Injector RF and LLRF

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for the Linac RF Group

The 23rd KEKB Accelerator Review Committee, July 8-10, 2019

List of Installation and Replacement

New Installations for SuperKEKB

- Injector Master Oscillator Phase Shifter (HER/LER Injection Phase Control)
- S-band Phase Shifter for DR Downstream (for Bucket Selection)
- Phase Drift Compensation System between Linac MO and Ring MO
- LLRF Control Unit (Amplitude/Phase Control, EVR, VSWR Meter)
- RF monitor (AMP/Phase Detection, EVR) & Applications
- Beam Induced RF Monitor
- Klystron KL_DN/KL_DS Units
- High Precision Pulse Modulator (installed in KL_A1A)

Replacement

- SHB1 (114MHz) / SHB2 (571MHz) Solid State Amplifier(SSA) replacement to new one
- RF Reference Signal Transfer Line : Coaxial Cable -> Phase Stabilized Optical Fiber *to each sector*
- Seven pulse modulators were replaced to small inverter-type for making space

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Linac Reference RF Distribution System

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RF Monitor System

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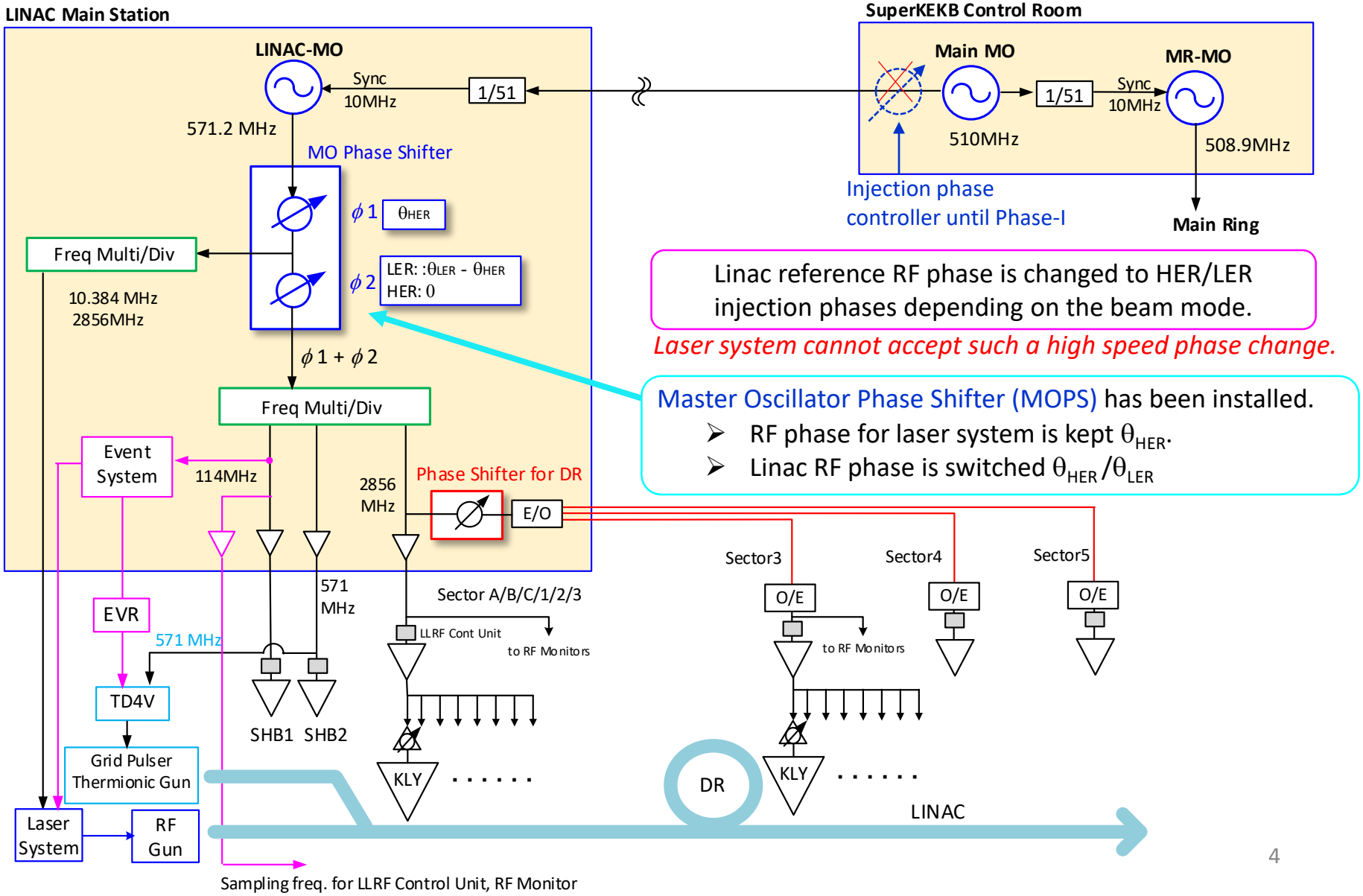
Linac Reference RF Distribution System



Linac reference RF phase is changed to HER/LER injection phases depending on the beam mode.

