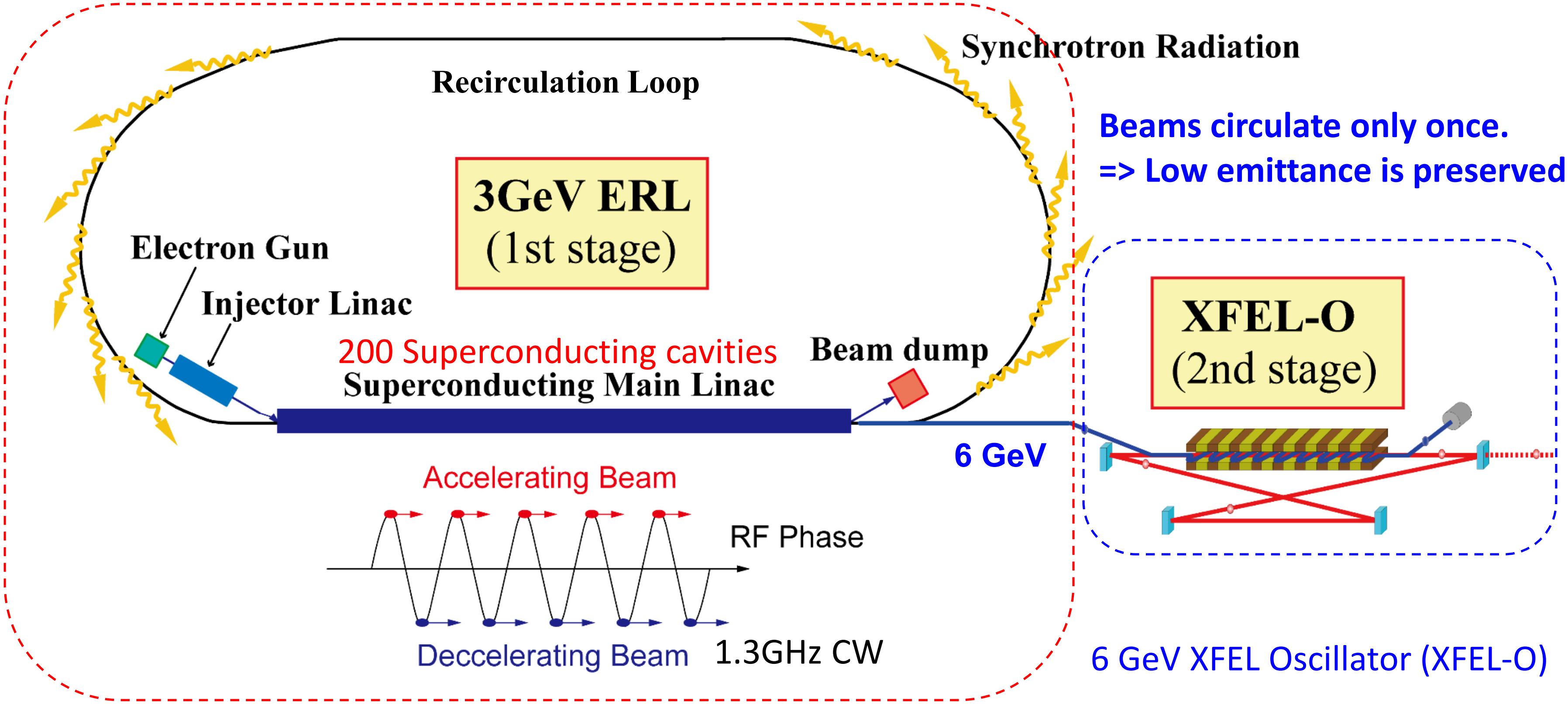
# Performance of the cERL LLRF System

Compact ERL (Energy Recovery LINAC)


Takako Miura (KEK)

# Future Plan of 3GeV ERL Light Source at KEK

[1] **3GeV ERL as VUV and X-ray SR source** (high flux and short pulse)
(10 mA – 100 mA, $\varepsilon_n$: 0.1 mm·mrad, bunch length:100fs@min)
[2] **6GeV XFEL Oscillator** (2 times acceleration by 2 circulations)



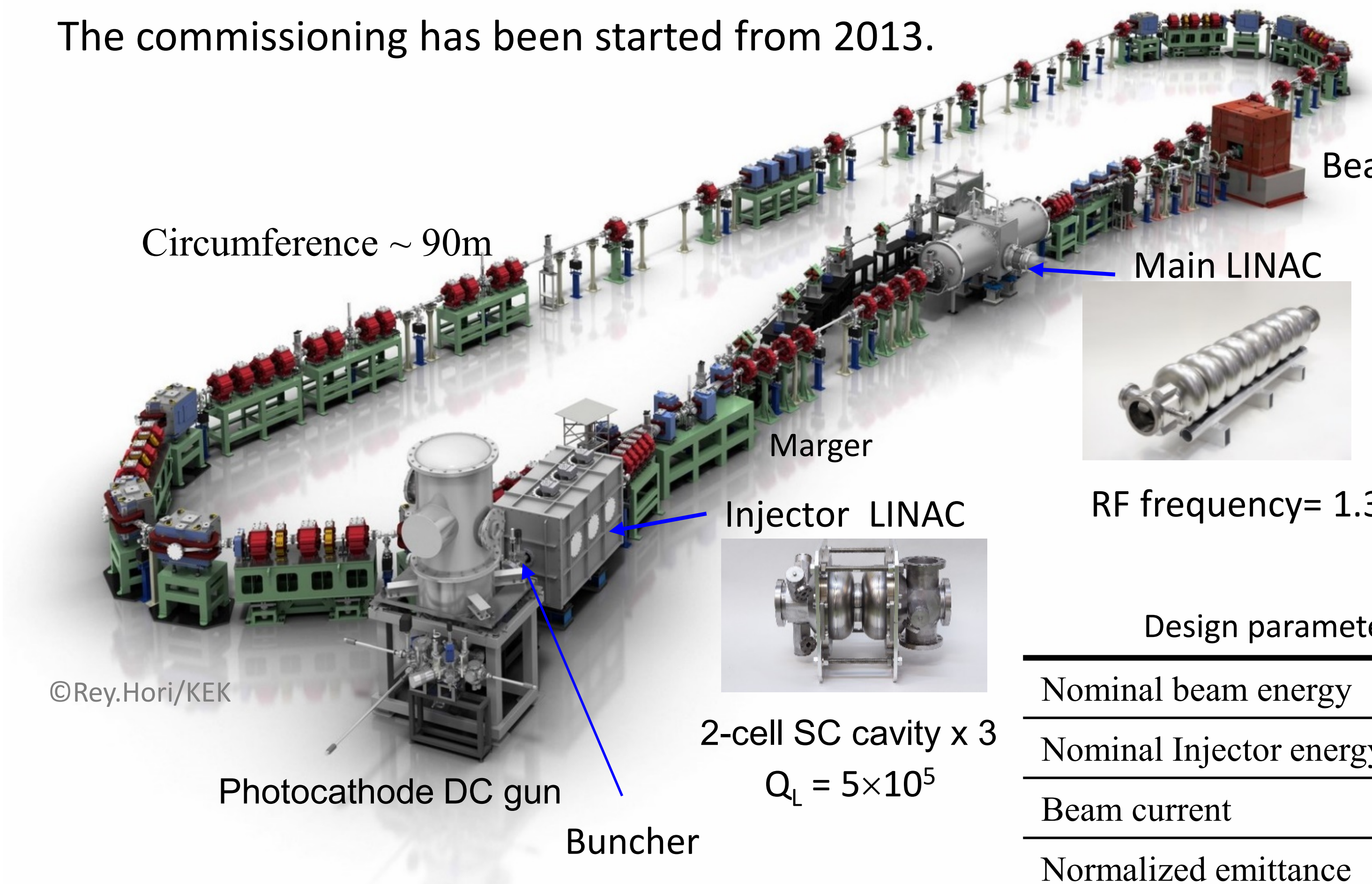

**Beams circulate only once.**
**=> Low emittance is preserved.**

6 GeV XFEL Oscillator (XFEL-O)

# Introduction of cERL

Compact ERL (**cERL**) has been constructed as a test facility of a 3-GeV ERL future plan.

