LLRF System Performance at S1-Global in KEK

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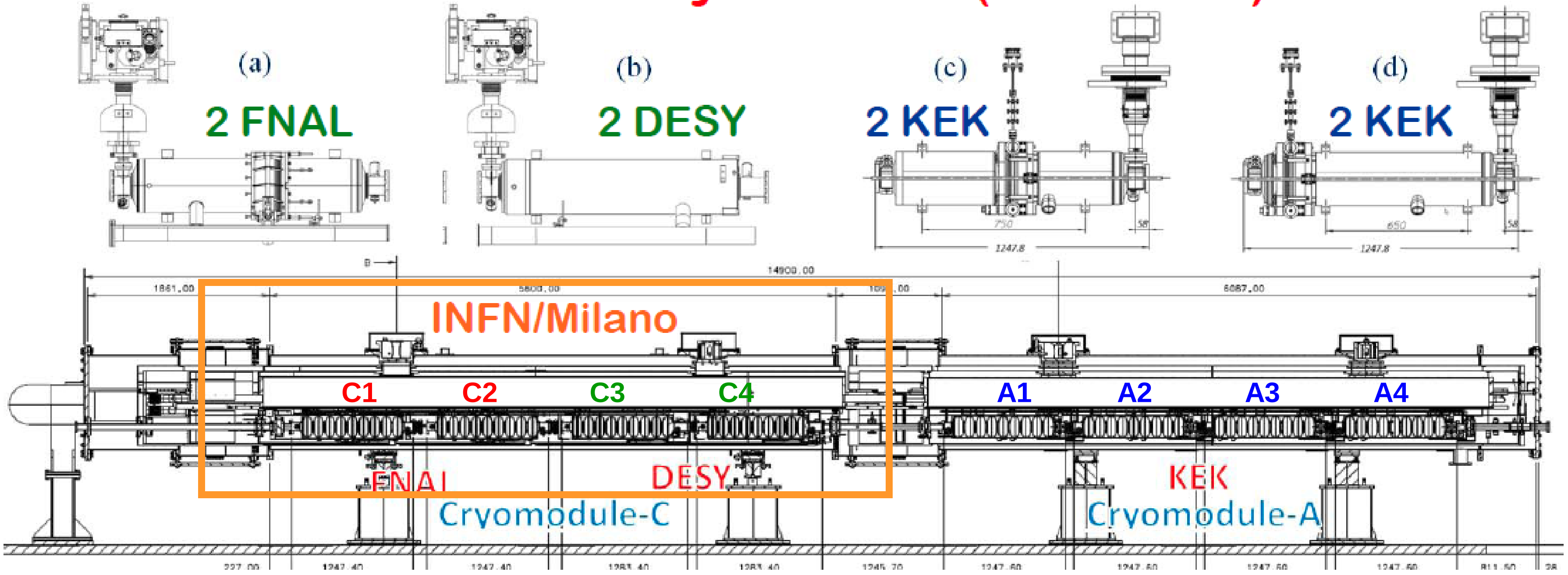
S1-Global

S1-Global : International collaboration
to examine cavity performance for ILC.
Sep,2010 ~ Feb, 2011 @KEK-STF.

Total 8 SC cavities are installed into two half-size cryomodules, which are similar to the planned setup at ILC.

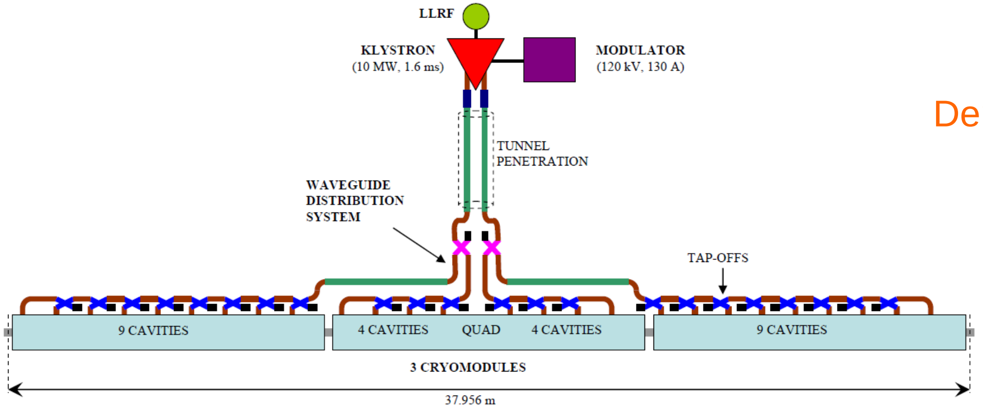
S1-Global Cryomodule (8 cavities)



HLRF schemes for ILC

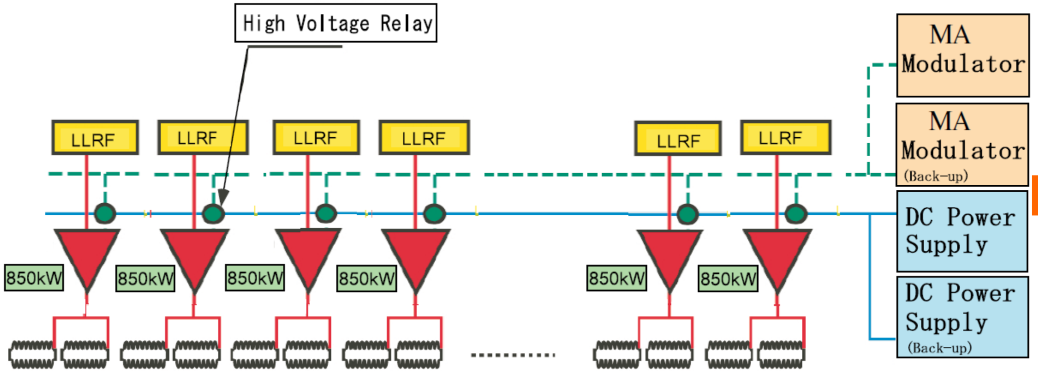
- **RDR**: Reference Design Report of ILC

