# The development of LLRF system for STCF

**Reporter:** Ziyu Xiong, Chunjie Xie, Zeran Zhou

**Time:** 2024.01.17

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# /01 Introduction

- The overview of STCF.
- The RF system of STCF.

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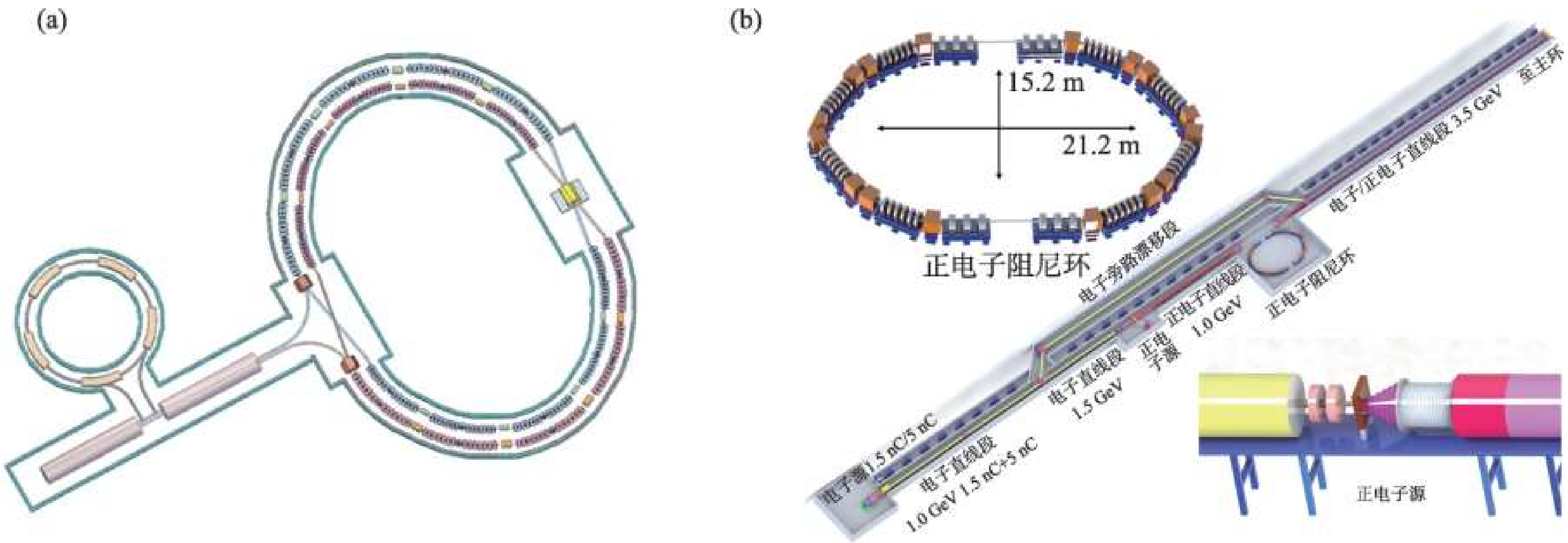
# 1.1 | The overview of STCF






Center-of-mass energy: 2-7 Gev （-charm threshold)

Designed brightness: > $0.5\times10^{35}$ $cm^{-2}s^{-1}$

Physical design:
- linear injector
- storage ring
- damping ring

- double-ring completely symmetric
- positive and nagative electron beam energy is equal
- only one collision point

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**A1** Administrator, 2024/1/12

# 1.1 | The overview of STCF

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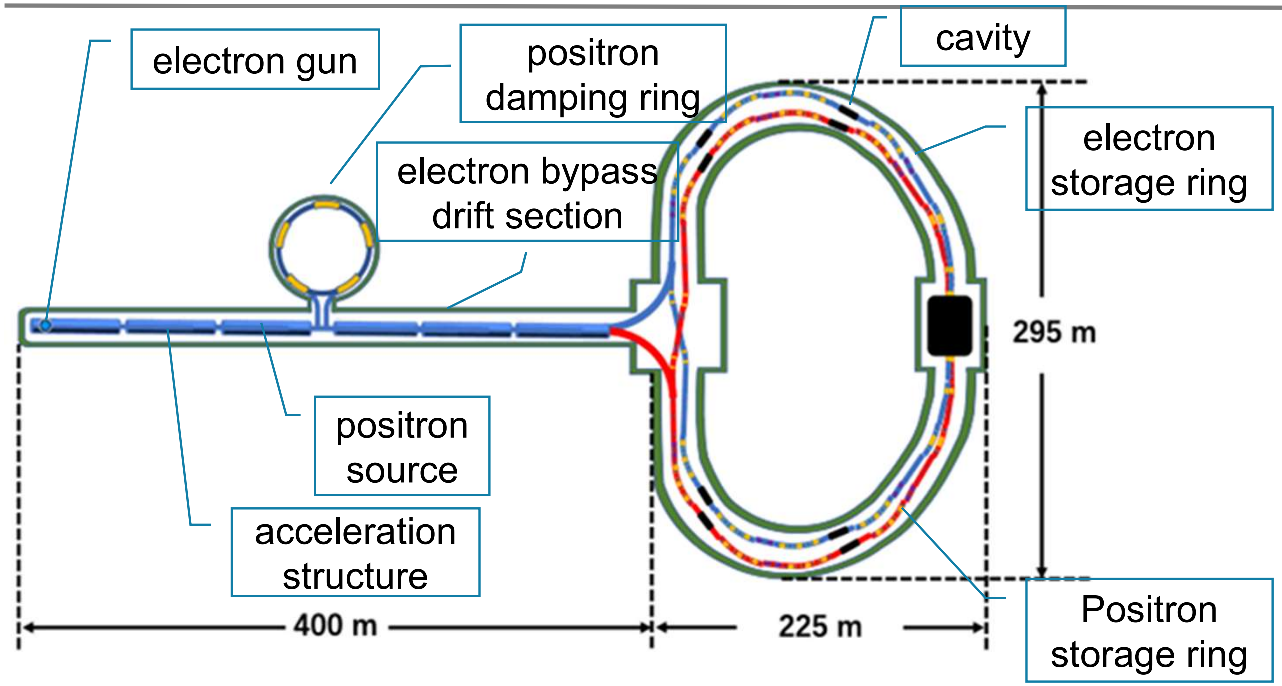
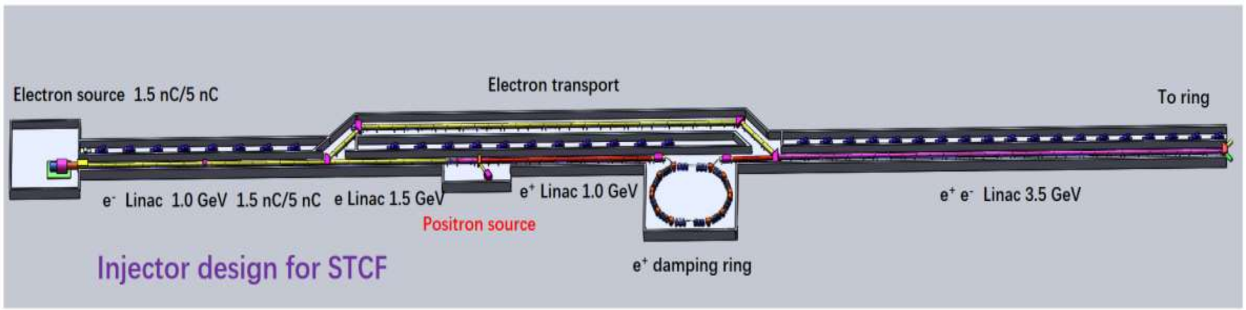



