



深圳先进光源研究院
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Loop Delay Identification in LLRF Systems via Self-Excited Loop Control

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On behalf of the IASF LLRF Team

October, 2026

Outline

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- 02** LLRF for S3FEL
- 03** Loop delay identification in LLRF
- 04** Controller optimization
- 05** Summary

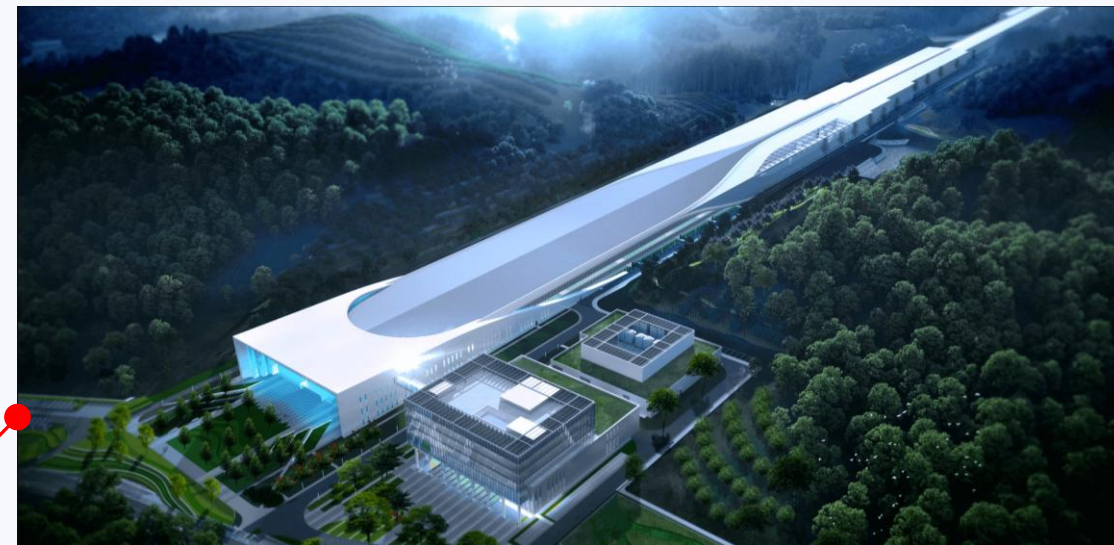


S3FEL introduction

S3FEL introduction

Where is S3FEL?

中国地图



Located in Shenzhen, the Great Bay Area(GBA)

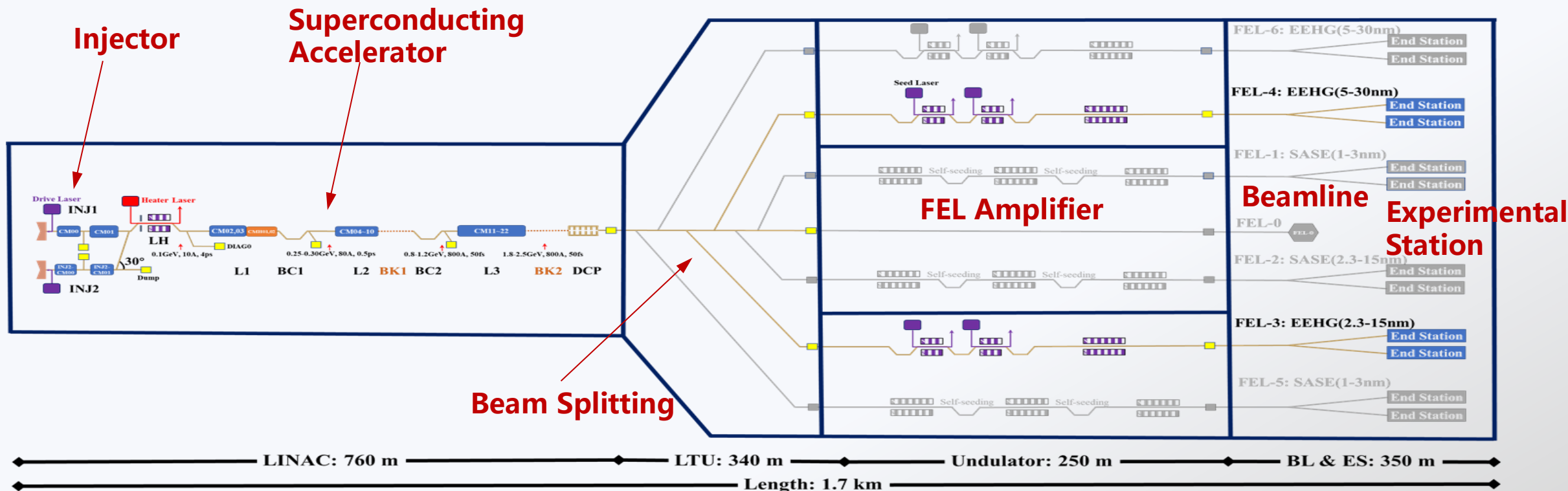
It's under construction, and beam commissioning targeted for 2030

S3FEL introduction

S3FEL facility layout and specifications:

- S3FEL is a 1.7-km superconducting soft X-ray free-electron laser.
- It will provide 2.3-30 nm radiation with a 1 MHz repetition rate and beam energy of 2.0-2.5 GeV.

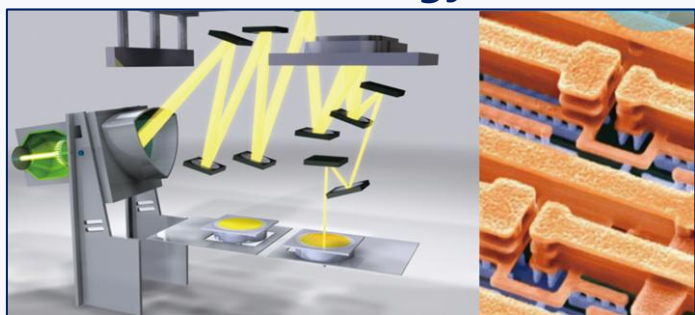
Parameter	Design Spec.	Acceptance Spec.	Unit
Electron Energy	2.5	2.0	GeV
Rep. Rate	1 M	100 k	Hz
Beam Emittance	0.8	1.0	mm-mrad
Bunch Charge	100	20	pC
FEL-3	2.3-15	4-15	nm
FEL-4	5-30	7-30	nm



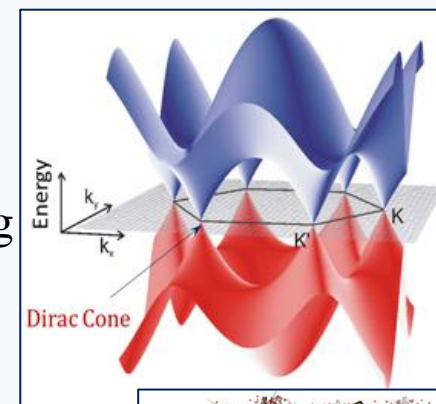
S3FEL introduction

S3FEL will promote the development of various disciplines and technologies

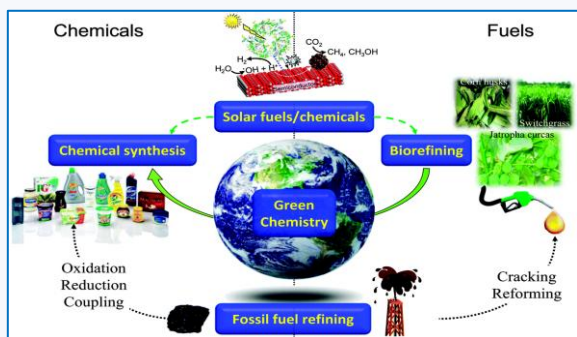
Semiconductor Technology



High brightness, short pulse duration, high coherence, and continuously tunable wavelength of S3FEL enable non-destructive, dynamic probing of atomic, molecular, and outer-shell electronic structures on the hundred-femtosecond timescale