  One klystron drives 26-cavities



- **DRFS**: Distributed RF Scheme

  Each klystron drives 2-cavities in circulator-less PDS

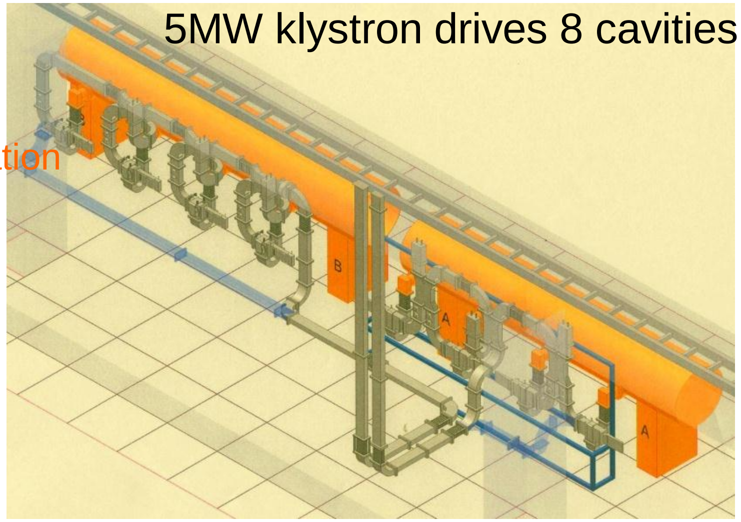


1 Klystron feeds power to 2 cavities.

1 DC power supply and MA modulator drive 13 klystrons.

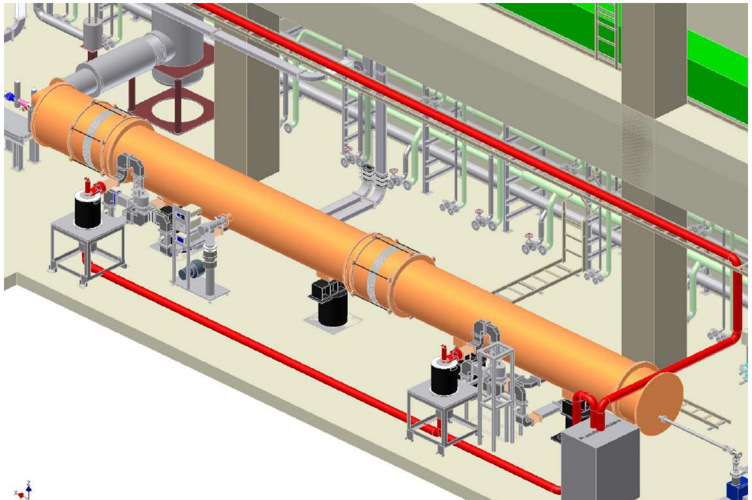
Demonstration

Layout in S1-Global



5MW klystron drives 8 cavities

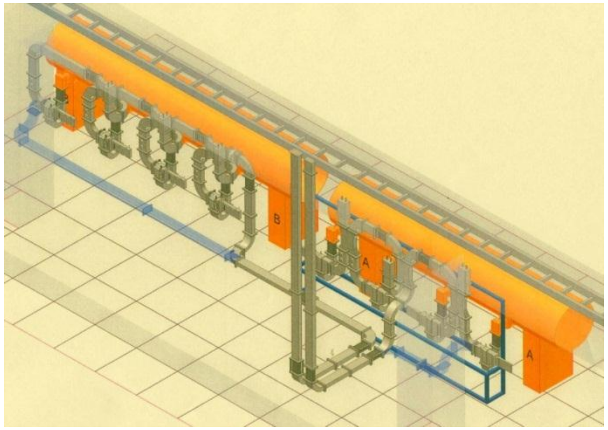
Minimum DRFS units



Each 800kW klystron drives 2 cavities

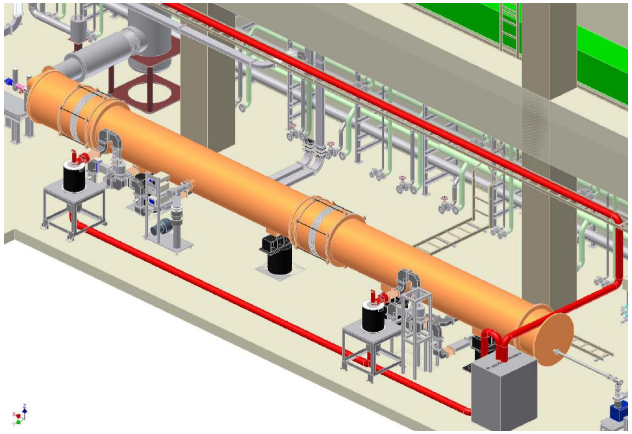
LLRF Studies in S1-Global

Contents



S1-Global (RDR)

- Diagnostics
  → Fast quench protection
  → Real time detuning monitor
- vector-sum performance for 8 cavities



S1-Global (DRFS)

- Diagnostics
  → Q_L calculation
- vector-sum performance

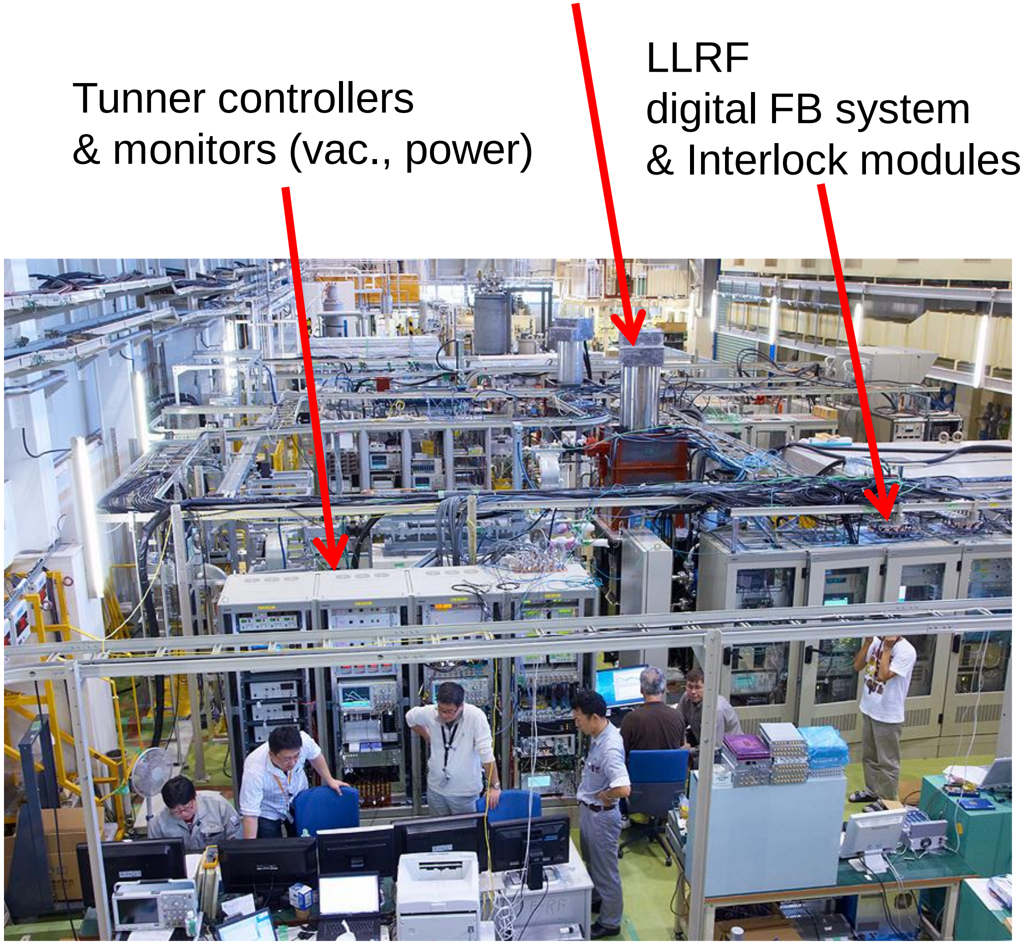
} without circulators

Photos of S1-Global (RDR-type)

5 MW klystron
(1.3GHz, 5 Hz, 1.6ms)

Tunner controllers
& monitors (vac., power)