| Parameters | |
|---|---|
| Beam current(A) | 2 |
| Beam energy(GeV) | 2(storage ring) |
| | 3.5(Linac) |
| RF frequency(MHz) | 497.5 (storage ring) |
| | 2998 (Linac) |
| Harmonic number | 1024 |
| Revolution frequency (kHz) | 486.08 |

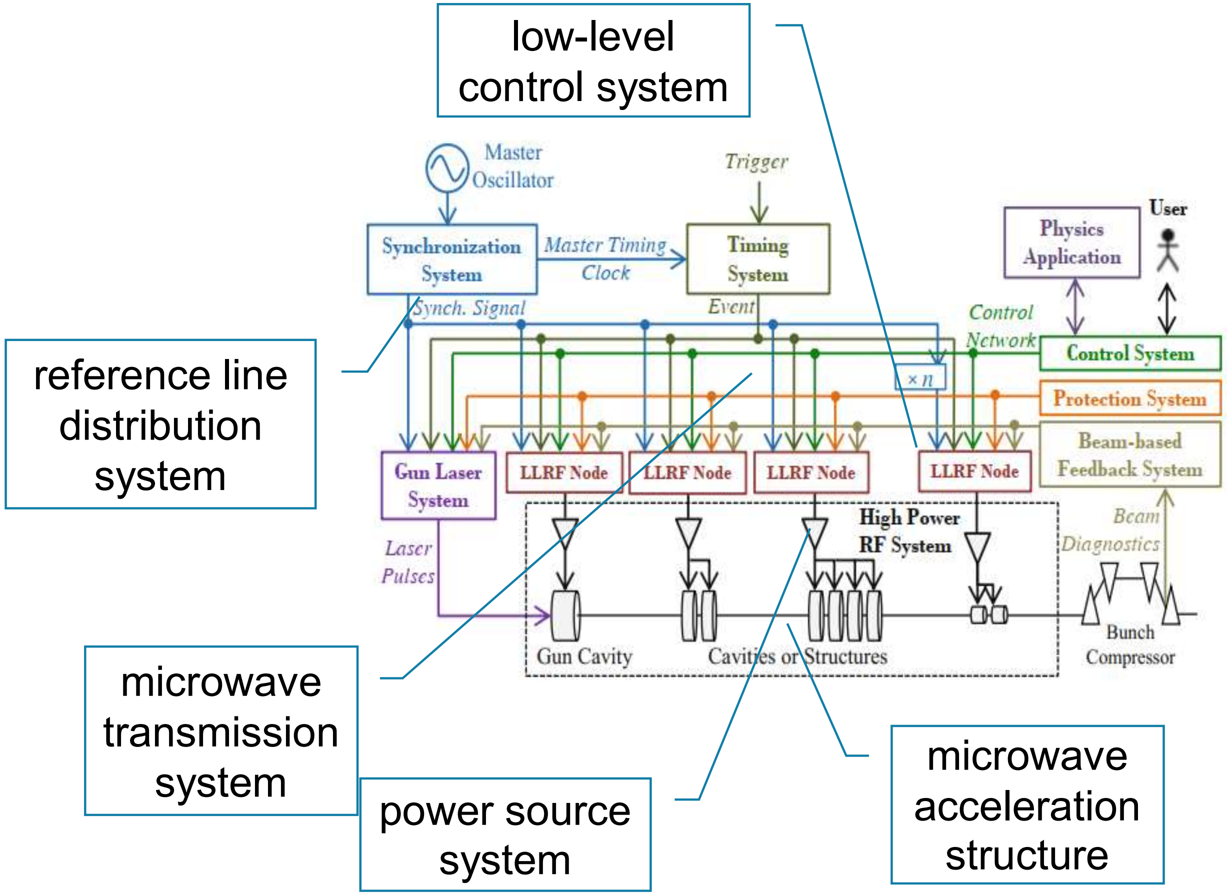
**Linear injector:**

- electron gun.
- beaming system.
- linear acceleration sections.
- positron source.
- electron bypass drift section.
- positron damping ring.

**Storage ring:**

- electron storage ring.
- positron storage ring.

# 1.2 | The RF system of STCF




- **low-level control system:** control and maintain the phase and amplitude stability of RF station during beam travelling;
- **reference signal distribution system**: provide reference signals;
- **microwave transmission system:** include high-power waveguide attenuator/phase shifter, waveguide transmission segment, input coupler, coaxial absorption load and so on;
- **pulse/continuous power source system**: include S-band klystron and focusing coil, high-voltage power supply, power source monitoring system and the solid state modulator;
- **microwave acceleration structure:** include accelerator tube, a pre-buncher and a buncher. The travelling-wave accelerating tube consists of an accelerating unit and a coupler.