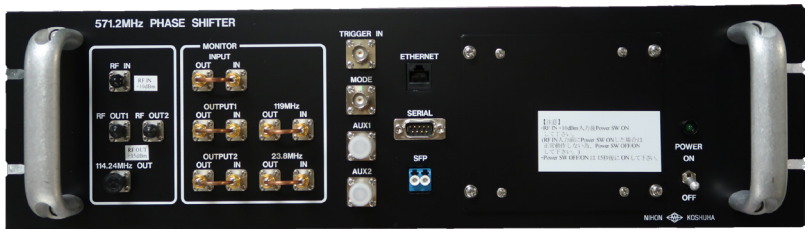
Laser system cannot accept such a high speed phase change.

Master Oscillator Phase Shifter (MOPS) has been installed.

- RF phase for laser system is kept θ_{HER}.
- Linac RF phase is switched $\theta_{HER}/\theta_{LER}$

MO Phase Shifter (MOPS)

571.2 MHz



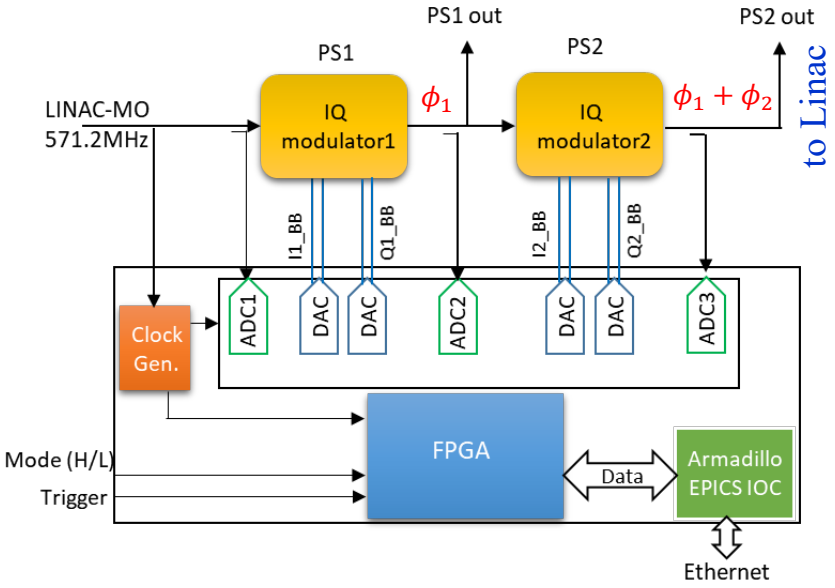
Specification of Phase Shifter	
Phase Range	-450.00 deg ~ + 450.00 deg
Resolution	0.01 deg
Speed	1 deg/ms ~ 1000 deg/ms
Linearity	< 0.1 deg
Mode	High: LER / Low: HER

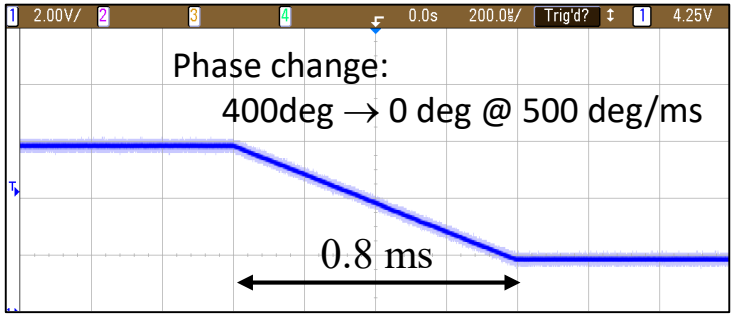
$\phi_1 = \theta_{HER}$

to Laser

$\phi_2 = 0$ (HER, PF, PFAR)

$\phi_2 = \theta_{LER} - \theta_{HER}$ (LER)