LLRF
digital FB system
& Interlock modules



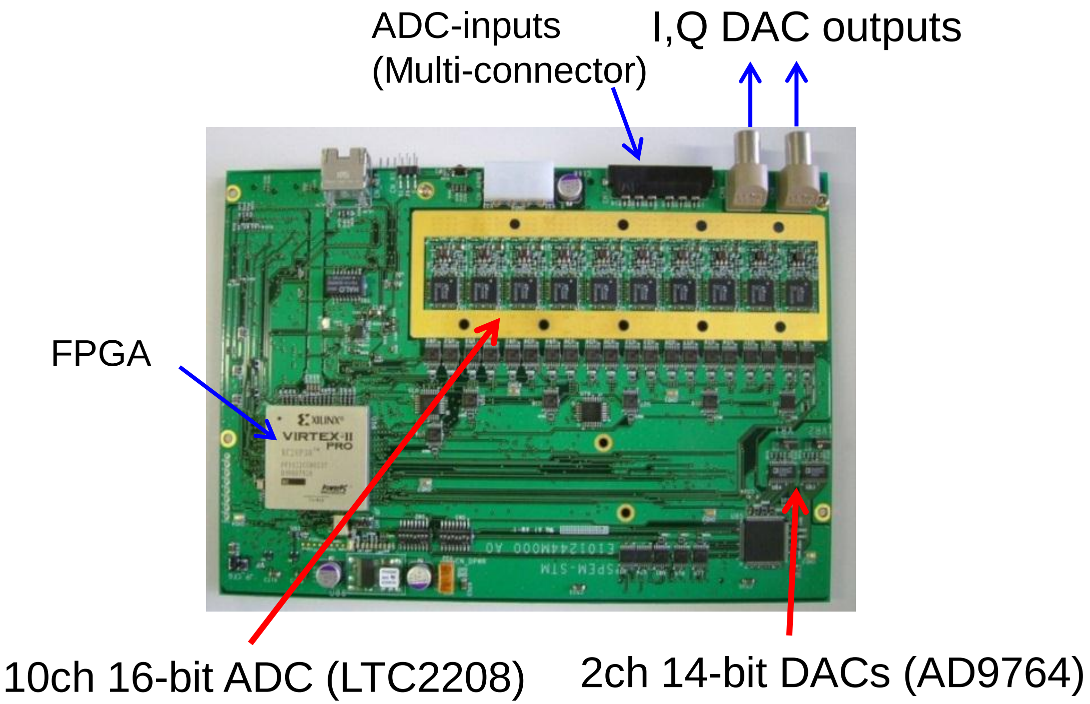
Klystron Hall

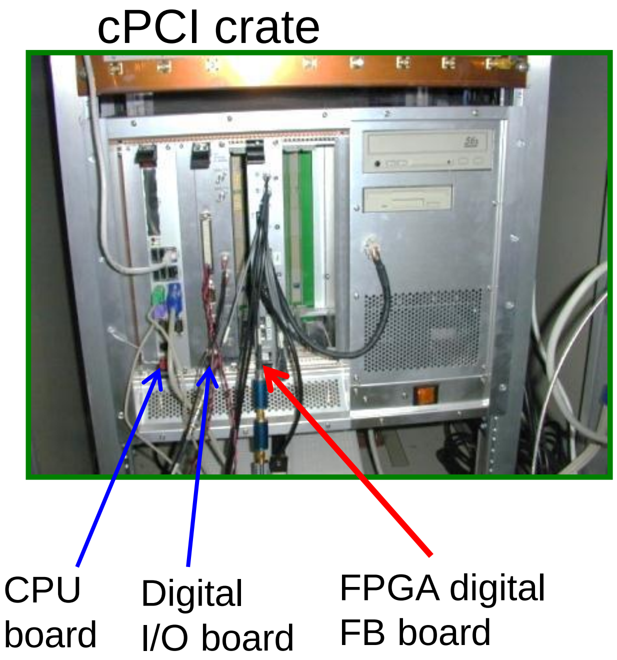
Cryomodule & WG in the tunnel

LLRF digital FB system

cPCI digital FB board

FPGA board is a daughter card of a commercial DSP board.



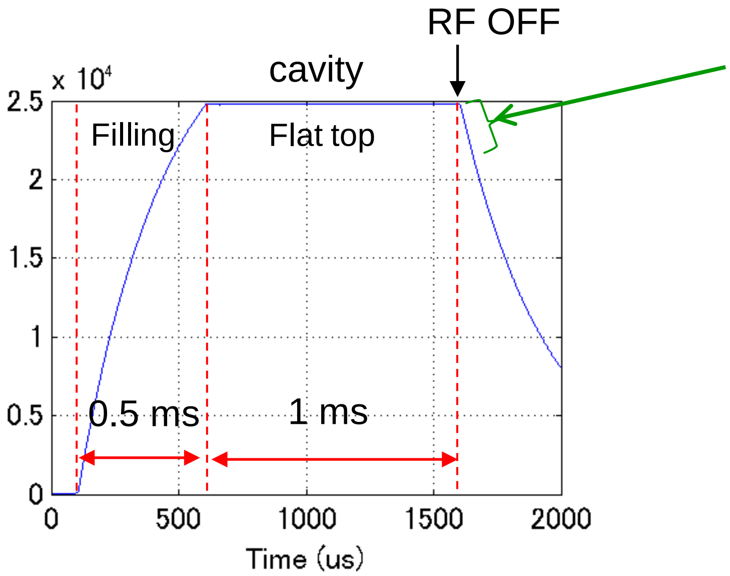


FB calc. → FPGA

Complex calc. like derivation of Q_L
Data communication
} → DSP

Loaded-Q interlock for quench protection

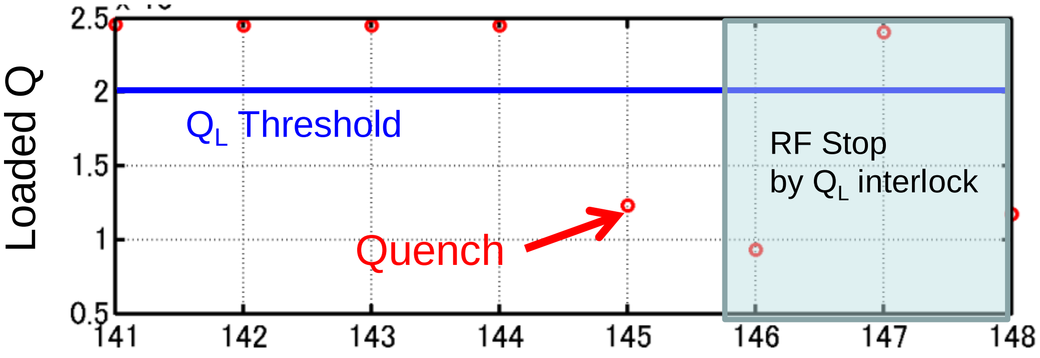
Loaded Q (Q_L) interlock system was installed to quit RF quickly in quench occurrence.



Q_L is calculated from decay curve.

$$V_{cav} \propto e^{-t/\tau}, \Rightarrow Q_L = \frac{\tau\omega_0}{2}$$

Q_L of each cavity is calculated in DSP on the cPCI FB board.



When quench event is detected, RF operation stops at the next pulse.

