UNIVERSITY OF SCIENCE AND TECHNOLOGY OF CHINA
National synchrotron radiation laboratory

The development of Low level RF system of Linac for STCF

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Workshop on future Super c-tau factories 2021

Out line

- Motivation
- The development of LLRF System

  --Hardware

  --Software

  --Algorithms
- Summary

Introduction

What is low level radio frequency system doing?

-- Control and maintain the phase and amplitude stability of RF station during beam travelling

Why the low level radio frequency system is necessary?

-- Modulator drop and ripple
-- Temperature drift; crate noise
-- The beam loading effects
-- The detuning of cavities

The **status** of the low level radio frequency system.

-- From analog to digital
-- a variety of control algorithms to reduce perturbations
-- Automated operation and easy maintenance
-- High availability

Introduction

Introduction

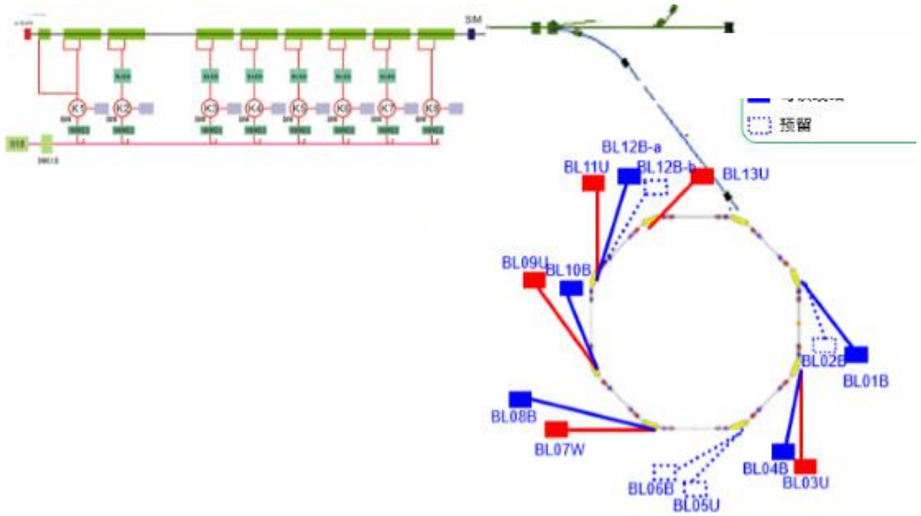
HLS II brief introduction

Linear segment (8 sections)

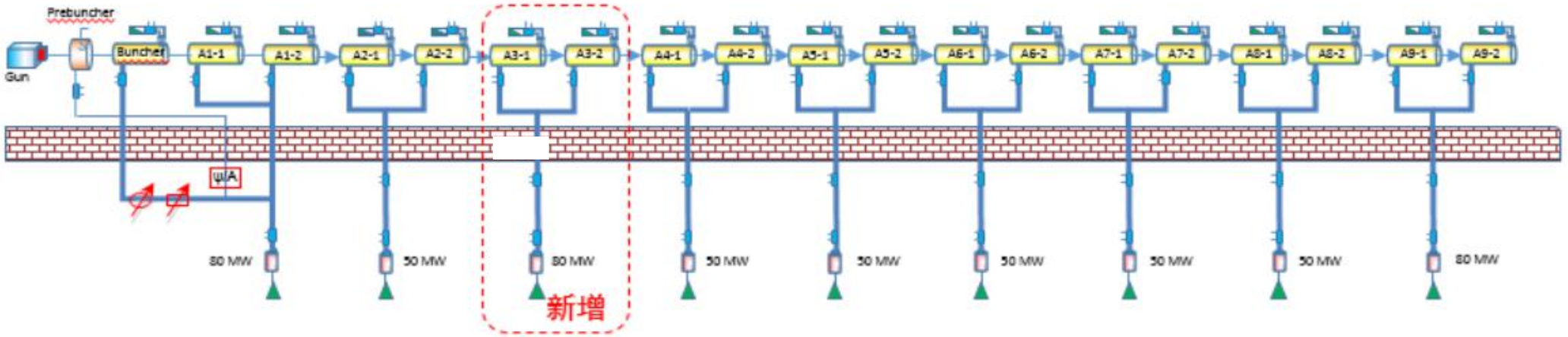
- electron energy 0.8GeV
- repetition frequency 1Hz
- working frequency 2856MHz