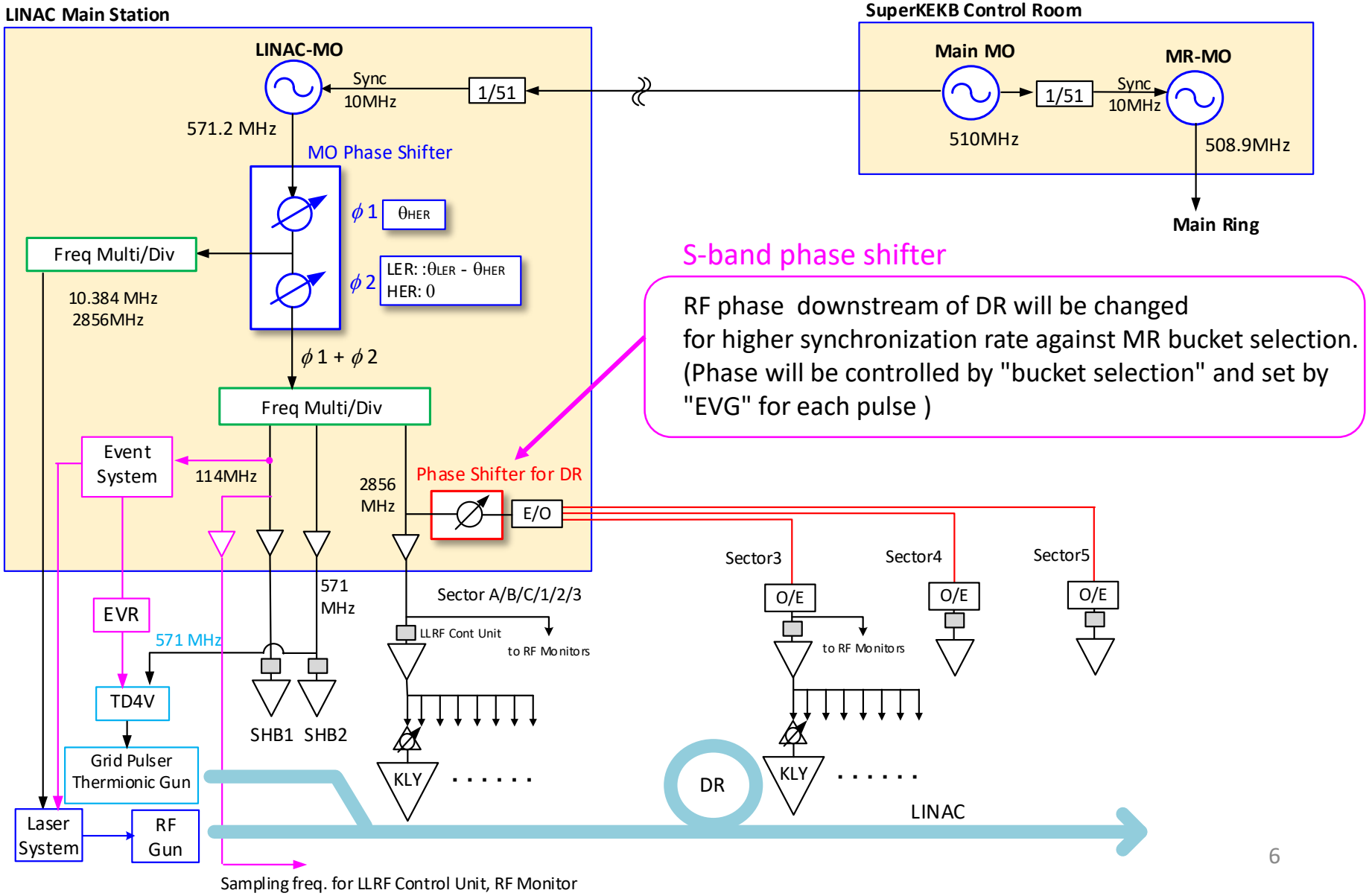


In the operation of SuperKEKB, phase change speed :

PS1 = 1 deg/ms

PS2 = 100 deg/ms

Linac Reference RF Distribution System

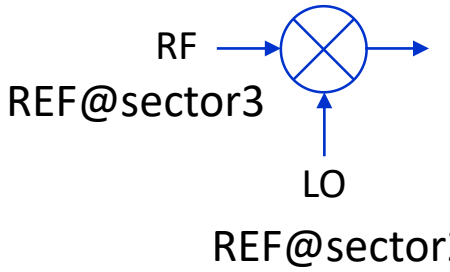


S-band phase shifter

RF phase downstream of DR will be changed for higher synchronization rate against MR bucket selection. (Phase will be controlled by "bucket selection" and set by "EVG" for each pulse)

