The progress of LLRF control system for SC linac in IMP

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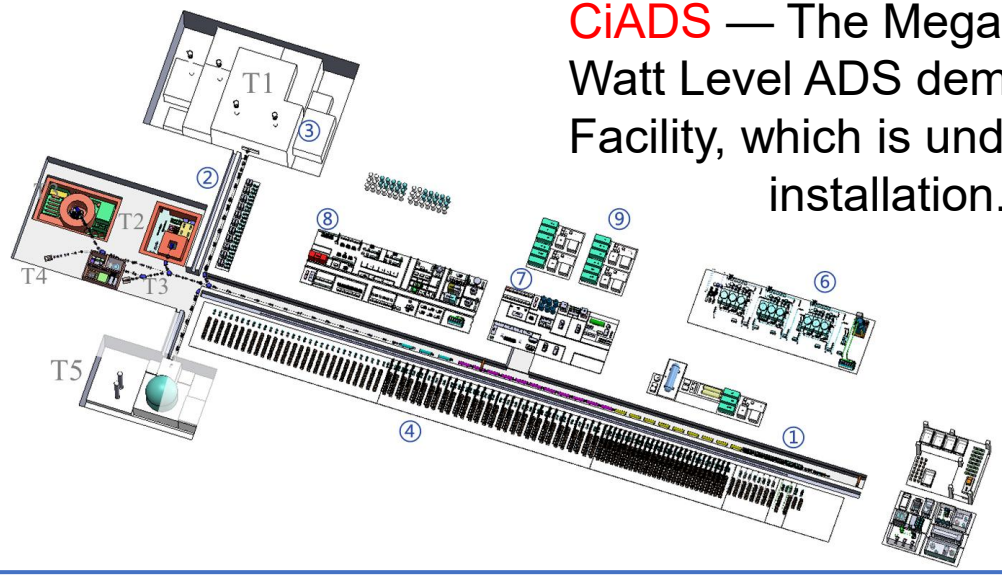
On behalf of IMP Linac LLRF group

Institute of Modern Physics, CAS

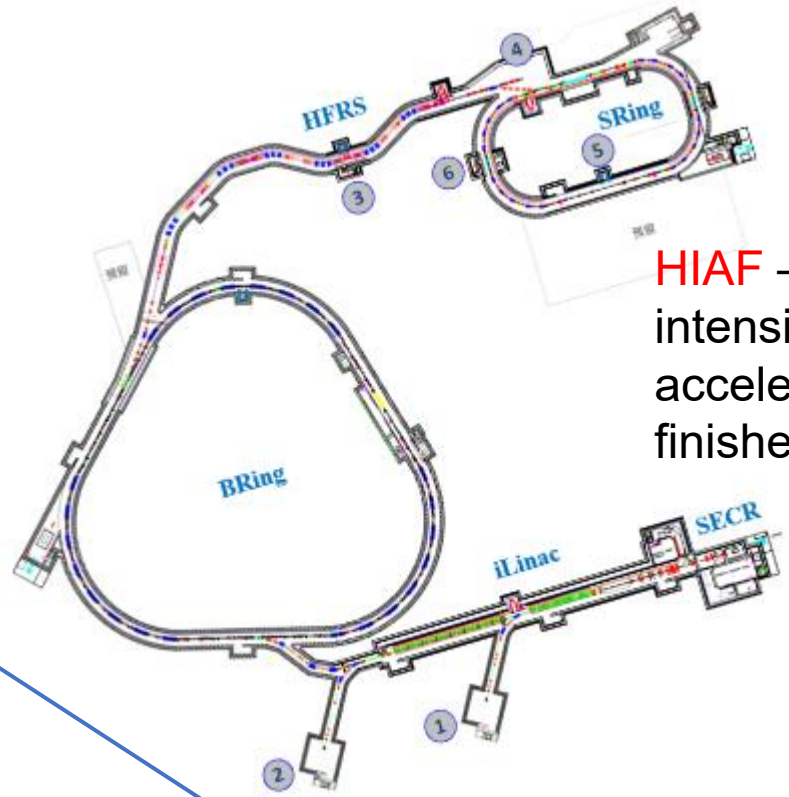
Content

- The superconducting iLinac of HIAF in IMP
- The RF reference distribution system for SC linac
- The new digital LLRF control system hardware
- The white rabbit timing integration with LLRF
- The installation and commissioning status

The SC Linac In IMP



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



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

CAFE2:

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

Start Operation in 2021

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.

The Superconducting iLinac of HIAF

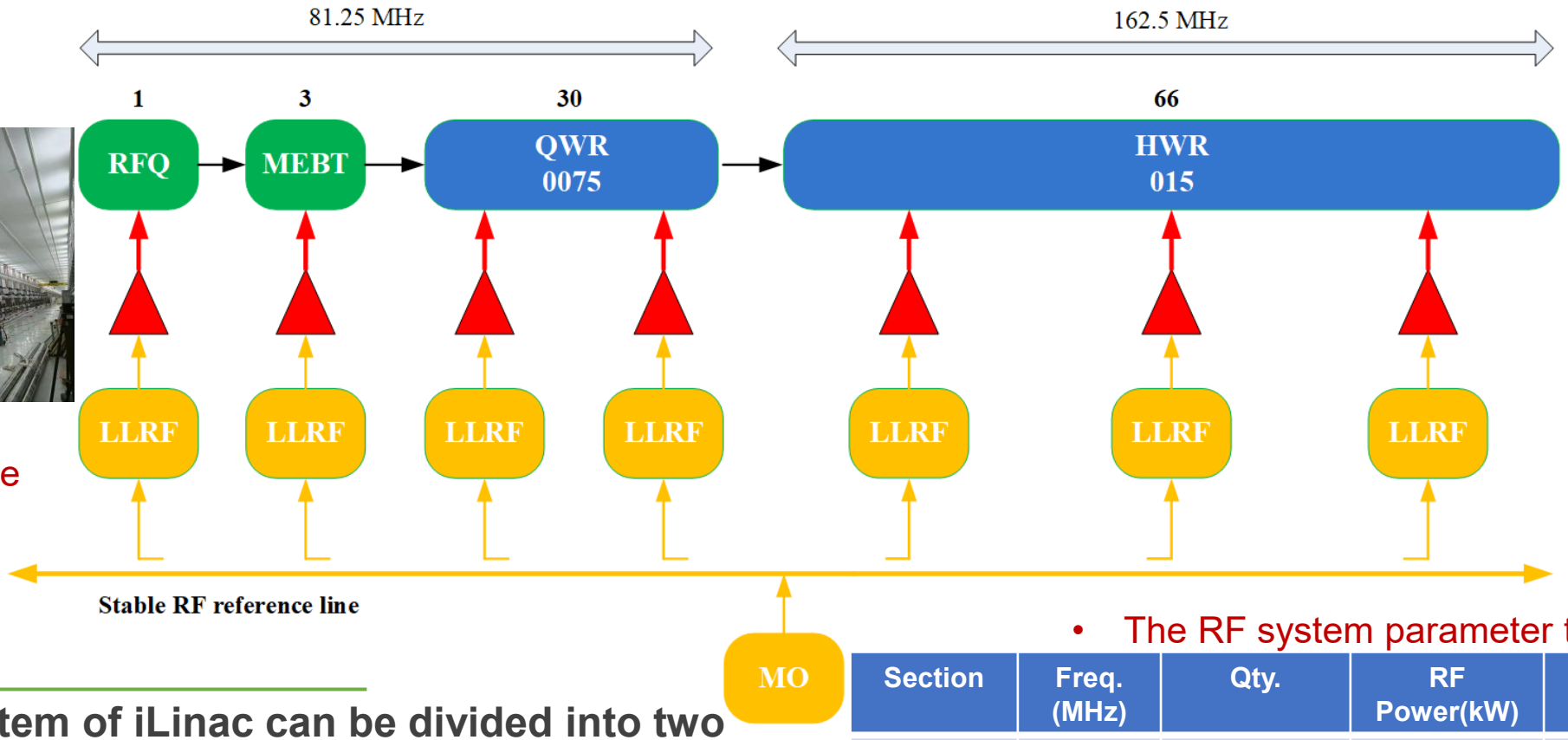
HIAF iLinac parameter table

Design Parameters	Design Specification	Unit
Particle（q/A）	1/2 ~ 1/7	
Beam Energy(U^{35+})	17	MeV/U
Beam Current	2	mA
RF Frequency	81.25/162.5	MHz
iLinac Length	115	m