LLRF

- MTCA architecture
- 1 LLRF system per cavity
- EPICS developments



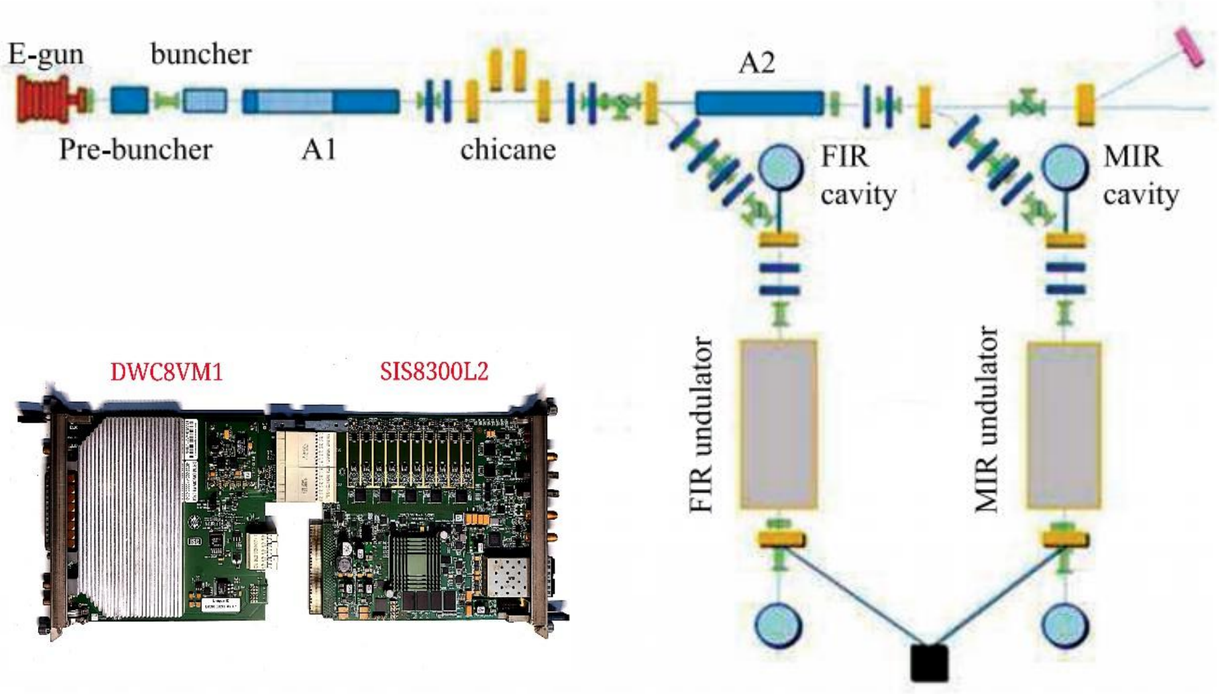
a 800 MeV synchrotron light source at the National Synchrotron Radiation Laboratory (NSRL) in university of science and technology,Hefei,China



Introduction

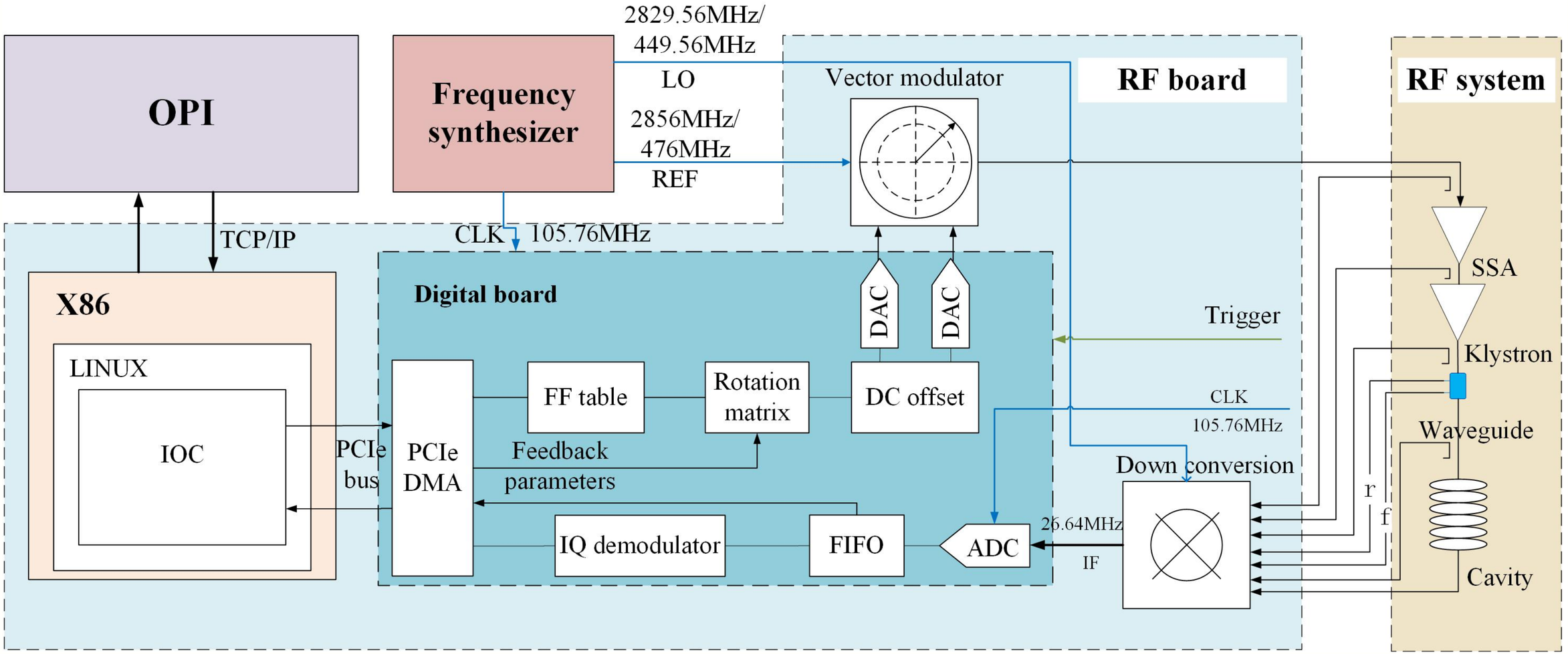
IRFEL brief introduction

Parameters	Specification
Covering spectrum	2.5 ~ 200 μm
MIR FEL oscillators	2.5 ~ 50 μm
FIR FEL oscillators	40 ~ 200 μm
Macro-pulse length(FW)	5~ 10 μs
Repetition of macro-pulse	20 Hz
Macro-pulse energy	~100 mJ
Micro-pulse length (RMS)	5 ~ 10 ps
Micro-pulse energy	1 ~ 50 μJ
Bandwidth	0.3 ~ 3 %
Continuous tunability	200 ~ 300 %



The linac drives two FEL oscillators to generate mid-infrared and far-infrared free electron lasers. Two accelerating tubes (A1, A2) are used to accelerate the electron beam to the maximum energy of 60 MeV. The LLRF operates a prebuncher, a buncher and two accelerating tubes and two klystrons. The structure is similar to HLS II except that it has a set of system operating at 476MHz.

