Resonance Control at the Compact ERL in KEK

Takako Miura (KEK)

on behalf of LLRF and SRF Cavity Group

LLRF Group

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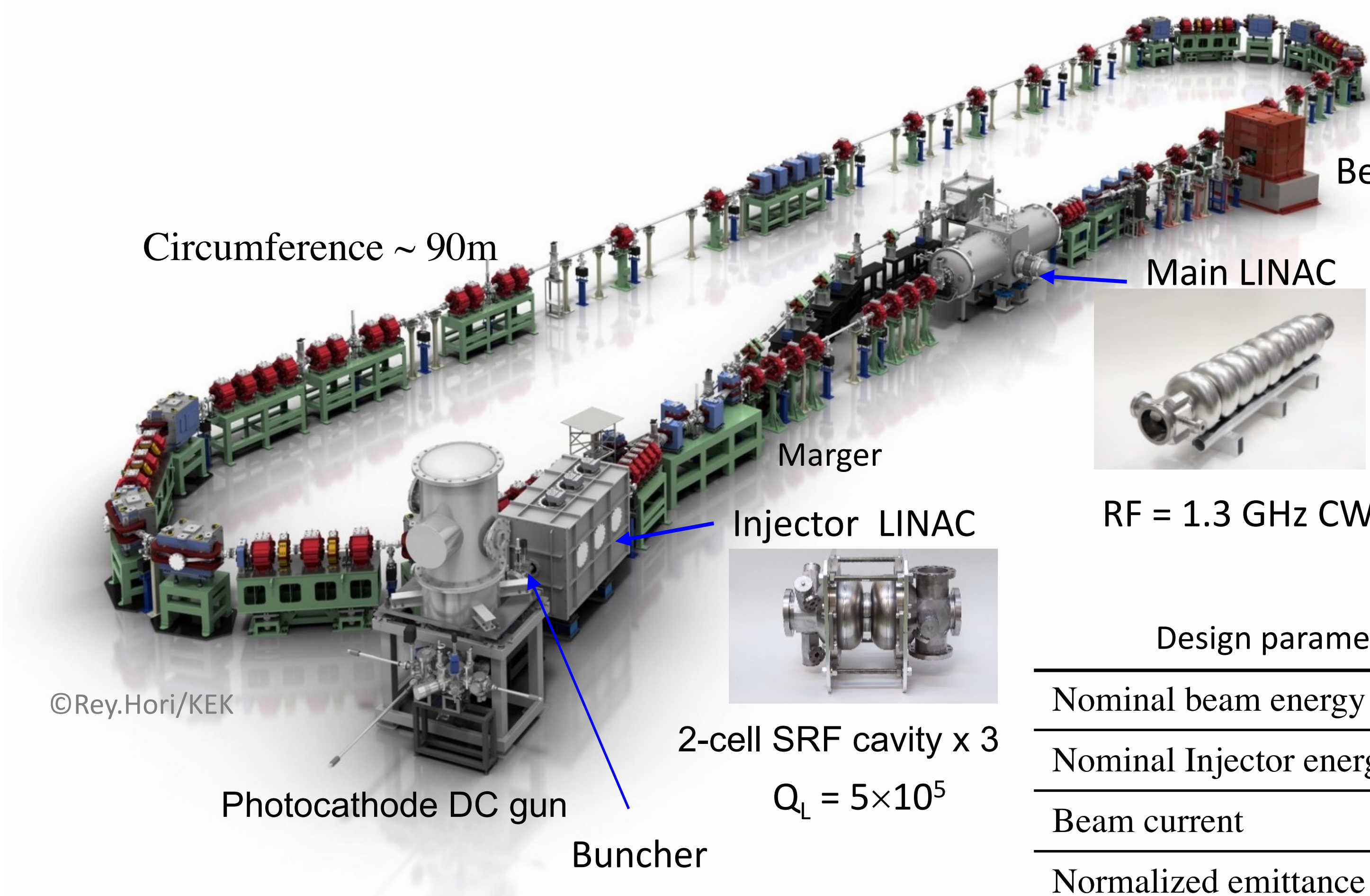
Introduction of cERL

Compact ERL (**cERL**) is a test facility of 3-GeV ERL as a future light source.



9-cell SRF cavity x 2

$Q_L = 1\times 10^7$

RF = 1.3 GHz CW

2-cell SRF cavity x 3

$Q_L = 5\times10^5$

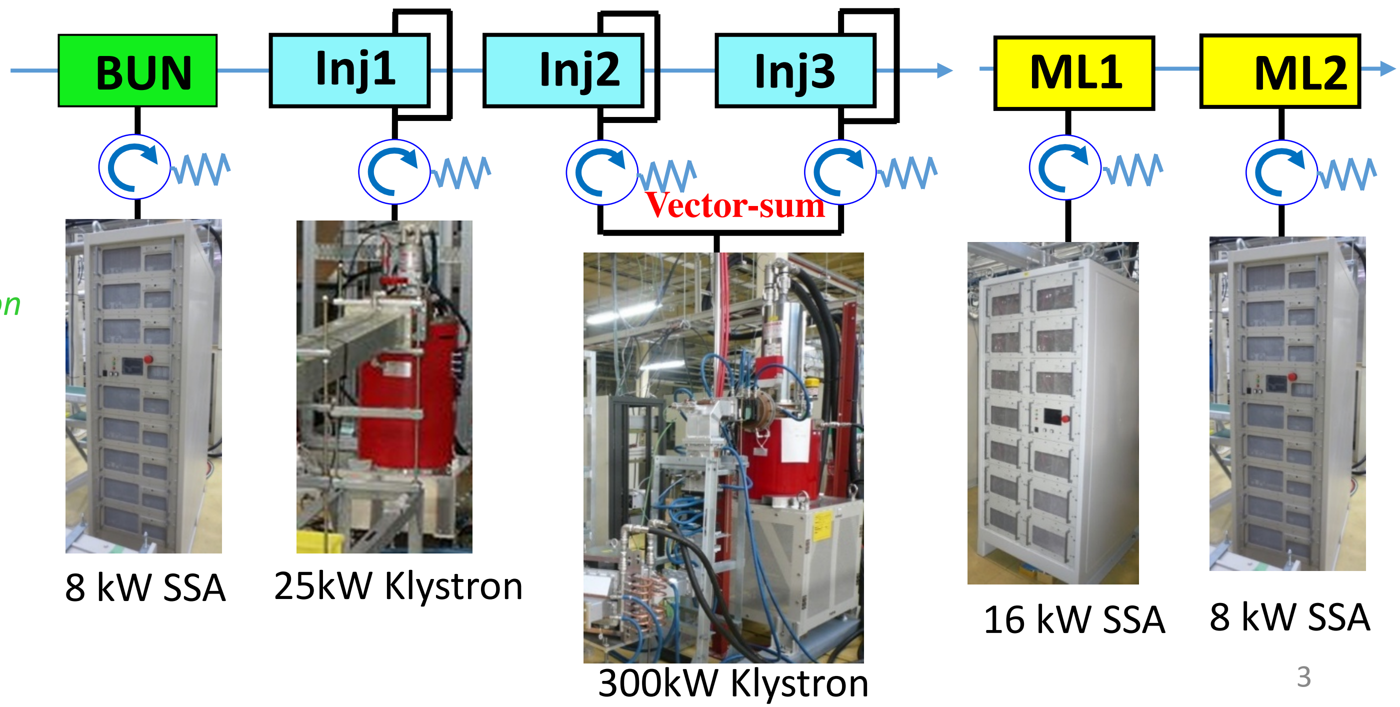
Requirements of RF stabilities for 3GeV-ERL
0.01%rms,0.01deg.rms

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) 100fs (short bunch)