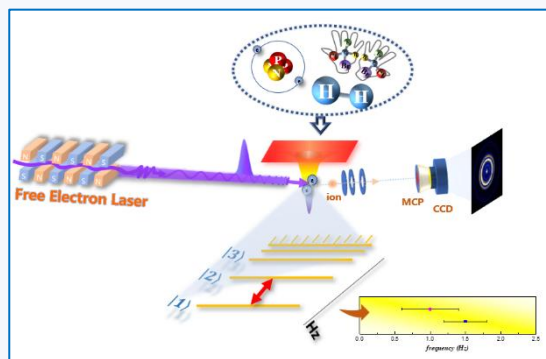


Quantum Materials

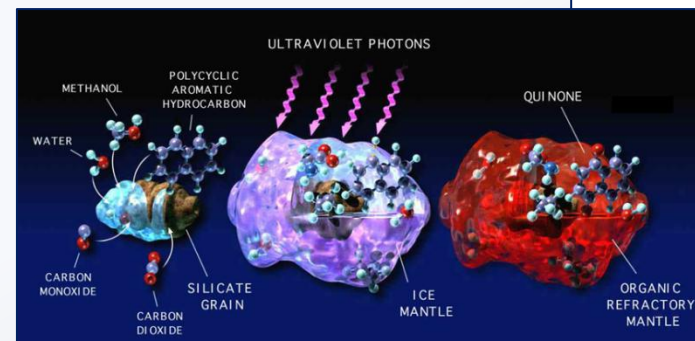
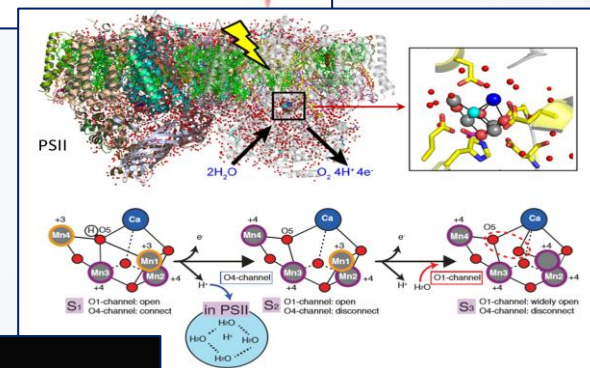


Energy Technology

Atomic Science



Biomedicine

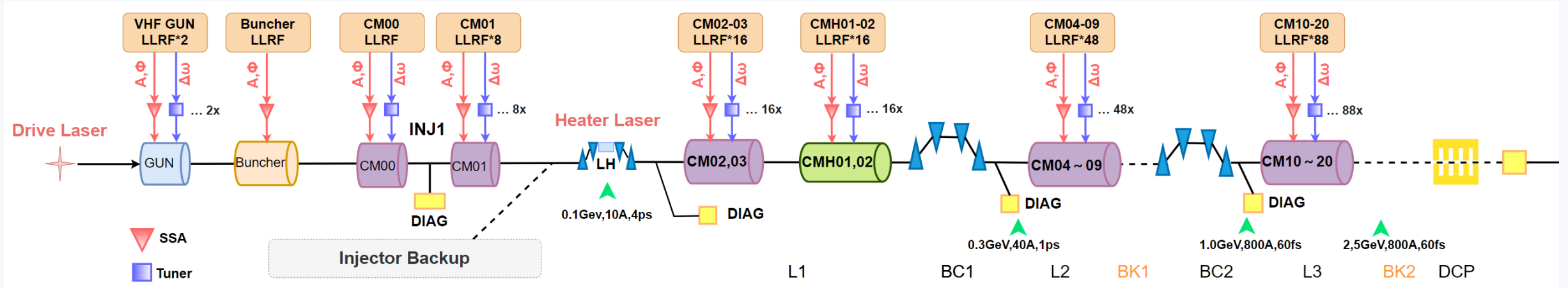


Interstellar Science



LLRF for S3FEL

LLRF for S3FEL



Part	Module No.	Quantity	Temperature	Function & Cavity	RF	RF stability Amplitude/Phase (RMS)	No. of LLRF units
INJ / INJ(Backup)	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

LLRF system is based on the MTCA.4 platform

Requirements:

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

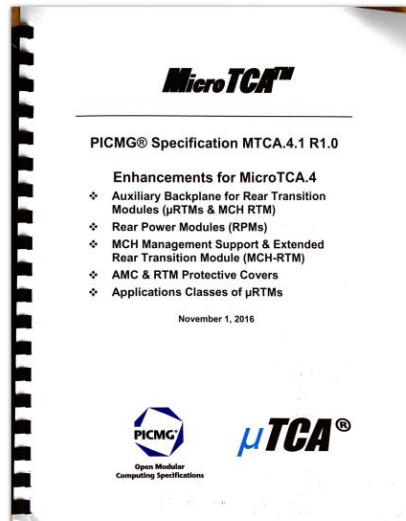
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Advantages of MTCA:

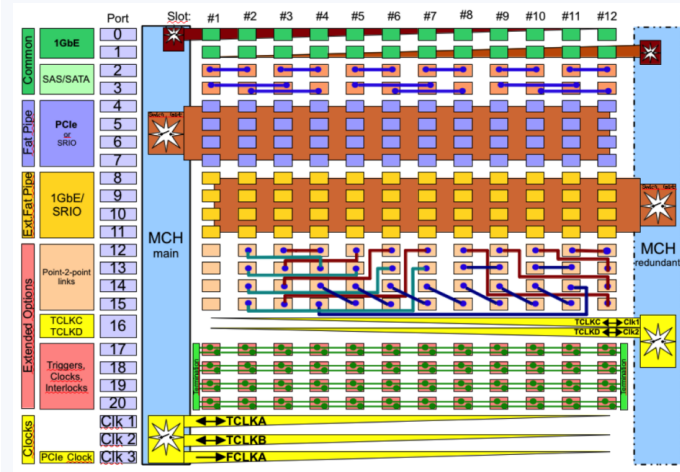
- High channel density
- AMC + RTM decoupling: Digital processing separated from analog I/O
- High backplane bandwidth
- Industrial reliability
- Scalability
- Simplified maintenance and upgrade

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MTCA.4.1



168 Pages



Status of S3FEL LLRF

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

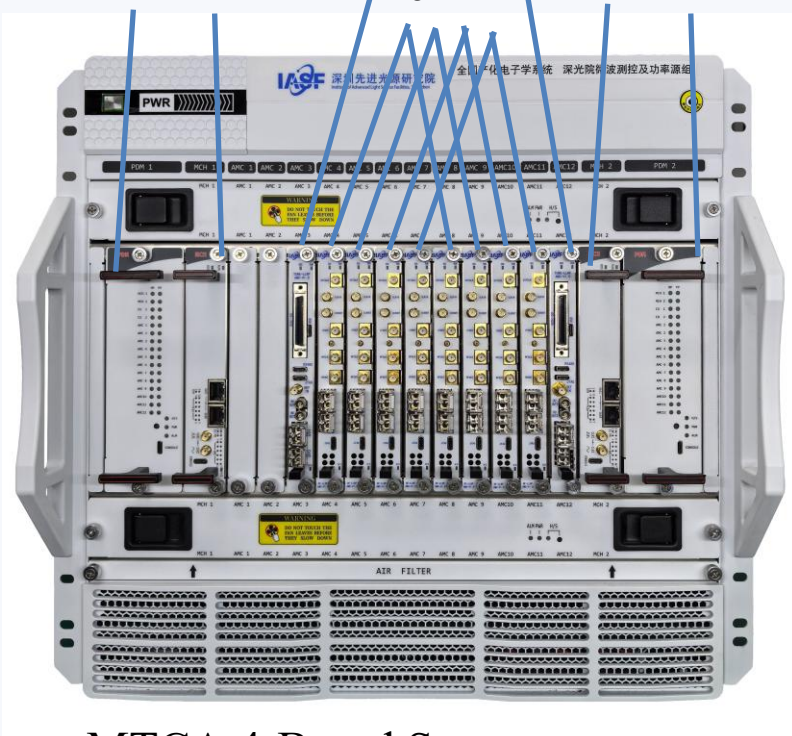
- Most main accelerating cavity LLRF systems, including those for the buncher, CM00, CM01, CM02-03, CM04-09, and CM10-20, have been verified.
- The LLRF systems for the GUN, CMH01-02 harmonic cavities, and diagnostic deflectors are still under development.

