Improvement of LLRF System

~ KEKB LLRF Team ~

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Talk Outline

1. Overview the new LLRF System

2. Prototype Performance & Improvements

- High power operation test results
  - Found problem and the solution projection
- Improvement of thermal stability
- The other improvement

3. Schedule & Summary

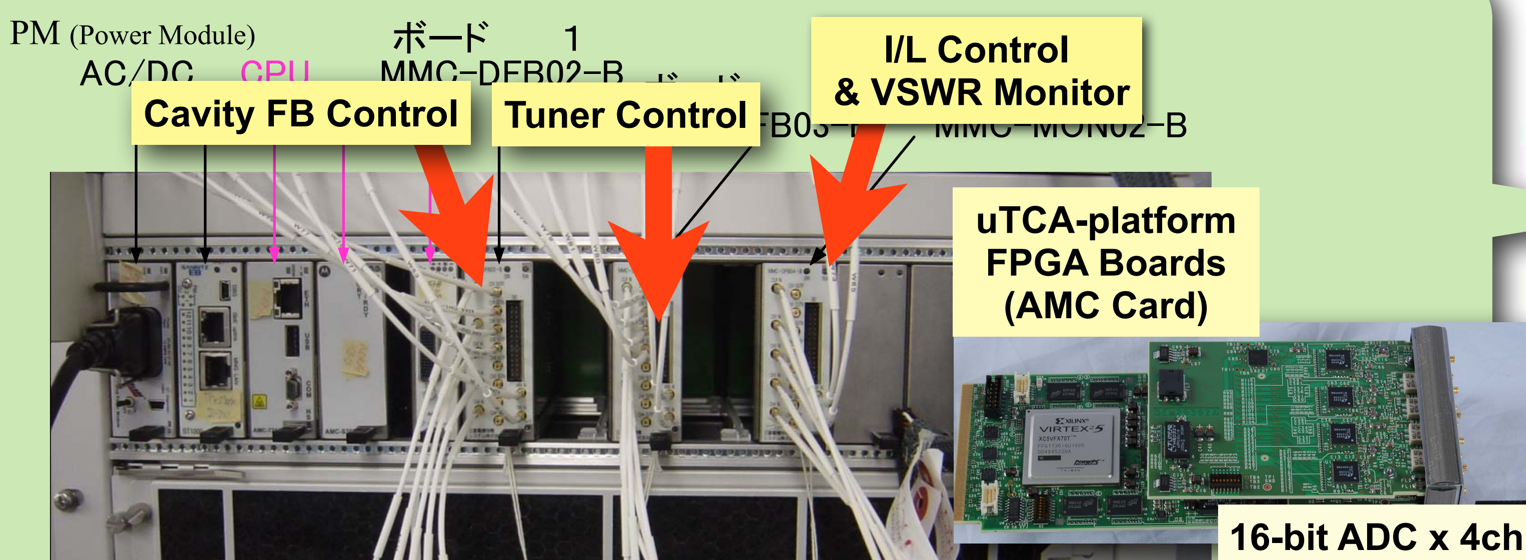
Recommendation (the 17th KEKB Review Committee)

1. Confirm the system performance with "out of the loop" measurements.
2. Demonstrate acceptable thermal stability with the revised version.

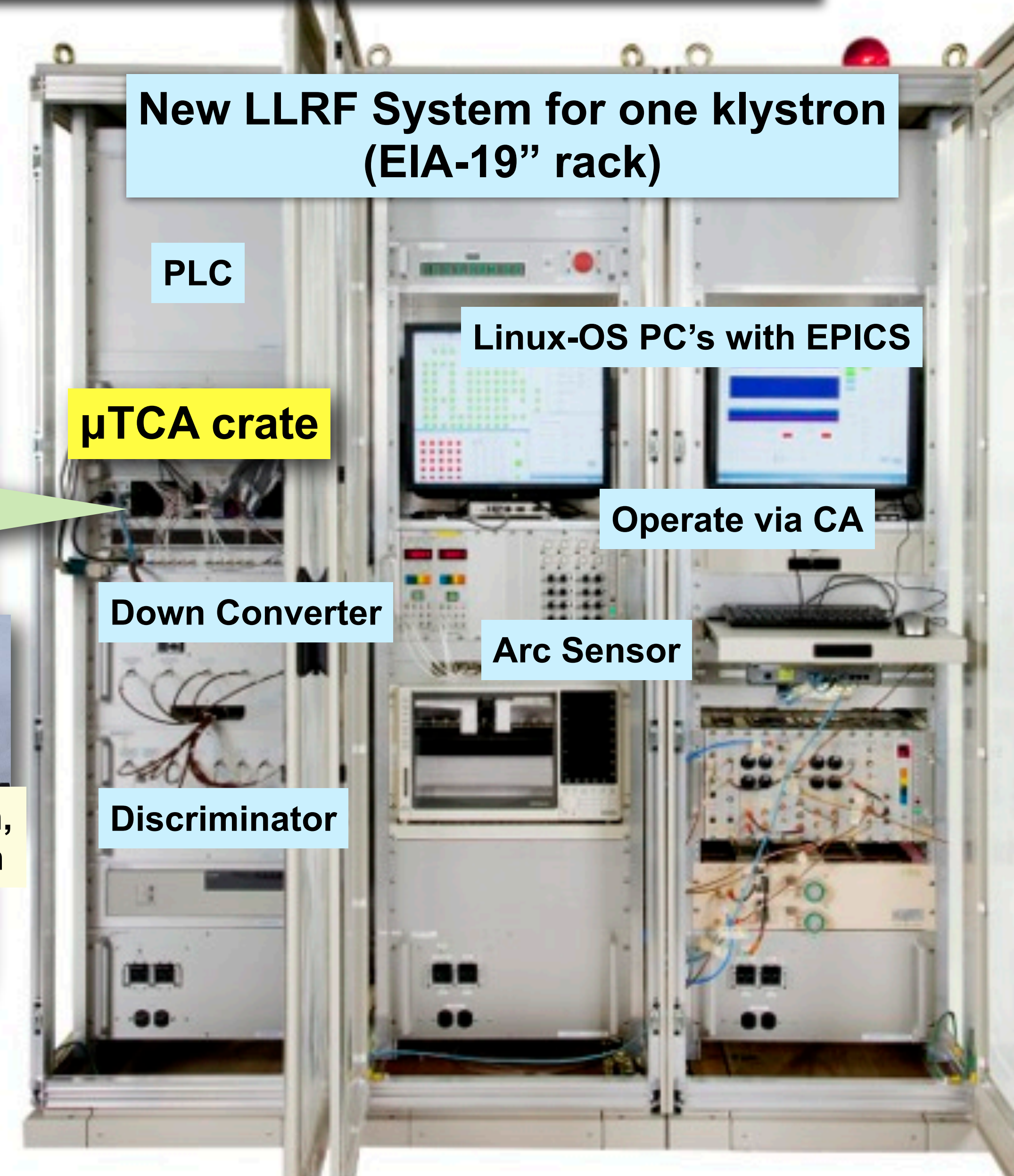
New LLRF System for SuperKEKB

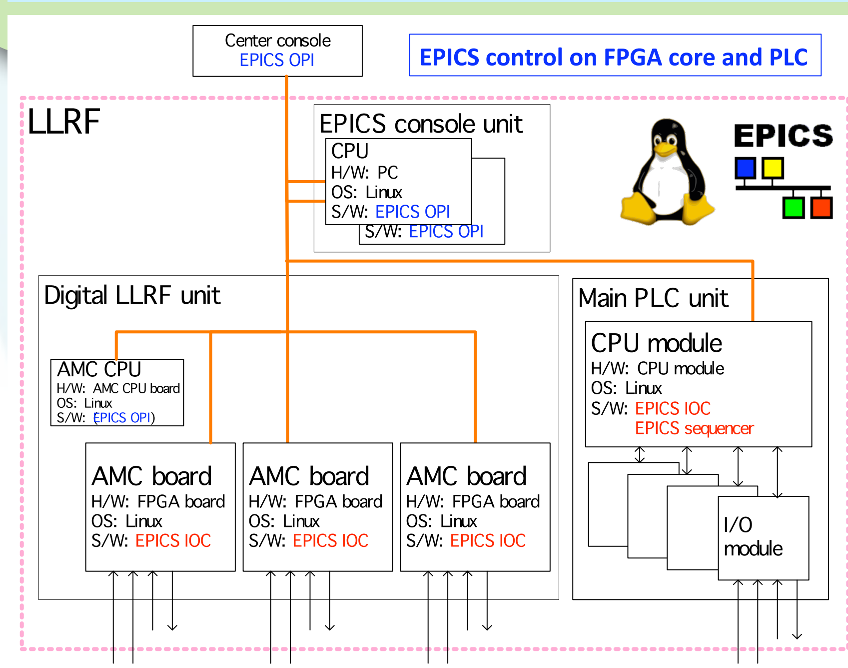
Preset analog systems will be replaced by new digital ones step-by-step.

A prototype of new LLRF system (α-version) has been developed and the performance was evaluated last year.



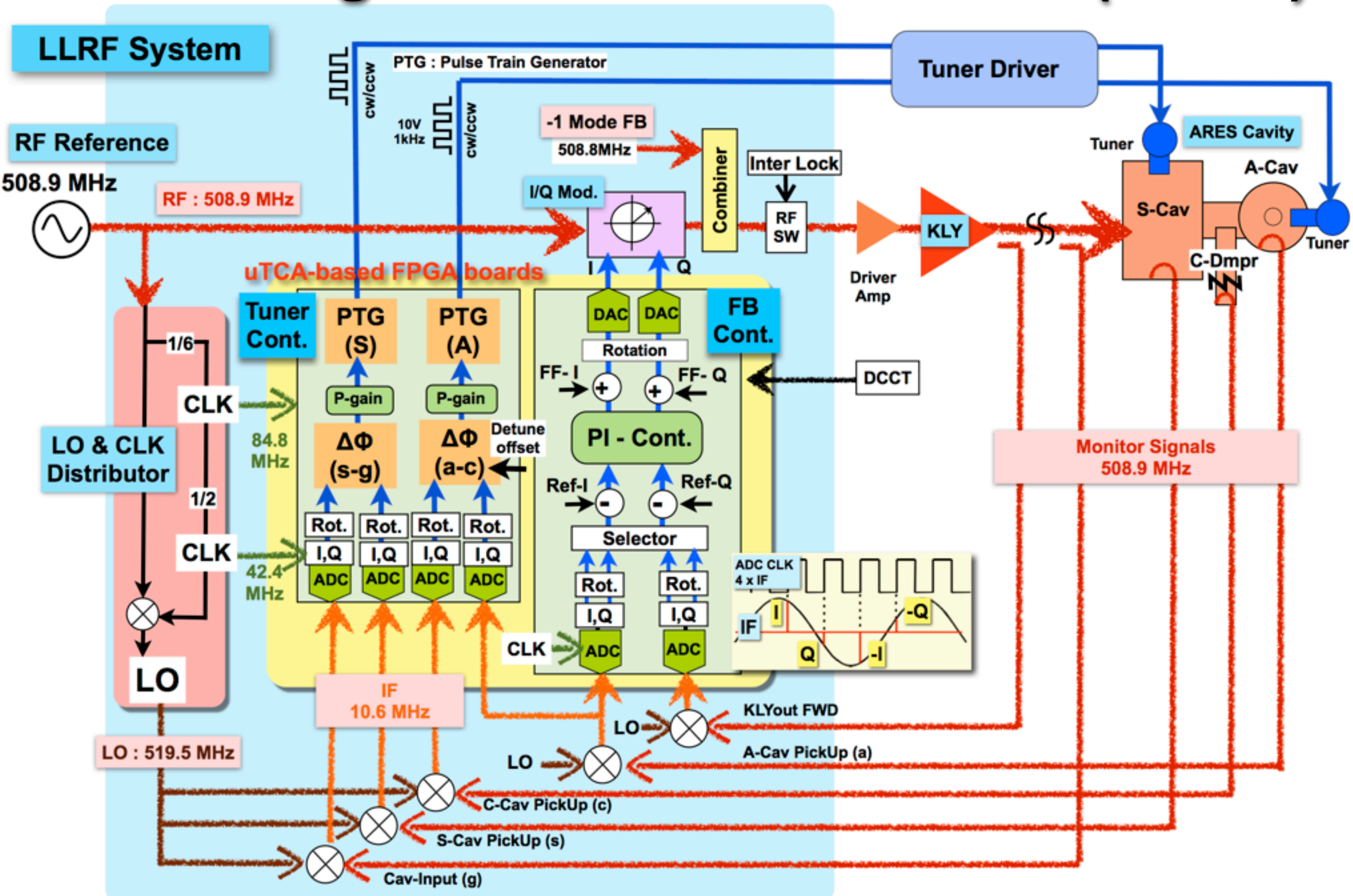
Each board has a CPU (PPC), and the EPICS-IOC on Linux-OS is embedded.