The commissioning has been started from 2013.




9-cell SC cavity x 2

$Q_L = 1\times 10^7$

RF frequency= 1.3 GHz

2-cell SC cavity x 3

$Q_L = 5\times10^5$

Design parameters of the cERL

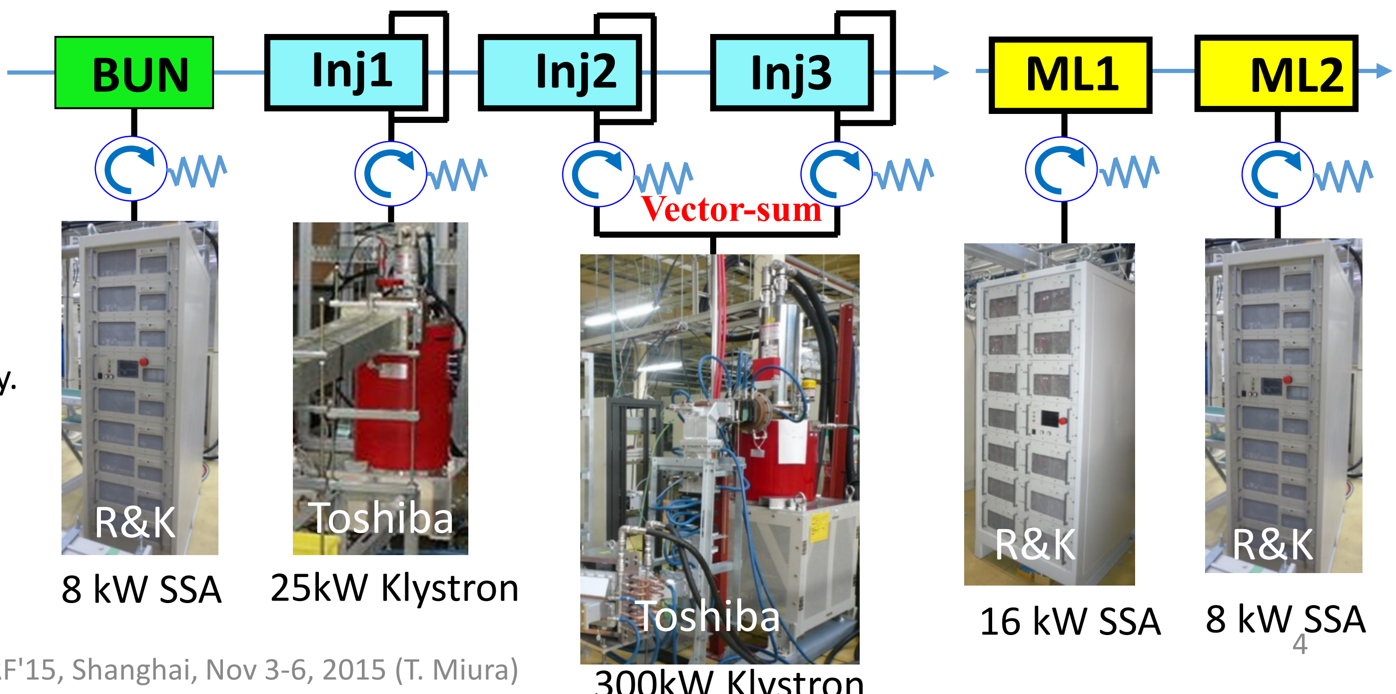
| | |
|---|---|
| Nominal beam energy | 35 MeV |
| Nominal Injector energy | 5 MeV |
| Beam current | 10 mA (initial goal) |
| Normalized emittance | 0.1 – 1 mm·mrad |
| Bunch length | 1-3ps (usual)<br>100fs (short bunch) |

# Current status of high power RF sources

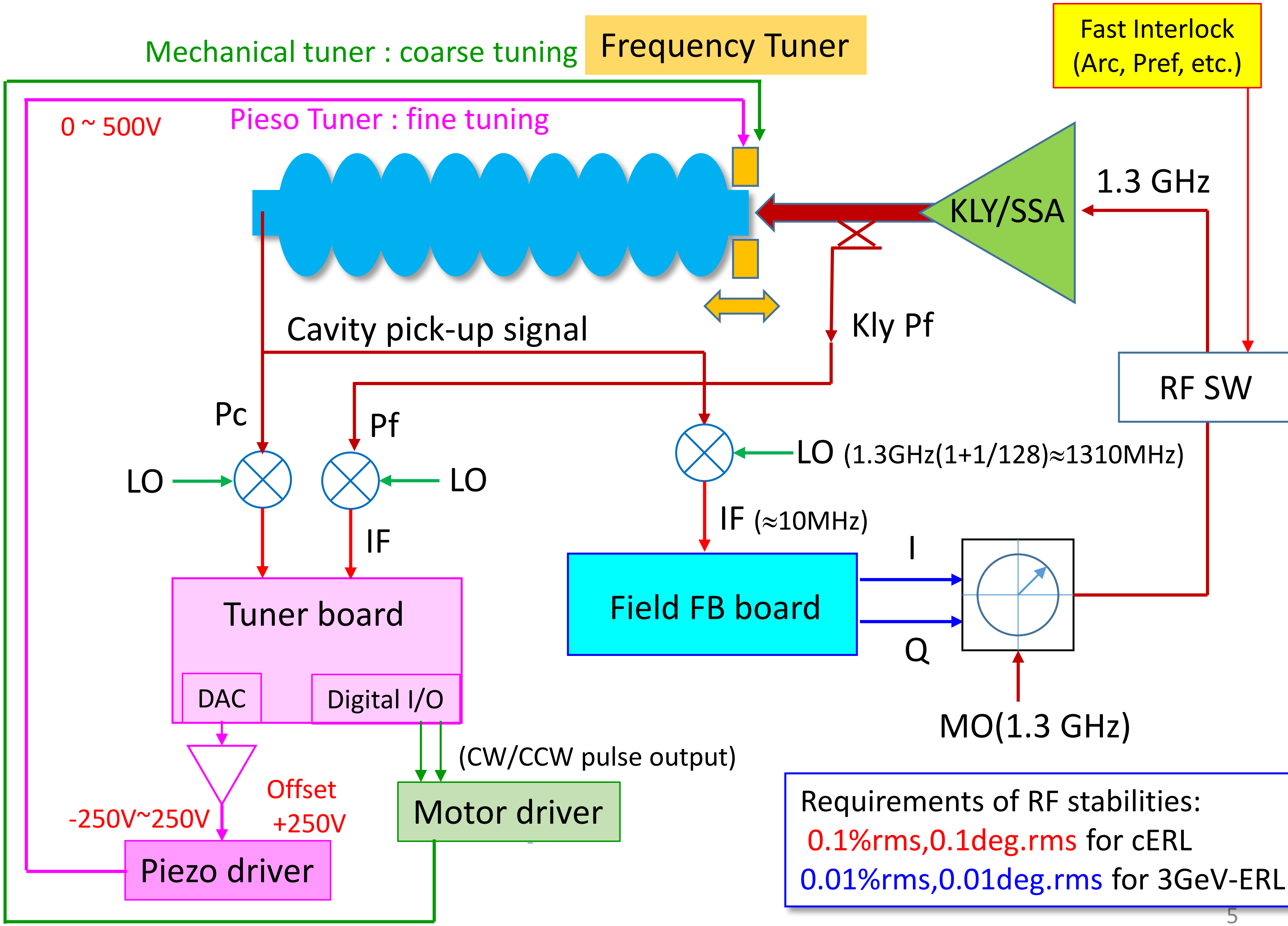
| | Buncher | Inj-1 | Inj-2 | Inj-3 | ML-1 | ML-2 |
|---|---|---|---|---|---|---|
| Cavity | NC | 2cell-SC | 2cell-SC | 2cell-SC | 9cell-SC | 9cell-SC |
| Cavity Voltage | 114 kV | 0.7 MV | 0.7 MV | 0.7 MV | 8.6 MV | 8.6 MV |
| Field Gradient (Desgin) | | 3 MV/m (7.5MV/m) | 3MV/m (7.5MV/m) | 3MV/m (7.5 MV/m) | 8.6 MV/m (15MV/m) | 8.6 MV/m (15MV/m) |
| $Q_L$ | $1.1\times 10^5$ | $1.2 \times 10^6$ | $5.8 \times 10^5$ | $4.8 \times 10^5$ | $1.3 \times 10^7$ | $1.0 \times 10^7$ |
| Cavity Length | 0.068 m | 0.23 m | 0.23 m | 0.23 m | 1.036 m | 1.036 m |
| RF Power @Low beam current | 3 kW | 0.53 kW | 2.6 kW | | 1.6 kW | 2 kW |