LLRF system design



System design of the self developed LLRF system for one RF station

LLRF system design

LLRF structure

Frequency reference subsystem:

- Frequency reference subsystem: *REF, LO, clock;*

hardware:

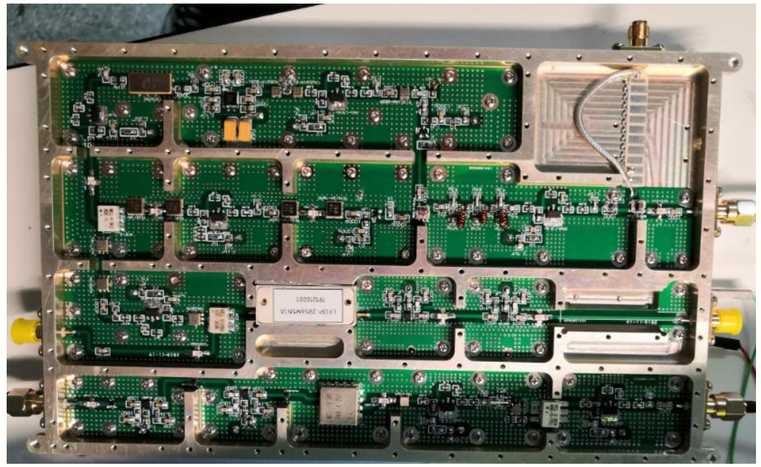
- Digital board:*signal acquisition and control;*
- RF board:*mixing (up and down frequency conversion), vector modulation;*
- CPU; Power module; etc.

software:

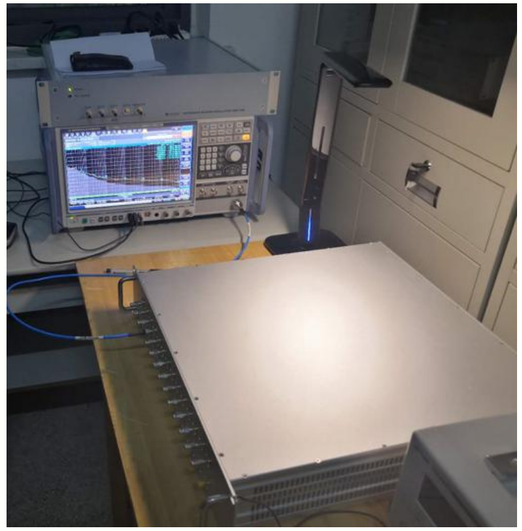
- Developed based on EPICS
- IOC: *hardware driver*
- *Application software*
- OPI: *display, monitoring and man-machine interaction.*

Frequency reference subsystem

Frequency synthersizer



parameter	value
Output power stability	0.012dBm/℃
Fan out signal consistency	＜0.1db
Operating temperature	-20℃ ~ 50℃
Matching impedance	50Ω
Frequency range	100MHz ~ 4000MHz