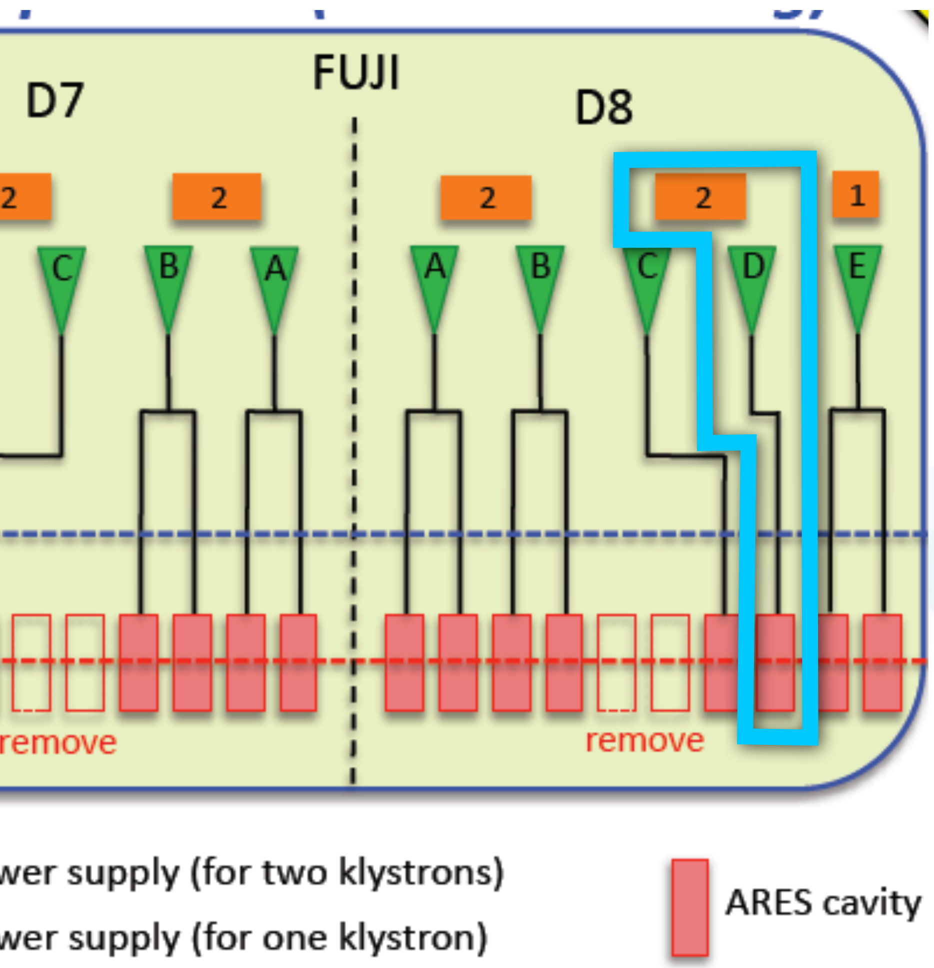


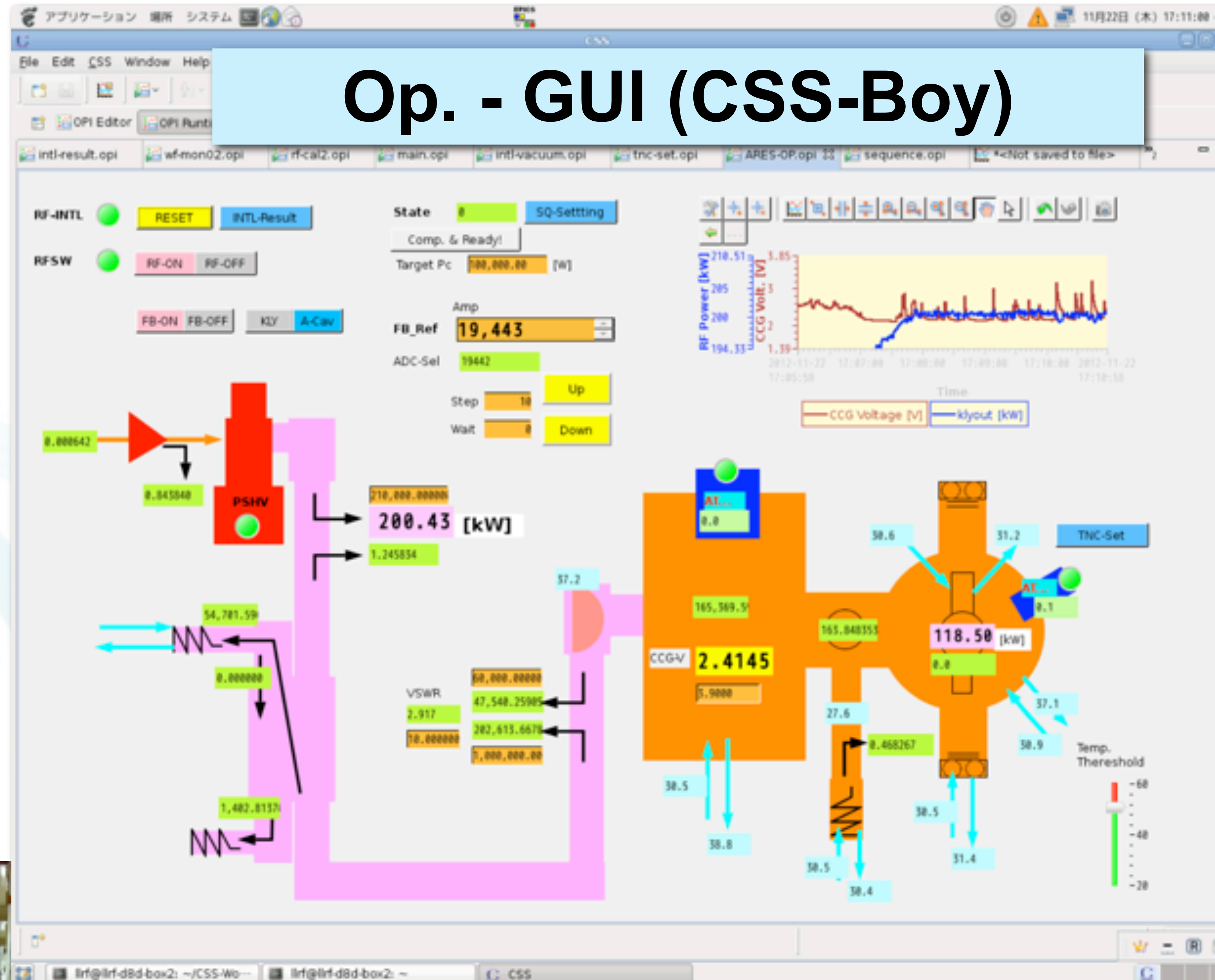
- **This system consists of μTCA-based FPGA boards & PLC.**
- **EPICS-IOC on Linux-OS is embedded in each of them. They can be operated remotely via EPICS-Channel Access.**
- **Hardware is common for both of ARES & SC Cavity. (Also both softwares are much the same.)**
- **Klystrons (LLRF) : Cavity unit = 1 : 1 (SuperKEKB)**

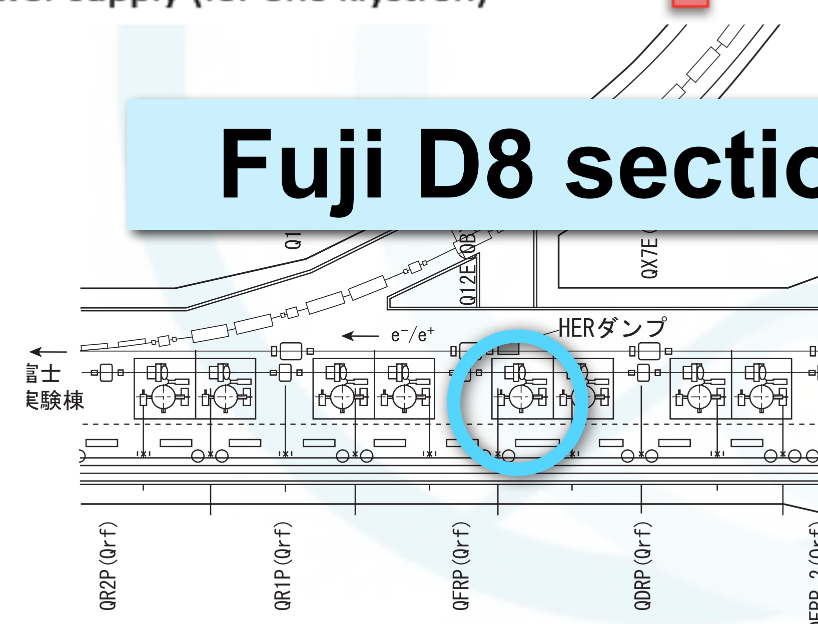
Block Diagram of FB&Tuner Cont. (ARES)

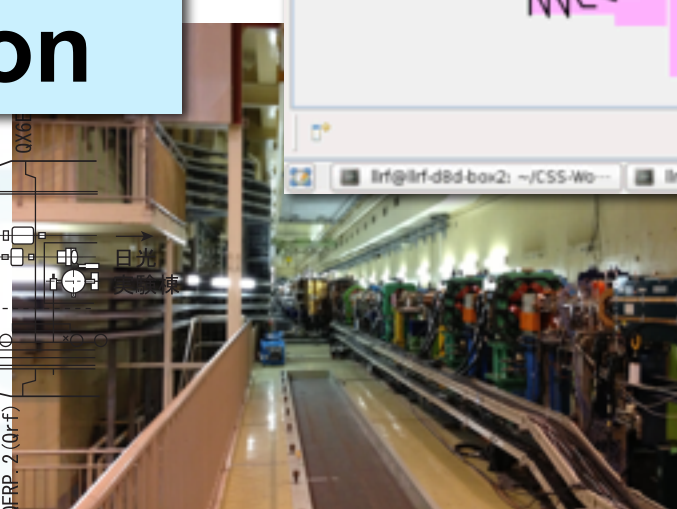


High Power Test of α-ver. with ARES Cavity @D8D (Nov. 2012)

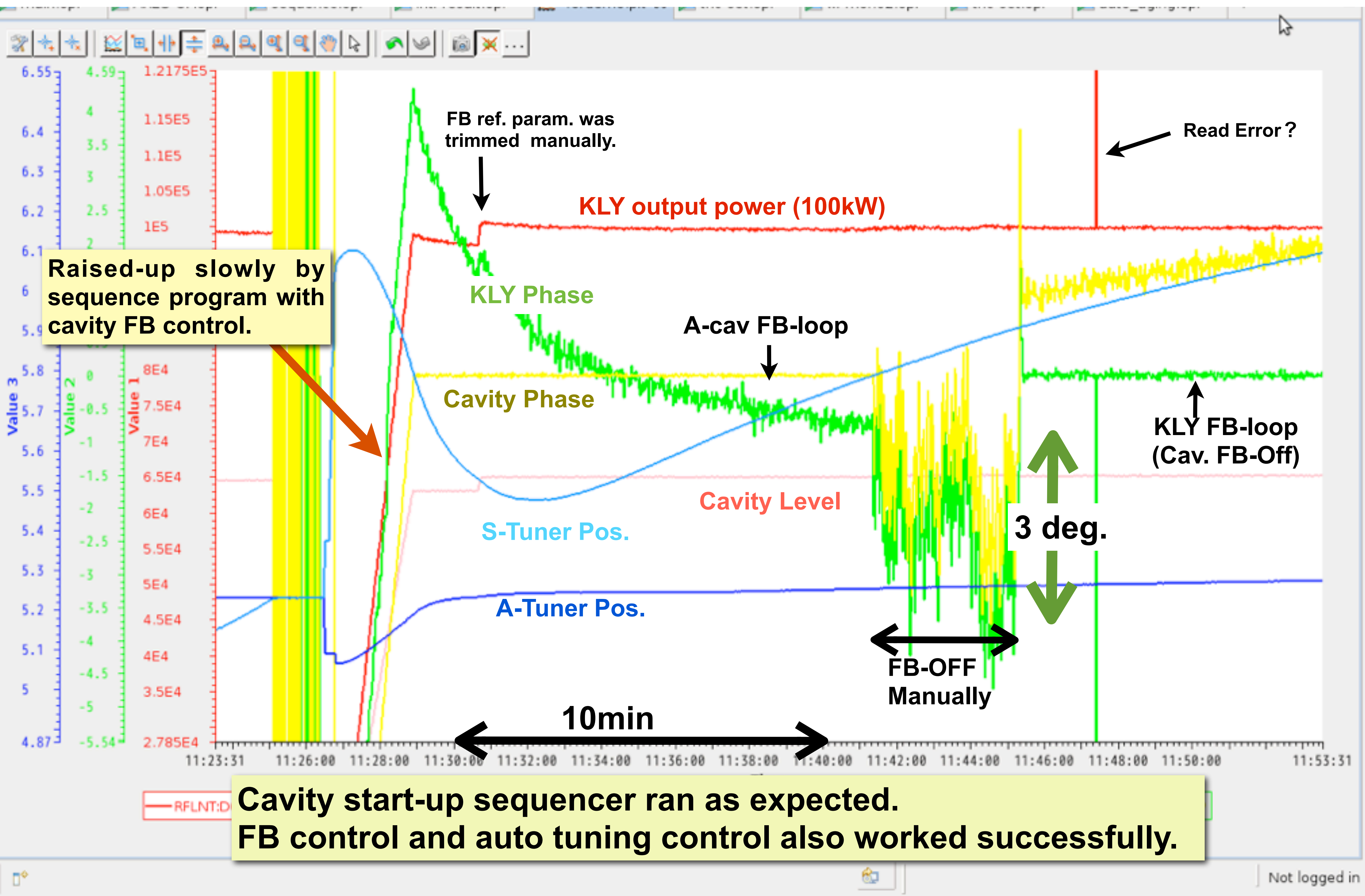






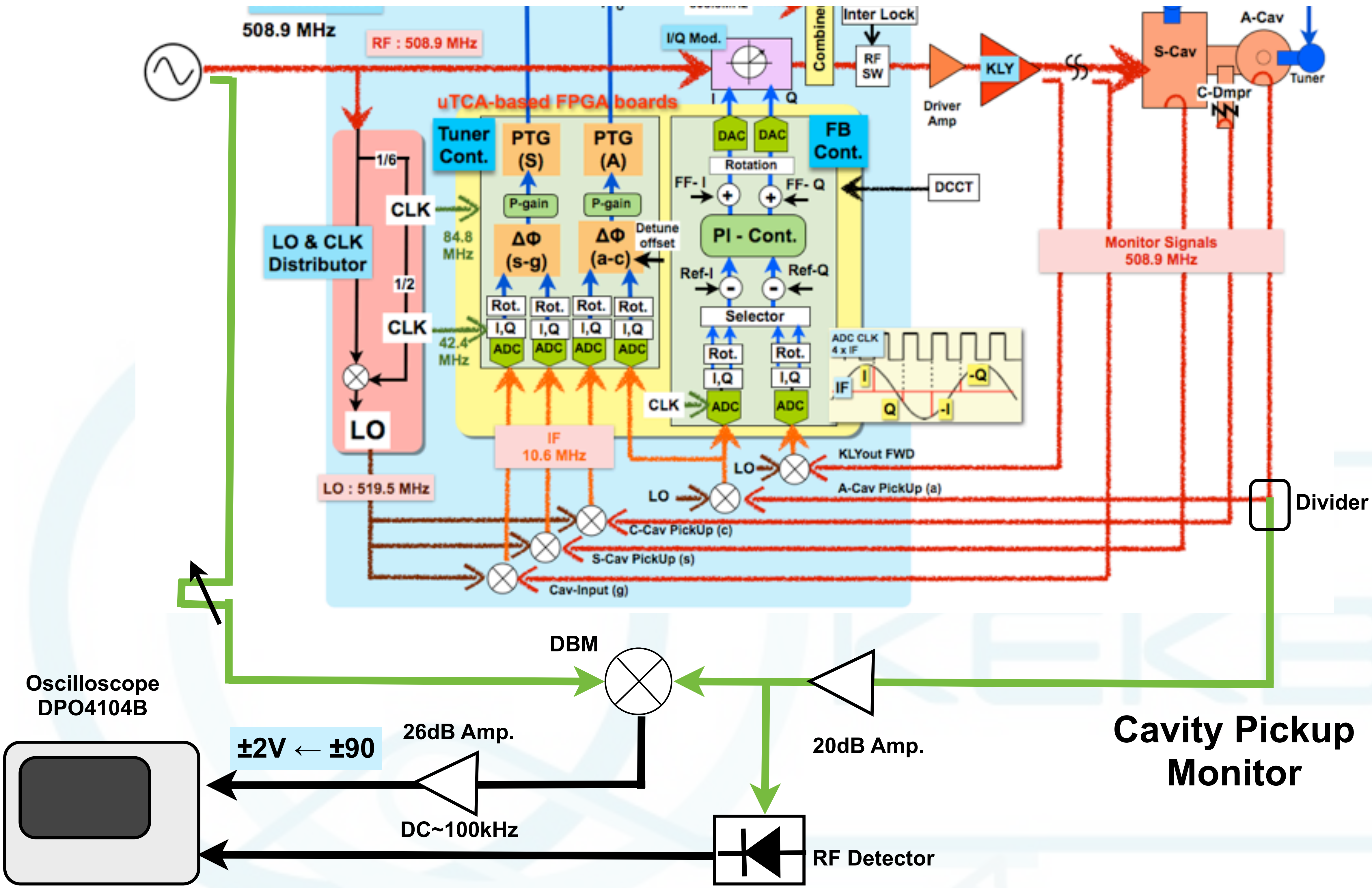


Strip-chart of Cavity Start-up Sequence



Cavity start-up sequencer ran as expected.
FB control and auto tuning control also worked successfully.