# /02 LLRF for Linac

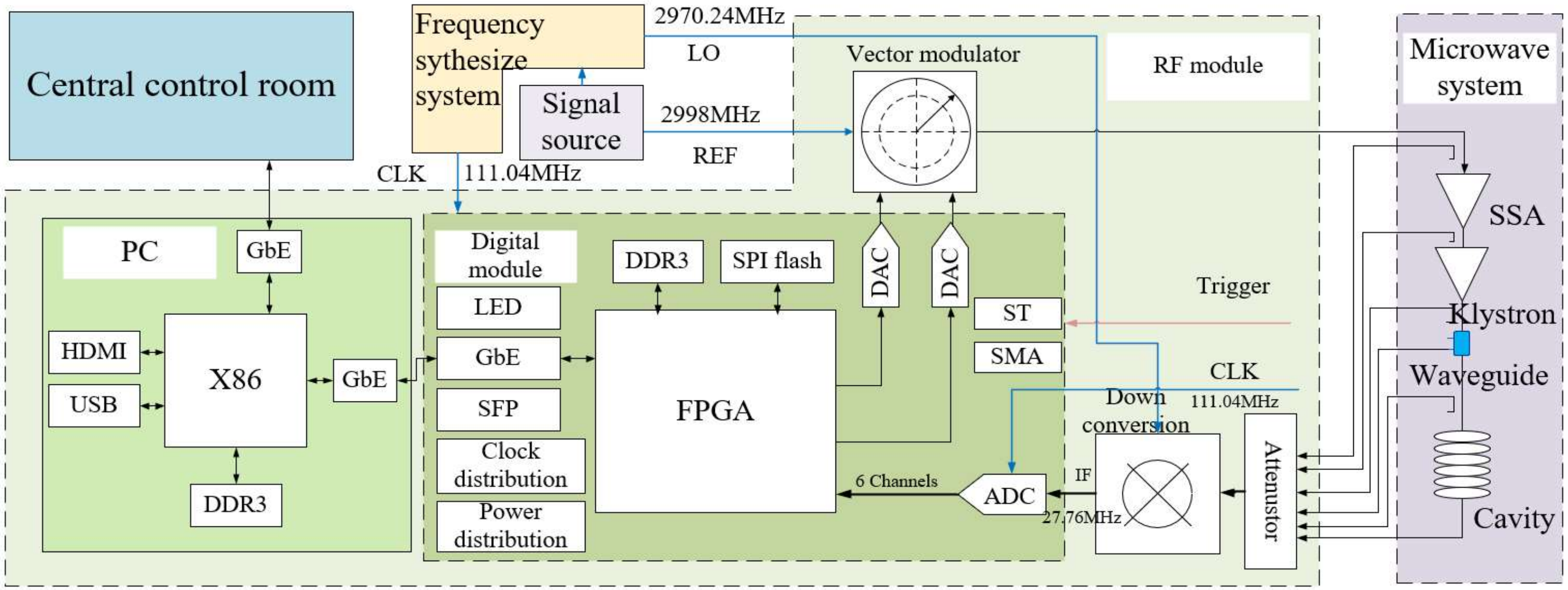
- The schematic of the LLRF for Linac(@2998 MHz, pulsed).
- Former research basis of 2856 MHz LLRF for NSRL.
- The following work of LLRF for STCF Linac.

# 2.1 | The schematic of the LLRF for Linac(@2998 MHz, pulsed)

## RF system (@2998 MHz)

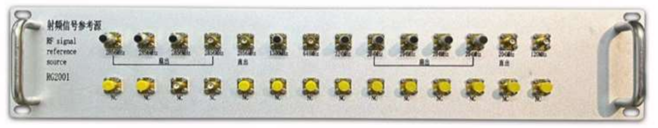
The STCF requires the construction of electron injectors and positive injectors, and its microwave system needs to provide S-band (2998MHz) acceleration structure and microwave power. (**Accelerator pre-research** project has been launched in Nov. 2023)

To ensure the steady infusion of energy, we develop a 2998MHz low-level RF system, including signal source, frequency synthesizer, signal processor.



## 2.2 | Former research basis of 2856 MHz LLRF for NSRL

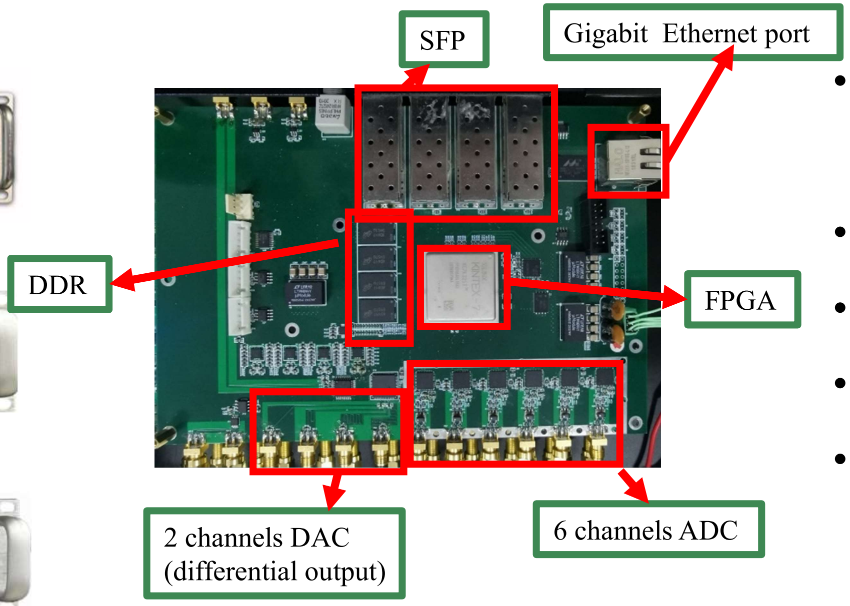
Signal source



Frequency synthesizer

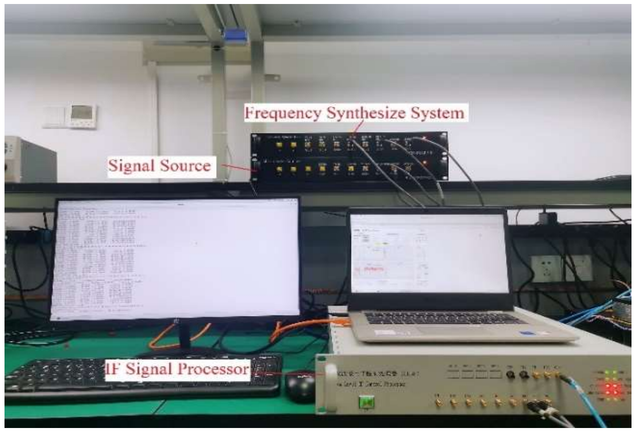
Signal processor

The LLRF system(2856M) operating at HLS II




The digital board in LLRF

- 6 channels 125MS/s 16bit ADC(2 channels reserved);
- 2 channels 250MS/s 16bit DAC;
- *6 channels down-converters;*
- *1 channel s-band vector modulator;*
- *Adjustable attenuator (31 dB).*




The offline workbench

### Hardware

- **Signal source**: generate REF signal (2856 MHz) for Linac RF system and frequency synthesizer.
- **Frequency synthesizer**: generate LO (2829.56 MHz) and CLK signal (105.78 MHz).
- **Signal processor**: monitor & control the solid-state amplifier, klystron and cavity.