- The HIAF iLinac tunnel

The RF System Layout of HIAF iLinac

The RF power transmission line



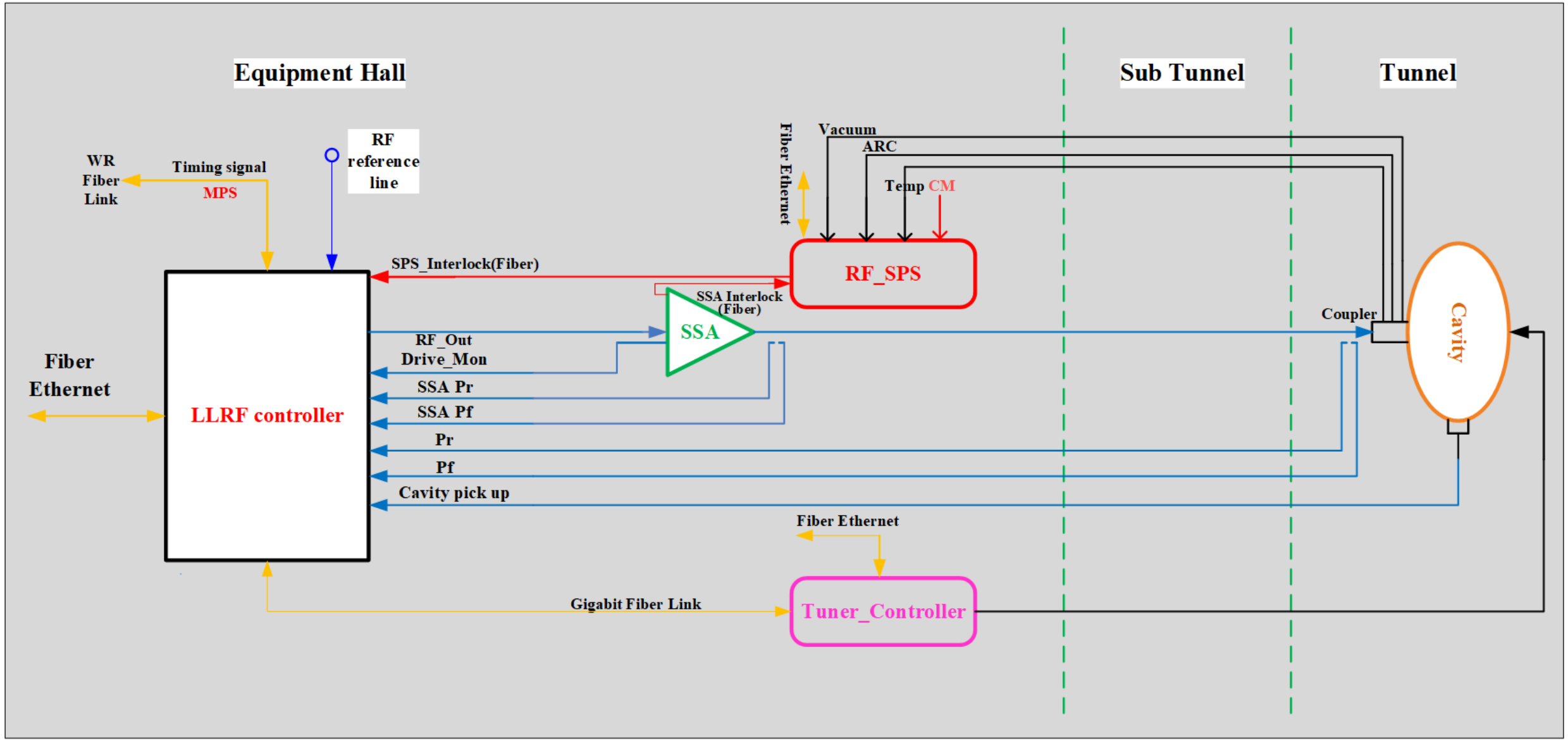
The SSA rack

- 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 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 diagram of LLRF Control for One RF Station



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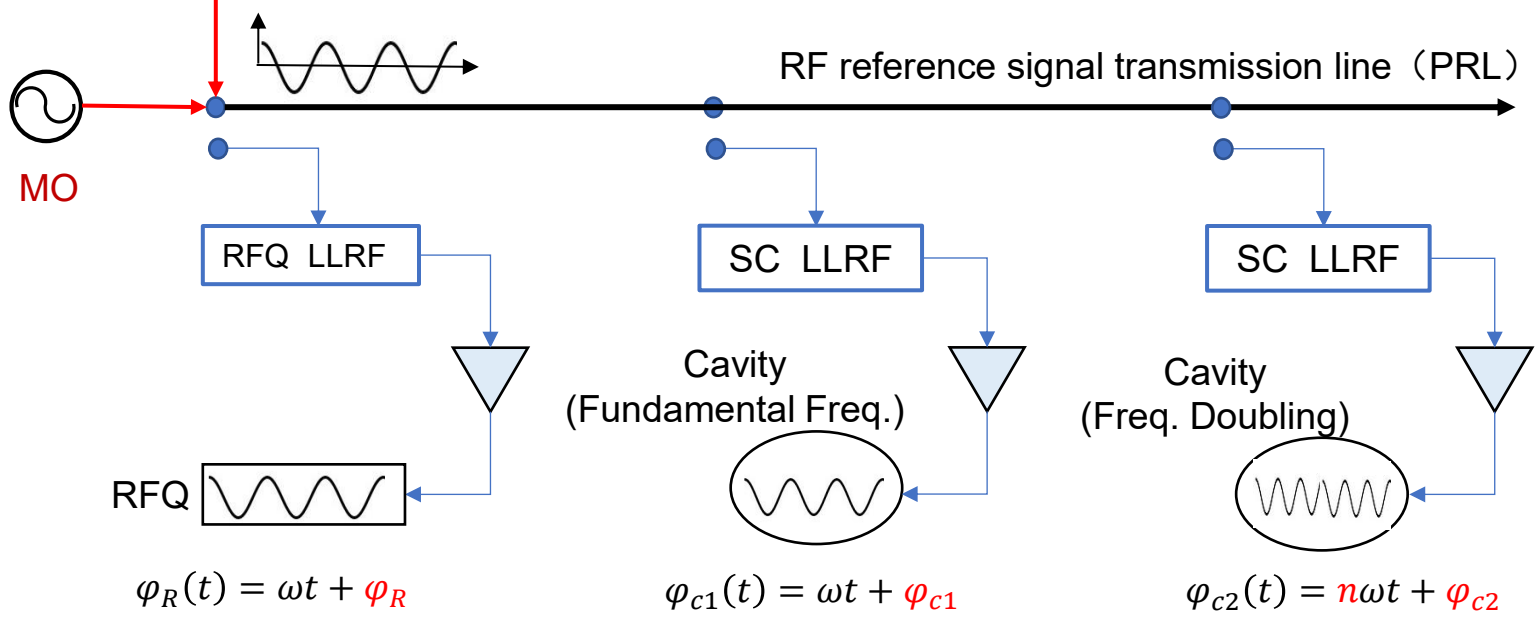
The RF Reference Phase Distribution System for SC Linac

The reference point of time and phase frame $\varphi_0(t) = \omega t$



Beam passes through RFQ to form a bunch, The relative phase of RFQ to the RF reference is φ_R, the relative phase of each cavity is φ_c

! To guarantee that the beam is effectively accelerated through each cavity：

The phase of each cavity φ_c maintain stable with the RF reference

RF phase of each cavity φ_c keep constant with phase of RFQ φ_R

$$\varphi_{C-R} = \varphi_C - n\varphi_R = const$$

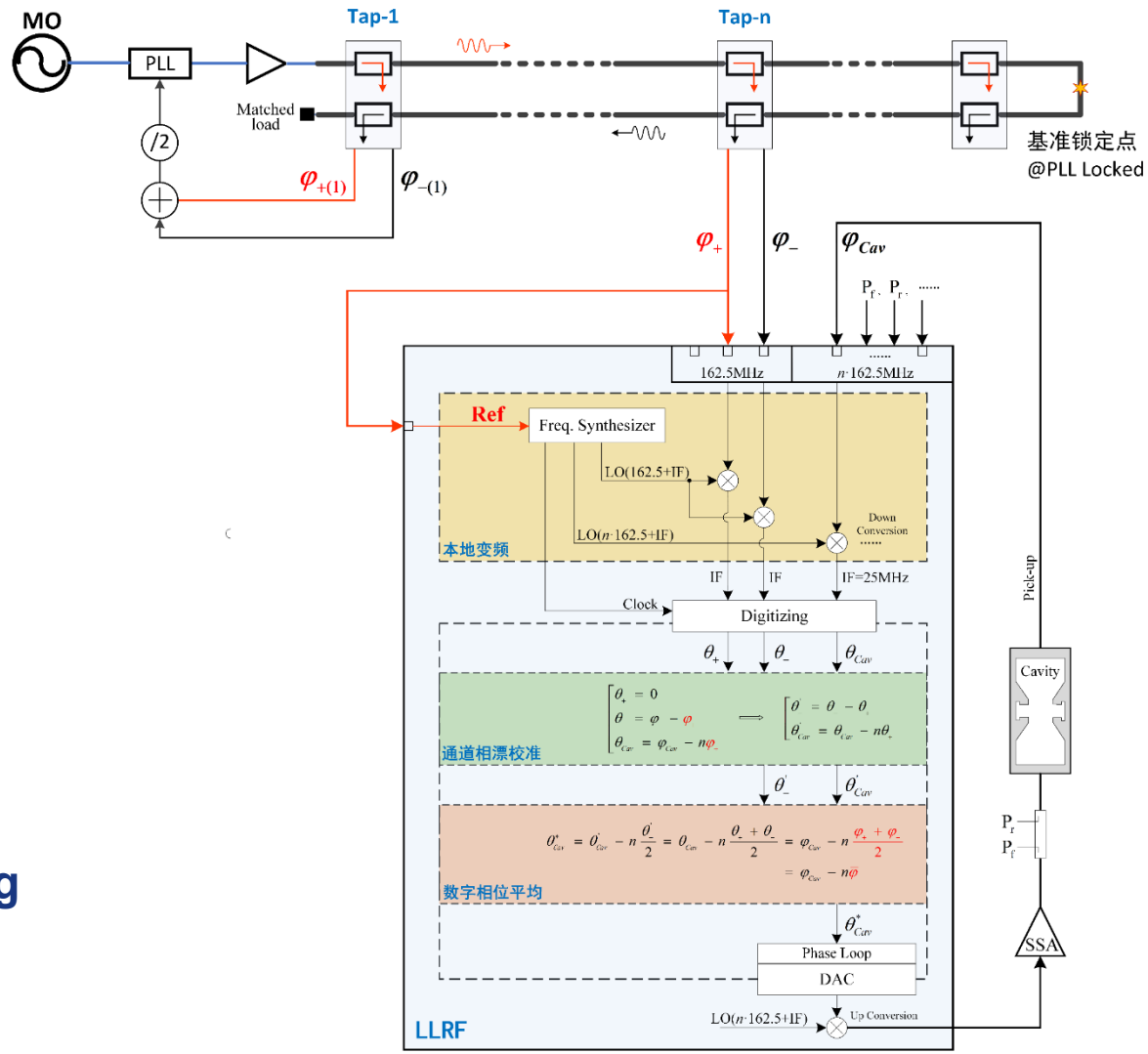
The cavity phase value measured by LLRF remains stable compared to the common reference

