SRF LLRF for CSNS-II LINAC

LLRF2023,Korea

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Outline

01 **CSNS-II Overview**

02 CSNS-II Linac SRF LLRF

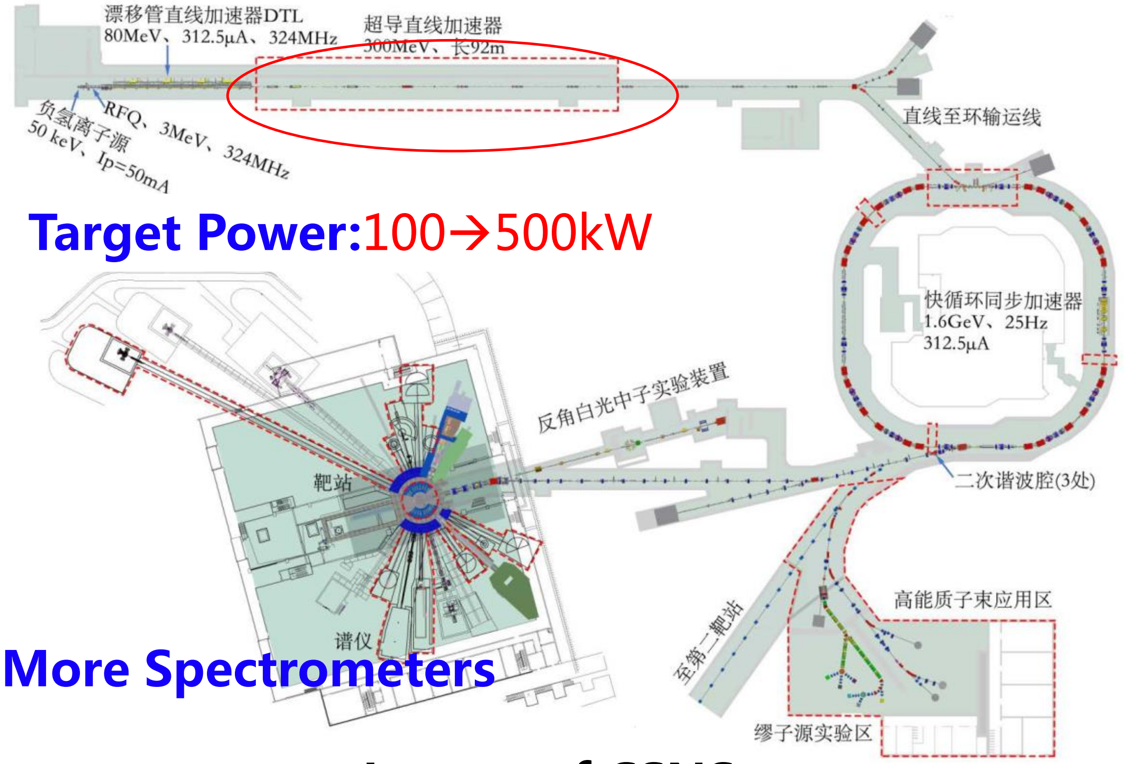
- Pre Research at C-ADS Injector I
- Simulation Work
- SRF Coupler Conditioning

03 Summary and Future Work

CSNS-II Overview

- Construction Time:2023.12 ~ 2029.3
- A SRF section is to be added to increase energy from 80 to 300MeV.

Linac Energy:80MeV→300MeV



Target Power:100→500kW

More Spectrometers

Layout of CSNS

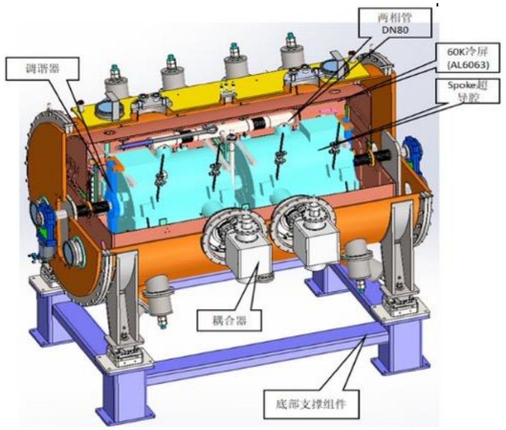
CSNS	Phase I	Phase II
Beam power on target(kW)	100	500
Linac energy (MeV)	80	300
Extraction beam energy (GeV)	1.6	1.6
Average beam current (μA)	62.5	312.5
Linac Peak beam Current(mA)	15	40
Repetition(Hz)	25	25
Linac Beam Len(μs)	500	~500

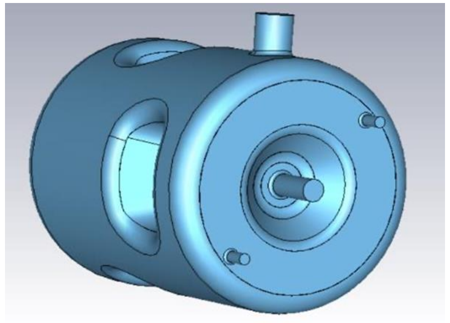
SRF Accelerator Section

- **SRF cavity is processing and testing.**

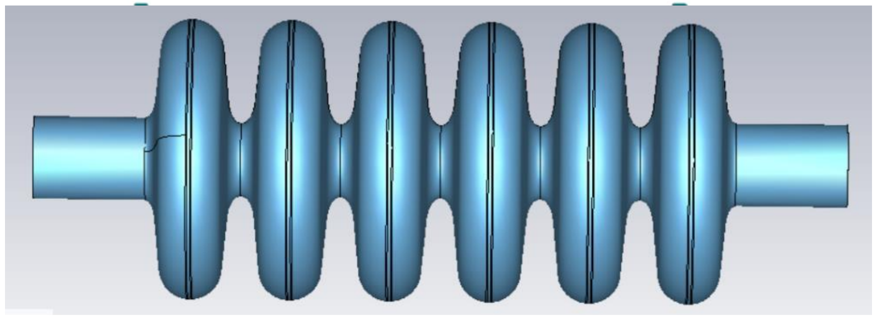
Items	SPOKE	SPOKE (Improved)	ELLIPTICAL
Freq(MHz)	324	324	648
Gradient(Mv/m)	**7.3**	**9**	14
Length(m)	0.694	0.694	0.86
R/Q (Ω)	410	401	309
QL	2.3e5	2.3e5	9.6e5
LFD Hz/(MV/m)^2	**-10.7**	**-4.56**	-1.5
LFD@ Max Gradient	530	369	250
f_{3db}	1408	1408	674
df/dp(Hz/mbar)	0.773	38	6.3

*Most of data are simulation.





324MHz Double-Spoke Cavity X 20



648MHz Elliptical Cavity X 24

Outline

LLRF Parameters and Hardware

- Stability requirement: ±0.3%, ±0.3°
- mTCA.4 based, SIS8300KU + DS8VM1/DWC8VM1
- Domestic digital cards maybe used

Items	Parameter	UNIT
Frequency	324/648	MHz
RF Len	1.2	ms
Repetition	25	Hz
Beam Len	~500	μs
Beam current	30	mA
Beam Chop rate	1	MHz
Amplitude	±0.3	%
Phase	±0.3	Deg
RF Power Source	Solid SA/Klystron	-

DESY DWC8VM1

DESY SIS8300KU

Zynq Based mTCA.4 Designed in China

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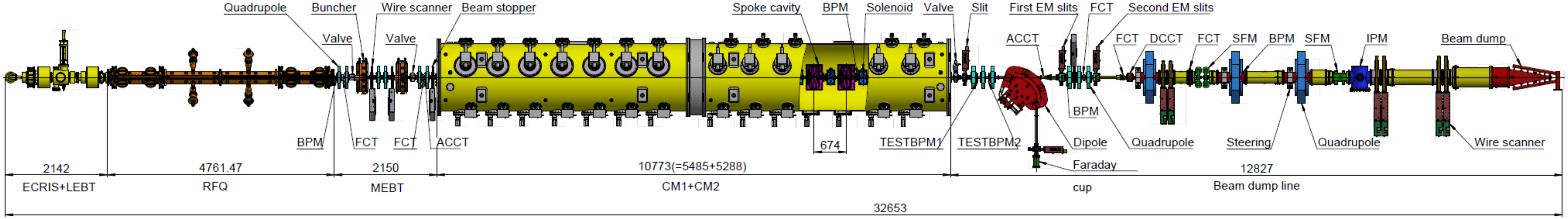
Pre Research work at C-ADS Injector I