MTCA.4 Hardware Platform

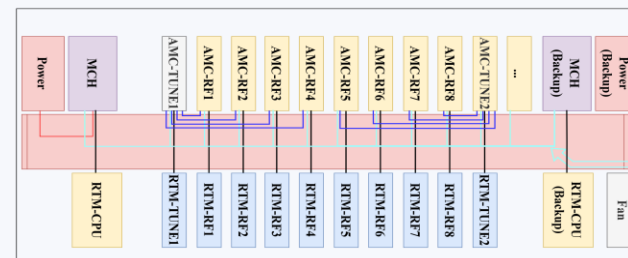
Main Power
management,
MCH & CPU

2×TUN
8×RF

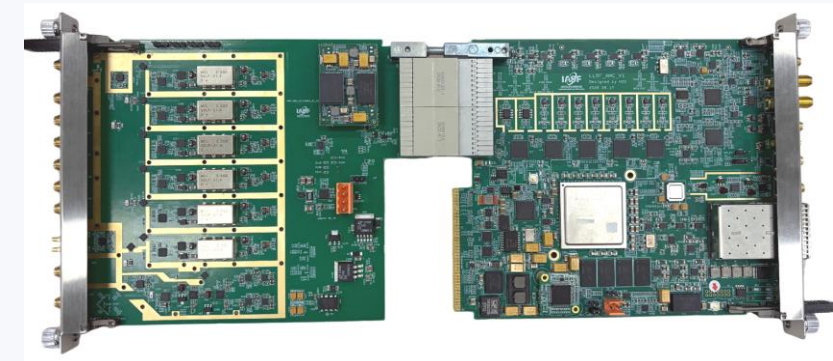
Backup Power
management,
MCH & CPU



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



RF Boards [IASF & THU]



RF Boards [IASF & USTC]



Tuning Boards [IASF]

LO & RF Boards

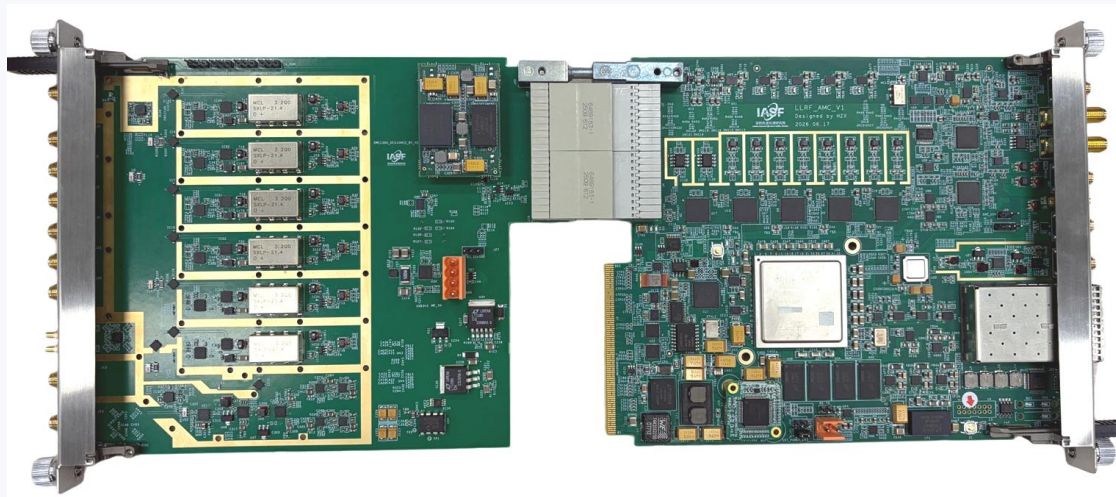
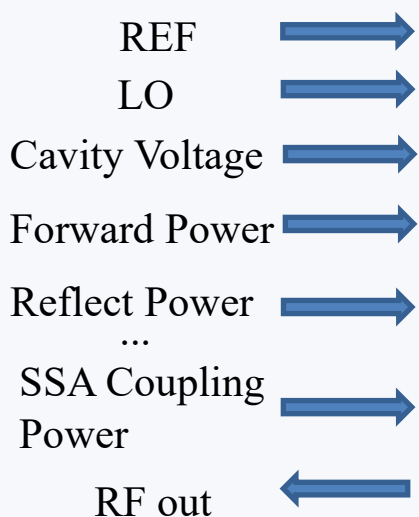


LO (front view)



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.



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)



FMC Card 2
(Motor Control)

Tuning-RTM

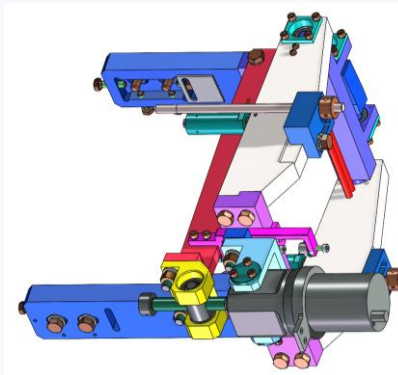
Tuning-AMC



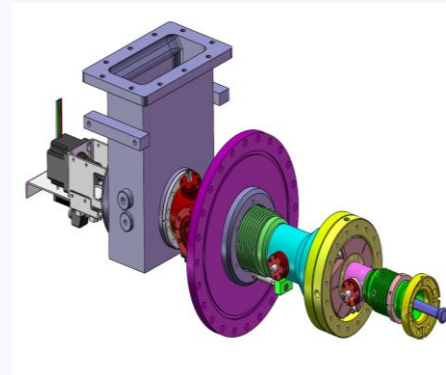
Piezo Driver



Motor Driver



Tuner



Coupler

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

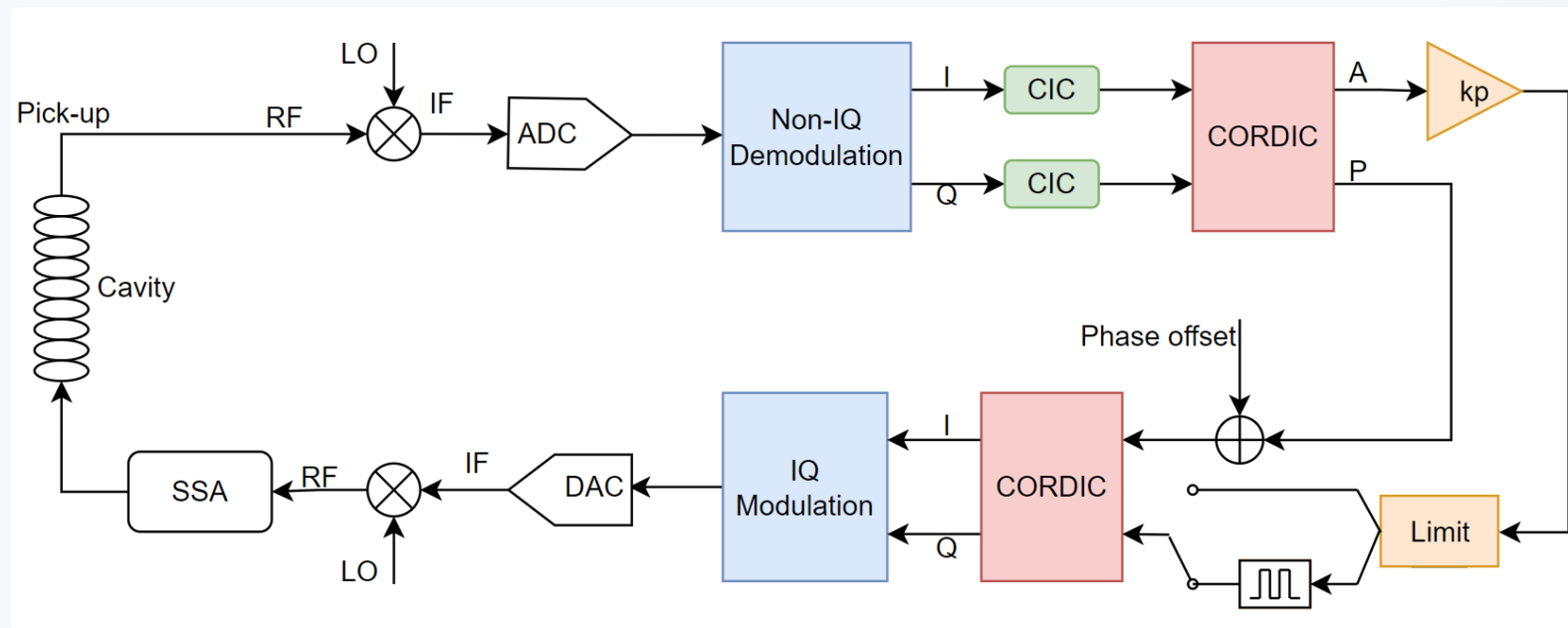
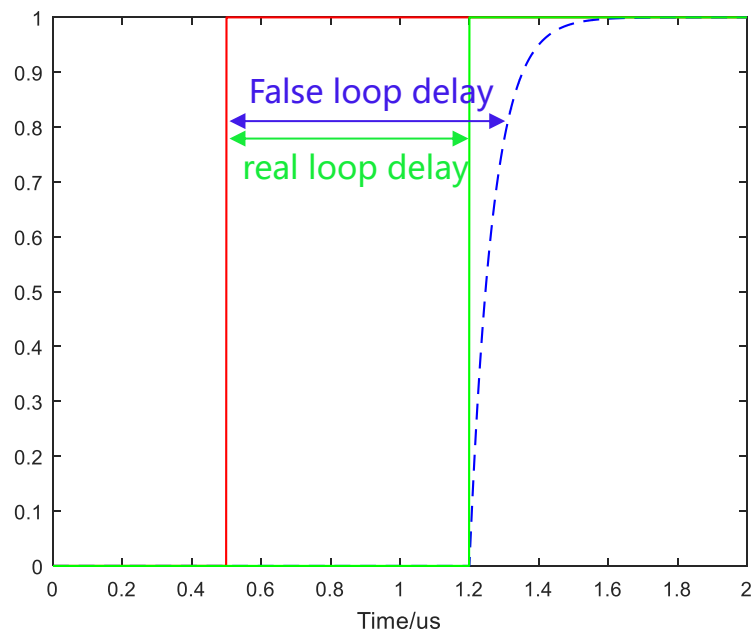


