Prototype Performance of Digital LLRF Control System for the SuperKEKB

~ KEKB LLRF Team ~

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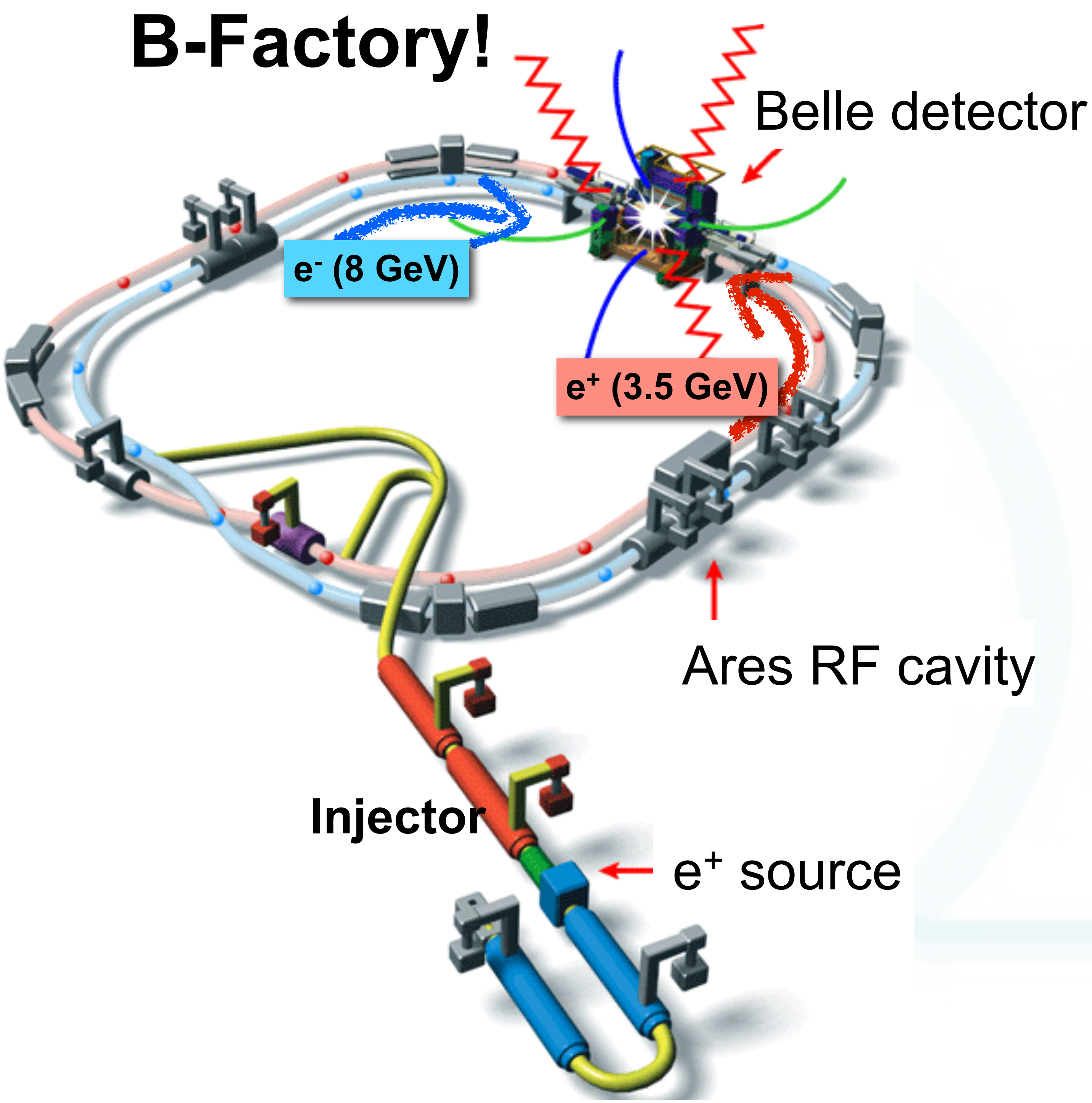
Talk Outline

1. SuperKEKB (SKB) Project
2. Digital LLRF System for the SKB
3. the Performance Evaluation
4. Summary

KEKB Accelerator

Operation: 1999. ~ 2010

Shut down : June, 2010



- **e^- (8.0GeV) × e^+ (3.5GeV)**
  ➡ Y(4S) -> $B\bar{B}$
- **Circumference**
  ~3018m
  Use TRISTAN Tunnel
- **RF System (CW)**
  f_{RF} ~ 509MHz
  ARES Cavities (LER)
  ARES + SCC (HER)

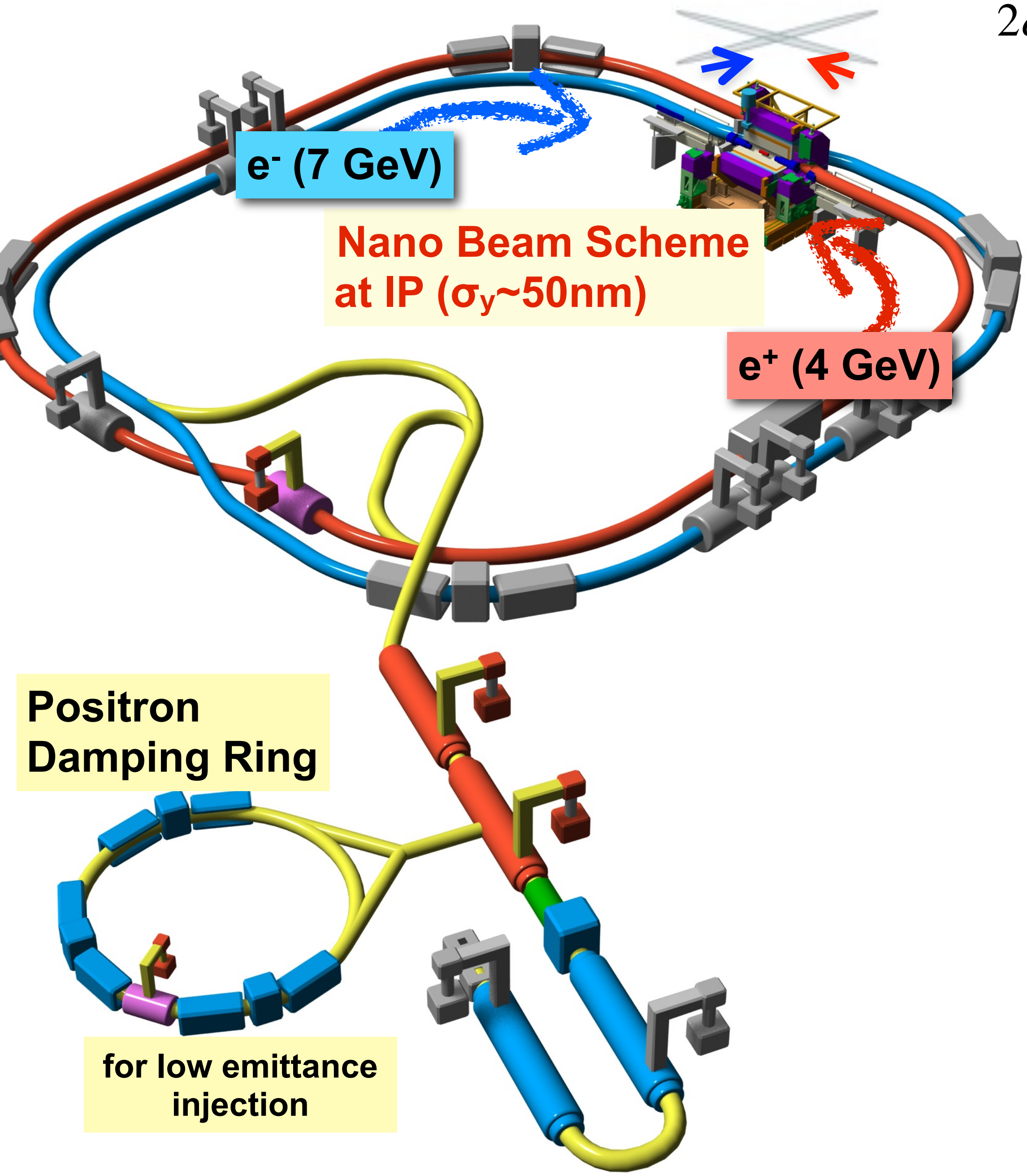
Peak Luminosity
1.8 x 10^{34} $cm^{-2}s^{-1}$!

The World Highest Luminosity!

Upgrade to SuperKEKB

Luminosity : x 40 !

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$



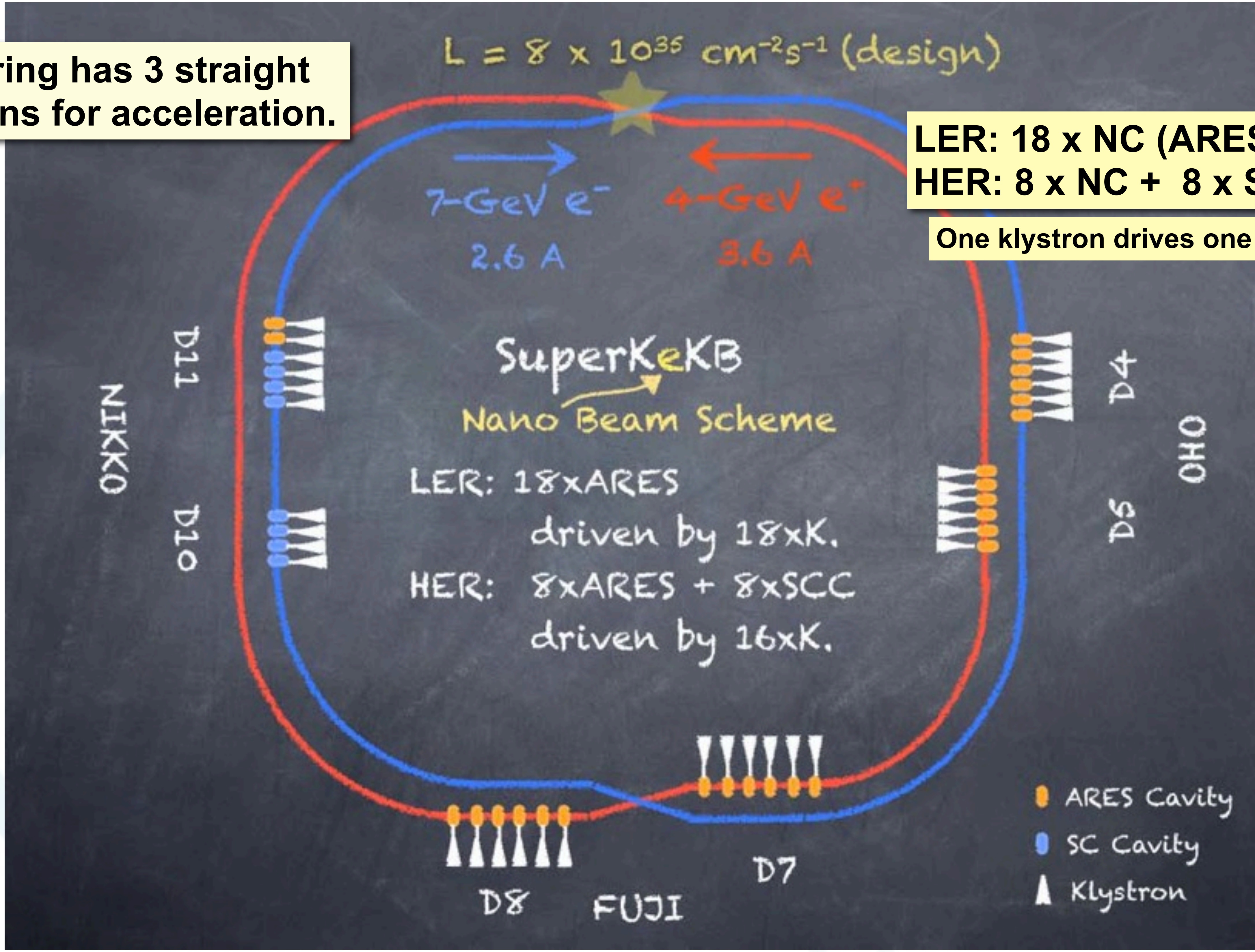
	KEKB (Achieved)		SuperKEKB (Designed)	
	LER/HER		LER/HER	Unit
Beam Energy	3.5/8.0		4.0/7.0	GeV
Emittance ε_x	18/24	x5	3.2/5.3	nm
Beta Function β^*_y	5.9/5.9	x20	0.3/0.3	mm
Bunch Length σ_z	6/7		6/5	mm
Beam Current	1.8/1.5	x2	3.6/2.6	A
Luminosity	1.71	x40!	80	10^{34} $cm^{-2}s^{-1}$
# of Bunches	1293		2503	
Beam Power	3.5/5.0	x3	9.3/6.5	MW
RF Frequency	508.887		508.887	MHz
Harmonic Number	5120		5120	
Revolution Freq.	94.4		94.4	kHz
RF Voltage	8.0/13.0		9.6/12.0	MV
# of Cavities	20/20		18/16	
Klystrons : Cavity	1:2	x2	1:1	
RF Input Power	375		~800kW	kW / cav

Commissioning Start FY2014 !

Layout of Acc. Cavity Location

(Design for SuperKEKB)

Each ring has 3 straight sections for acceleration.