□Algorithm verification at C-ADS Injector I

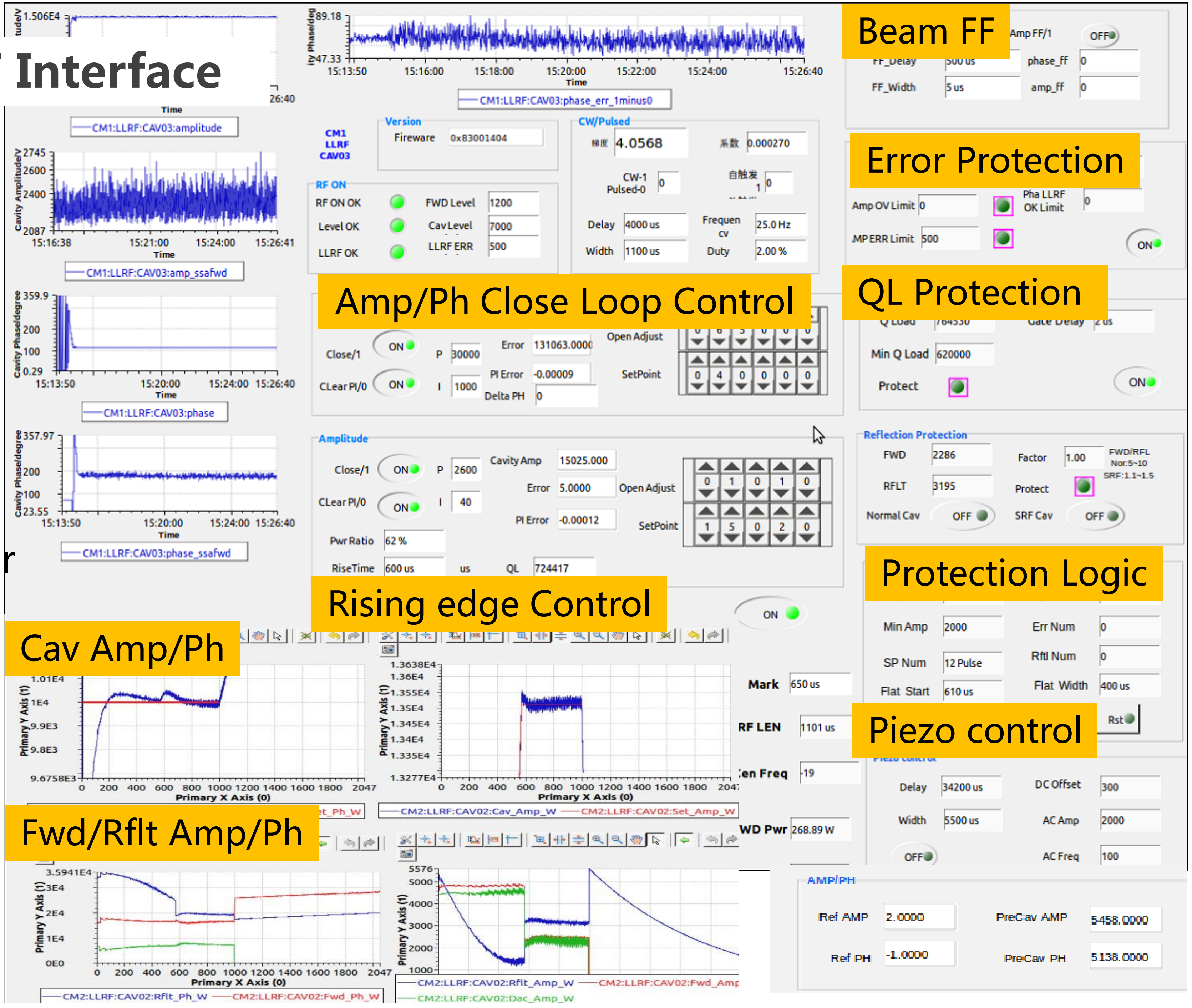


ADS Injector I SRF Cavity

- ✓ **14 Spoke Cavities**
- ✓ **Freq:** 325MHz
- ✓ **Beam Current :** 1-10mA
- ✓ **Q_L :** ~7e5
- ✓ **Gradient :** 4~7Mv/m
- ✓ **R/Q:** 142
- ✓ **LDF[Hz/(Mv/m)^2]:** -15
- ✓ **df/dp [Hz/mbar]:** -120

C-ADS: China Accelerator-Driven Subcritical

C-ADS Injector I : LLRF Interface



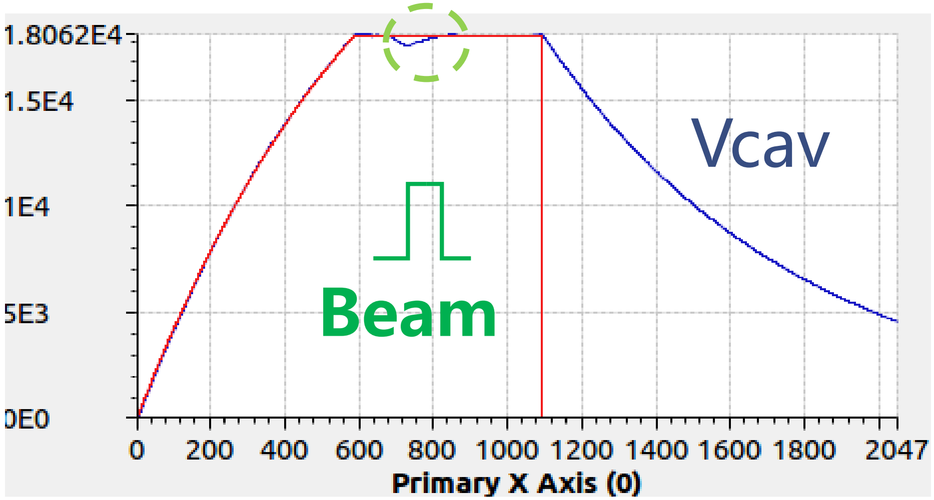
Functions :

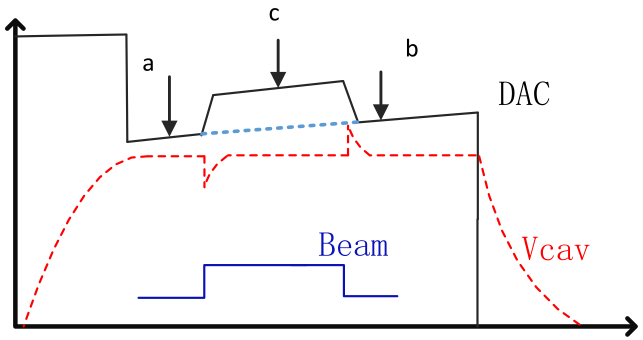
- ✓Continue → Pulse Mode
- ✓ Quench Detection
- ✓ Beam Feedforward
- ✓ Piezo Control
- ✓ Gradient/ Fwd/Rflt power
- ✓ Detune frequency
- ✓……

Vertex 5 FPGA

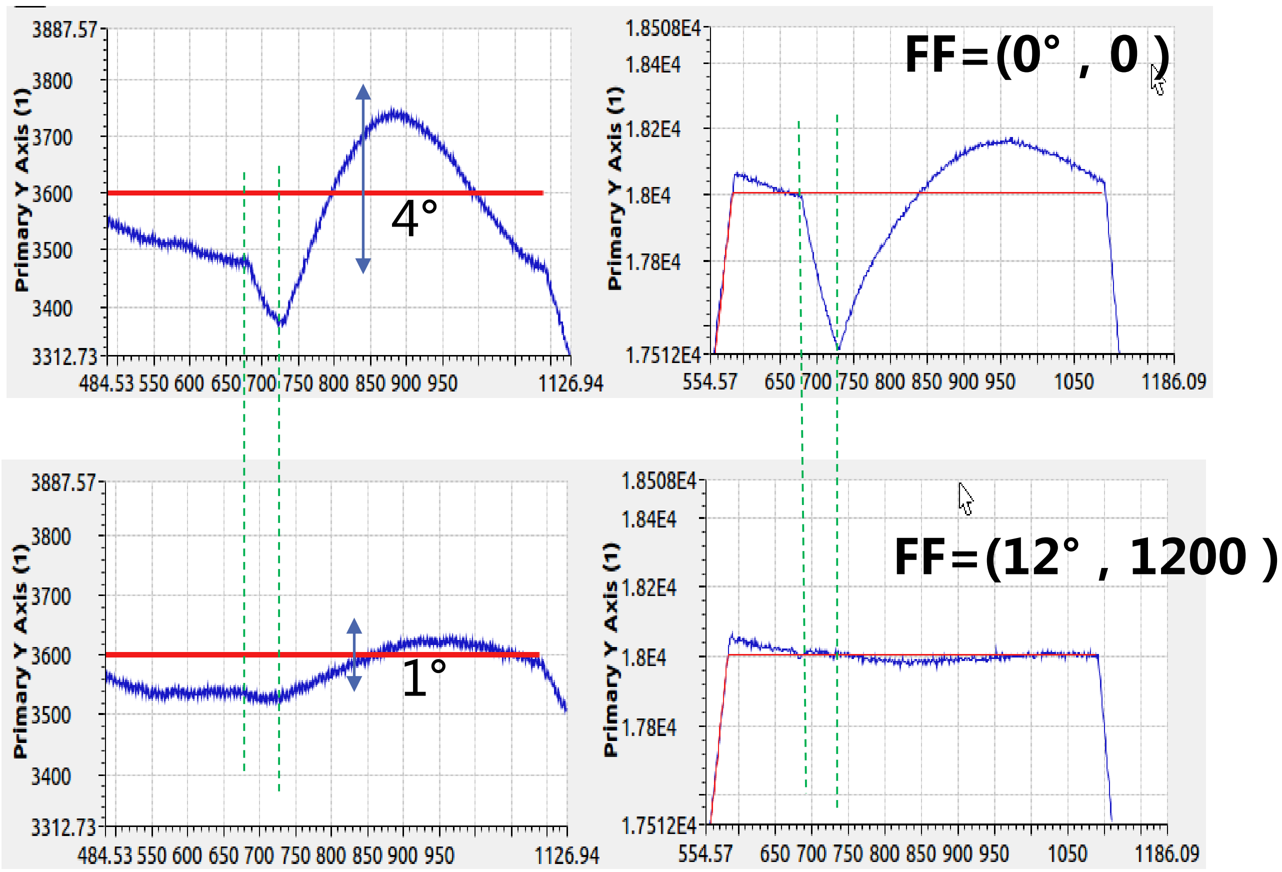
C-ADS Injector I : Beam Loading Compensation

➢ FF vector can be calculated from DAC waveform with feedback loop is closed.