03

Loop delay identification in LLRF

➤ Loop delay identification in LLRF

- The common method for measuring loop delay is to apply a step signal, then read back the acquired step signal and compare the time difference between the rising edges.
- However, components such as cavities or filters exist in the loop, which induce a step response and thus cause the measured loop delay to be larger than the actual value.
- Loop delay is critical in parameter optimization, and therefore should be determined as accurately as possible.
- We have designed a method for loop delay identification via SEL. The delay obtained by this method can be directly used to design and optimize controller parameters. The optimized controller parameters have been verified online test and yield good control performance.



➤ Loop delay identification in LLRF

The principle of loop delay identification via SEL:

Based on the actual control system, the SEL loop is modeled as follows

➤ The controller is a proportional controller: $K(s) = kp$

➤ The controlled plant is the cavity transfer function: $G(s) = \frac{w_{1/2}}{s + w_{1/2} - j\Delta w}$

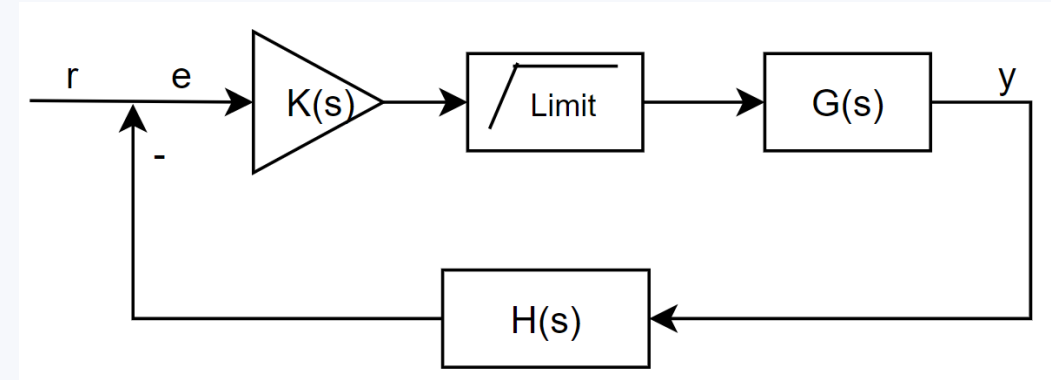
➤ The feedback path transfer function is the loop delay and loop phase shift: $H(s) = e^{-s\tau - j\varphi}$

➤ Then, the close-loop transfer function of the system can be derived:

$$\Phi(s) = \frac{kp \cdot w_{1/2}}{s + w_{1/2} - j\Delta w + kp \cdot w_{1/2} \cdot e^{-s\tau - j\varphi}}$$

➤ From this close-loop transfer function, we can obtain the resonant frequency related to loop delay:

$$w_r - \Delta w - kp \cdot w_{1/2} \cdot \sin(w_r\tau + \varphi) = 0$$



➤ When $w_r\tau + \varphi = k\pi$, dose $w_r = \Delta w$, but in reality, when $w_r\tau + \varphi = 2k\pi$, the system is in negative feedback and cannot sustain self-oscillation. Therefore, only when $w_r\tau + \varphi = 2k\pi + \pi$, does $w_r = \Delta w$

➤ The method for identifying loop delay is as follows:

- Simultaneously vary the detuning Δw and the loop phase shift φ
- Observing the maximum cavity voltage amplitude to

ensure $\Delta w_r\tau + \Delta\varphi = 0$, thus $\tau = -\frac{\Delta\varphi}{\Delta w_r}$

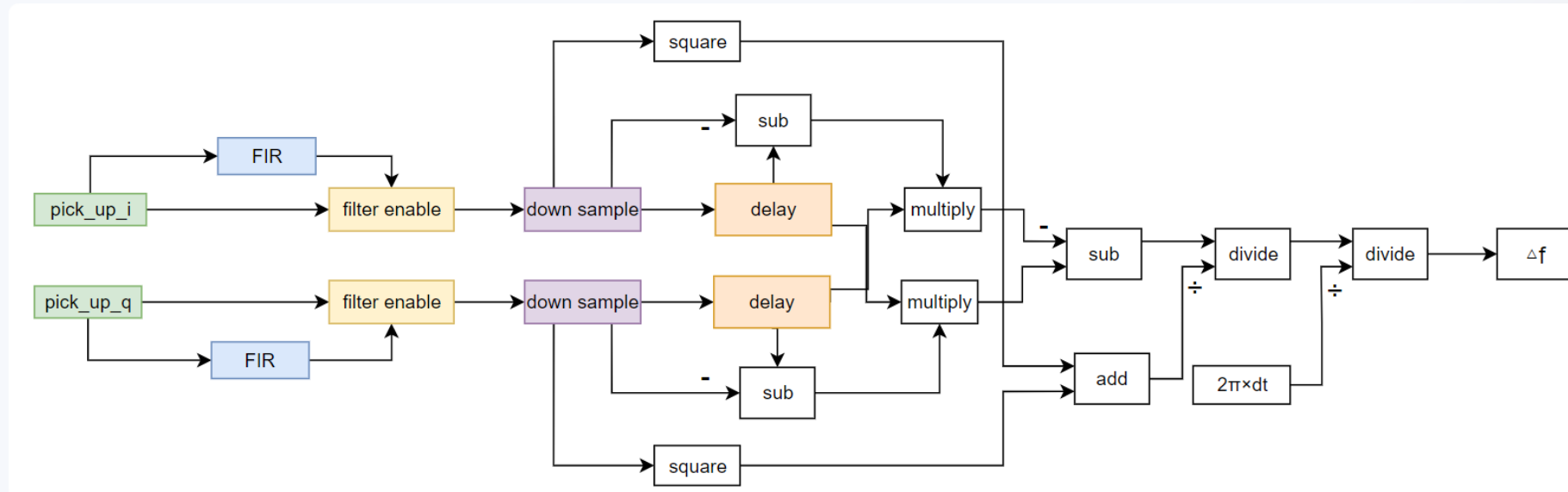
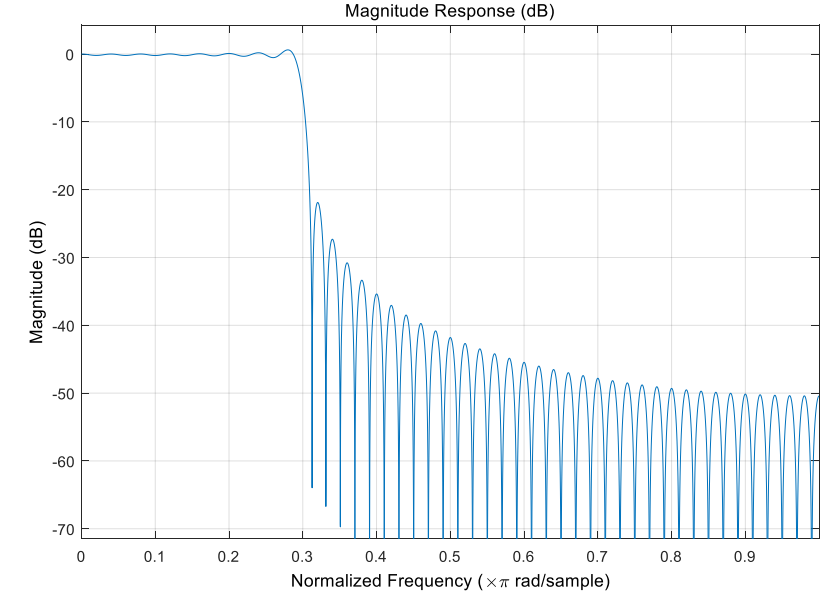
➤ Loop delay identification in LLRF