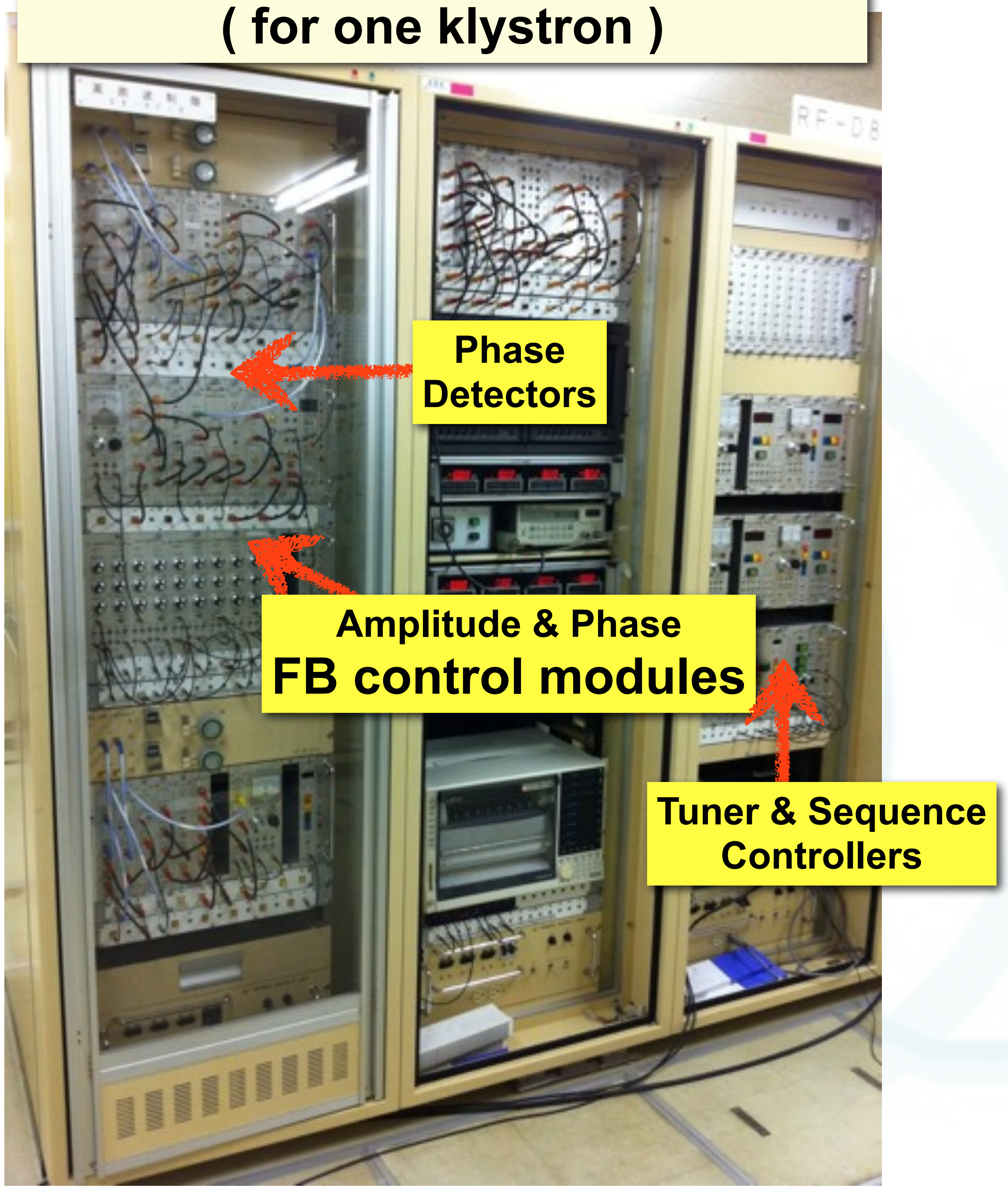


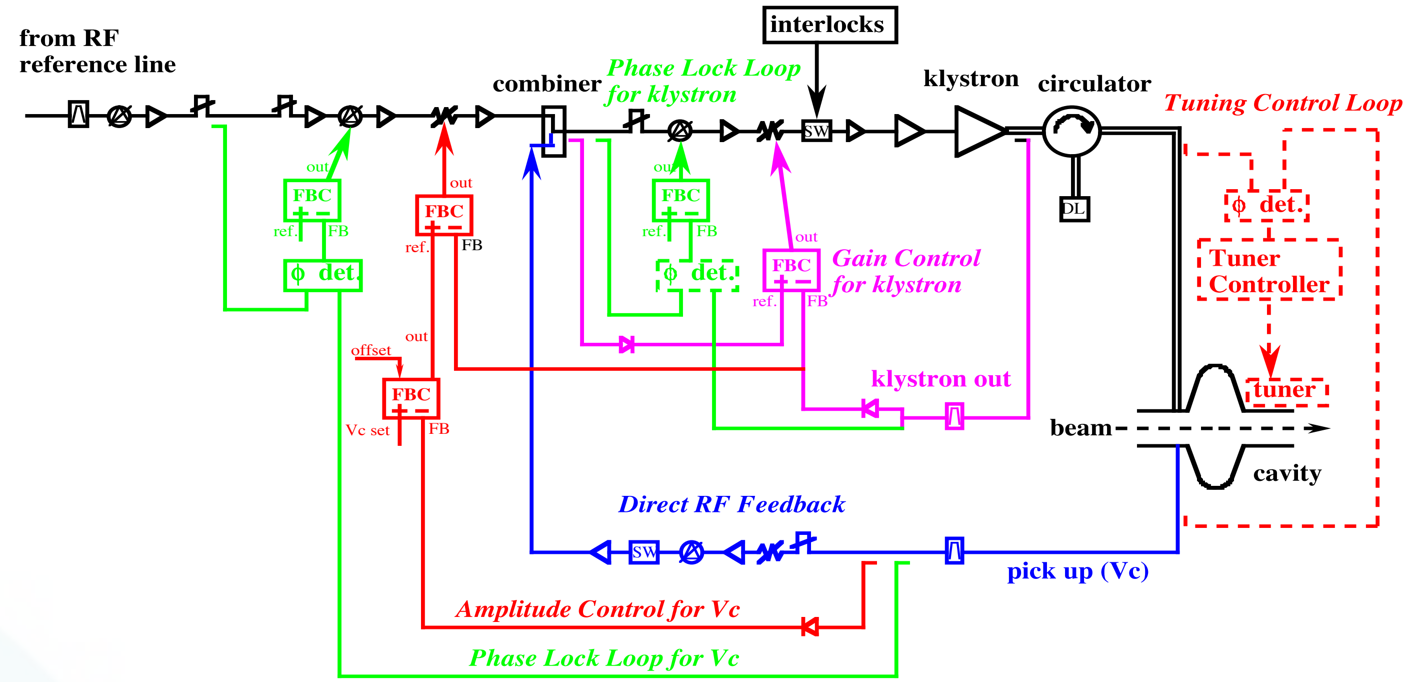
LER: 18 x NC (ARES)
HER: 8 x NC + 8 x SC

One klystron drives one cavity

KEKB-LLRF System (Present)

Present LLRF System of the KEKB (for one klystron)





The KEKB has been operated until 2010, by using this system.

KEKB LLRF systems are composed of combination of analog NIM modules.

These were controlled remotely by using CAMAC systems with EPICS-IOC from central control room.

LLRF Upgrade for SuperKEKB

Replace all preset analog systems to new digital LLRF Systems.

- with μTCA-based FPGA boards& PLC.
- performs as EPICS-IOC.

KEKB → SuperKEKB : Lower emittance & Higher beam current $\frac{P_b}{P_c} \approx 5$

LLRF system — More accurate, More stable & More flexible!

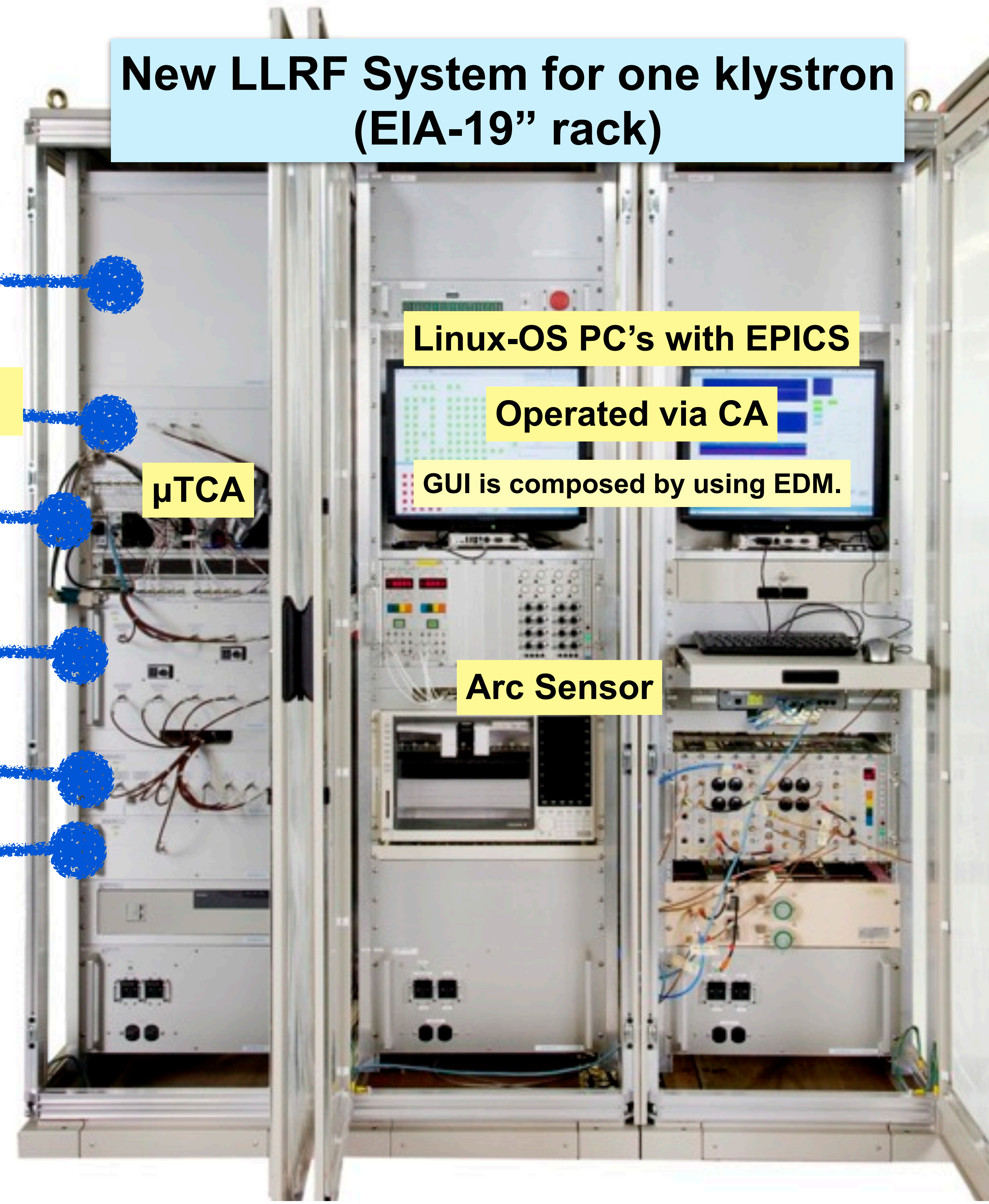
for acc. gradient
Required Stability — 1% in Amp. , 1 deg. in Phase

Our target value of the stability
for LLRF System — 0.3% in Amp., 0.3 deg. in Phase

Prototype of New LLRF System

for the SuperKEKB

A prototype of new digital LLRF system was produced for the SuperKEKB in this year.
It is now under evaluation to fix the design for the quantity-production.



uTCA-based Digital FB Unit

It consists of 3 FPGA boards.

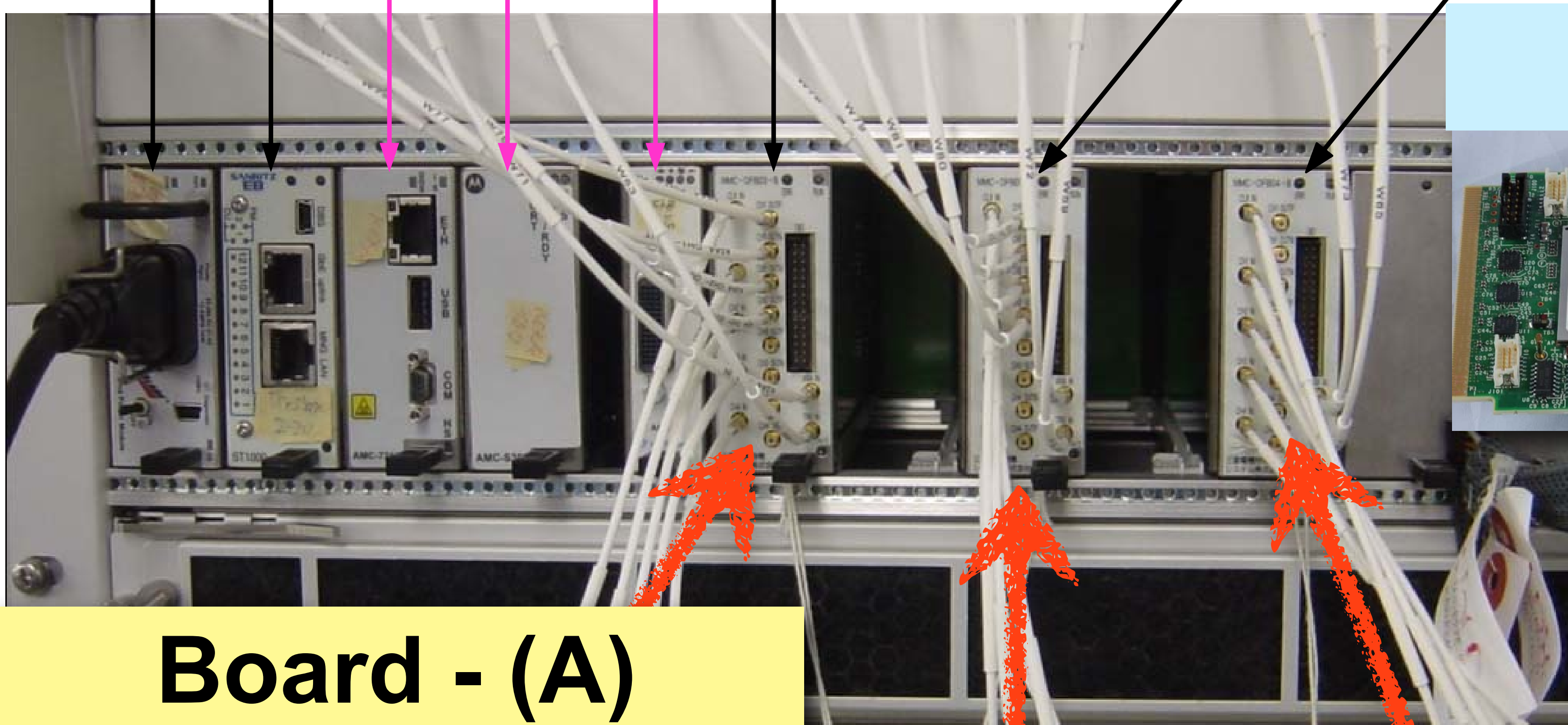
It is common with the STF.

PM (Power Module)
AC/DC
MCH
CPU
HDD
DVI

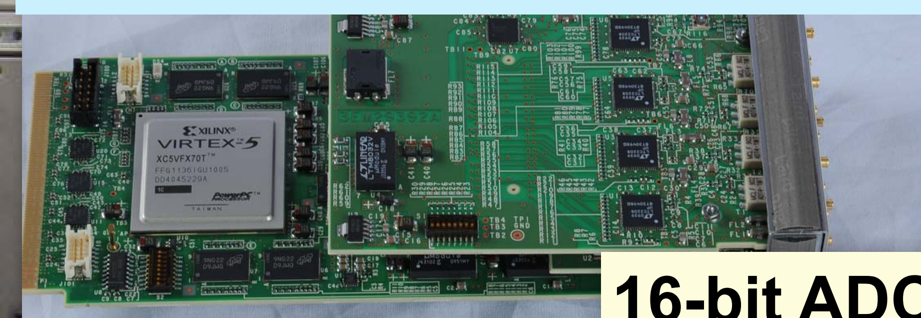
Board - (A)
MMC−DFB02−B

Board - (B)
MMC−DFB03−B

Board - (C)
MMC−MON02−B



FPGAボード



16-bit ADC x 4ch,
16-bit DAC x 4ch

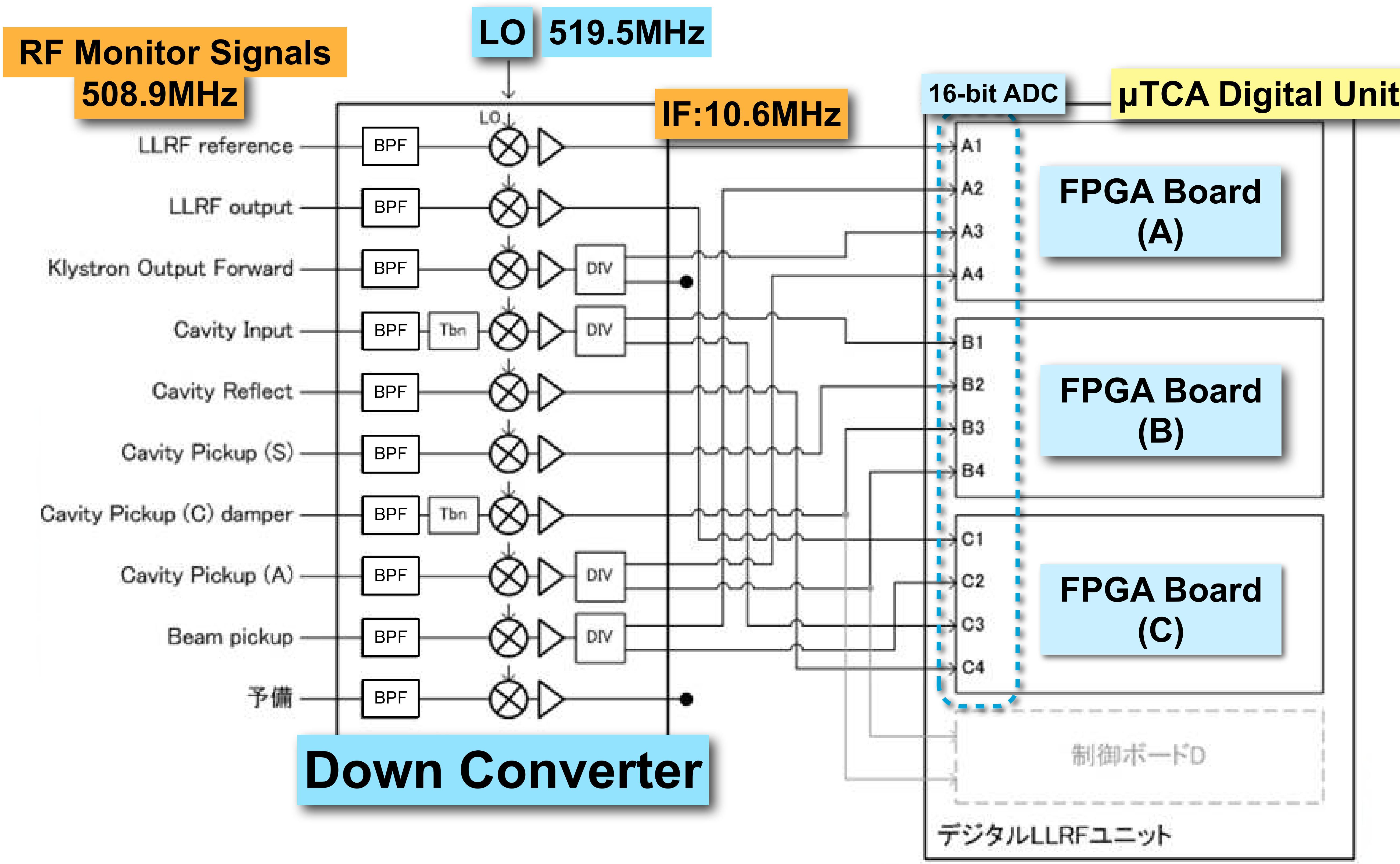
Each board has a CPU (PPC), and the Linux-OS is installed. It behaves as EPICS-IOC.