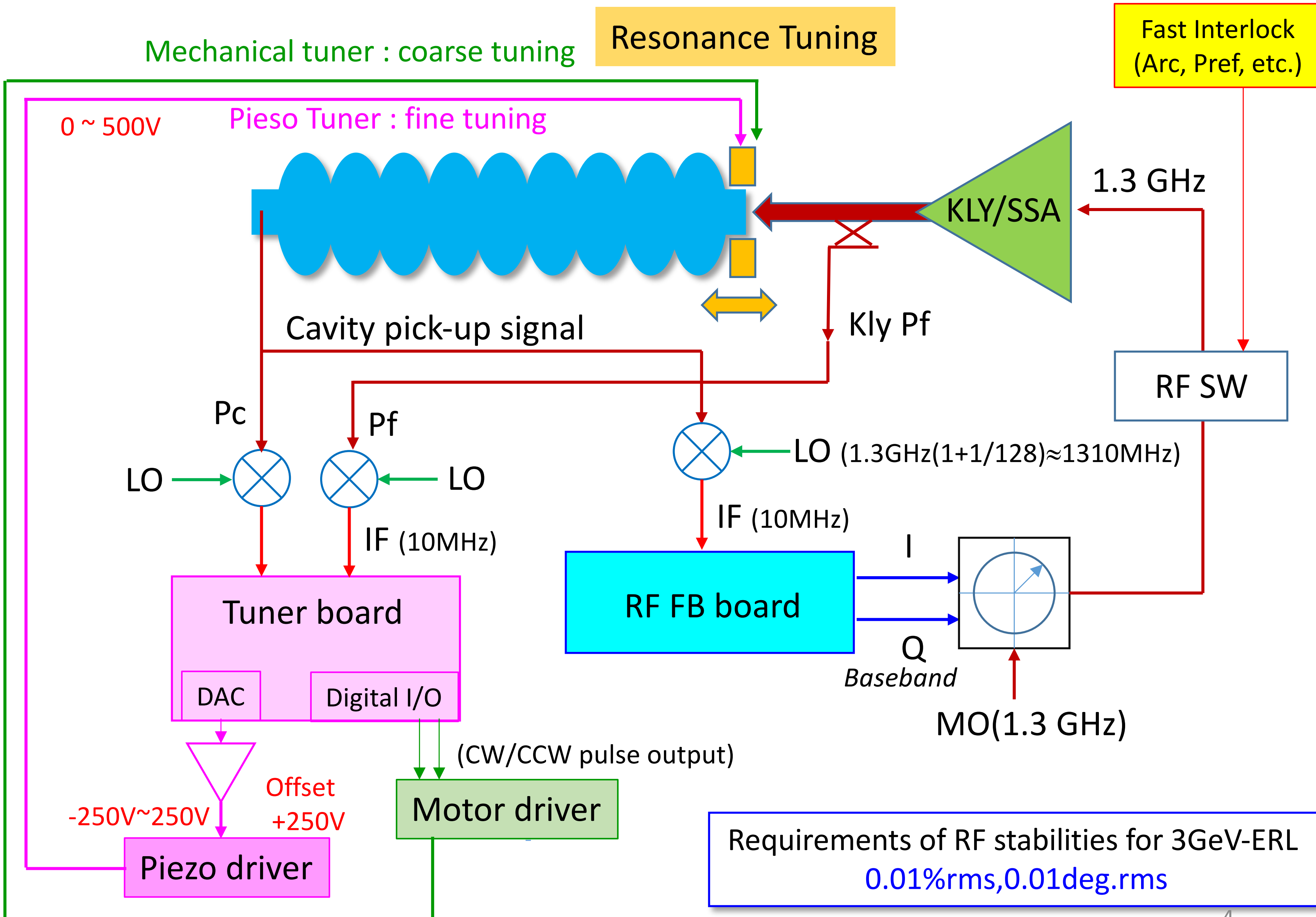
Current status of high power RF sources

	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	1.1×10^5	1.2×10^6	5.8×10^5	4.8×10^5	1.3×10^7	1.0×10^7
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



The "vector-sum" operation in low energy region, β<1, has some difficulties.
-> transit time change
-> RF phase change

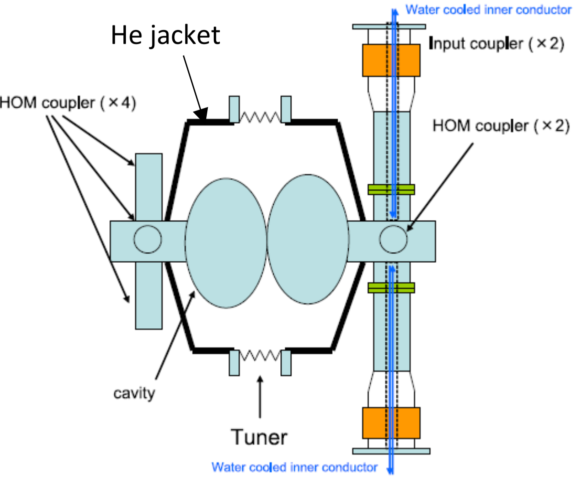
Digital LLRF System at cERL



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

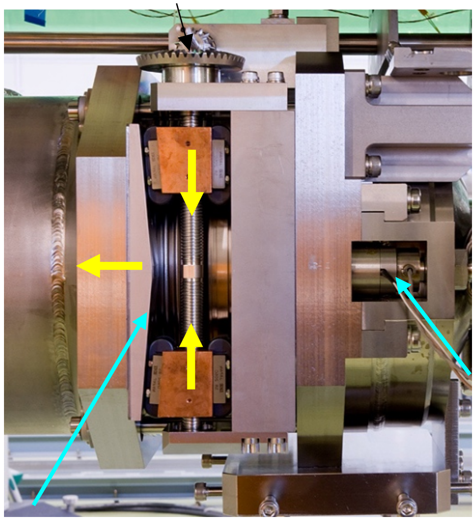
Tuner System

Tuner system of Injector Linac



Slide-Jack tuner

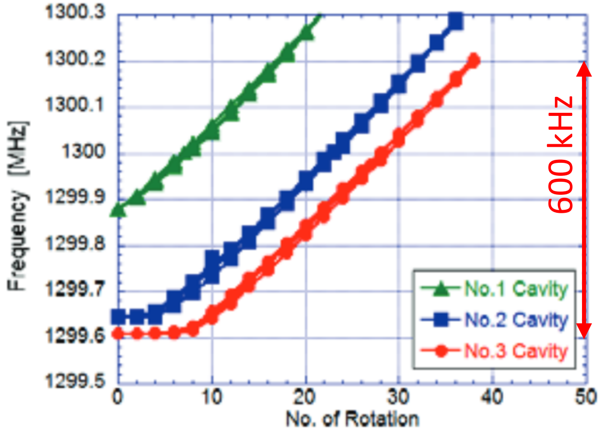
E. Kako, IPAC2013



Piezo tuner
0-500V
stroke= 4 μm@2K

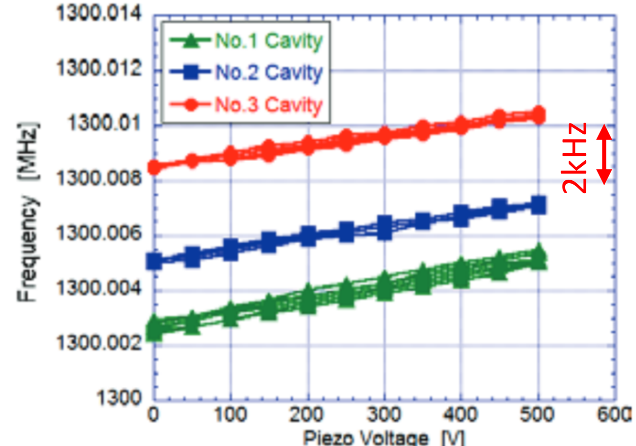
The same as KEK-STF tuner system

20 kHz/rotation

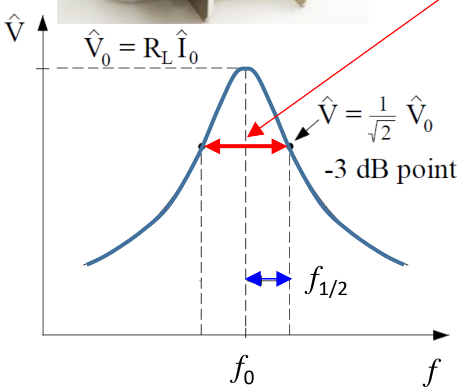


performance of slide-jack tuner

Piezo: 0-500V => 2 kHz



performance of piezo tuner



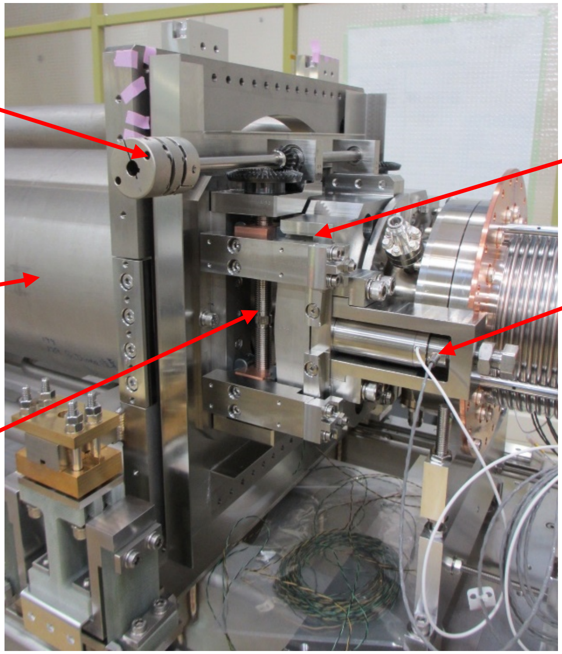
$2\Delta f_{1/2} = f_0 / Q_L$

Inj1: $Q_L = 1.2 \times 10^6$, $2\Delta f_{1/2} = 1.1$ kHz
Inj2: $Q_L = 5.8 \times 10^5$, $2\Delta f_{1/2} = 2.2$ kHz
Inj3: $Q_L = 4.8 \times 10^5$, $2\Delta f_{1/2} = 2.7$ kHz

Piezo tuner can cover the band width.