How to measure detuning:

- Detuning can be measured by acquiring the demodulated IQ signal through the Pick-up

$$\Delta f_{i+1} = \frac{1}{2\pi(I_i^2 + Q_i^2)} \left(I_{i+1} \frac{Q_{i+1} - Q_i}{\Delta t} - Q_{i+1} \frac{I_{i+1} - I_i}{\Delta t} \right)$$

- This method is affected by noise, so a filter needs to be designed.
- It is also affected by computation time Δt . And it is designed to be 23 clock cycles.
- The effective frequency range for the detuning measurement is 1 kHz to 500 kHz



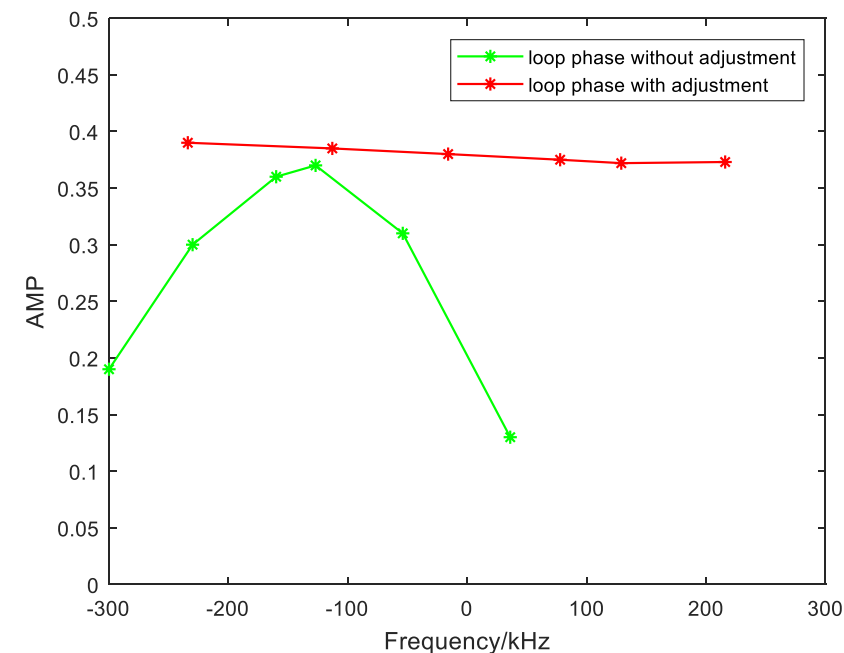
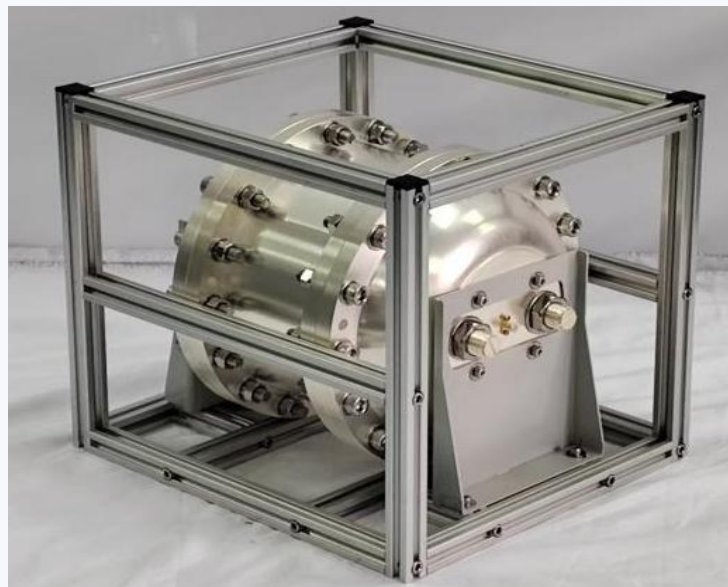
➤ Loop delay identification in LLRF

After completing the algorithm design and implementation, offline simulation tests were conducted first. The tests primarily used a simulated cavity, which can be regarded as a low-power cavity that the LLRF can drive directly.

From the test results, the following observations can be made:

- When the resonant frequency of the simulated cavity was changed, the SEL failed to track the resonant frequency due to loop delay, leaving the cavity in a detuned state.
- When the resonant frequency of the simulated cavity was changed and the loop phase shift was simultaneously adjusted to compensate for the Loop delay, the simulated cavity remained in a resonant state.

parameter	value
Operation frequency	1.3GHz
Bandwidth	30kHz
Tuning frequency range	-400kHz ~400kHz



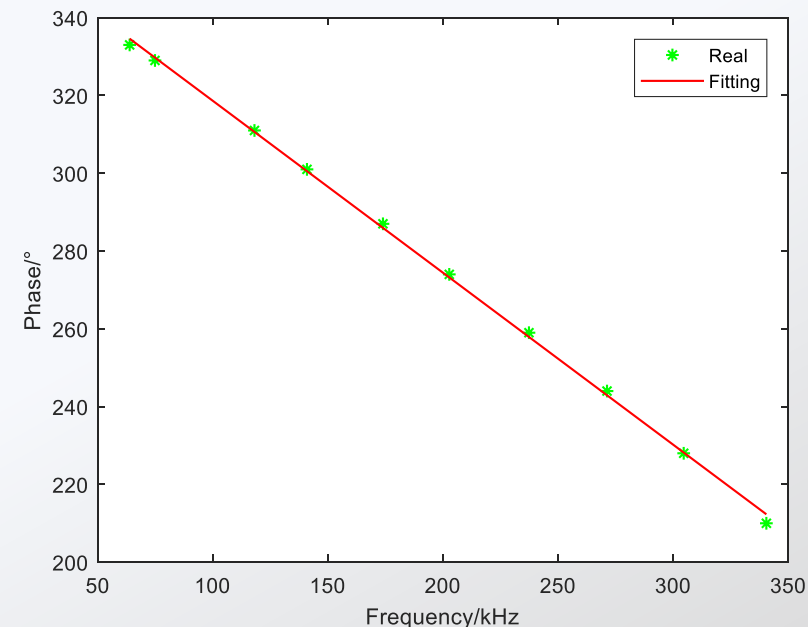
➤ Loop delay identification in LLRF

The online test used the VHF electron gun, because its resonant frequency changes automatically during the SEL process before reaching thermal equilibrium.

The test results show that:

- The resonant frequency variation exhibits a linear relationship with the synchronously adjusted loop phase shift, confirming that the theory corresponds with practice, and that what was measured is indeed the loop delay.
- Using $\tau = -\frac{\Delta\varphi}{\Delta\omega_r}$, the loop delay was calculated to be $\tau = 1.3 \mu\text{s}$.

parameter	value
Operation frequency	216.7MHz
Bandwidth	7kHz
Tuning frequency range	-400kHz ~400kHz