$$\overrightarrow{FF} = (P_c - \frac{P_a + P_b}{2}, A_c - \frac{A_a + A_b}{2})$$



Phase

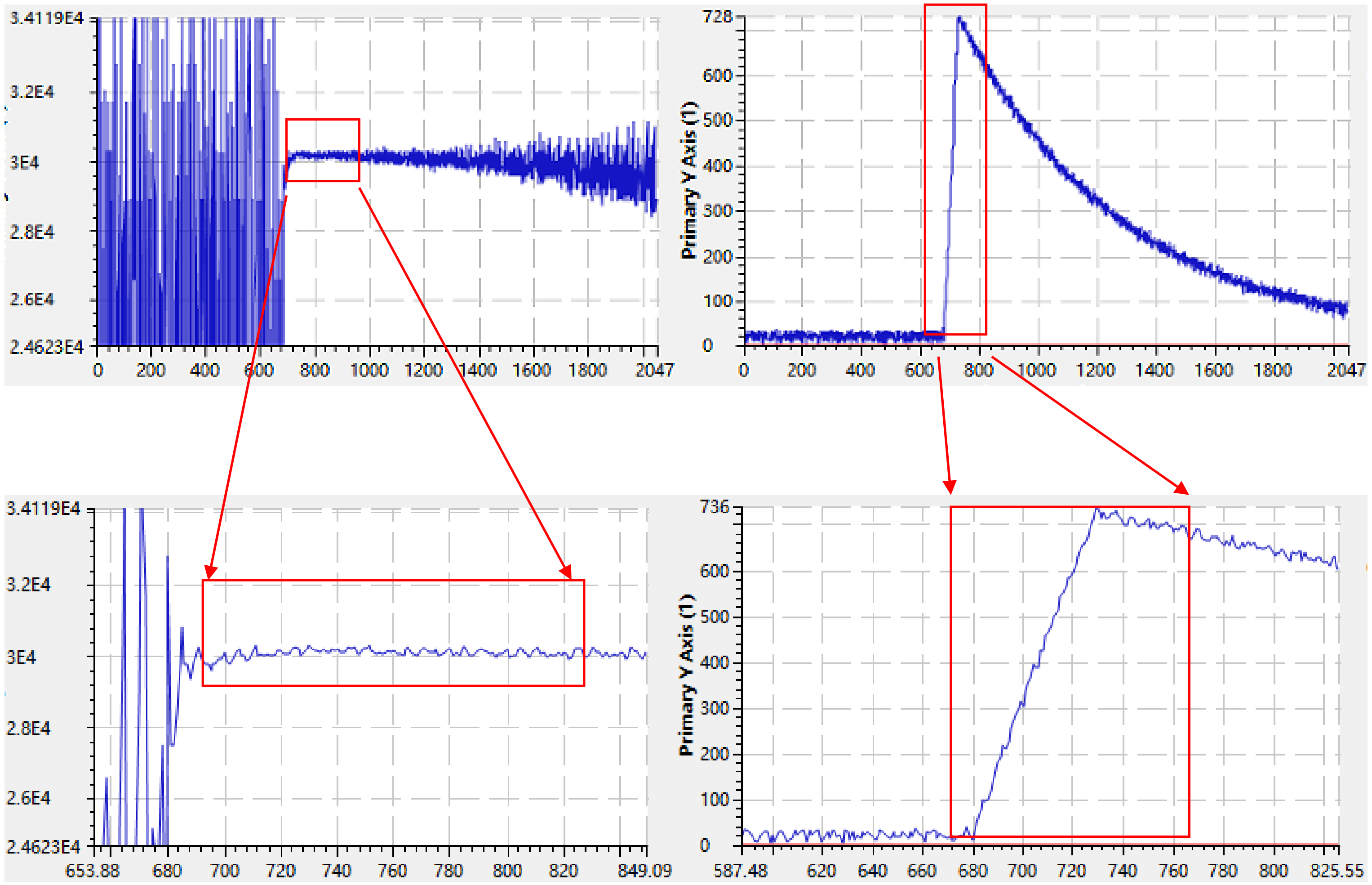
Amplitude

C-ADS Injector I : Beam-Loading Method

◻ Beam-Loading Method

1. RF Power off
2. Beam Output
3. Find out Decelerating Phase
4. Calculate Synchronic Phase

Cavity	Beam-Loading	Phase -Scan	Err
Buncher1	100°	95°	5
Buncher2	-80°	-85°	5
Cav01	43°	39°	4
Cav02	180°	175°	5
Cav03	170°	164°	6
Cav04	61°	66°	5



Beam-Loading Phase Beam-Loading Amplitude

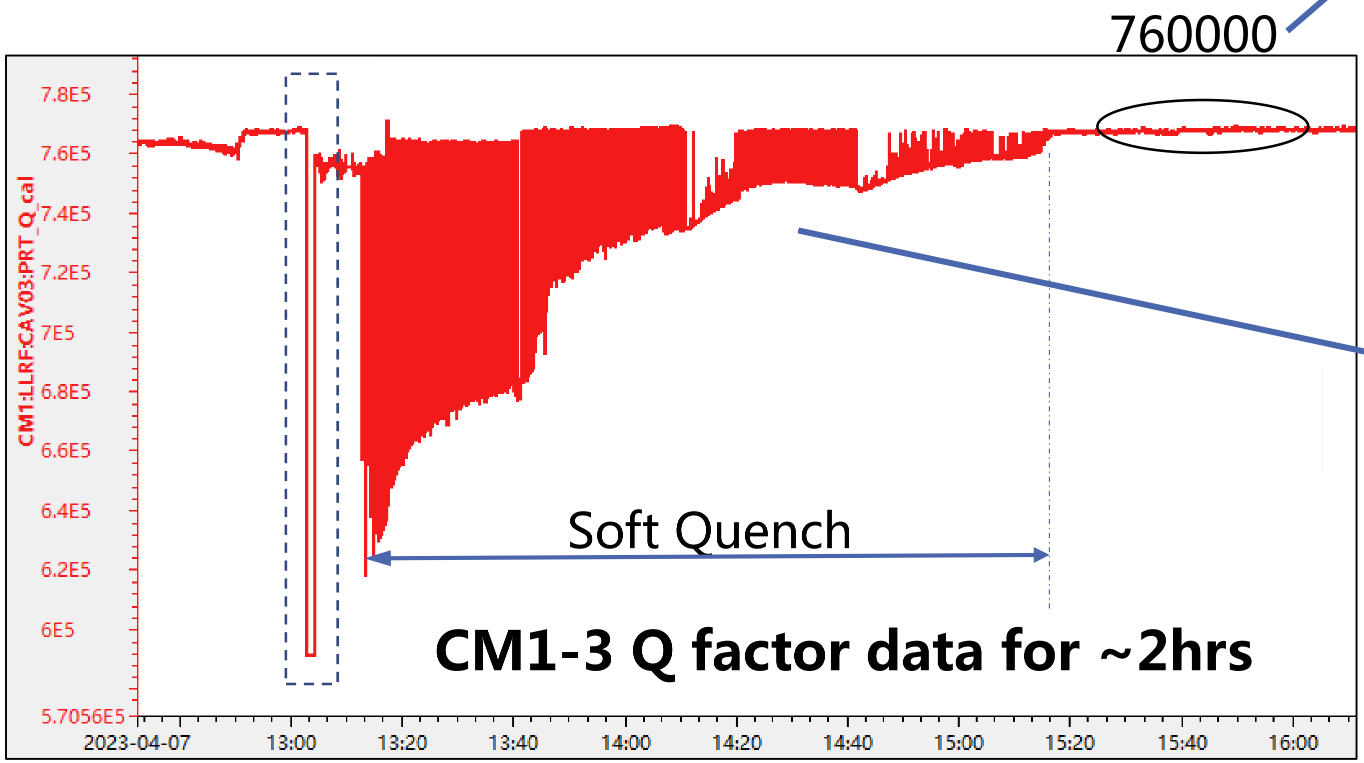
More convenient than Phase scan method.

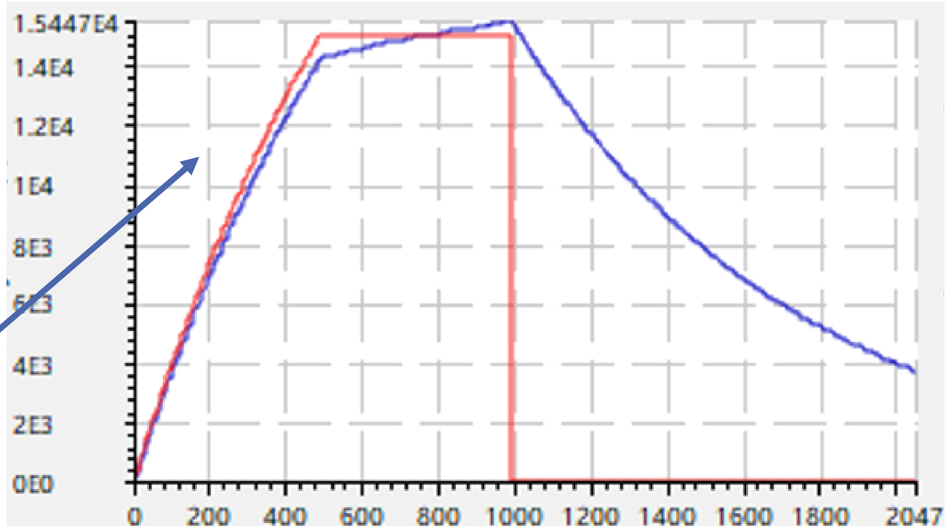
There are some difference between the two method maybe because of detuning problem.

[1] Zeng, R. , & Troeng, O. . (2016). Transient Beam Loading Based Calibration for Cavity Phase and Amplitude Setting

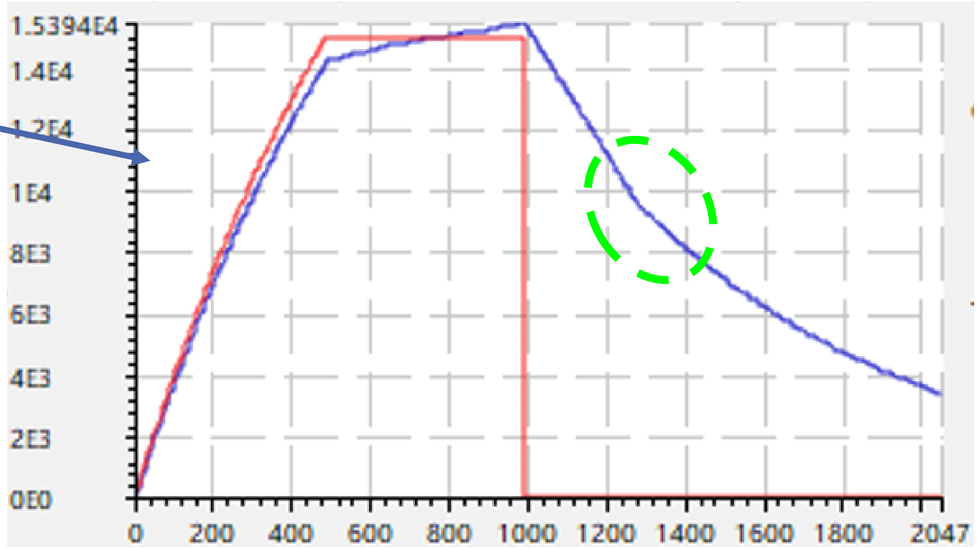
C-ADS Injector I : Quench Protection

- Use decay of the Cavity field calculate Loaded Q;
- Q factor Drops and jump up and down after ~2 hours of conditioning