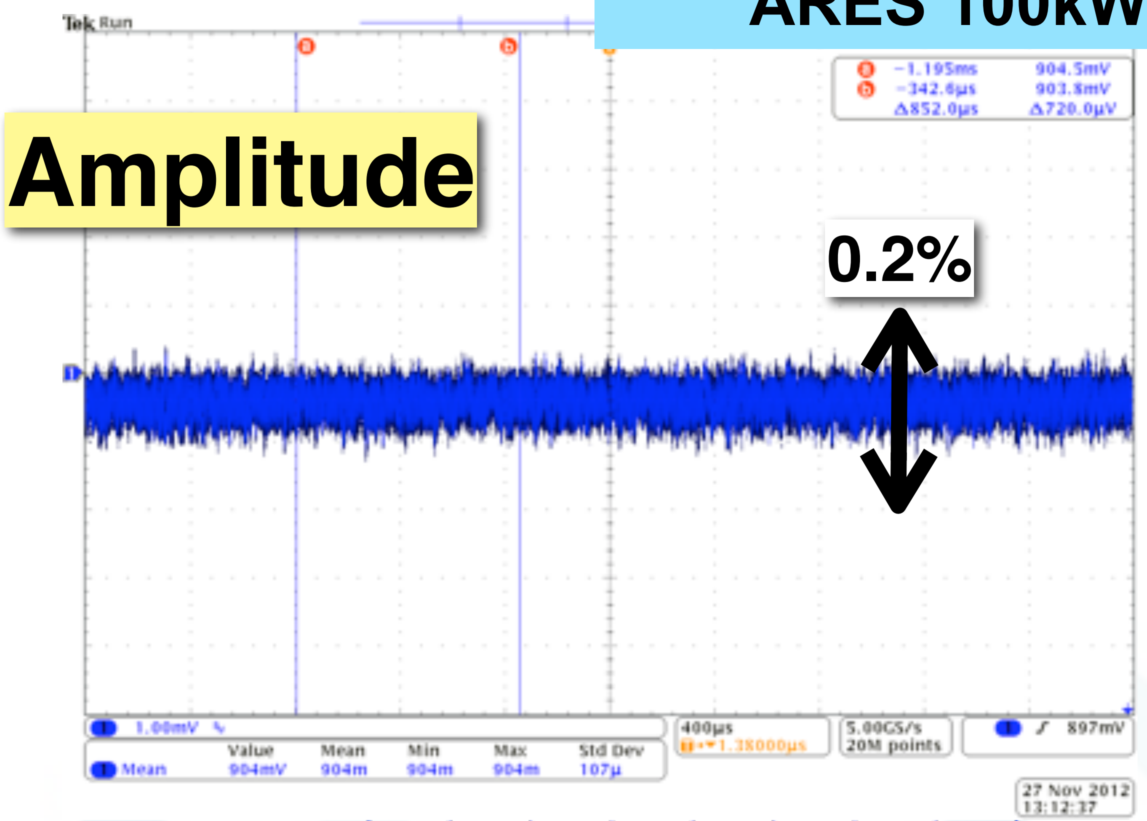
Stability Evaluation by "out of the loop" Measurement

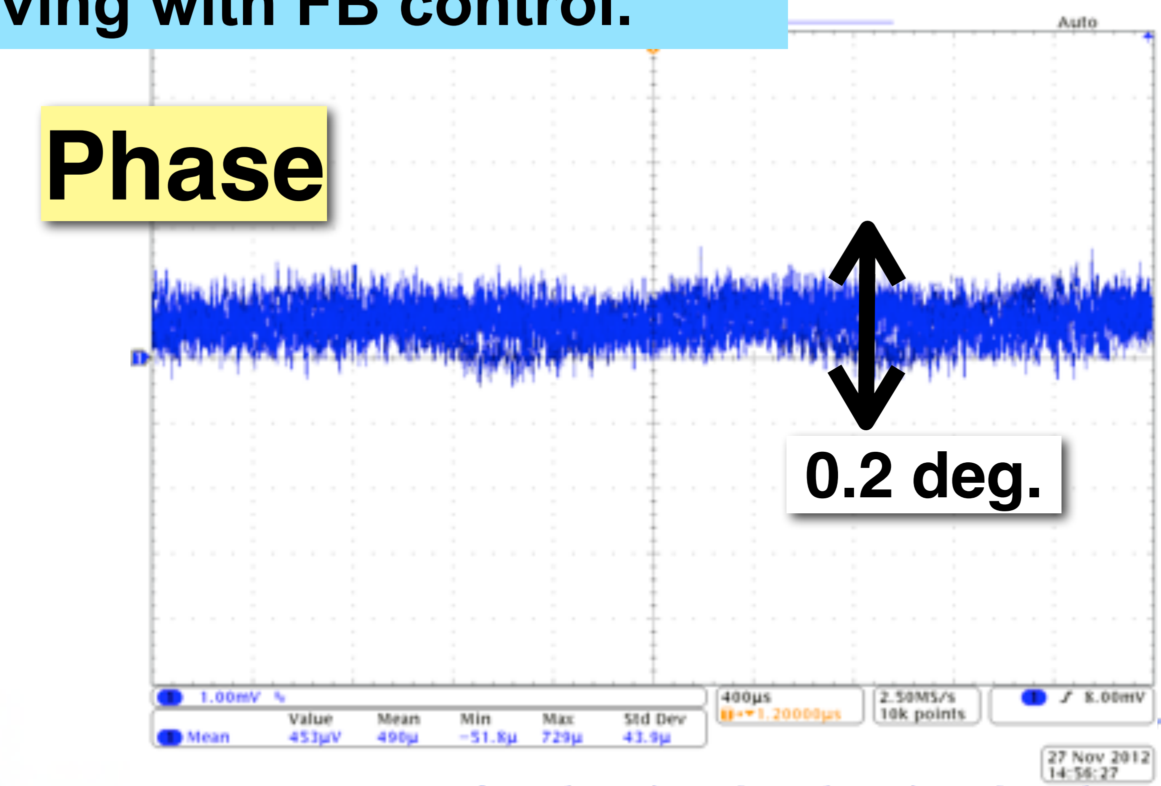


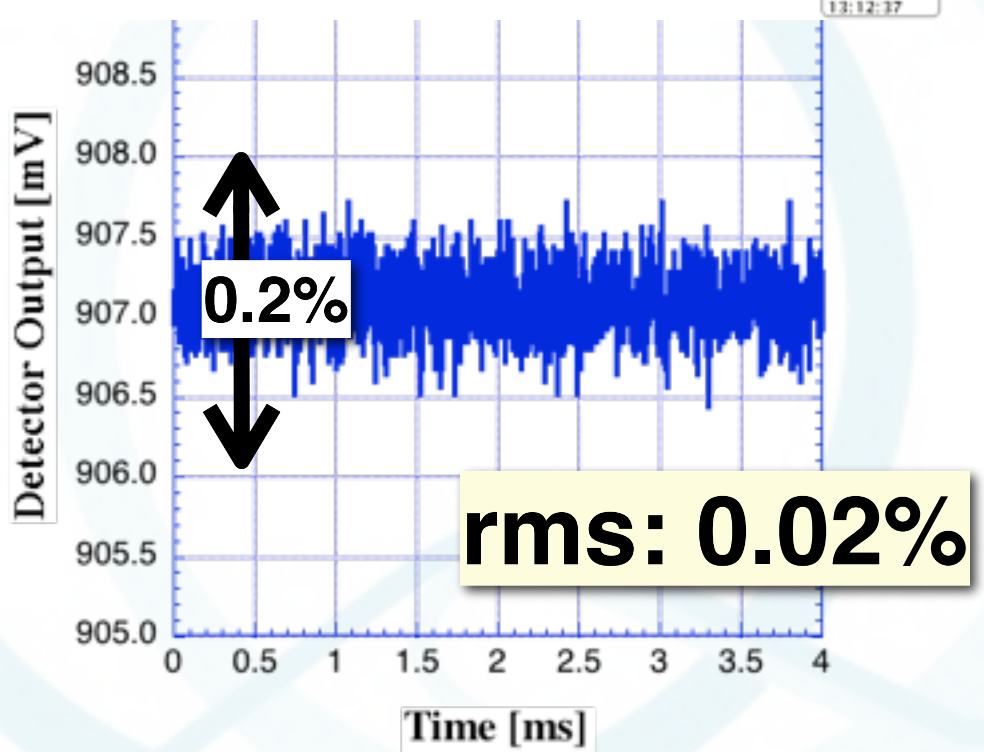
For the amplitude measurement, base-line voltage was off-set in the oscilloscope.

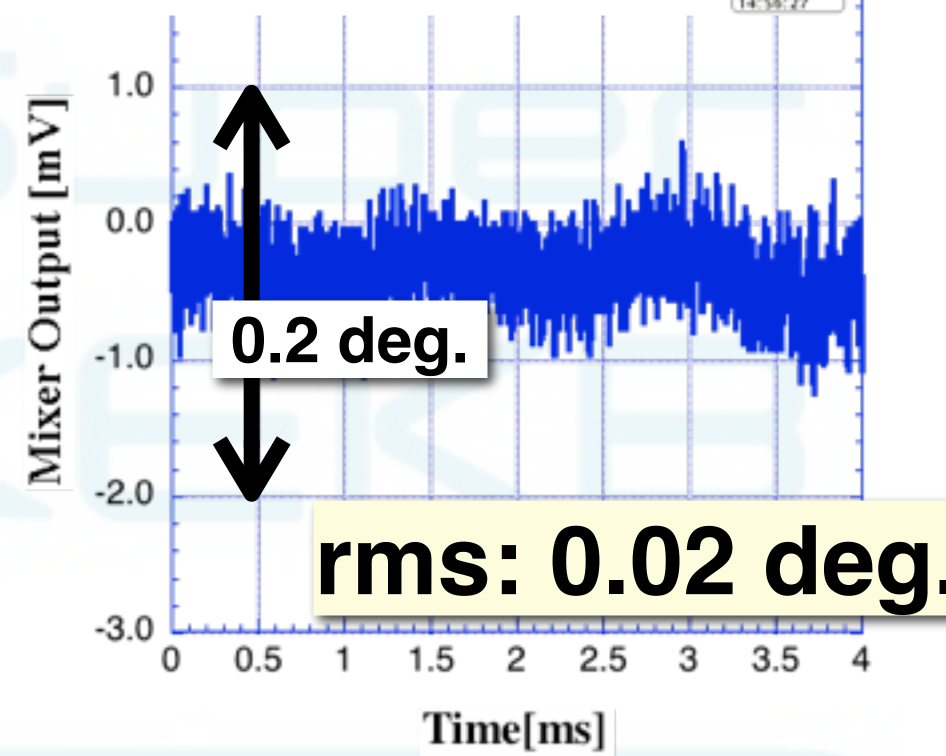
Measurement Result of Stability

ARES 100kW driving with FB control.





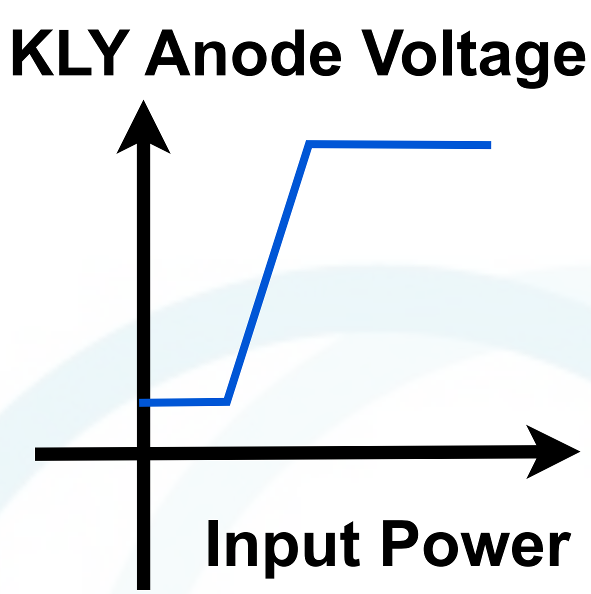




No difference between FB-gains was found in this measurement method.