<Design>
100mA beam &
Vc= 2MV at Inj.Cav

200kW RF power is
necessary for each inj. cavity.

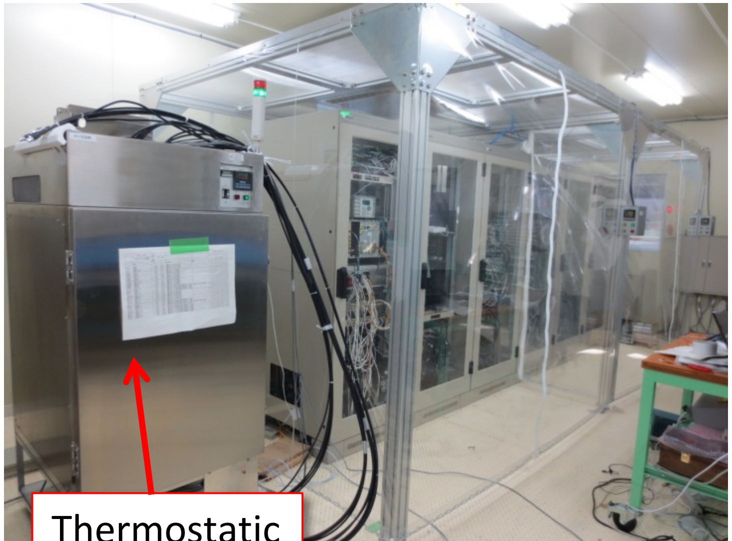


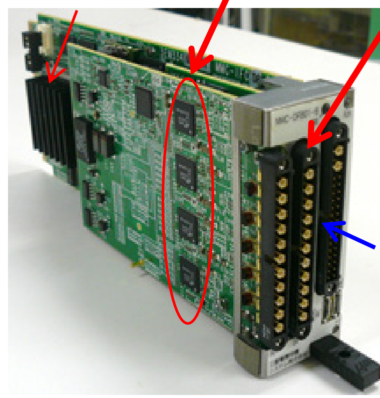
# Digital LLRF System at cERL




Requirements of RF stabilities:
0.1%rms,0.1deg.rms for cERL
0.01%rms,0.01deg.rms for 3GeV-ERL

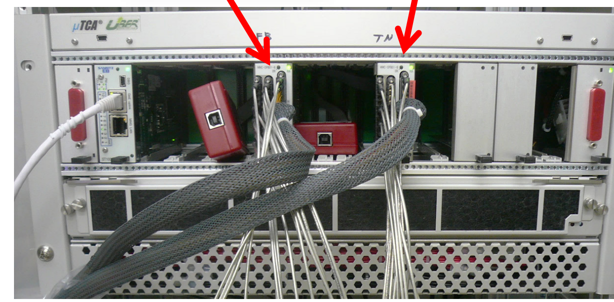
# Digital LLRF Boards




AMC(Advanced Mezzanine Card)

(Mitsubishi Electric TOKKI Systems Co.,Ltd.)



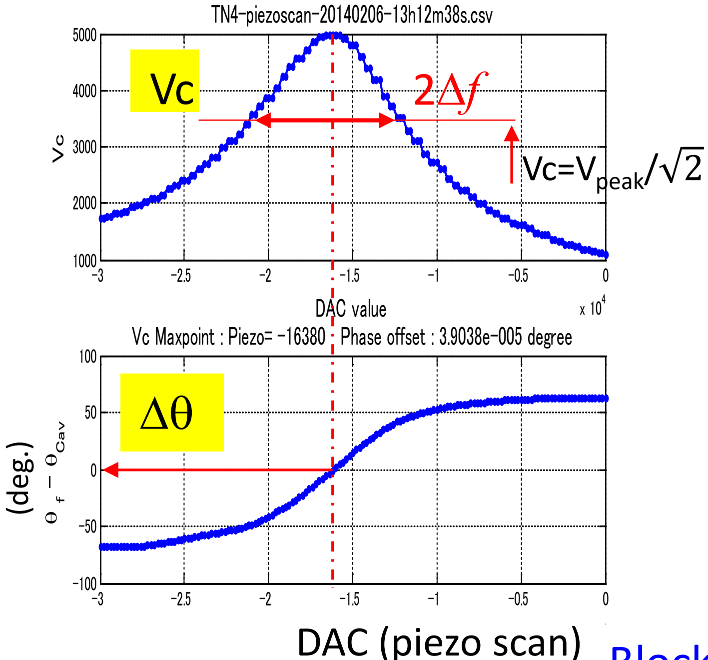

MicroTCA

Total 11 boards are used for operation.

| | BUN | Inj1 | Inj2 | Inj 3 | ML1 | ML2 |
|---|---|---|---|---|---|---|
| RF FB board | FB0 | FB1 | FB2 (Vec-sum) | | FB4 | FB5 |
| Tuner board | TN0 | TN1 | TN2 | TN3 | TN4 | TN5 |

- Embedded Linux is working in the PowerPC on FPGA.
- Each board acts as an EPICS IOC.
- Data acquisition is performed through GbE bus on the backplane.