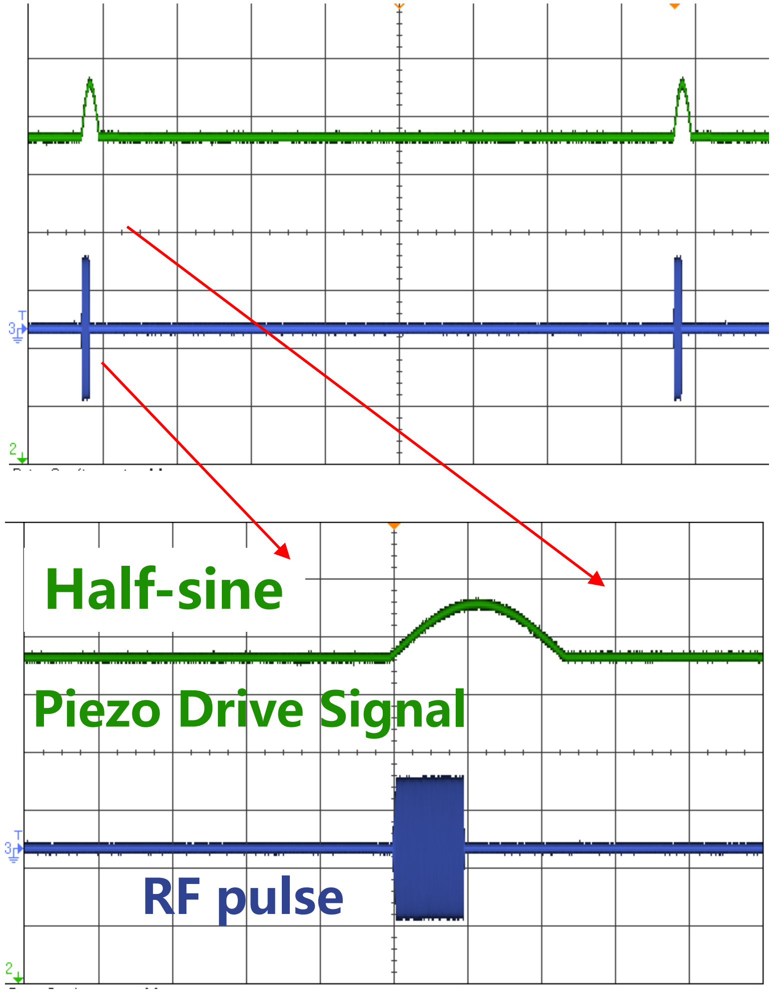
Normal，Q=760000

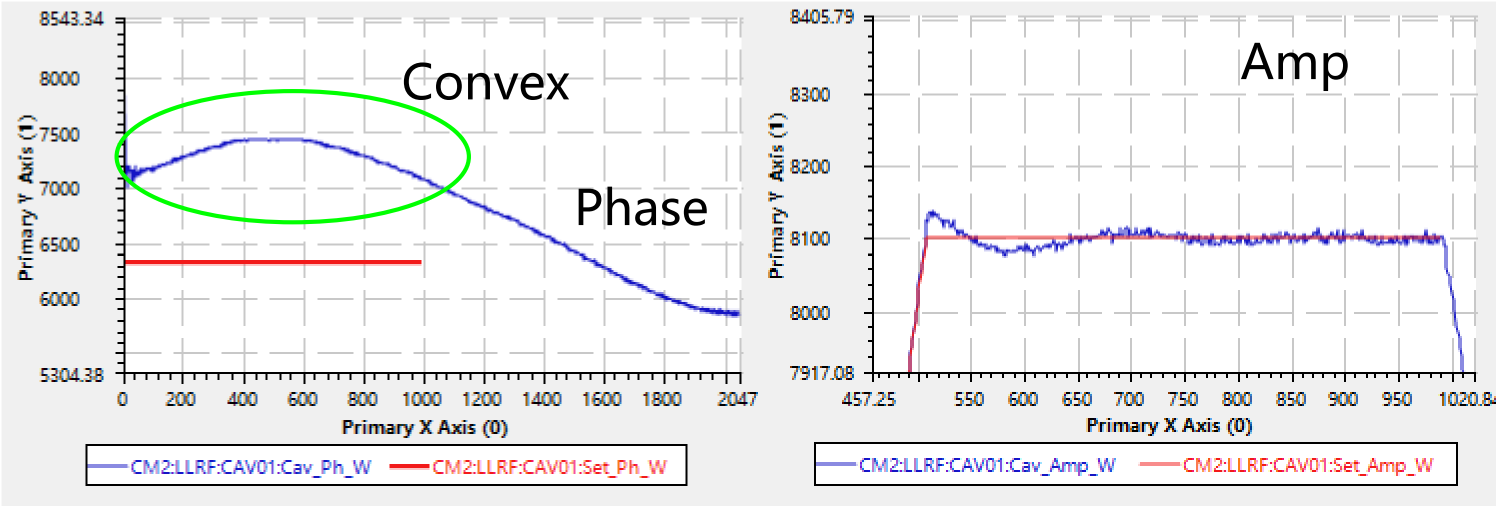


Abnormal，Q=620000

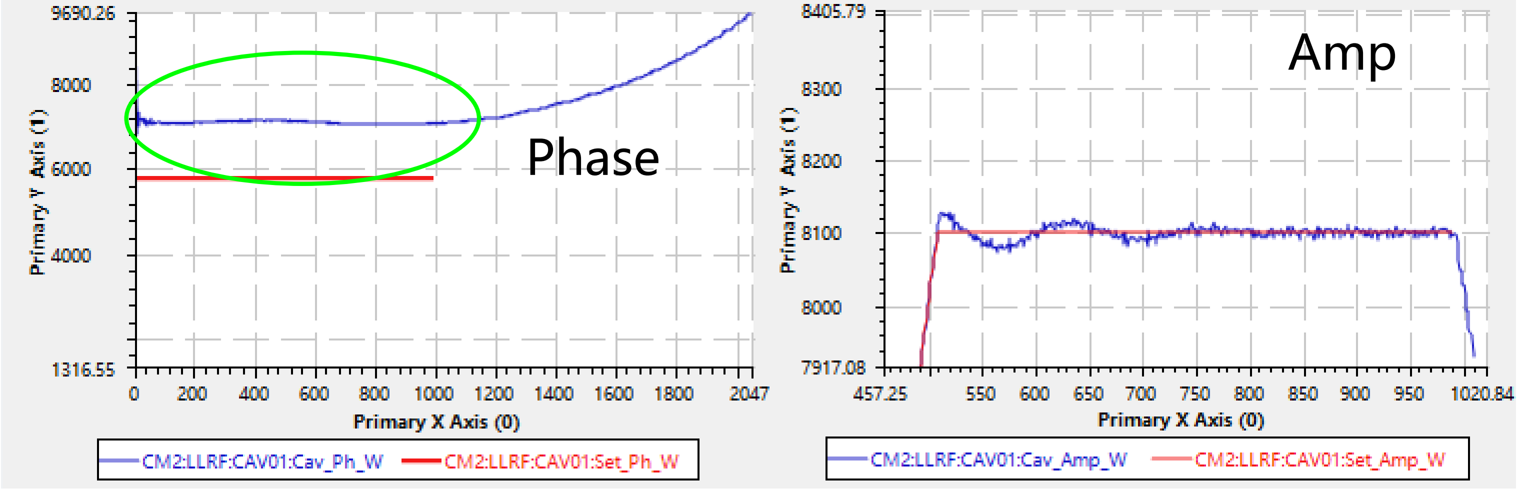
C-ADS Injector I : Lorentz Force Detuning Compensation