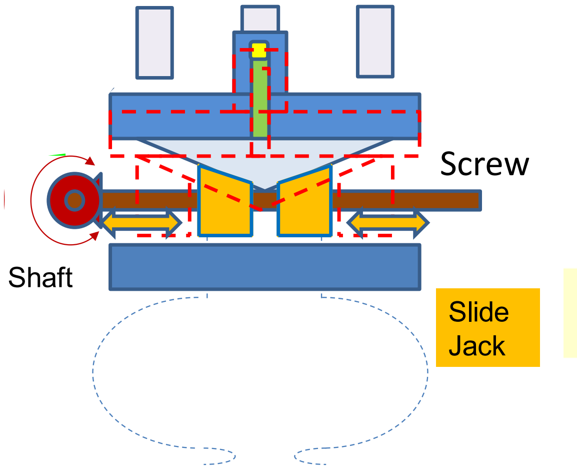
Tuner system of Main Linac

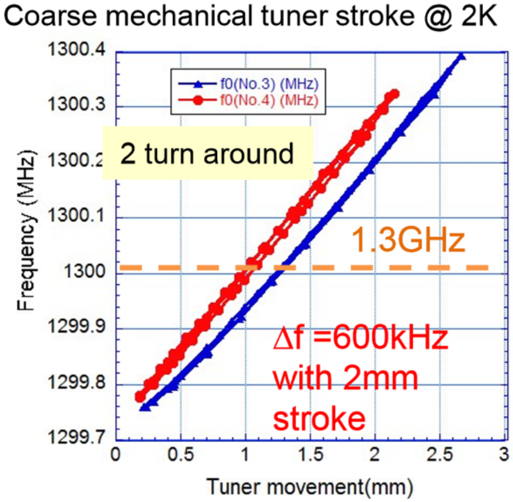
H. Sakai, SRF2013 @Paris

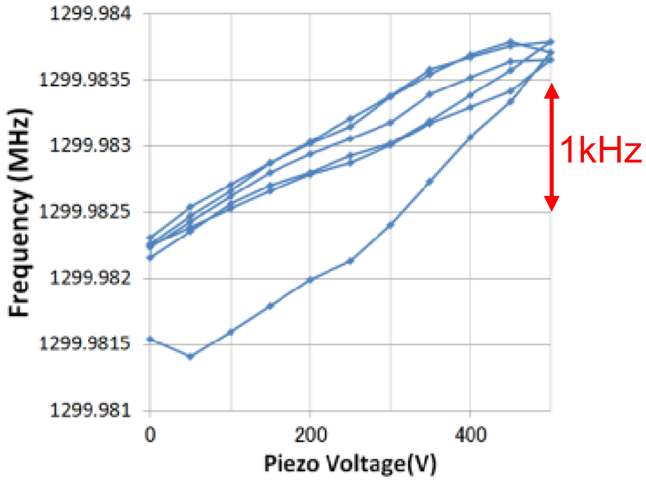


Piezo tuner
0V - 500V (offset=250V)
Stroke= 4 μm @ 2K
40 μm @ 300K
(1 μm: 300Hz)

$Q_L = 1\times10^7$
$2\Delta f_{1/2} = f_0 / Q_L = 130$ Hz







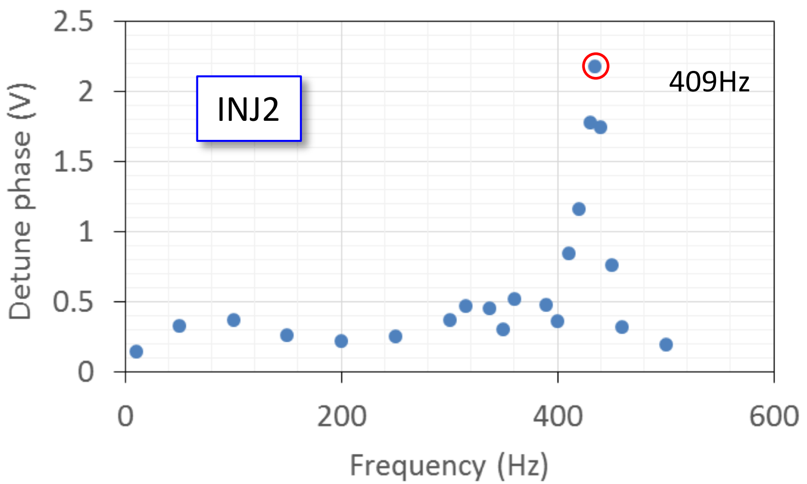
Mechanical Resonance of Inj Cav

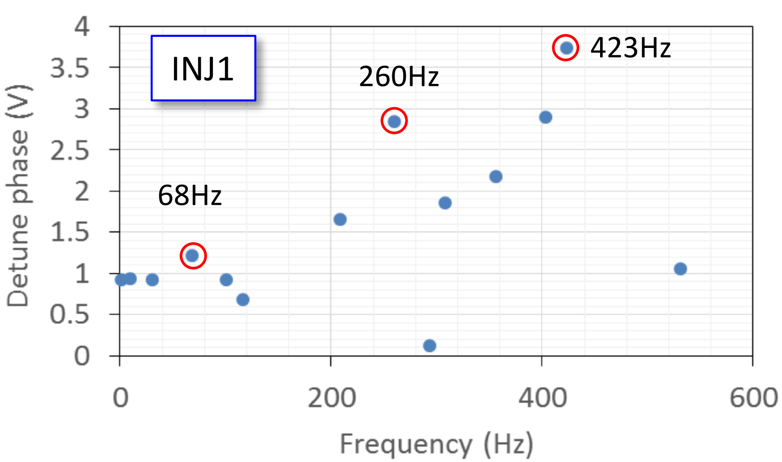
<Injector>

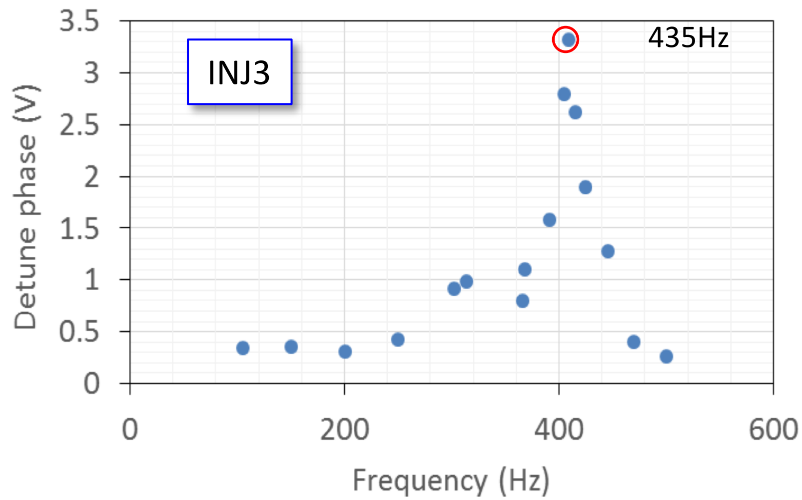
Eacc: 1MV/m

Sinusoidal wave ($40V_{pp}$) was fed to piezo tuner.
Mechanical resonance is scanned by sweeping the input frequency.