Board - (A)
Digital FB Control

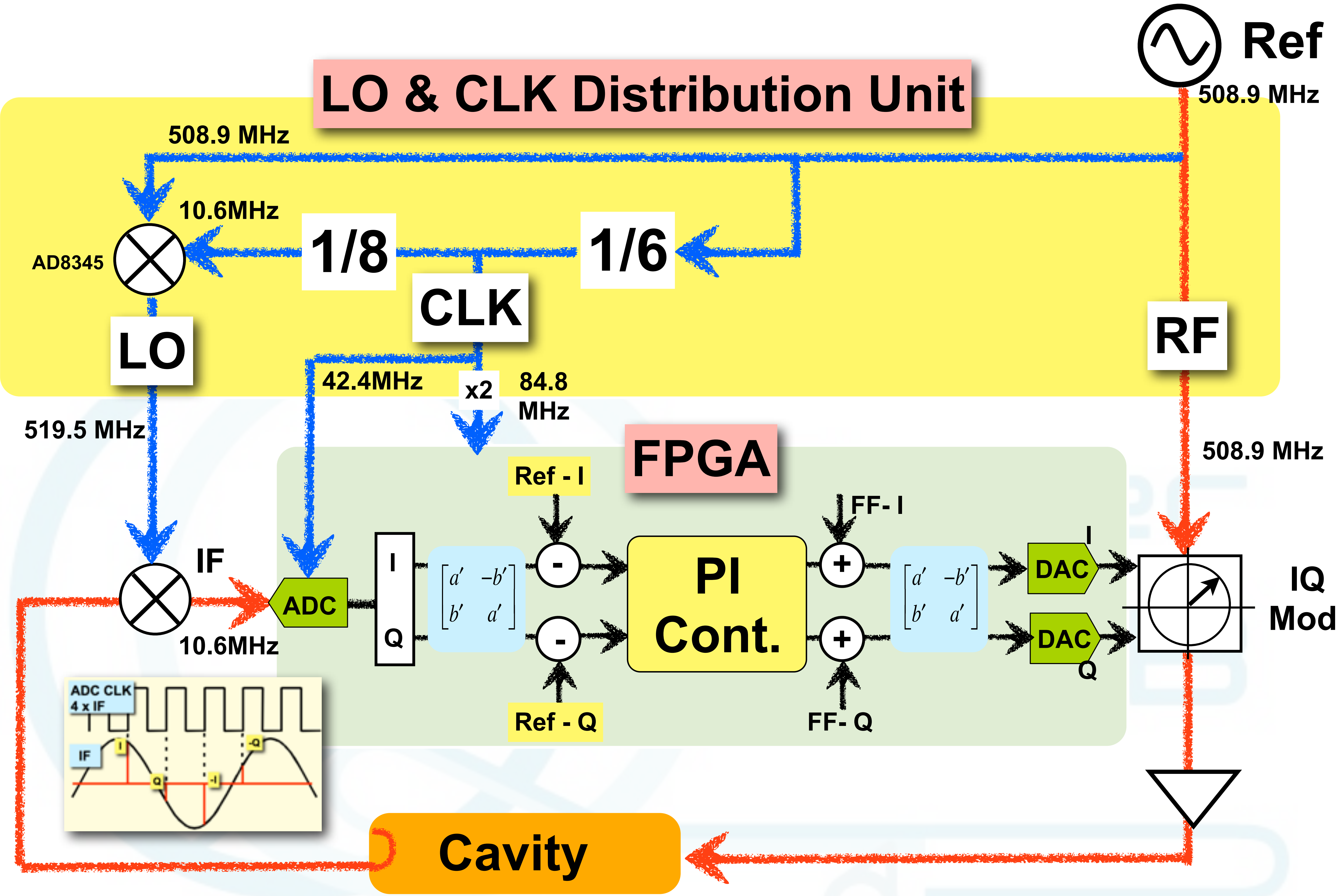
Board - (B)
Tuner Control

Board - (C)
VSWR Monitor for I/L

RF Monitor Signals (Down converted to 10-MHz IF)

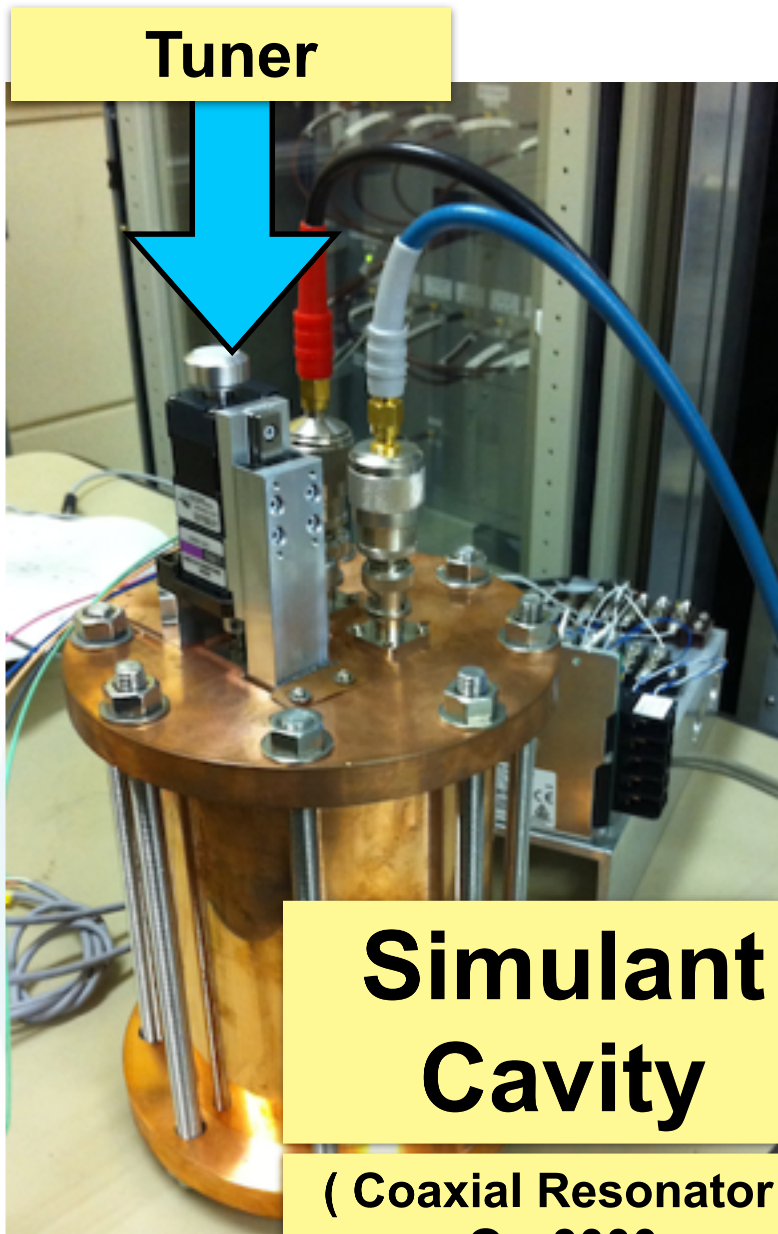


Basic Technique of digital FB Cont.



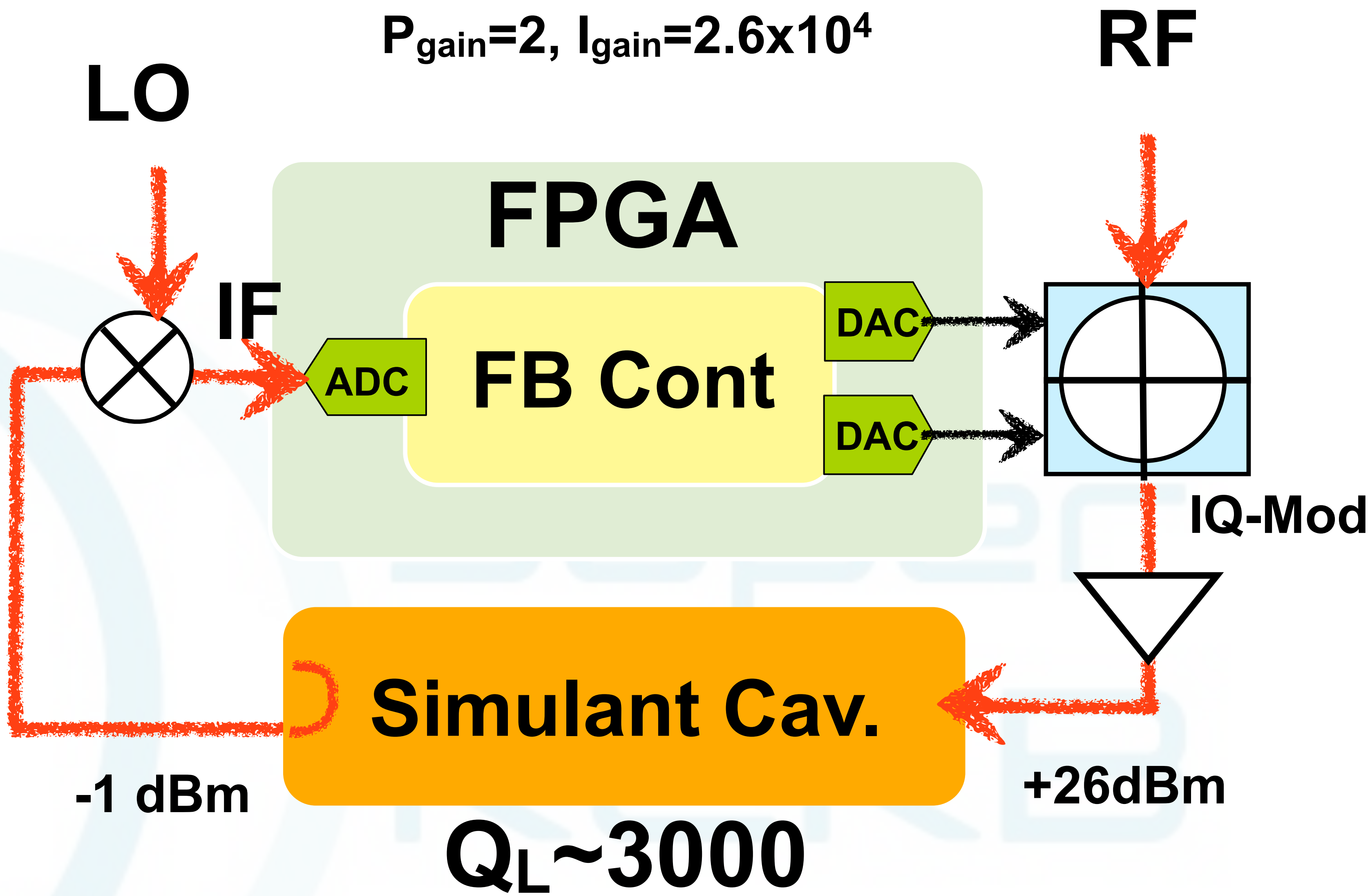
Evaluation of FB Control

FB control performance was evaluated by using a simulant cavity



Simulant Cavity

(Coaxial Resonator)
Q_L~3000



This evaluation condition is more adverse than the real operation for the stability.

KEKB ARES Cavity (Normal cond.): Q_L~24000

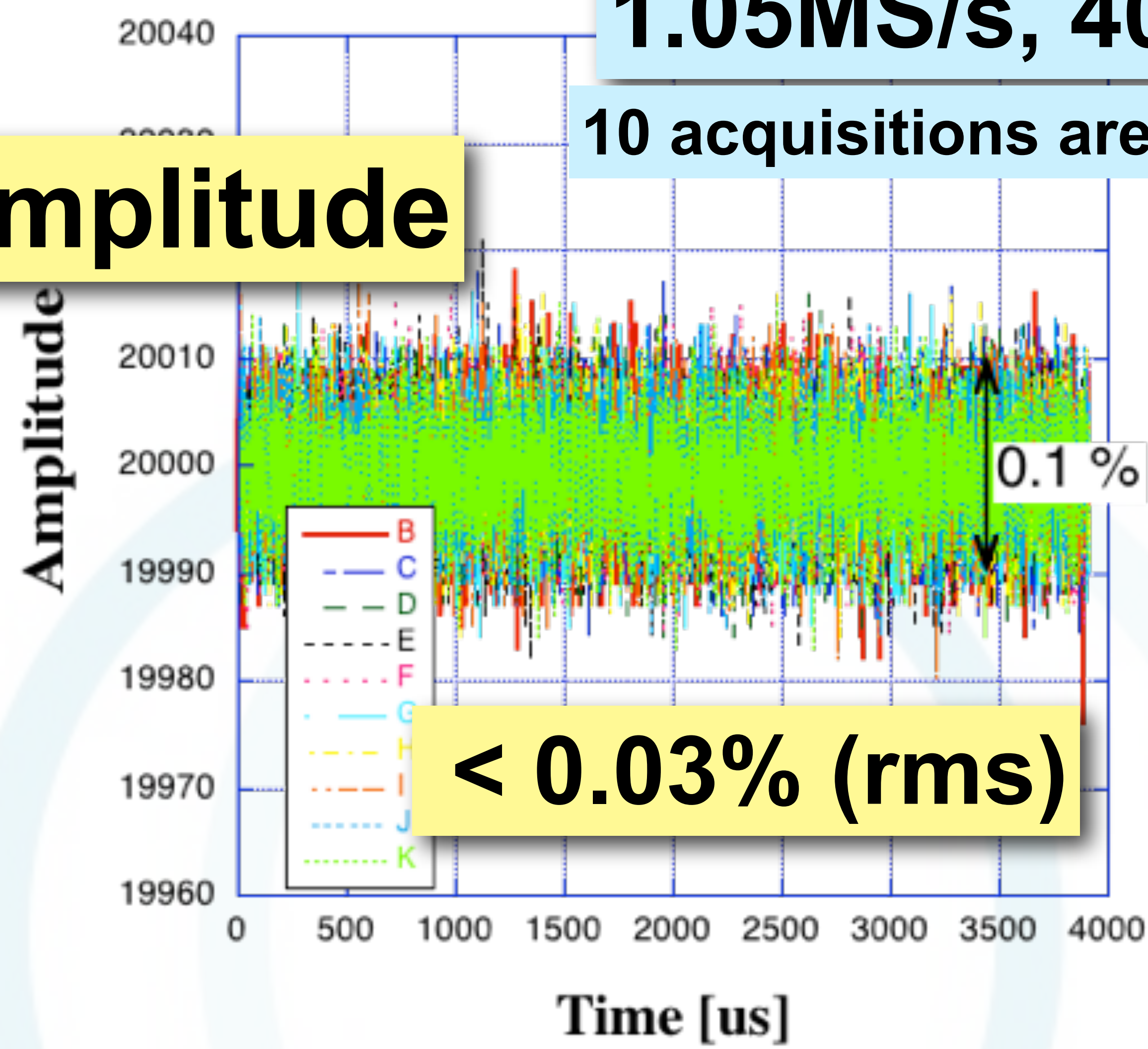
FB Control Result

(Monitored Data by FPGA acting FB cont.)

1.05MS/s, 4096 points (~ 4-ms duration)

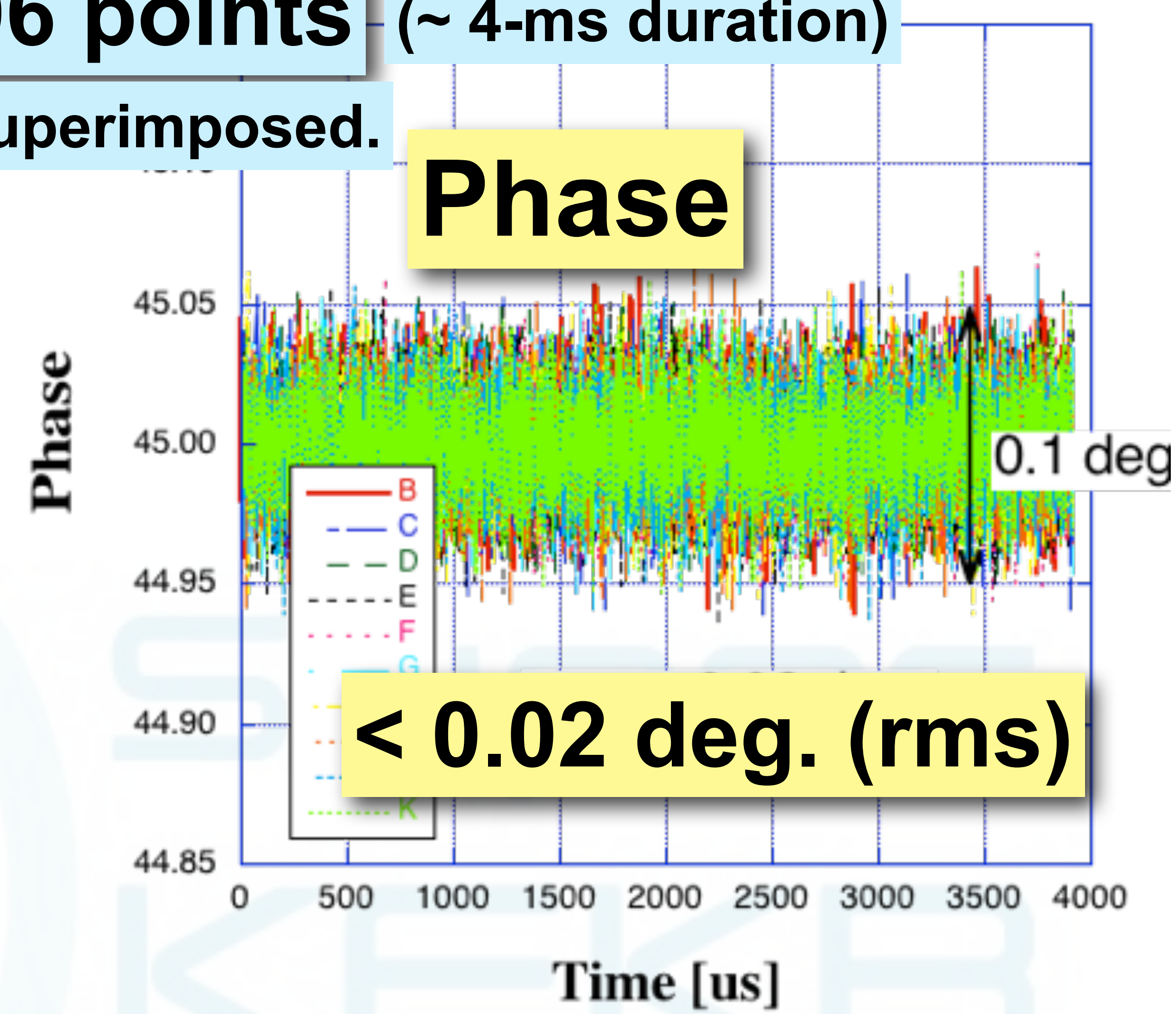
10 acquisitions are superimposed.

