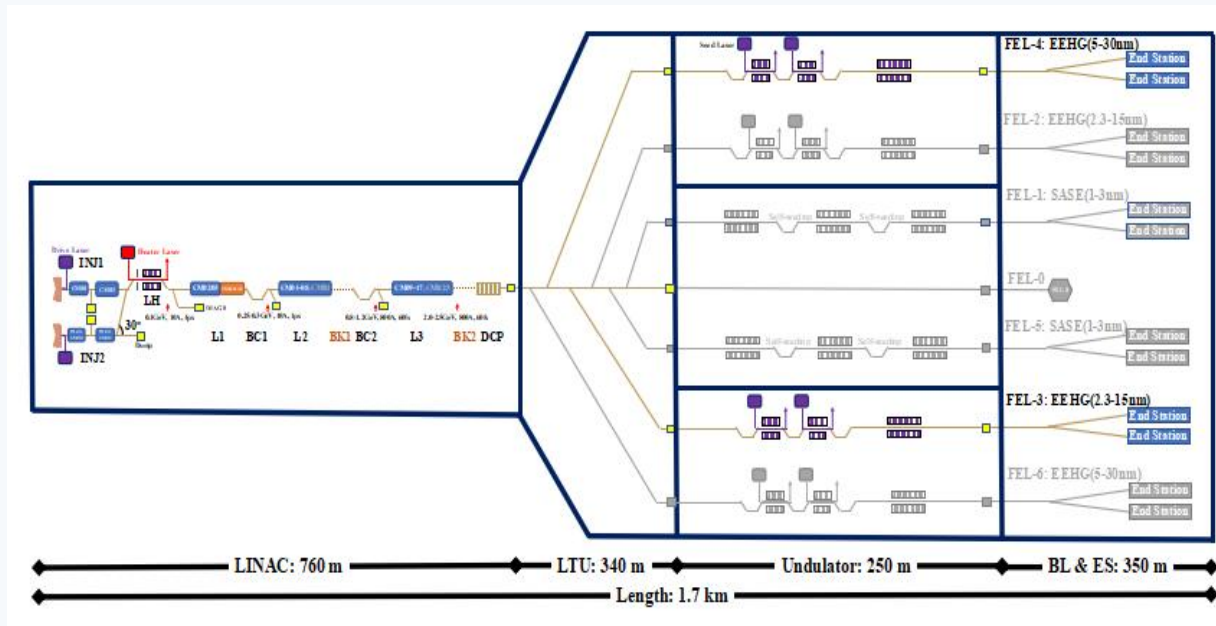
Tuning Boards [IASF]

Parameter	Value
Repetition rate	1003.88 kHz
Average charge	113 pC
Beam energy	129.7 MeV
Beam energy jitter	0.01739 %
Quantum conversion efficiency	15.96 %

Prototype of MTCA.4 platform for LLRF system in S³FEL

Validated at DAL5

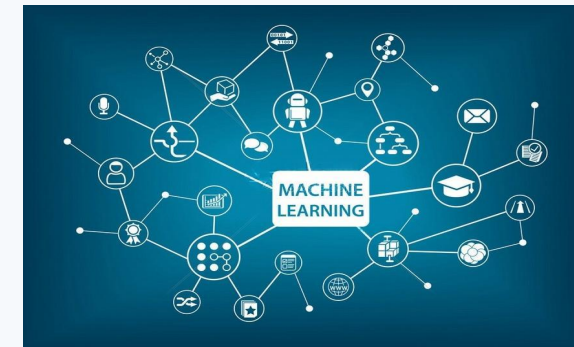
- Complete the development and verification of the VHF gun, harmonic cavities, and diagnostic LLRF systems.
- Preparing for mass production and the engineering transition from prototype to production.
- Intelligent fault diagnosis and self-recovery, and machine-learning-assisted control.