Phase detector : 20 mV/deg



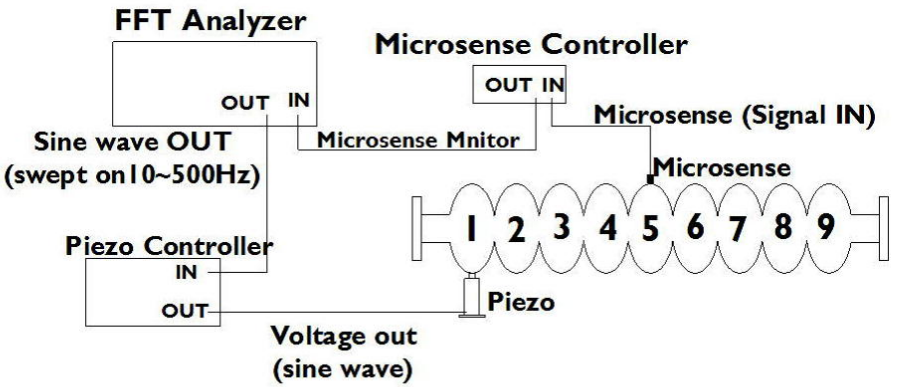


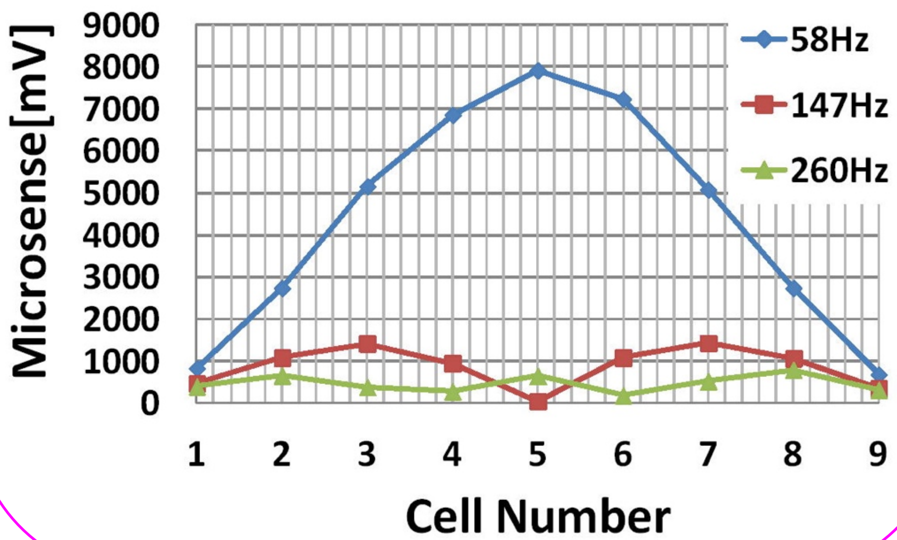


Large mechanical resonance exists around 400 Hz.

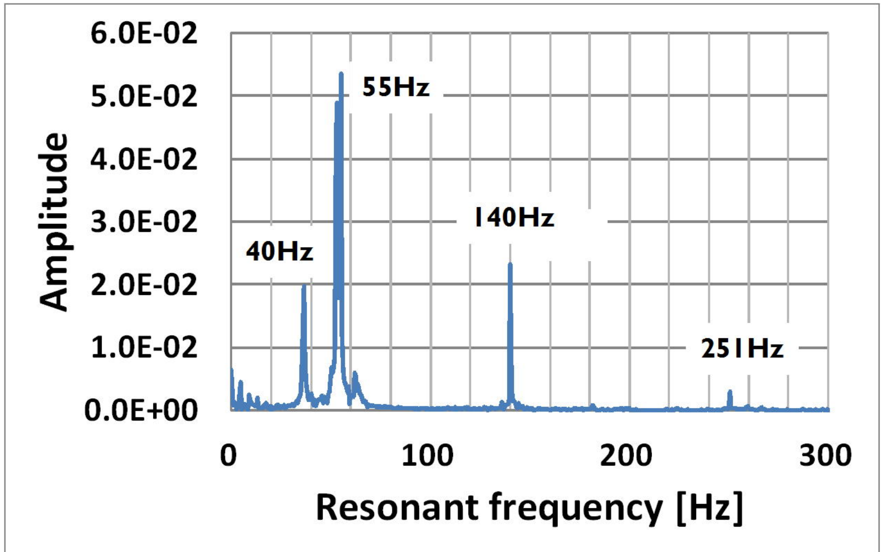
Mechanical Resonance of ML Cav

M. Satoh, IPAC2014





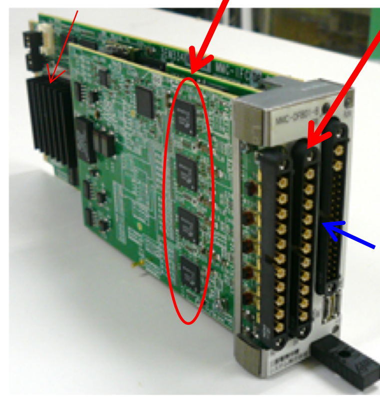
Impulse hammer response



Large mechanical resonance exist near 50 Hz.

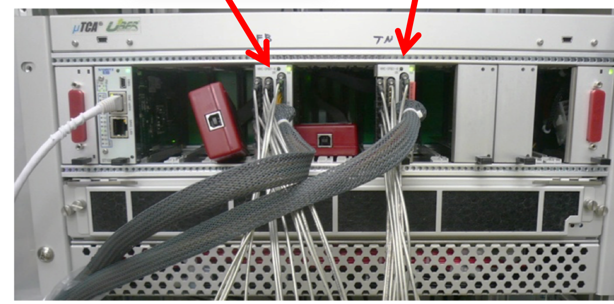
LLRF System

Digital LLRF Boards



AMC(Advanced Mezzanine Card)

(Mitsubishi Electric TOKKI Systems Co.,Ltd.)



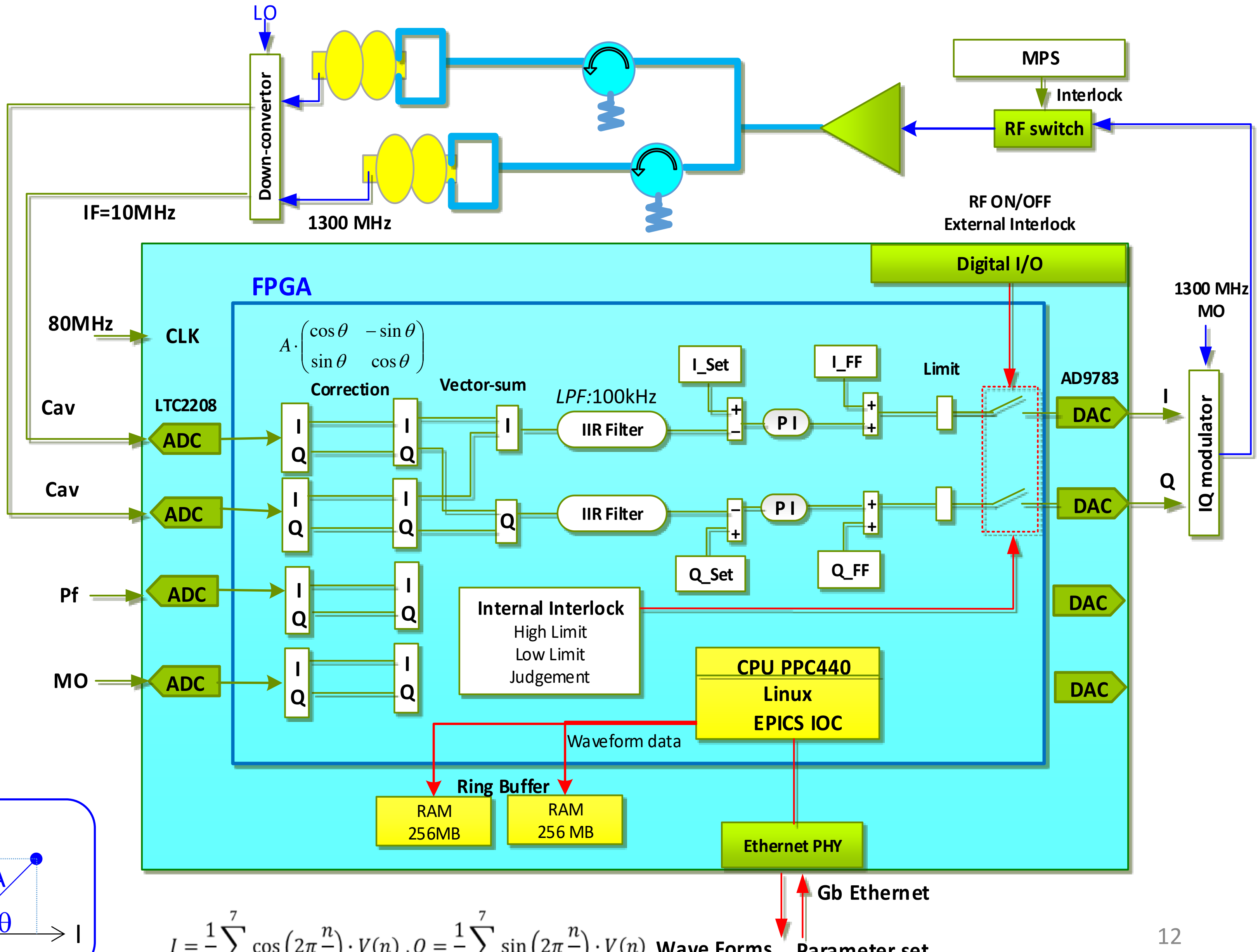
MicroTCA

Total 11 boards are used for operation.

