

Installation and Optimization of the LLRF System for the Hefei Advanced Light Facility (HALF) Injector

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Overview

1. HALF Injector Microwave System
 - Hefei Advanced Light Facility (HALF) Introduction
 - Microwave System Layout
 - Reference Signal Distribution System Layout
2. Installation and Optimization of the HALF Injector LLRF System
 - Hardware Composition and FPGA Algorithm Design
 - Acquisition Channel Design
 - Equipment Layout inside the RF Station
 - Vector Modulator Calibration
 - BIOS Settings Optimization
3. HALF Injector LLRF Tests
 - OPI Design of the HALF Injector LLRF System
 - High-Power Closed-loop Test

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1. Hefei Advanced Light Facility (HALF) Introduction



Main Parameters of the HALF Injector

Parameter	Value
Beam Energy [GeV]	2.2
Energy spread [‰]	2
Bunch charge [nC]	0.3~0.5
Emittance [nm·rad]	12

Hefei Advanced Light Facility - HALF

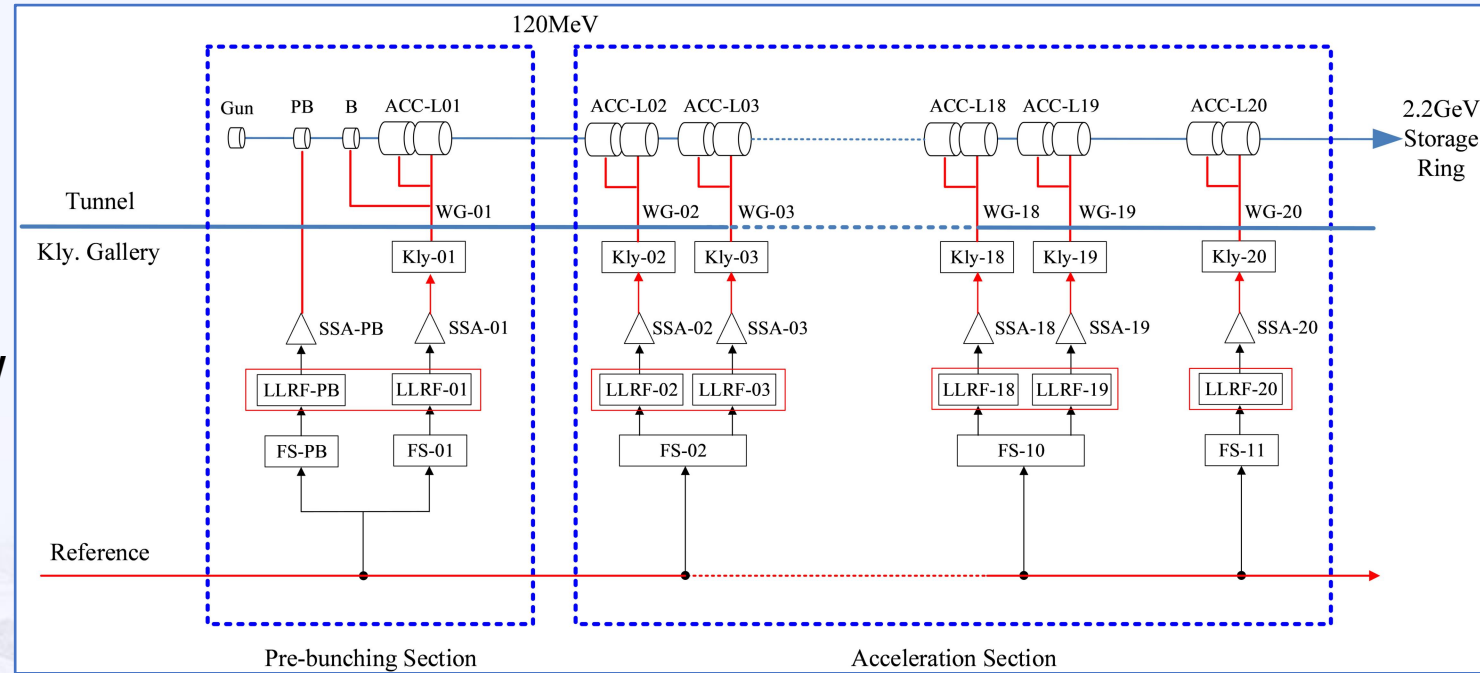
- HALF is a **fourth-generation** synchrotron radiation facility based on diffraction-limited storage ring, operating in the low-energy region (2.2 GeV).

Main Parameters of the HALF Storage Ring

Parameter	Value
Beam Energy [GeV]	2.2
Current [mA]	350
Circumference [m]	479.86
Natural emittance [pm·rad]	85.8
RF frequency [MHz]	499.8

1. HALF Injector - Microwave System Layout

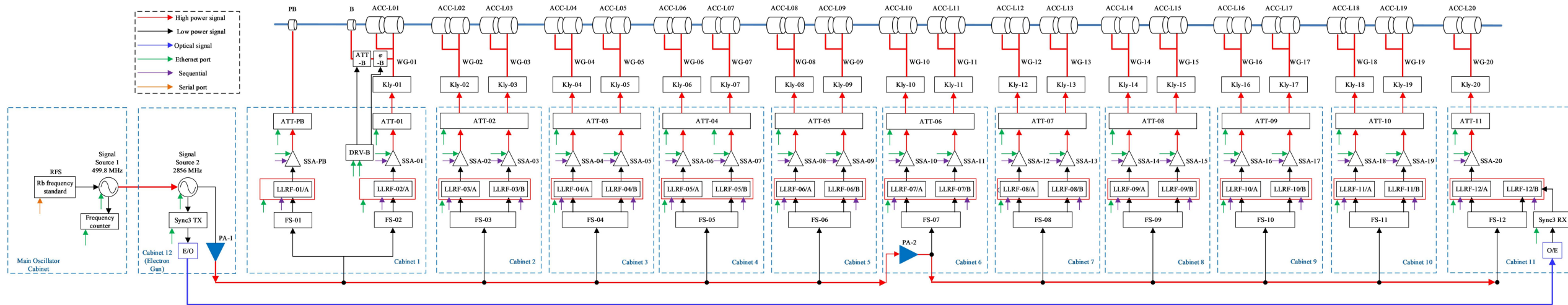
- Top-off injection with 2.2 GeV electron beam from injector
- **RF Stations: 11 units total**
- **Pre-bunching Section:**
 - Thermionic electron gun
 - 476MHz pre-buncher (PB)
 - 2856MHz buncher (B)
 - Two room-temperature 2856MHz TW accelerating structures (ACC-L01)
- **Accelerating Section:**
 - 38 room-temperature 2856MHz TW accelerating structures (19 groups)
- **LLRF System:**
 - Stabilizes amplitude/phase of microwave fields in PB, B and ACC.
 - Closed-loop stability specification:
0.2% / 0.2 ° (RMS)



HALF Injector Microwave System Layout

1. HALF Injector - Reference Signal Distribution System

RF Reference Signal Distribution System and Microwave System Layout



➤ 2856 MHz Reference Signal for Injector:

- Transmitted length: ~200 m
- Amplified by **two 10 W CW amplifiers**
- Added phase noise of amplifier : **≤ 2 fs**
- Synchronized with storage ring source via 100 MHz signal (sync cable ~ 500 m)
- Reference cable is installed in $\pm 0.1^\circ\text{C}$ constant-temperature water bath
- Optical synchronization systems at injector entry & exit for drift monitoring