Controller optimization

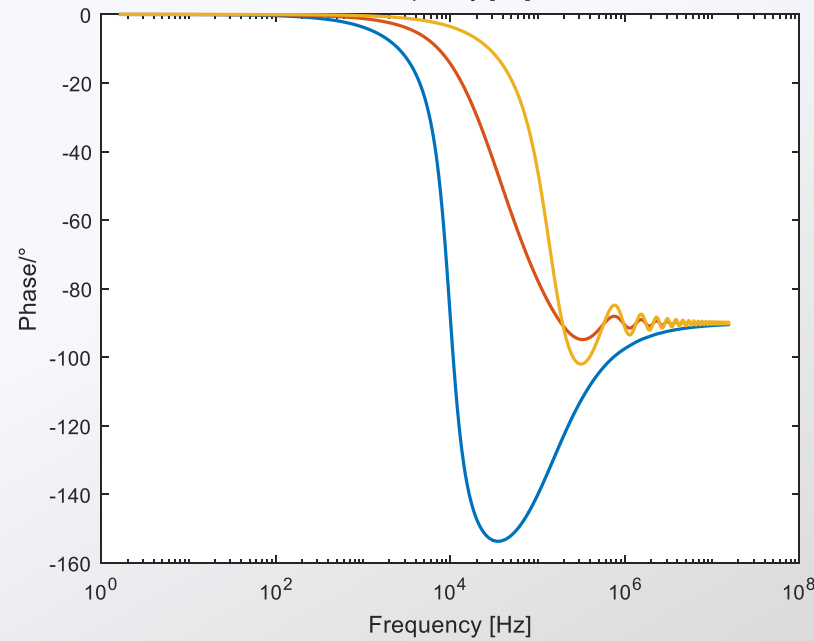
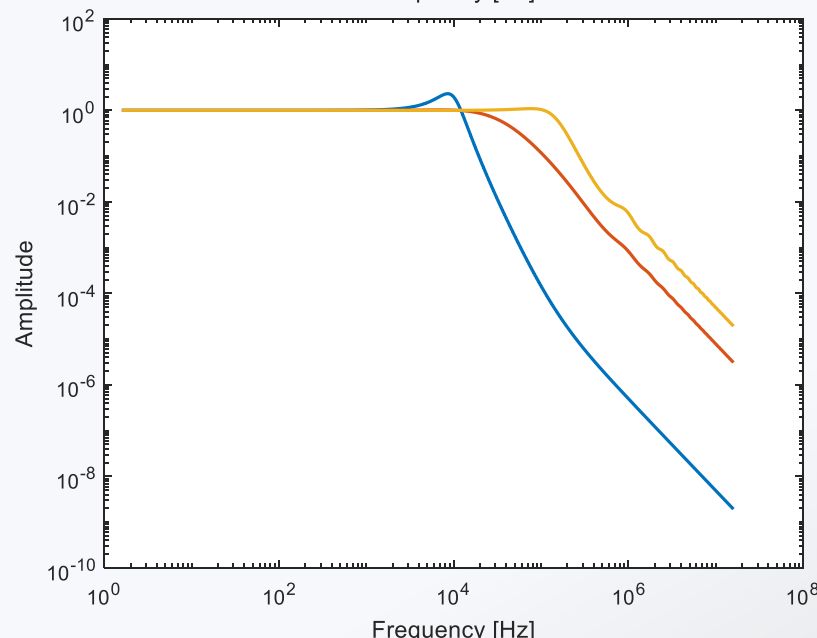
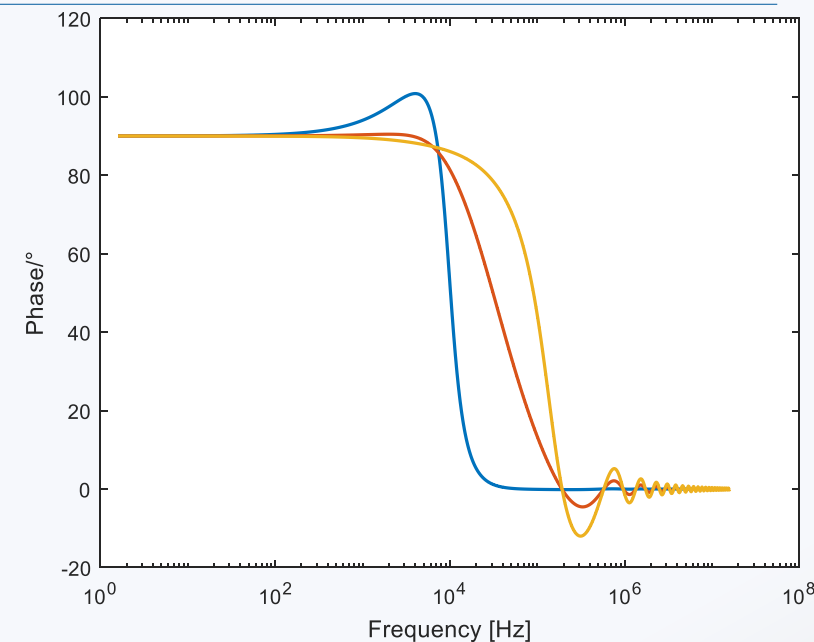
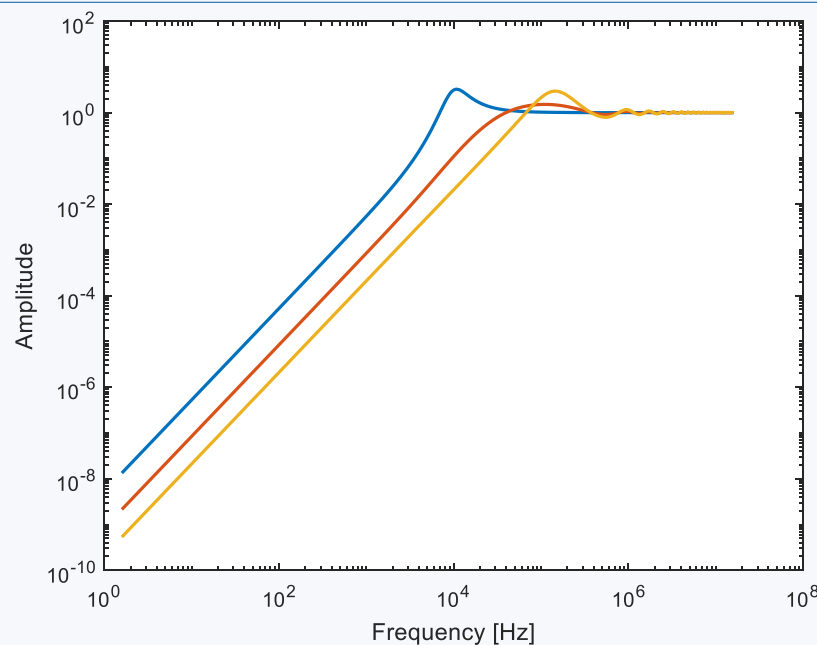
➤ Controller optimization

Optimization of the GDR Closed-Loop
Controller Using the Identified Loop delay

$$\tau = 1.3 \mu\text{s}$$

The optimization objectives are:

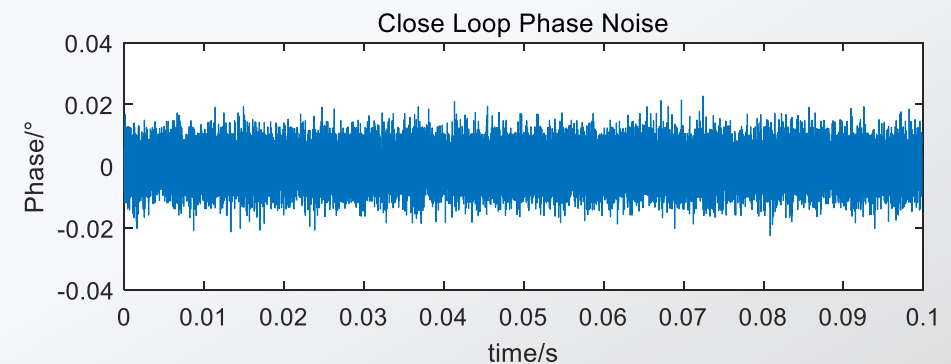
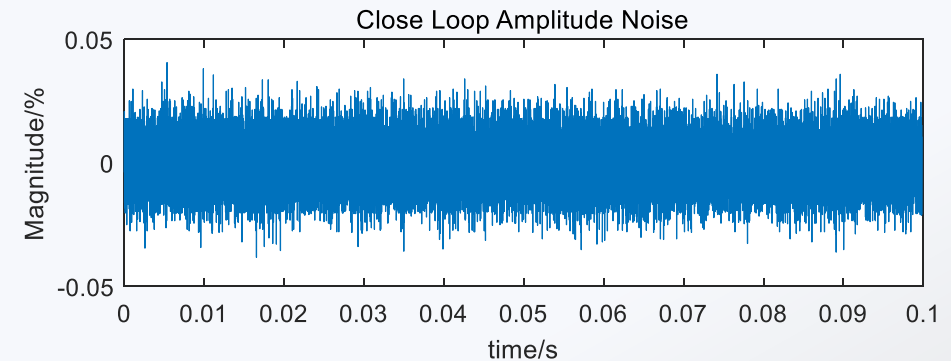
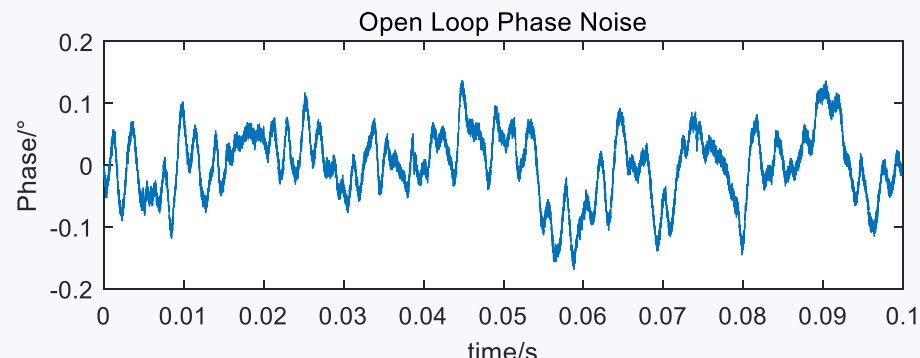
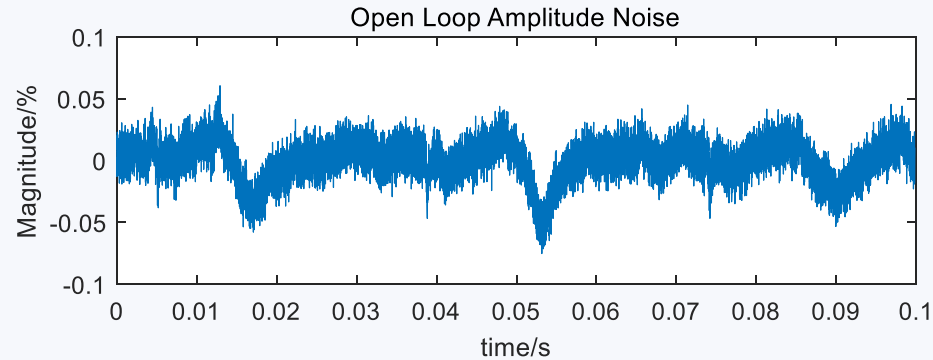
- To obtain appropriate sensitivity and complementary sensitivity functions
- To get a balance between closed-loop bandwidth and gain/phase margins