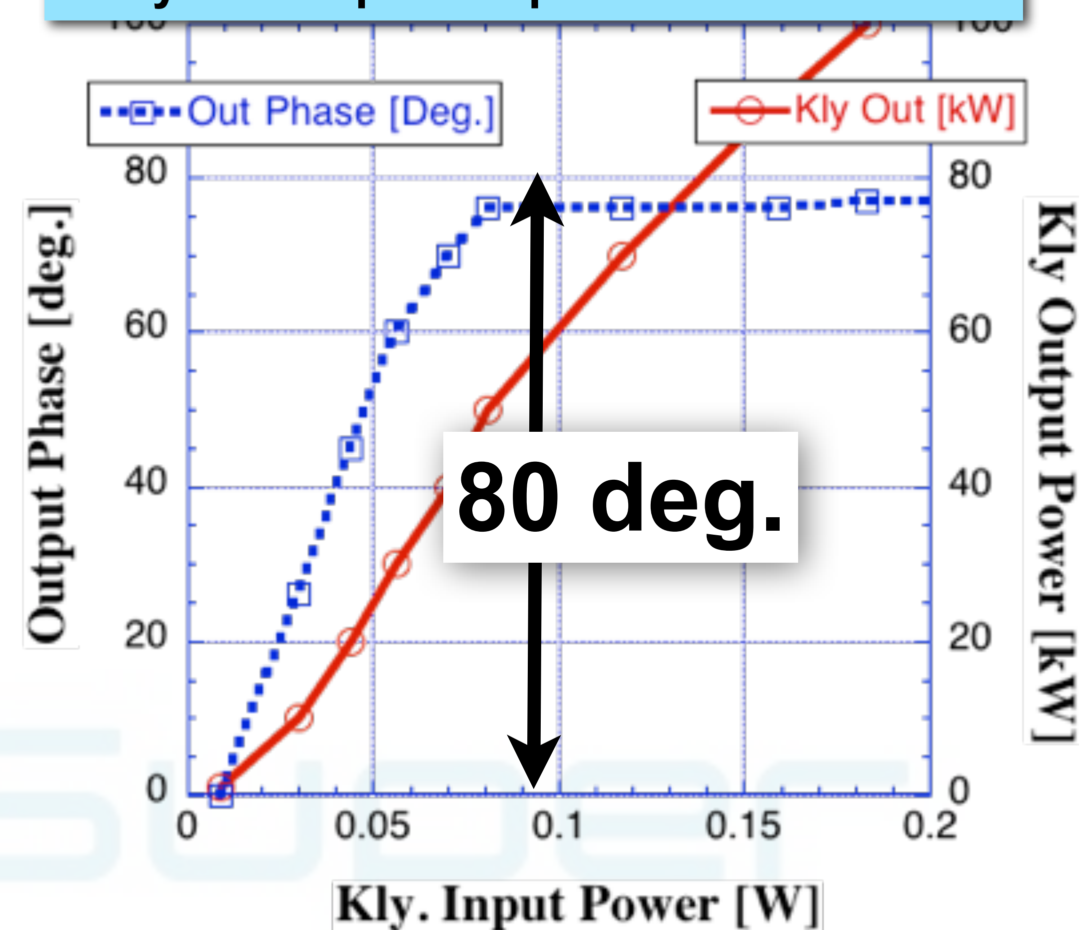
Klystron Phase Change due to Anode Voltage Control

For efficiency optimization, the anode voltage is controlled depending on klystron input power to reduce the collector loss.



The kly. output phase shifts greatly in response to input/output power.

Klystron Input-Output Characteristics



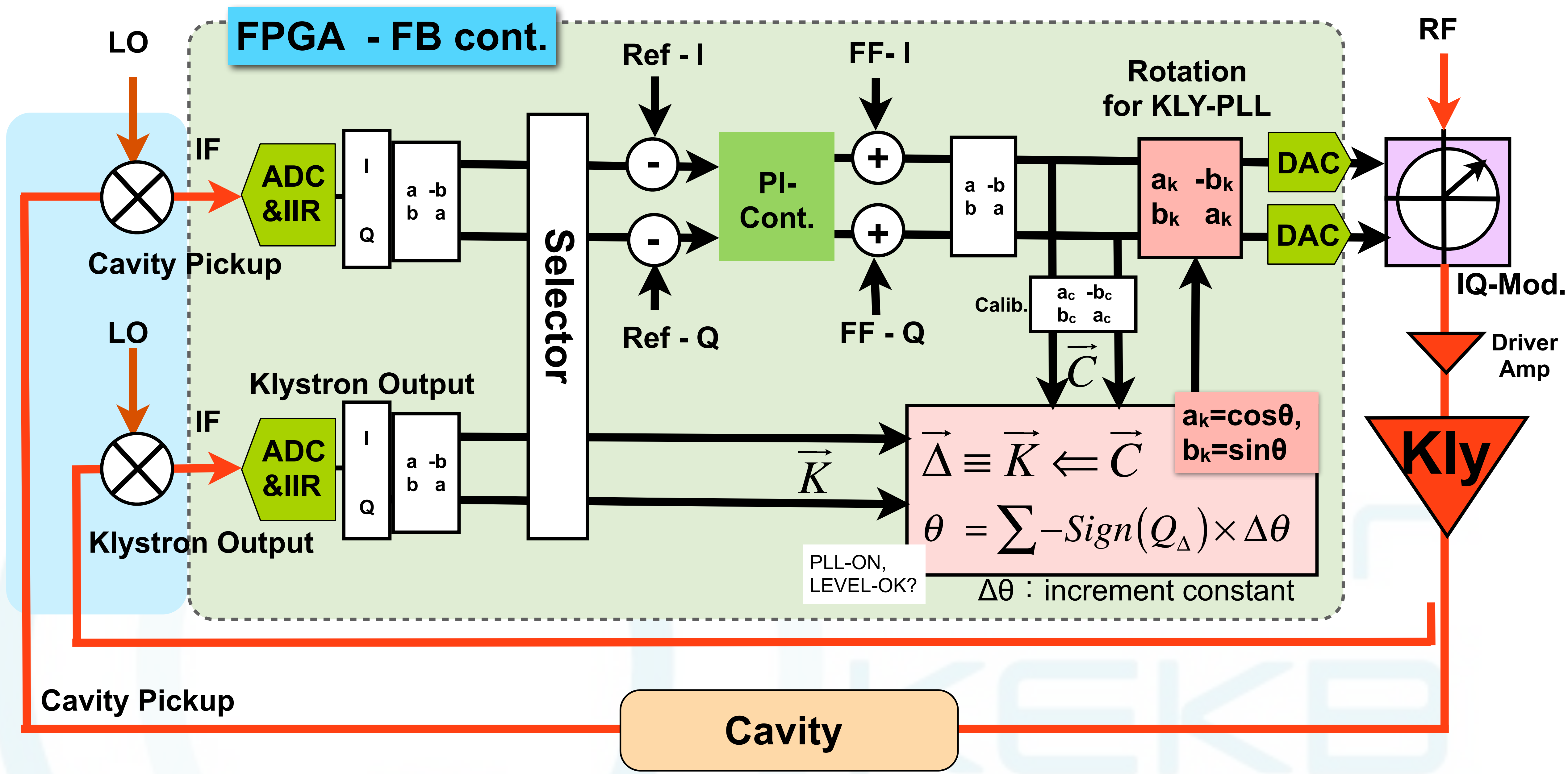
This loop phase shift of 80 deg. might be critical problem for the cavity FB control, because for I/Q-FB technique, controllable loop phase change is only +/- 90-deg. in principle.

In practical operation, acceptable phase change is about +/- 60 deg. (depending on FB gain.)

This phase change is unexpectedly-large.

Klystron Phase Lock Loop (KLY-PLL) is necessary.

Implementation of Klystron PLL
(future plan)



Cos and sin values are given by reference table in 2-deg. step and can be interpolated by 1st-order approximation.

Required loop band : ~1kHz (The anode voltage response : about 10Hz.)

Time Domain

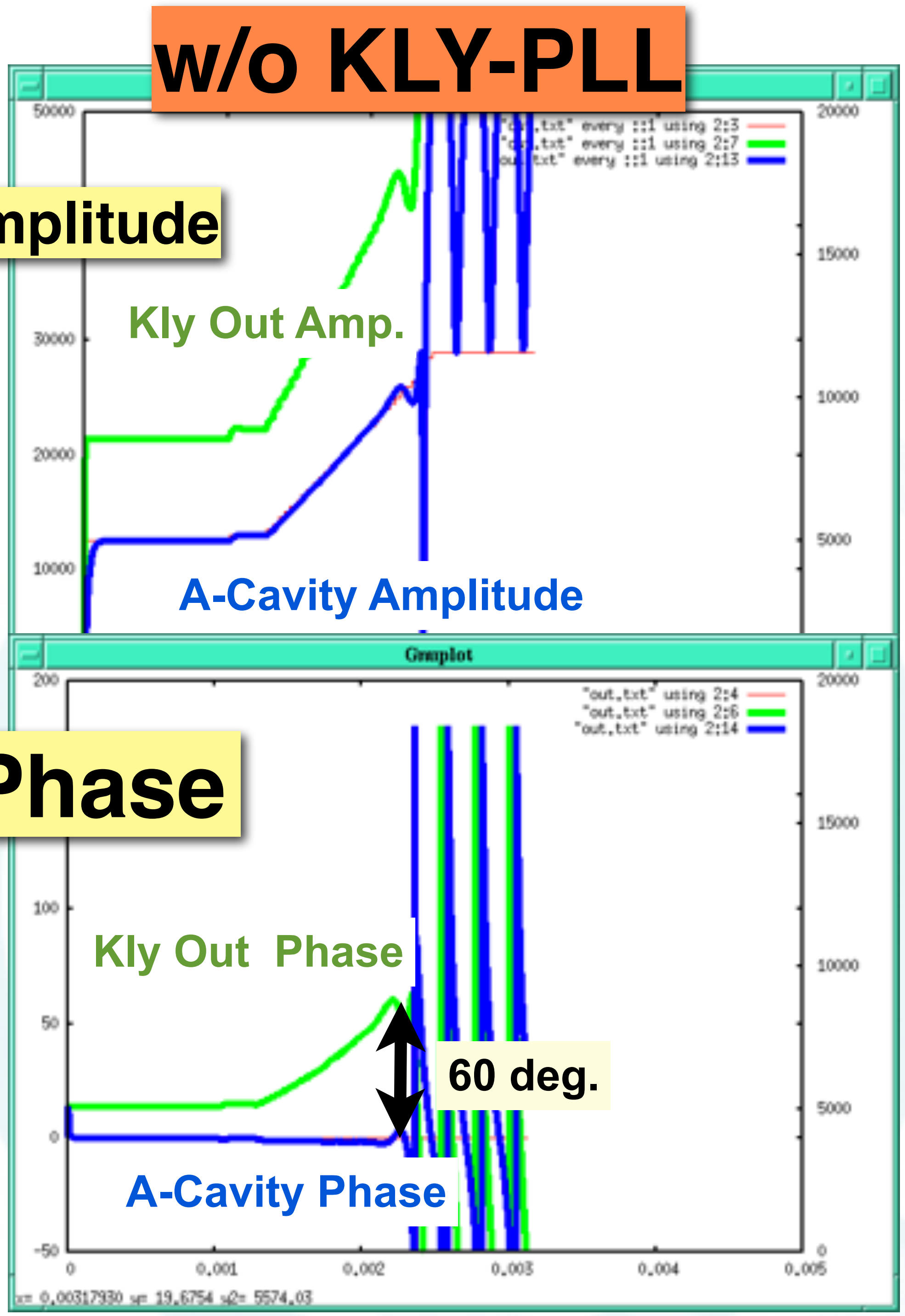
Simulation Result of the KLY-PLL

Cavity FB control with KLY-PLL

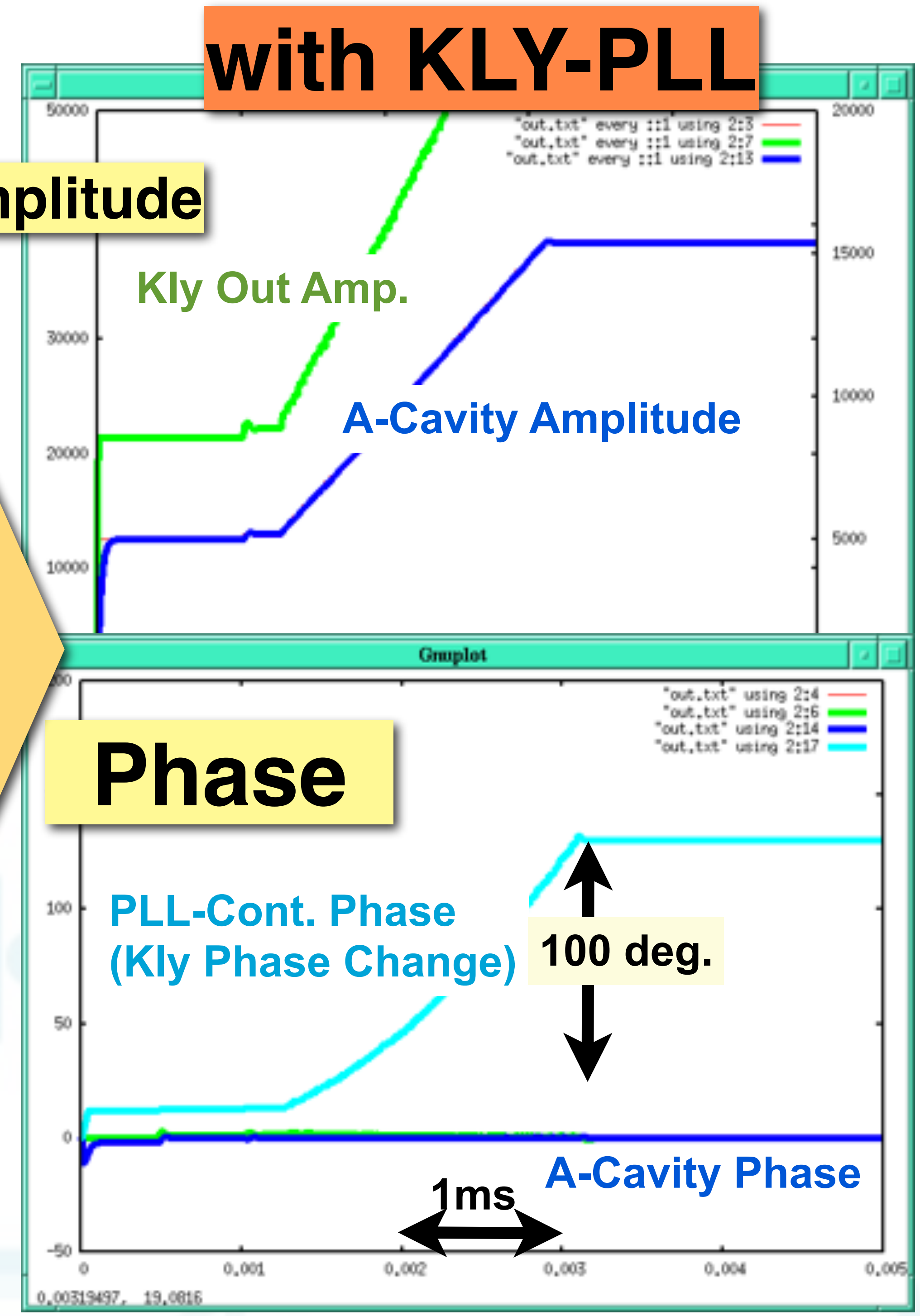
P_{gain}=2.5, I_{gain}=2.0e5
Cavity Loop Delay=2us, Δω=0

KLY loop Delay=1us
Δθ=0.01 deg. @CLK40MHz

In this simulation, the considerably faster response than the supposition is assumed.