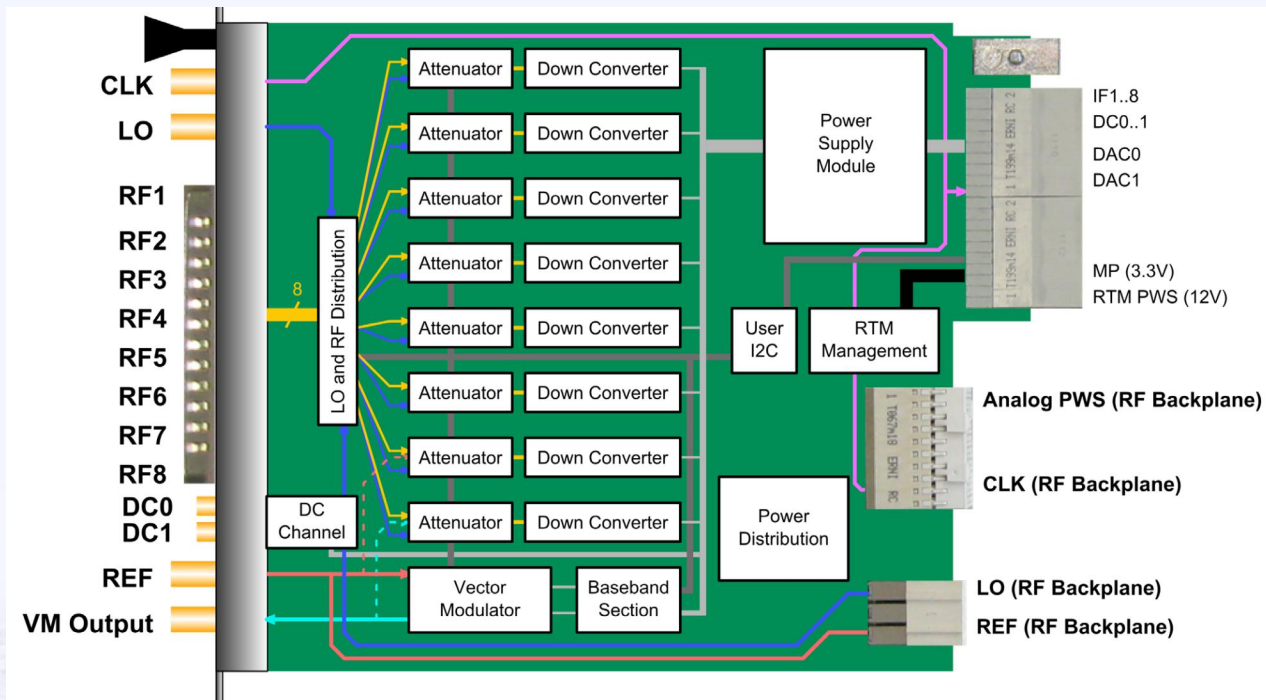


Overview

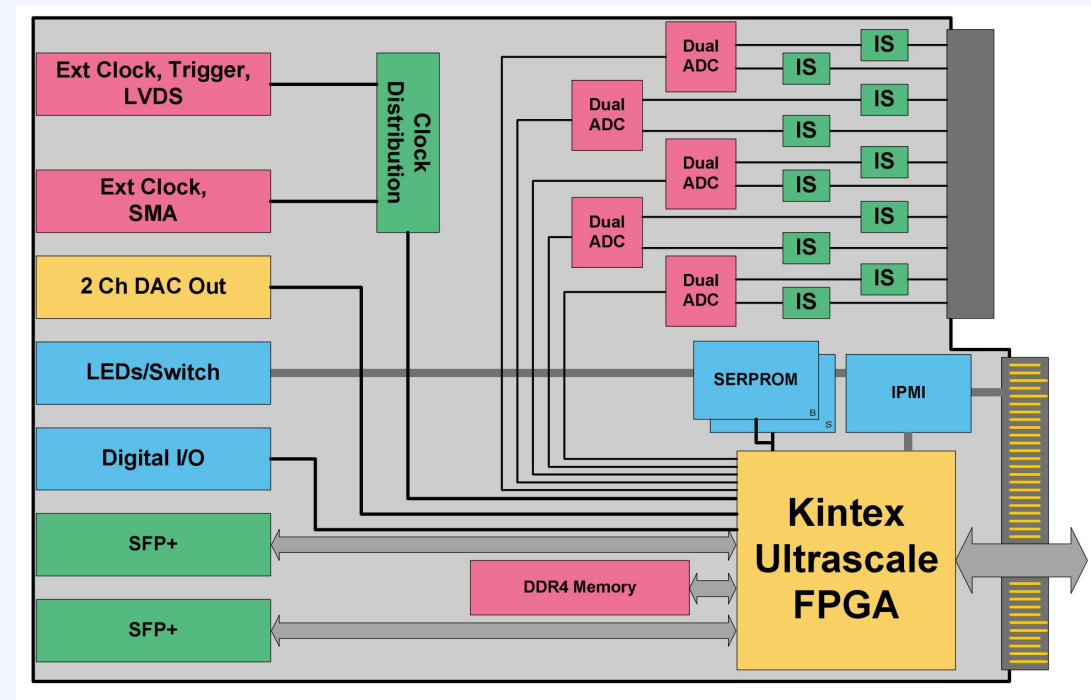
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2. LLRF - Hardware Composition

MTCA.4 RF Board (DWC8VM1)



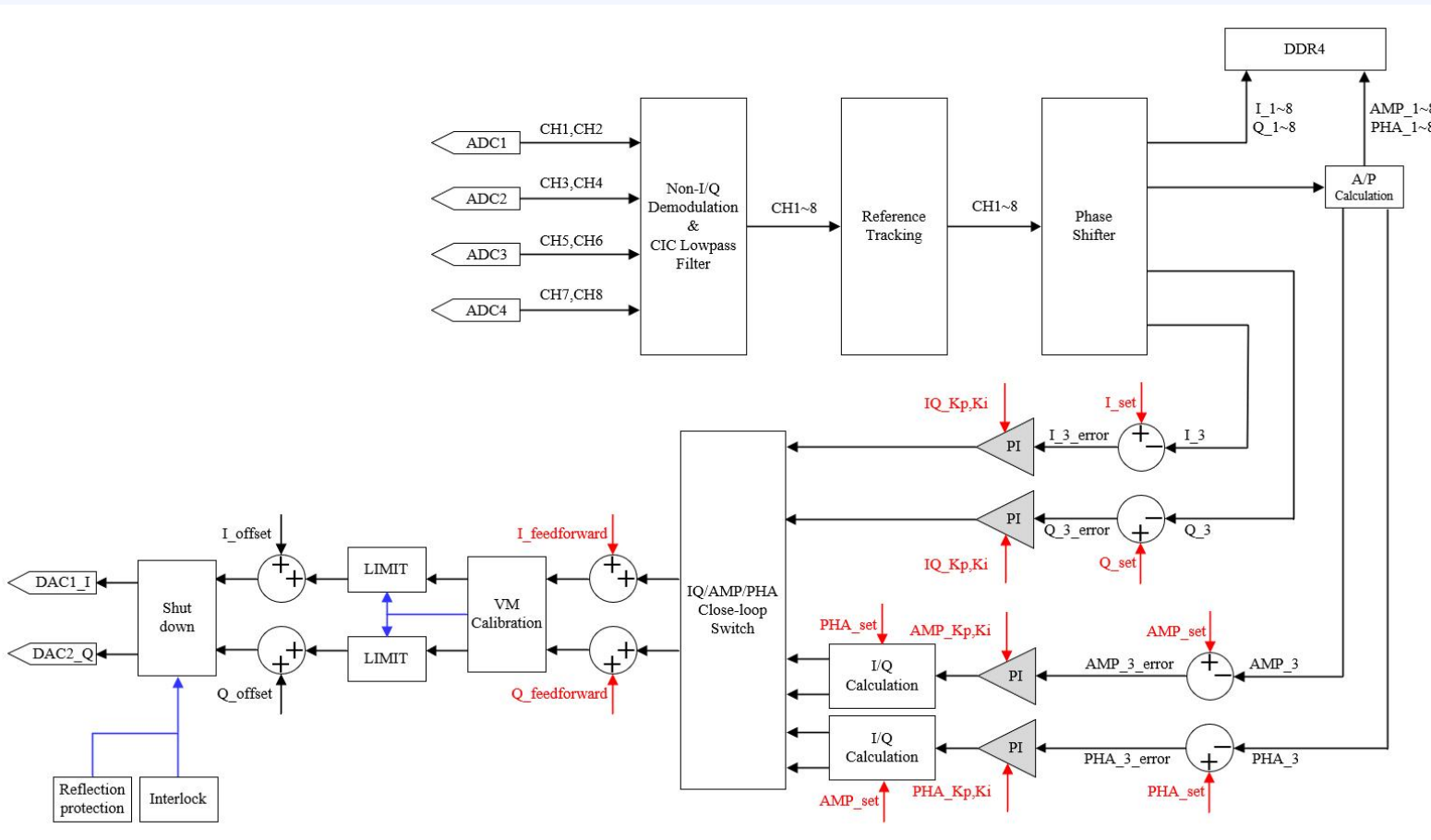
MTCA.4 Digital Board (SIS8300-KU)



➤ Commercial MTCA.4 boards (Struck Innovative Systeme)

- **RF Board:** 8 ch microwave attenuation & down-conversion, 1 ch vector modulator (VM) output (2856/476 MHz), 2 ch DC signal inputs
- **Digital Board:** 10×16-bit ADC, 2×16-bit DAC, 1 FPGA, DDR4 data buffer