The New Phase Averaging Scheme Developed for SC Linac

Courtesy of Xinghao Ding @ IMP

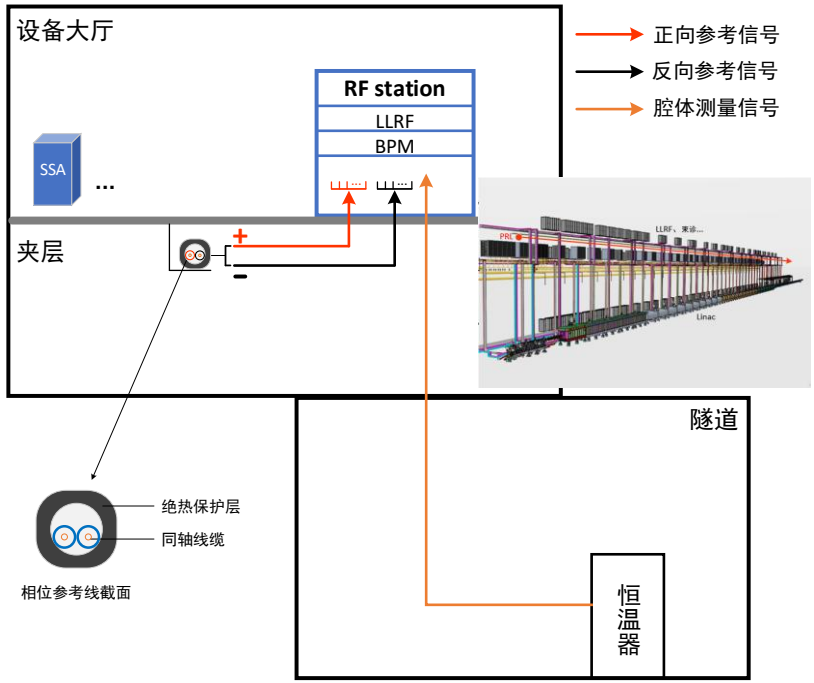
The main features of the half PLL phase average PRL

- **Reference signal with single frequency and unidirectional transmission, terminal matching, no reflection wave**
  - ✔ **Simple and stable, and reference lock is easy with single frequency**
  - ✔ **Reduce the standing wave effect and remove the limit on the number of nodes**
- **Dual line and dual coupler design, half phase calibration**
  - ✔ **The crosstalk can be avoided, and no need for very hight isolation with constant coupling**
- **Local frequency synthesis, digital phase averaging**

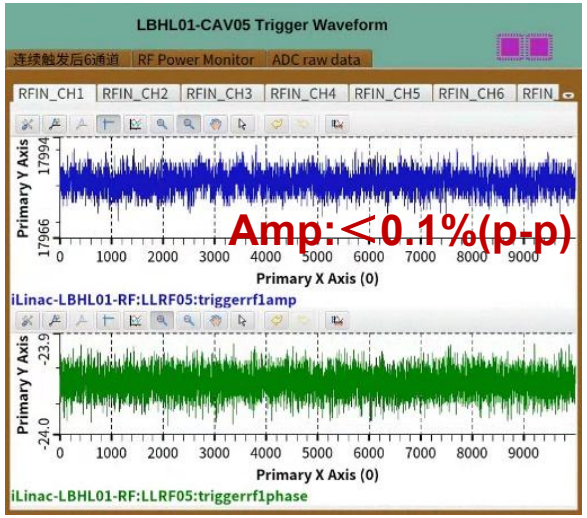


The RF Reference Distribution System for HIAF Linac

✓ The new phase average based PRL in HIAF iLinac

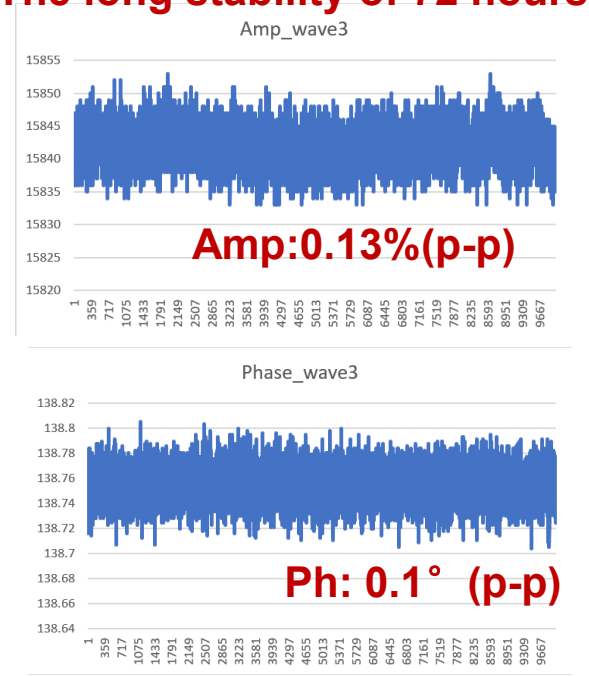


Stability of reference signal from one node:



Ph:<0.1°(p-p)

The long stability of 72 hours



- Transmission line

- Connection Section

- Coupler Port

- Master Source

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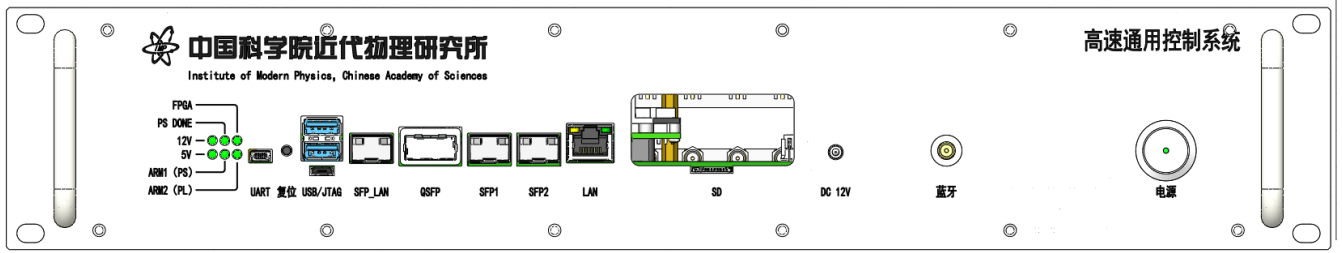
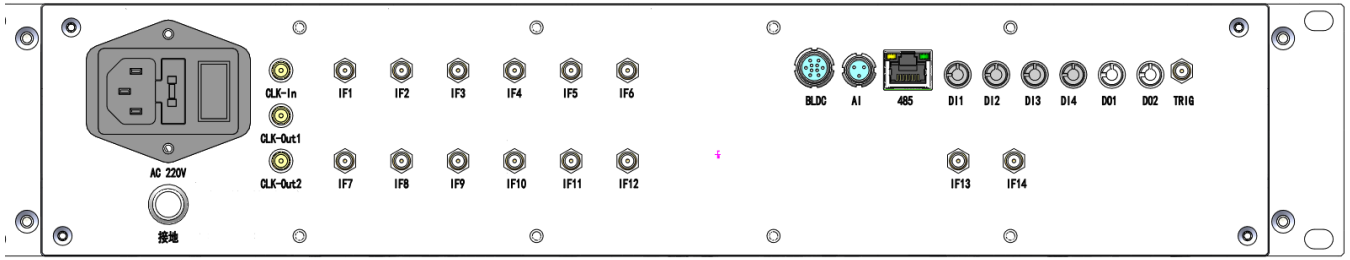
The new Digital LLRF Control Chassis

➢ The new LLRF main controller chassis



➢ The front panel of LLRF chassis

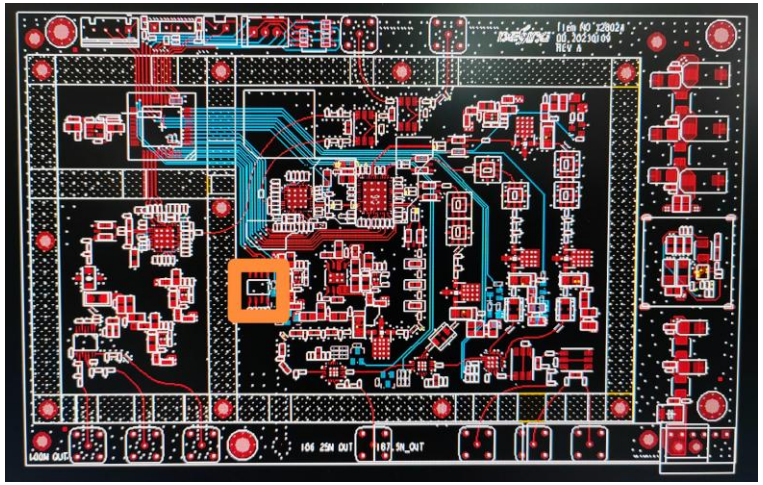


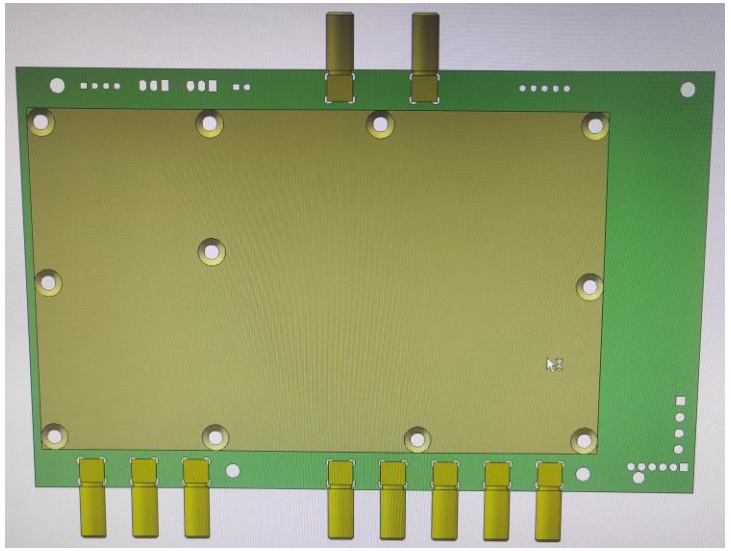
➢ The back panel of LLRF chassis

The LLRF high speed digital controller:

- 2U industrial shelf chassis;
- 1 set of LLRF control chassis corresponds to 1 cavity (each one system work independently);
- Hardware boards in the chassis: digital board+RF front-end board

The new RF Front End Development





➢ The LO frequency synthesizer board

Local LO combination mode for multi frequency signal measurement

Freq. Combination 1 (MHz)	Reference Input 162.5	CLK Out 100	LO1 Out -	LO2 Out 187.5
Freq. Combination 2 (MHz)	Reference Input 162.5	CLK Out 100	LO1 Out 187.5	LO2 Out 350
Freq. Combination 3 (MHz)	Reference Input 162.5	CLK Out 100	LO1 Out 187.5	LO2 Out 675

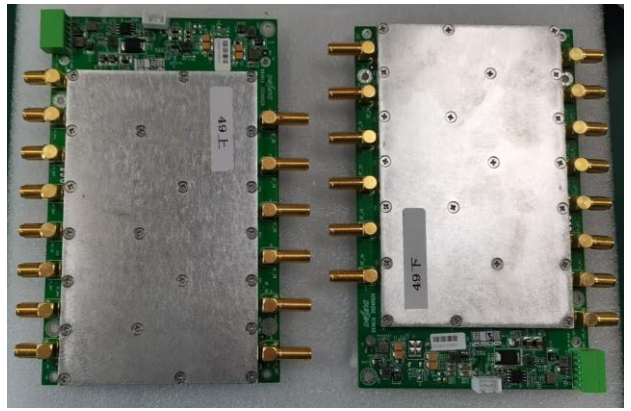
Unified RF frequency synthesis scheme design:

- Complete the scheme design of frequency synthesis unit;
- Can adapt to 8 different frequency combinations, covering all frequency mode of SC linac in IMP;
- Temperature and voltage/current monitoring functions was realized；
- Work modes can be switched remotely;
- Isolation enhanced by shield design.

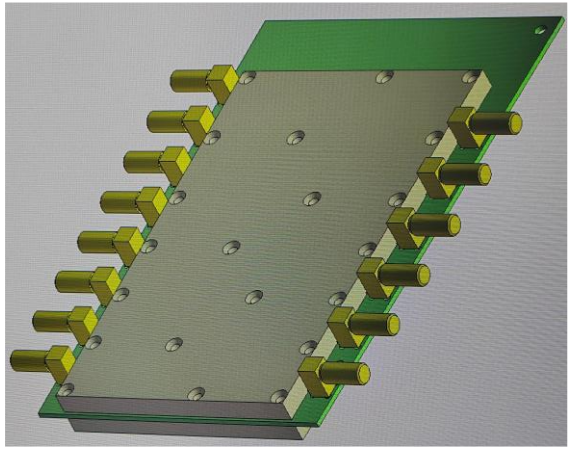
The new RF Front End Development

The features of RF front-end:

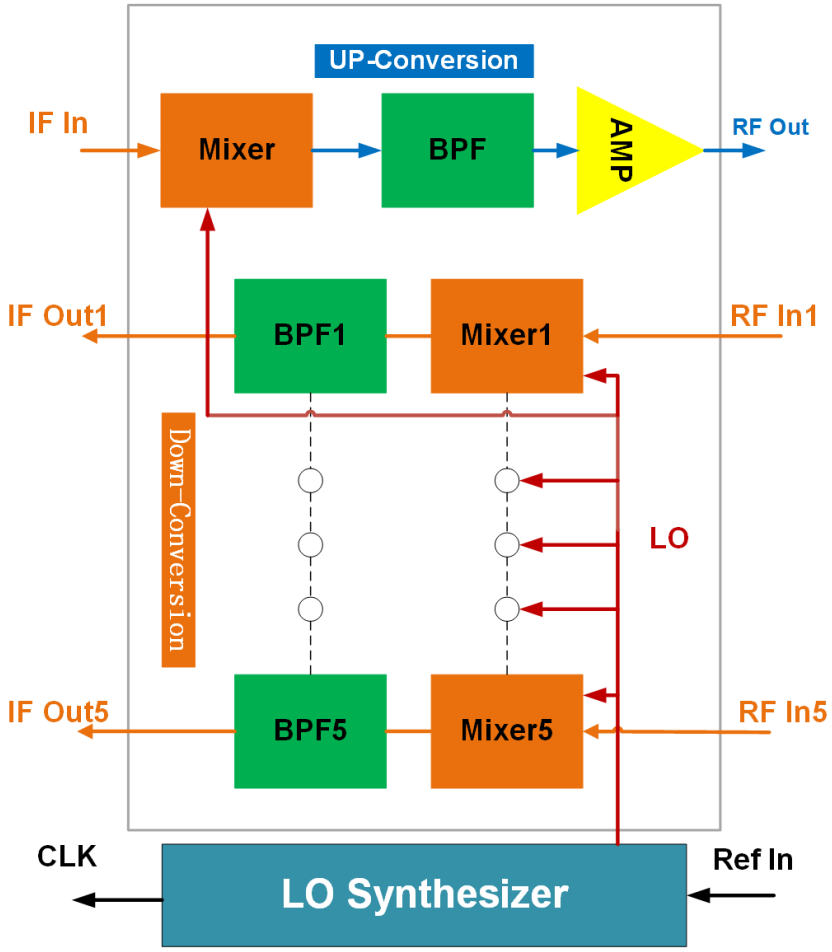
- The RF front-end consists of two same 3U PCI sized boards.
- By mixing and downconverting with LO, the 10-channel RF signal is downconverted into an IF signal, and the IF signal output from the DAC is upconverted into a RF signal.
- In this design scheme, 5 down conversion channels and 1 up-conversion channel are integrated into the one same board.
- The P-1 dB point of up-conversion channel is more than 15 dB, and the typical gain of the down conversion channel is 0 dB.