- Half-sine wave to Drive Piezo
- No used in routine operation





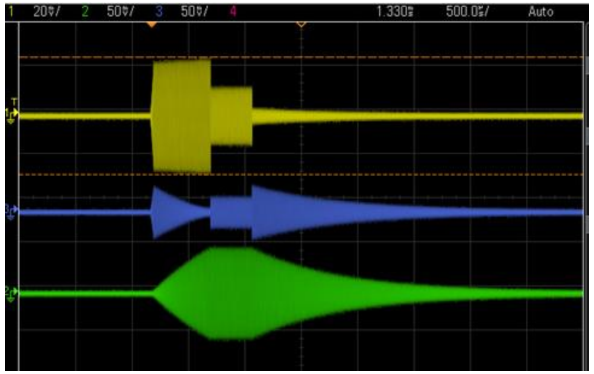
Without Piezo compensate

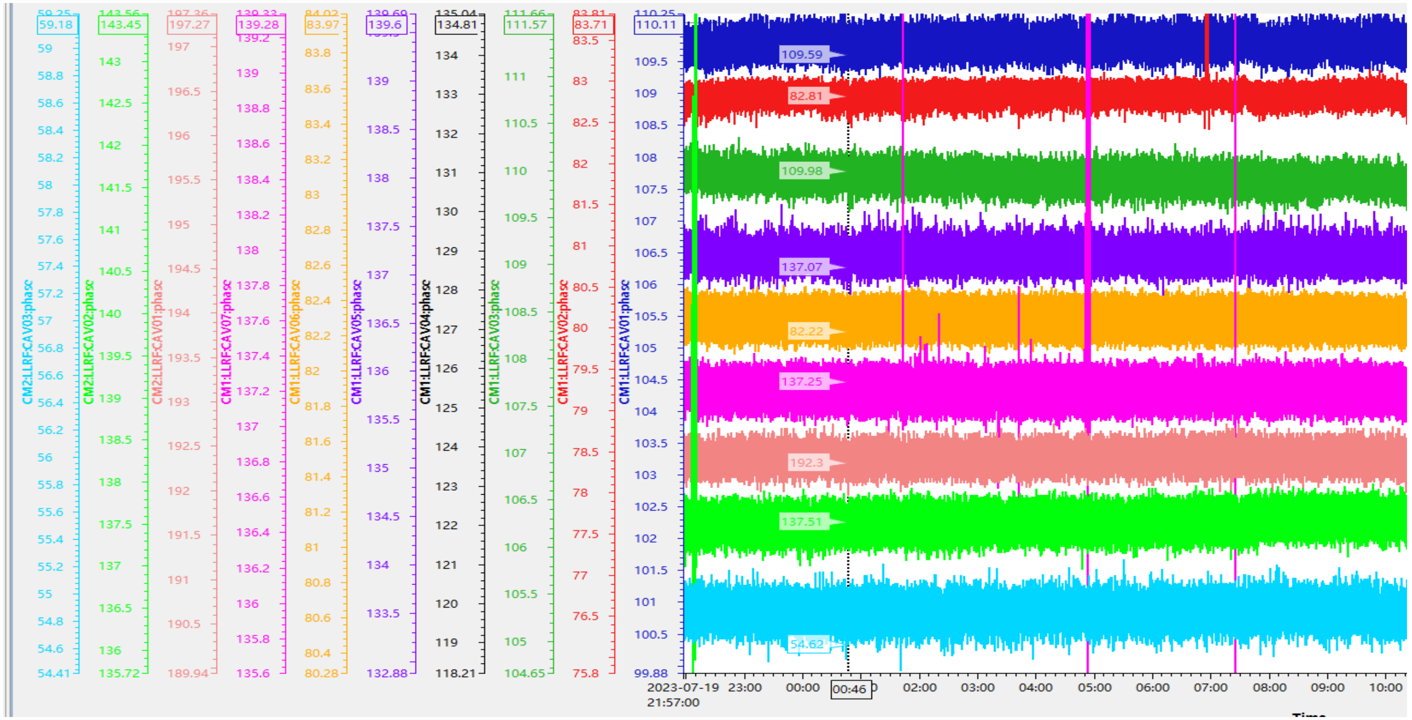


With Piezo compensate

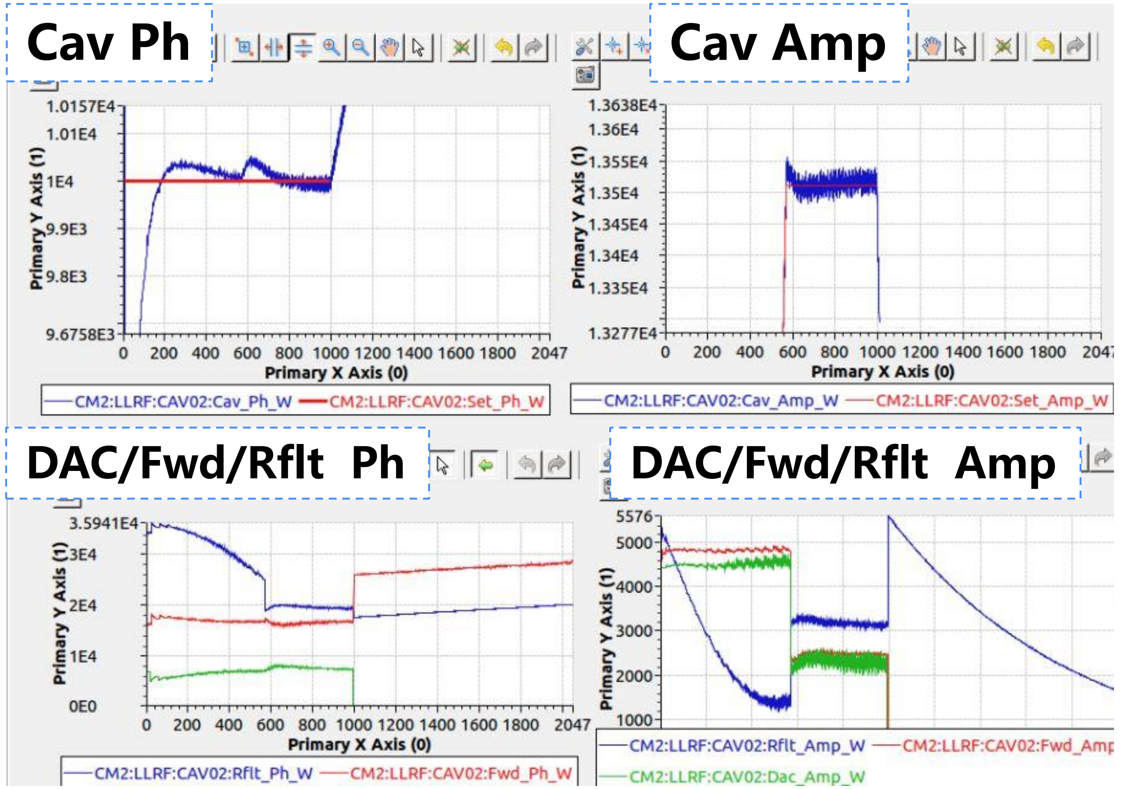
C-ADS Injector I : Experimental Results

- 25 Hz 1.2 ms stable operation more than 20 hours;
- Amp and phase stability: **~± 0.3% and ±0.3°;**
- Meet CSNS-II Requirements, higher accuracy can be achieved with newer FPGA chips





✓ Long-term variation of the Cavity phase(~±0.3°)



✓ Pulse Waveform

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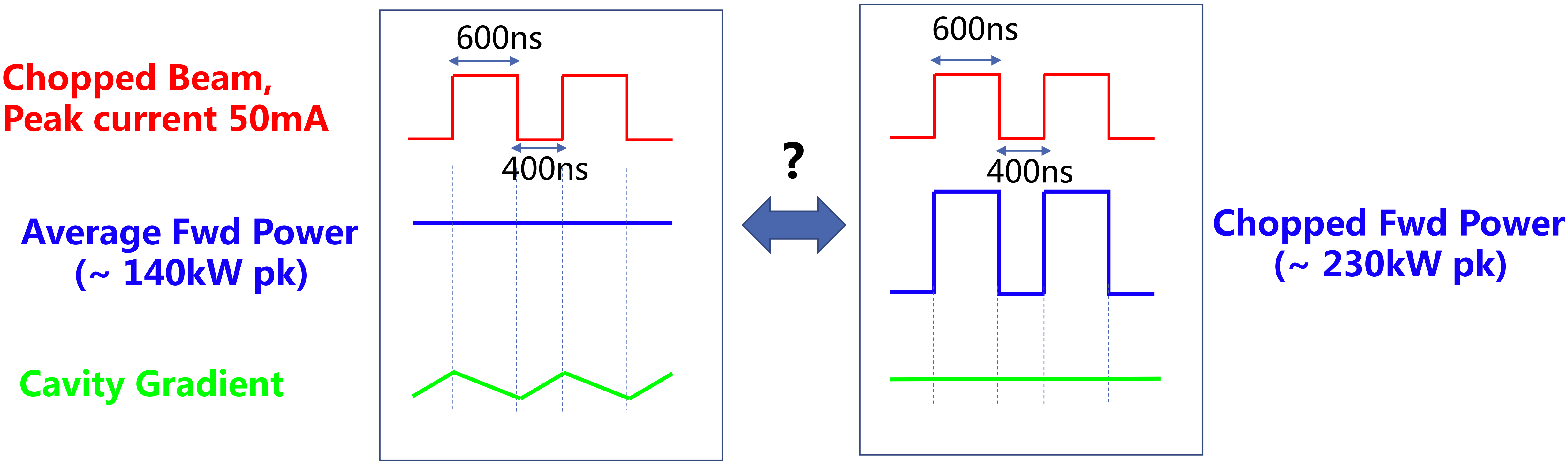
Chopped Beam Operation

□ The beam is modulated by a 1 MHz chopping signal.



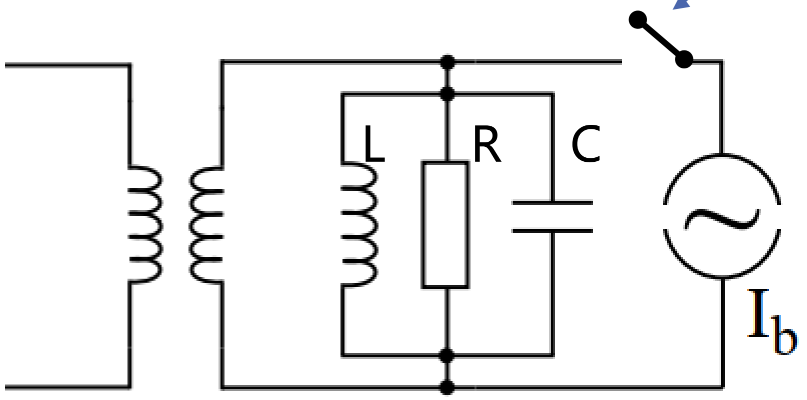
- How much ripple will be generated on the cavity field?
- Is there need a Chopped Forward Power to compensate the Ripple?

Chopped Beam Operation

□Simulation shows the ripple is small enough.

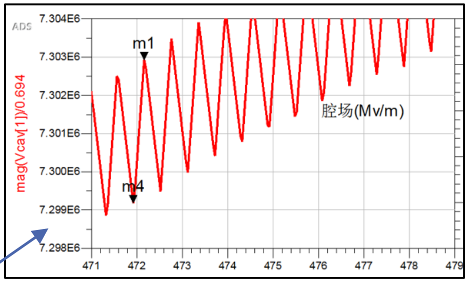
Q0=1.2e10
R_Q=410
R=0.5*R_Q*Q0
L=0.5*R_Q/w0
C=1/(0.5*R_Q*w0)
……