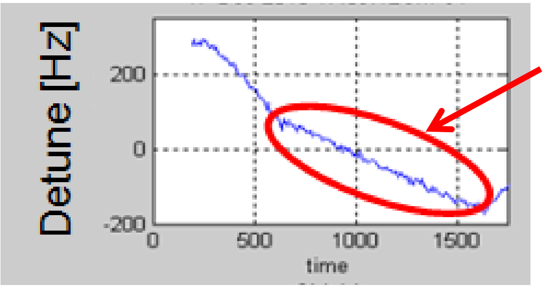
Q_L interlock worked well and contributed to the stable cryogenic operation.

Real time detuning monitor

Correction of the dynamic detuning in real time is effective to good RF performance.

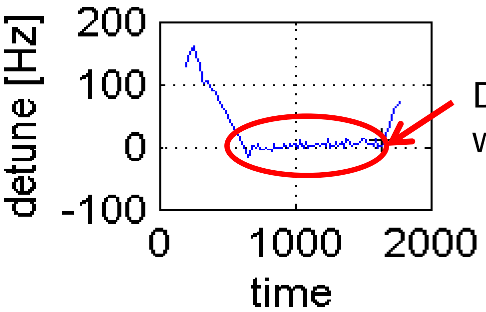
<Examples of detune curves>

Without correction by Piezo tuner



Dynamic detuning is seen at flat-top region

With correction by Piezo tuner



Dynamic detuning is well corrected.

Real time detuning monitor is quite helpful to adjust the Piezo tuners.

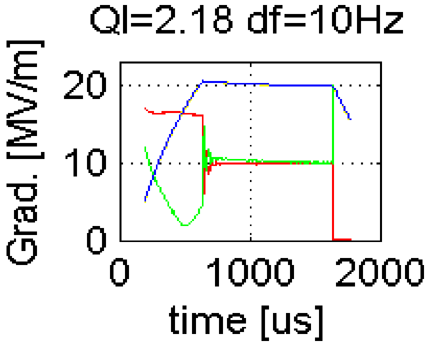
Derivation of dynamic detuning

$$V_{cav} = V_{for} + V_{ref},$$

$$\frac{d}{dt}V_{cav} = -\left(\omega_{1/2} - j\Delta\omega(t)\right)V_{cav} + 2\omega_{1/2}V_{for}$$

Detuning is derived by using these 3 signals;

V_{cav}: Cavity voltage
V_{for} : Cavity input voltage
V_{ref} : reflection voltage from cavity



For 8 cavities, total 8cav x 3 = 24 signals are required.

Data taking by IF-MIX

Advantage: 24 signals required for detuning monitor were taken with only 8 ADCs by using IF-MIX

IF-MIX: method to input different IF-signals into one ADC

$$f_{IF} = \sum_N \left(\frac{N}{M}\right) \cdot f_{SR}$$ (Sampling rate of ADC : f_{SR}= 40.625 MHz)

IF1= 4.514MHz (N=1, M=9)
IF2= 9.028MHz (N=2, M=9)
IF3=13.542MHz (N=3, M=9)

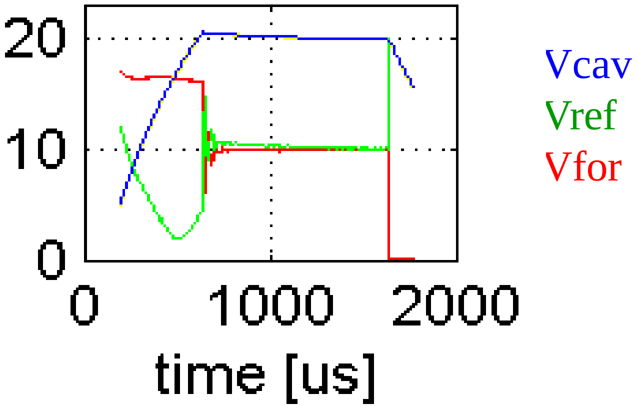
} ➡ Input into the same ADC.

Each signal is derived by Fourier expansion

$$I = \frac{2}{M}\sum_{n=1}^{M} x_i(n)\cdot\cos(\frac{2\pi\cdot N}{M}\cdot n)$$

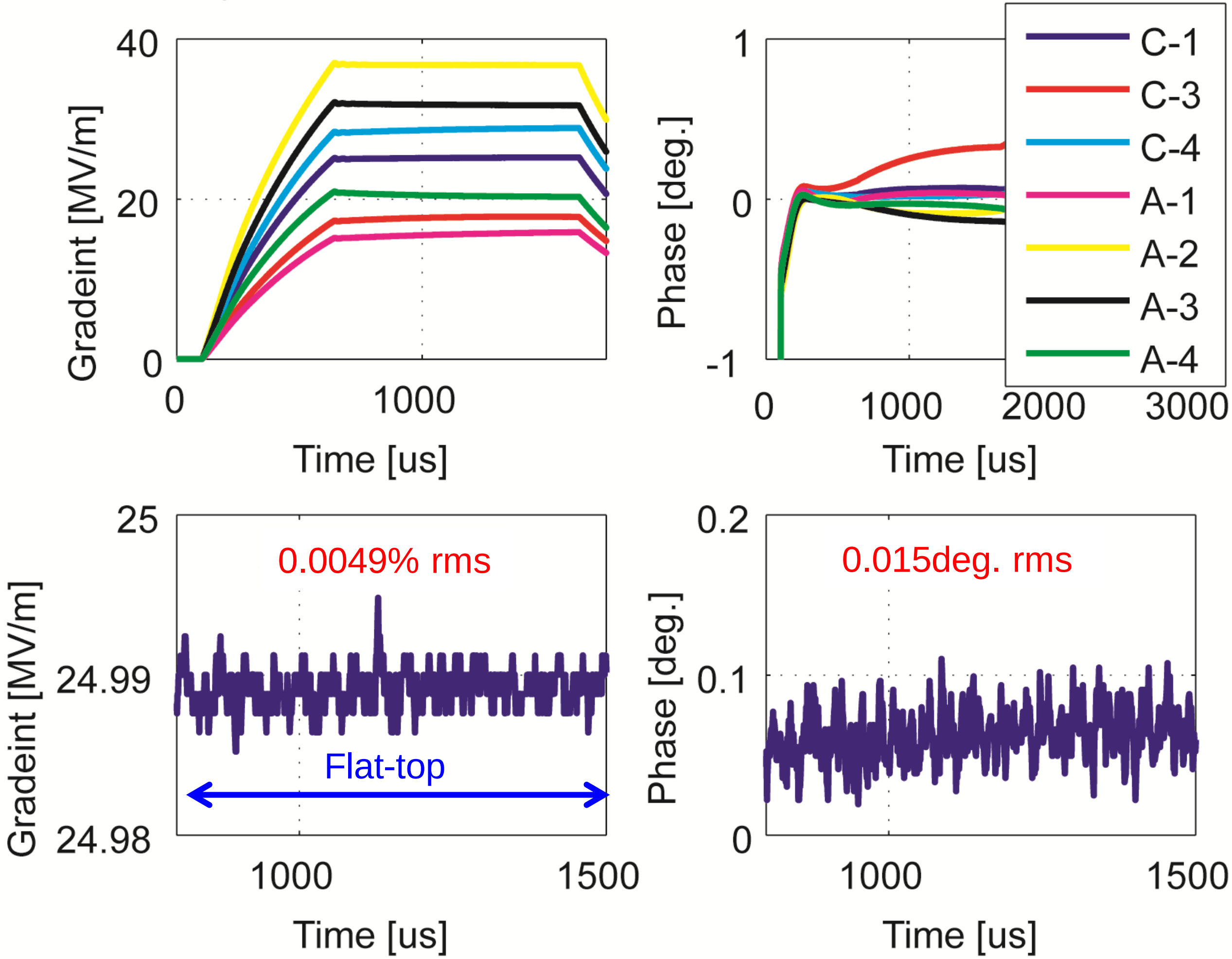
$$Q = \frac{2}{M}\sum_{n=1}^{M} x_i(n)\cdot\sin(\frac{2\pi\cdot N}{M}\cdot n)$$