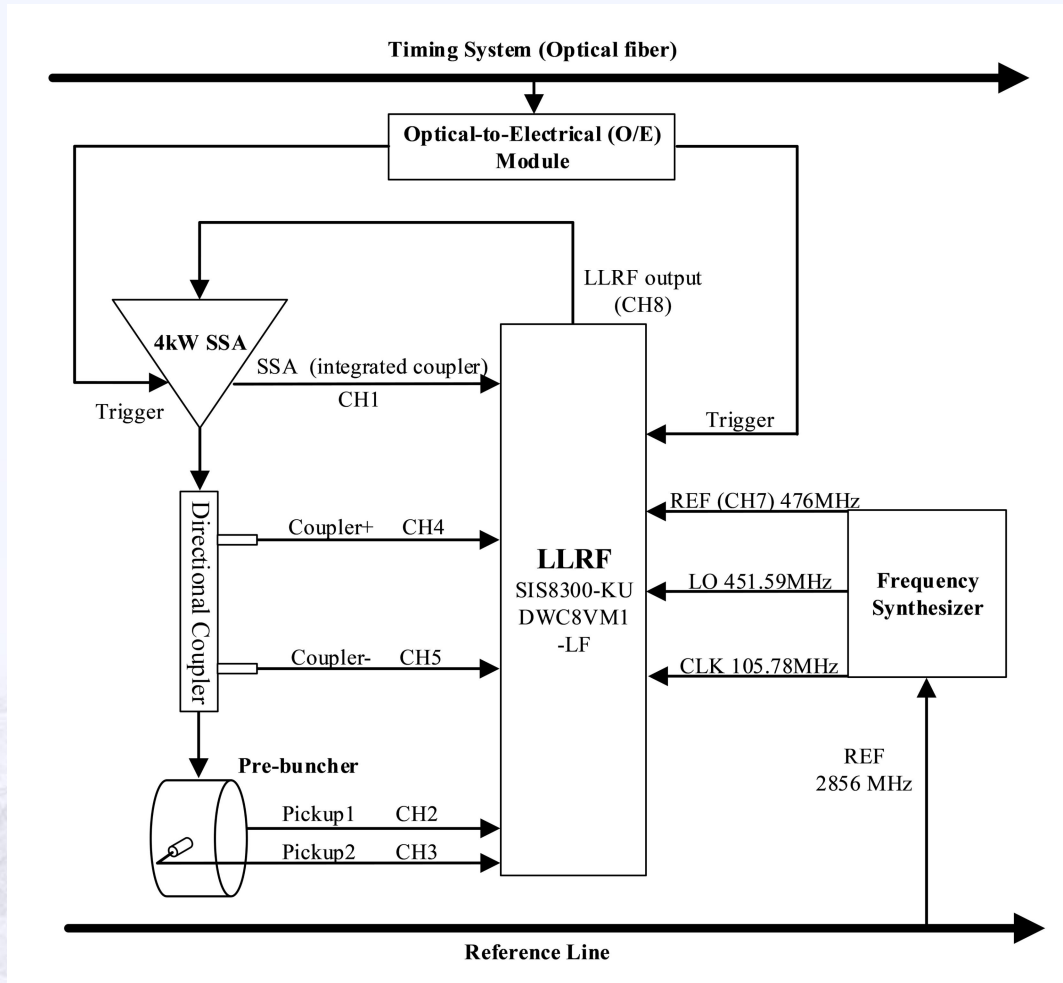
2. LLRF - FPGA Algorithm Architecture



FPGA Algorithm Architecture

- **13/3 Non-I/Q Demodulation:** IF 2856/117=24.410 MHz; CLK 2856/27=105.778 MHz
- **CIC Filtering:** Conserve FPGA resources while reducing high-frequency noise
- **Reference Tracking:** Reduce the phase drift of the acquisition channel relative to the reference signal caused by temperature variations
- **Feedback:** Based on I/Q or independent amplitude-phase feedback (online switchable)

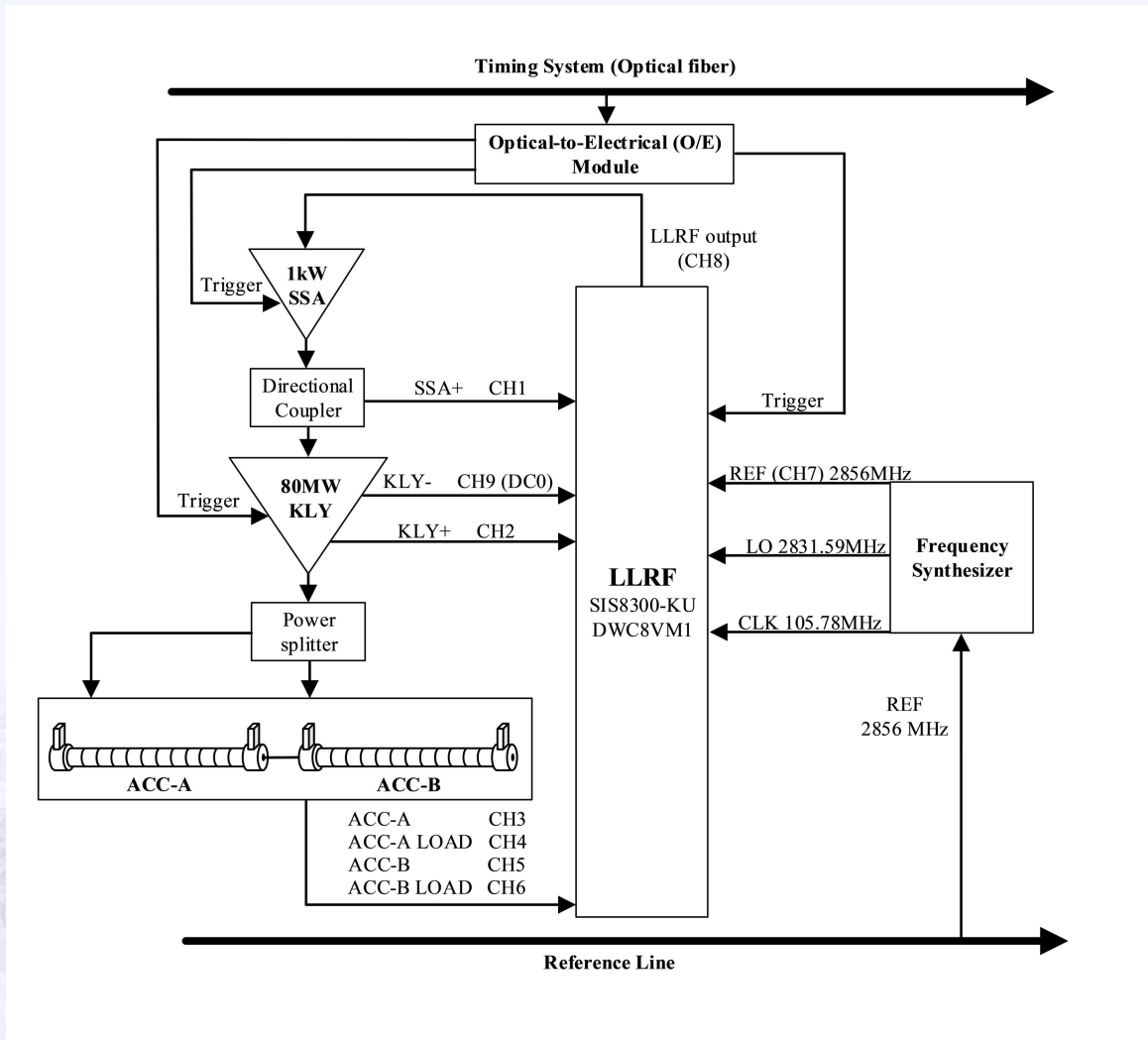
2. LLRF Installation – prebuncher LLRF acquisition channel design



RF Station Block Diagram

- **RF Driving Chain:**
 - 1 **LLRF** system + 1 4kW solid-state amplifier (**SSA**) + 1 pre-buncher (476MHz, **PB**)
- **LLRF Monitoring** (7 channels):
 - Solid-state amplifier forward output (integrated coupler)
 - Directional Coupler forward/reverse
 - 2 pickup channels on the pre-buncher (different coupling coefficient)
 - **Control signal:** pre-buncher pickup **OR** directional coupler forward (SSA output)
- **Frequency Synthesizer:**
 - Accepts injector reference signal
 - Provides **REF/LO/CLK** signals to LLRF

2. LLRF Installation – TW ACC LLRF acquisition channel design



RF Station Block Diagram

➤ RF Driving Chain:

- 2 **LLRF** system + 2 1kW solid-state amplifier (**SSA**) + 1 80MW Klystron (**KLY**) + 2 TW accelerating structures (2856MHz, **ACC**)

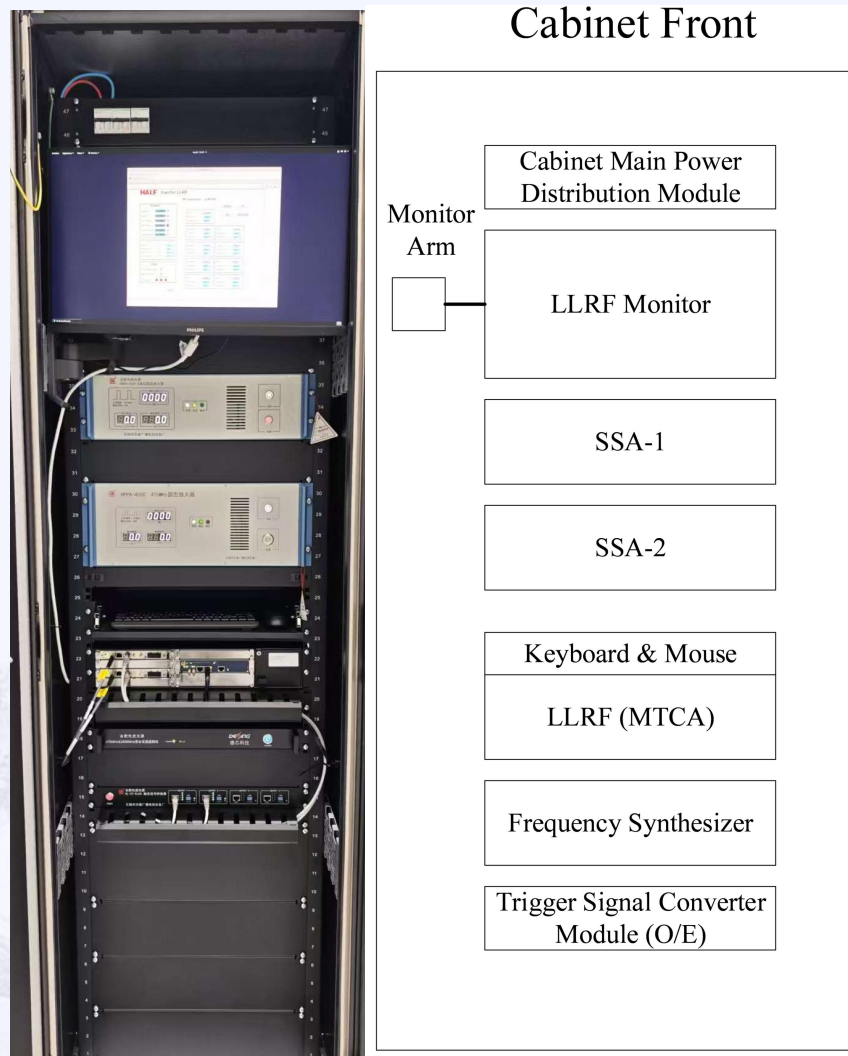
➤ LLRF Monitoring (9 channels, incl. 1 DC signal):