Test of S-band Phase Shifter

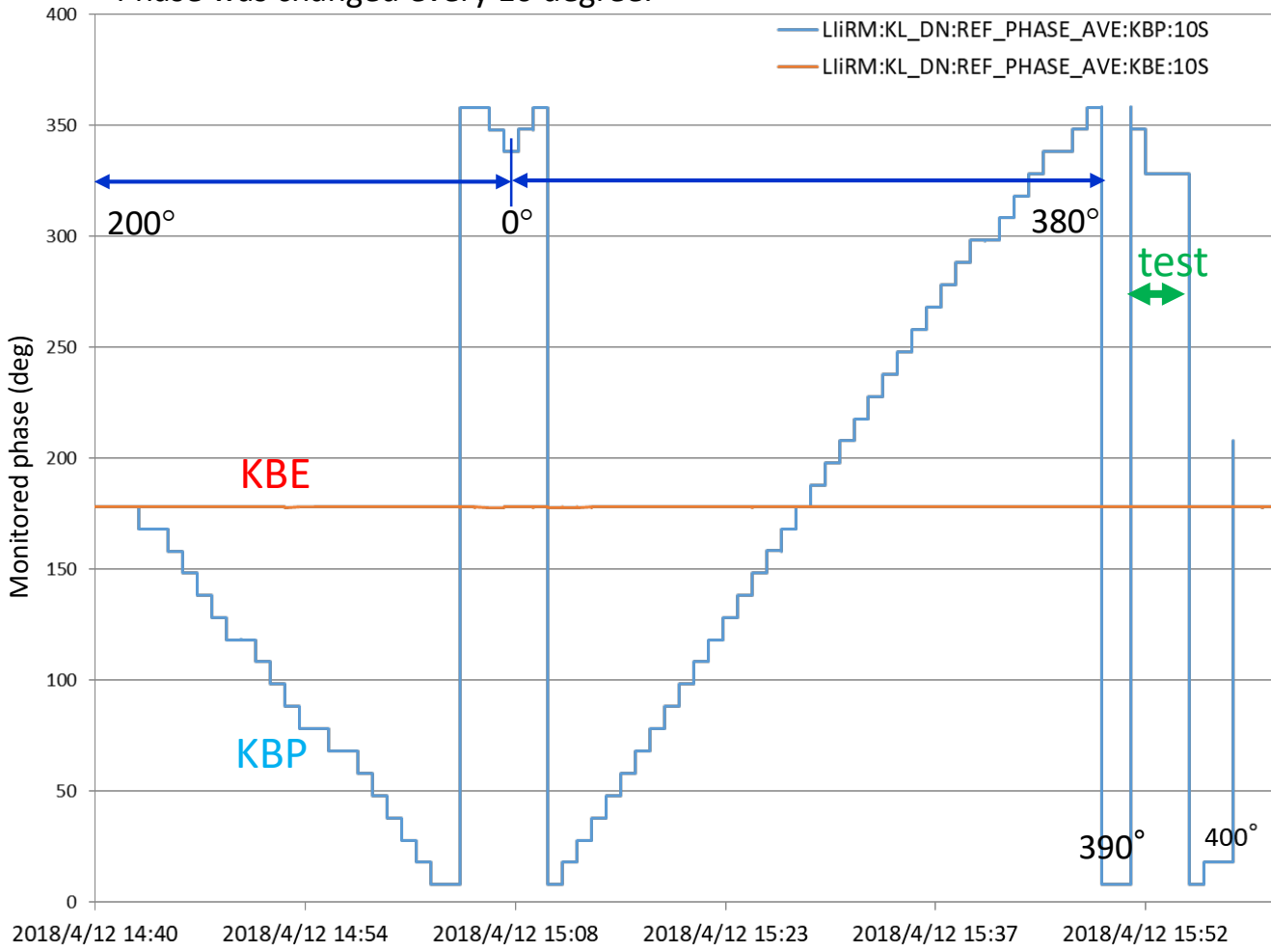
Phase Range : 0° - 400°
Resolution : 0.015°



RF monitor can detect phase difference of Ref(LO) & RF.
RF is generated by using Reference signal.
=> we cannot detect reference phase change.

By using upstream REF signal, ref phase rotation can be detected.

KBP phase was set by embedded-EVR via data-buffer of event record.
Phase was changed every 10 degree.