# 2.2 | Former research basis of 2856 MHz LLRF for NSRL

GUI

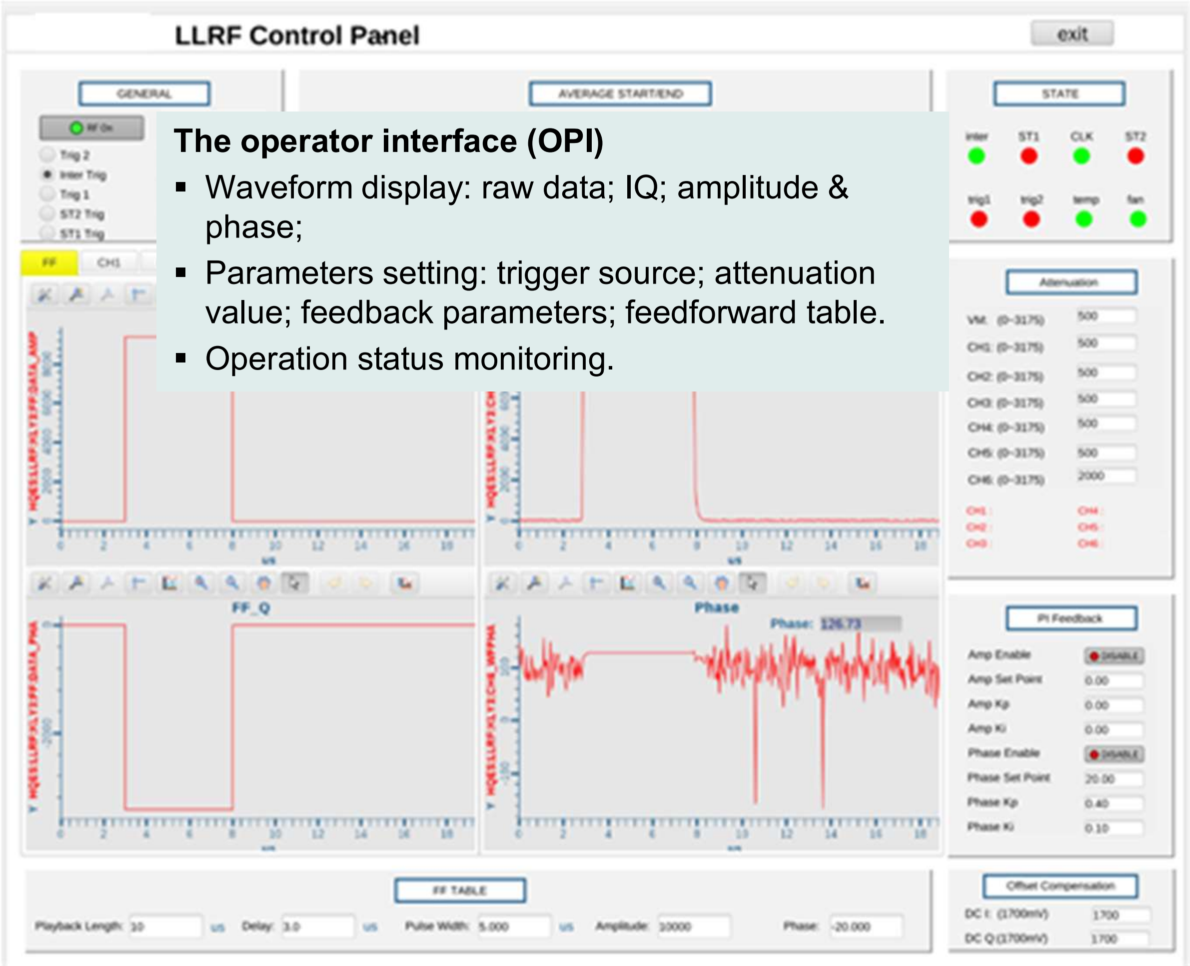
EPICS Application(RF control algorithms, …)

EPICS IOC(driver,kernel)

**Graphic user interface (GUI):**
Developed based on phoebus;
Implement remote control.

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

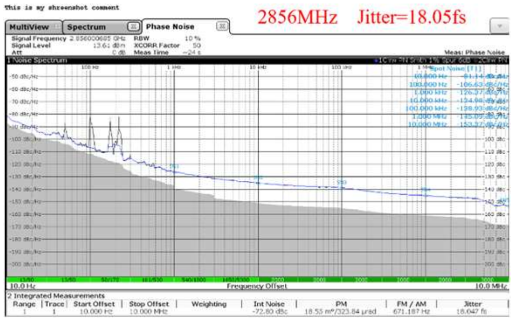
**EPICS IOC:**
Provide driver talk to the hardware;
Connect EPICS record with the physical hardware data;
Provide process value to the upper level.

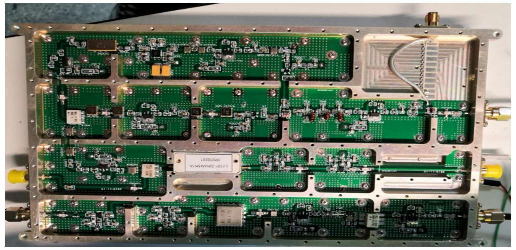


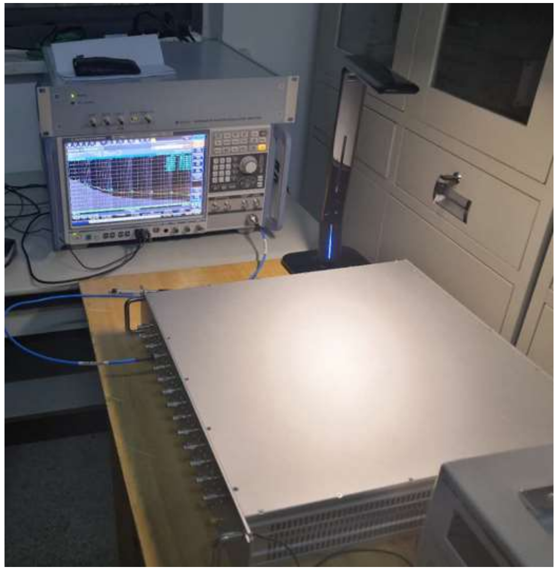

**The operator interface (OPI)**

- Waveform display: raw data; IQ; amplitude & phase;
- Parameters setting: trigger source; attenuation value; feedback parameters; feedforward table.
- Operation status monitoring.