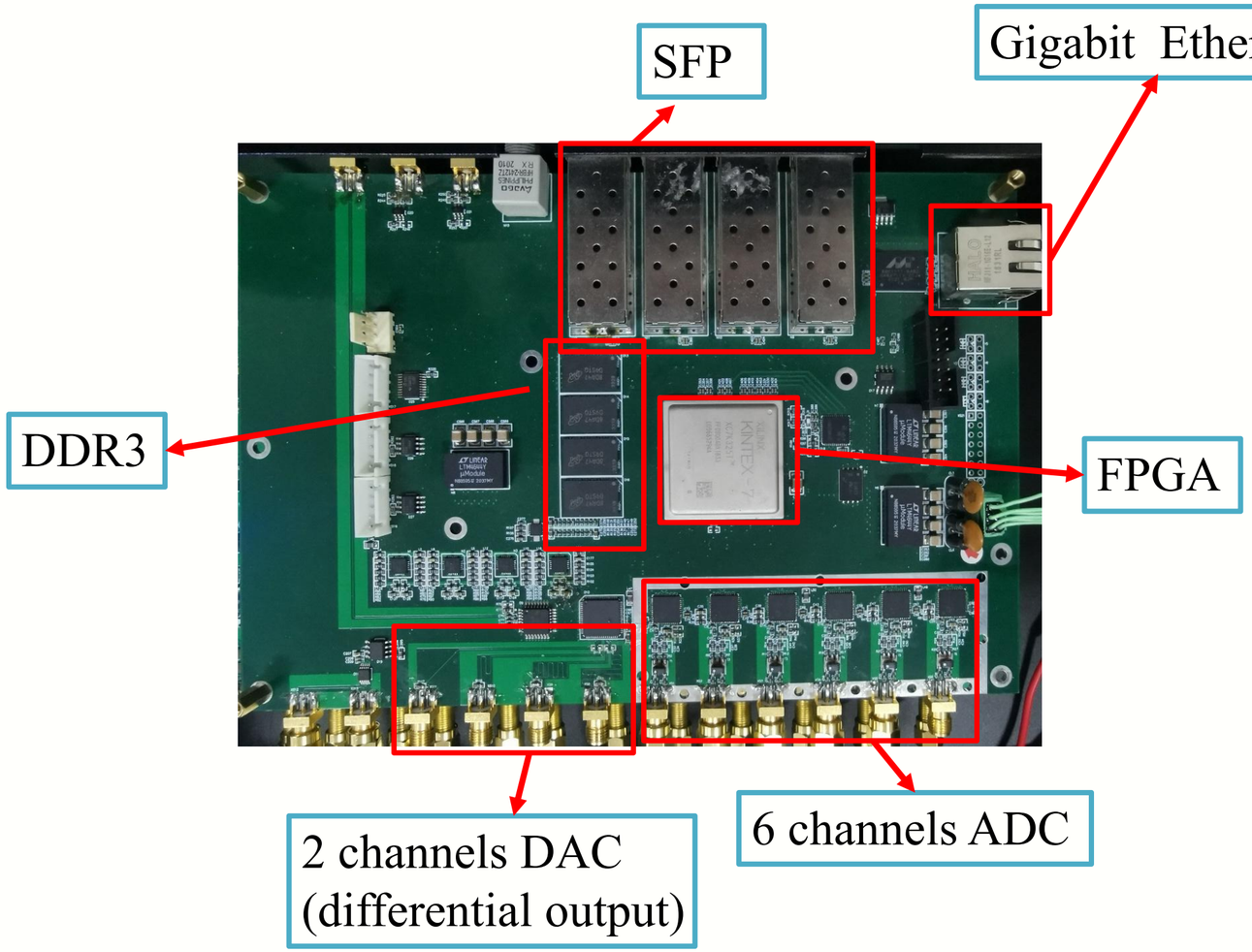


	Jitter(fs) 10Hz~10MHz	Frequency stability (ppm/24hours)	Amplitude stability(dbm)RMSE
105.78MHz	45.82	0.00945	0.0200
449.56MHz	41.18	0.00667	0.0174
476MHz	38.53	0.00630	0.0150
2829.56MHz	19.70	0.00071	0.0048
2856MHz	18.28	0.00175	0.0255

frequency synthesizer performance test

Hardware

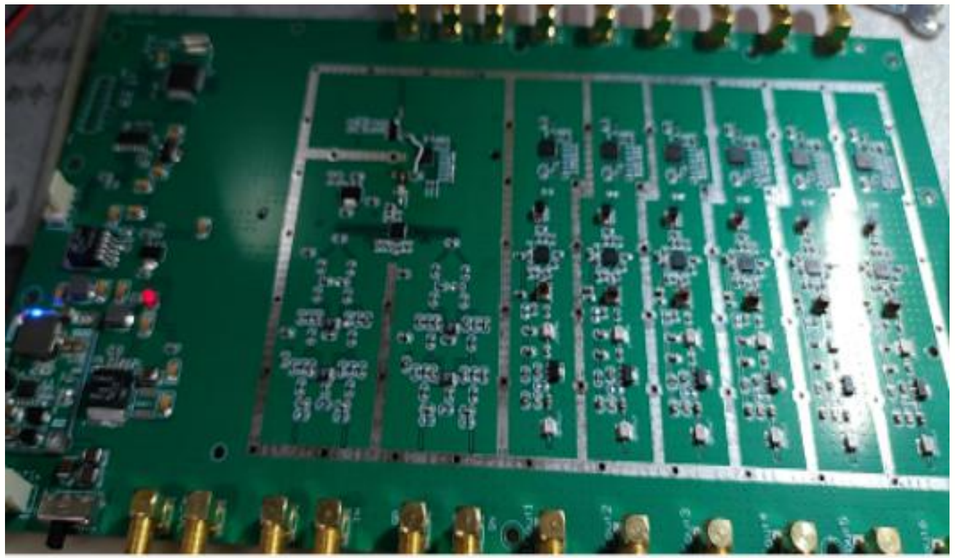
Digital signal processing subsystem



- 6 channels 125MS/s 16bit ADC(2 channels reserved);
- 2 channels 250MS/s 16bit DAC
- Kintex-7 FPGA
- 1.6GByte DDR3 memory
- High precision clock distribution circuitry
- Programmble delay of dual channel digitizer groups
- Gigabit link port implementation for data transmission
- SFP card cage for high speed system interconnects (not used)