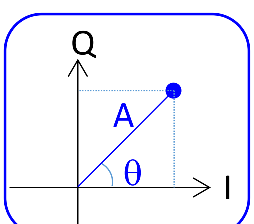
	BUN	Inj1	Inj2	Inj 3	ML1	ML2
RF FB board	FB0	FB1	FB2 (Vec-sum)		FB4	FB5
Tuner board	TN0	TN1	TN2	TN3	TN4	TN5

- 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.

Field Feedback Control

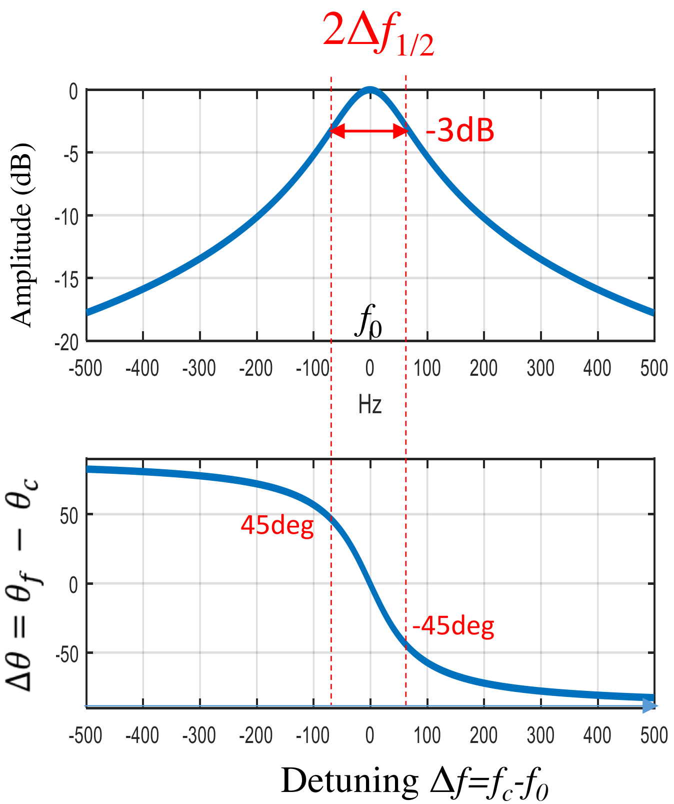


$$A \cdot \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$



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

Cavity Resonance



$\Delta f_{1/2}$ =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

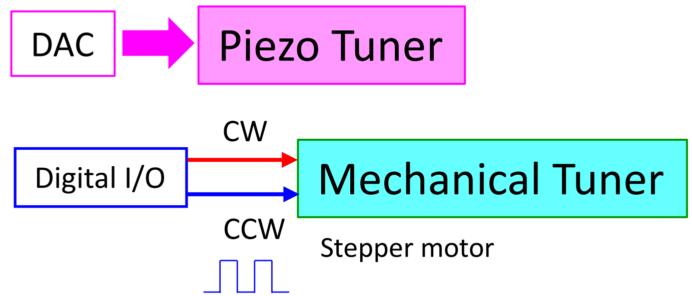
$$tan\Delta\theta \approx 2Q_L \frac{\Delta f}{f}$$

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

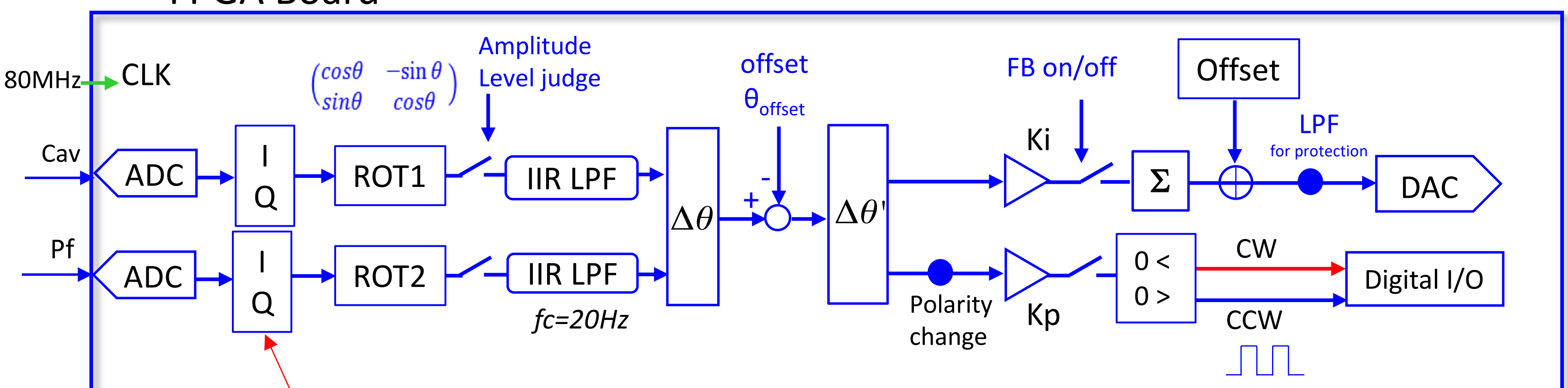
For constant acceleration field,
double input power is necessary at $\Delta f = \Delta f_{1/2}$

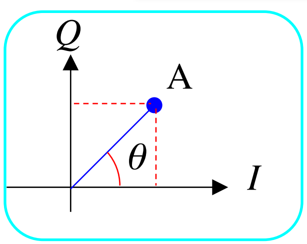
Block Diagram of Resonance Control

Feedback Control: $\Delta\theta = \theta_f(\mathrm{Pf}) - \theta_c(\mathrm{cav}) \Rightarrow 0$