Amplitude



< 0.03% (rms)

Phase



< 0.02 deg. (rms)

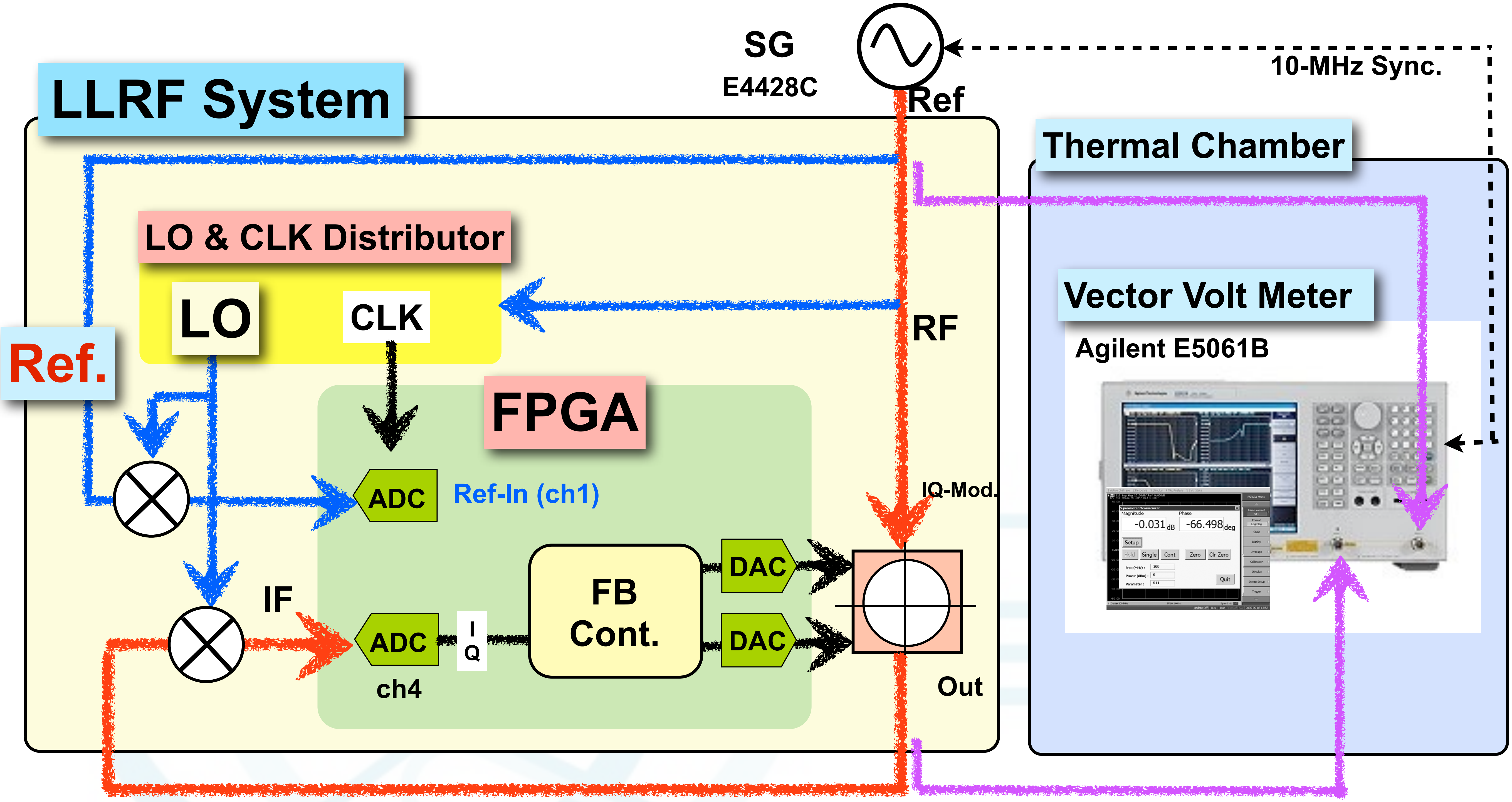
Very good stability was obtained.

The amplitude and phase stabilities are 0.03% and 0.02 deg., respectively.

The FB control performance satisfy the requirements very well in short term stability.

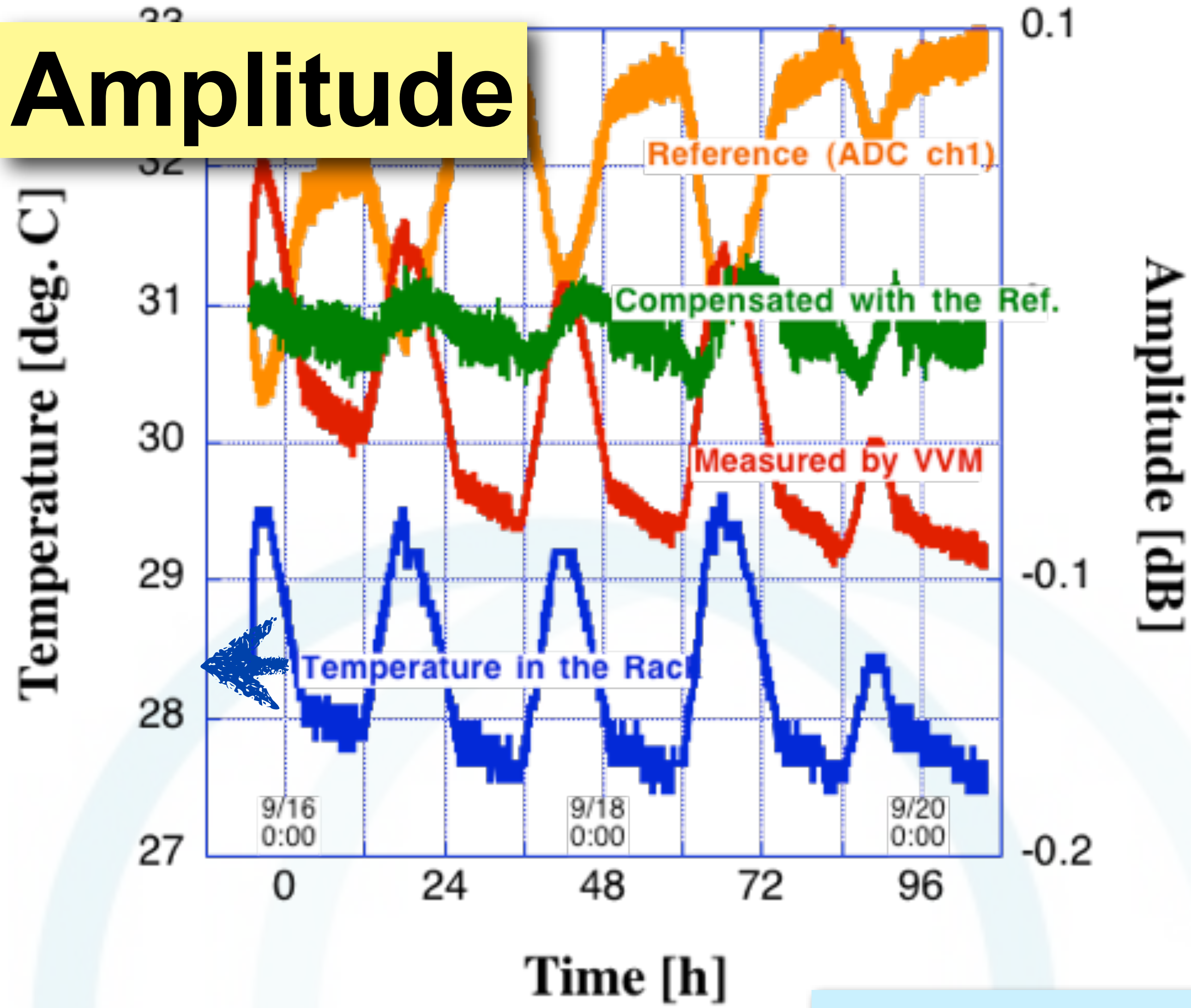
Temperature Dependency Eval.

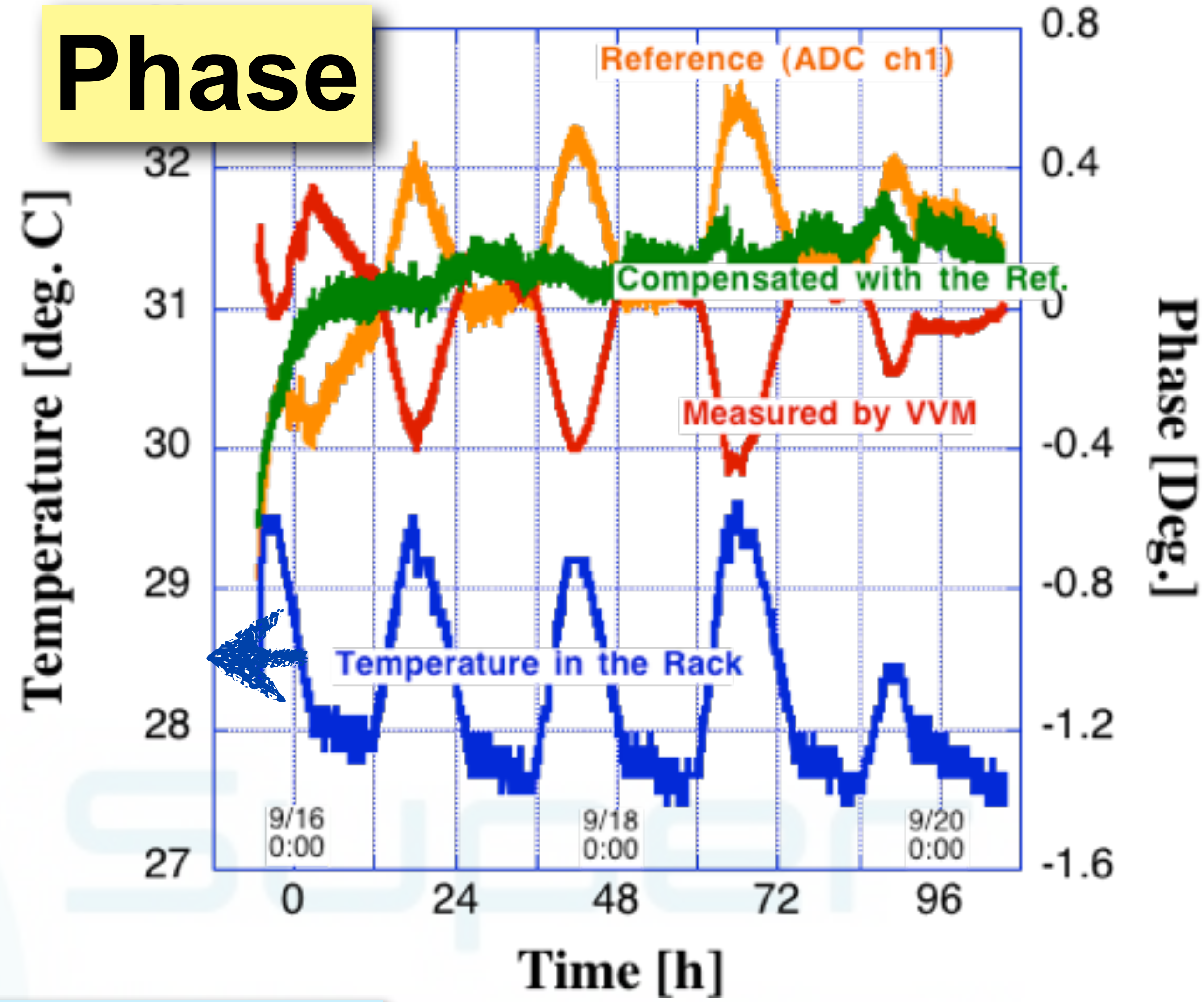
(Measuring of Long Term Stability)



- Temperature dependency of the total system was evaluated.
- Output signal was directly returned to make FB closed loop with a digital filter.
- Output amplitude and phase was monitored by using a Vector Volt Meter (VVM) .

Monitoring Result for 4 Days





Temperature Coefficient

Amplitude **0.6 % / deg.C**

Phase **0.25 deg. / deg.C**

Not negligible!