Results of 3 waveforms taken in one ADC by IF-MIX



Result of vector sum operation

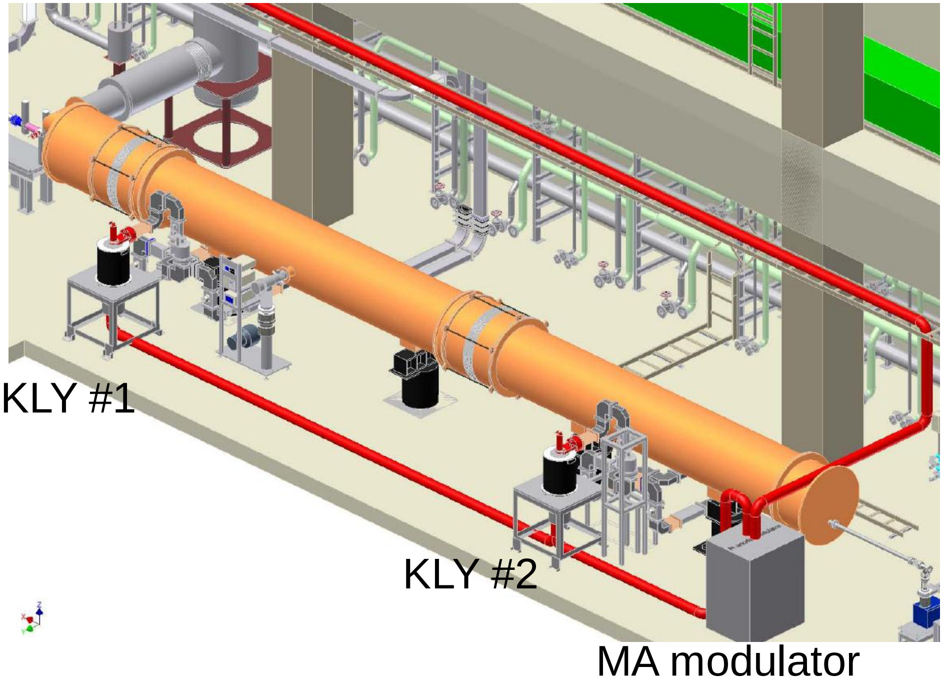
Average acceleration field=25 MV/m



These results satisfy the requirement of ILC, 0.07% and 0.24°.

S1-Global (DRFS)

The first test of DRFS for ILC was conducted at the end of S1-Global.



- Two klystrons with modulation anodes(MA) were connected to a DC power supply and an MA-modulator .
- Each klystron drove 2 cavities. (KLY#1→C1+C2, KLY#2→A2+A3)

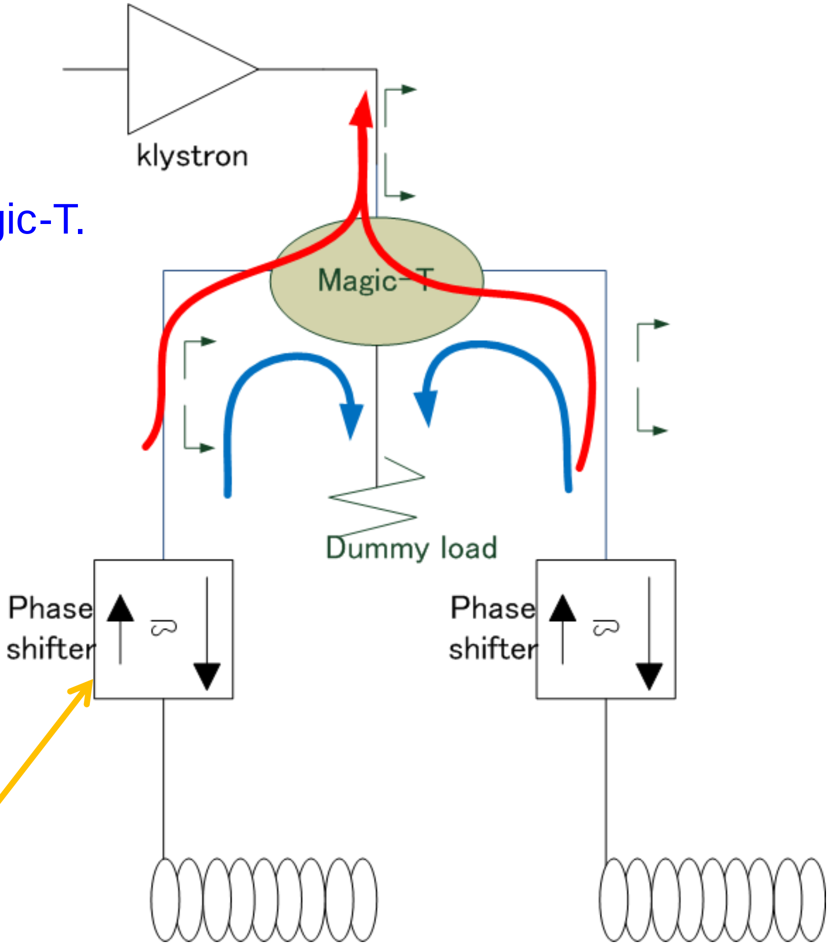
WG system in DRFS

Circulator-less operation using Magic-T

In DRFS,
reflections from 2 similar cav. are canceled by magic-T.
Therefore circulator is possible to be omitted.