Reference RF Control Station

Thermostatic chamber : 28 ± 0.05 °C

Freq Mult/Div (#0)
MO Phase Shifter

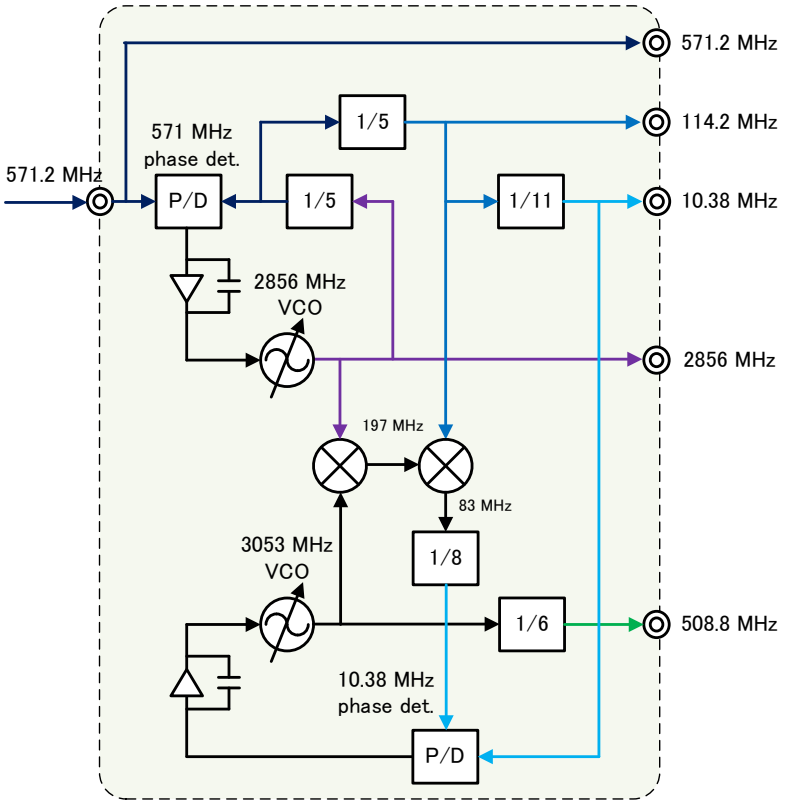
Freq Mult/Div (#1)
Amplifiers

S-band Phase shifter
(for sect.3- sect.5)

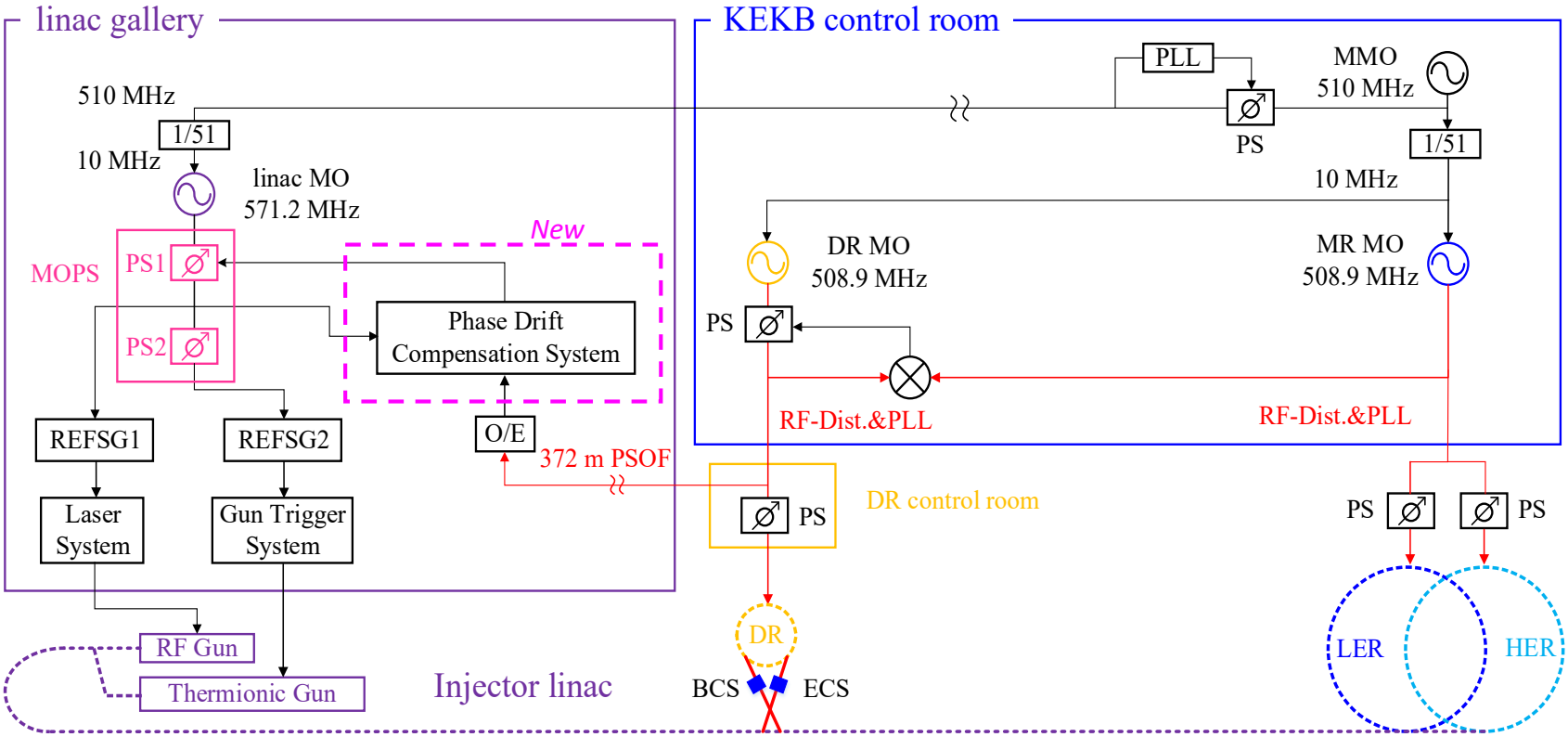
Linac Master Oscillator
571.2 MHz

Sampling oscilloscope for phase monitoring of the reference signals

Reference Signal Generator
(Frequency Multiplier/Divider)