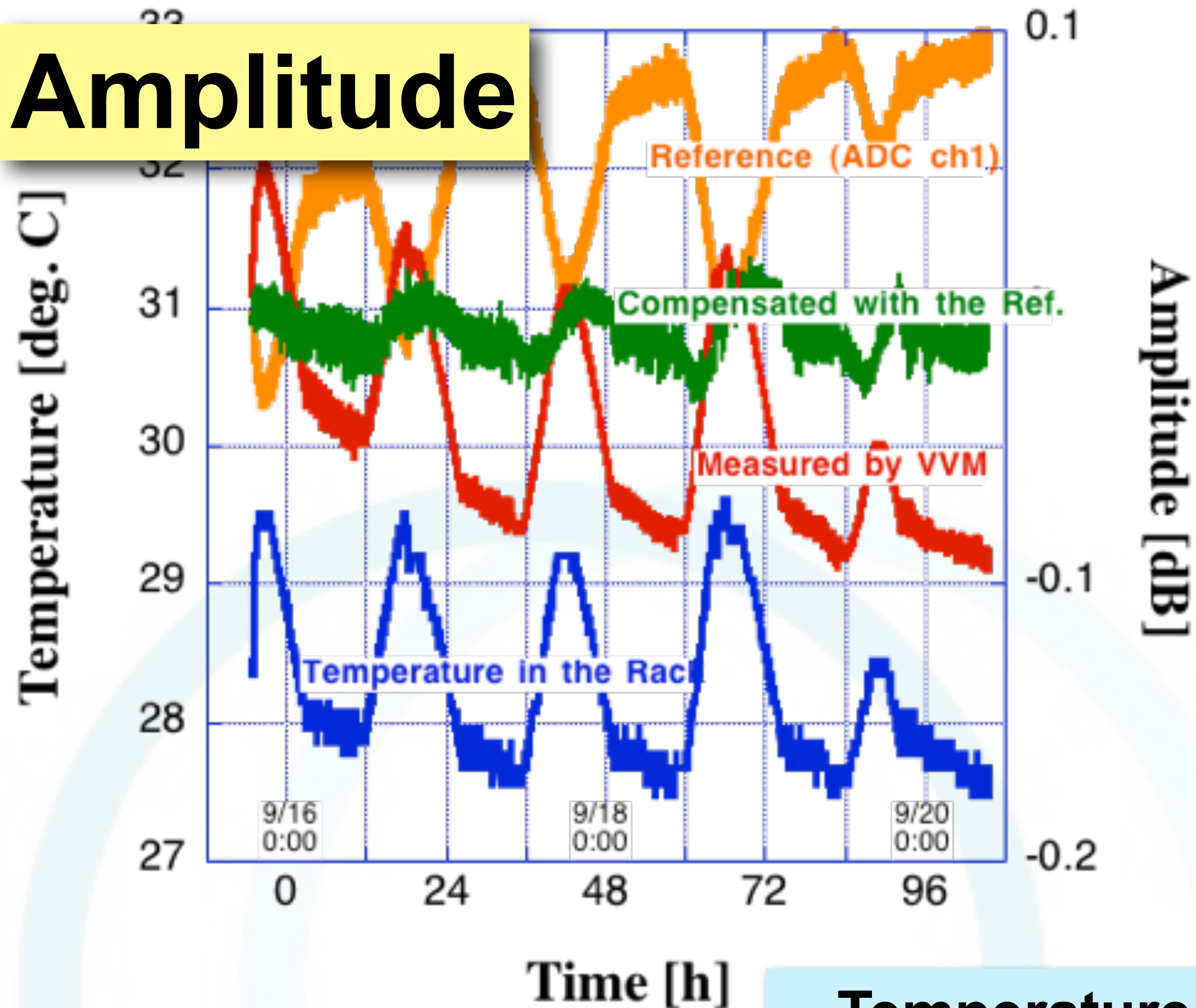
Mixer amp. change

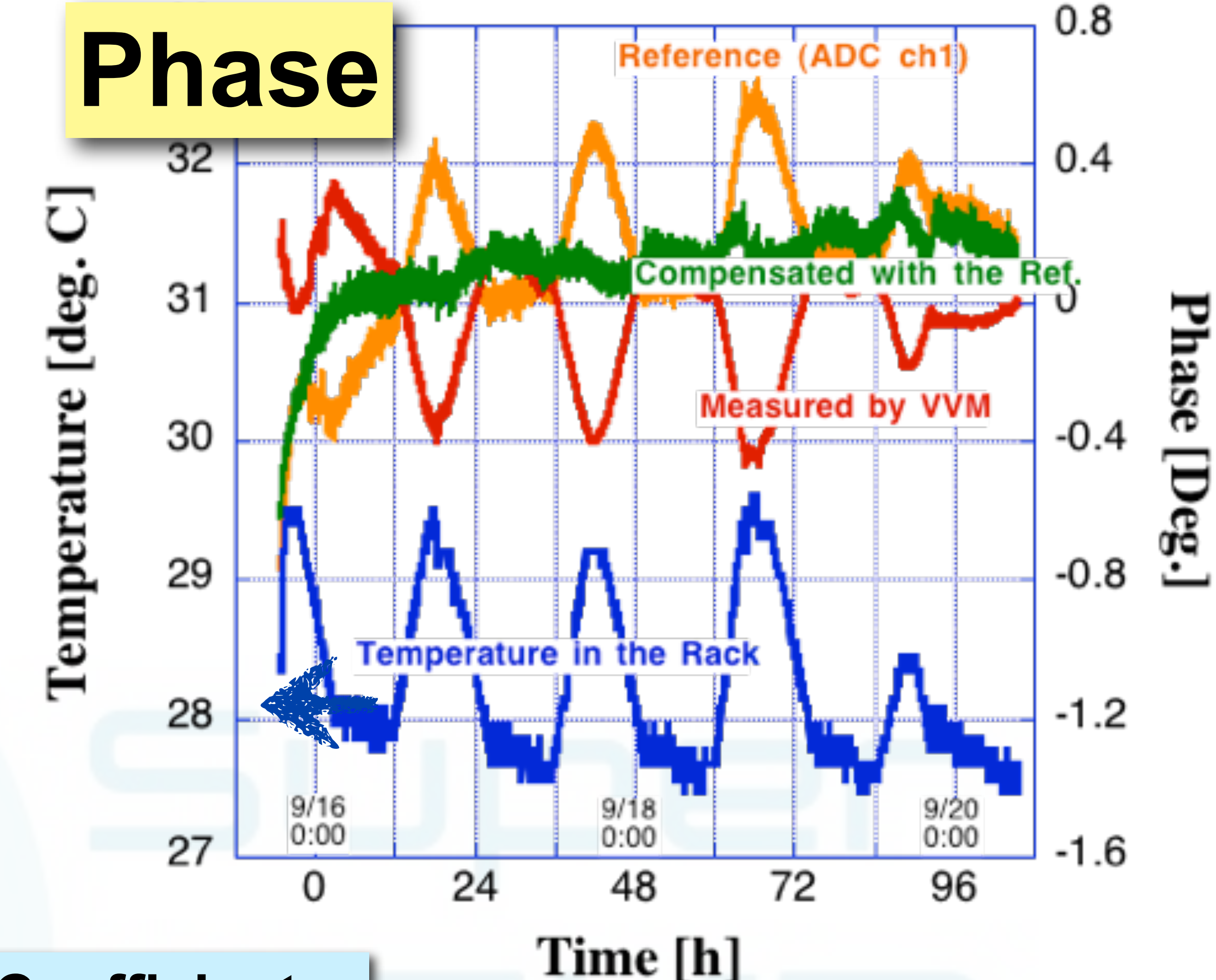
Temperature dependency of the mixer is most effective.

LO phase drift

This origins are RF devices in the LO generation and distribution, such as a band-pass filter, a balun, and so on.

Record Results for 4 Days





Temperature Coefficient

Amplitude **0.6% / deg.C**

Phase **0.25 deg. / deg.C**

Compensation with the Reference change

0.1 % / deg.C

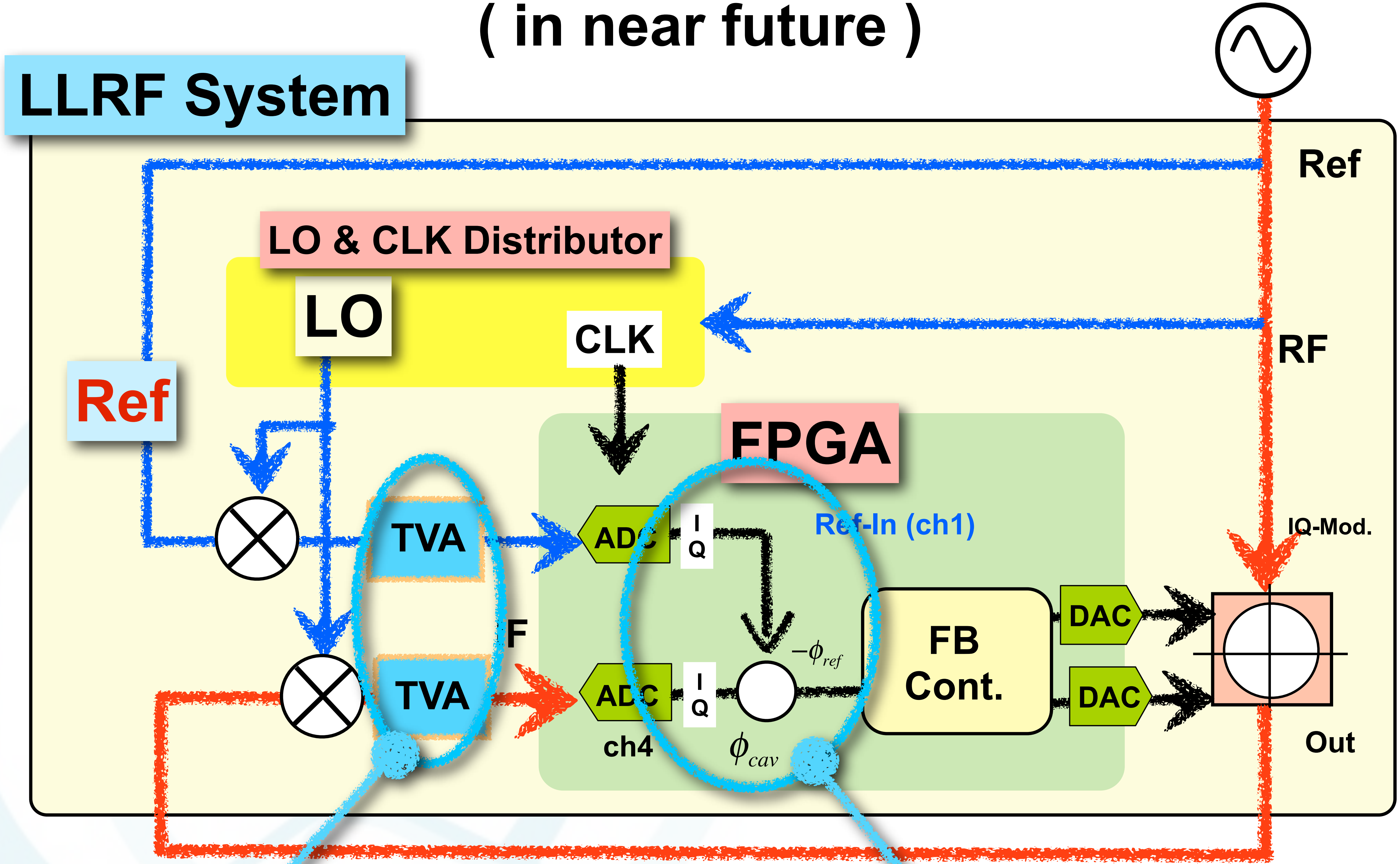
still not enough

Expected Value

0.04 deg. / deg.C

Countermeasure for Temperature Dependency

(in near future)



For the amplitude stability, "Thermal Variable Attenuators (TVA)" will be inserted to compensate the mixer temperature dependency. Then it should be evaluated again.

For the phase stability, the FB-control will be calibrated with the reference in the FPGA. It will be implemented in this year and evaluated again.

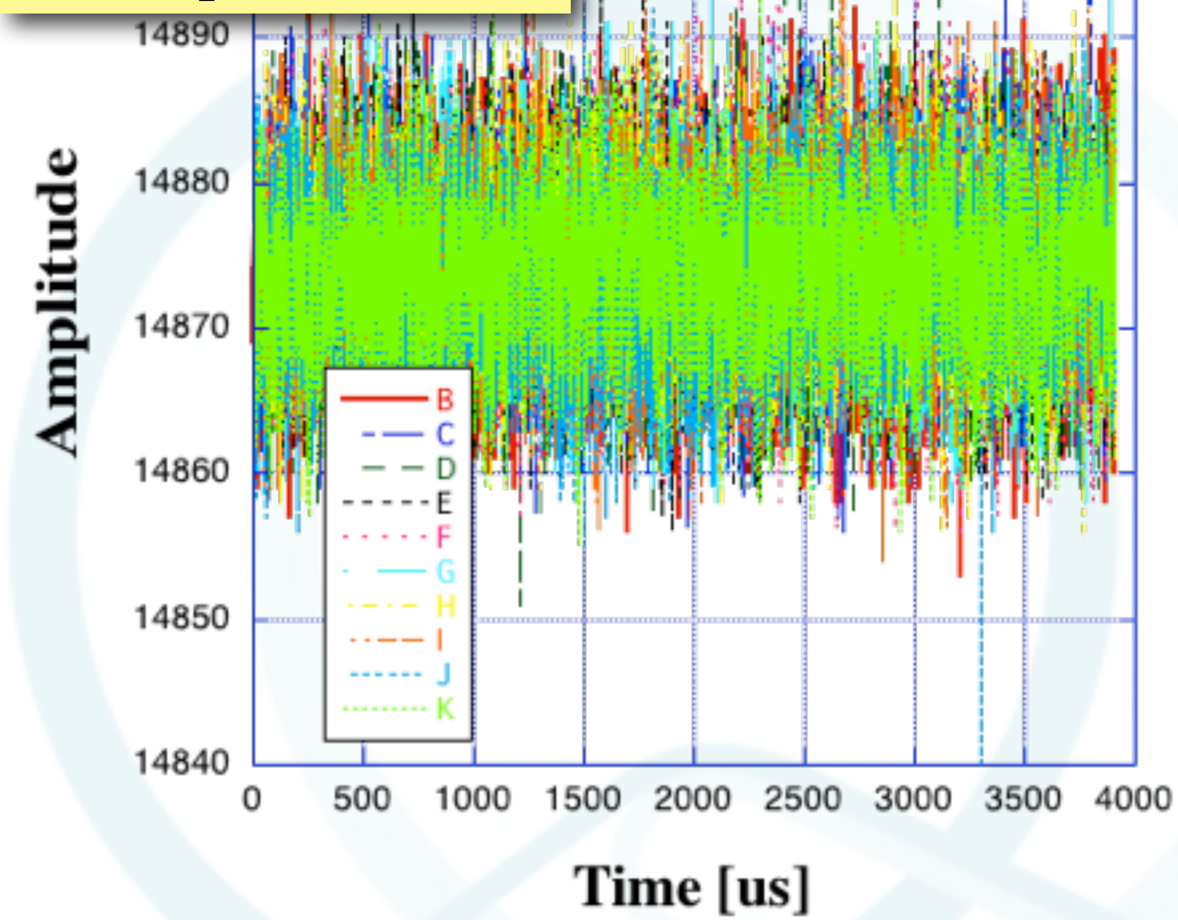
Slow Beat in Phase

FB-OFF (open loop)