➢ The RF front-end board

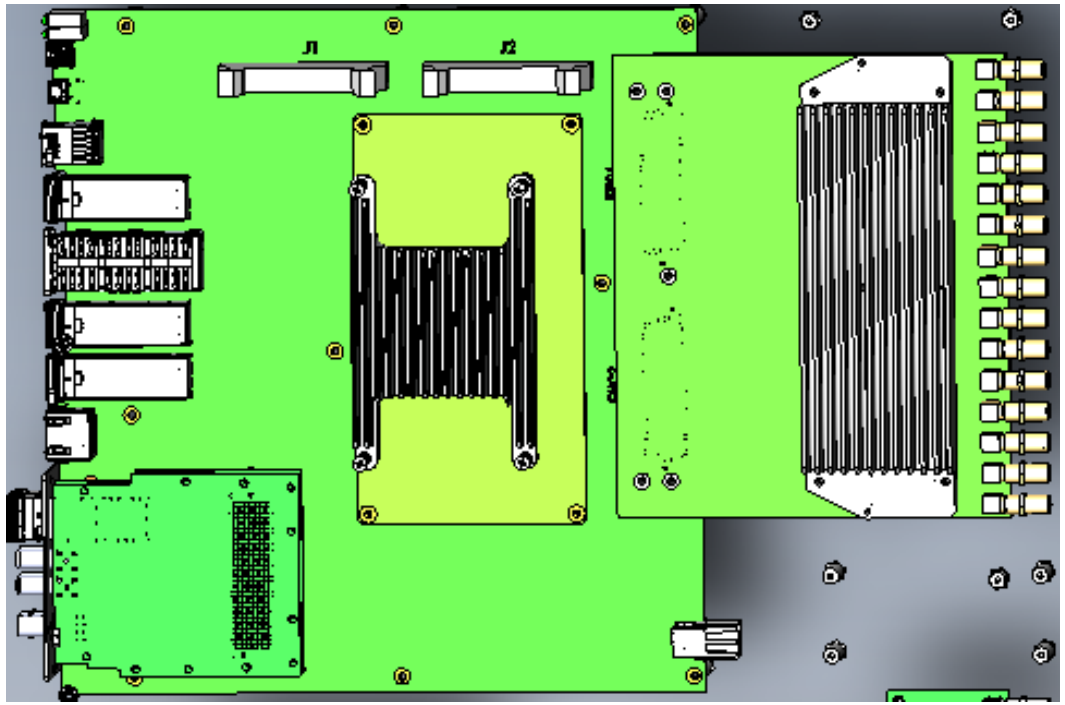


➢ The structure diagram of RF front-end board

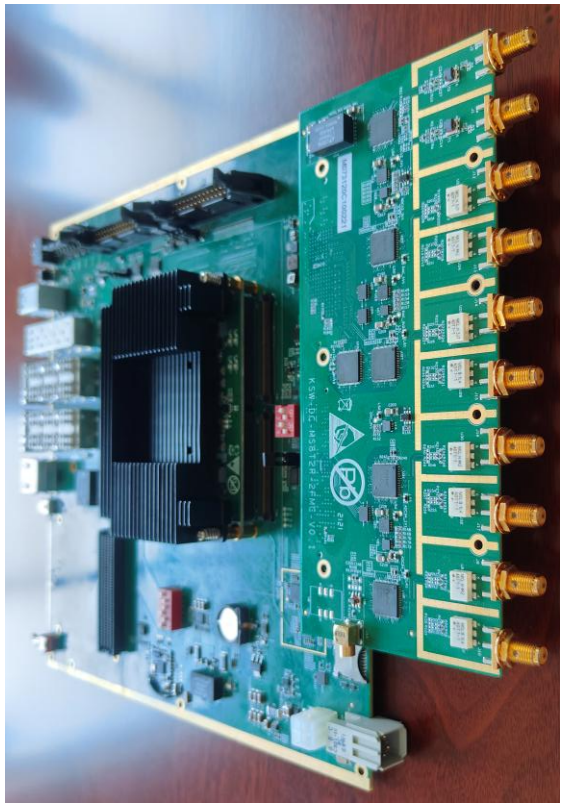


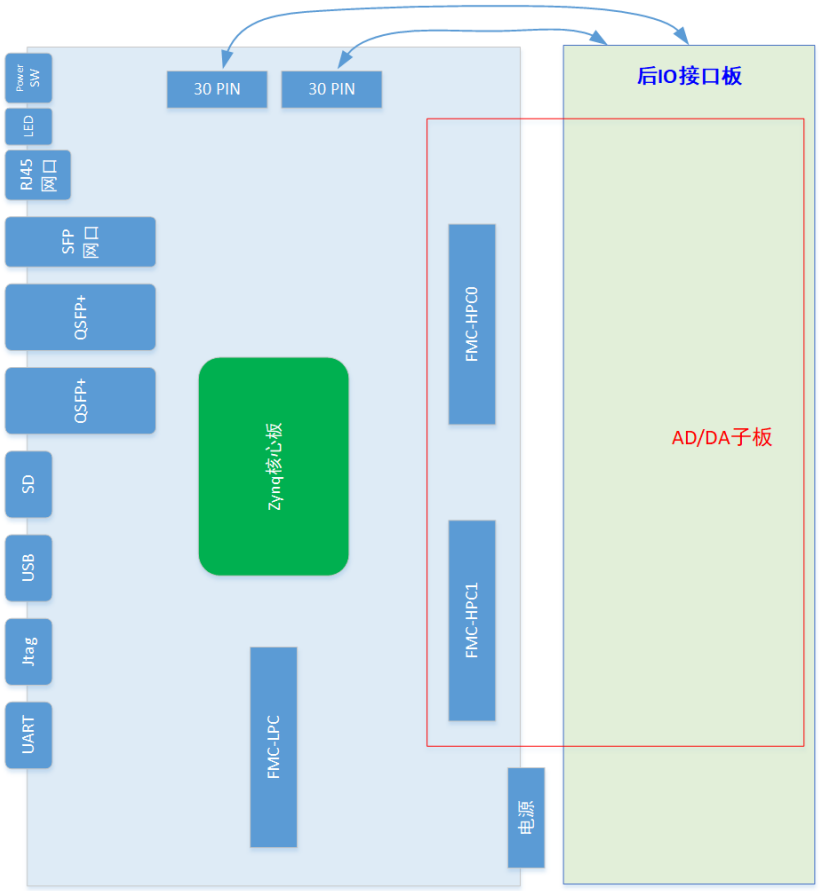
➢ The schematic diagram of RF front-end board

The Digital Control Board of LLRF Hardware



➢ Digital LLRF controller board





➢ The schematic of digital board

The digital boards of LLRF controller:

- 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 quad-core Cortex-A53 ARM processor was integrated.
- The baseline design of AD board is 10 channels, cover 8 channels card.

- Modular design with high speed connector
- Highly integrated with system on module
- Compatible design guided by standardization

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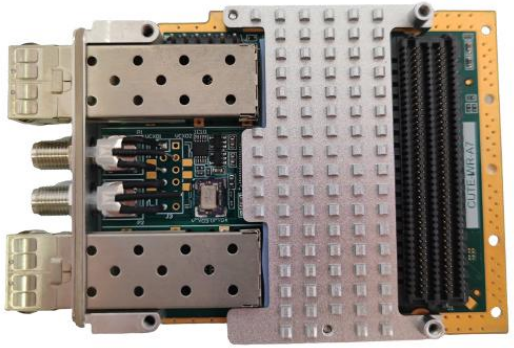
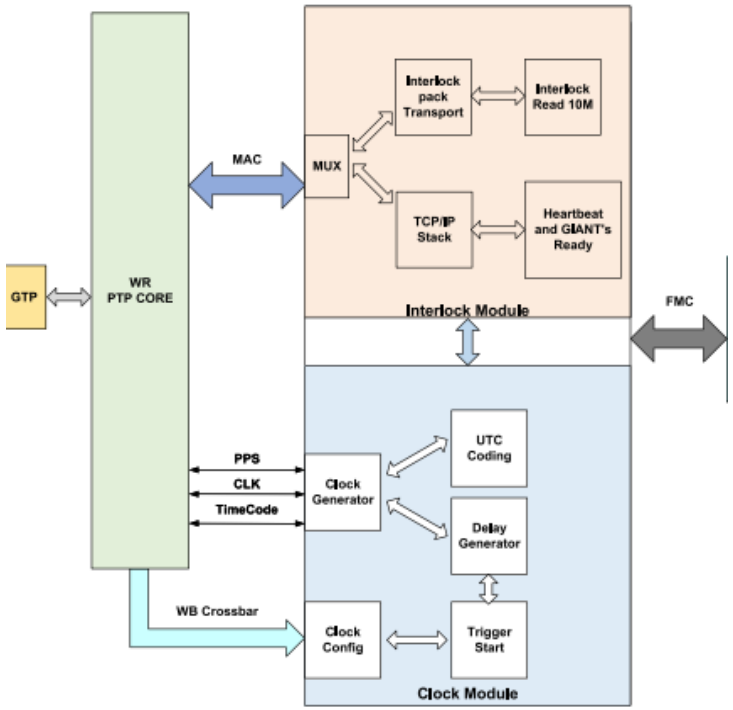
The White Rabbit based Timing System