- Solid-state amplifier (**SSA**) forward output
- **KLY** forward/reverse (DC, for reflection protection)
- Forward inputs of 2 **ACCs**
- Forward inputs of terminal **loads** of 2 **ACCs**
- **Control signal**: Forward input of 1st **ACC** **OR** vector sum of both tubes

➤ Frequency Synthesizer:

- Accepts injector reference signal
- Provides **REF/LO/CLK** signals to LLRF

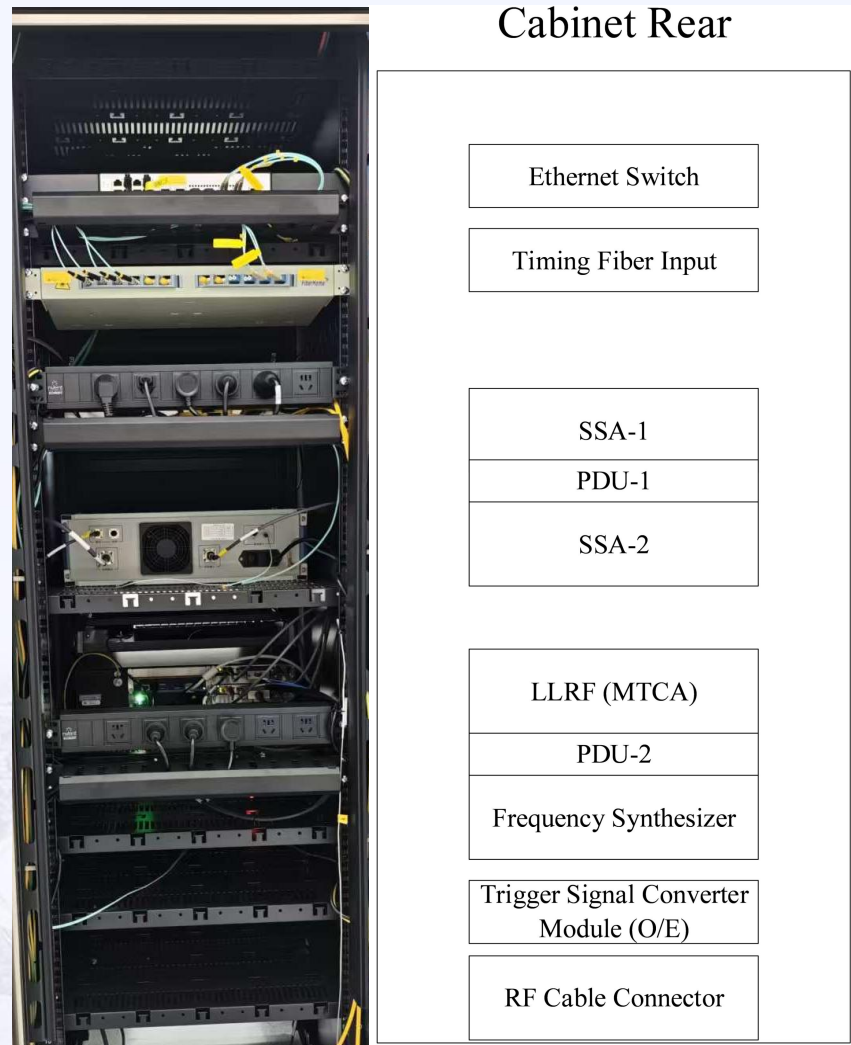
2. LLRF Installation – Equipment Layout inside the RF Station



- **Each RF Station:**
 - 1 MTCA chassis
 - 2 solid-state amplifiers
 - 1 frequency synthesizer
 - 1 Trigger Signal Converter Module (O/E)
- **MTCA Chassis:**
 - 2U MTCA.4 chassis
 - 2 LLRF systems (SIS8300-KU & DWC8VM1)
- **Cable Routing:**
 - RF cables between equipment are routed on both sides of the cabinet

RF Station Equipment Layout (Front)

2. LLRF Installation – Equipment Layout inside the RF Station



RF Station Equipment Layout (Rear)



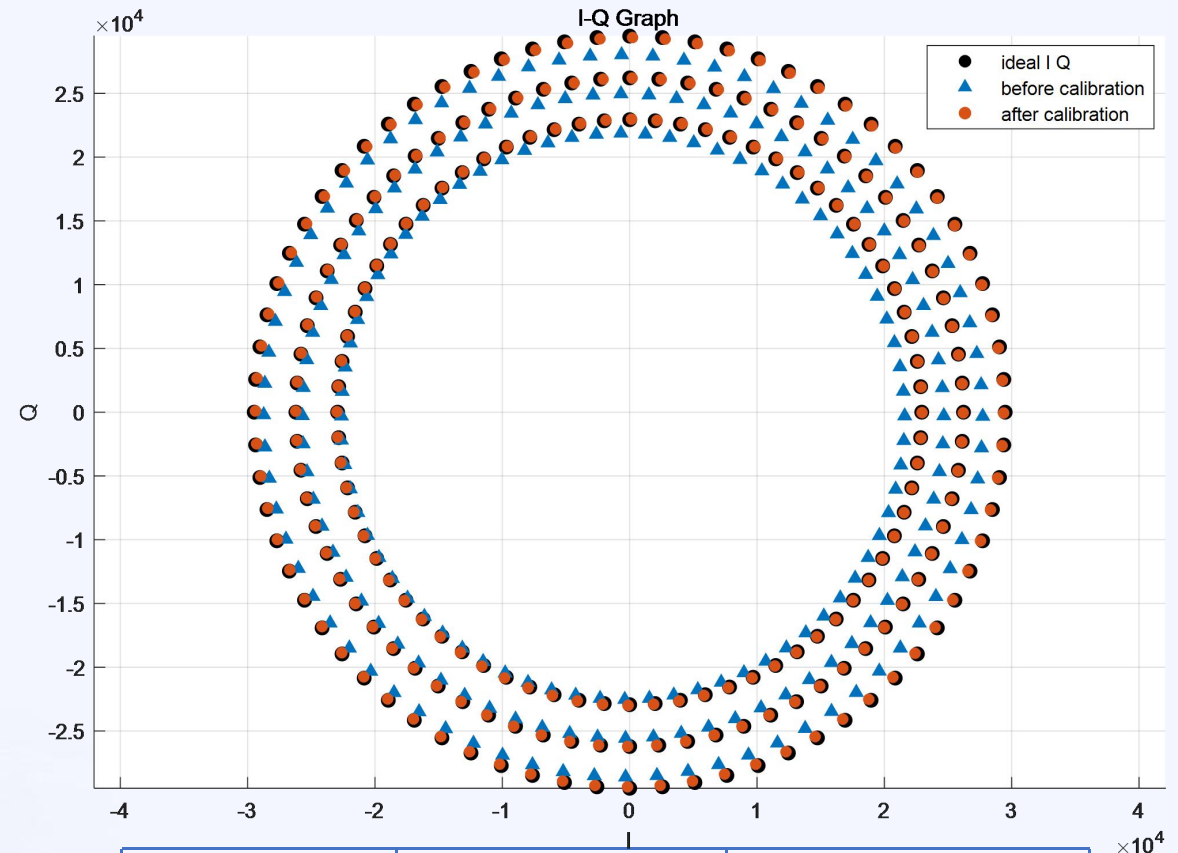
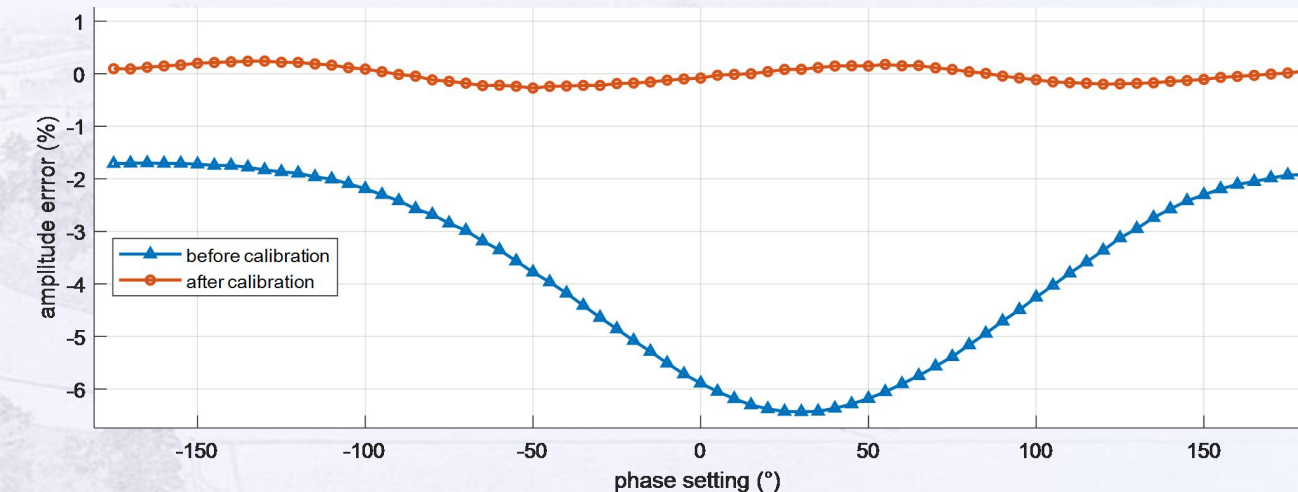
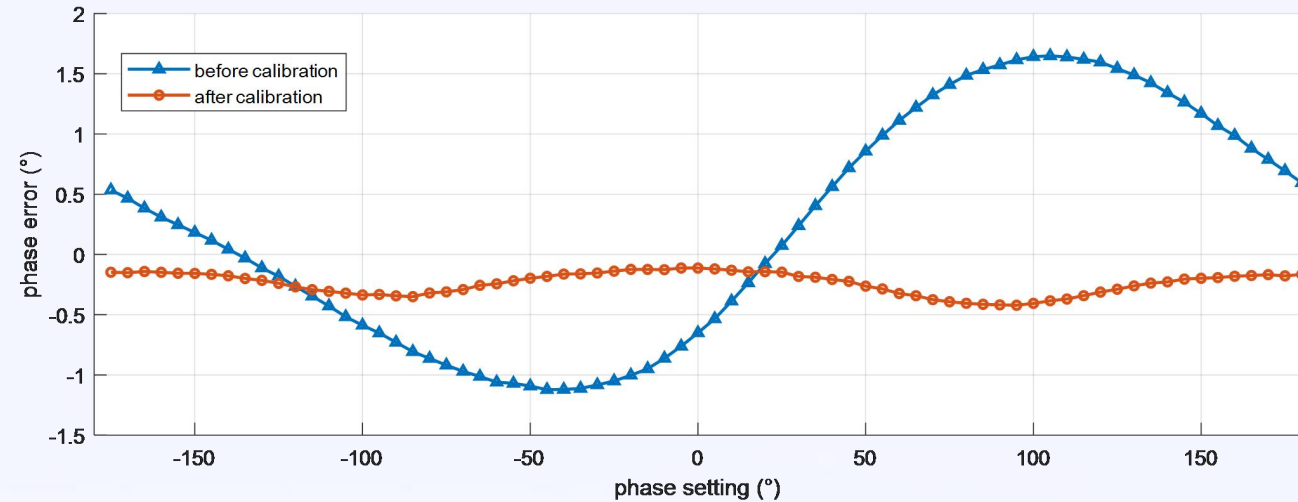
RF Cable Connector