# Frequency Feedback Control




$\Delta f$=65 Hz for ML cavities ($Q_L=10^7$)

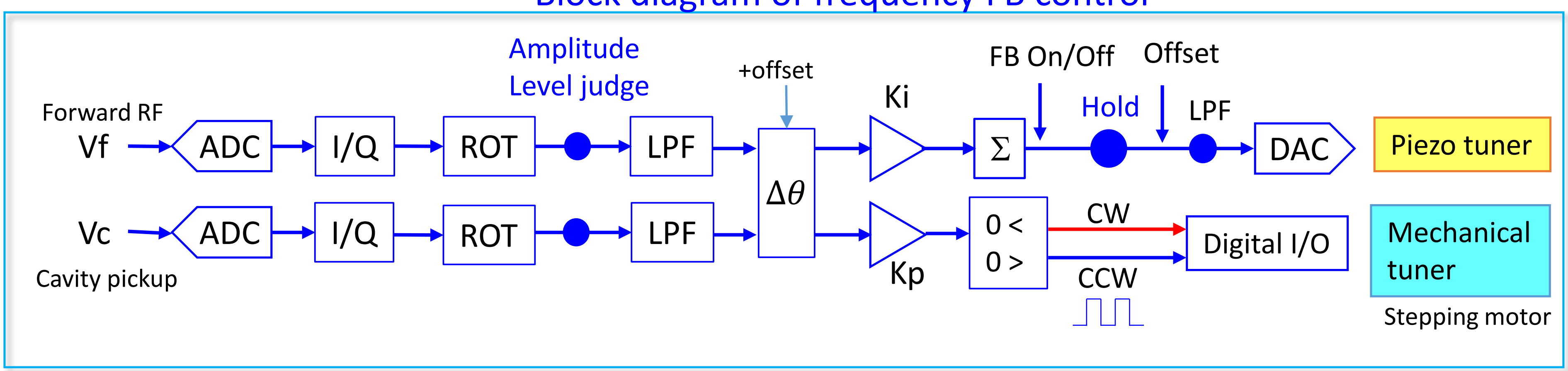
Narrow bandwidth for $f_0$=1.3 GHz

$\Delta\theta = \theta_f - \theta_c$ : The phase difference between the input RF and the cavity pickup signal

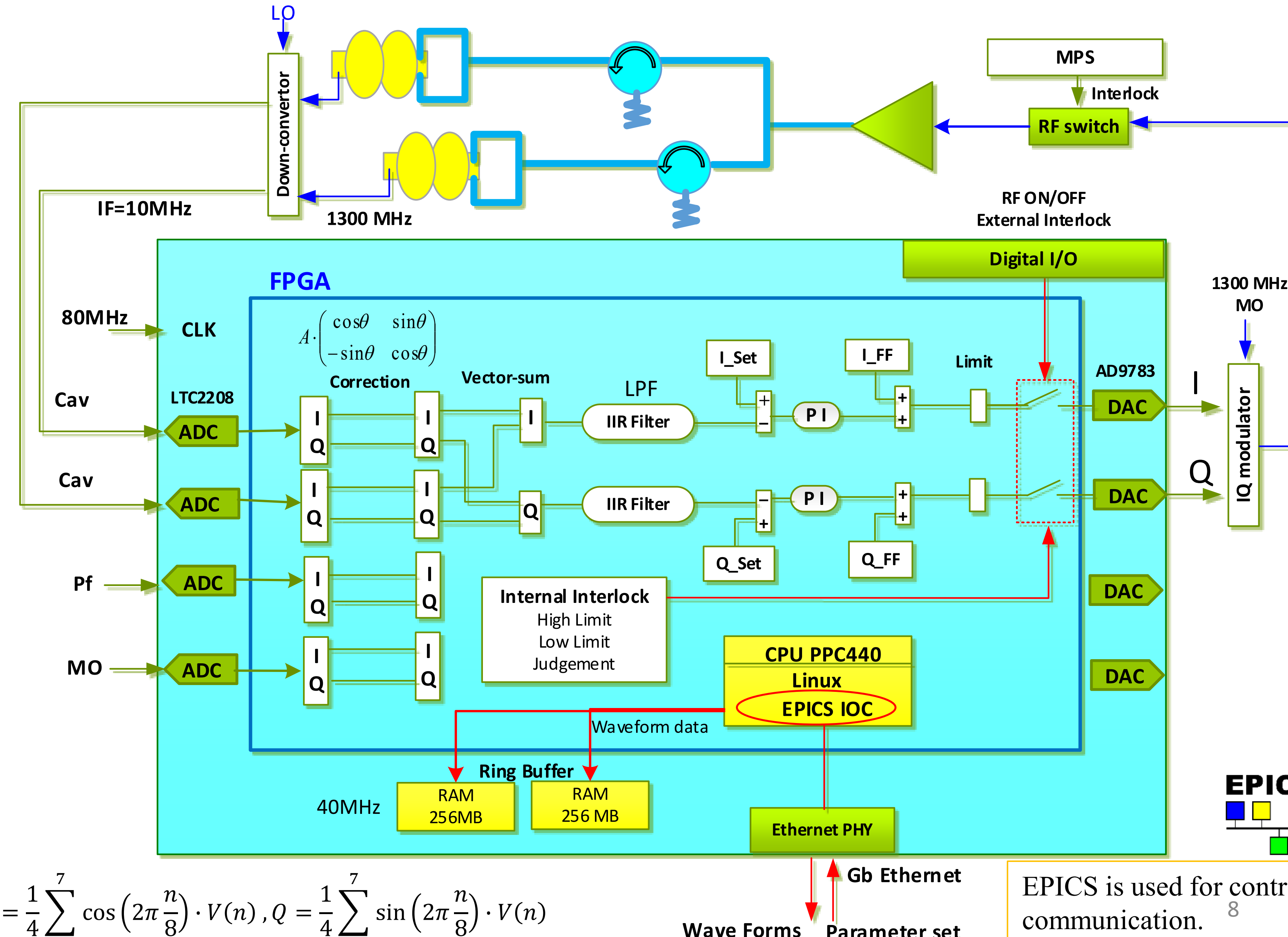
$$tan\Delta\theta \approx 2Q_L\frac{\Delta f}{f}$$

To keep resonance frequency, tuner should be controlled to maintain $\Delta\theta$ at zero.

Block diagram of frequency FB control



# Field Feedback Control

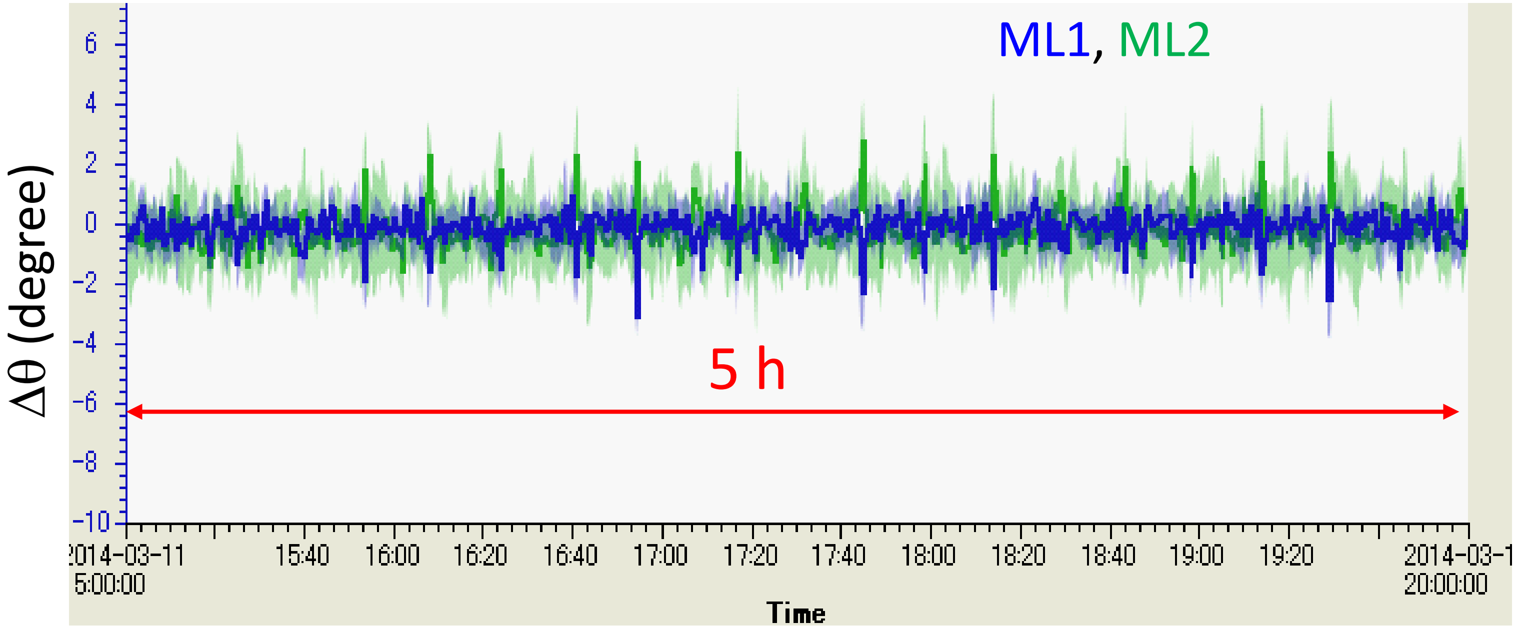



$$I = \frac{1}{4}\sum_{n=0}^{7} \cos\left(2\pi \frac{n}{8}\right) \cdot V(n)\ ,\ Q = \frac{1}{4}\sum_{n=0}^{7} \sin\left(2\pi \frac{n}{8}\right) \cdot V(n)$$

EPICS is used for control communication.