Hardware

RF signal processing subsystem

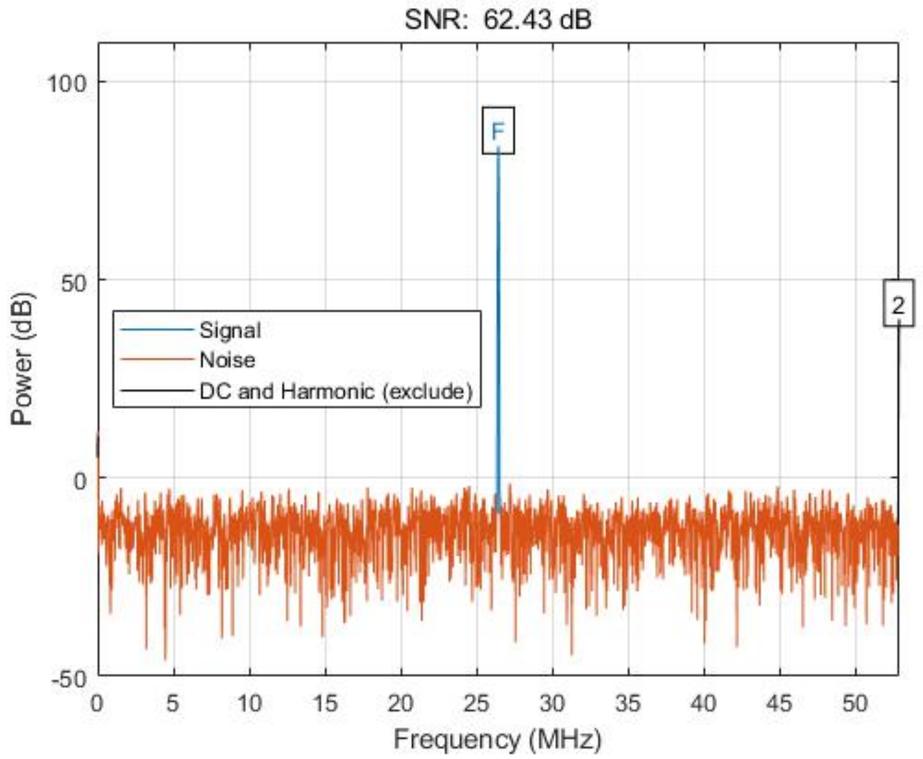


S-band modulation and demodulation function board

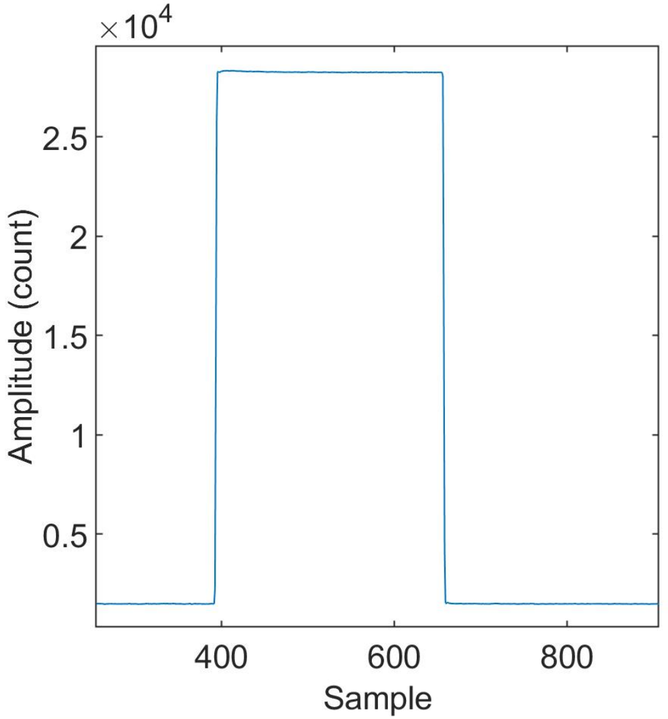
- 6 channels down-converters;
- 4 differential I/Q
- 1 channel s-band vector modulator
- VM output interlock
- Adjustable attenuator (31 dB)
- RF return loss < -15 dB
- channel crosstalk < -65 dB
- Downconverter P1dB > 12 dBm
- VM P1dB > 13 dBm

Hardware

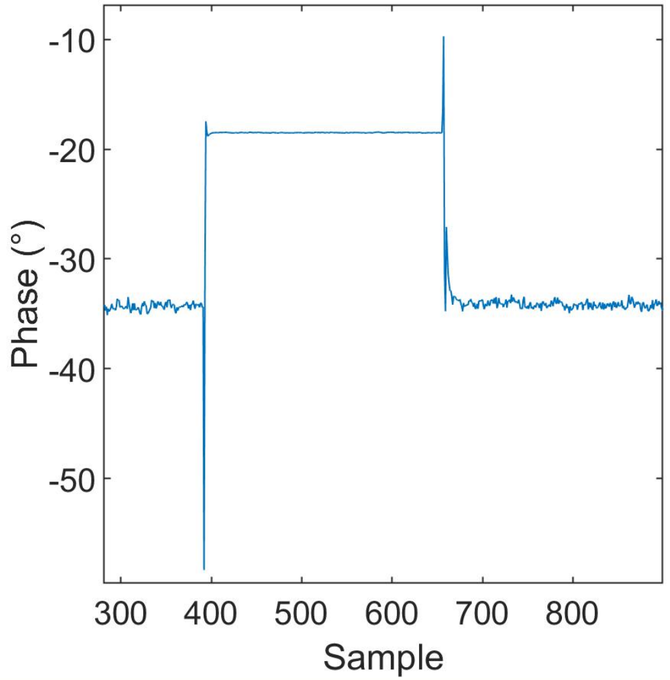
Offline test



ADC SNR > 60 dB



VM output of amplitued

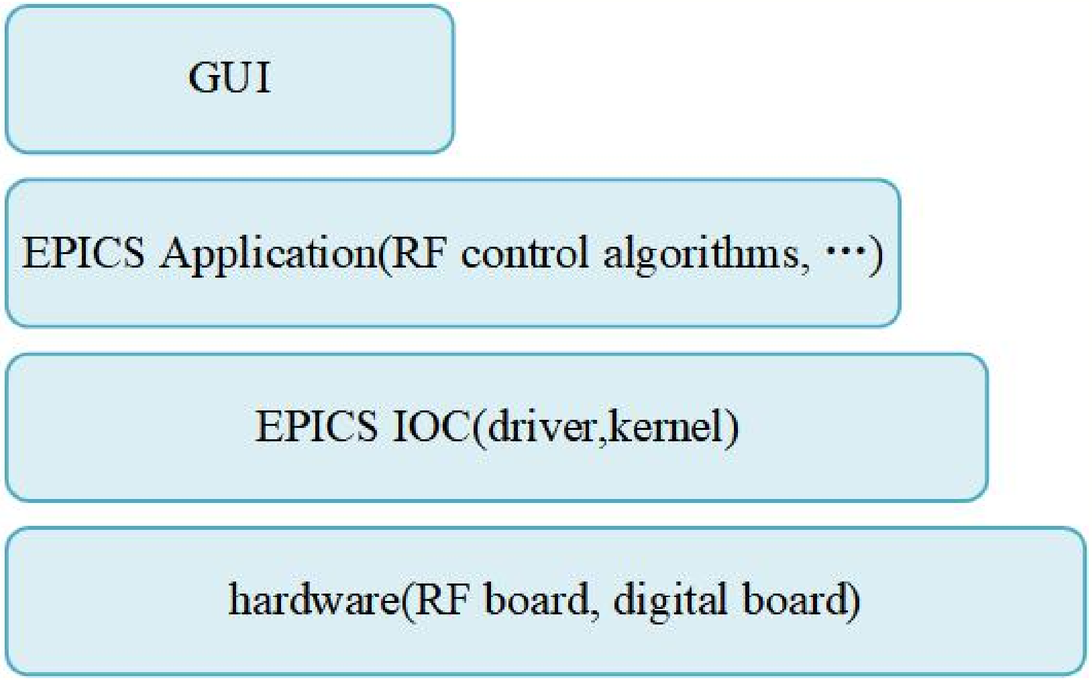


VM output of phase

the stability of amplitude is less than 0.03% , the stability of phase is less than 0.03°

Software

Software architecture of the LLRF system



Epics IOC:

Provides driver talk to the hardware;
Connects Epics record with the physical hardware data;
Provides process value to the upper level.