- **Power Supply:**
 - 1 main power distribution module at the top of the cabinet interior
 - 2 PDUs at the center of the cabinet rear
- **Cable Routing:**
 - Accepts reference and acquisition channel from the bottom of cabinet rear

2. LLRF Optimization – Vector Modulator Calibration

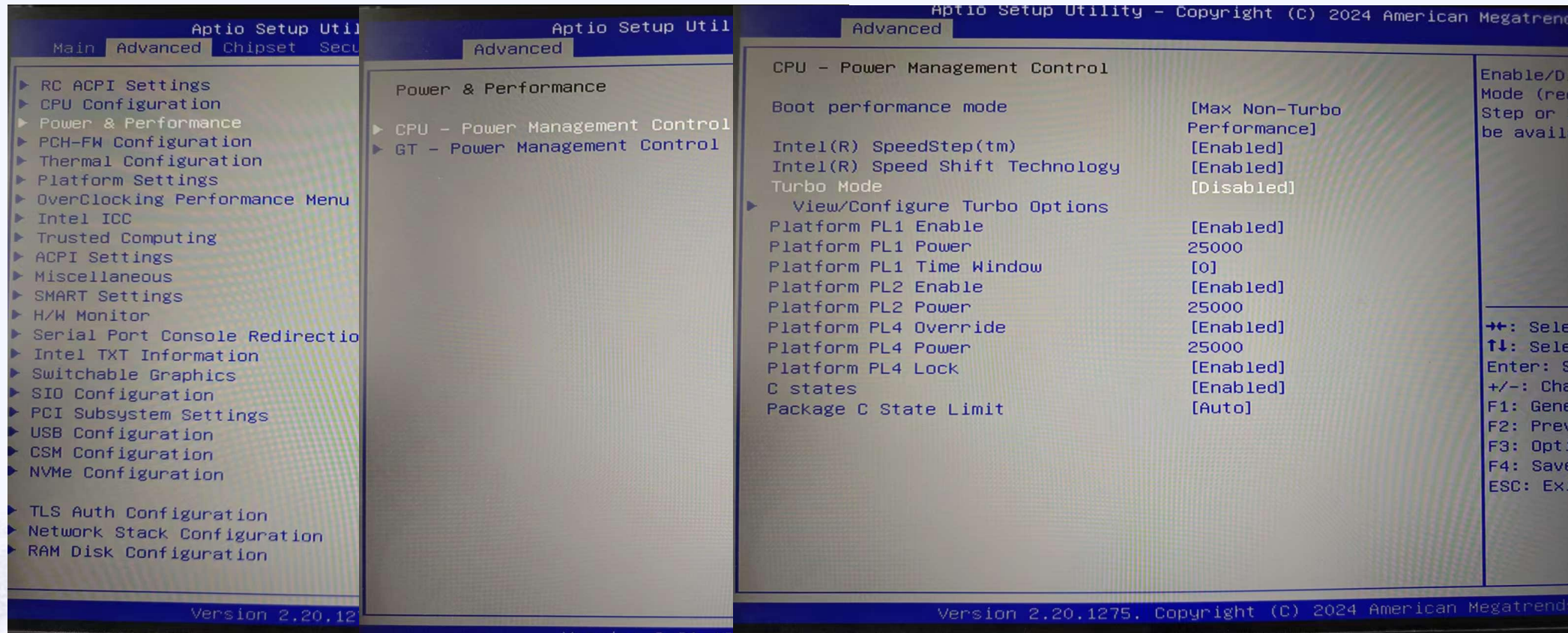
➤ Vector Module Calibration:

- Phase scan from -179° to 180°



	Before VM Calibration	After VM Calibration
Amplitude Variation (%)	4.73	0.51
Phase Variation ($^\circ$)	2.77	0.31

2. LLRF Optimization – BIOS Settings Optimization

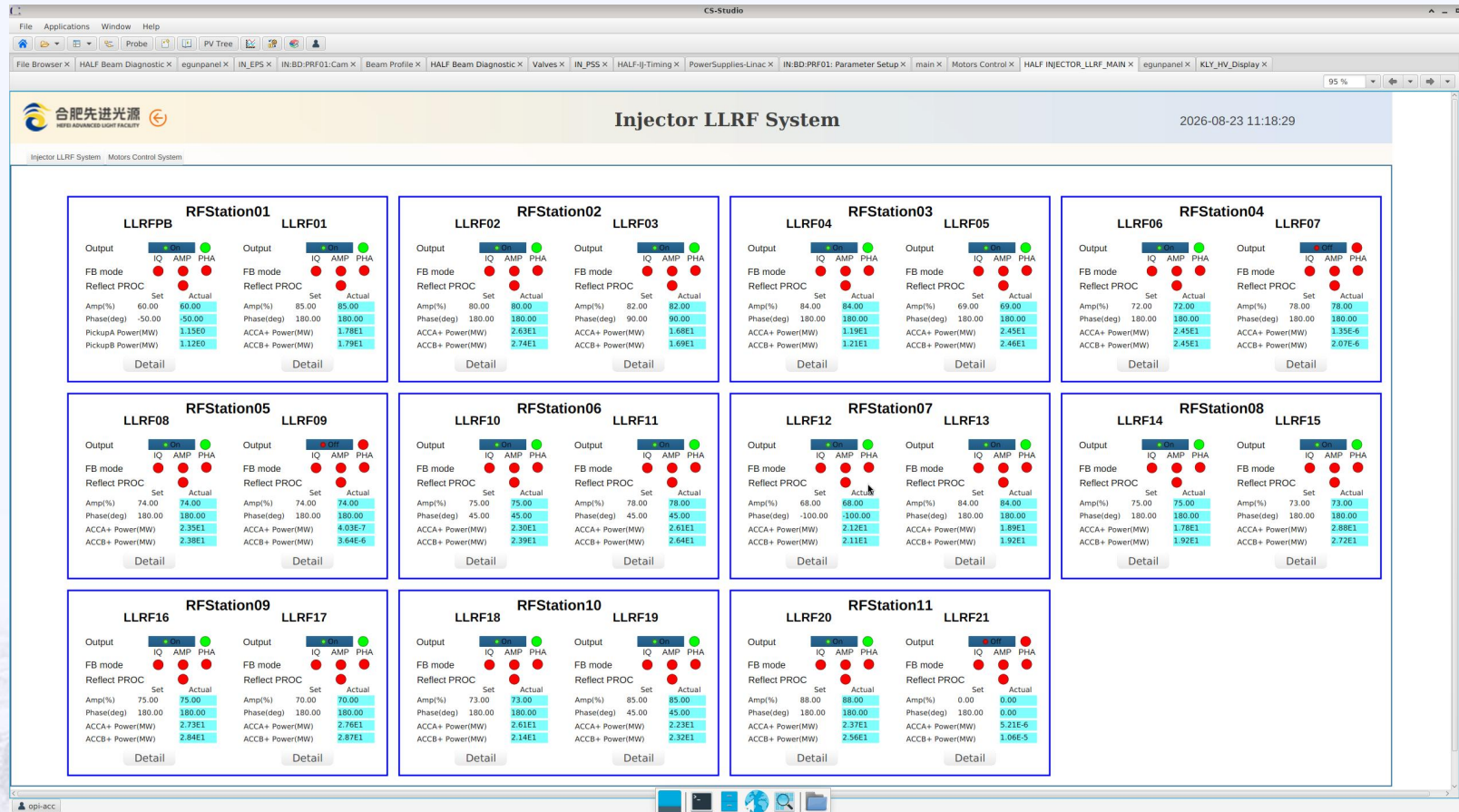


- **Problem:**
 - Within one week, 4 of the 11 MTCA CPU modules crashed (Debian 11)
- **Solution:**
 - **Disable** Advanced/Power & Performance/CPU – Power Management Control/Turbo Mode