# Results of Frequency Control

$$\Delta\theta = \theta_f - \theta_c$$




$$tan\Delta\theta \approx 2Q_L\frac{\Delta f}{f}$$

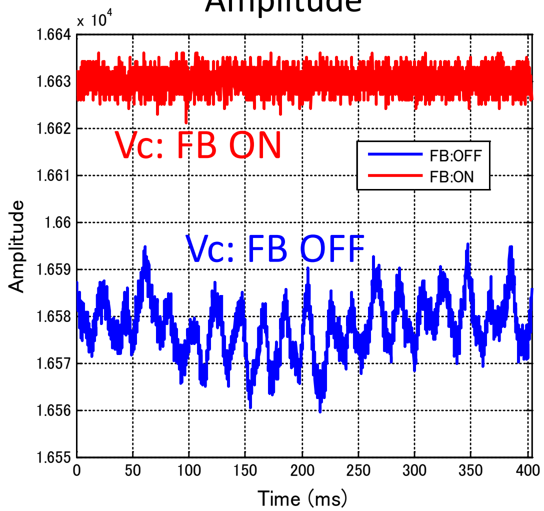
$\Delta\theta = \pm 3deg.$ $\quad Q_L \approx 10^7 \Rightarrow \Delta f \approx \pm 3.4$ Hz

# Performance of RF Feedback Control

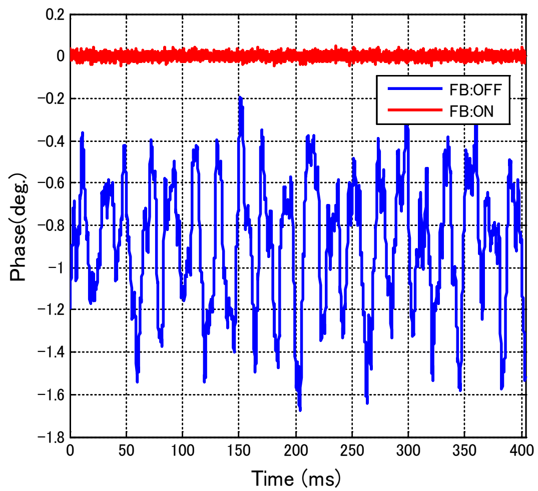
ML1

Waveforms of cavity pick-up

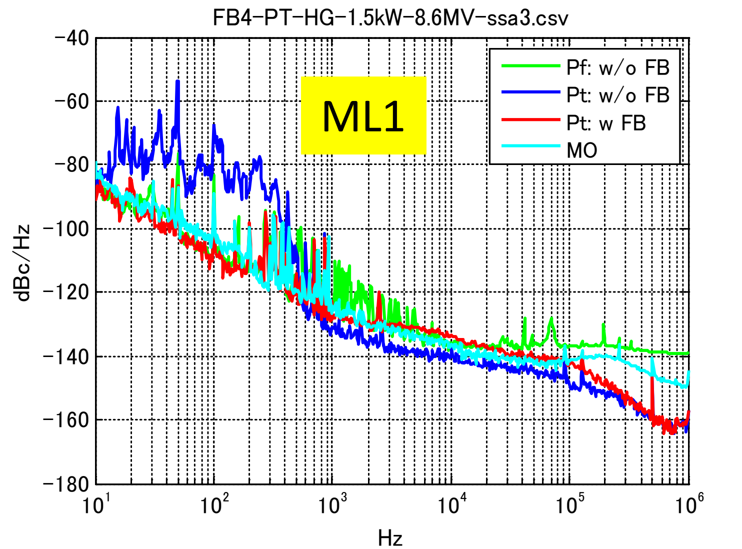
Amplitude




Phase

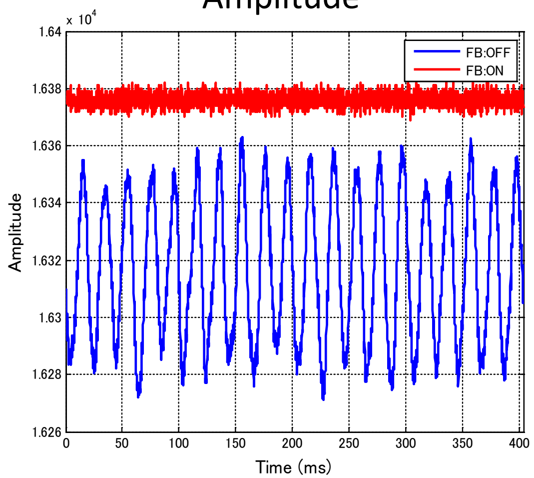



***Phase noise measurement using signal source analyzer***

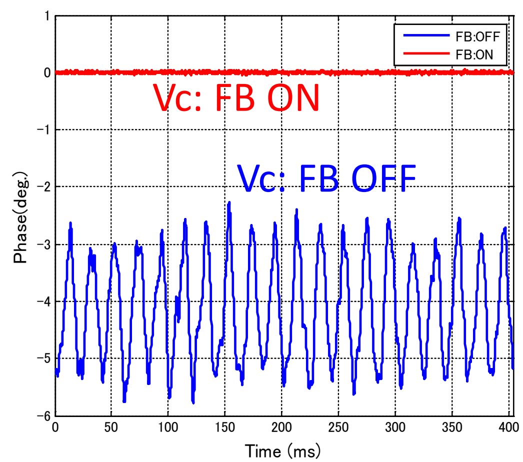


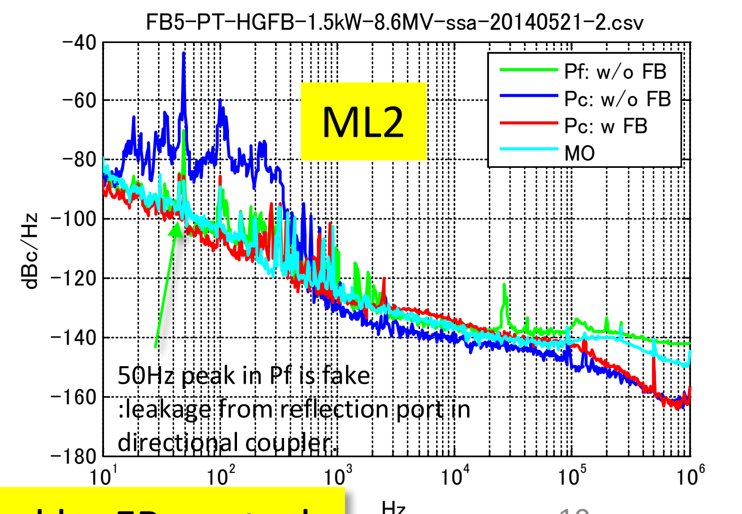

ML2

Amplitude




Phase




Fluctuations by microphonics have been well suppressed by FB control.