S³FEL layout



Electronics Mass Production



Machine Learning

Thanks for your attention

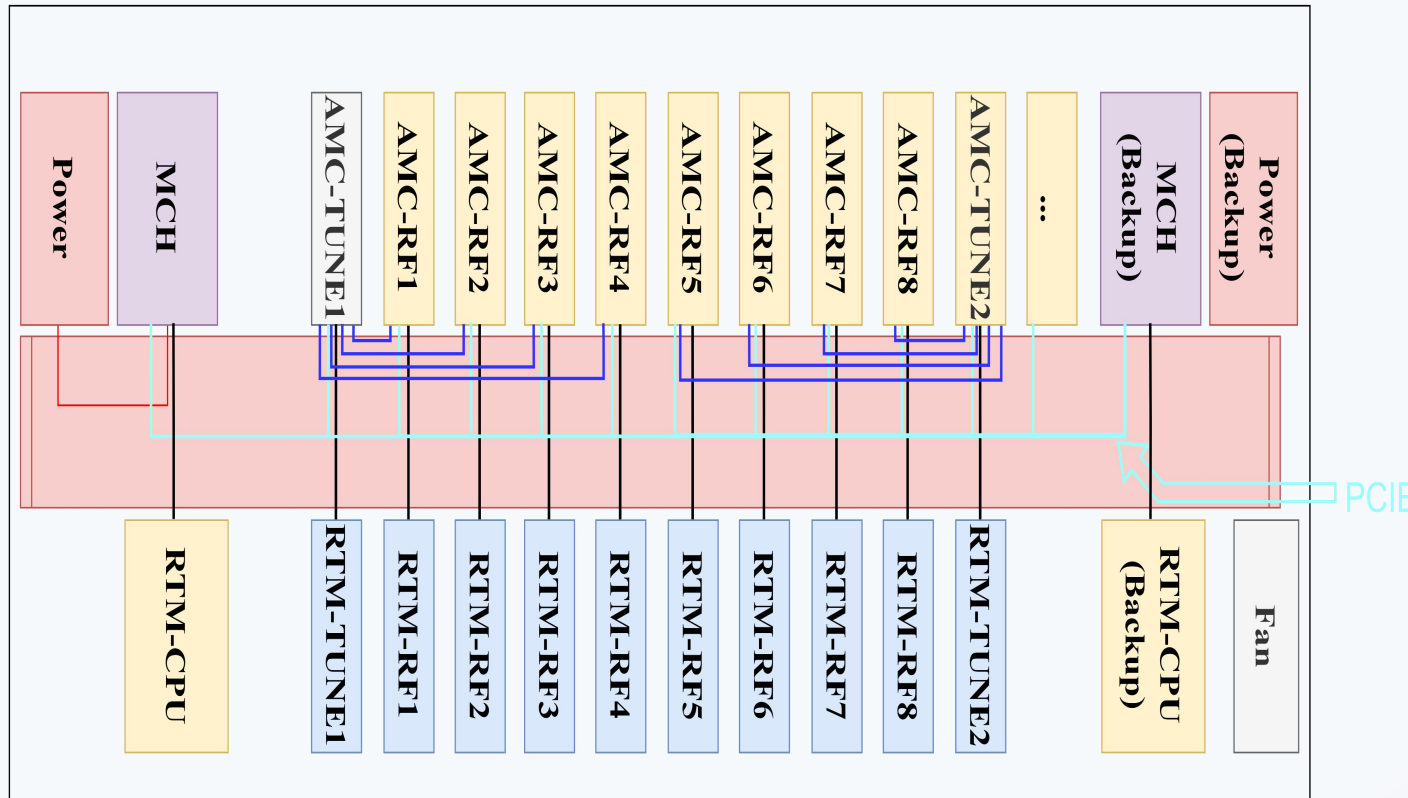
Our group would like to thank DESY and domestic institutions Tsinghua, Peking, USTC, SHINE, IHEP, IMP, etc. for their support over the years.

➤ Thanks !



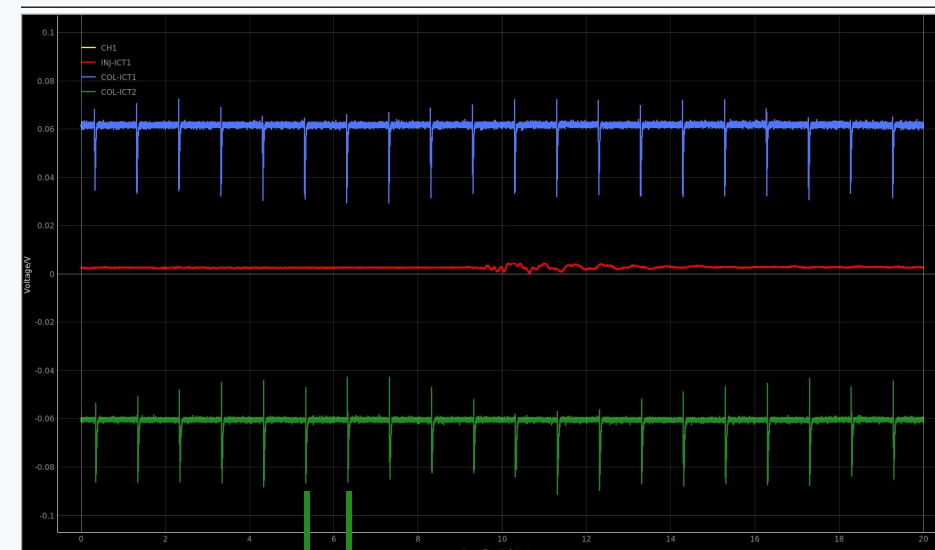
Backup slices

- **Considerations** :channel density, backplane bandwidth, industrial reliability, scalability.
- **Why MTCA.4** :AMC+RTM functional decoupling, clear separation of digital processing and analog I/O, simplified maintenance and upgrade



- Dual MCH and CPU, one active and one backup.
- Eight pairs of RF boards and two pairs of tuning boards are installed in one chassis; one MTCA chassis controls one standard module.
- AMC cards are connected through the chassis backplane(PCIE)

1 MHz operation



$\sim 1 \mu\text{s}$

BPM

➤ $Q_L = 6e7$ VS $4e7$