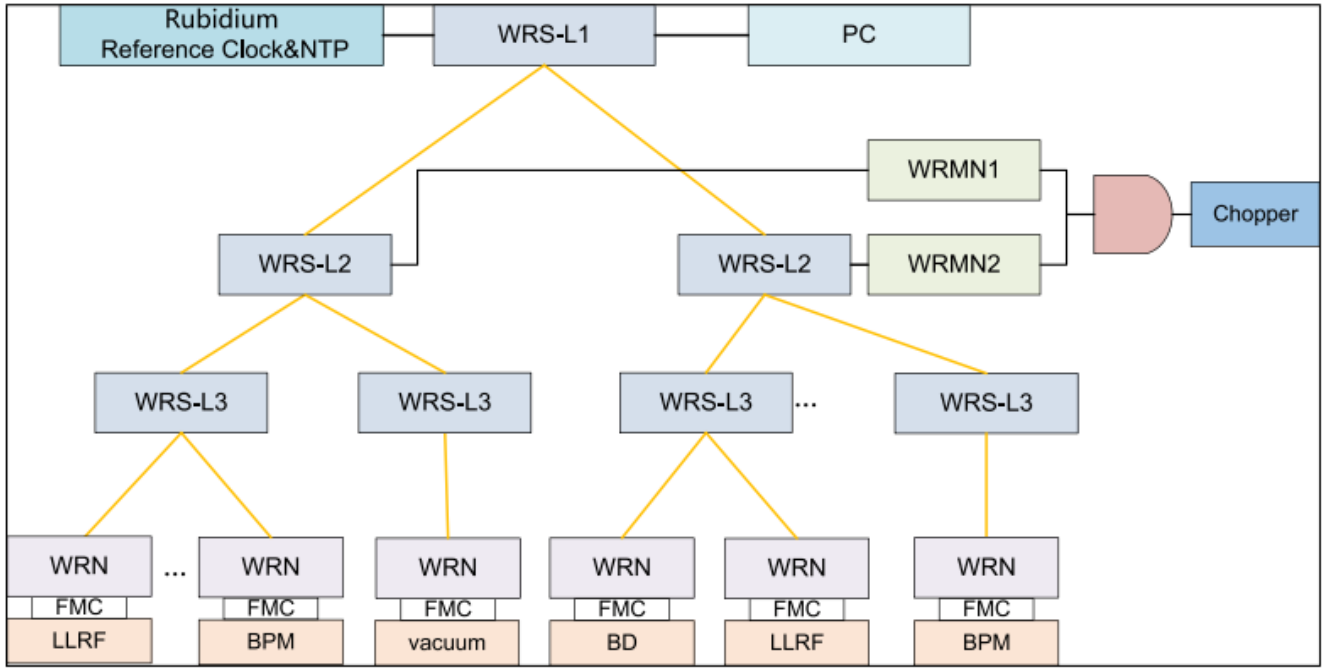


➢ The White Rabbit Node



➢ The software diagram of White Rabbit Node

Courtesy of Hai Zheng @ IMP

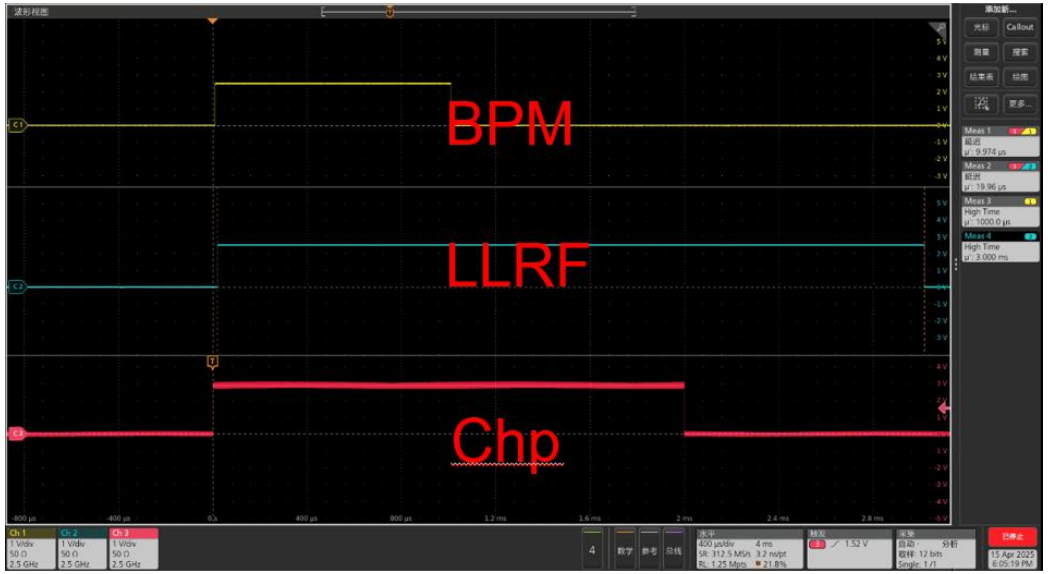


➢ The architecture of timing system for SC linac

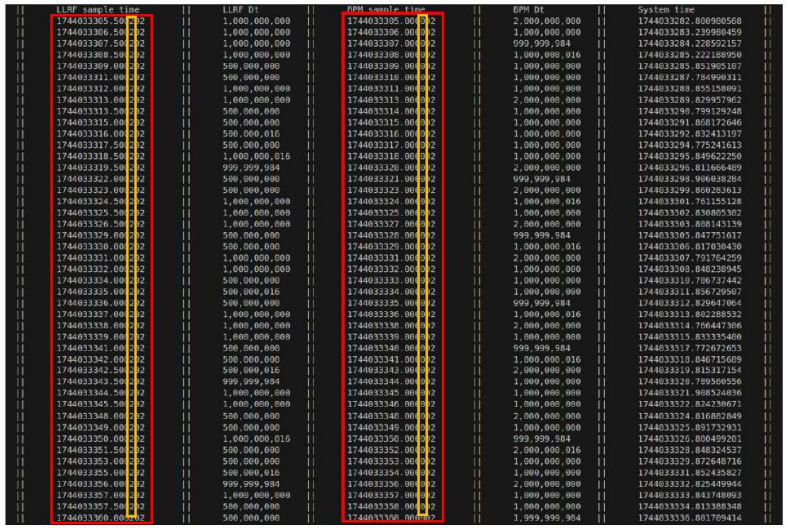
- The new timing system was designed and implemented for superconducting linac in IMP.
- The white rabbit technology with sub-nanosecond time synchronization precision was adopted.
- The innovative architecture of combining fast machine protection and timing system with deterministic network reliability was realized.

The white rabbit timing integration test with LLRF

➤ The timing integration test UI



➤ The output trigger signal



➤ The synchronization test with LLRF

- The integration of the self developed new timing system with LLRF is a complex systematic process.
- The integration test was involved into two phases, test bench was built for early validation stage, the second stage is large scale test on site.
- Extensive functional testing has verified that all performance metrics satisfy the specified design goals.

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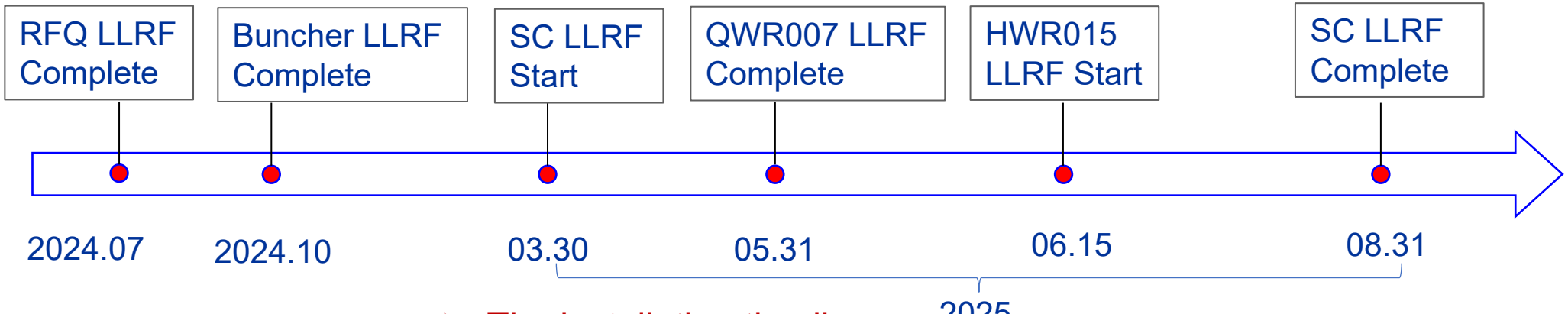
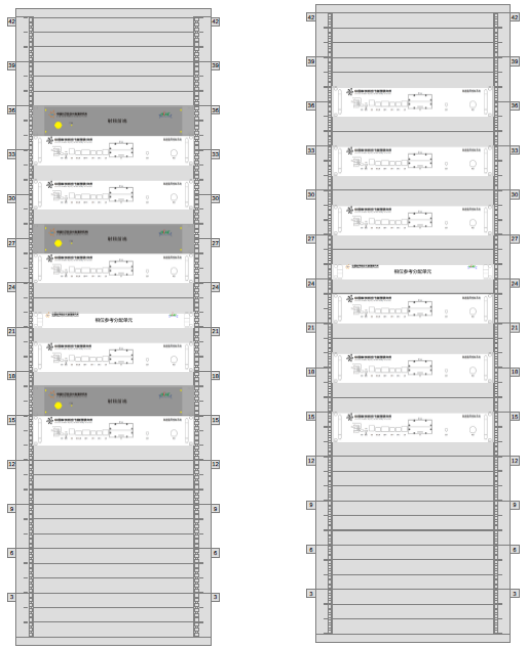
The Installation of HIAF iLinac LLRF



➢ The installation timeline of HIAF iLinac LLRF



➢ The layout of SC LLRF rack (Left:QWR007, Right:HWR015)