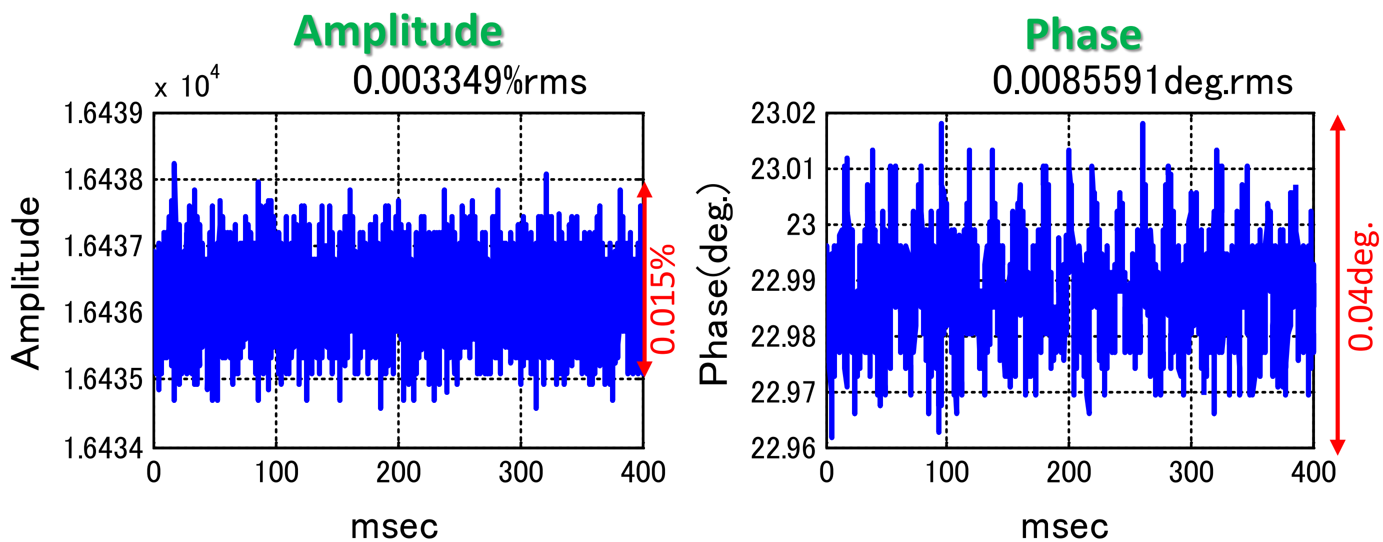
# RF Stabilities

Monitored with IIR LPF(5kHz)

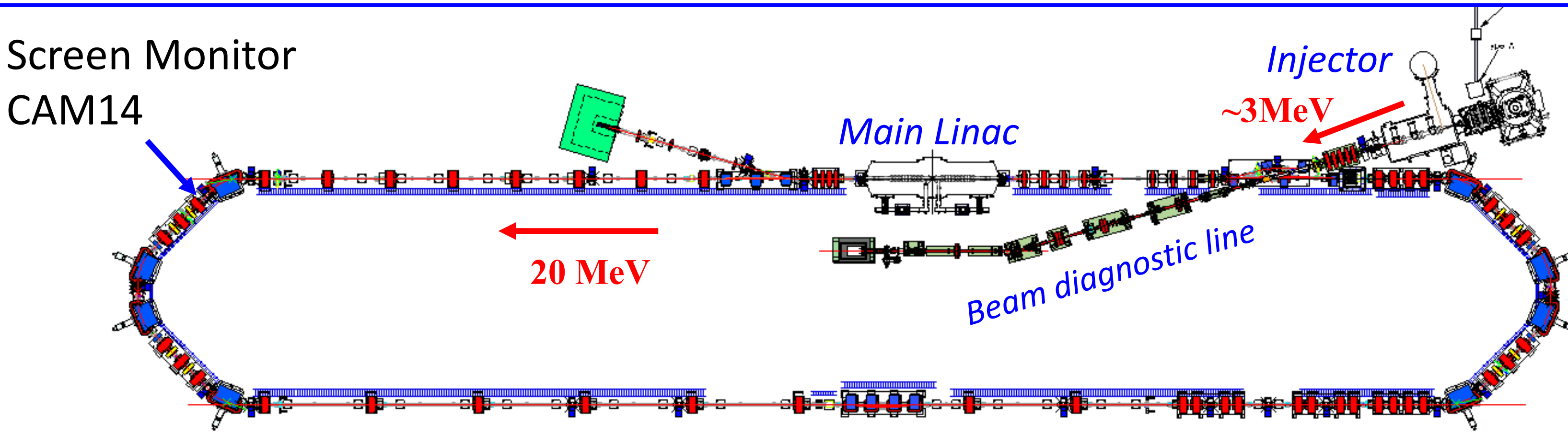
| | Inj1 | Inj2 & Inj3 | ML1 | ML2 |
|---|---|---|---|---|
| Amplitude | 0.006% rms | 0.007% rms | 0.003% rms | 0.003% rms |
| Phase | 0.009° rms | 0.025° rms | 0.010° rms | 0.009° rms |