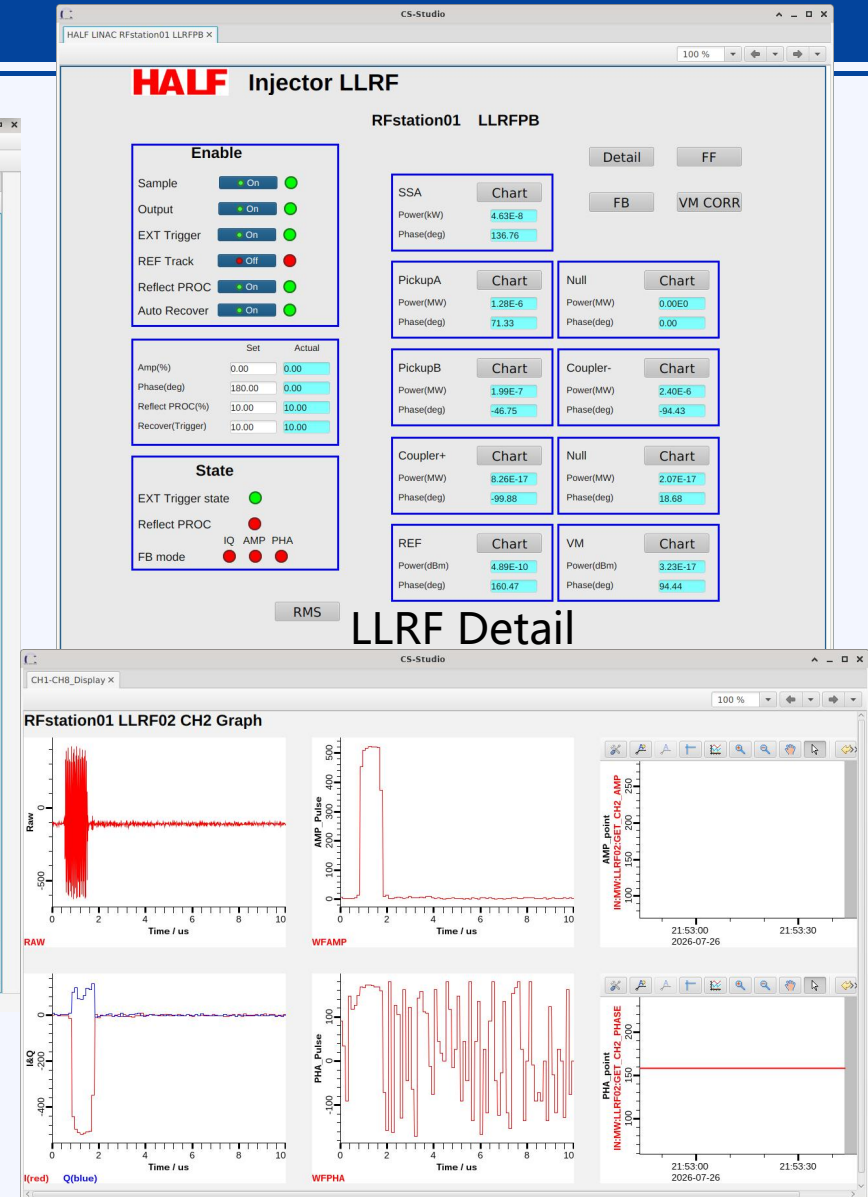
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3. LLRF Test – OPI Design



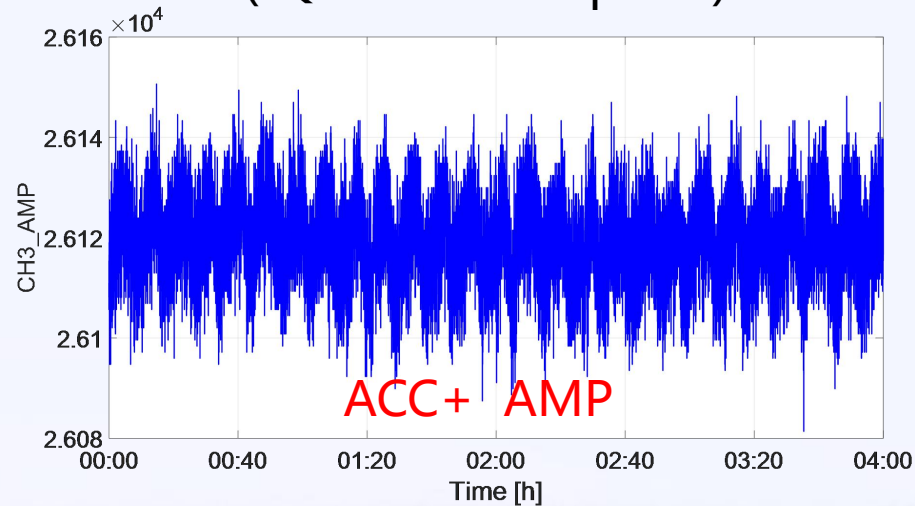
HALF Injector LLRF Main Panel (Phoebus)



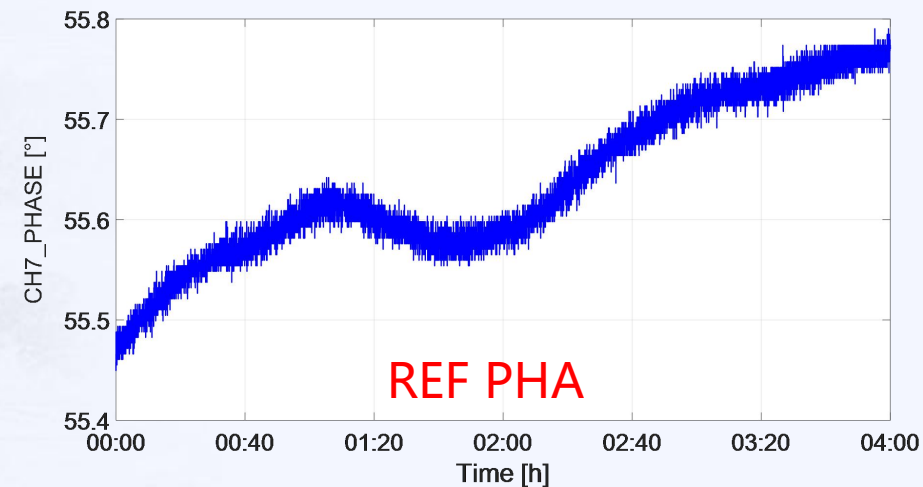
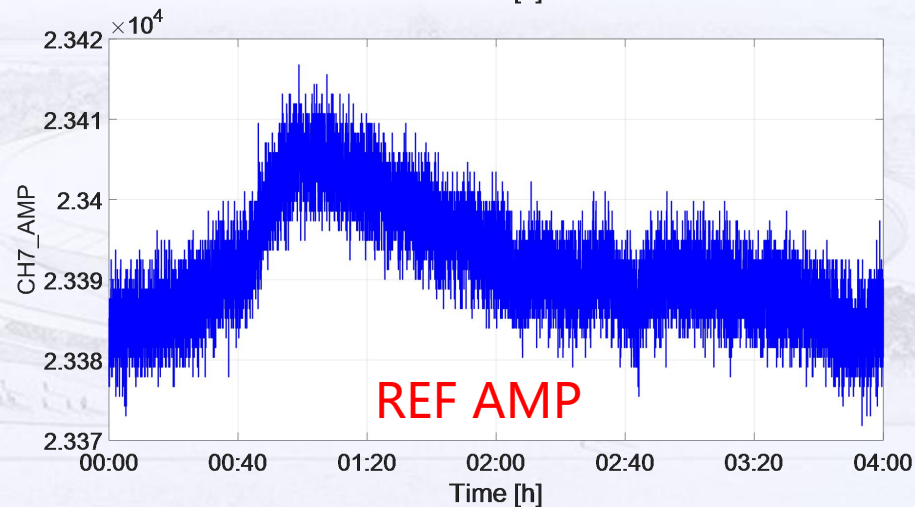
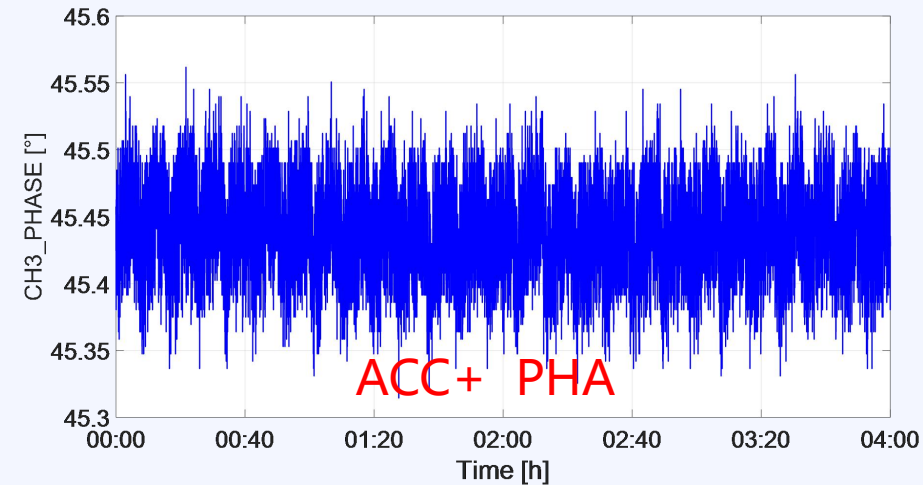
LLRF Channel Graph