KLY-PLL ON



Upgrade to β-Version

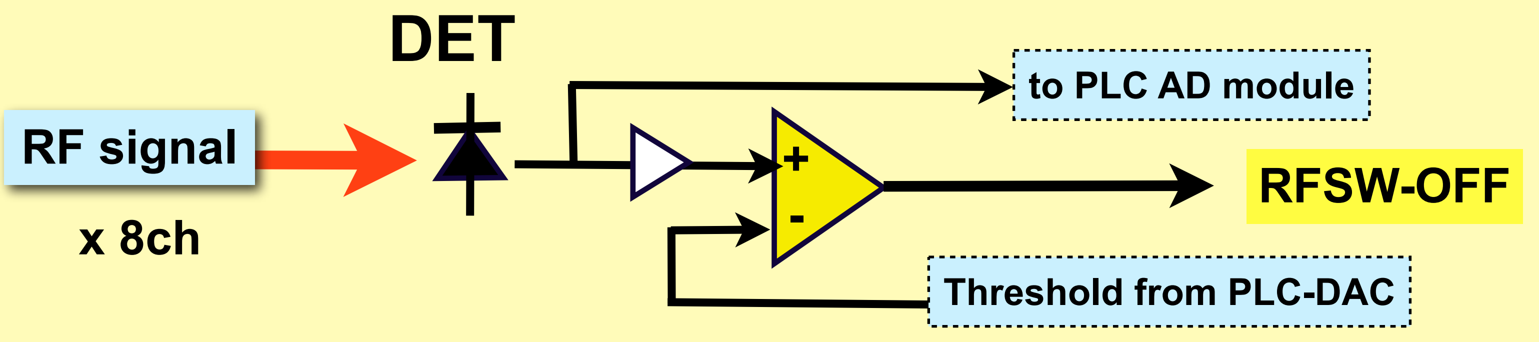
The second trial model (β-version) has been produced, and now under evaluation.
The high power test is planned in march 2013.

The fist prototype

α version

Discriminator for some RF signals I/L, which is independent of digital control.

Analogue comparators are used to detect abnormal.

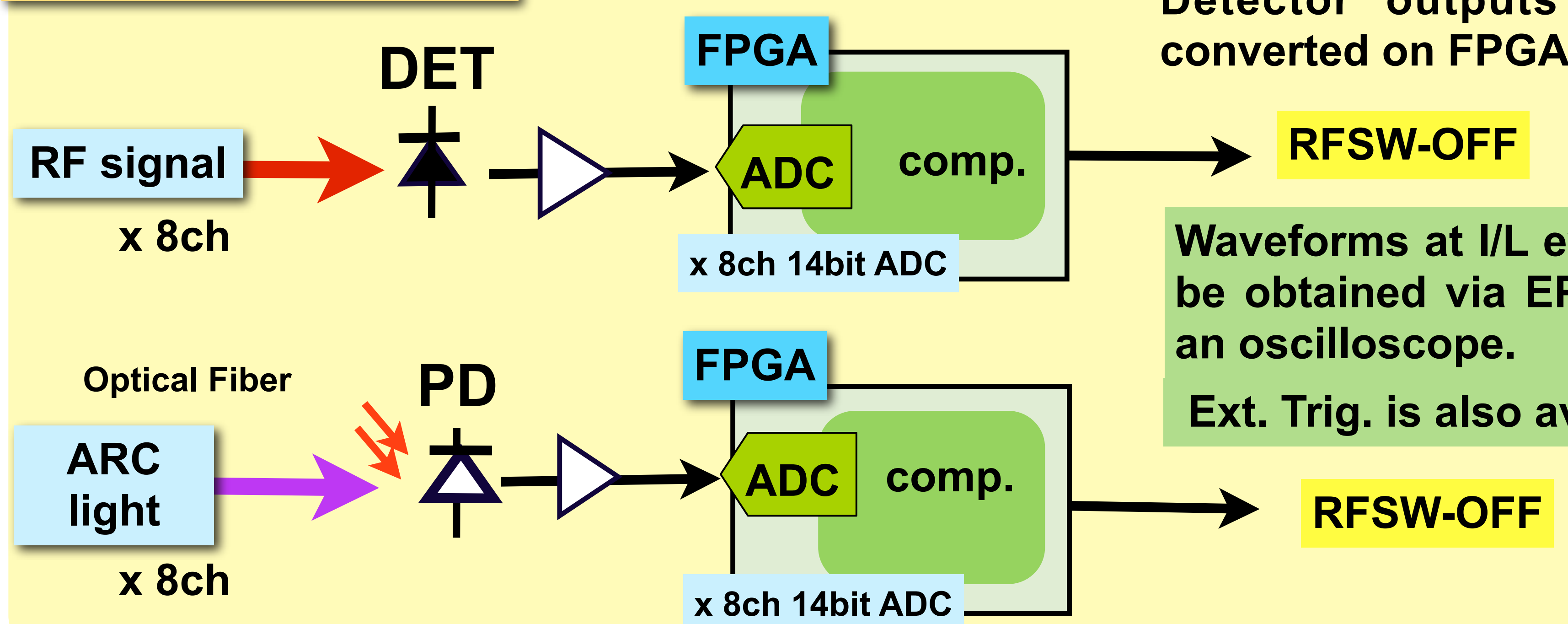


β version

Detector outputs are A/D-converted on FPGA at 10MHz.

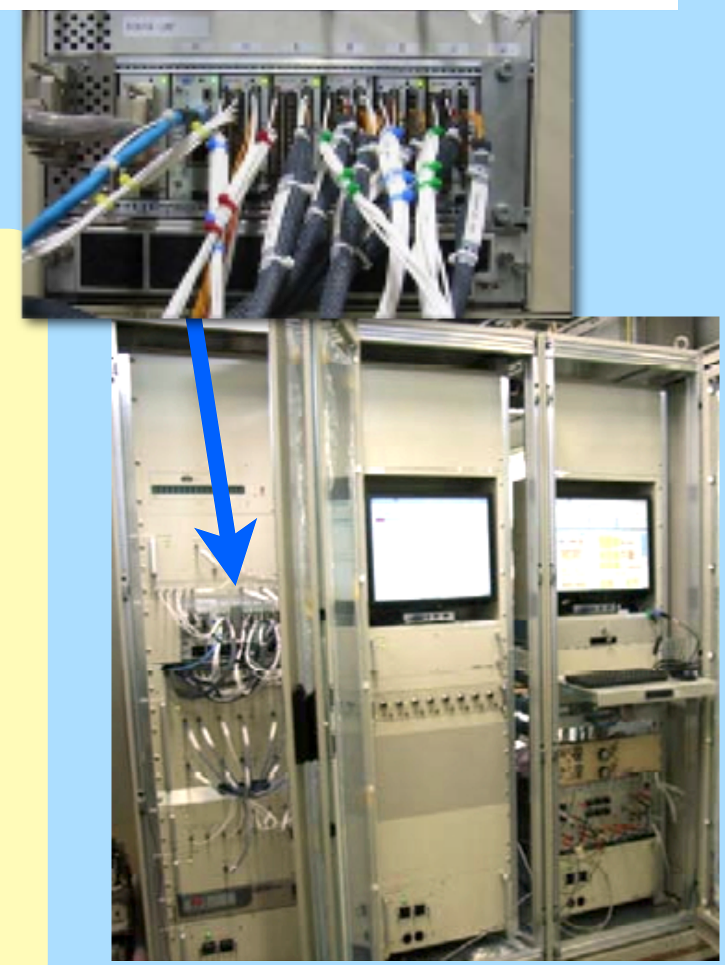
Waveforms at I/L event can be obtained via EPICS like an oscilloscope.

Ext. Trig. is also available.



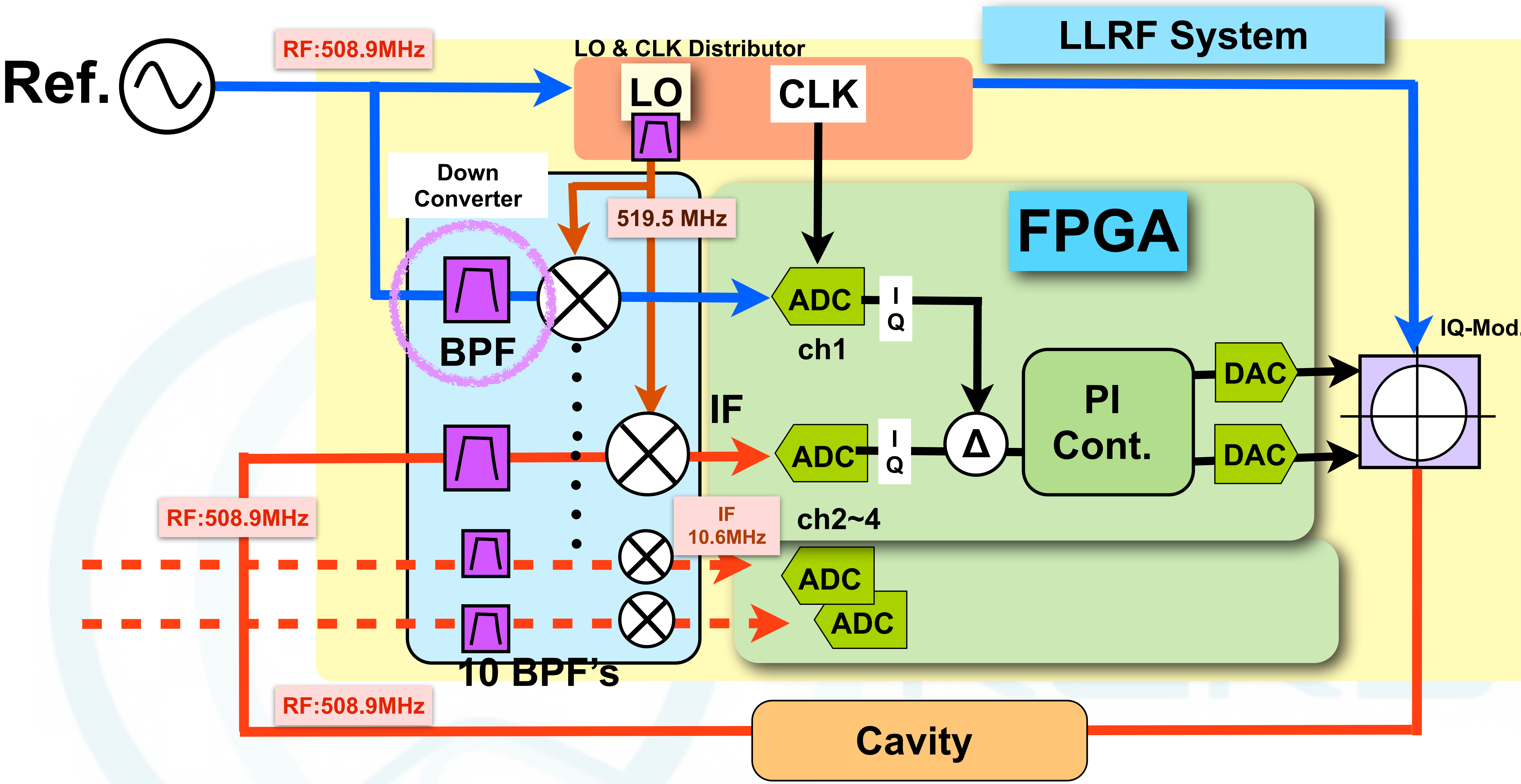
β-version LLRF System

5 FPGA cards in uTCA



Thermal Stability (reported in the previous review.)

Acceptable Temp. Coefficient	0.1%/deg.C in Amplitude 0.1 deg./deg.C in Phase	Measured Result	Amplitude: 0.5 % / deg.C Phase: 0.25 deg. / deg.C



From the evaluation of each RF element device, it is found that the main factor is BPF property in the downconverter for the temperature dependency.

BPF Choice & Fine Tuning of temp. coefficient

α-ver. Lumped Constant Circuit Type

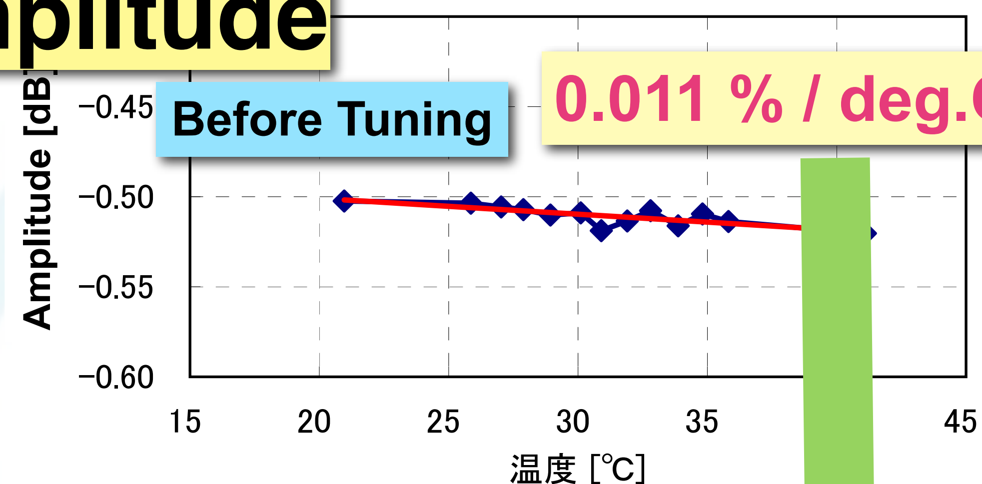
β-ver. Cavity Type (K&L - 4FV50)

for good regularity in characteristics between manufacture lots.