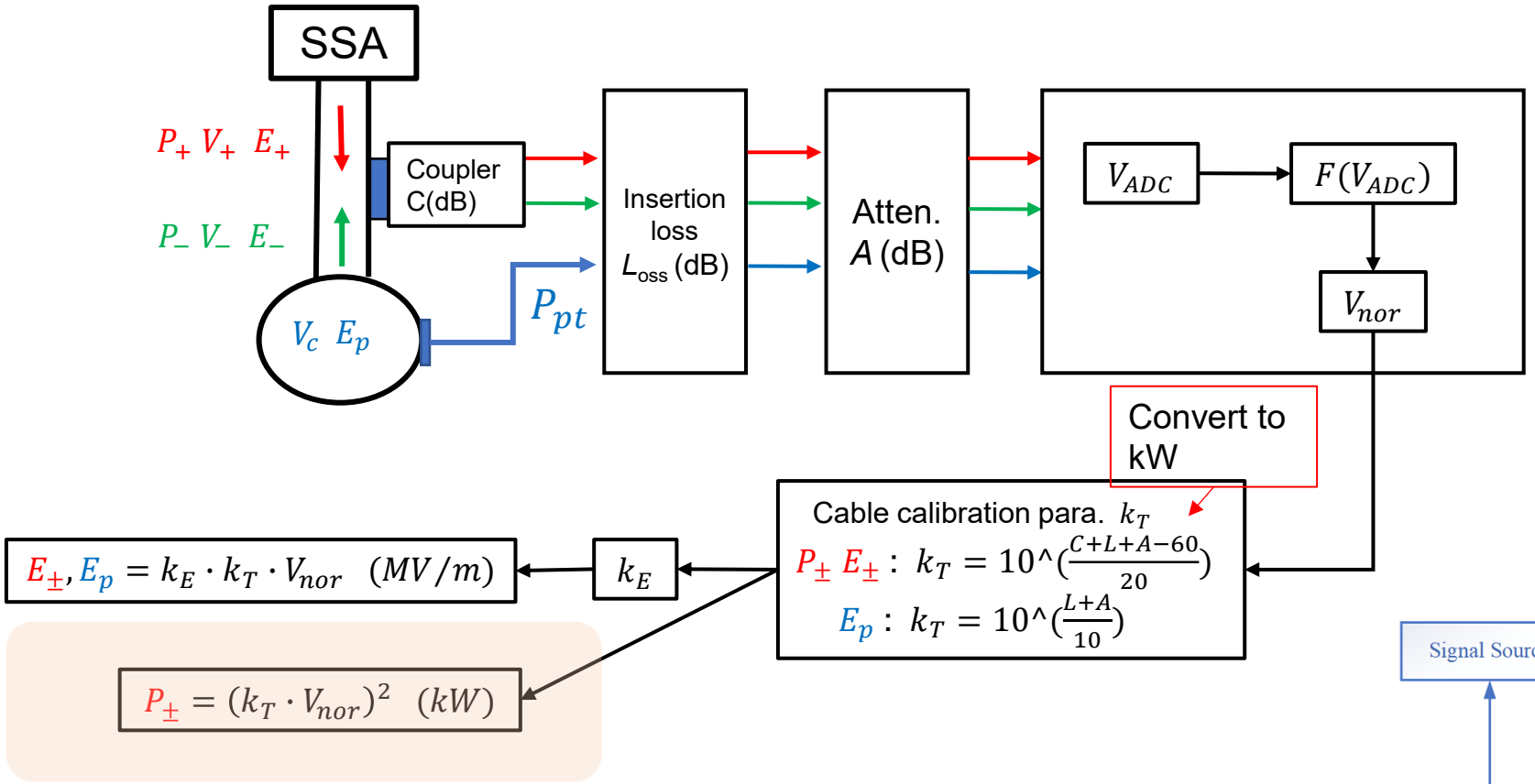
➢ HIAF iLinac Equipment Hall

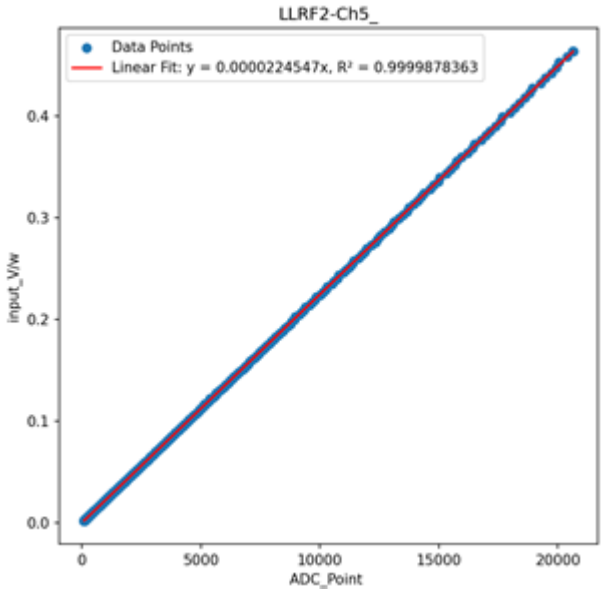
➢ QWR007 LLRF rack

➢ HWR015 LLRF rack

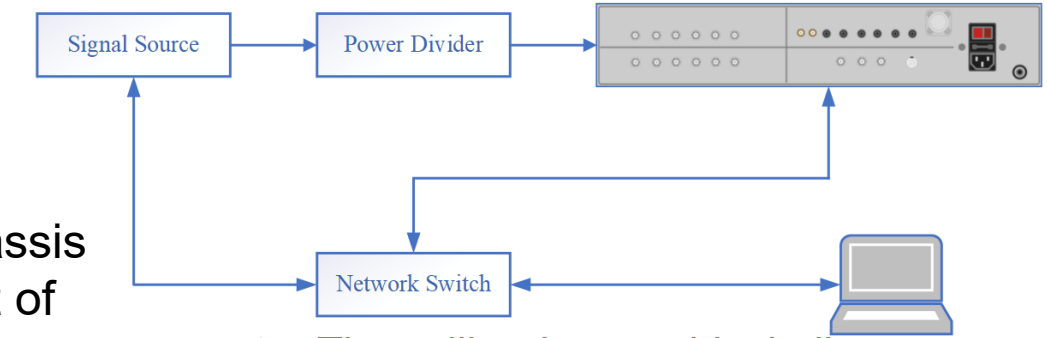
The LLRF Calibration for Commissioning

Courtesy of Shihui Wei @ IMP





➢ The calibration data of one LLRF RF measuement channel

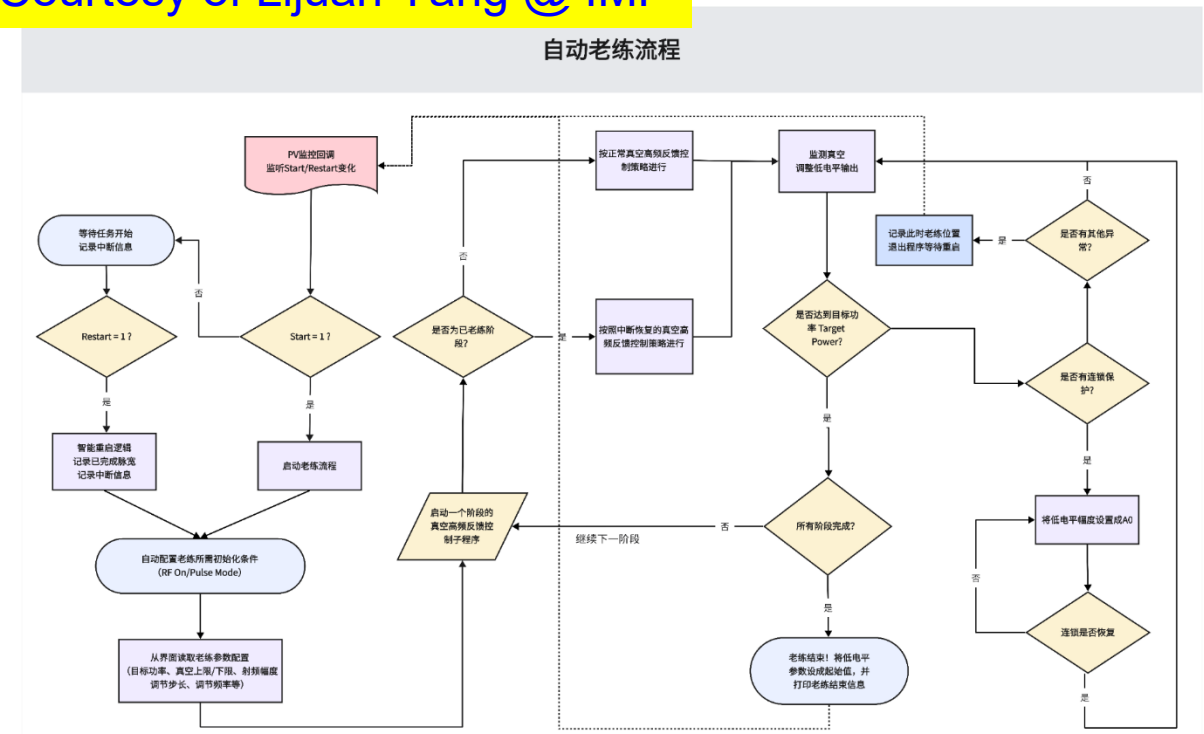


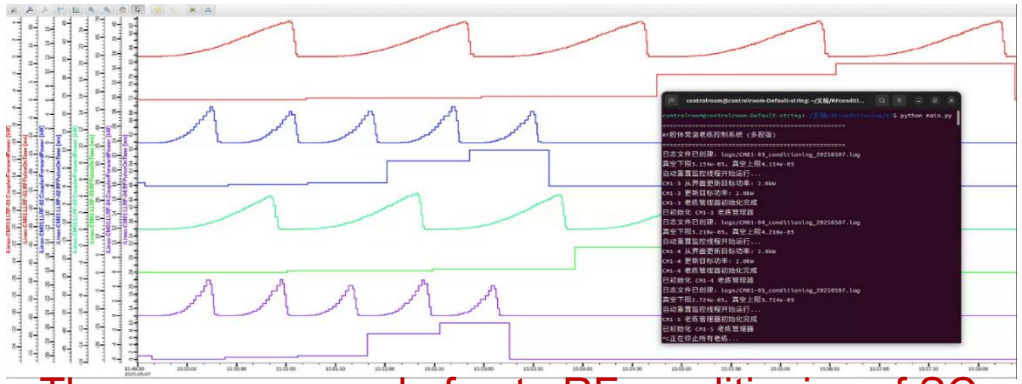
➢ The calibration test block diagram

- The RF calibration before commissioning including the LLRF chassis calibration is the key process to guarantee precise measurement of RF field amplitude and phase and RF power.