3. LLRF Test - High Power Closed-loop Test

HALF Auto-conditioning Platform (ATCP)
High Power Closed-Loop Test (with Klystron)
(IQ Closed-Loop- 4h)

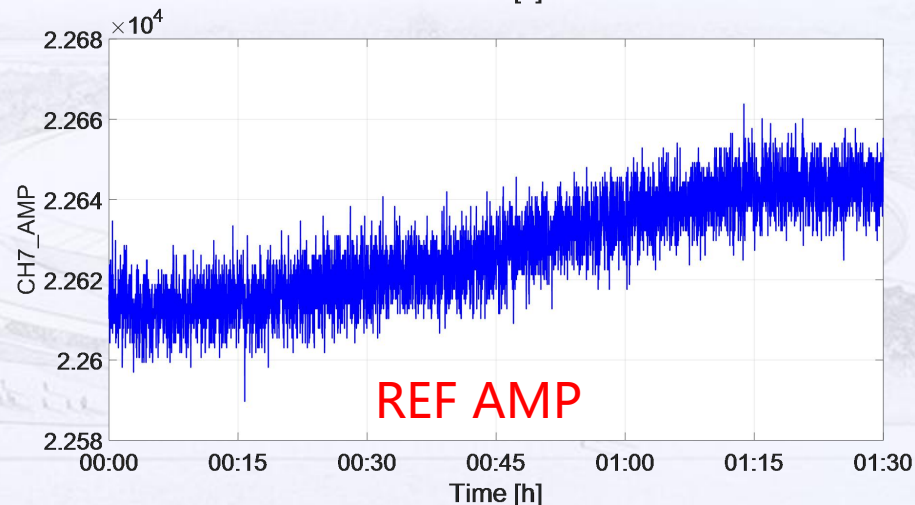
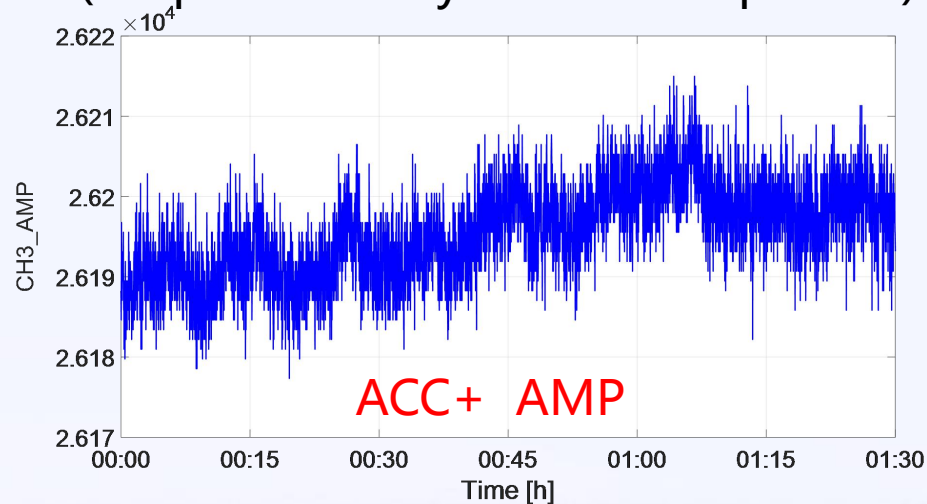


ACC+ AMP: 0.035% (RMS) , PHA: 0.035° (RMS)
REF AMP: 0.030% (RMS) , PHA: 0.079° (RMS)



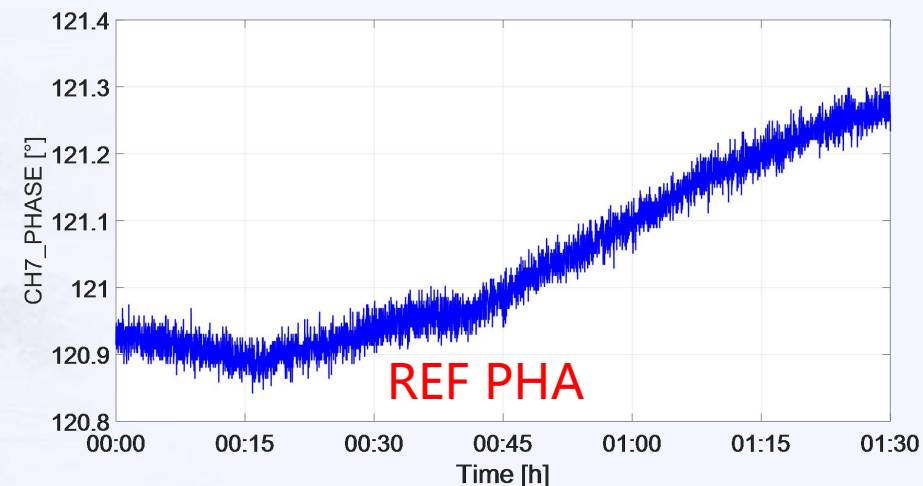
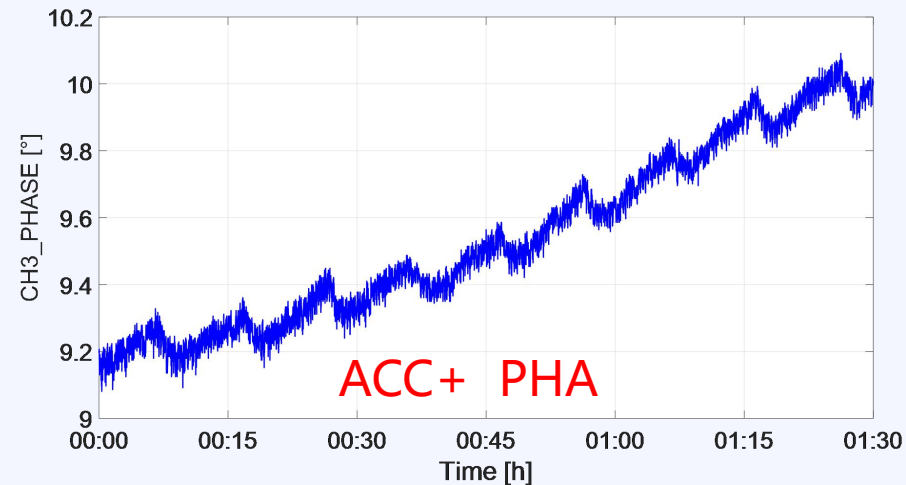
3. LLRF Test - High Power Closed-loop Test

HALF Auto-conditioning Platform (ATCP)
High Power Closed-Loop Test (with Klystron)
(Amplitude-Only Closed-Loop- 1.5h)



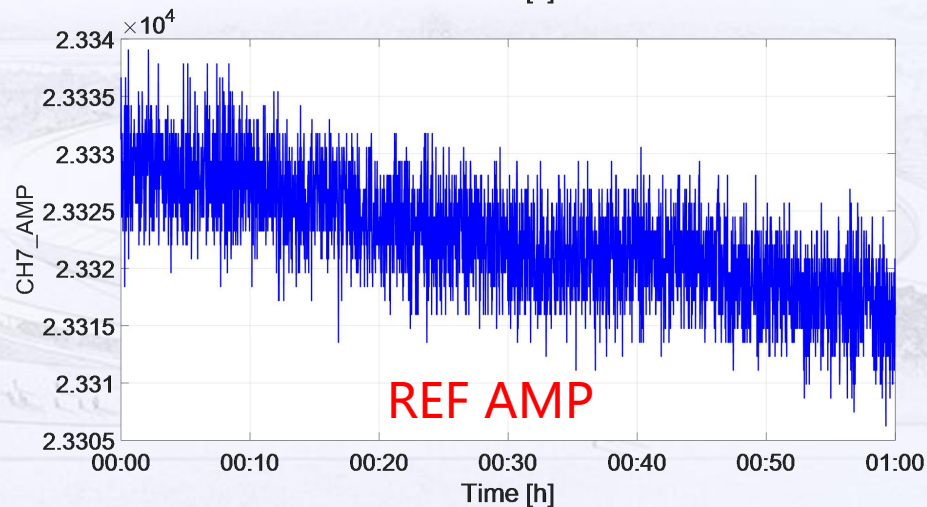
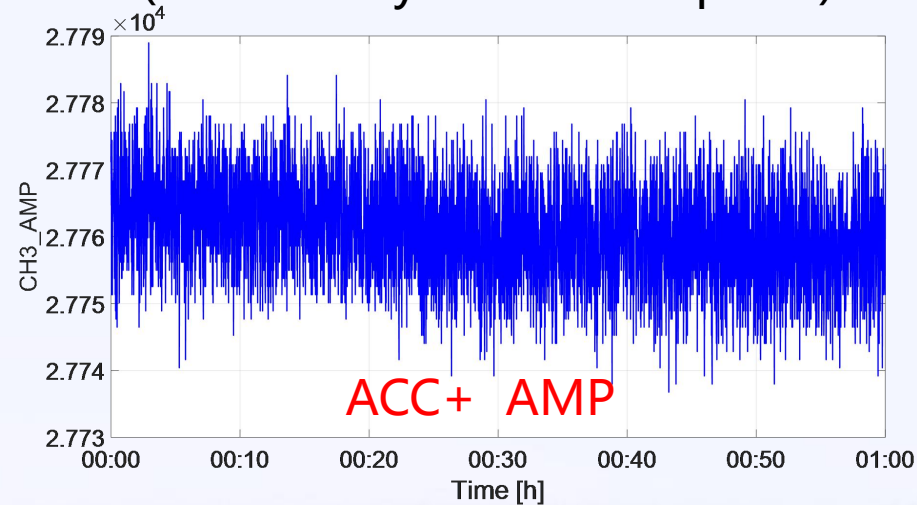
ACC+ AMP: 0.022% (RMS) , PHA: 0.264° (RMS)