FPGA Board





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

Cavity field Stability & Microphonics

Waveform of ML Cavities

T. Miura, IPAC2014 @Dresden

ML1

ΔA = 0.012% rms
$\Delta\theta$ = 0.014° rms

ΔA = 0.035% rms
$\Delta\theta$ = 0.3° rms

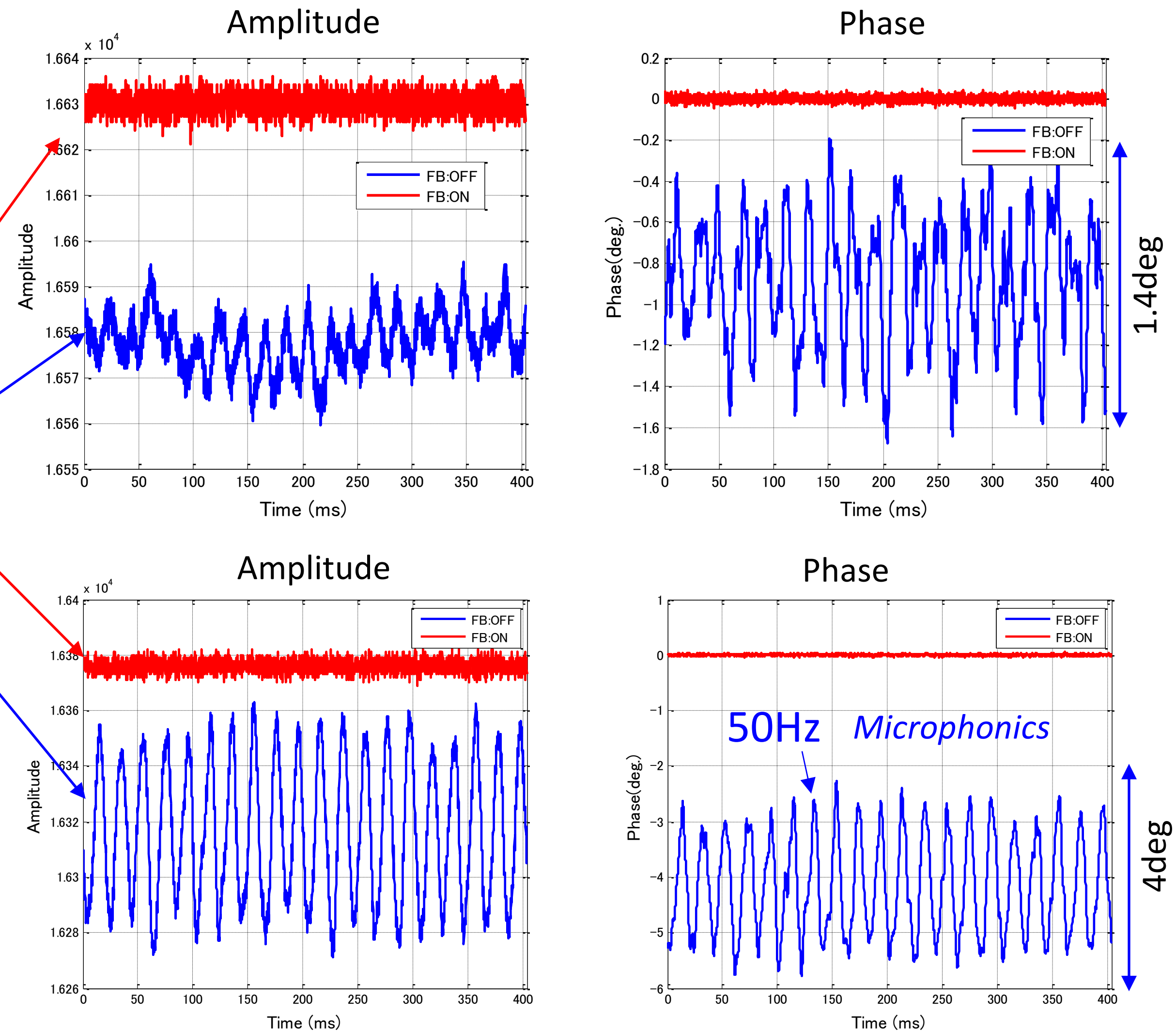
Vc: w RF Feedback

Vc: w/o RF Feedback

ML2

ΔA = 0.013% rms
$\Delta\theta$ = 0.015° rms

ΔA = 0.15% rms
$\Delta\theta$ = 0.6° rms



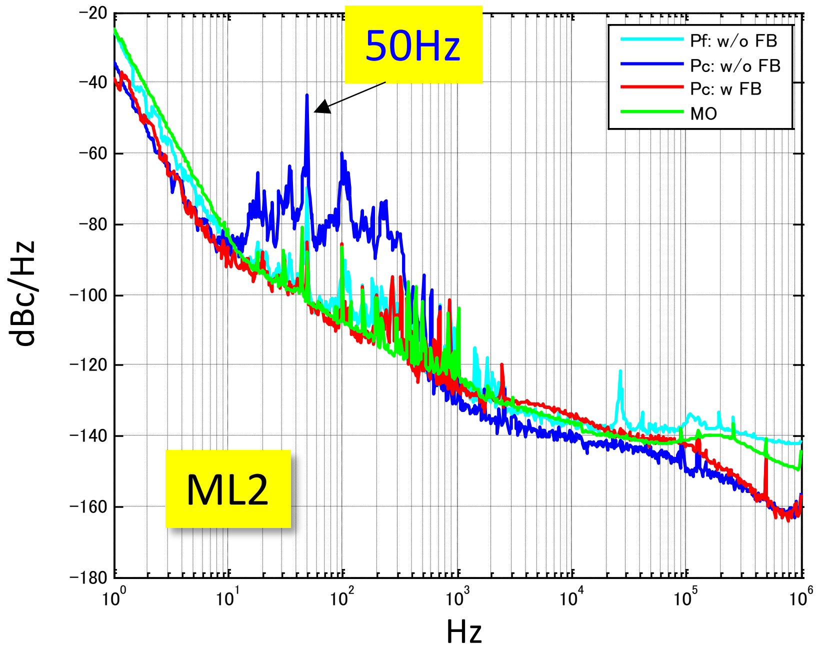
Field fluctuation by Michrophonics is stabilized by RF Feedback

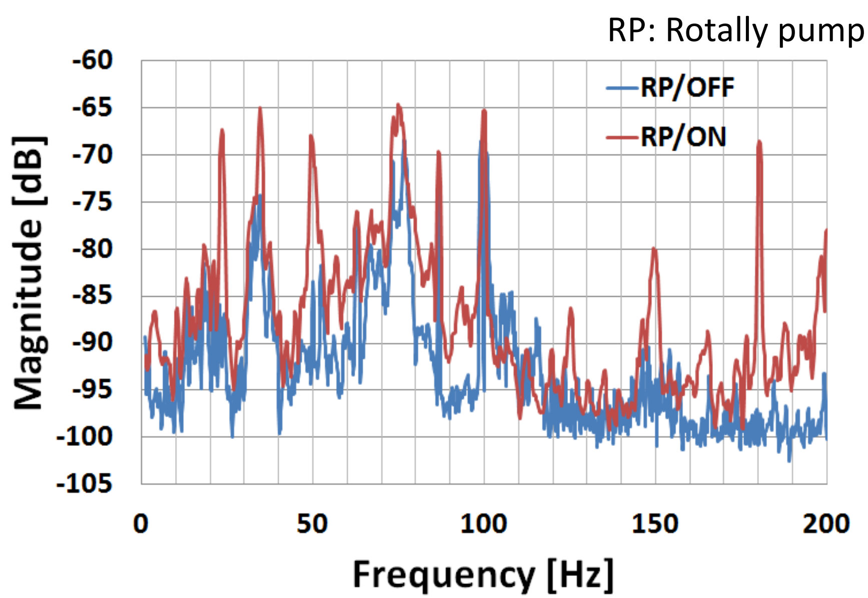
Phase noise jitter measurement using Signal Source Analyzer

Agilent E5052B

T. Miura, IPAC2014 @Dresden

M.Egi, PASJ2016 (MOP025)





Vc Phase Noise with RF FB (10Hz-1MHz)=0.017deg

Vc Phase Noise w/o RF FB (10Hz- 1MHz)=0.73 deg

Microphonics is observed at 10 Hz - 400Hz.

Phase noise by Microphonics was suppressed well by RF FB.
Phase noise of Vc with FB was almost the same as that of Master Oscillator.

Countermeasure against Scroll Pump Vibration

9-cell SC cavity: $Q_L=10^7$

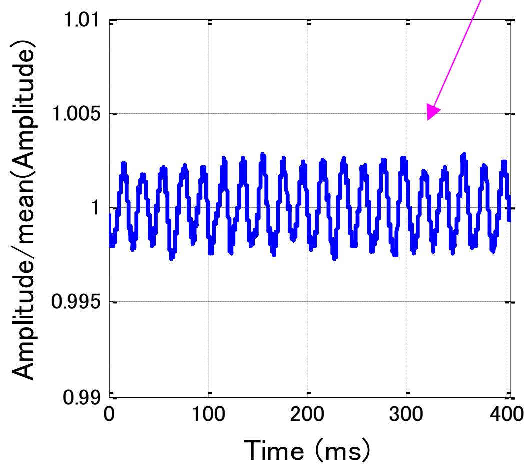
Field gradient
8.3 MV/m : Operation point
(15 MV/m : Design)

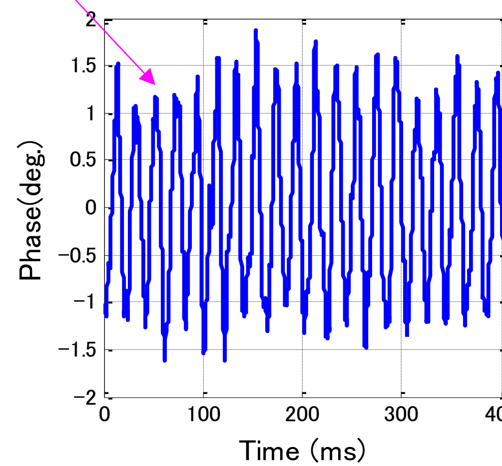
The rubber sheet was inserted under the scroll pump.
The 50 Hz vibration is suppressed.