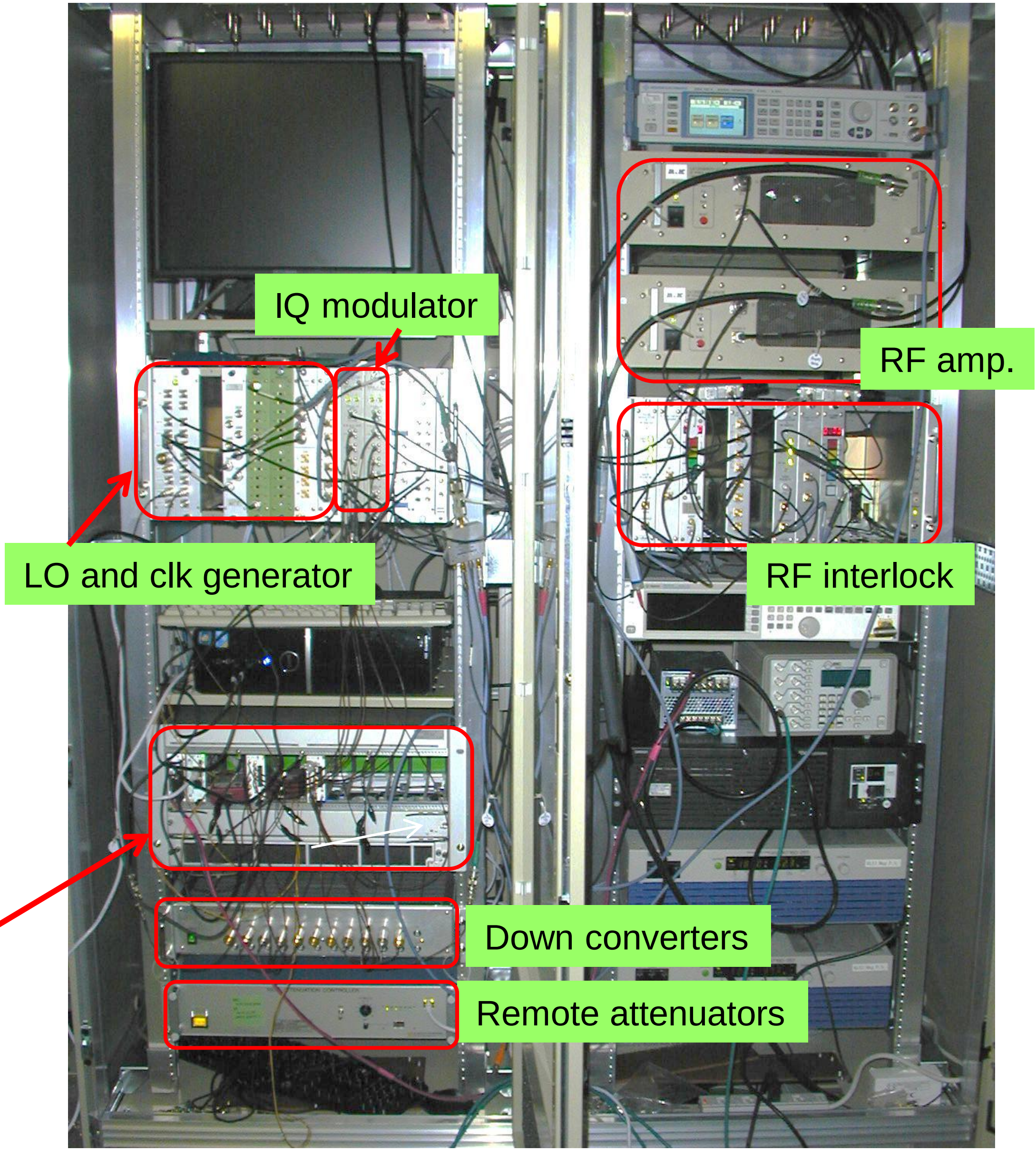
In the case of un-balanced reflection(amp., phase), reflection power go to the klystron.
Therefore performance should be checked.

S1-Global examined this situation as described later.



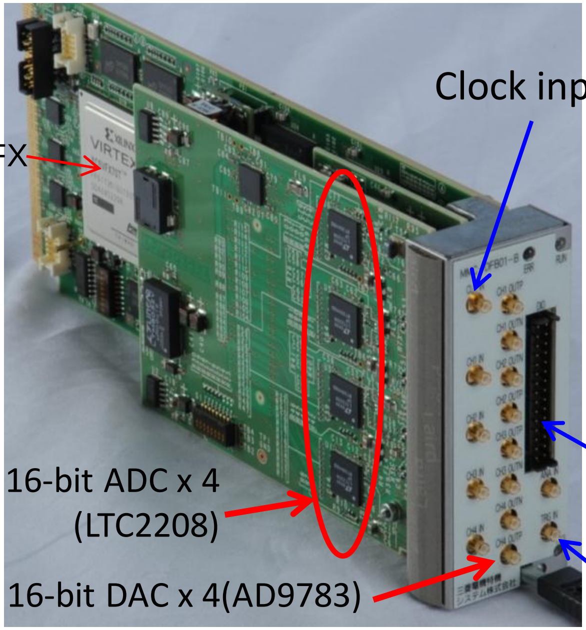
Phase-shifters are introduced to evaluate the system. (not to be used at ILC-DRFS

LLRF rack layout in the tunnel



- LLRF rack is located near the cryomodule.
- µTCA digital feedback system are used for DRFS.

Micro-TCA digital feedback board



AMC(Advanced Mezzanine Card)

Shelf

Data communication is performed through Gb Ethernet bus at the backplane.

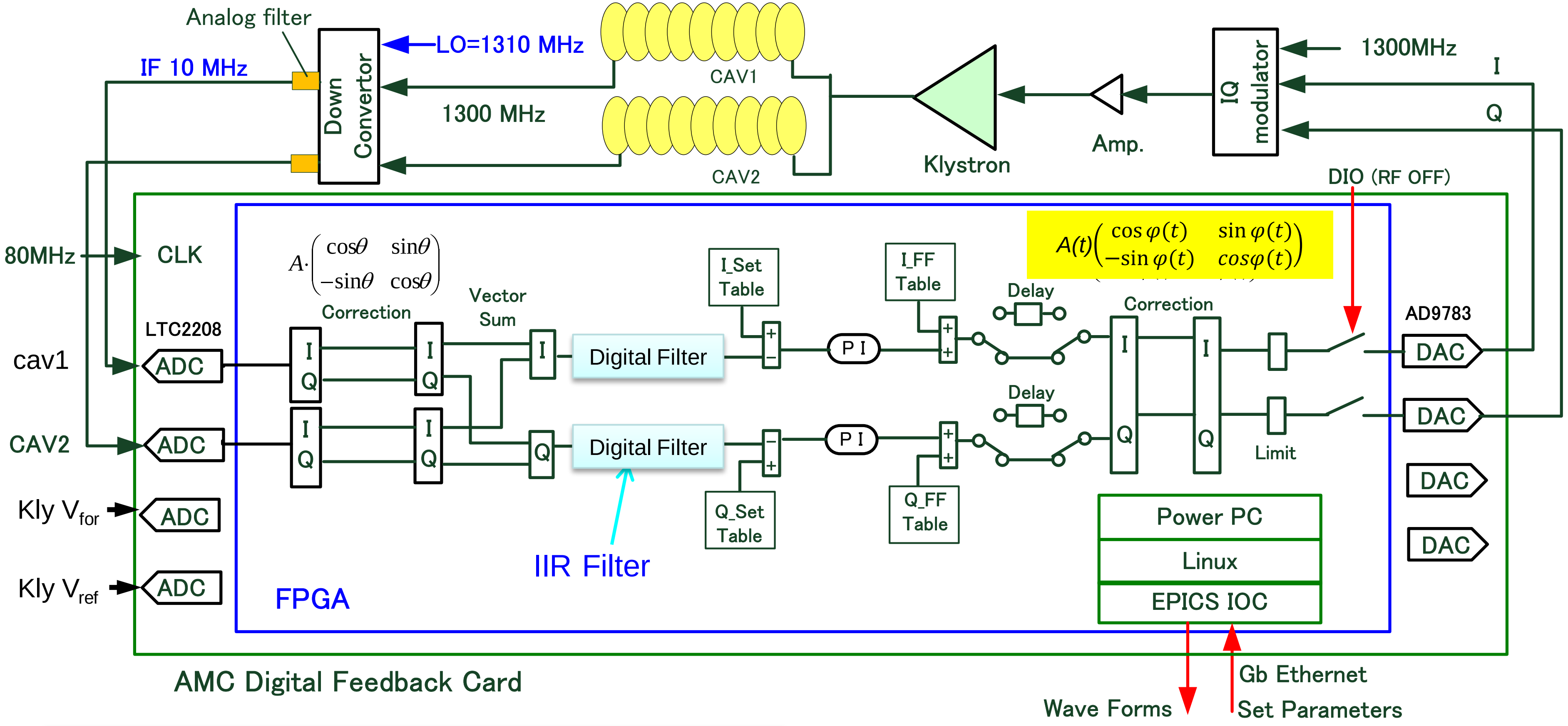
EPICS was installed in the digital board for communication control.