REF AMP: 0.056% (RMS) , PHA: 0.126° (RMS)



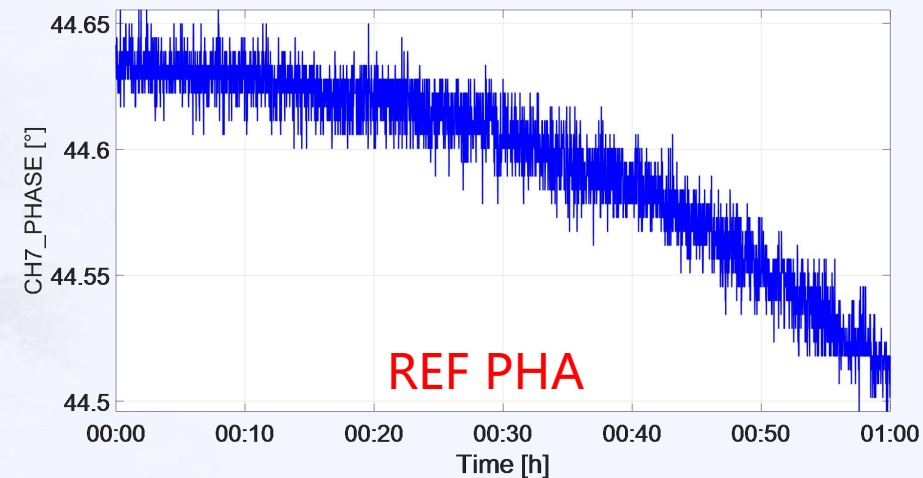
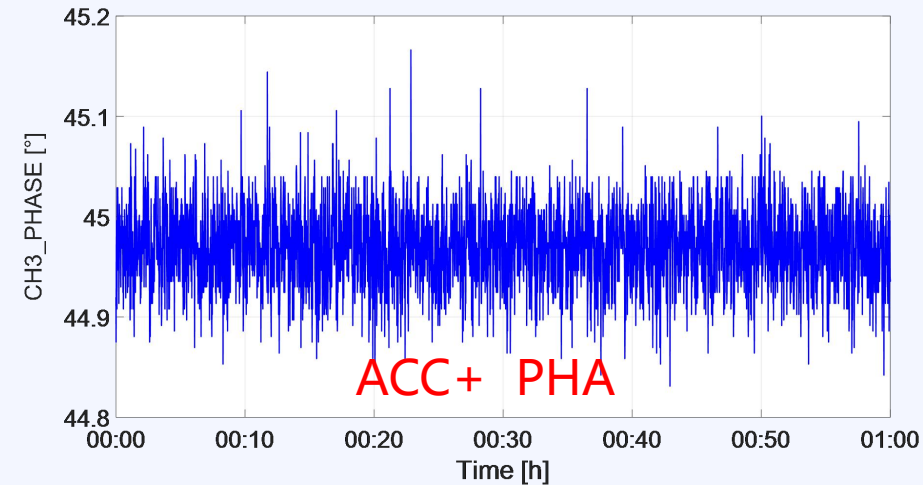
3. LLRF Test - High Power Closed-loop Test

HQES Platform
High-Power Closed-Loop Test (with Klystron)
(Phase-Only Closed-Loop- 1h)



ACC+ AMP: **0.029%** (RMS) , PHA: **0.038°** (RMS)

REF AMP: 0.022% (RMS) , PHA: 0.036° (RMS)



3. LLRF Test - High Power Closed-loop Test

➤ Test Platform: HALF ATCP

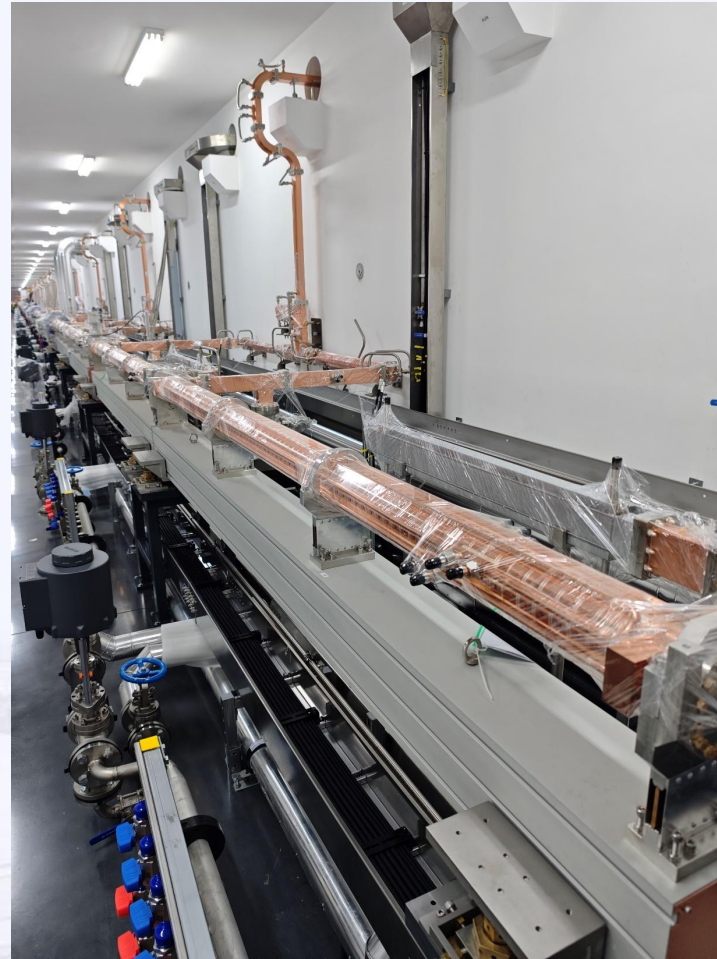
Closed-Loop Type	Stability	Value
IQ	Amplitude Stability AMP /% (RMS)	0.035
	Phase Stability PHA /° (RMS)	0.035
Amplitude-Only	Amplitude Stability AMP /% (RMS)	0.022
	Phase Stability PHA /° (RMS)	0.264

➤ Test Platform: HQES

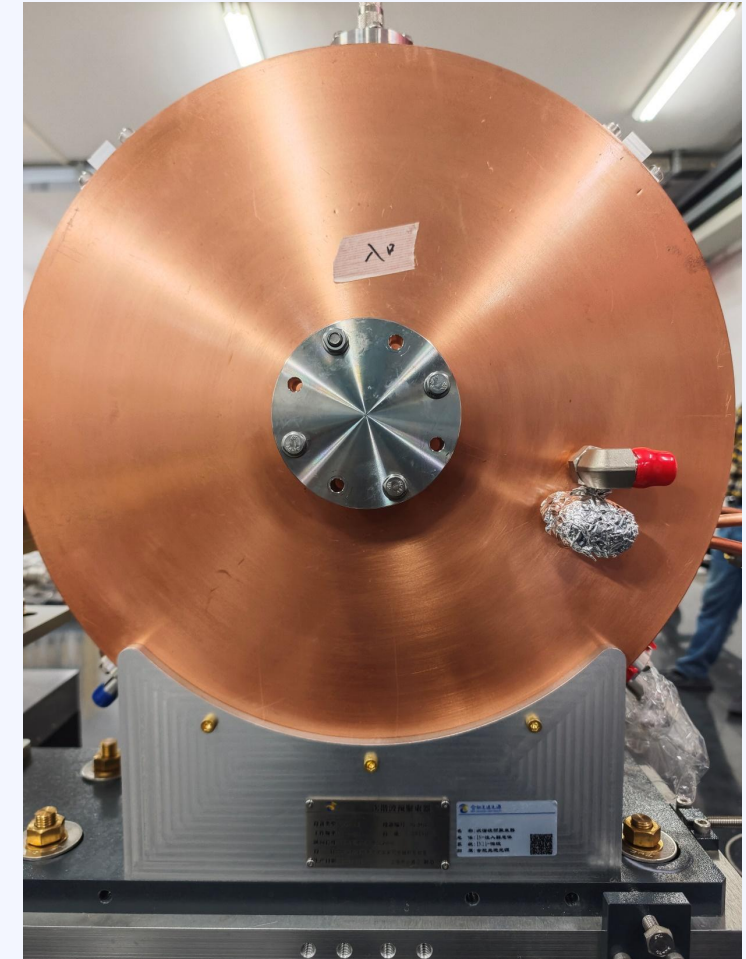
Closed-Loop Type	Stability	Value
Phase-Only	Amplitude Stability AMP /% (RMS)	0.029
	Phase Stability PHA /° (RMS)	0.038



HALF Injector Klystron Gallery



HALF TW Accelerating Structures



HALF Injector pre-buncher

**Thanks to Baiting DU and Kunlin WU for their contributions
to the HALF injector LLRF system.**





HEFEI ADVANCED LIGHT FACILITY

合肥先进光源

Thanks for your attention!