# 2.2 | Former research basis of 2856 MHz LLRF for NSRL

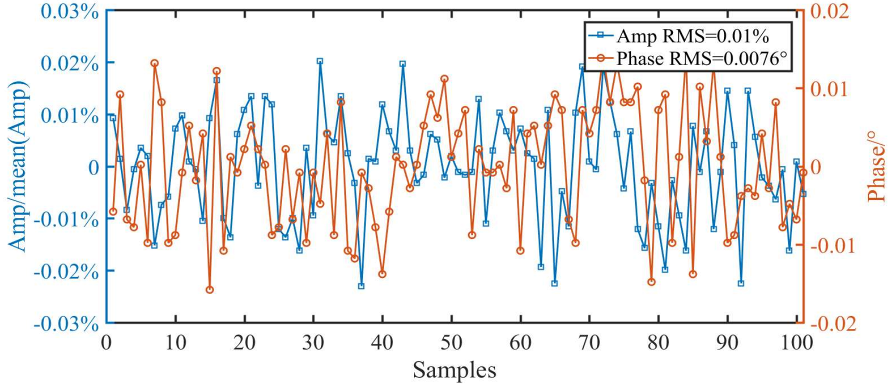


| Main technical specification | |
|---|---|
| Number of channels | 6 |
| Channel isolation | 65 dB |
| Input signal range | 15 dBm |
| The rising edge | 50 ns |
| The phase noise | 19.17 fs |
| Short term amplitude stability(RMS) | 0.010% |
| Short term phase stability(RMS) | 0.0076 ° |
| RF input attenuation range | 0~31.75 dB in 0.25 dB steps |

| | 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 | 18.05 | 0.00175 | 0.0255 |

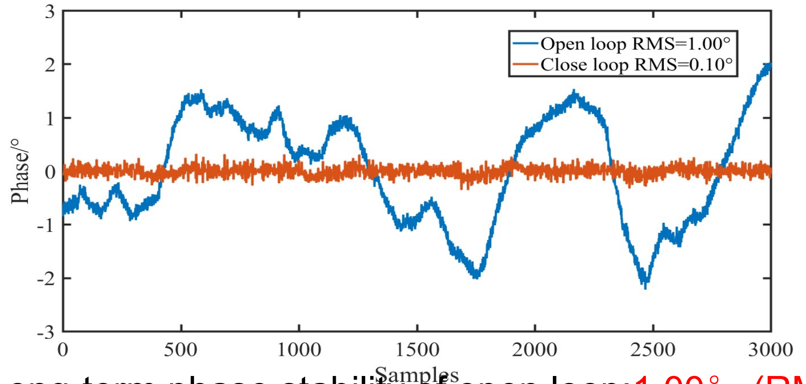
# 2.2 | Former research basis of 2856 MHz LLRF for NSRL

## Offline bench test



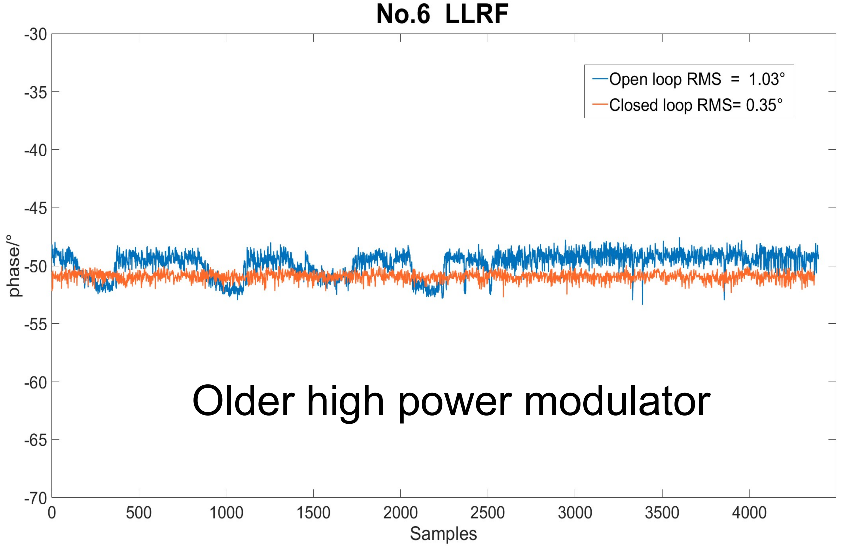

- Short-term amplitude stability:0.01% (RMS).
- Short-term phase stability: 0.0076° (RMS).

## Beam test at photocathode radio frequency gun




- Long-term phase stability of open loop:1.00° (RMS).
- Long-term phase stability of closed loop: 0.10° (RMS).

## Operating results at HLS II




Since May. 2022, three self-developed LLRF processors have replaced the No. 6,7, and 8th MTCA based processors in HLS II. They have been running smoothly and reliably over one year and a half, without any failure, which ensuring the stable operation of HLS II under the top-off injection mode.

# 2.3 | The following work of LLRF for Linac

**Hardware aspects:**

- Design a signal source which provides the 2998MHz reference signal and a frequency synthesizer which provides the ADC sampling signal(CLK) and local signal(LO);
- Design an IF processor which can generate pulses with repetition rate of 50Hz;
- Design the microwave reference line and phase calibration system, which ensures the consistency among different LLRF systems.

**Software aspects:**

- Use the Debian OS to replace the centos system(longer update cycle, higher long-term stability) ;
- Use the package EPICS 7.0 instead of EPICS 3.1(less bugs);
- Use the PYDM instead of Phoebus(open source, higher development efficiency).

## /03 LLRF for storage ring

- The schematic of the LLRF(@497.5MHz,CW).
- Modeling and simulation of LLRF.
- The design of closed-loop control.

# 3.1 | The schematic of the LLRF(@497.5MHz,CW)

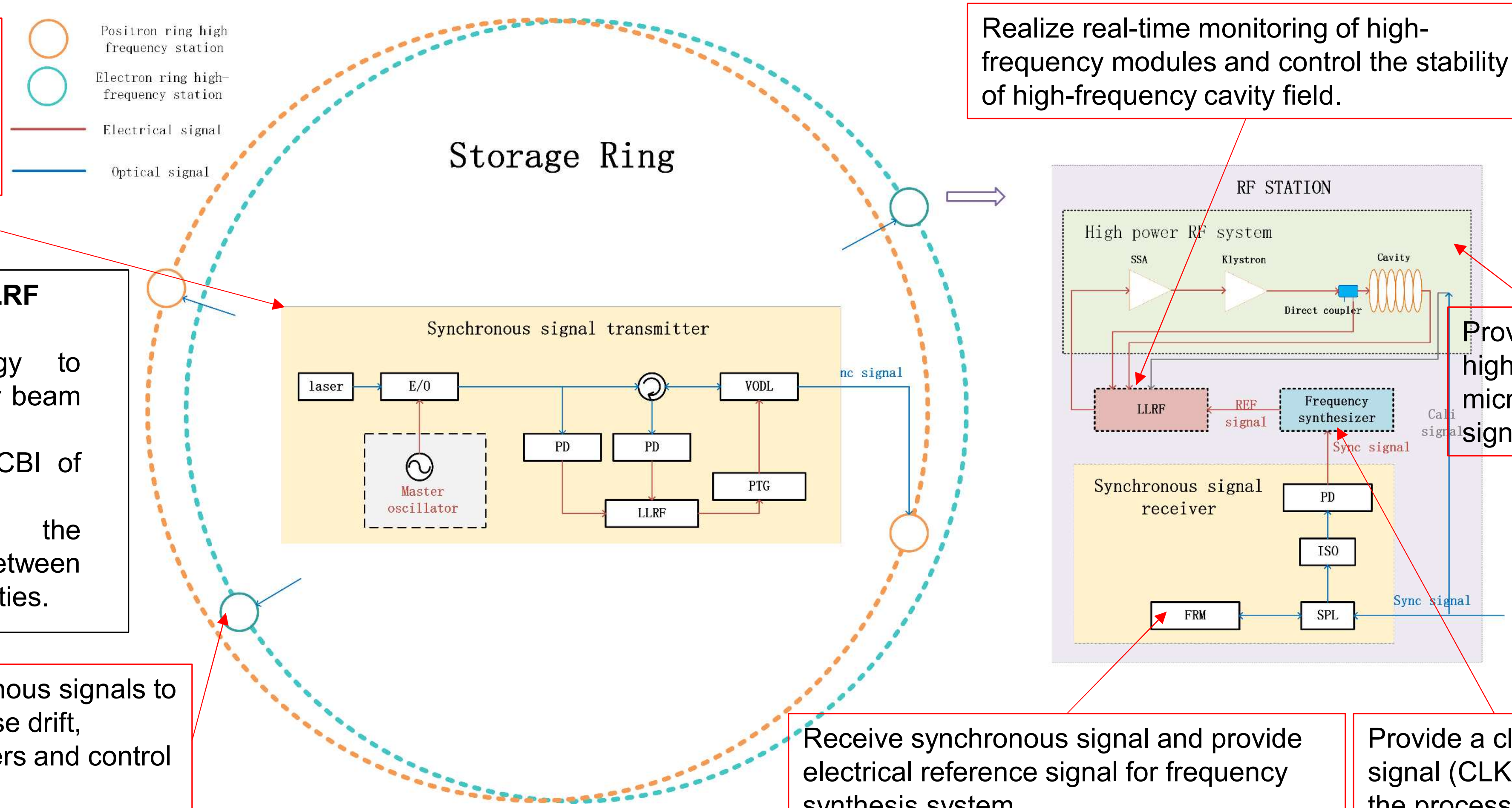
Provide the reference signal to every RF station to let them lock each other.