Application software:

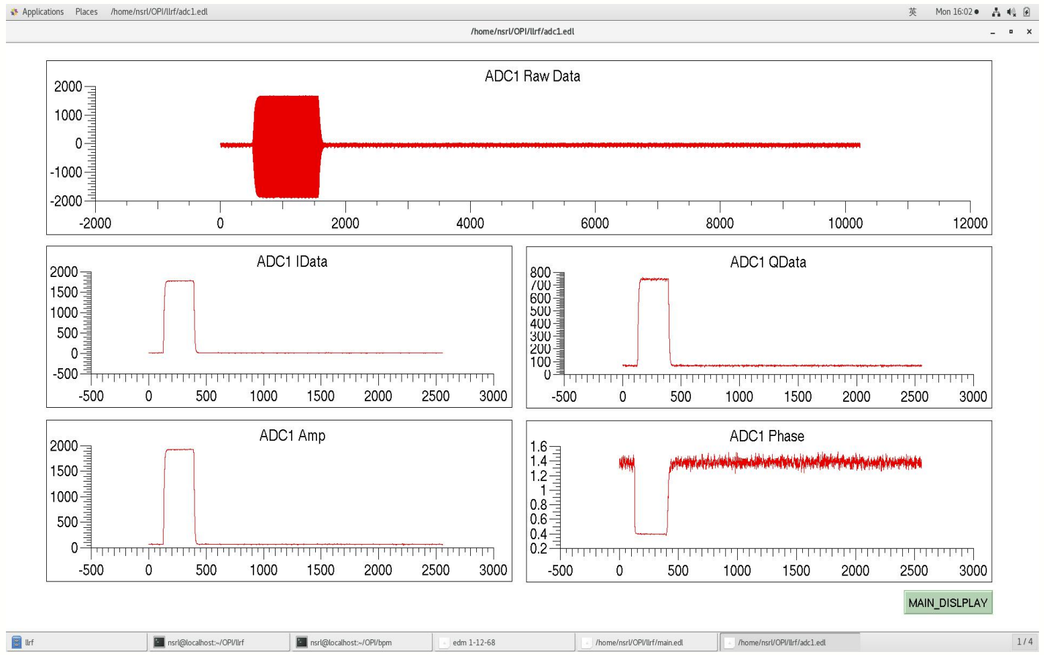
Amplitude and phase calculation;
Inter-pulse feedback/pulse-to-pulse feedback;
Adaptive feedforward;
System exception handling.

Graphic user interface (GUI):

Developed based on EDM;
remote control.

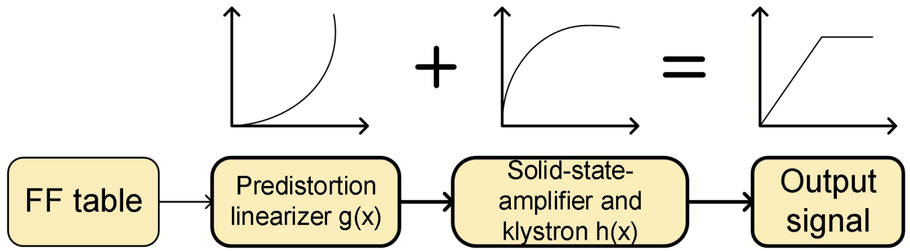
Software

EDM based LLRF OPI (Optimizing)