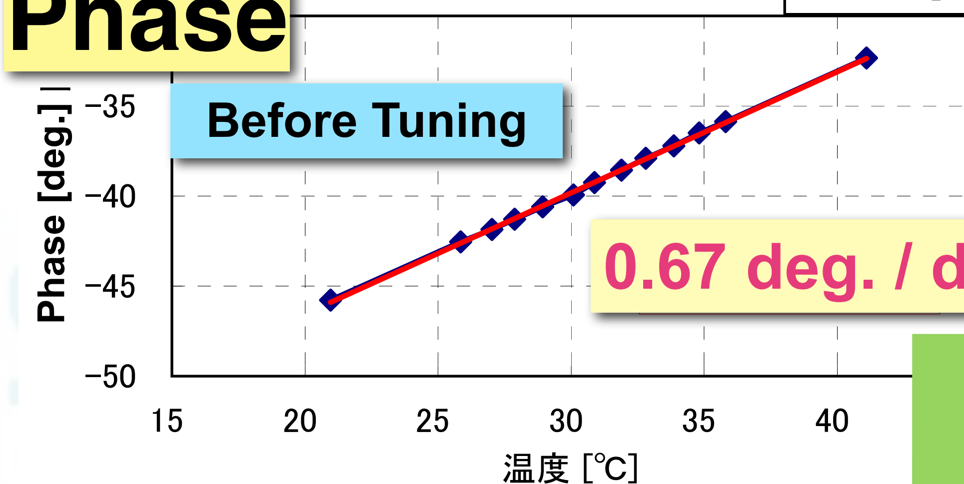
Additionally, fine tuning was applied to all BPF's.

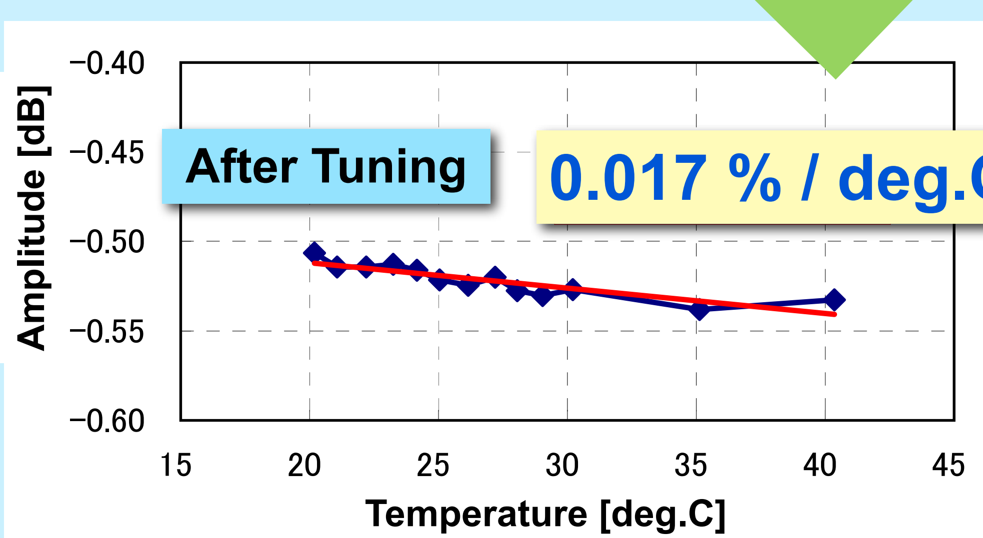
sample data

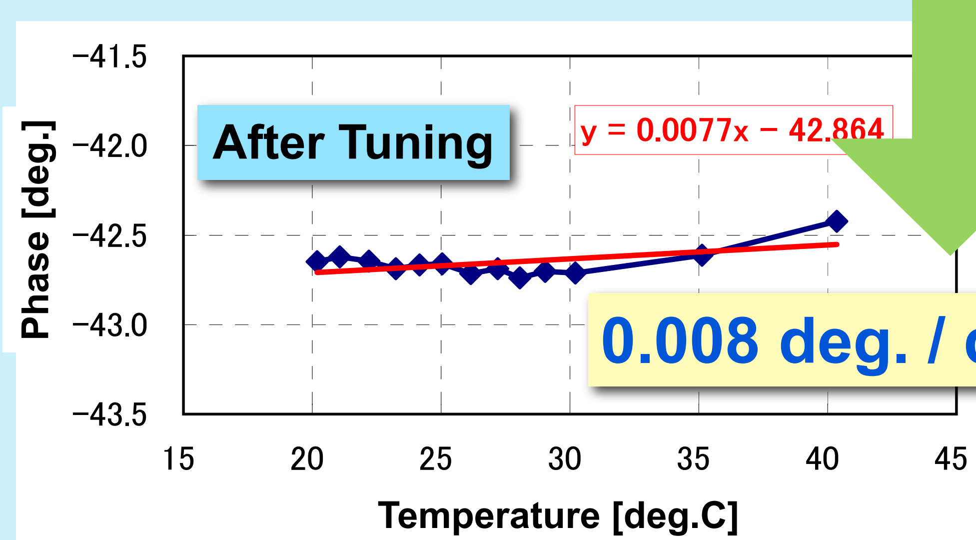
Amplitude



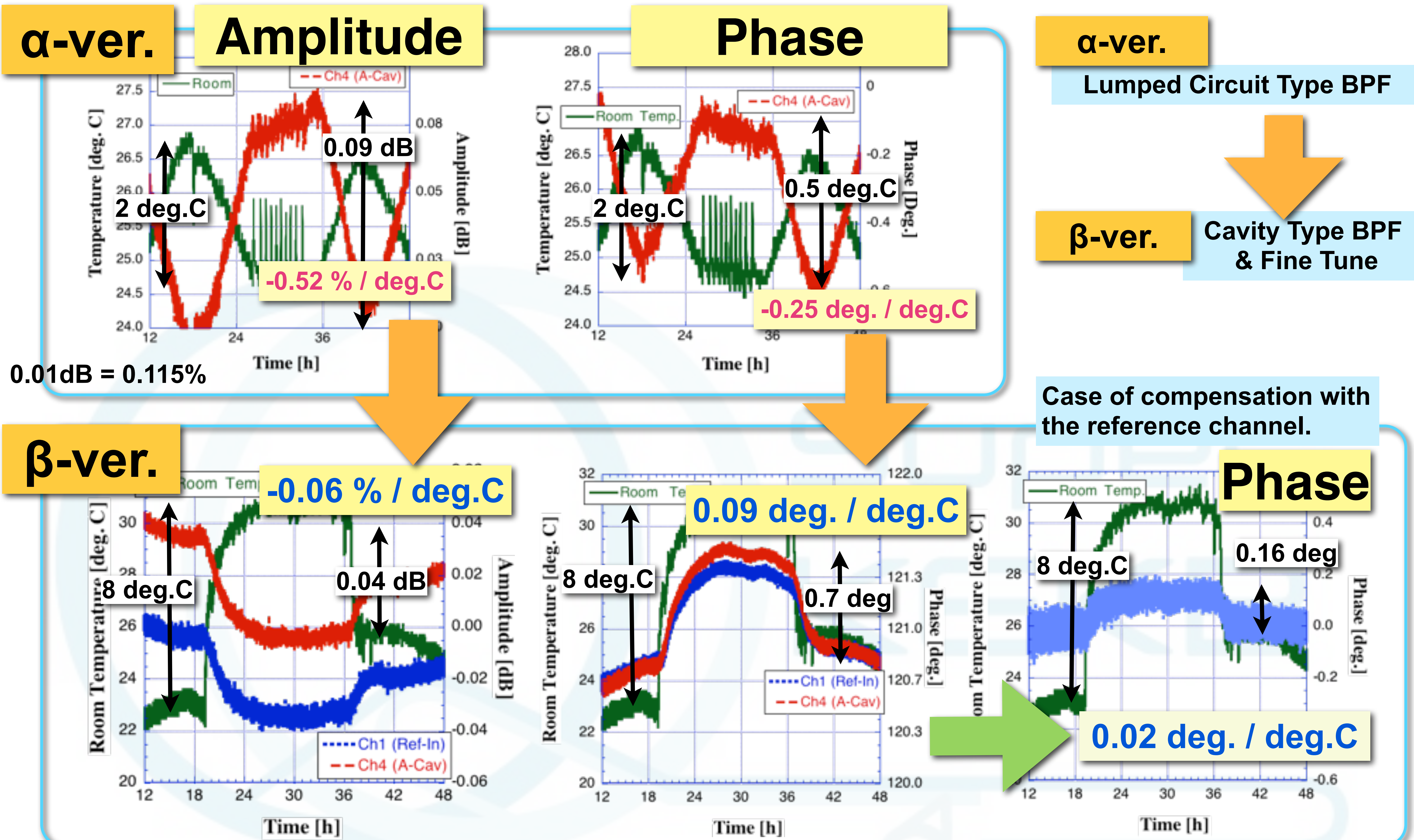
Phase



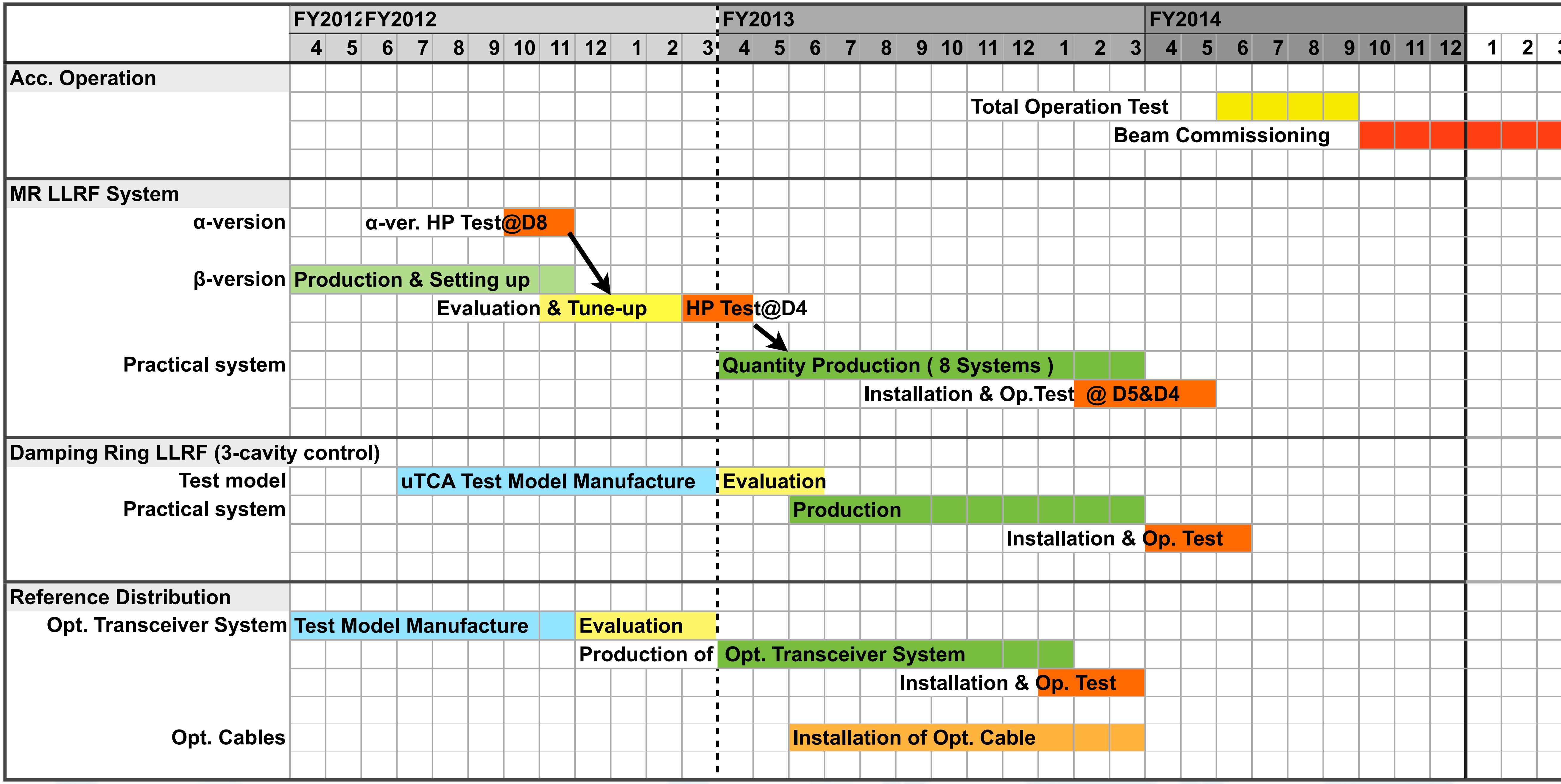




Improved Thermal Stability of the System (measurement results)



Schedule of Production and Installation



- High-power (HP) test of the α-version was performed last year, then the result was reflected into β-version. The HP test of the β-version is scheduled in march 2013.
- 8 new systems (actual operation model) will be produced and installed in D5 & D4 station in FY2013. For the DR, uTCA test model will be evaluated soon, and the practical production will also start in FY2013.
- Optical transceiver system and cables will be also installed in FY2013 for the reference distribution.