**The roles of LLRF**

- Provide energy to compensate for beam loss;
- Suppress the CBI of beams;
- Synchronize the electric field between accleration cavities.

Receive synchronous signals to calibrate the phase drift, monitor parameters and control them.

Realize real-time monitoring of high-frequency modules and control the stability of high-frequency cavity field.

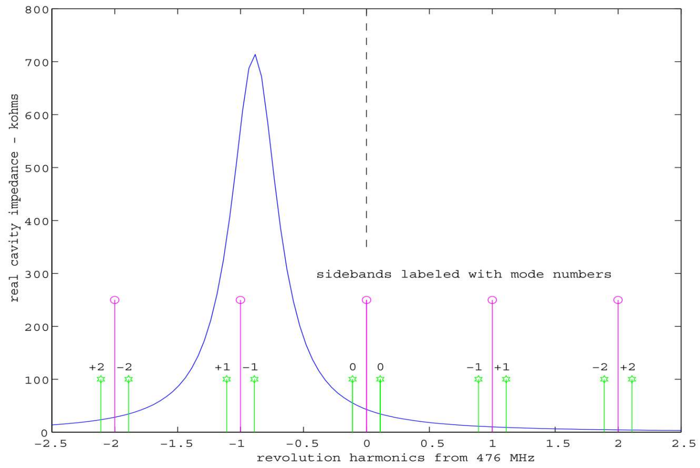



Provide high power microwave signal.

Receive synchronous signal and provide electrical reference signal for frequency synthesis system.

Provide a clock signal (CLK) for the processor.

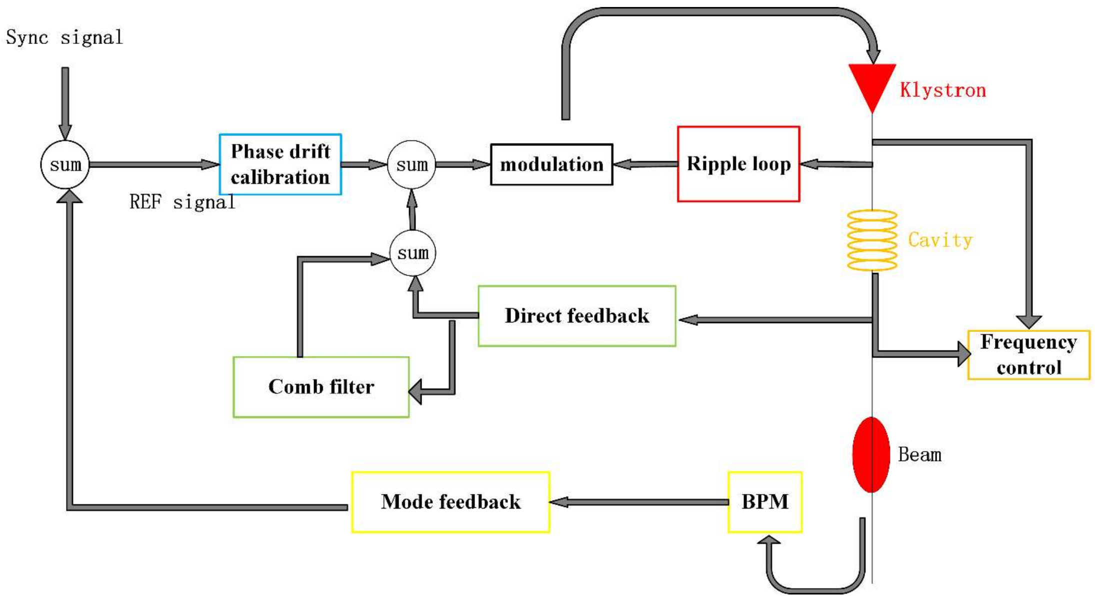
# 3.1 | The schematic of the LLRF(@497.5MHz,CW)




$$\frac{1}{\tau} = \left( \frac{I_0 \eta f_{rf}}{2\nu_s \beta^2 \frac{E}{e}} \right) R_{cb}$$

I0=average DC beam current
η=momentum compaction
β=paiticle velocity factor
$v_s$=synchrotron tune
E=particle energy
e=electron charge
$f_{rf}$=RF frequency
$R_{cb}$=total real （$Z_{upper}$-$Z_{lower}$)

Large perimeter and beam current leads to a more severe longitudinal growth rate, so we need to design multiple feedback loops to reduce the observed impedance of the beam.




The collider low-level control loop includes direct control loop, comb filter feedback loop, mode feedback loop, modulator jitter feedforward loop, frequency control loop, and so on.