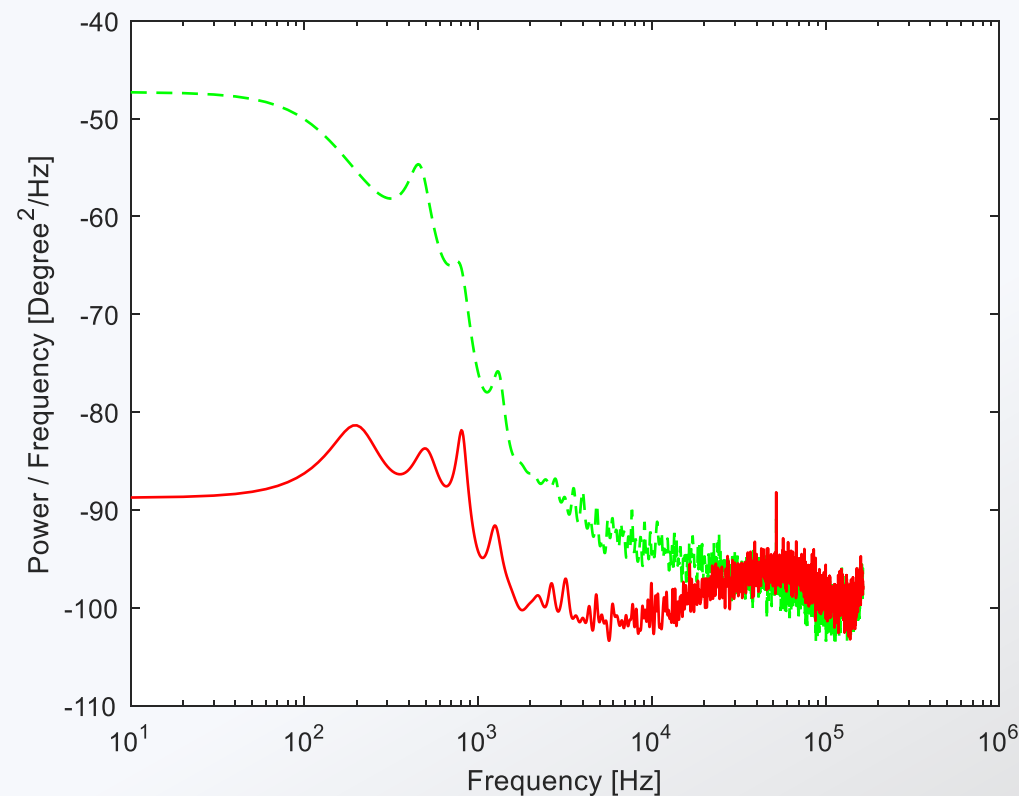
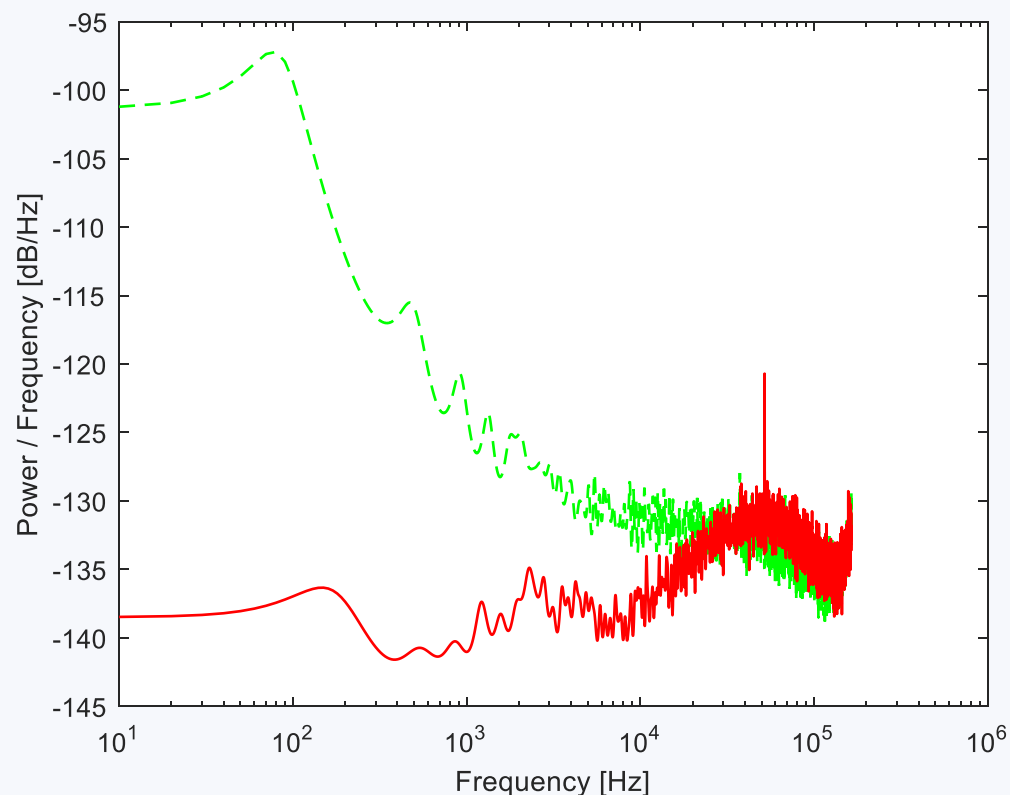
➤ Controller optimization

- The optimized control parameters were applied to the GDR closed loop of the VHF electron gun.
- The amplitude and phase fluctuations over 0.1 s were compared between open-loop and closed-loop operation.
- The RMS values of the amplitude and phase were calculated for both open-loop and closed-loop cases. The closed-loop performance shows a significant improvement.