The RF Commissioning Status

Courtesy of Lijuan Yang @ IMP

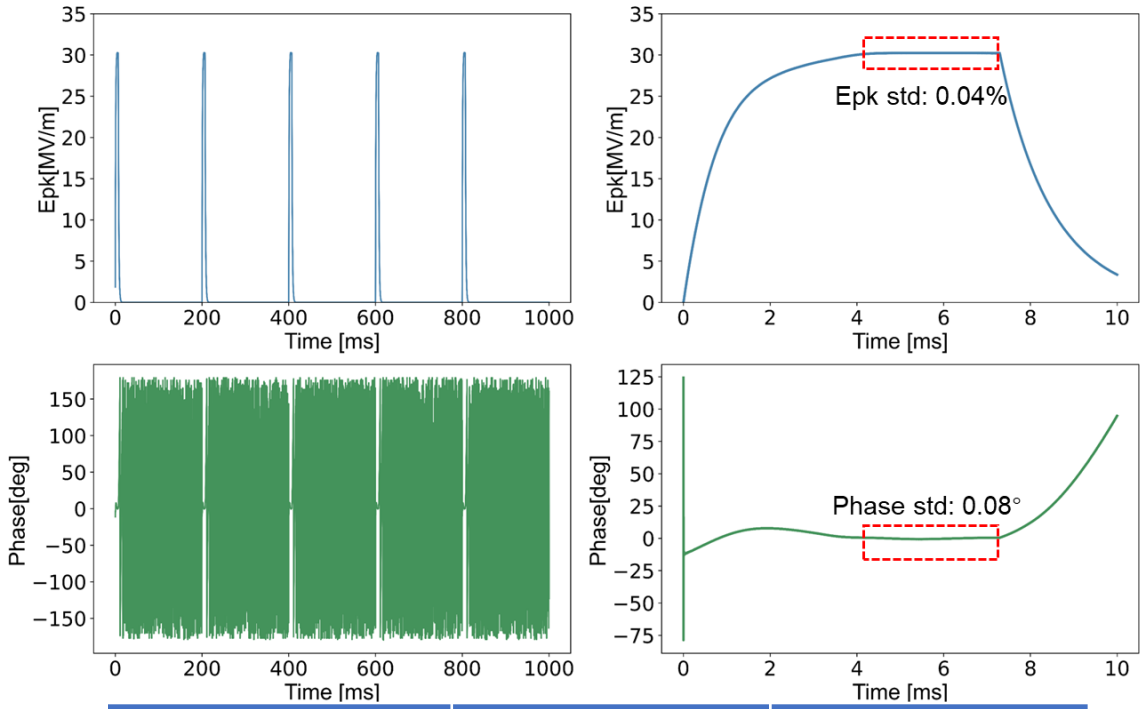




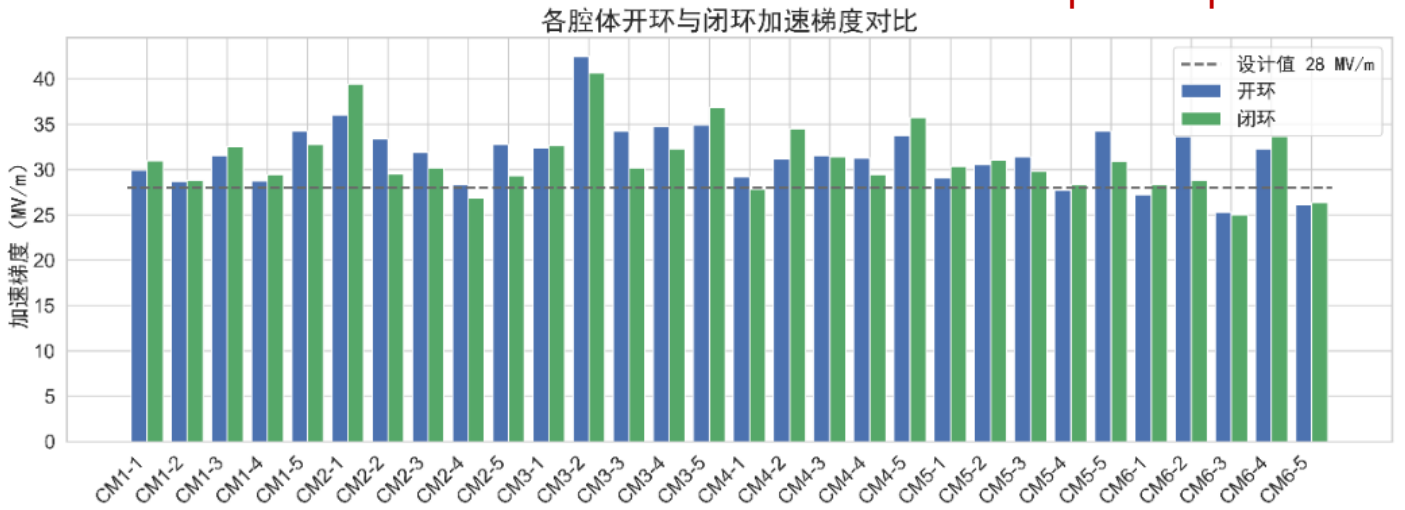
➢ The process record of auto RF conditioning of SC

- Automated, modular, intelligent, and scalable accelerator automatic RF conditioning system was developed.
- Security guarantee, Efficiency improvement, labor cost optimization and data-driven can be realized by using the automation system.
- The new RF auto conditioning system was successfully tested during RF conditioning of HIAF iLinac SC

The Pulse Close Loop Control Mode Test of LLRF



- Green bar is pulse close loop
- Blue bar is open loop

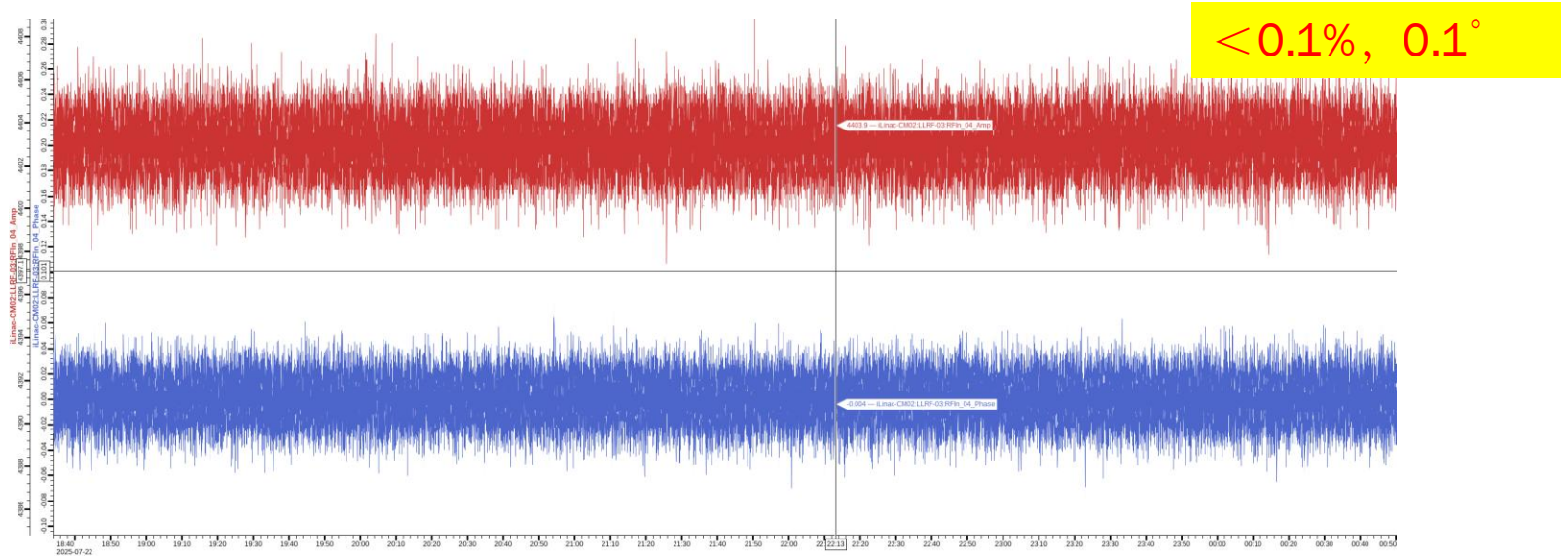


➢ The comparison of Epk value for QWR007 operate in different mode

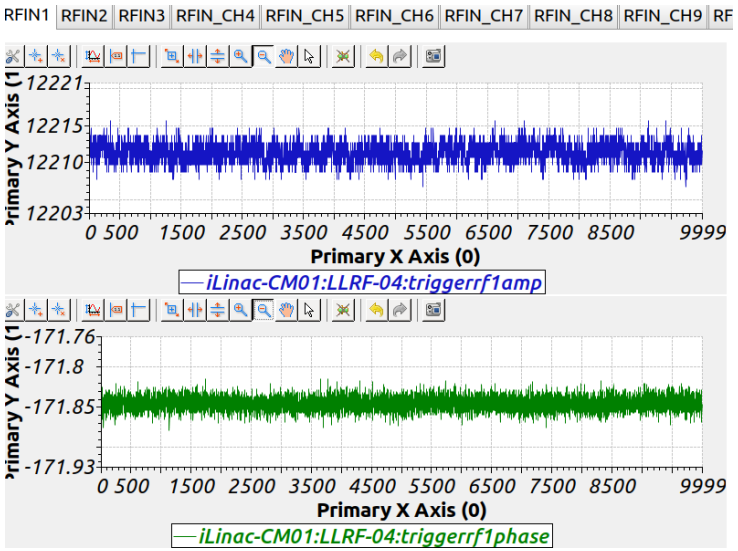
Cavity Para.	QWR007	HWR015
Freq.（MHz）	81.25	162.5
Epeak/Eacc	4.69	4.7
E_{acc} @β_{opt}（MV/m）	5.97	5.96
R/Q (Ω)	485.7	292
Q_0 @2K	1.43E+09	2.8E+09

- As an injector of HIAF, the iLinac will usually operate in pulse mode during beam commissioning.
- At the beginning of project construction, all RF system was designed and fabricated with aim for CW mode, the development of LLRF pulse control mode face many problem.
- By well designed control algorithms and software, the new RF pulse control mode was successfully tested in beam commissioning of QWR007.

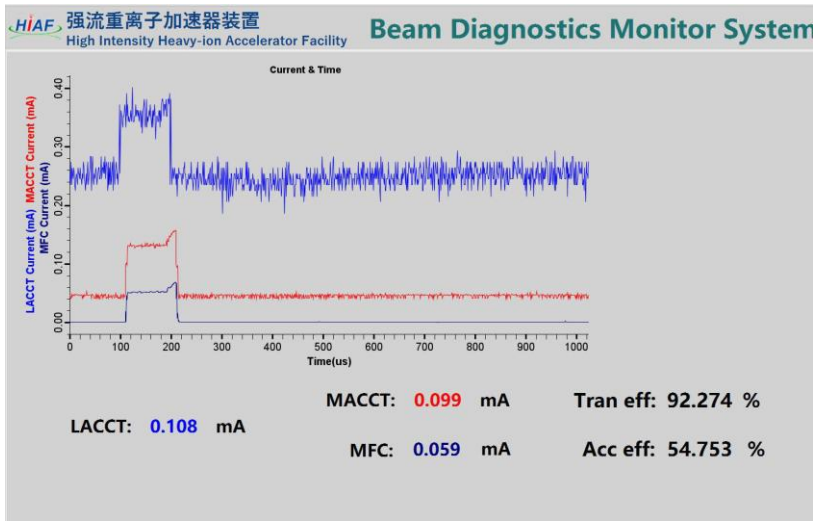
The Commissioning Status



✓ 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 on QWR007: $16O^{6+}$, 9.77MeV/u

Summary

- The superconducting linac in IMP is under large scale construction
- The new LLRF control system was successfully developed by adopting new technology
- The first mass deployment of the LLRF on HIAF iLinac, and the installation and commissioning result shown desired performance

Thanks