# 3.2 | Modeling and simulation of LLRF

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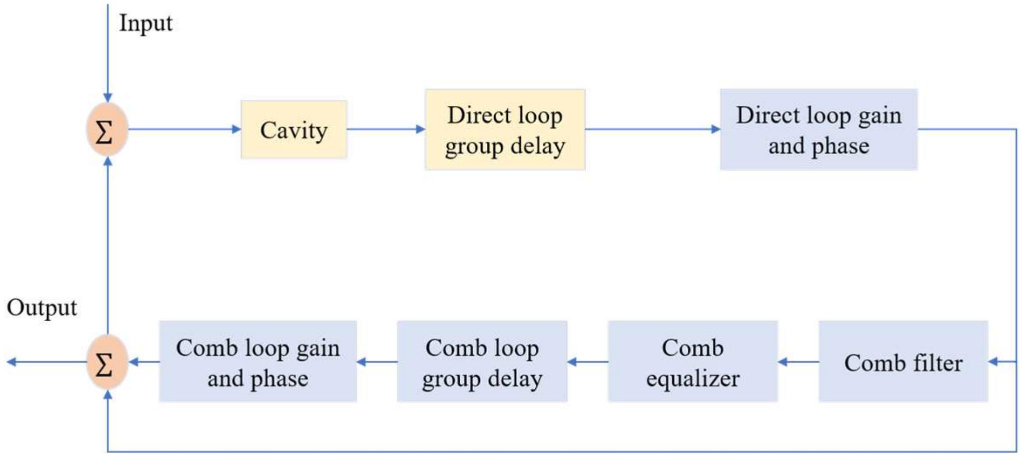
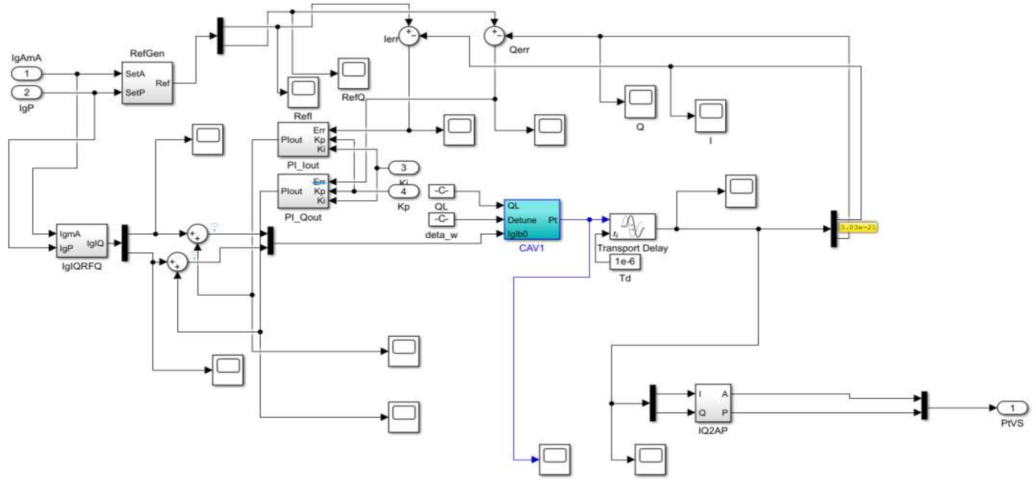



Simulation of the direct feedback loop(@ 500 MHz)

The closed-loop transfer function of the feedback system, $L_{dir}$ is the open loop transfer function of the direct feedback loop, and $L_{comb}$ is the open loop transfer function of the comb filter feedback loop:

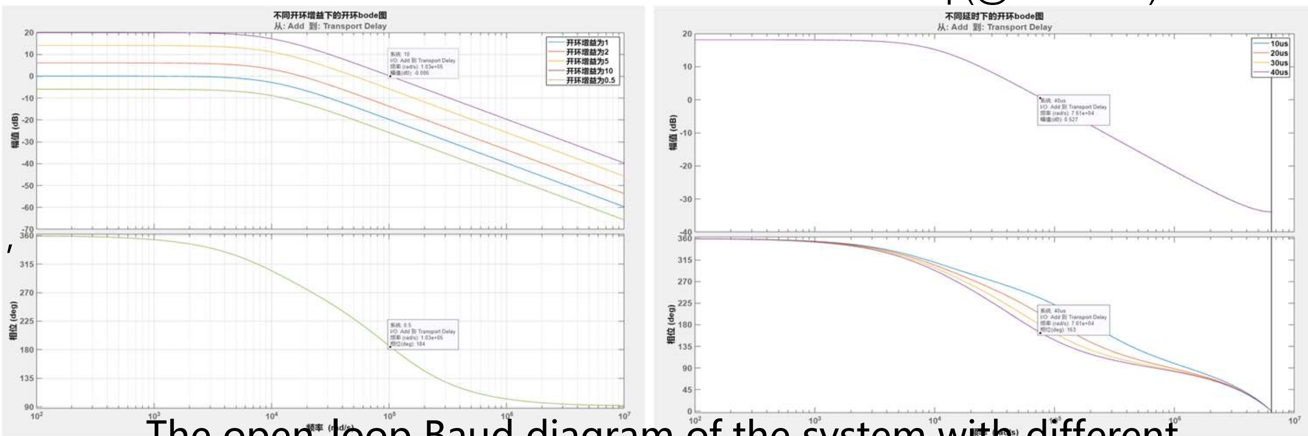
$$H_{meas}(s) = \frac{L_{dir}(s)}{1-(1+L_{comb}(s))L_{dir}(s)}$$

Where σ is the damping time of the high-frequency cavity ,

$$\sigma = \omega_{rf} / (2Q_l)$$

$$L_{dir}(s) = \frac{2\sigma s}{s^2 + 2\sigma s + \omega_r^2} H_{lead}(s) G_d e^{i\phi_d - (s - i\omega_{rf})T_d}$$

$$L_{comb}(s) = H_{comb}(s) H_{eq}(s) G_c e^{i\phi_c - (s - i\omega_{rf})T_c}$$




The open-loop Baud diagram of the system with different feedback coefficients (left) and different time delays (right)