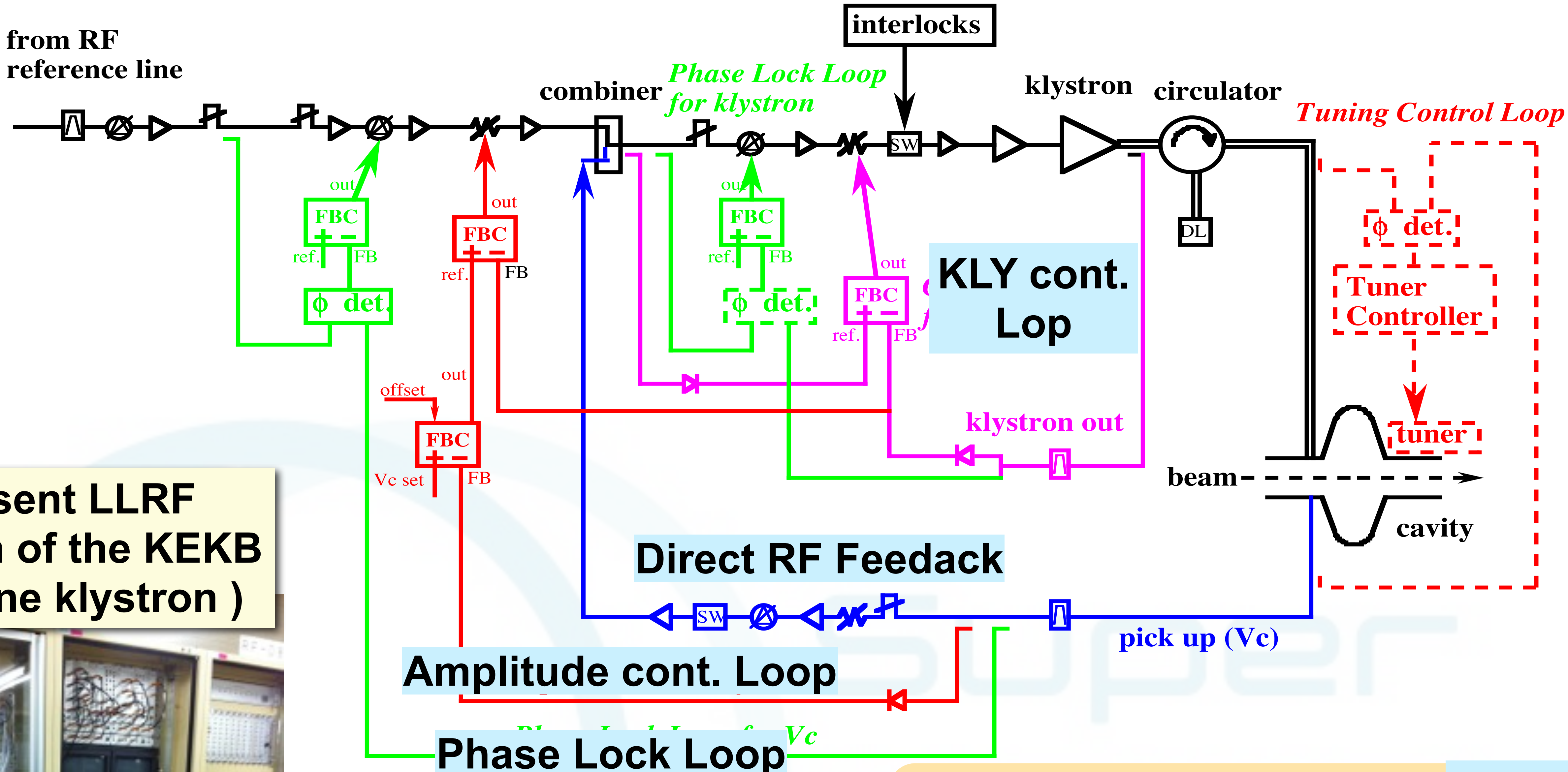
Summary

- High power test of the prototype system (α-version) was performed, and FB control and auto tuning control worked successfully.
- Very good FB stability was obtained in "out of the loop" measurement. (0.02% in amp. & 0.02 deg. in phase)
- Large klystron phase shift, depending on input power, was found due to the efficiency optimization. This loop phase shift might be critical problem for the I/Q FB control, therefore KLY-PLL function should be implemented into the FPGA as the future issue.
- Thermal stability was improved by BPF tuning, then acceptable temperature coefficient was achieved (0. 06%/deg.C in Amp. 0.02 deg./deg.C in Phase)
- Most of the practical system will be produced and installed in FY2013.

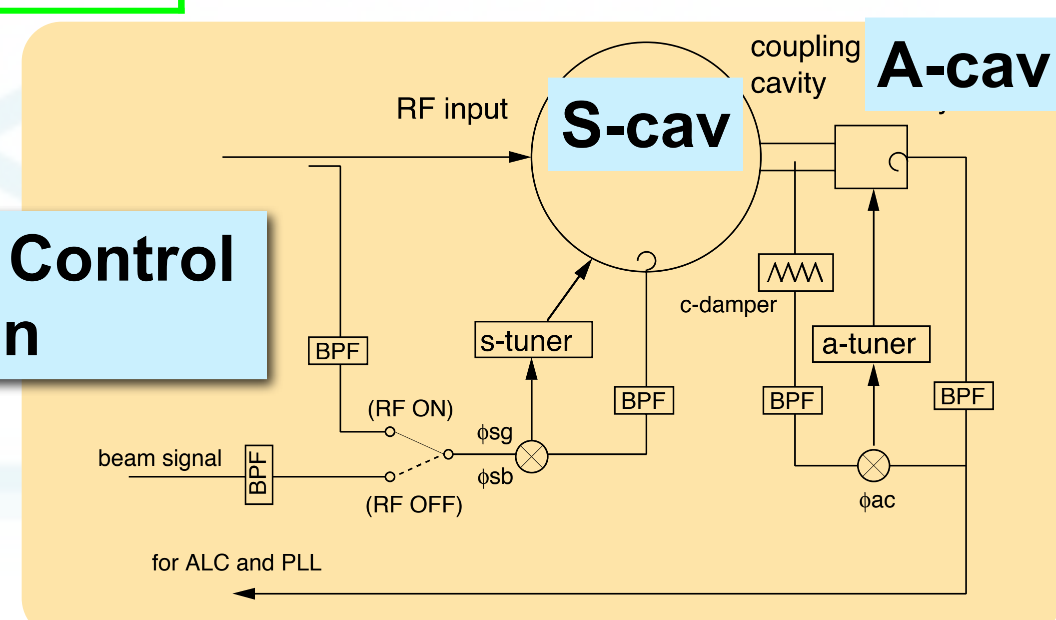
Thank you for your attention !

Followed by Backup Slides

KEKB-LLRF System (Present)

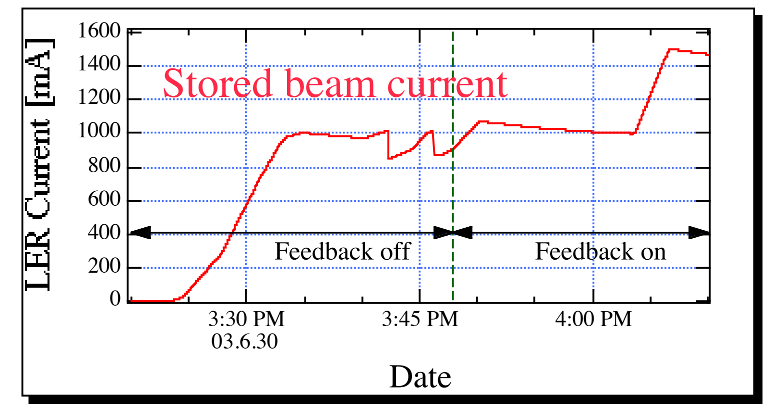


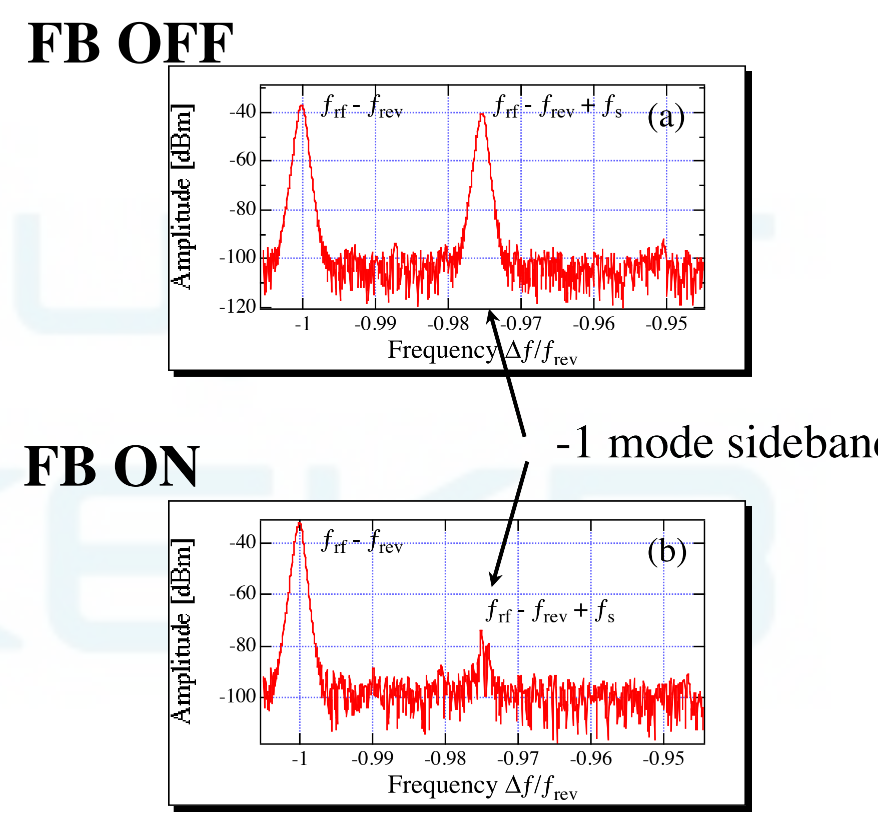
Present LLRF System of the KEKB (for one klystron)

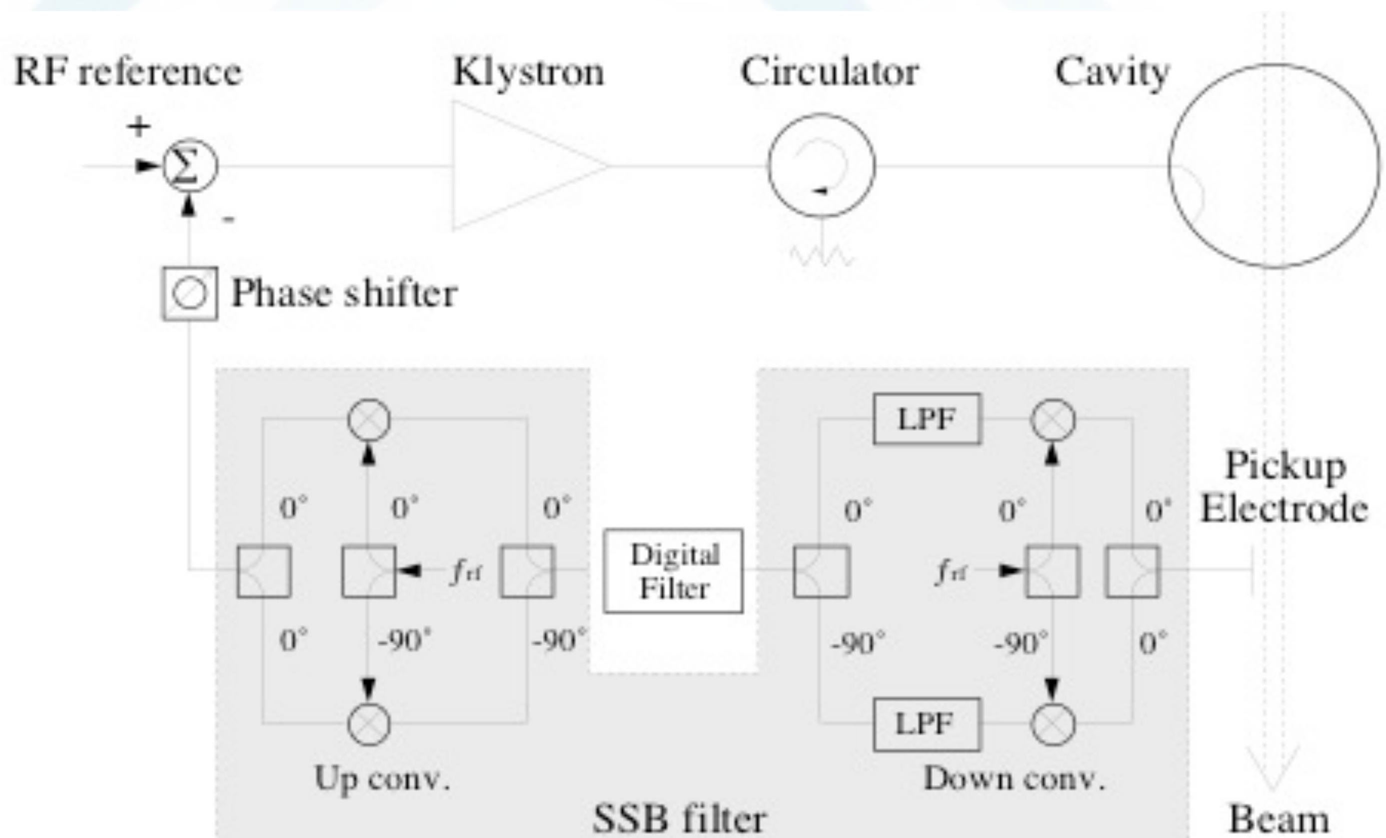


The -1 mode feedback

- Beam current was limited due to the -1 mode instability at 1 A in LER and 1.2 A in HER, much lower current than expected.
- The -1 mode digital feedback selectively reduces impedance at the driving frequency.
- After the -1 mode feedback was installed, the beam current could be successfully increased.