Block Diagram of MO Synchronization System

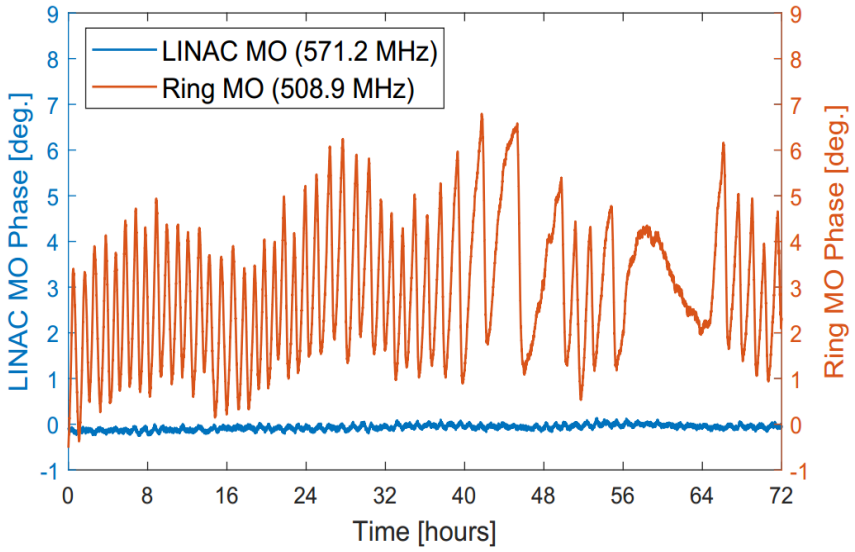


MR MO and DR MO phases have been locked by PLL.
⇔ Linac MO phase had not been locked to Ring MO phase.

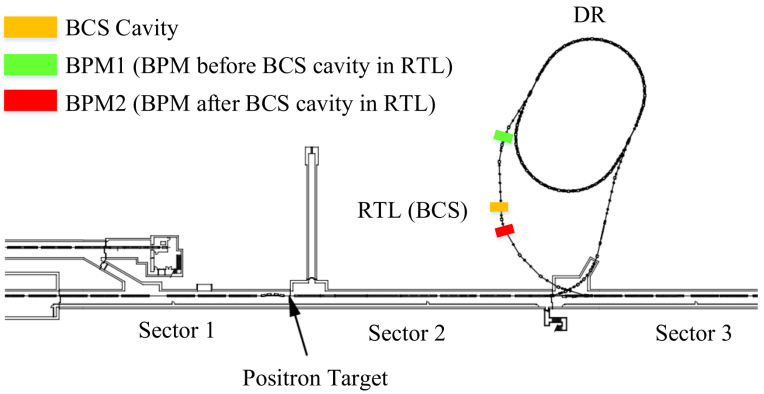
Phase monitor system for Linac MO (571.2 MHz) and Ring MO(508.9 MHz) was installed at Linac side.
The phase drift compensation system was also installed.

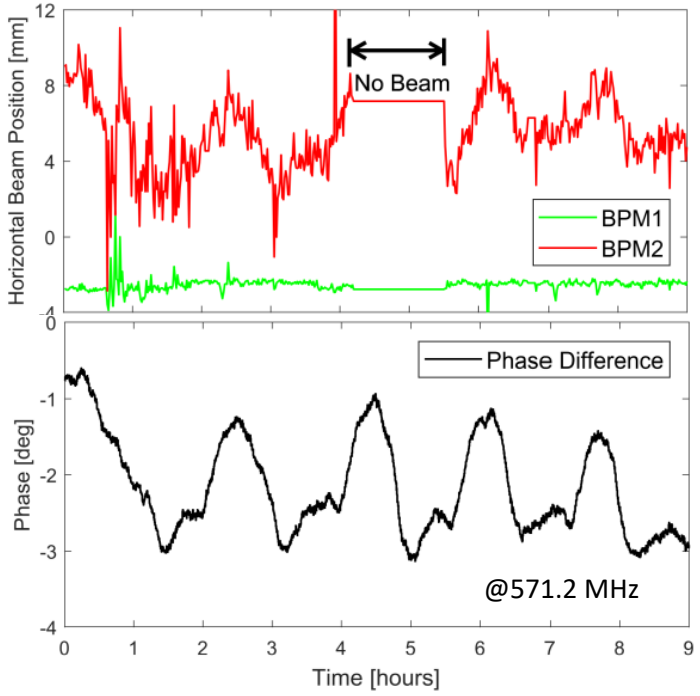
Phase Drift between Linac MO & Ring MO

Linac MO & Ring MO phases are monitored with the clock based on Linac MO



This phase drift has strong correlation with Ring MO room temperature (by T. Kobayashi)