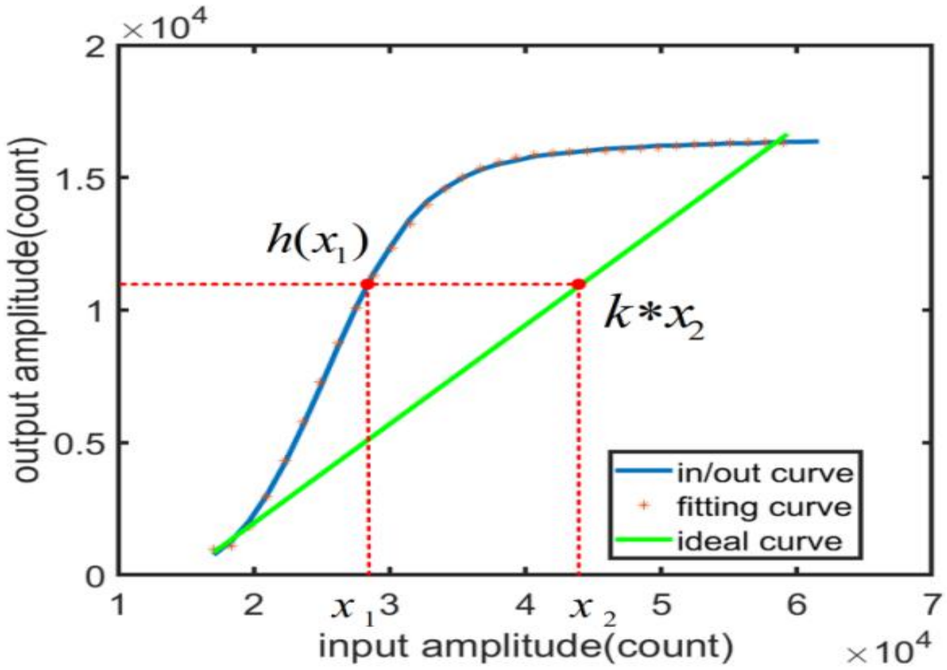


Algorithms

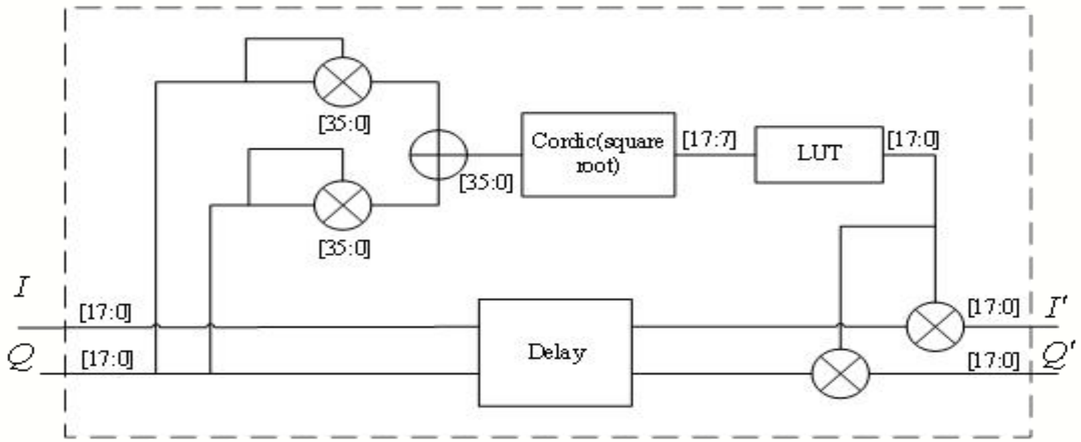
Klystron predistortion

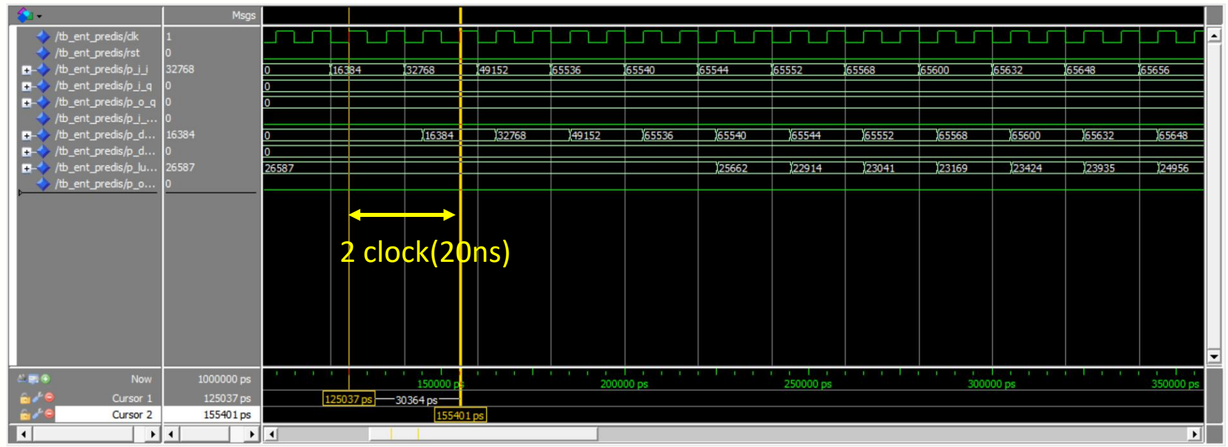


The nonlinear characteristics of the input and output of the klystron reduce the control gain in the near saturation region, resulting in the reduction of the feedback efficiency.



Pre-linearization





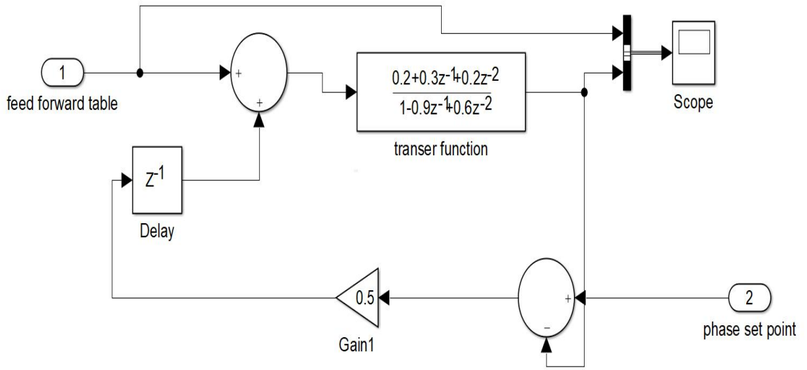
Algorithms

Intra-pulse feedforward

$$e(k,n) = r(n) - y(k,n)$$

$$\varphi_e(k+1,n) = k_p \cdot e(k,n-d) + k_i \cdot \sum_{j=0}^{k} e(j,n-d)$$

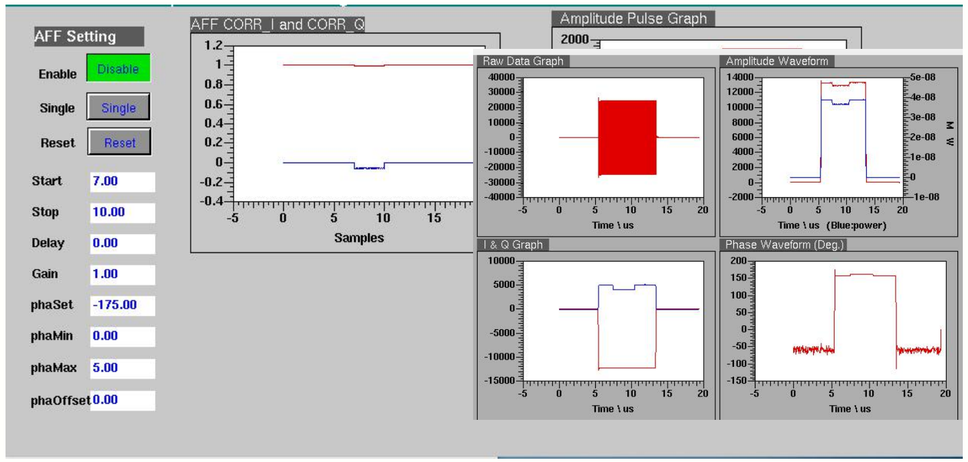
$$\begin{pmatrix} I' \\ Q' \end{pmatrix} = \begin{pmatrix} \cos(\varphi_e) & -\sin(\varphi_e) \\ \sin(\varphi_e) & \cos(\varphi_e) \end{pmatrix} \begin{pmatrix} I \\ Q \end{pmatrix}$$