Requirements:
0.1%rms,0.1deg.rms for cERL
0.01%rms,0.01deg.rms for 3GeV-ERL

ML2



# Stability of Beam Momentum (1)

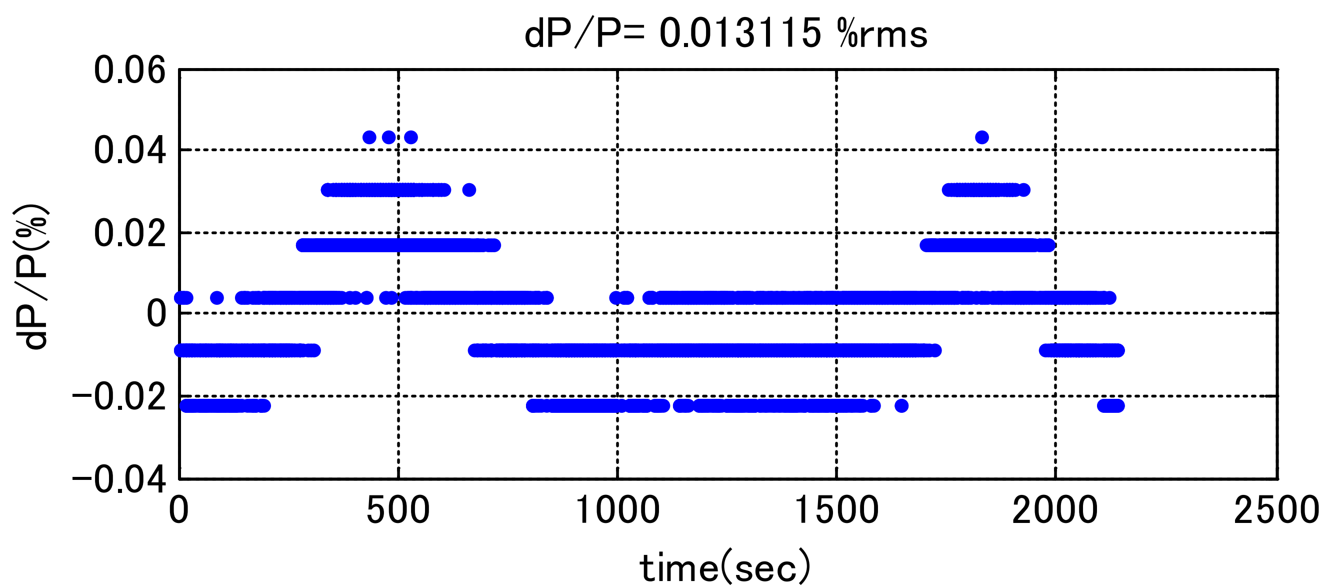



Dispersion : $\eta_X$= 0.487m

Beam: 5Hz, 3ps rms, 23 fC, total Energy=19.9 MeV

Screen Monitor

63.7 um/pixel



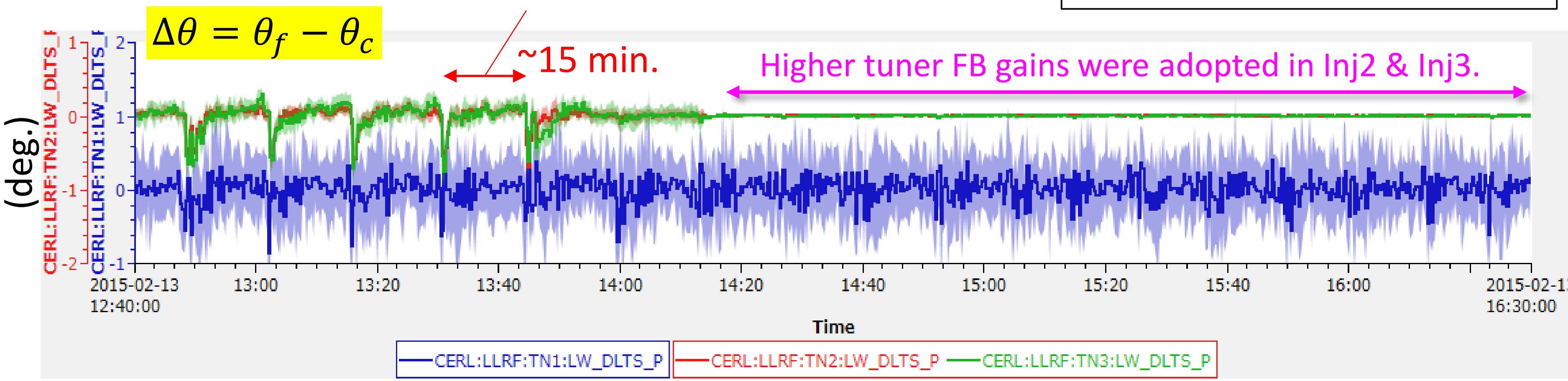

Momentum drift in the period of ~15 minutes was observed.

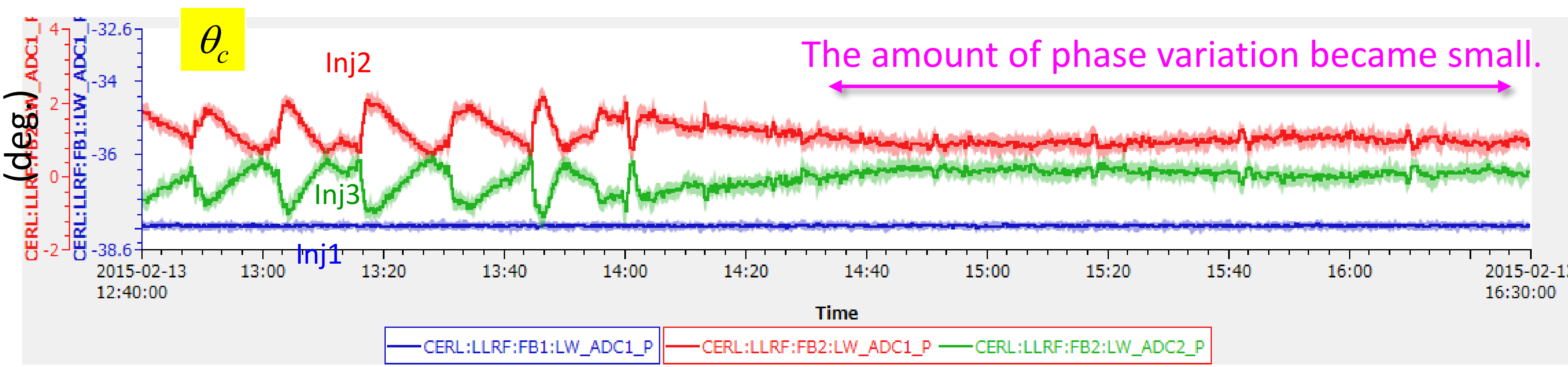
# Reduction of the Effect of Vector-sum Error

$$tan\Delta\theta \approx 2Q_L \frac{\Delta f}{f}$$

The time interval of detuning is similar to the interval of energy drift.

Blue: Inj1, Red: Inj2, Green: Inj3



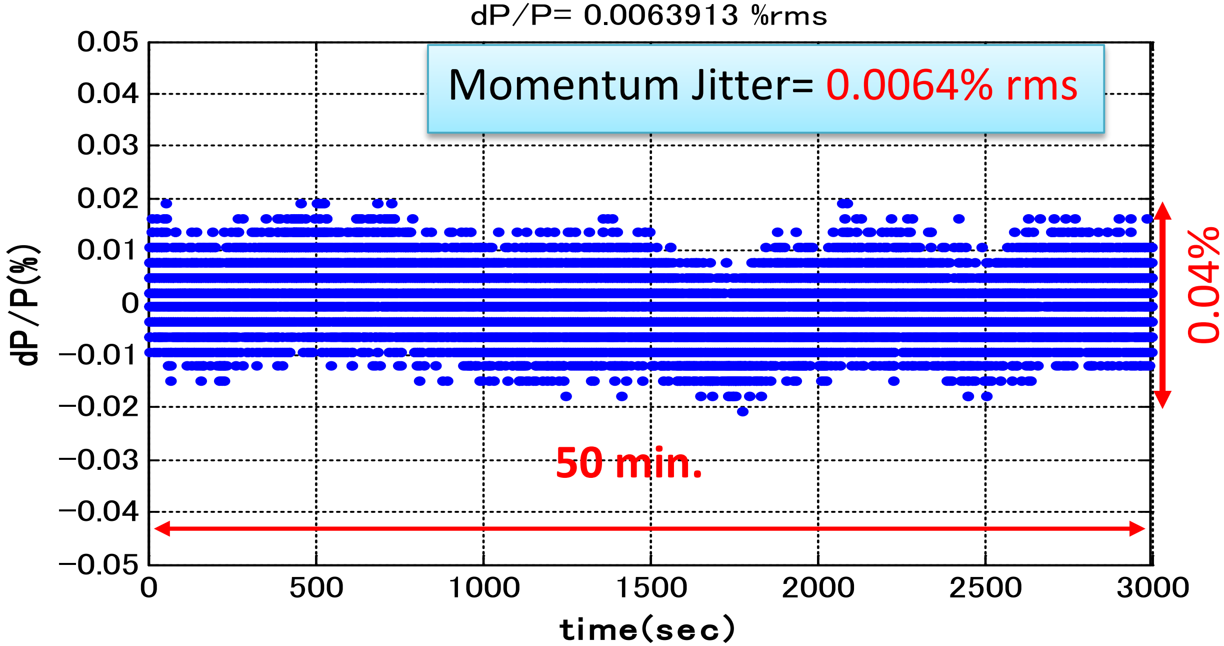

If error is included in vector-sum calibration, energy drift can occur.

In the region of Inj2 and Inj3 cavities, β < 1. Transit time is different in each cavity.

=> weight of vector-sum is different between Inj2 and Inj3.

# Stability of Beam Momentum (2)

Measurement after modification of tuner feedback gain for Inj2 and Inj3




Large momentum drift disappeared.