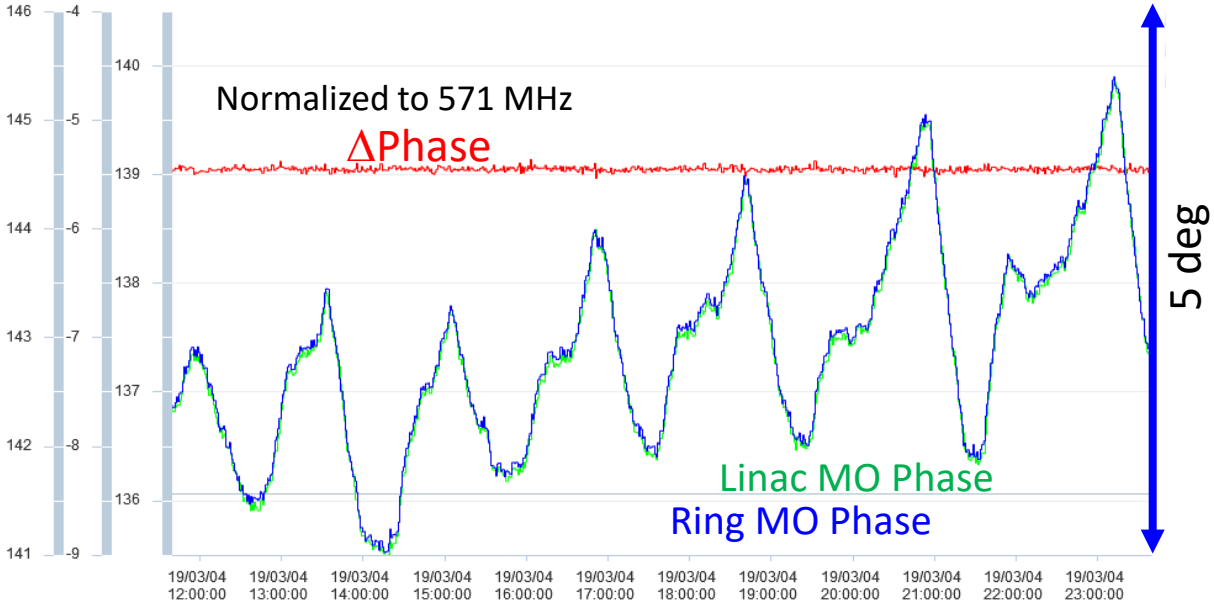


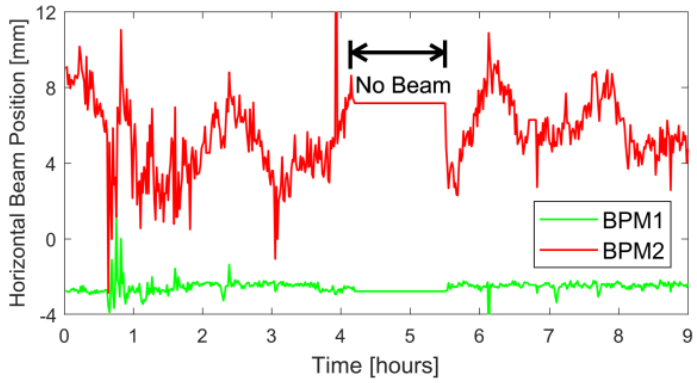
Large phase drift between Linac MO and Ring MO

- Making BCS@RTL tuning difficult
  BCS RF : 2856 MHz (Linac MO x 5)
- Drift of MR injection phase

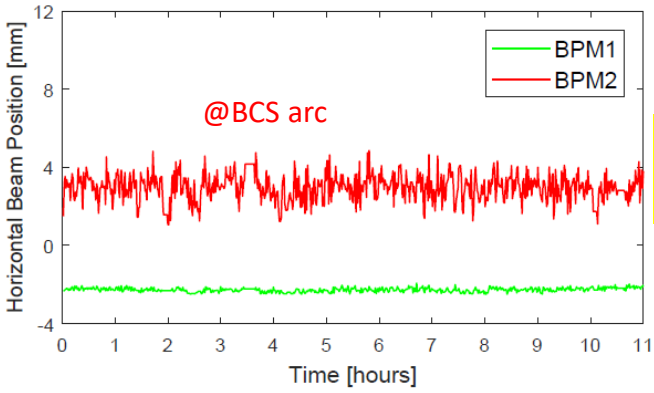
Linac MO Phase Feedback

For the drift compensation between Linac MO & Ring MO,
Linac MO phase is changed to follow Ring MO phase by using MO Phase shifter.