# 3.3 | The design of closed-loop control

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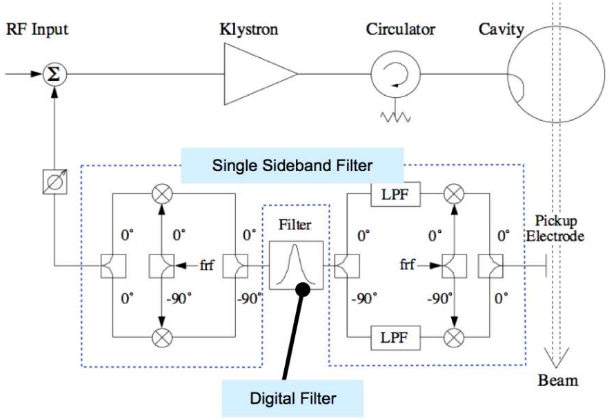
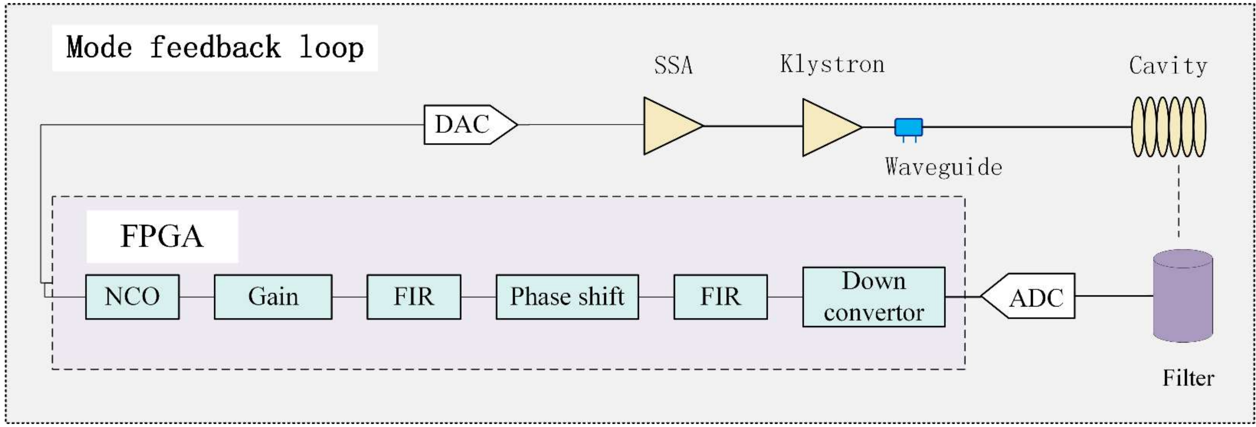
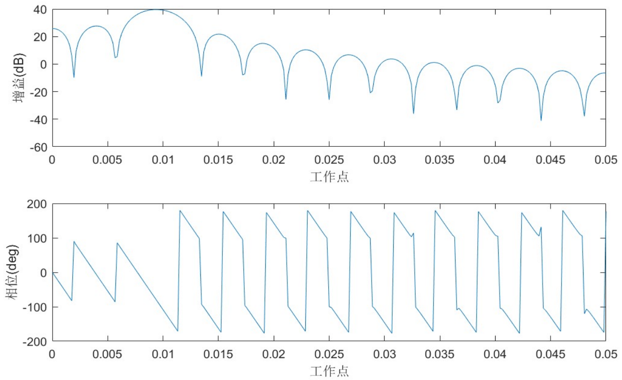
## The suppression of specific synchronous oscillation frequency




Mode feedback loop




Mode feedback loop（FIR）

The function(time domain) of the FIR filter is:

$$C_n = \sin(2\pi\nu(n-1)-\phi)$$

Where n is the filter order, ν is the tune of the storage ring, and ϕ is the tunable phase.
Under the current tune of 0.0097, the longitudinal feedback filter of 105 order is shown in figure (left).

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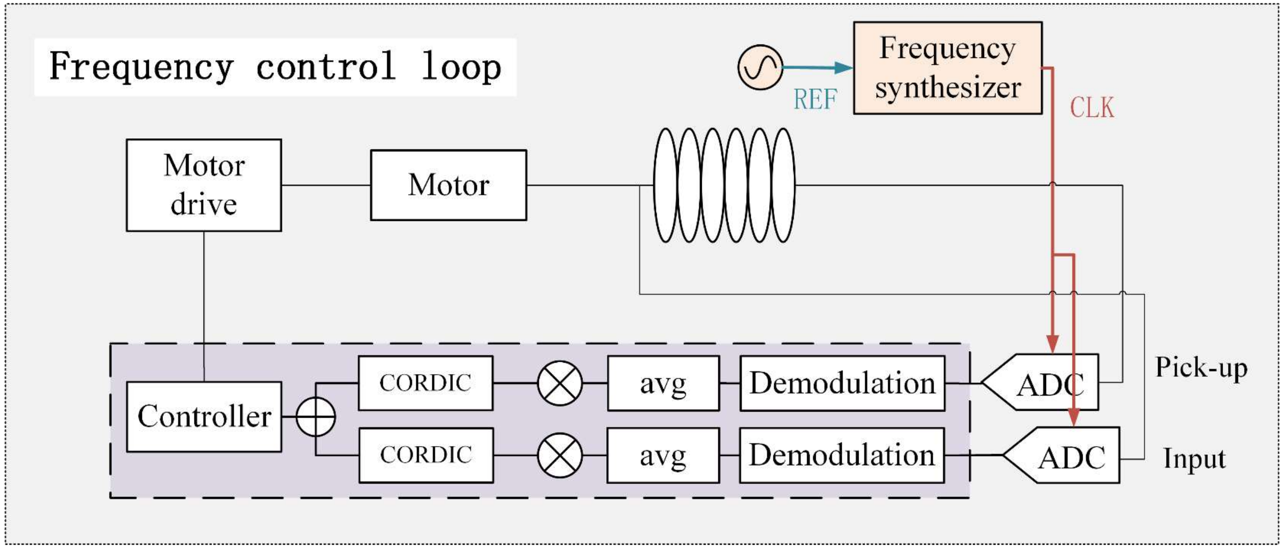
## Frequency control

The relationship between the detuning Angle(Δφ) of the high-frequency cavity and the detuning frequency(Δf):

$$\tan\Delta\varphi = -2\frac{\Delta f}{f_0} * Q_L$$




The frequency control loop is generally composed of a digital phase detector module, control tuning motor (tuner) and piezo.

- **Digital phase detection module:** Calculate the phase difference between pickup and the input signal.
- **Control tuned motor (large range, slow speed) :** By changing the axial length of the accelerator cavity, the equivalent capacitance of the accelerator cavity is changed, and the resonant frequency is changed.
- **Piezoelectric ceramics (small range, fast speed) :** Piezoelectric ceramics use high pressure to change the length of the piezoelectric ceramics, which causes the axial length of the acceleration cavity to be stretched or compressed.

# /04 Summary

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## Current progress:

- Complete the hardware and software of the LLRF for NSRL(@2856 MHz, S-band, pulsed).
- Design a series of feedback loops for the storage ring, including direct control loop, comb filter feedback loop, mode feedback loop, modulator jitter feedforward loop, frequency control loop.
- Simulation of the feedback loops for the storage ring.

## Future plans:

- Design and complete a new LLRF system(@2998 MHz) for the Linac on the basis of former work;
  - Redesign the frequency of CLK and LO;
  - Change the data transmission mode to accommodate the high repetition frequency mode;
  - Add phase drift calibration function to increase system control accuracy.
- Design and complete the hardware and software for the storage ring LLRF(@497.5 MHz, CW);
- More complete modeling and simulation to support our design;
- Design a new system to achieve reference line synchronization and phase drift calibration.


Thanks!