For constant input RF power

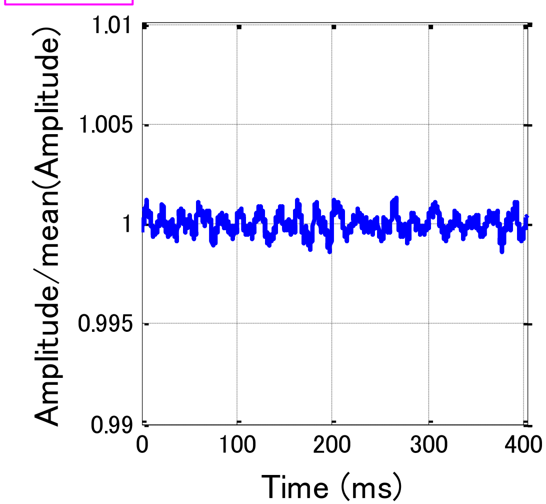
Before

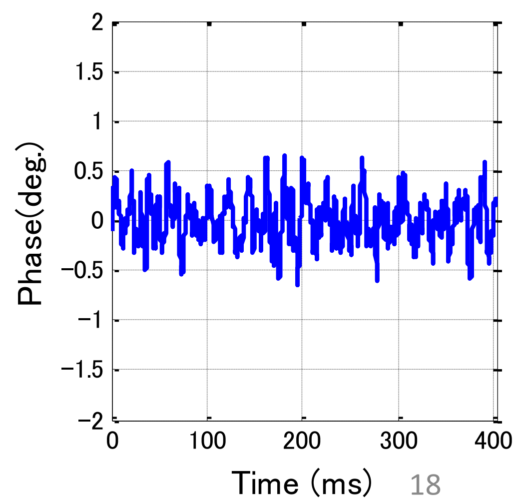
50 Hz vibration by scroll pumps





After





Momentum Error due to Vector-sum Error
&
Improvement by tuner feedback parameter

RF Performance

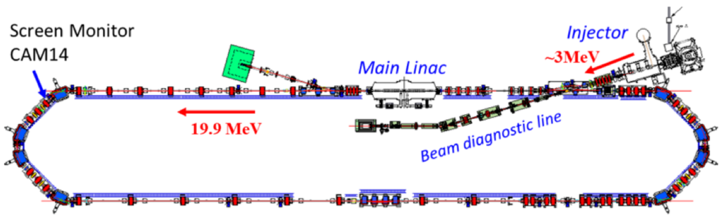
RF Stabilities for Short Time

	Inj1	Inj2 & Inj3	ML1	ML2
Amplitude	0.006% rms	0.012% rms	0.003% rms	0.003% rms
Phase	0.009° rms	0.022° rms	0.010° rms	0.009° rms

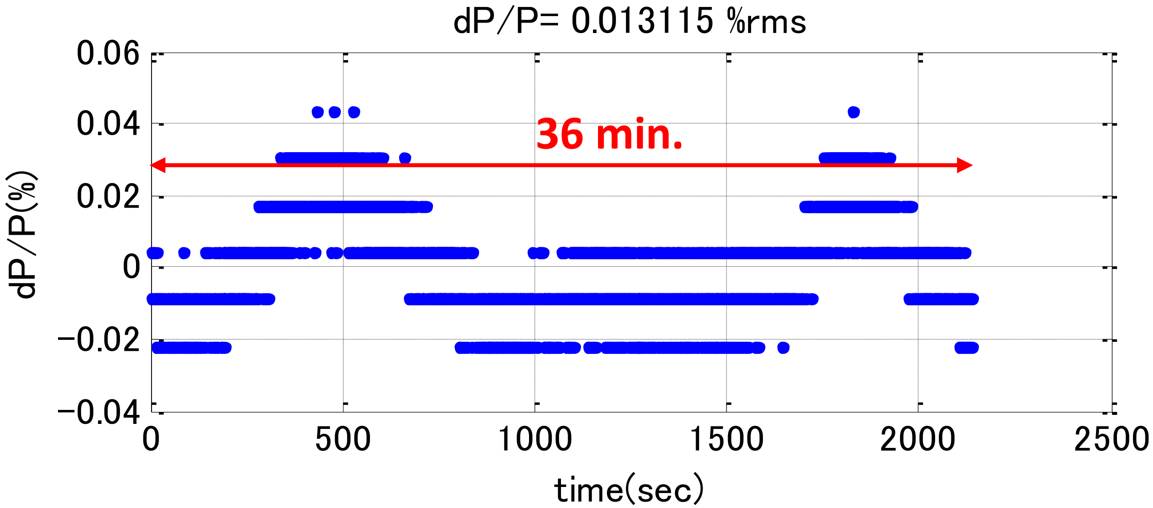
Almost satisfied the requirement of 3-GeV ERL

Measurement of Beam Momentum Stability

for confirmation of RF stability



<Measurement condition>
Beam: 5Hz, 3ps rms, 23 fC, total
Energy=19.9 MeV

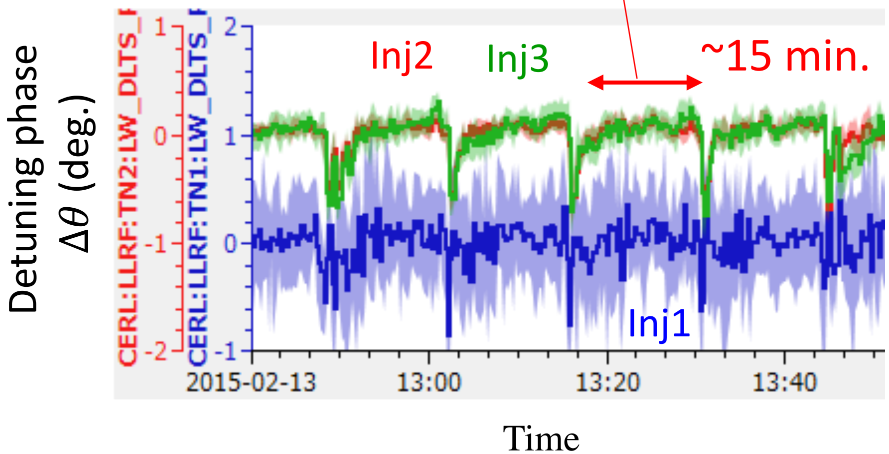


Momentum stability = 0.013% rms

Momentum drift of ~15 minutes period was observed.

What causes Energy Drift ?

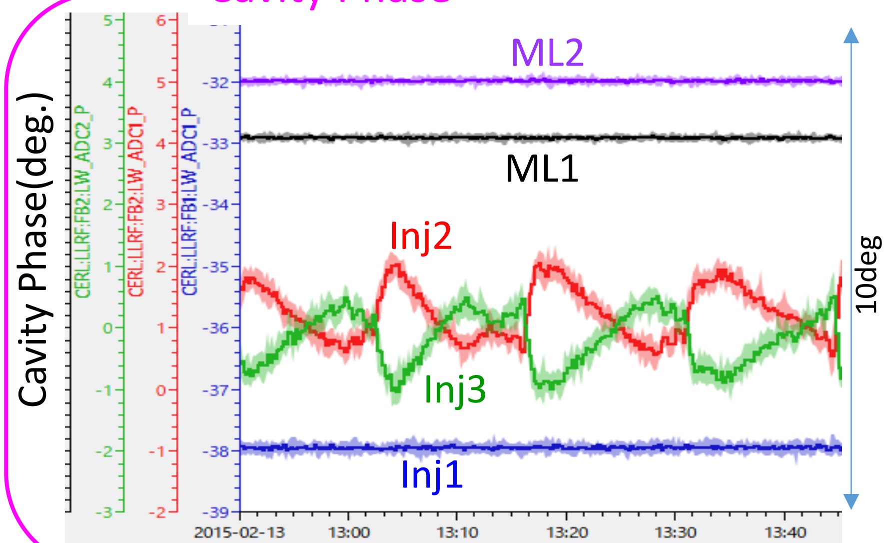
Time interval of detuning is similar to the interval of energy drift.



Large ripple depends on valve control for liquid N_2.

Input-couplers of injector are cooled by liquid N_2.

Cavity Phase



<RF source : cavity =1:1 >

Cavity phase is stabilized by RF FB.

<Vector-sum operation>

Vector-sum is constant,
but each cavity phase fluctuates.

Vector-sum error may cause energy drift.

Vector-sum Error

Possibility of momentum drift caused by vector-sum error

(1) Vector-sum calibration error
Amplitude & Phase calibration error

(2) for low beam energy (β < 1),
transit time is affected by cavity field.

Injection energy : 1.63MeV@Inj2, 2.36 MeV@Inj3

Cavity fields changes => Beam phase changes.