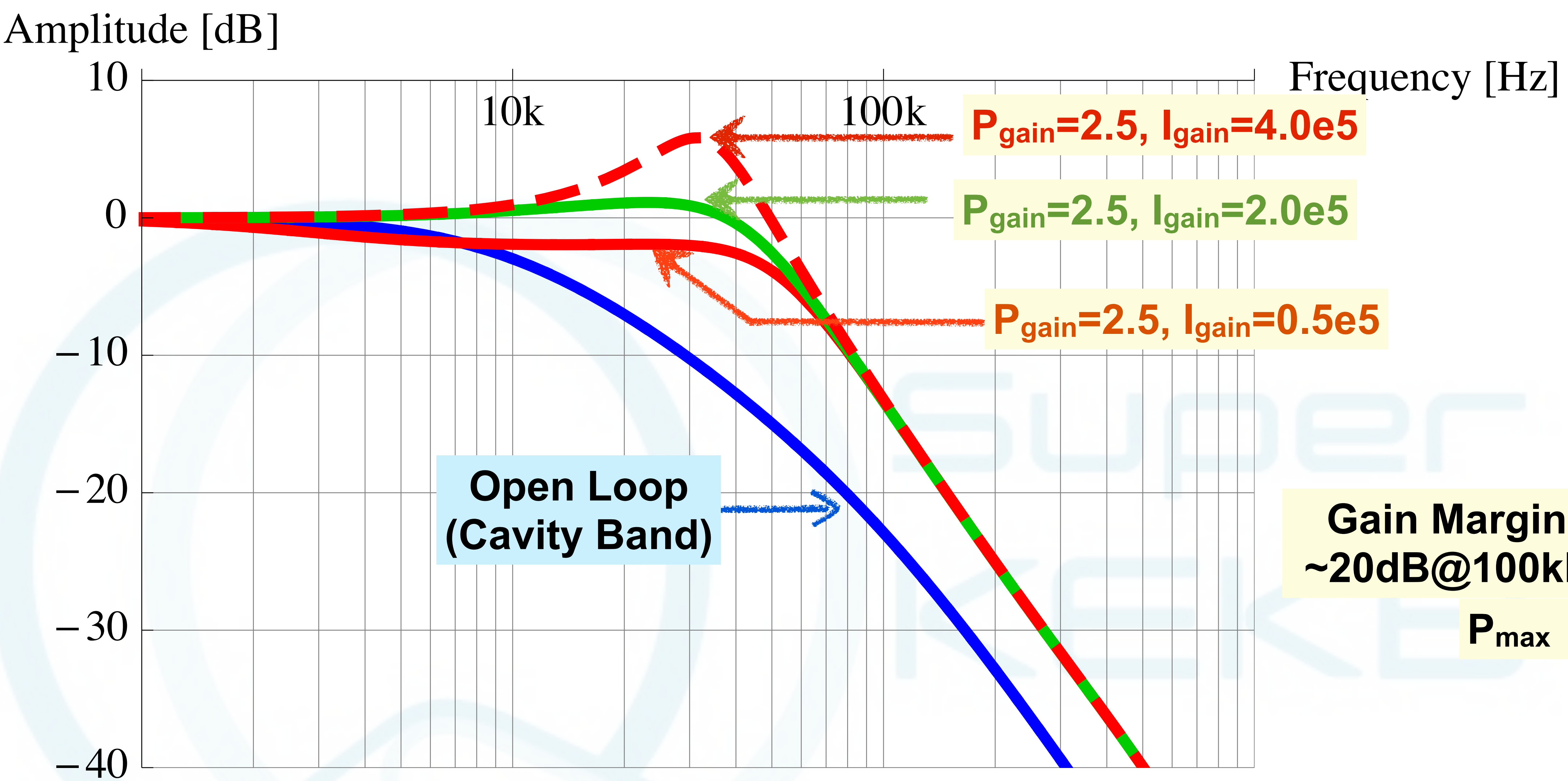




Bode Plot of ARES FB cont.

Q_L=27000   Δω = 0   Loop Delay = 2us   Klystron band = 100kHz

(Q_0=110000, Coupling=3)

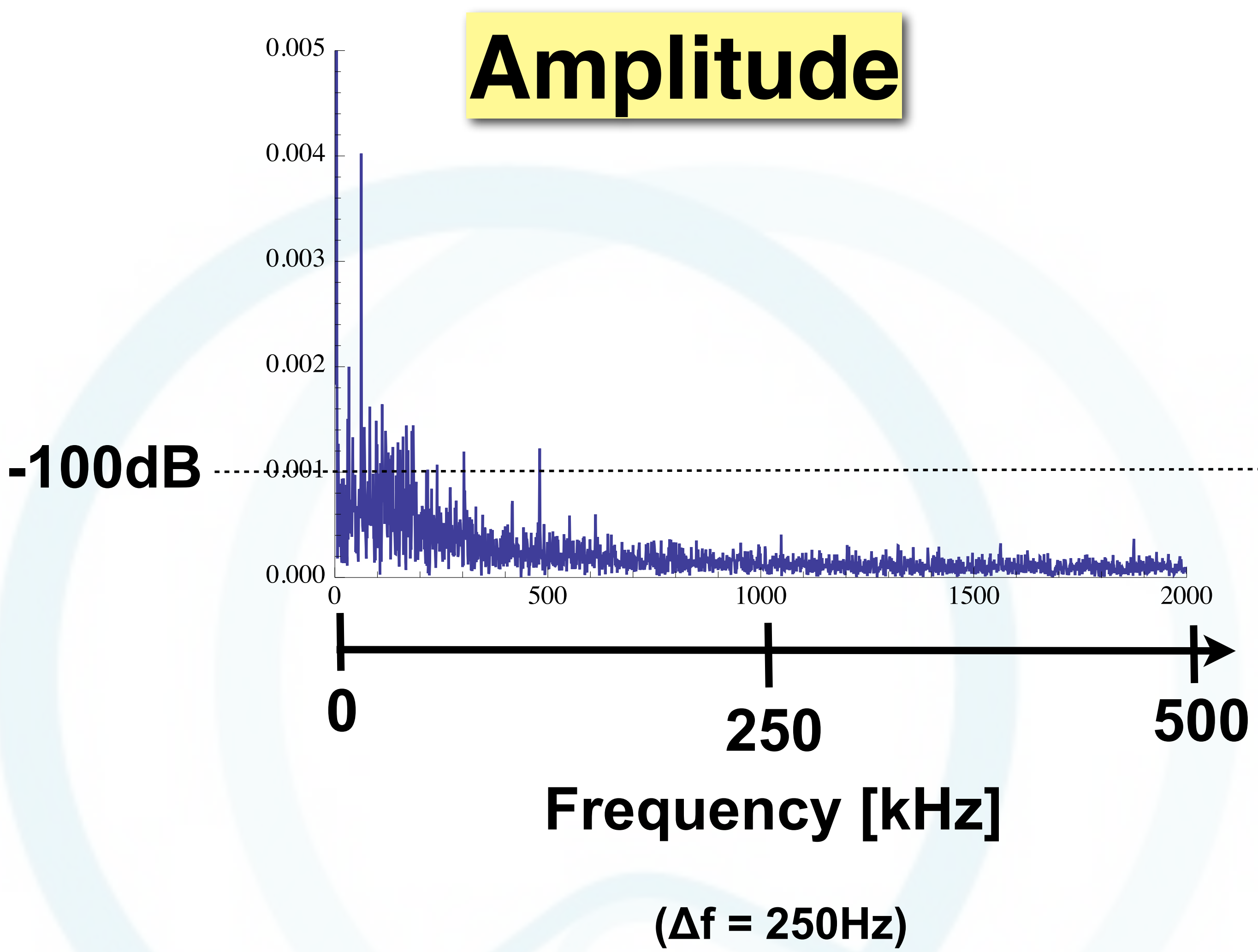


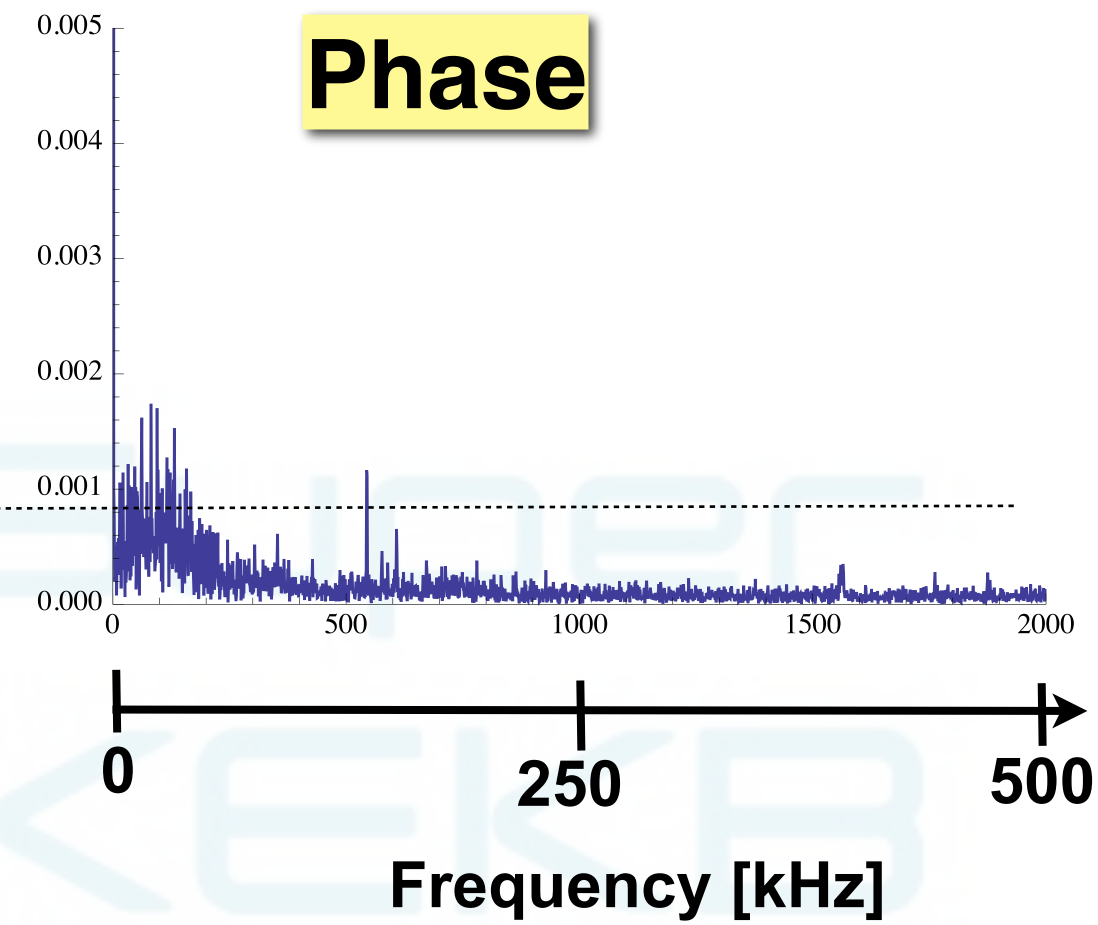
Gain Margin : ~20dB@100kHz

P_{max} ~ 5

Discrete Fourier Transform

of the stability measurement in the page 8





Thermal Stability (2012)

for acc. gradient

Required Stability

+/- 1% in Amplitude
+/- 1 deg. in Phase

Our target value of the stability

for LLRF System

+/- 0.3% in Amplitude
+/- 0.3 deg. in Phase
(pk-pk)

Ambient Temperature Change : about +/- 2 deg.C

Acceptable Temp. Coefficient

0.1%/deg.C in Amplitude
0.1 deg./deg.C in Phase

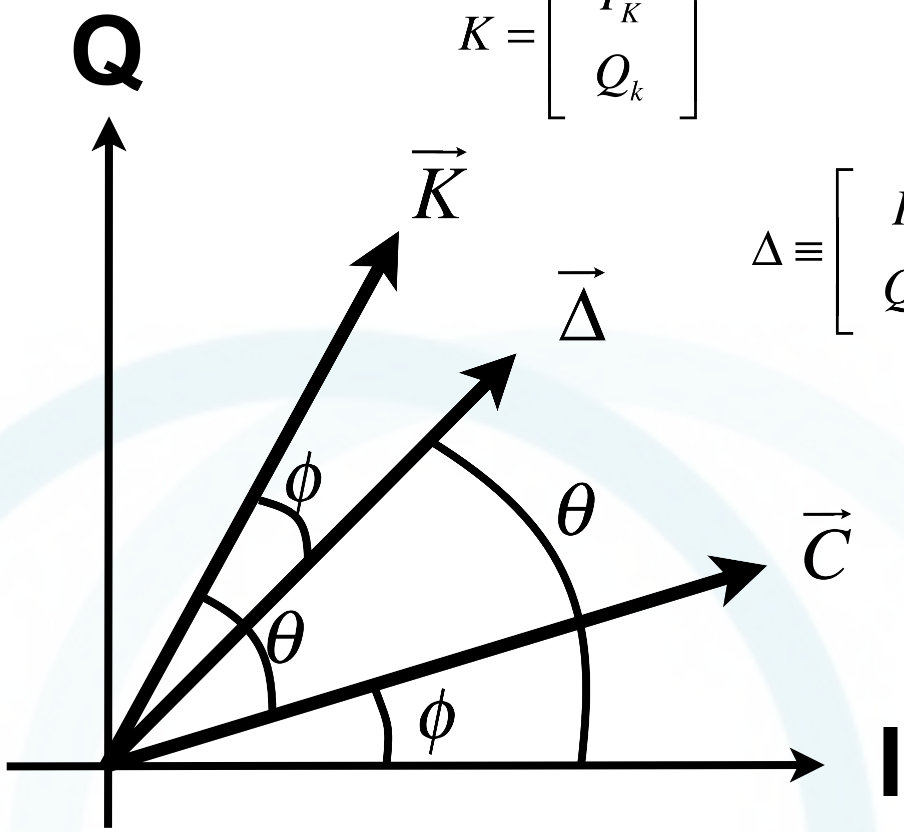
Measured Result

LLRF system total

Amplitude: 0.5 % / deg.C
Phase: 0.25 deg. / deg.C

Requirements are not satisfied.

Phase Difference between two Vectors



$$K = \begin{bmatrix} I_K \\ Q_k \end{bmatrix}$$

$$\Delta \equiv \begin{bmatrix} I_\Delta \\ Q_\Delta \end{bmatrix} = \begin{bmatrix} \cos(-\phi) & -\sin(-\phi) \\ \sin(-\phi) & \cos(-\phi) \end{bmatrix} \begin{bmatrix} I_K \\ Q_k \end{bmatrix}$$

$$C = \begin{bmatrix} I_C \\ Q_C \end{bmatrix} \qquad \cos\phi = \frac{I_c}{\sqrt{I_c^2 + Q_c^2}}, \quad \sin\phi = \frac{Q_c}{\sqrt{I_c^2 + Q_c^2}}$$

$$\Delta_I = \frac{I_c I_K + Q_c Q_k}{\sqrt{I_c^2 + Q_c^2}} \qquad \Delta_Q = \frac{-Q_c I_K + I_c Q_k}{\sqrt{I_c^2 + Q_c^2}}$$

$$\tan\theta = \frac{\Delta_Q}{\Delta_I} = \frac{-Q_c I_K + I_c Q_k}{I_c I_K + Q_c Q_k}$$