	Amplitude Stability (%)	Phase Stability (°)
Open loop	0.016	0.055
Close loop	0.0086	0.0055

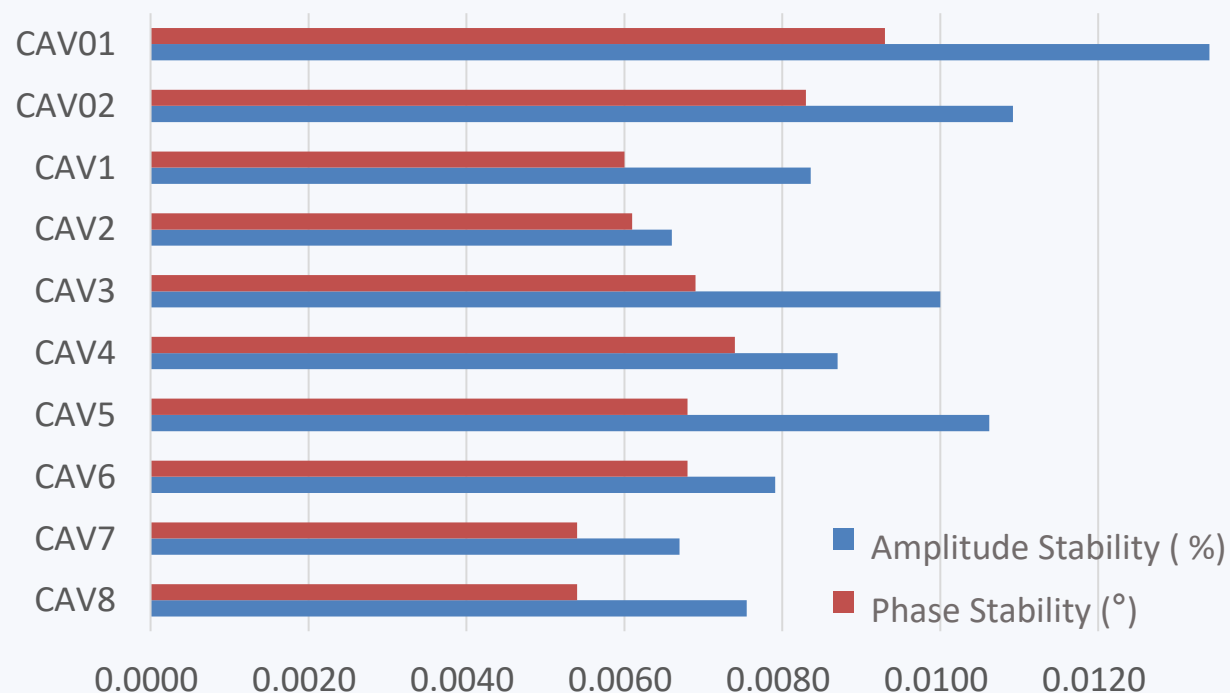


By comparing the PSD of the amplitude and phase between open-loop and closed-loop operation, it can be observed that the achieved closed-loop bandwidth is consistent with the theoretically optimized closed-loop bandwidth.



Controller optimization

- The DALS injector has 10 superconducting cavities: 2 two-cell cavities and 8 nine-cell cavities.
- The loop delay identification and controller optimization methods were applied to all 10 superconducting cavities.
- Each cavity achieves a closed-loop amplitude/phase stability of better than 0.02%/0.02°.

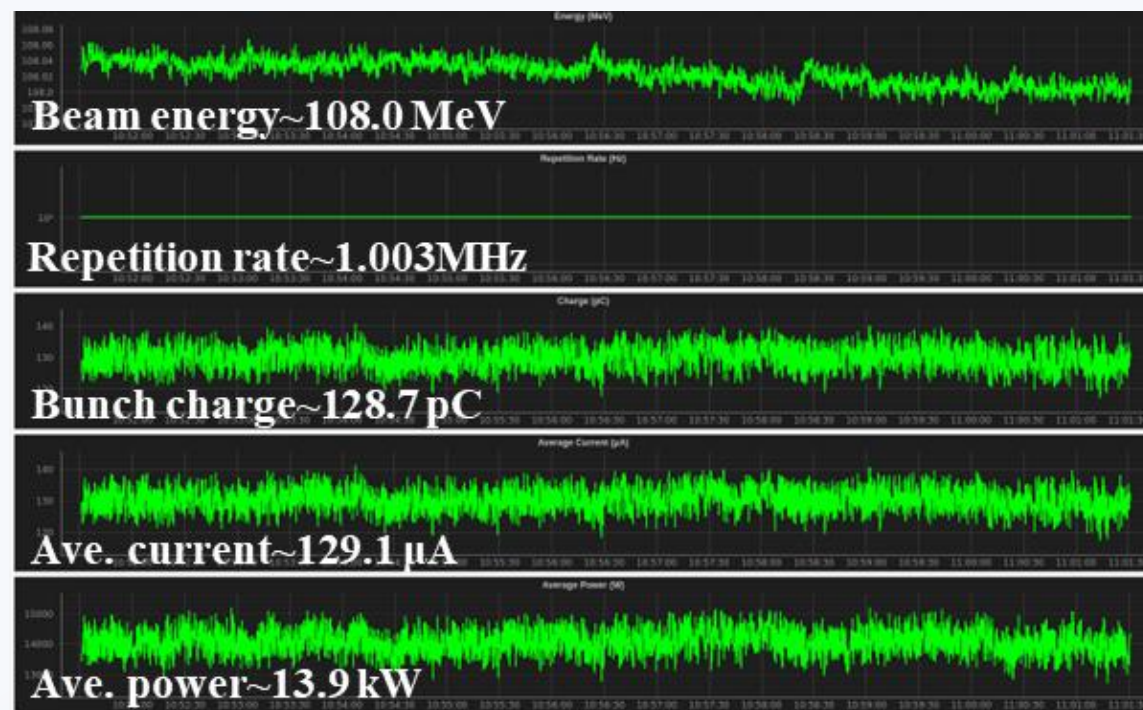
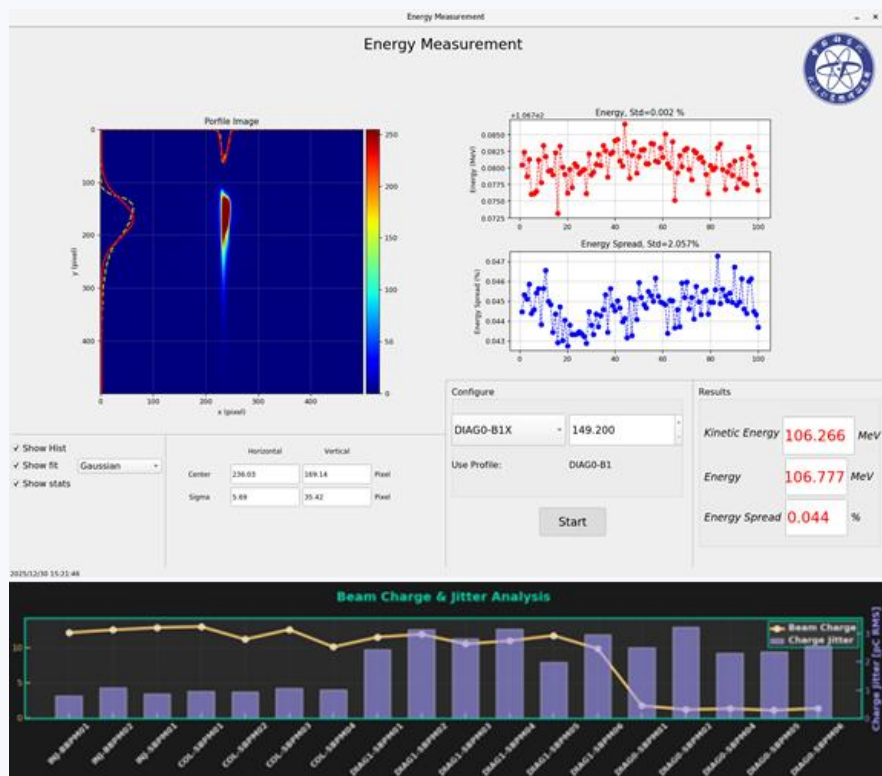


GDR Amplitude and Phase Stability



➤ Controller optimization

- Using this method, high-repetition-rate beam experiments were conducted on the DALS injector.
- Successfully achieving beam transmission with 100 pC bunch charge. The beam energy reached 108 MeV at 1 MHz
- Marking the successful acceptance of first high-repetition-rate, high-energy electron beam source facility in china.





Summary

- S3FEL is under construction, and beam commissioning targeted for 2030
- LLRF system is based on the MTCA.4 platform for S3FEL, validated on superconducting cavities.
- A method for identifying loop delay using the SEL (Self-Excited Loop) was designed.
- The loop delay was used to optimize the control parameters, and experimental tests demonstrated good control performance.
- This method was applied to control all cavities in the DALS injector, achieving stable high-repetition-rate beam operation.

An aerial photograph of a large industrial or manufacturing facility. The facility features a long, white, multi-story building with a series of green-roofed sections. It is situated in a lush, green environment with dense forests and a river flowing nearby. The text "Thanks for your attention!" is overlaid in the center of the image.

Thanks for your attention!