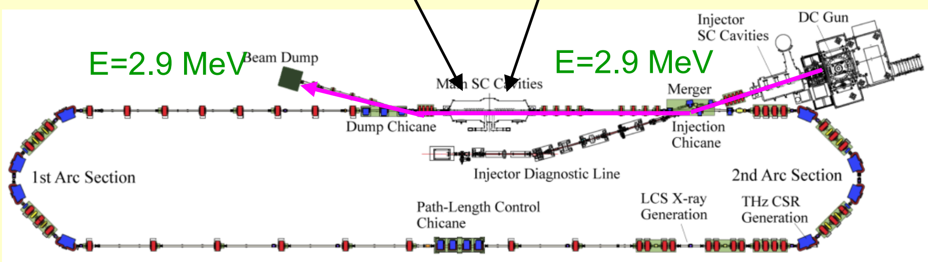
Good stability of beam momentum was achieved.
=> It was confirmed that the RF field for the beam is stable.

By H. Sakai

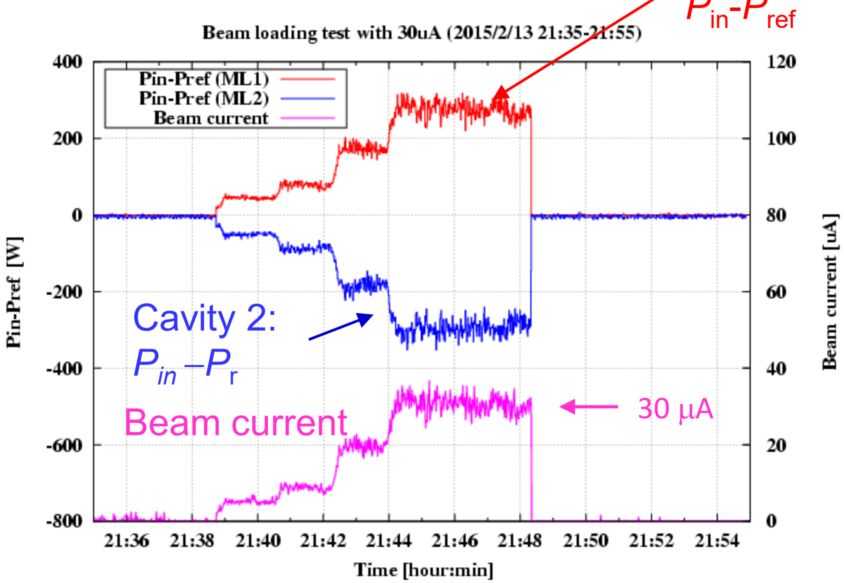
# Demonstration of Energy Recovery ($I_0$ = 30 μA)

## Non-ERL operation

Cavity 2: deceleration (Vc=8.57 MV/cavity)    Cavity 1: acceleration (Vc=8.57 MV/cavity)

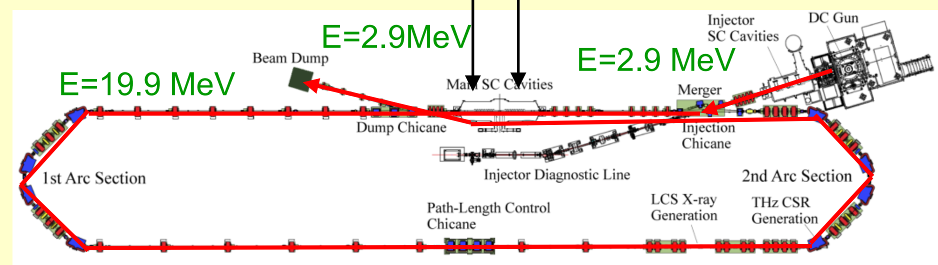



Beam loading (+ and -)



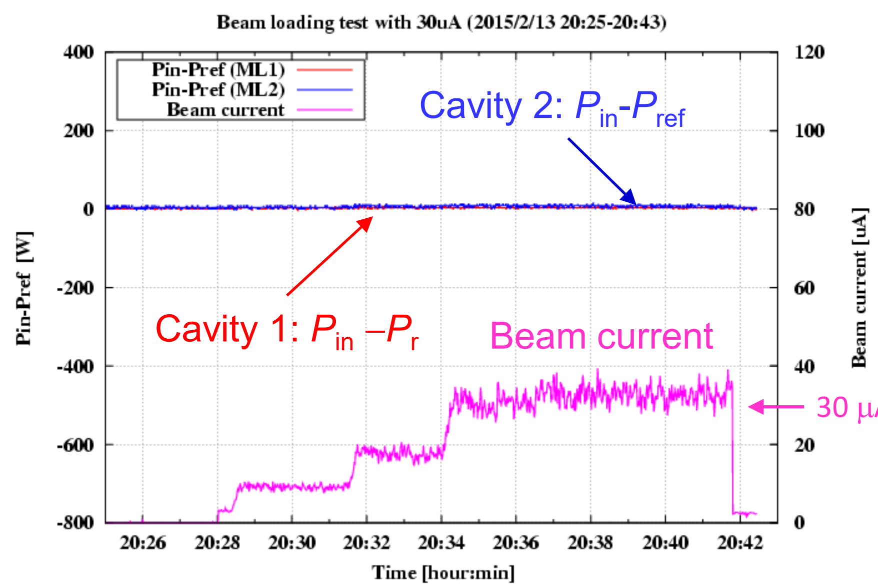

## ERL operation

Cavities 1 and 2: acceleration (1st pass) and deceleration (2st pass)




No beam loading

Energy recovery: 100-98.6% (within accuracy of the measurement)



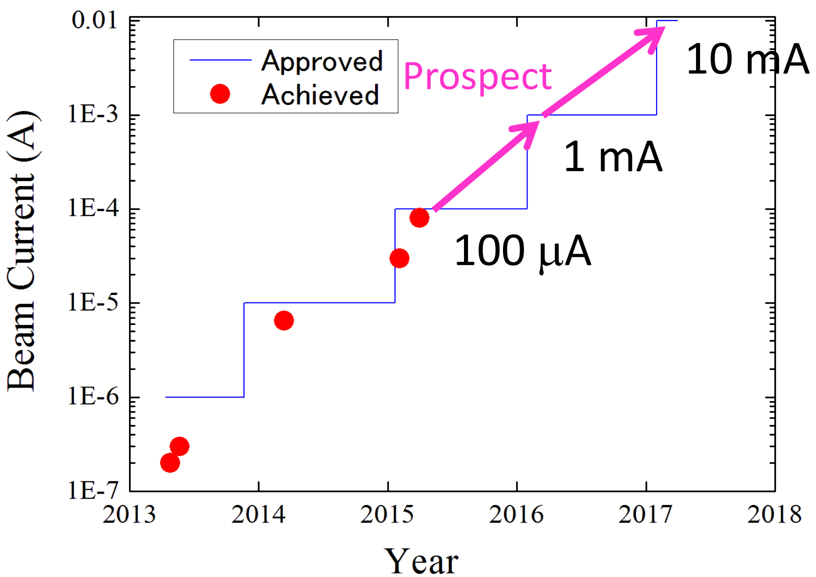

(Power lost in cavity) = ($P_{in}$ : input power to cavity) - ($P_{ref}$ : reflected power from cavity)

# Summary

- RF stabilities satisfied the requirement for cERL, and almost satisfied the requirement for 3GeV ERL.
- The beam momentum jitter of 0.006% rms was achieved.

## Future Plan

- Tuner feedback parameters have not been optimized enough.
  We will optimize the tuner control parameters.
- Beam current will increase and burst mode operation is planned.
  Beam loading compensation is necessary.
  [Feng Qiu (KEK), this afternoon]
- The evaluation of the long-term stability is necessary.



Thank you for your attention.