EPICS: Experimental Physics and Industrial Control System

The board has been developed for cERL-project (CW operation) at KEK.

For DRFS, the logic was changed for pulse operation.

Schematic diagram of LLRF system



IIR filter : 35kHz~150kHz LPF in normal operation

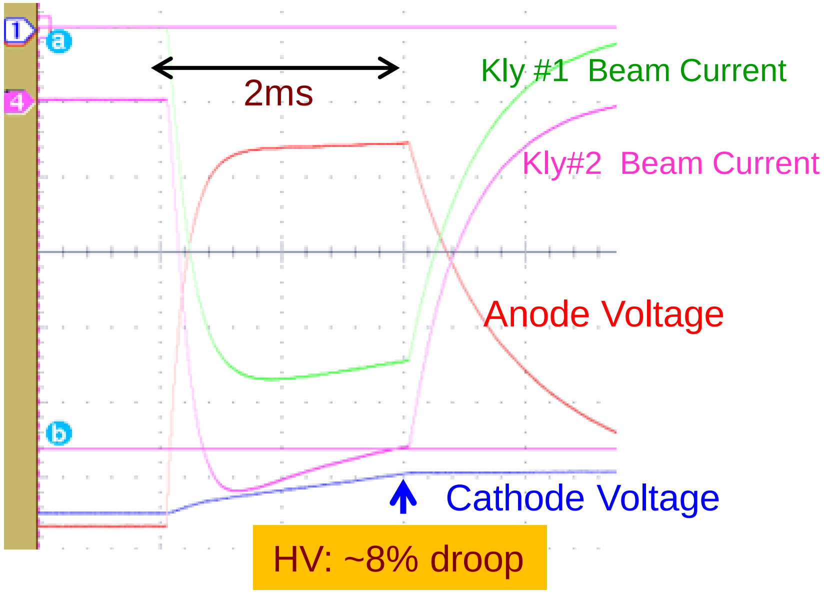
- 8/9π mode
- noise in ADC-input

→ rejected

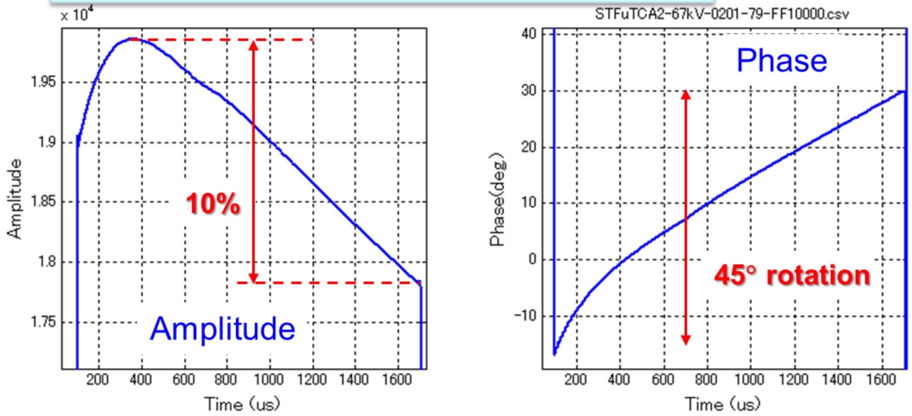
<Latency of FB board>
ADC : 7.5 clock, DAC :15 clock @ 81.25MHz
IQ separation & Correction : 5 clock@40.625MHz
Calculation in FPGA : 23 clock @ 81.25MHz
Total 55.5 clock @ 81.25MHz (0.68 μs)

Sag-compensation

Since bouncer circuit was not installed due to budget shortage, there are 8 % droop in HV.

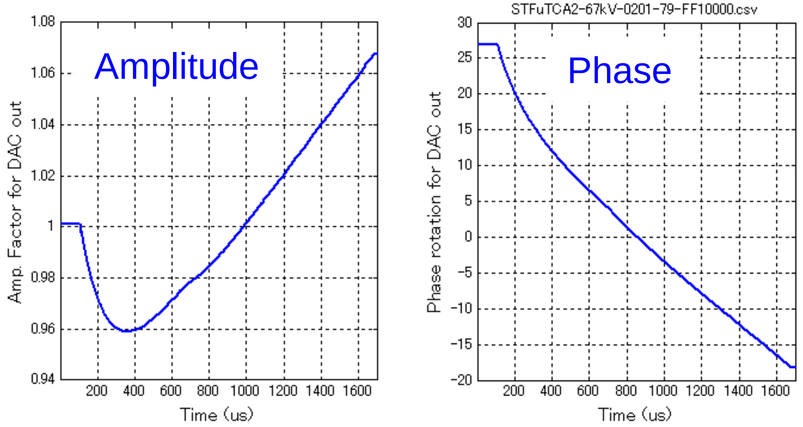


klystron output for flat 1.6ms-width RF input



Especially, phase rotation is too large to suppress by feedback only.

Correction Table



Sag compensation was performed at before the DAC-output

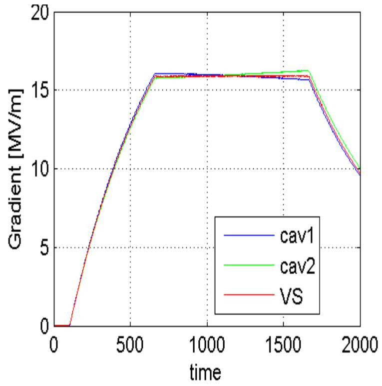
$$A(t)\begin{pmatrix} \cos\varphi(t) & \sin\varphi(t) \\ -\sin\varphi(t) & cos\varphi(t) \end{pmatrix}$$

Result for circulator-less operation

(When reflection is not canceled or large, circulator-less system should be checked.)