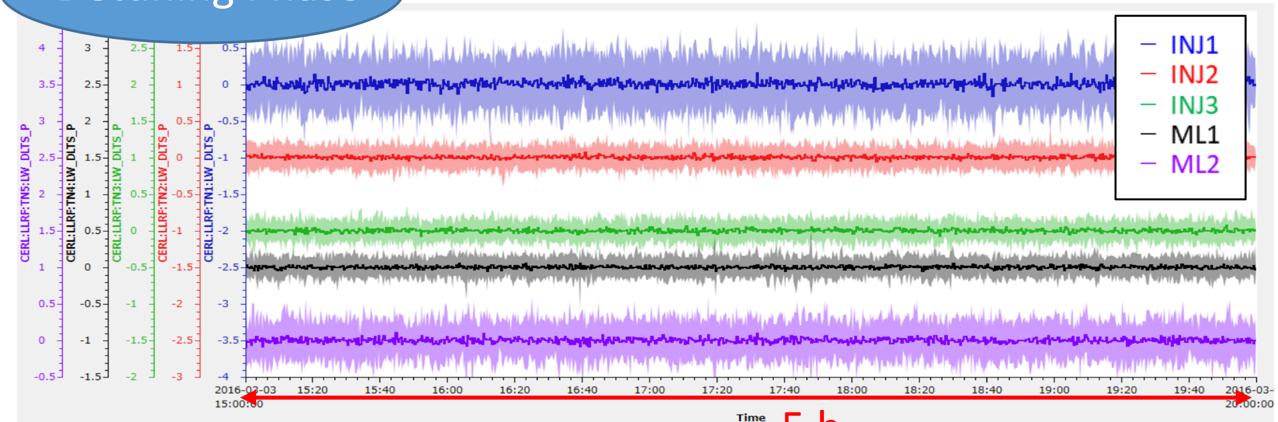
In order to minimize the momentum fluctuation due to the vector-sum error,
"detuning" should be stabilized.

Result of Resonance FB Control Improvement

Higher FB gain in resonance control is adopted for small detuning.

Detuning Phase

Detuning phase $\Delta\theta$ (deg)

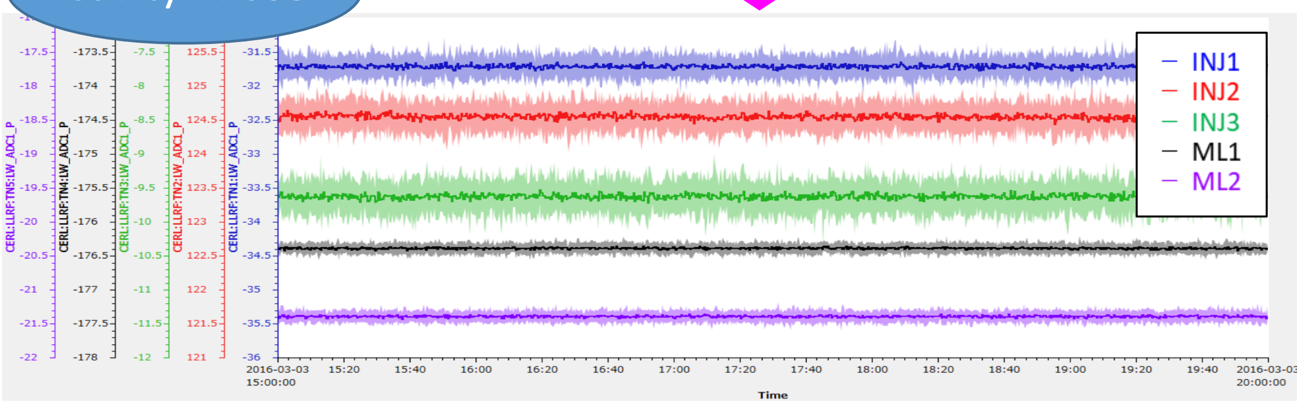


Cav	$\Delta\theta$ deg (rms)	Δf Hz (rms)
INJ1	0.23	2.2
INJ2	0.10	2.0
INJ3	0.09	2.1
ML1	0.09	0.08
ML2	0.16	0.18

Detuning due to liquid N_2 flow has been compensated.

Cavity Phase

Cavity phase θc (deg)

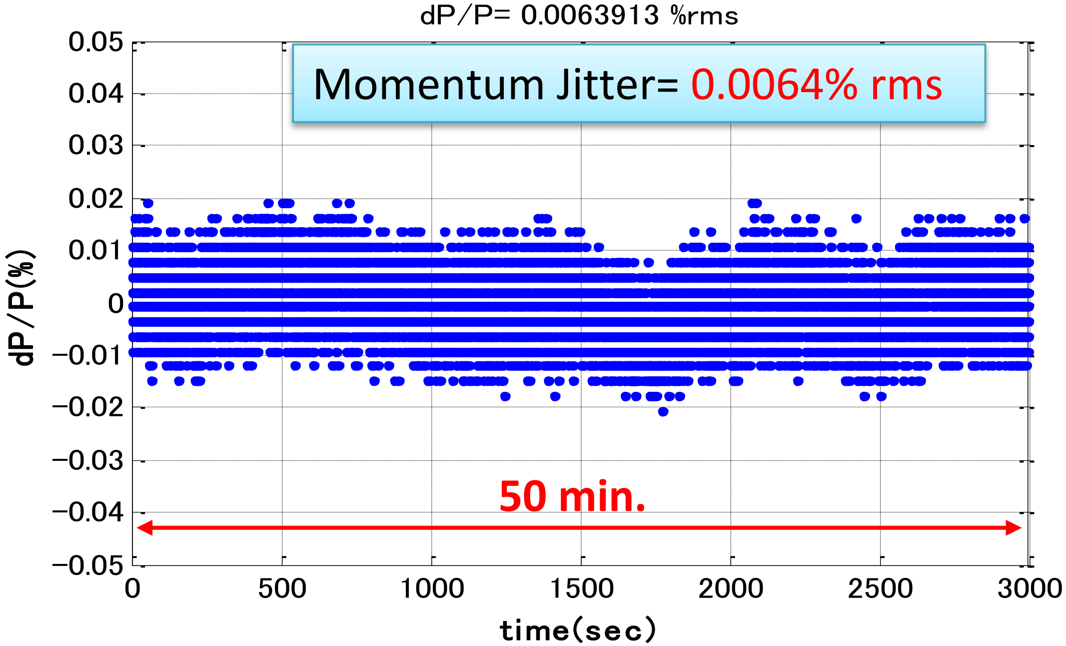


Inj2&Inj3 cavity phase become stable.

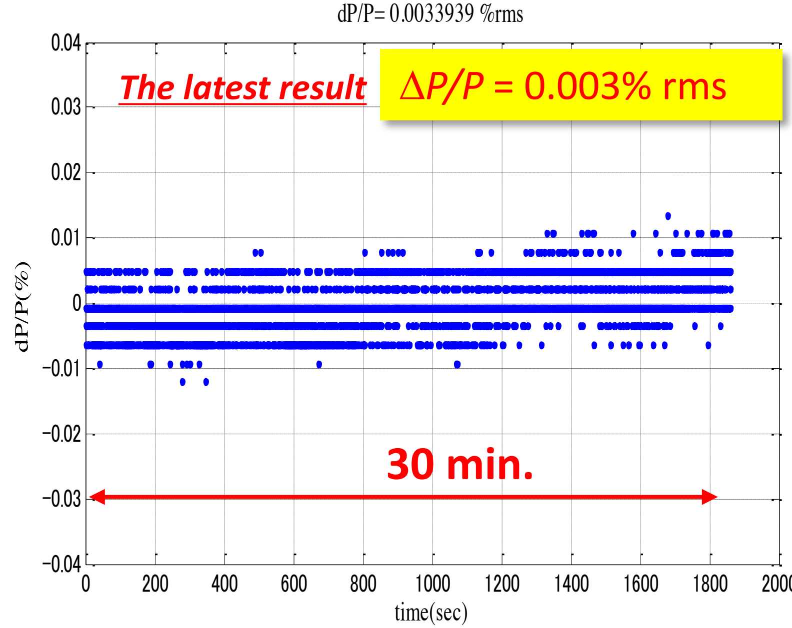
Stability of Beam Momentum (2)

Measurement after modification of tuner feedback gain

for Inj2 & Inj3 only



FB gain is optimized



Large momentum drift disappeared.

=> Beam momentum jitter ΔP/P =0.003% is achieved.

Summary

- Digital control boards are applied to RF feedback and tuner control.

- Owing to the stiff cavity structure, so detuning by Michrophonics does not influence to the operation.

- The field fluctuation due to Michrophonics is well suppressed by RF feedback.

- Vector-sum operation has some difficulty for low beam energy due to different transit time.

- By applying high FB gain for piezo tuning, the detuning fluctuation due to liquid N_2 flow rate has been suppressed.
  => Beam energy drift caused by vector-sum error has become small.

0.003% momentum stability is achieved.