1.05MS/s, 4096 points

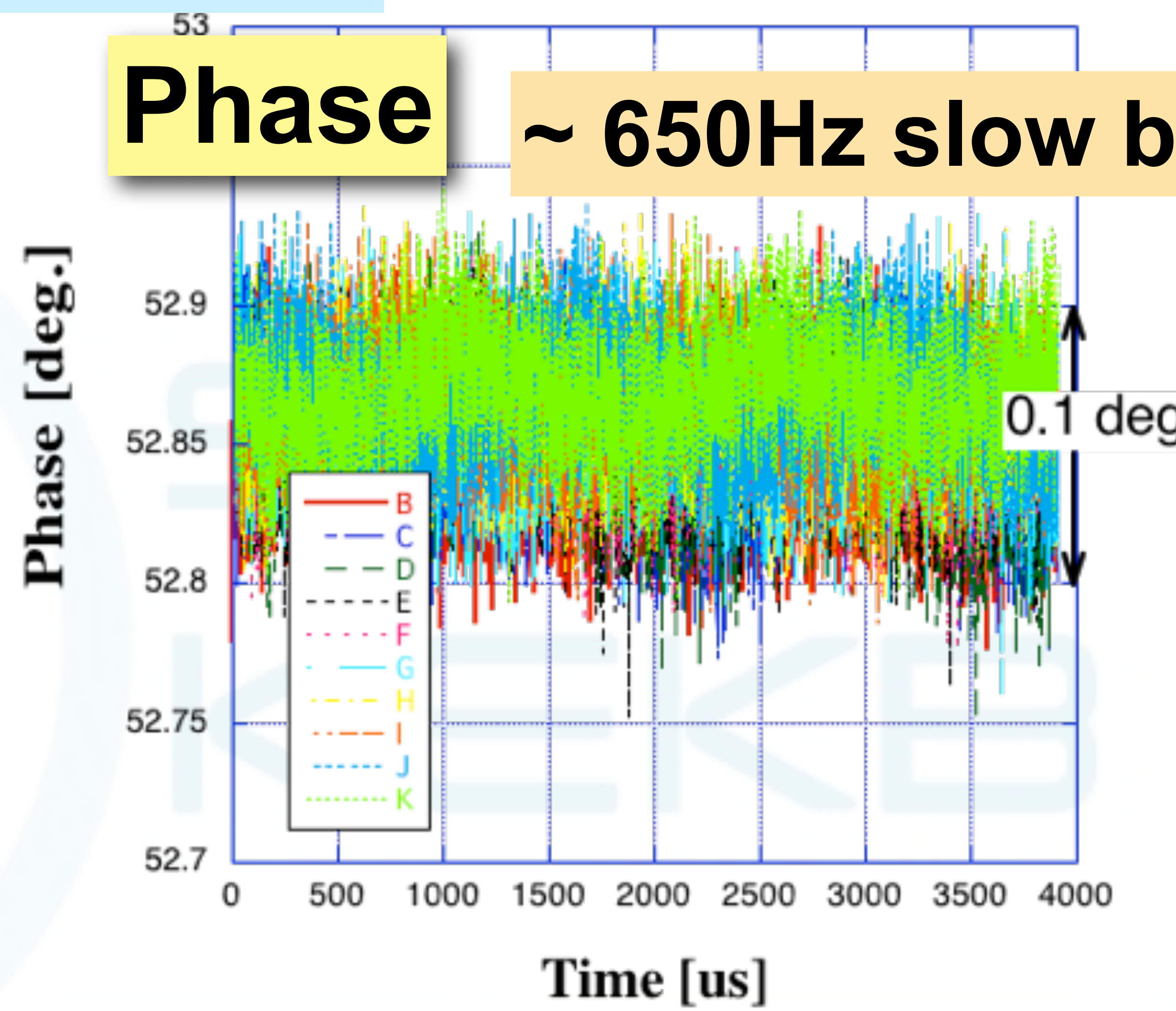
superposition of 10 data

Amplitude

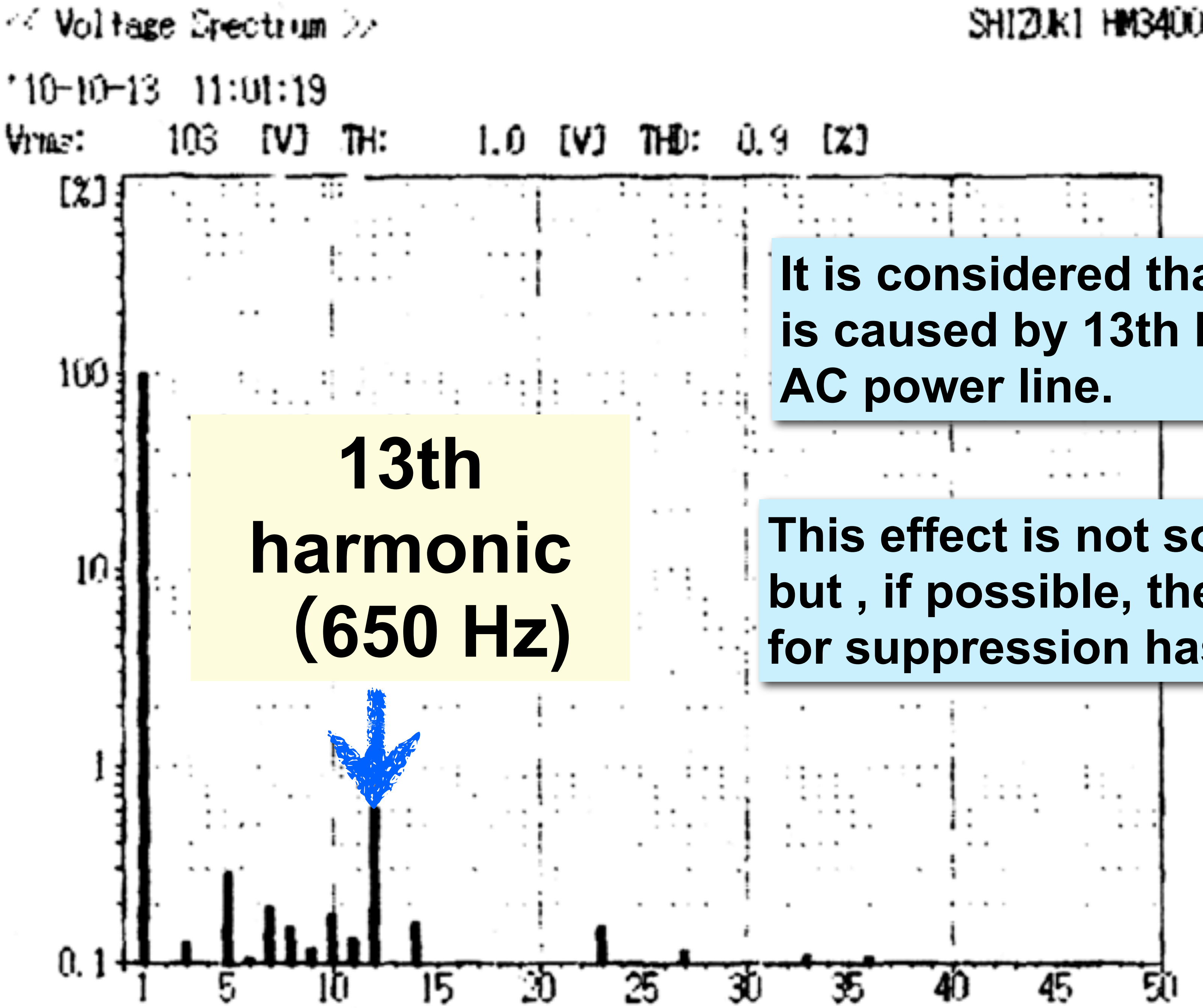


Phase

~ 650Hz slow beat



Harmonics of AC power line

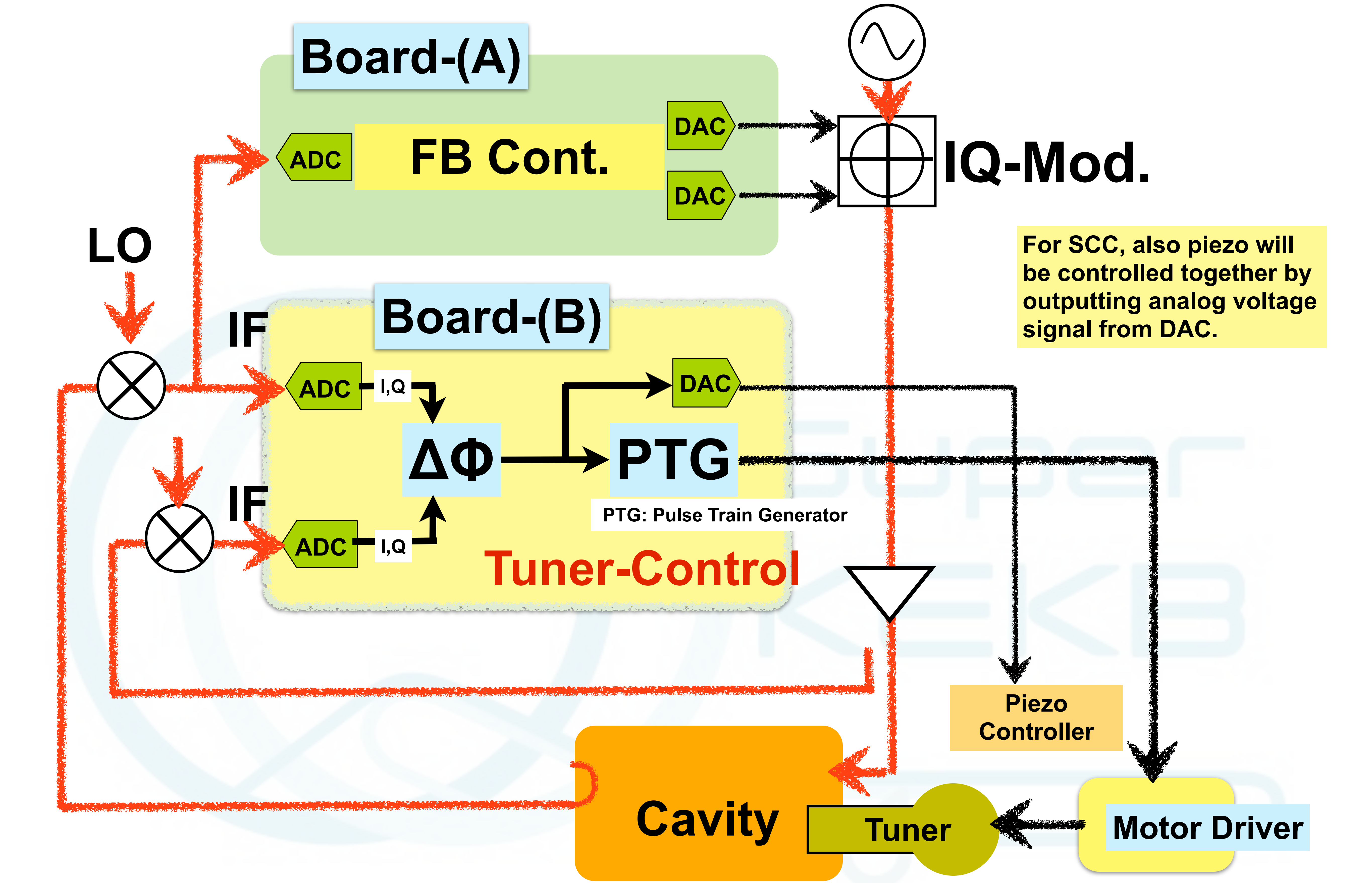


It is considered that the 650-Hz beat is caused by 13th harmonic of the AC power line.

This effect is not so problem,
but , if possible, the countermeasure for suppression has to be studied.

Harmonic # of AC power line

Tuner Control Function on FPGA
(Implementing now)



For SCC, also piezo will be controlled together by outputting analog voltage signal from DAC.

Summary

- Prototype of the digital LLRF system for the SuperKEKB was developed, and Its performance was evaluated.
- Very good stability of 0.03% in amplitude and 0.02 deg. in phase is obtained in FB control.
- But, temperature dependency is not negligible: the temperature coefficients are 0.6%/deg. C in amplitude and 0.3 deg. /deg. C in phase.

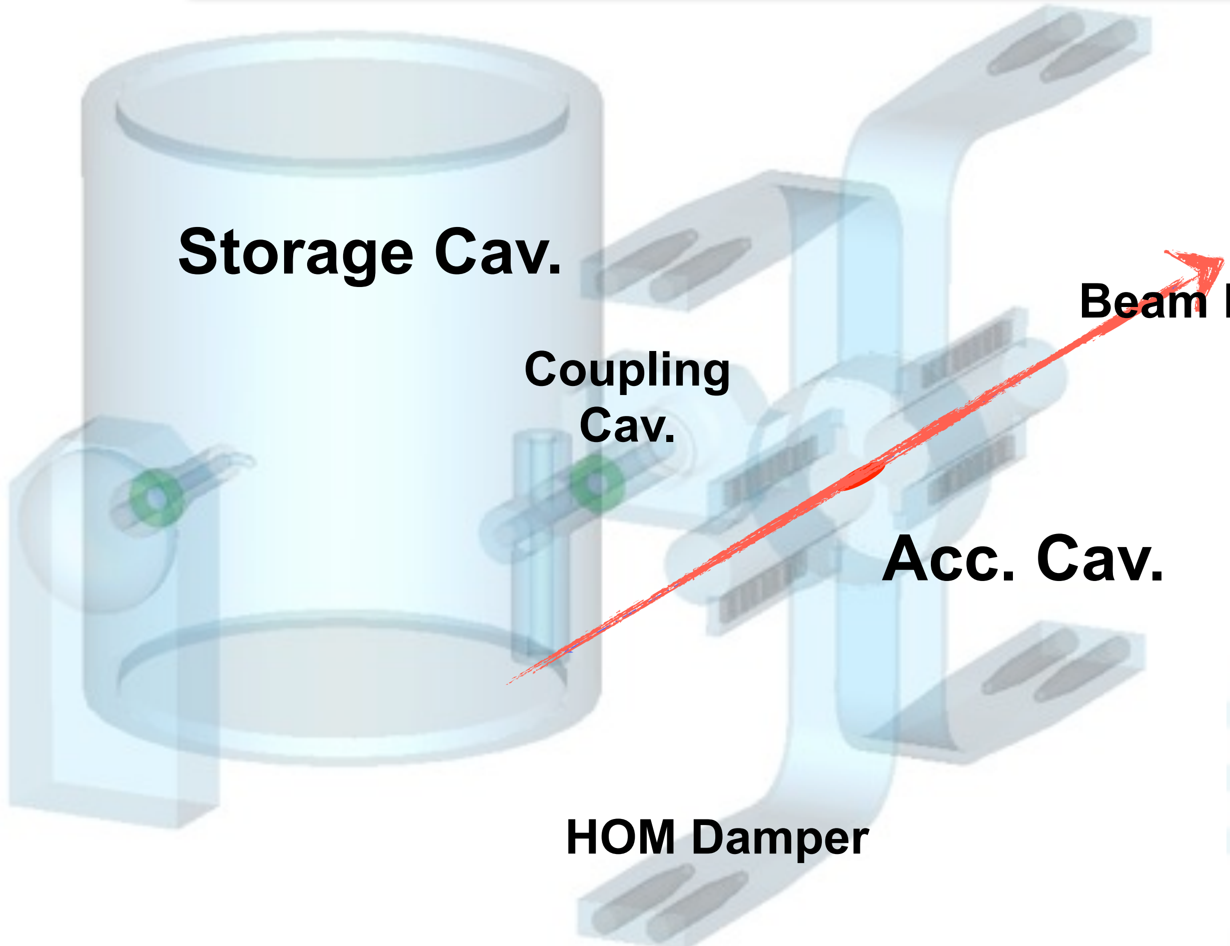
Future Issues

- In order to reduce the temperature dependency, some countermeasures will be implemented.
- Tuner Control function in the FPGA is now under implementation. Its control performance should be evaluated soon.
- For very high current beam, beam loading compensation and detuning control should be verified.

Followed by Backup Slides

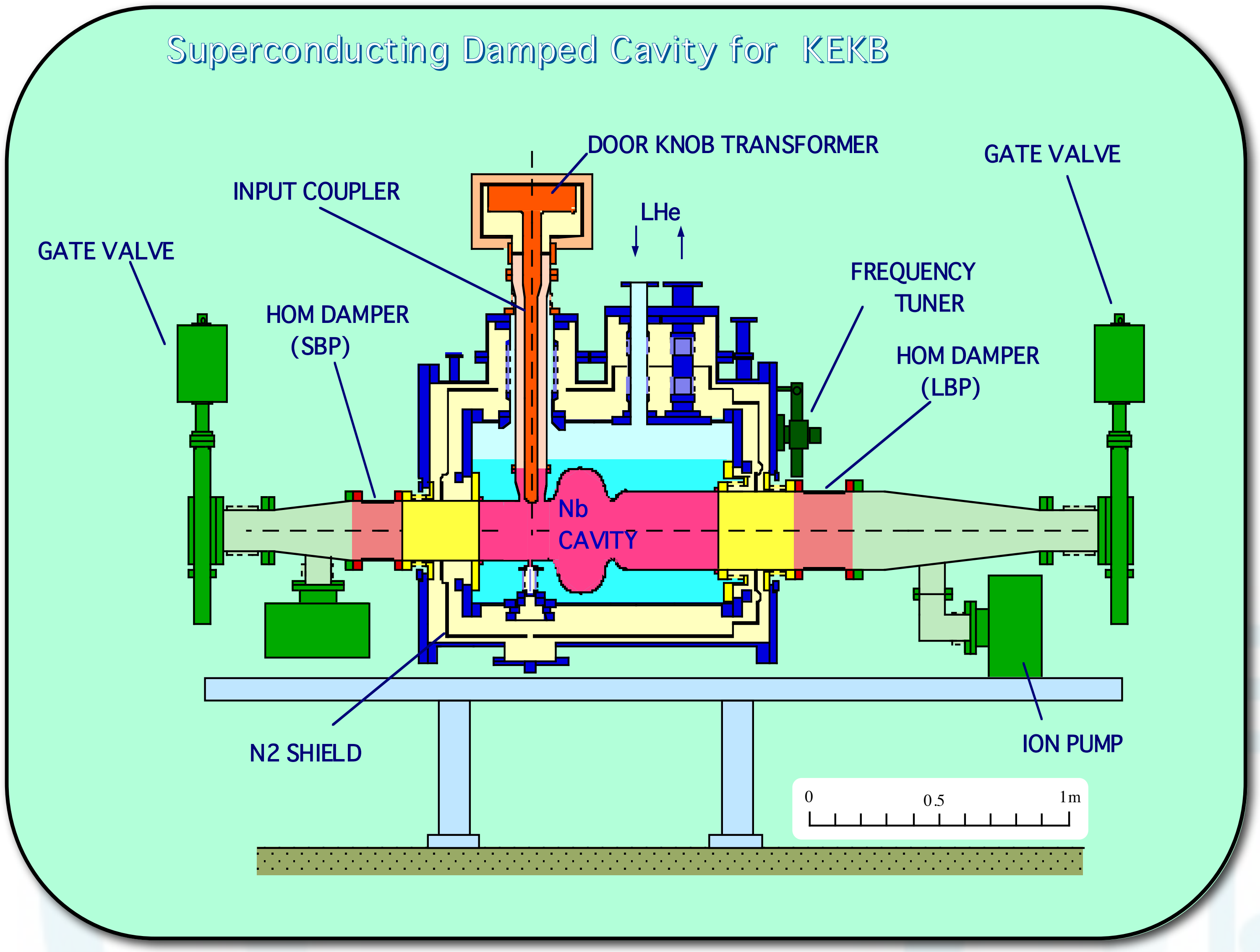
ARES Cavity

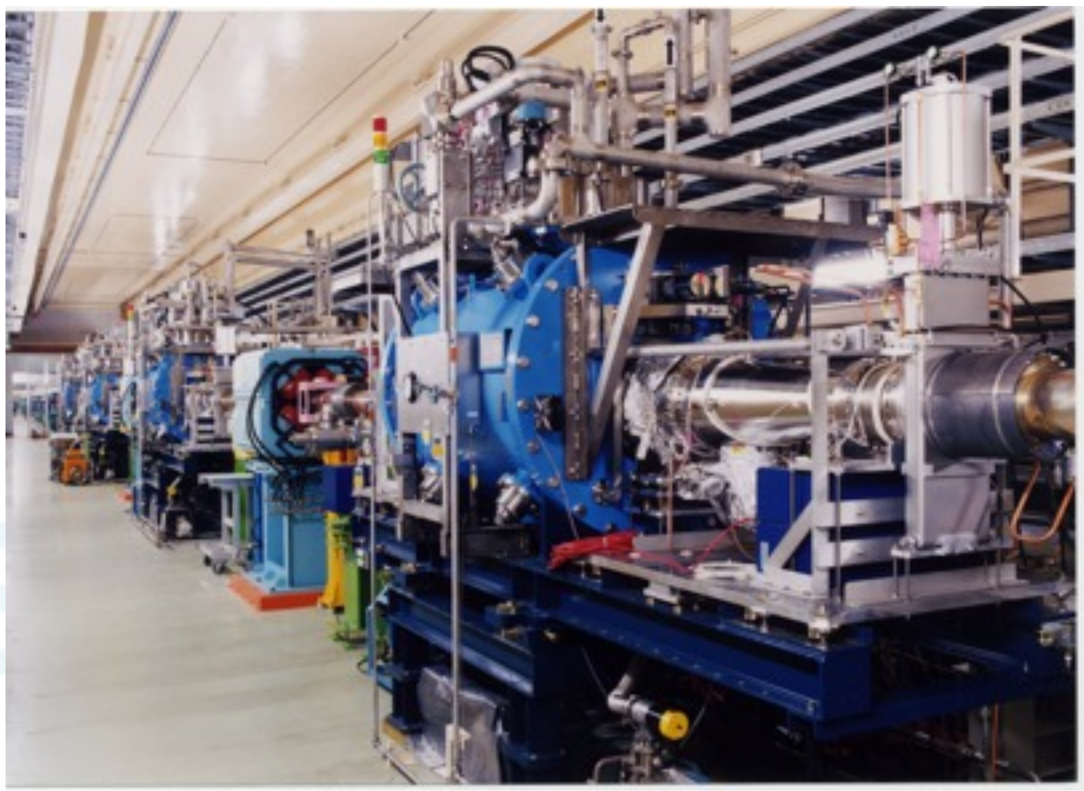
3-cavity system stabilized with theπ/2-mode operation



- Large stored energy (ARES, SCC)
  - Suppress the CBI associated with the accelerating mode.
  - Bunch gap transient effect is reduced.
- Heavily-damped structure
  - Suppress the CBI due to HOMs
- High stored energy in the storage cavity operating at TE013 mode.
- Three modes for the three-cavity system