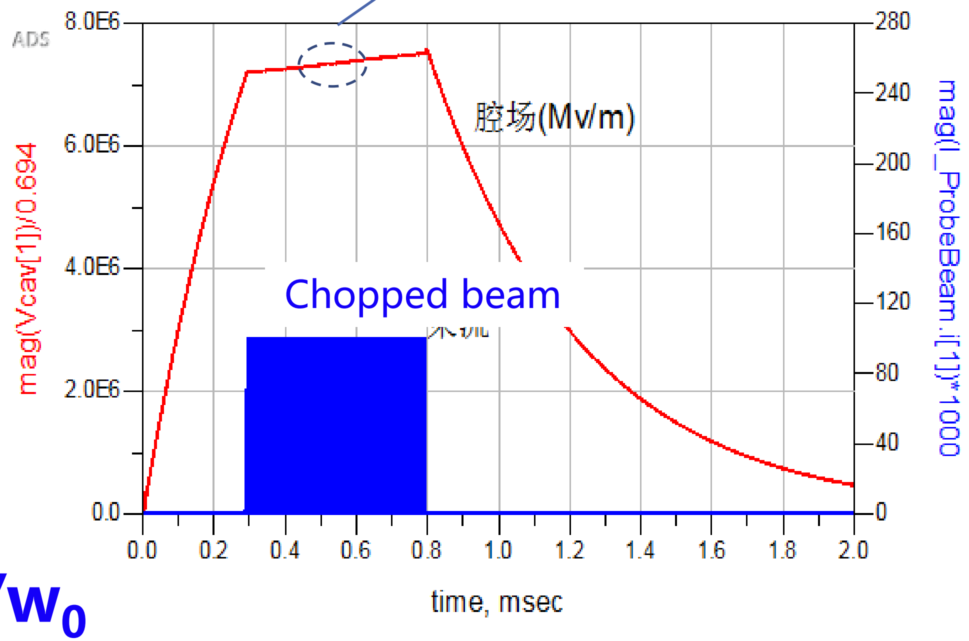
1MHz Switch



Circuit simulation

Amp 0.0506%
Phase 0.02°





➢ SRF cavity have **LARGE** constant time = $\mathbf{2Q_L/w_0}$

Simulation Software of SRF LLRF

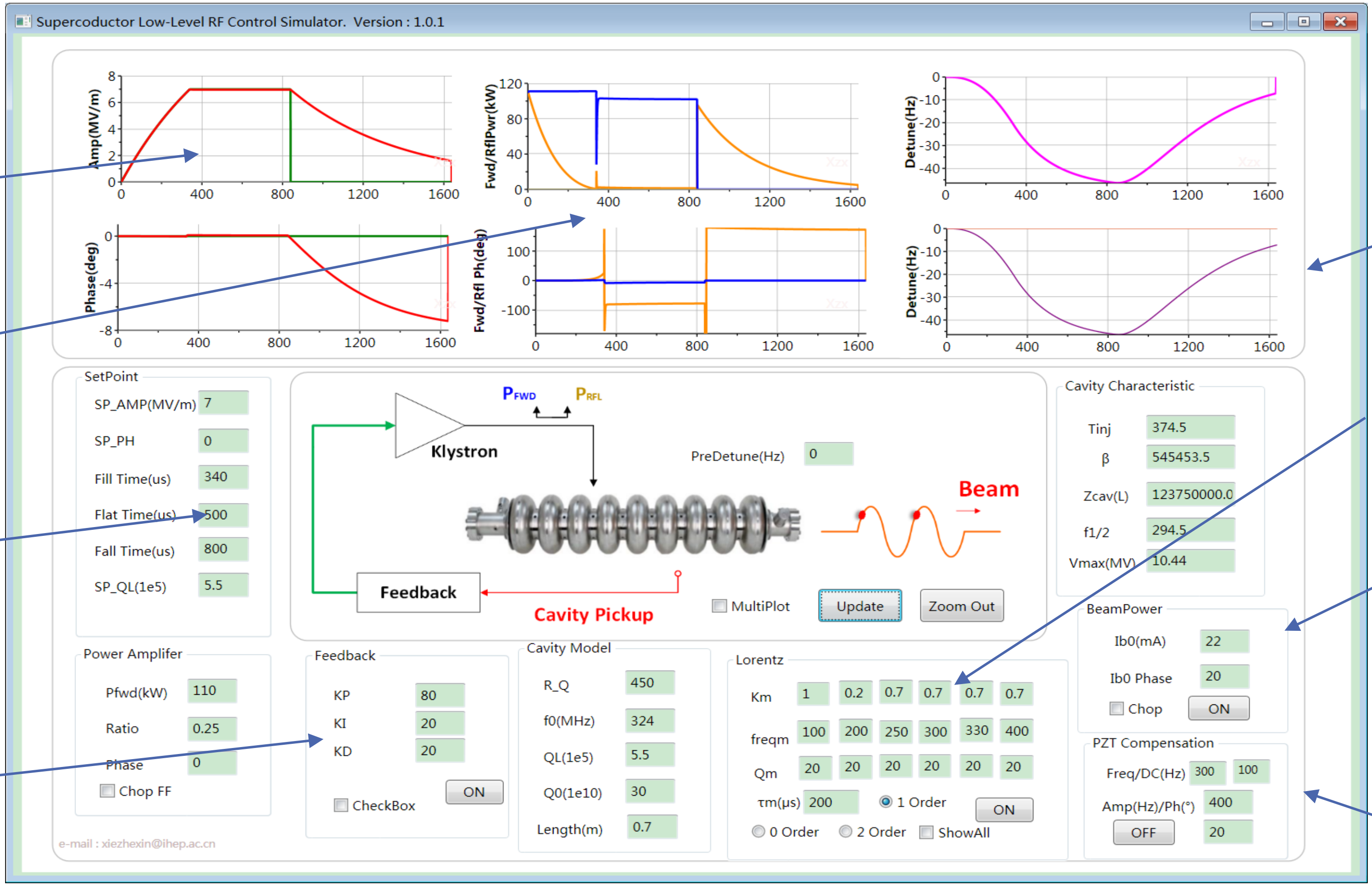
- A simulation software was developed to estimate cavity field ,RF power, Lorentz force detuning, beam-loading effect, etc.

Cavity Gradient

Forward/Reflect Power

Pulse Setting

PI Feedback



Lorentz force Detune waveform

Lorentz force detune

Beam Current

Piezo Compensation

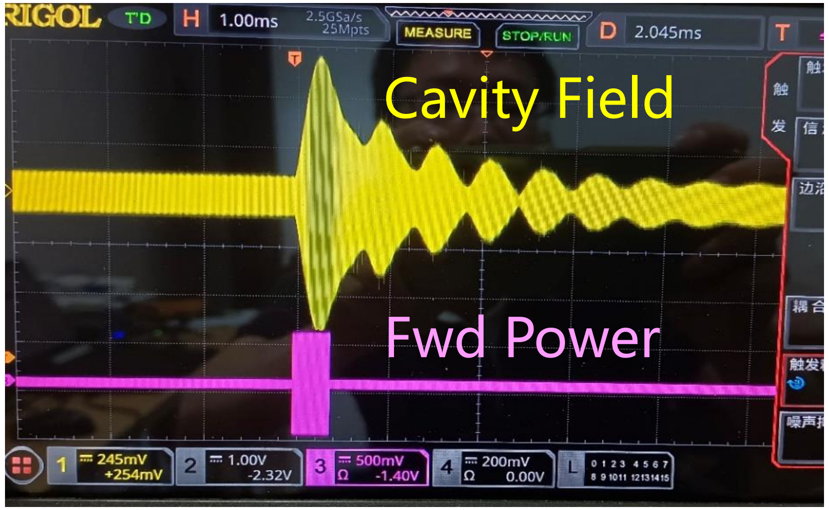
Download :https://github.com/happsky123/Superconductor-Cavity-control-Simulator-

SRF Cavity Simulator

- A FPGA-based cavity simulator as a substitute for real cavities;
- The data cover large range ,so floating point number is used in FPGA

$$\begin{bmatrix} V_{c,r}(n) \\ V_{c,i}(n) \end{bmatrix} = \begin{bmatrix} 1-T_S\omega_{1/2} & -T_S*\Delta\ \omega \\ T_S*\Delta\ \omega & 1-T_S\omega_{1/2} \end{bmatrix} * \begin{bmatrix} V_{c,r}(n-1) \\ V_{c,i}(n-1) \end{bmatrix} + \begin{bmatrix} T_S\omega_{1/2} & 0 \\ 0 & T_S\omega_{1/2} \end{bmatrix} * \begin{bmatrix} u_r(n-1) \\ u_i(n-1) \end{bmatrix}$$

Resonant



Detuned

SRF Cavity Simulator Waveform

[1]T. Schilcher, Ph.D. thesis, Hamburg University, 1998; [2] Feng Qiu, PRAB, 21, 032003 (2018)