Typical Operation

- Low reflection : VSWR~1.1

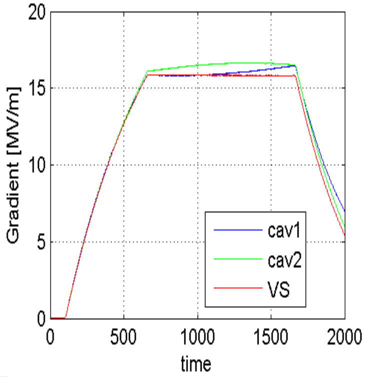


Stability 0.015% rms, 0.06deg.rms

Operation under different detuning

Δf1 > Δf2 ~130Hz

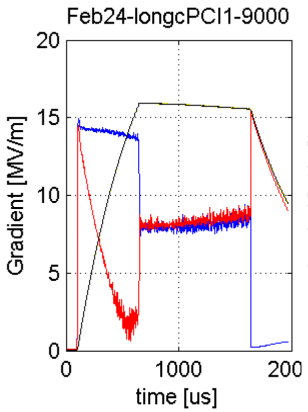
- Large reflection: max VSWR~3

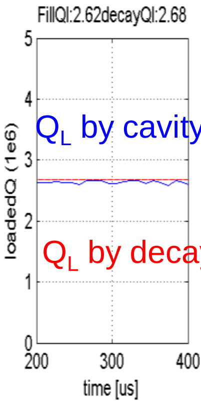


Vector sum is still regulated stably. (0.04%rms, 0.06deg.rms)

cavity eq.

$$Q_L = \frac{\omega_0\left(V_{for}^2 - V_{ref}^2\right)}{\frac{d}{dt}|V|^2}$$



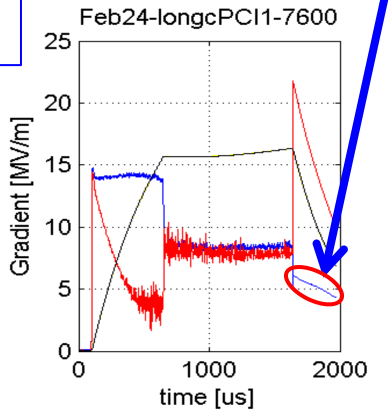


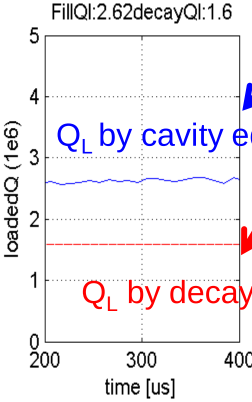
Q_L by cavity eq.

Q_L by decay

Both are same results.

V_{for} exists even after RF-off





Reasonable value

Q_L by cavity eq.

Wrong value

Q_L by decay

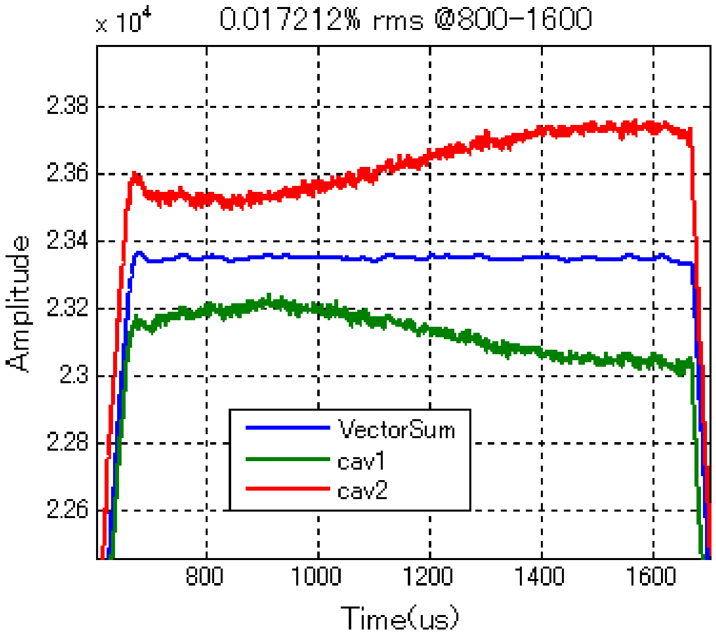
Although simple Q_L calculation is useful for interlock, this is not sufficient for diagnostics.

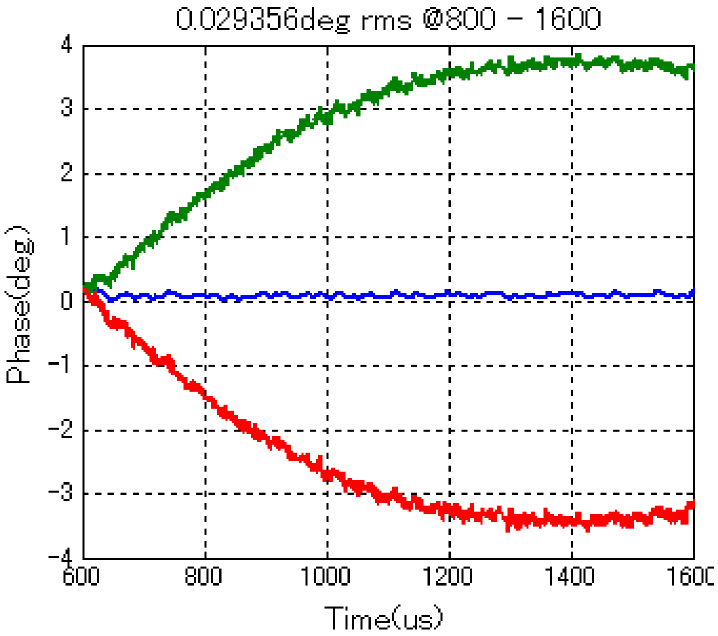
Therefore, under circulator-less operation, vector sum operation and Q_L diagnostics using cavity eq. worked well.

Feedback Performance in DRFS

μTCA2: HV=67kV, IIR=35kHz , Vector-sum Operation for Cav1,cav2

FB + FF Operation





Stability : 0.017% rms in Amplitude

0.03 deg. rms in Phase

These results satisfy the requirement of ILC, 0.07% and 0.24°.

LLRF system worked well without trouble in this machine-time despite placed in the tunnel.

Summary

S1-Global successfully completed operation in February, 2011.

Various diagnostics such as on-line quench pulse detector, dynamic detuning monitor were also implemented.

The digital FB system using cPCI or μTCA are adopted for vector-sum field regulation.

The vector-sum performance satisfied the ILC requirements.

Circulator-less system operated in good stability and
Q_L diagnostics worked well even in the large reflection condition.

Following operations are planned in future

Beam Operation will start at STF in KEK.

- Quantum beam project will start from Jan.2012. (10 mA, 40 MeV)
- STF-2 project will start from April 2013. (8.7mA, 273 MeV)

Thank you for your attention.

Cavity equation

- The cavity should satisfy the differential equation.
- In addition directivity (~20dB) of rf monitor-coupler should be concerned.
  -> The directivity can be corrected using this formula.

$$\dot{V} = -\left(\omega_{\frac{1}{2}} - j\Delta\omega\right)V + 2\omega_{\frac{1}{2}}V_{for}$$

$$\dot{V}_{cav} - j\Delta\omega V_{cav} = \omega_{1/2}V_{dif}$$

$$V_{dif} = V_{for} - V_{ref}$$

$$\dot{V}_{cav} - j\Delta\omega V_{cav} = \omega_{1/2}V_{dif}$$

$$\dot{V}_{cav\,R} + \Delta\omega V_{cavI} = \omega_{1/2}V_{difR}$$

$$\dot{V}_{cavI} - \Delta\omega V_{cavR} = \omega_{1/2}V_{difI}$$

$$\omega_{\frac{1}{2}} = \frac{\frac{1}{2}\frac{d}{dt}|V|^2}{V_{for}^2 - V_{ref}^2}$$

$$\mathbf{Q_l = \frac{\omega_0\left(V_{for}^2 - V_{ref}^2\right)}{\frac{d}{dt}|V|^2}}$$