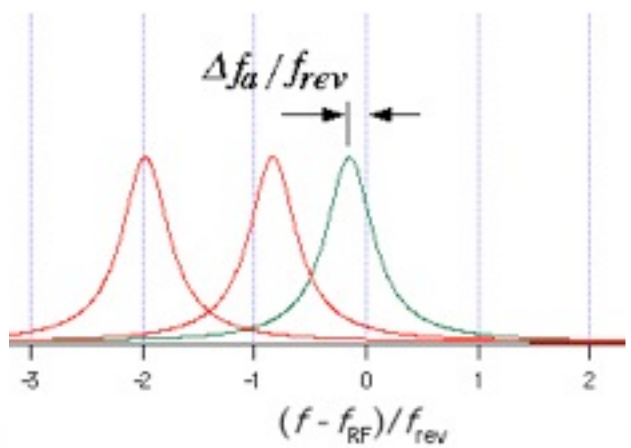
Super Conducting Cavity

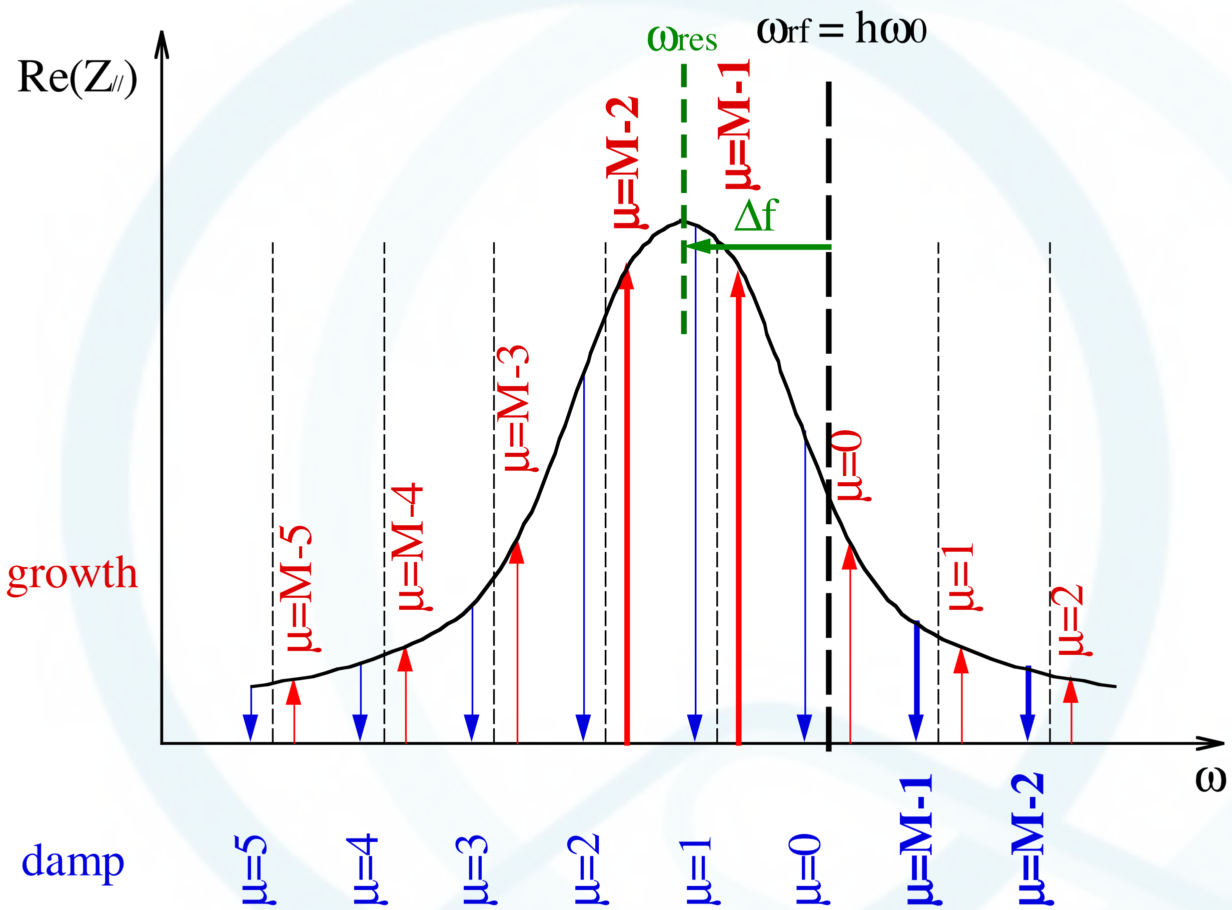




- **Features**
  - **Single-cell HOM damped cavity.**
  - **Lower R/Q value and higher voltage than NC cavity: the CBI due to the accelerating mode can be suppressed.**
  - **Ferrite is attached inside the beam pipe by Hot Isostatic Press method.**

CBI due to the accelerating mode





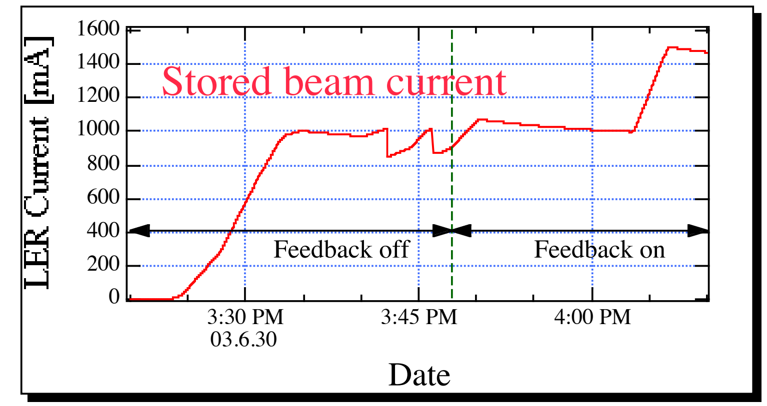
- Detuning in storage rings,
  - Resonant frequency of the accelerating mode should be detuned to match to beam (optimum tuning)

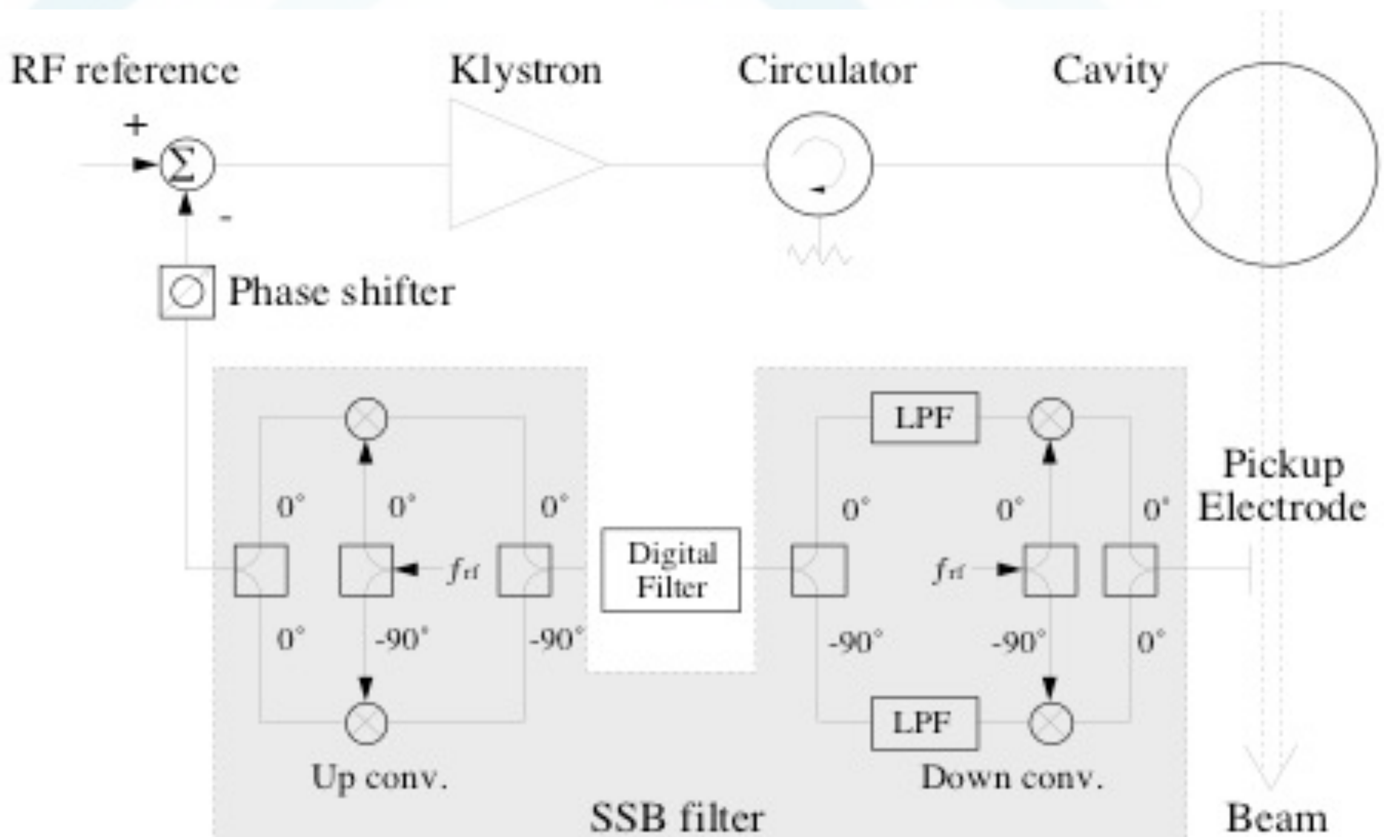
$$\Delta f = -\frac{I_b \sin\phi_s}{2V_c} \times \left(\frac{R}{Q}\right) \times f_{rf} = -\frac{P_b \tan\phi_s}{4\pi U}$$

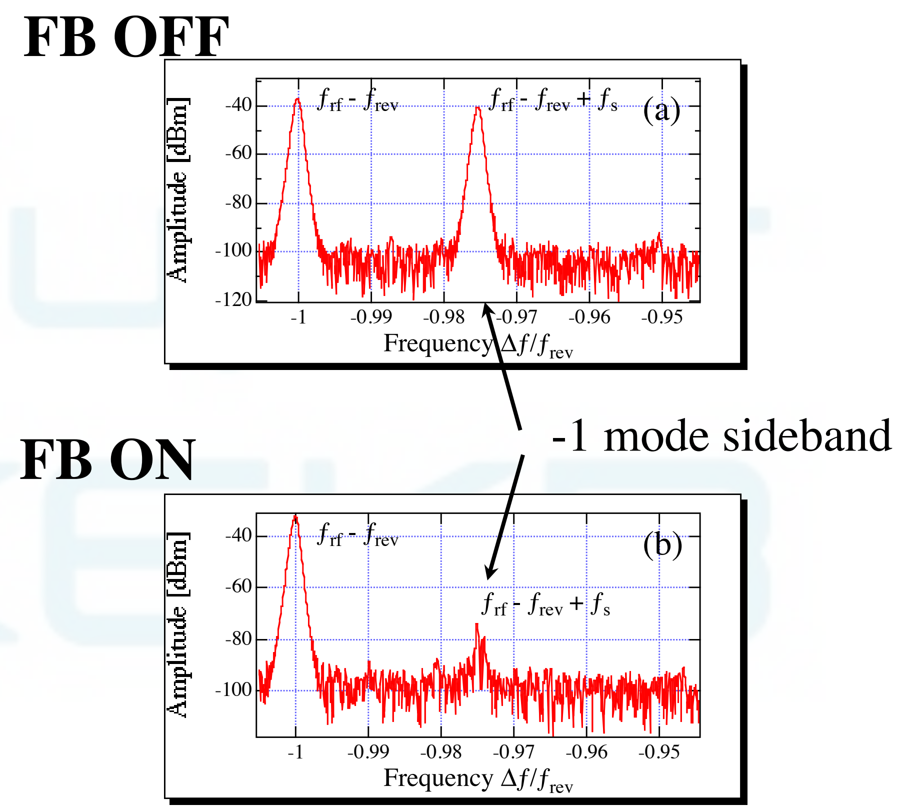
- In a large circumference ring with high beam current,
  - Large detuning due to high beam current
  - Small revolution frequency
  - High impedance of the accelerating mode
- CBI of -1, -2, etc. modes can arise, growth rate can be very high.
- To reduce the detuning frequency,
  - Operate with high RF voltage
  - High stored energy in cavity
  - Reduce R/Q value of cavity

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.