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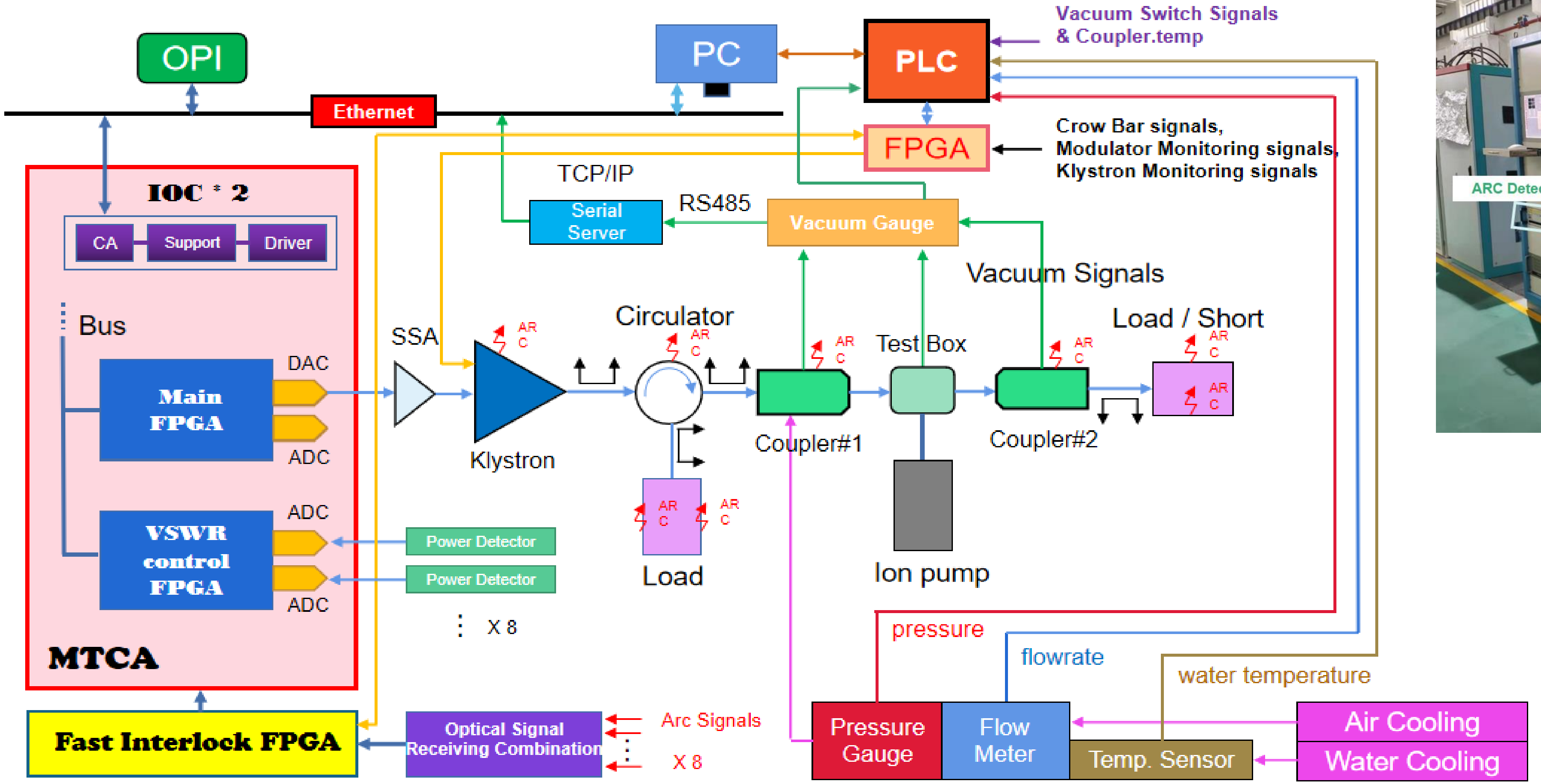
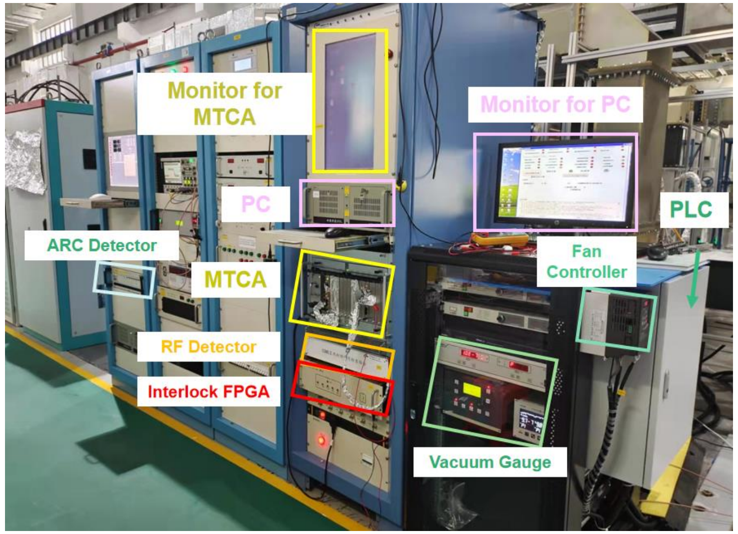
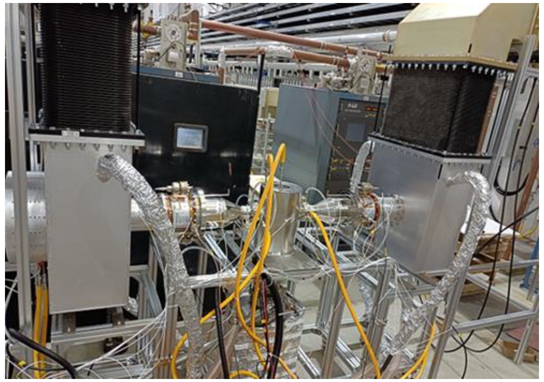
SRF Coupler RF Conditioning Control System

- SRF coupler is critical component of RF System
- An automatic control logic is developed base on vacuum



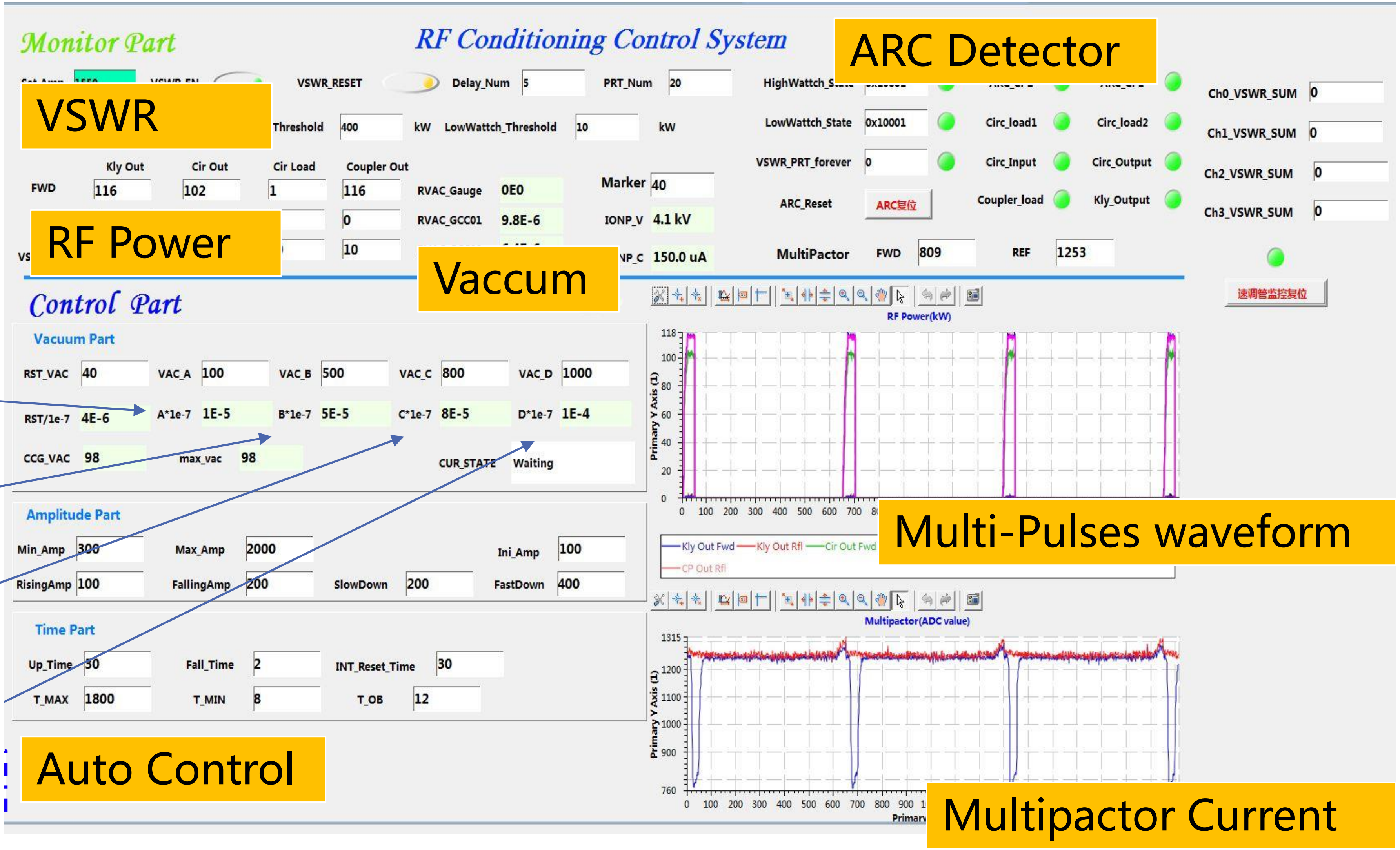
Schematic of Condition System





SRF Coupler RF Conditioning Control System

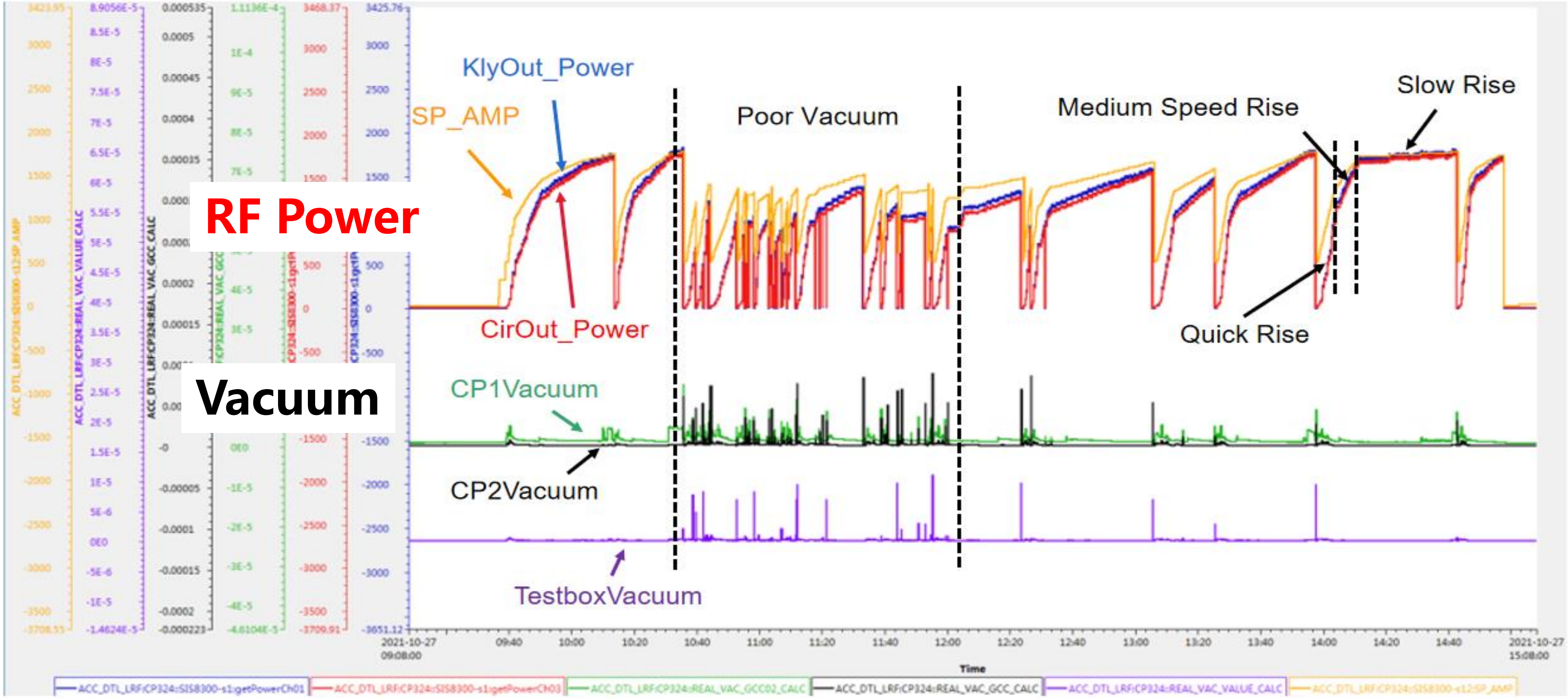
- Functions
  - RF power
  - VSWR Protection
  - ARC Protection
  - Multipactor Detection
  - Automatic RF Power control



4 vacuum levels are used for auto control the RF power .