☆ error waveform： Feed forward setting of phase subtract klystron output phase;

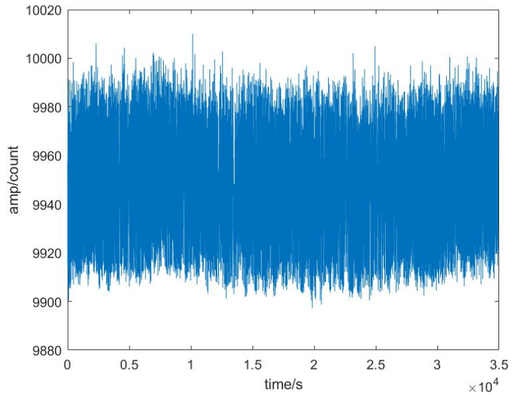
☆ feedforward phase： PI-type adjustment (the delay of DAC output to klystron output);

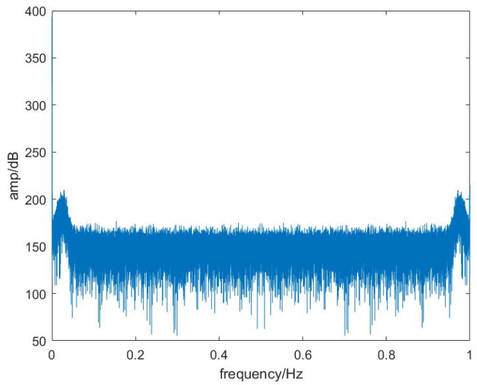
☆ output of intra-pulse feedforward： use the rotation matrix.



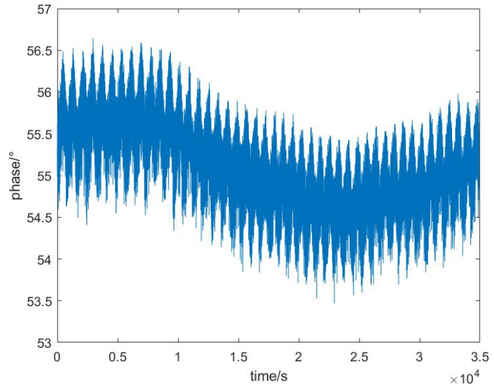
Algorithms

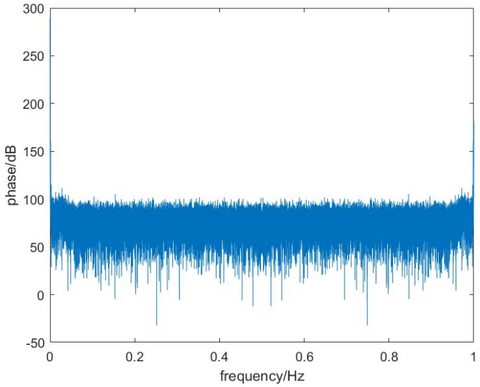
Pulse-to-pulse feedback



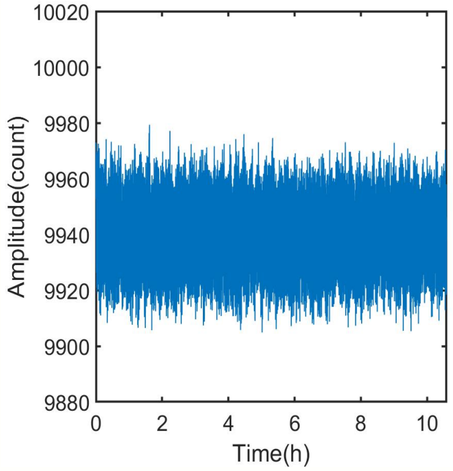


Klystron output amplitude waveform and spectrum (10 hours)



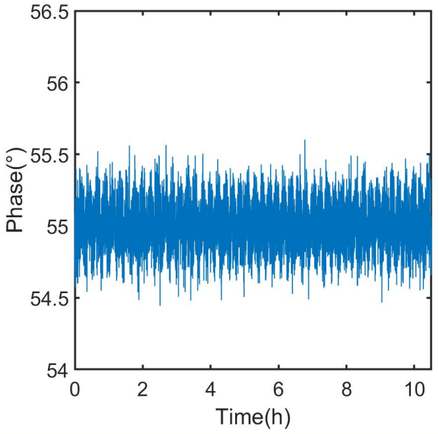


Klystron output phase waveform and spectrum (10 hours)



	Open loop	Closed loop
Amplitude	0.20%	0.15%
Phase	0.44	0.15

The amplitude and phase fluctuation of open loop can be suppressed by PI feedback between pulses. Over 10 hours of monitoring, amplitude fluctuations (the klystron operating at saturation zone) were shown to decrease from 0.2% to 0.15% (RMS) and phase from 0.44° to 0.15° (RMS).



Summary

Brief introduction

- The introduction of LLRF
- The application of LLRF in HLS II and IR-FEL

Self developed LLRF

- LLRF controller and peripherals
  - Hardware
  - Software
  - Algorithms
- Offline tests have been finished
- Online tests is being prepared

THANK YOU FOR YOUR ATTENTION !