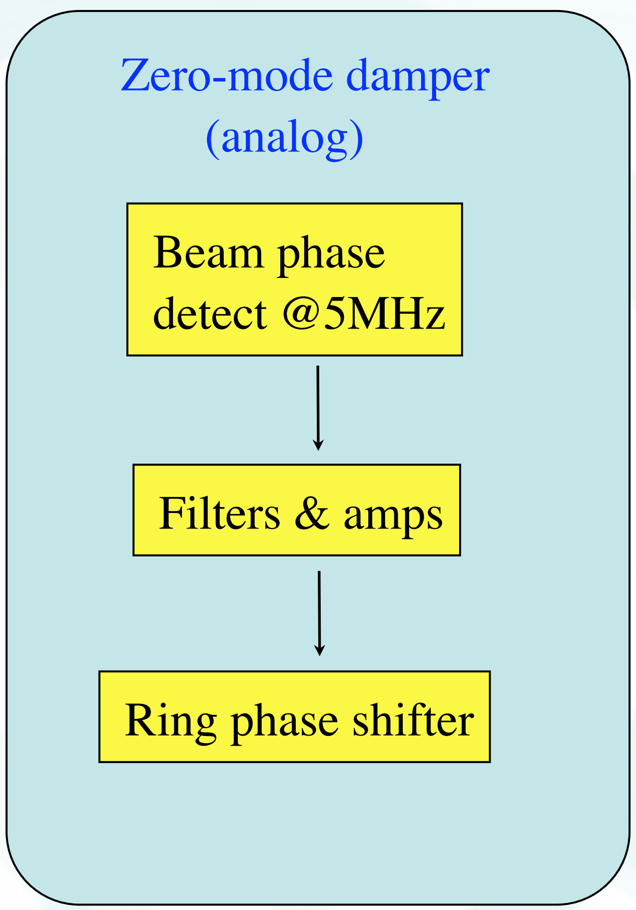


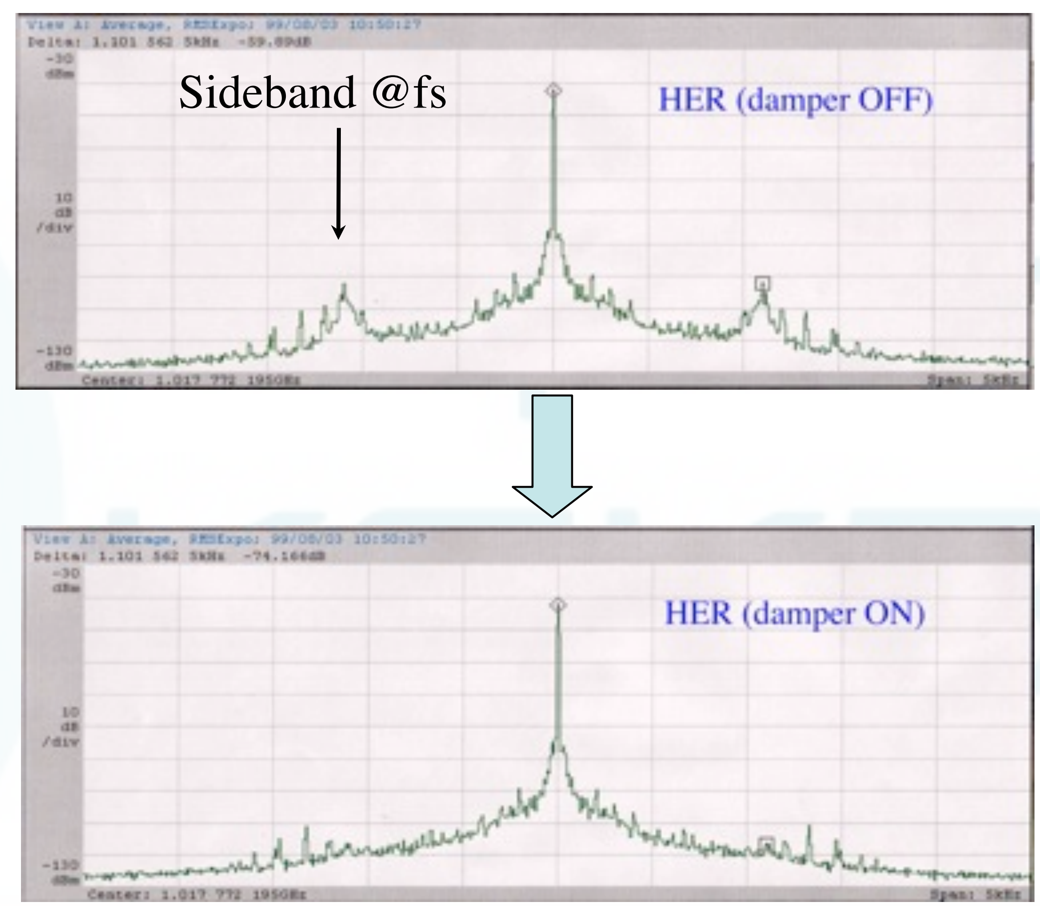




Zero-mode oscillation

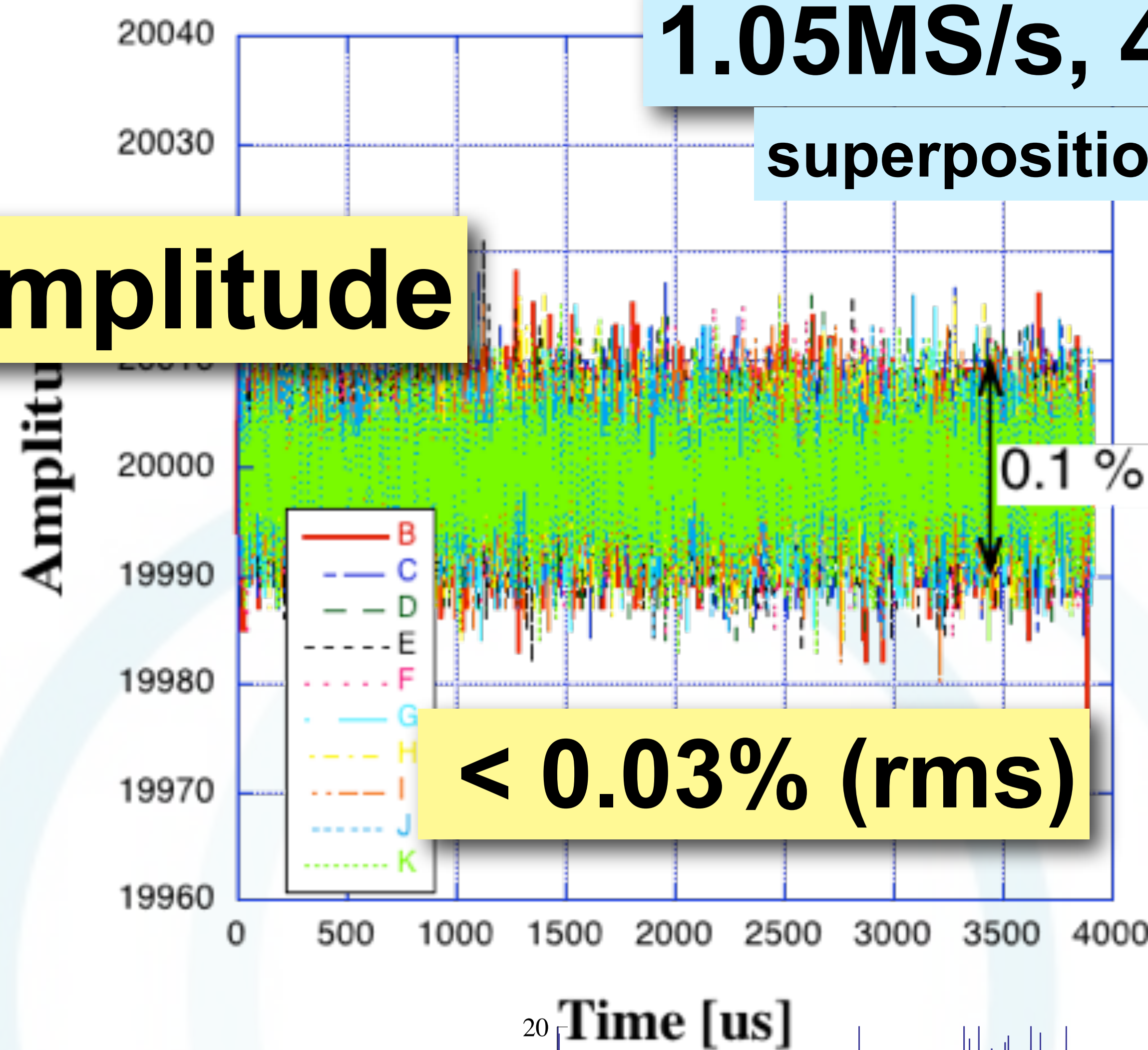
- At the beginning we observed zero-mode synchrotron oscillation even at a low beam current.
  - The amplitude was about 0.5 degree p-p.
  - It is probably caused by noise in the RF reference line system.
- The amplitude is reduced by 15dB by the zero-mode damper.

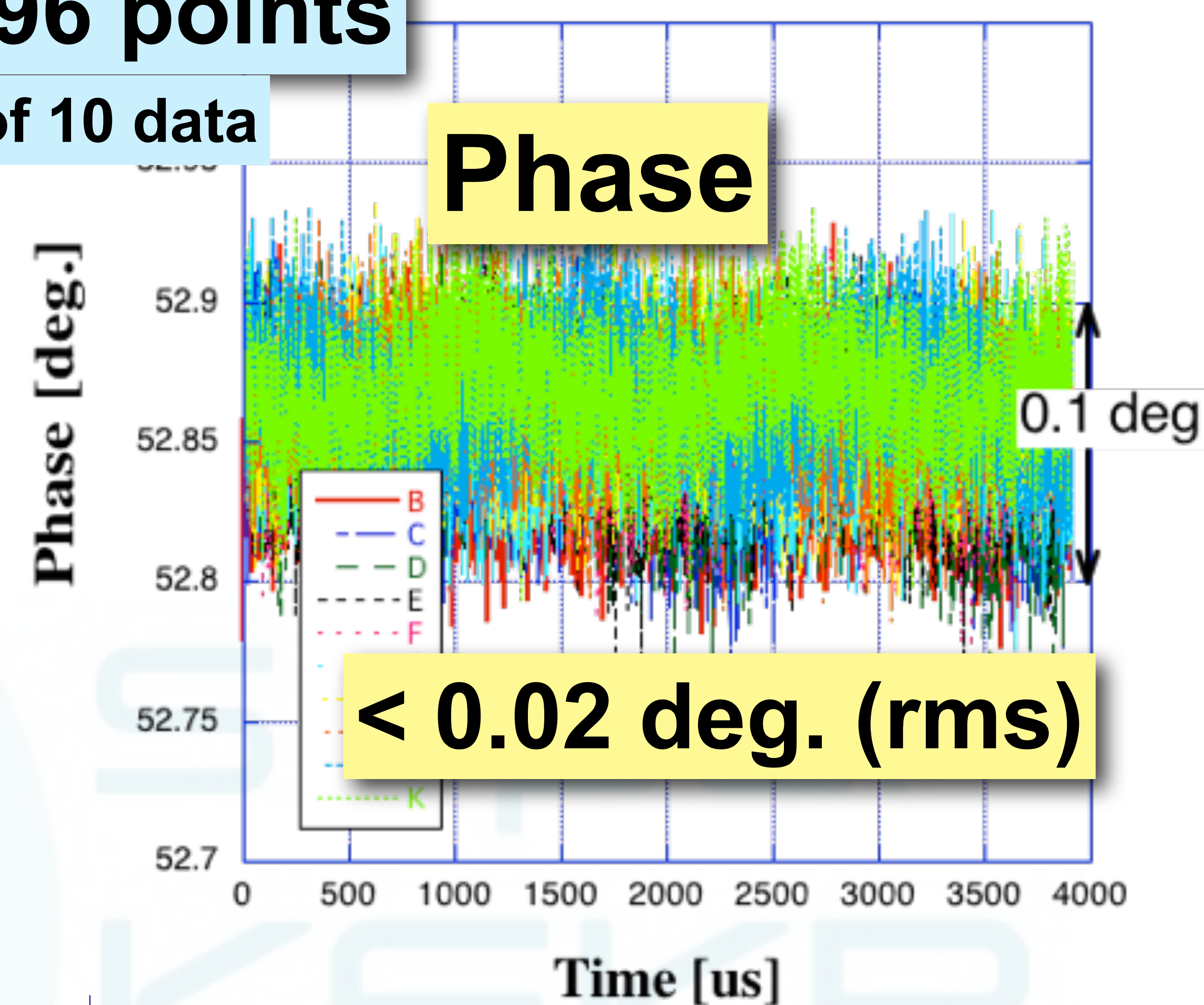


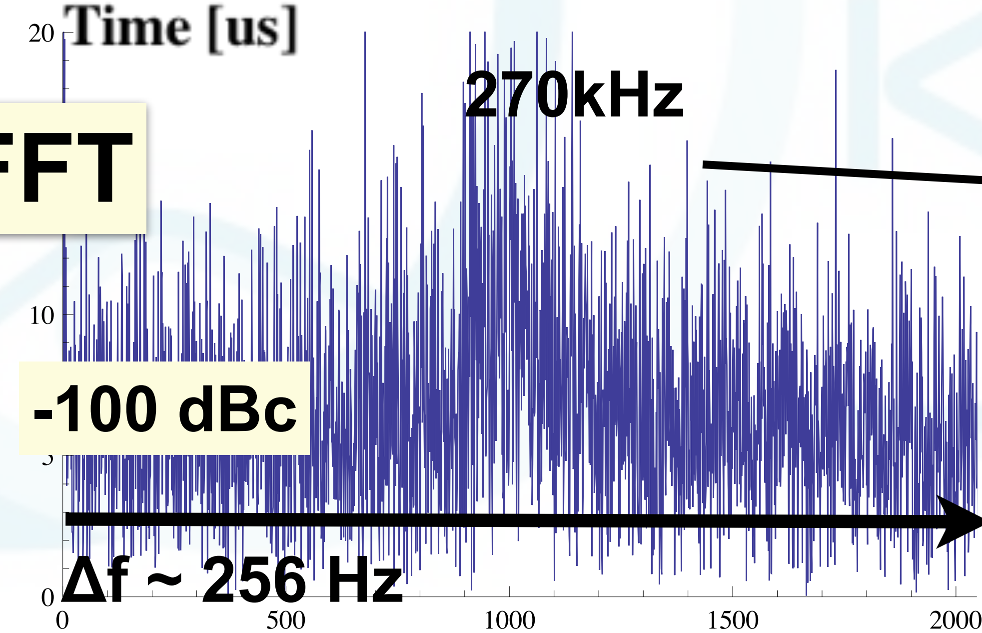


1.05MS/s, 4096 points

superposition of 10 data

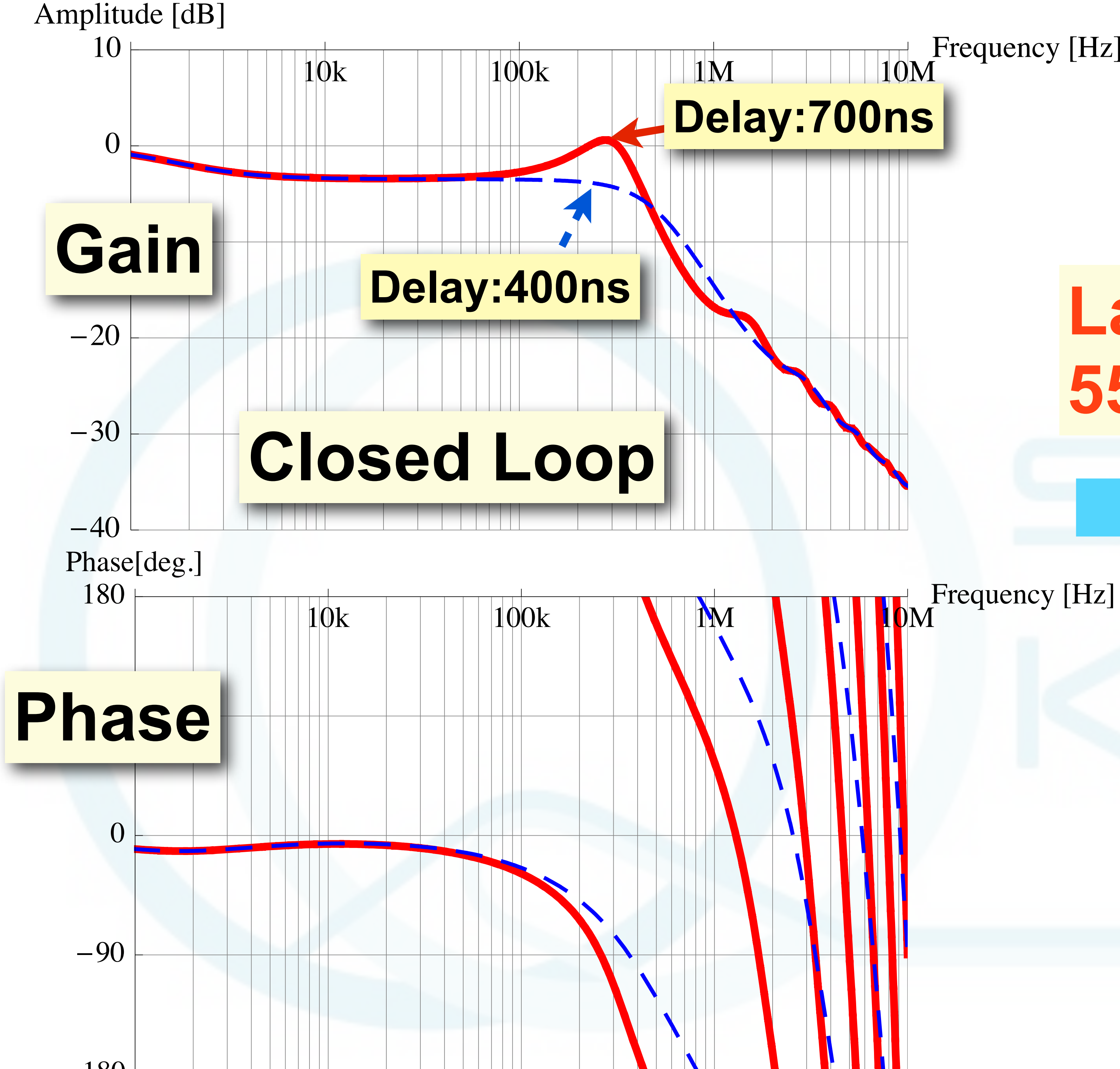






Due to the latency of the FPGA and DAC, which makes 650ns-loop delay.
No problem for the ARES Cavity (Q_L~20000).

P_{gain}=2, I_{gain}=2.6x10^4



Q_L=3000

Δω = 0

Loop Delay = 700ns

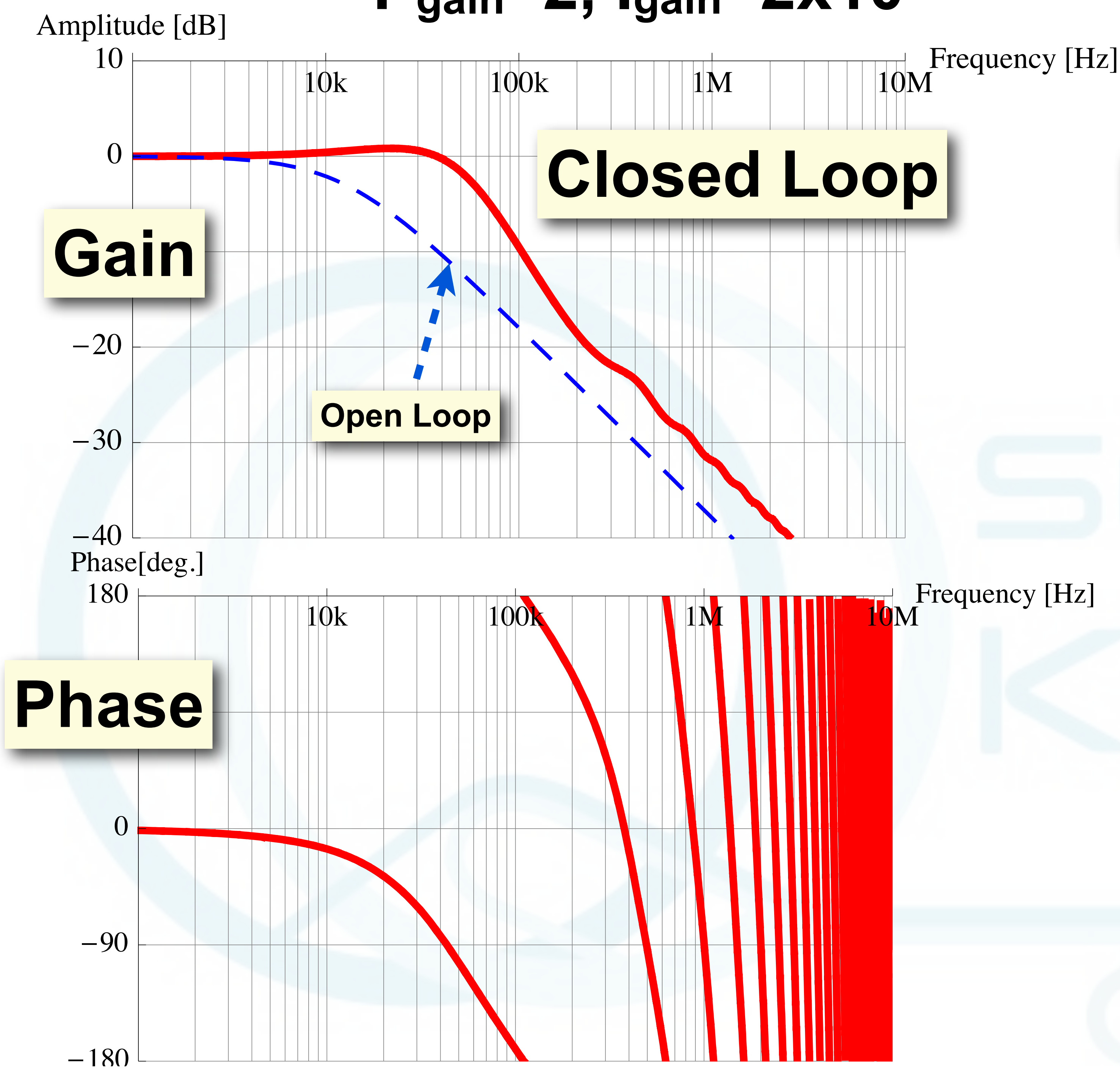
Latency in the FPGA : 55 clock

→ Loop Delay : ~650ns

Gain Mergin : ~13dB

P_{max} ~2.2

P_{gain}=2, I_{gain}=2x10^5



Q_L=20000 **Δω = 0**

Loop Delay = 3us

Gain Mergin : ~18dB

P_{max} ~4

LO signal phase noise