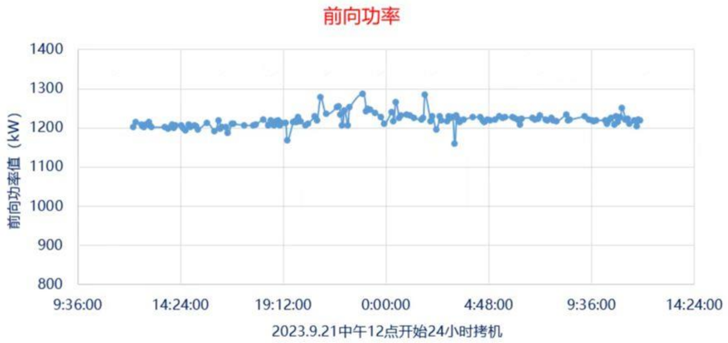
SRF Coupler RF Conditioning Control System

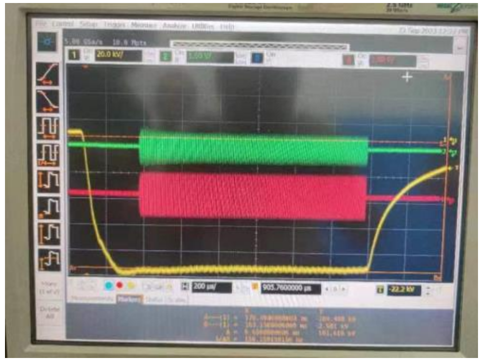
- RF 1.2ms 25Hz;
- Standing wave: 550Kw; Traveling wave: 2Mw.



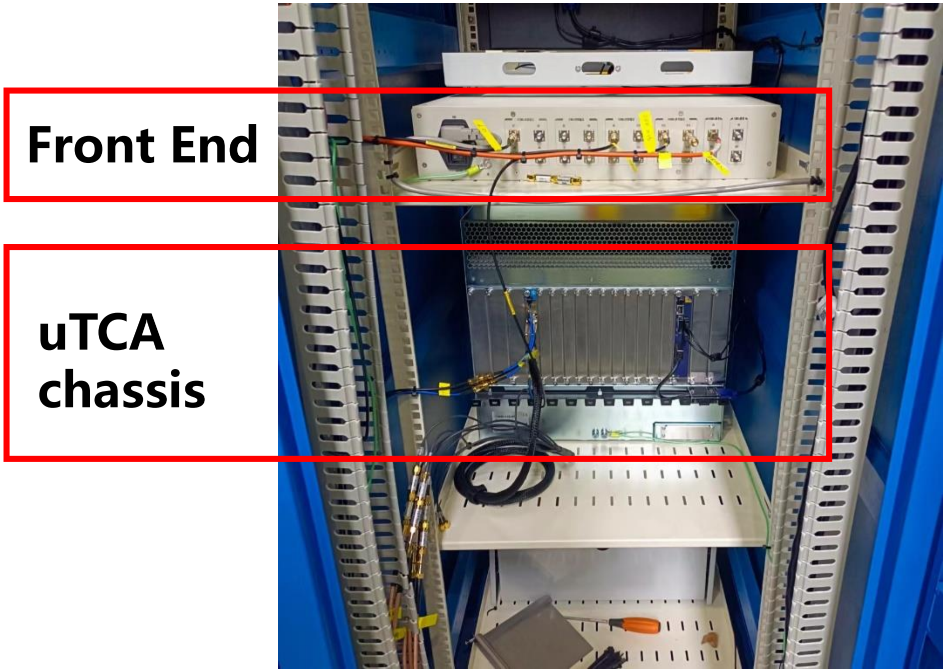
648 MHz LLRF with Domestic Klystron

- SIS8300KU+DWC8VM1
- Finish 24 hrs Klystron testing
- Further plan :
  - ✓ 648MHz SRF coupler conditioning
  - ✓ 648MHz De-buncher Cavity conditioning
  - ✓ 648MHz SRF LLRF





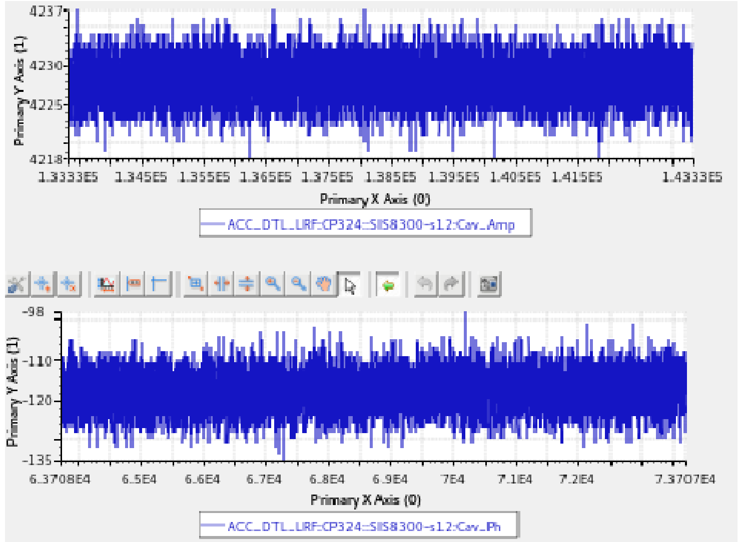
24hr 1.2Mw Output Power

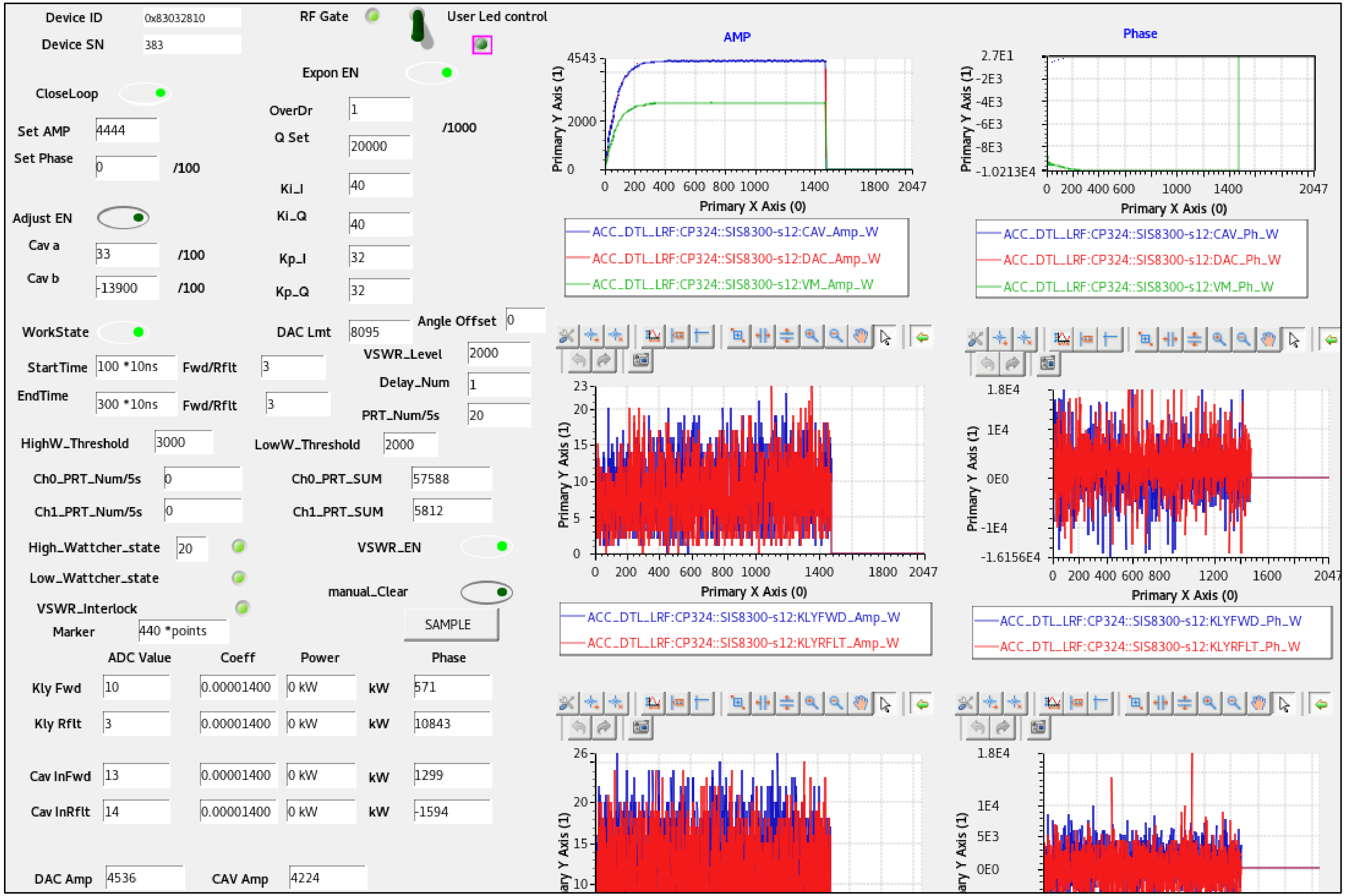


648 MHz LLRF with Domestic Klystron

Items	Frequency	UNIT
Cen	648	MHz
LO	675	MHz
IF	27	MHz
CLK	108	MHz

Down-conversion Frequency





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Summary and Future Work

- **Summary**
  - The preliminary work of SRF LLRF is ongoing, the verification at C-ADS shows a good result, the performance meeting the requirements of CSNS-II.
  - Some simulations were developed for better LLRF design;
  - Some high RF power conditioning platform are implemented .

- **Future Work**
  - Develop automated program control about 50 SRF machines;
  - Machine learning will be used to optimize parameters, anomaly detection, quickly recover.

Thanks for your attention!