FB ON



Slow drift was disappeared

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  to each sector
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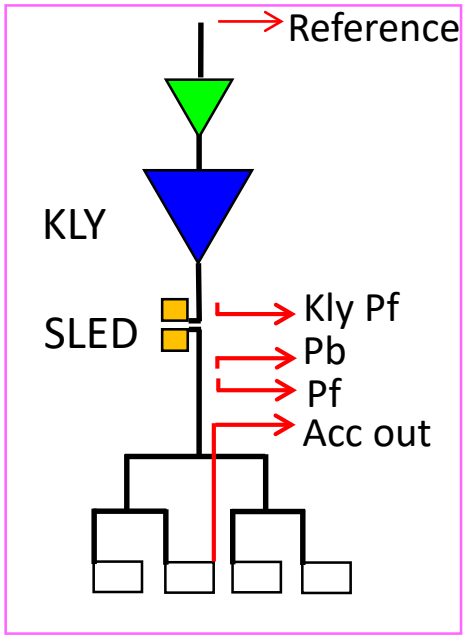
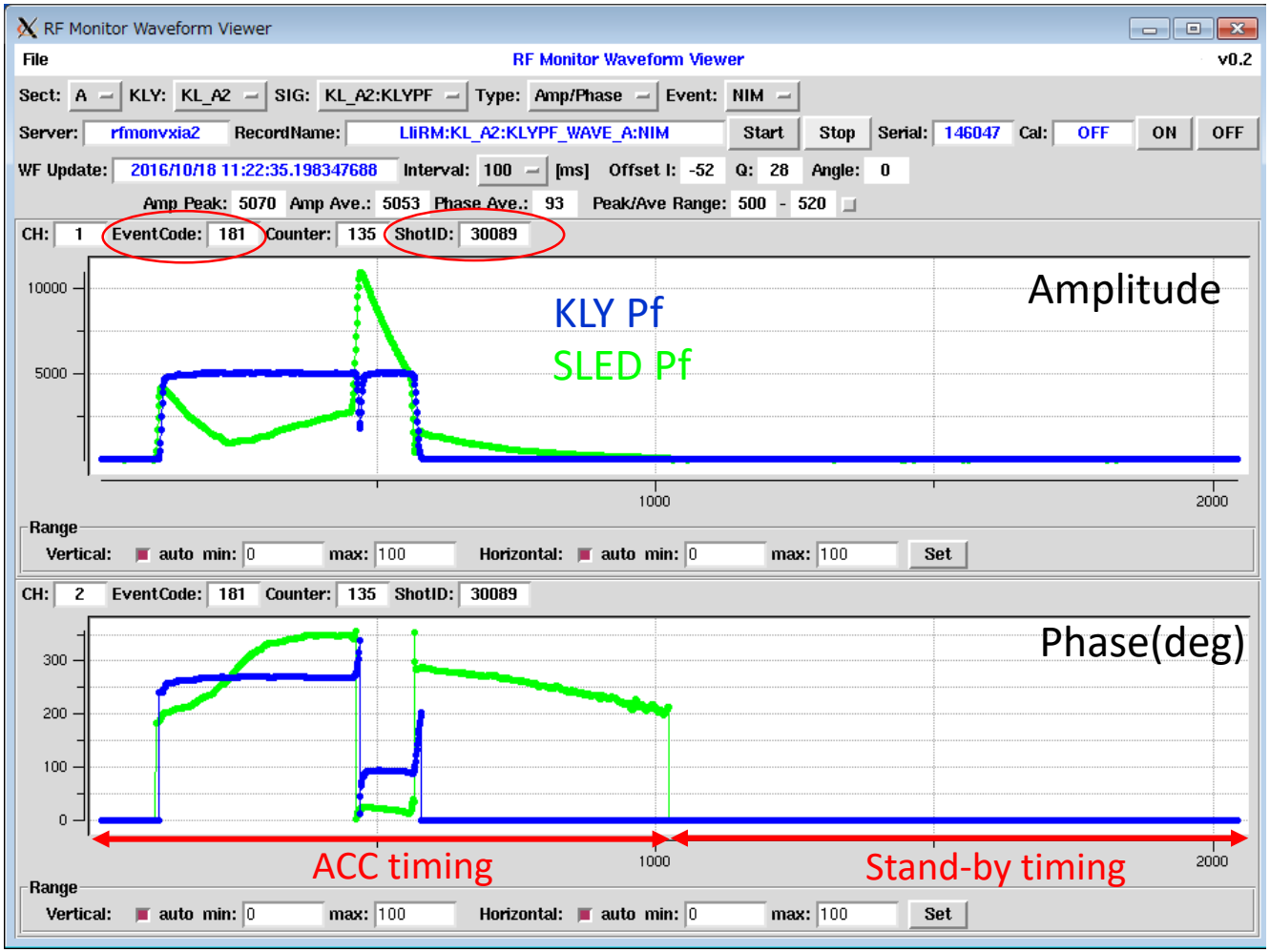
RF Monitor

RF monitors are installed for all RF sources (60 Klystron units & SHB1/SHB2)

Moni: 5 ch
Rep. rate: 50 Hz



"EVR" is built-in.
Identify the Event code & Shot ID



For each pulse, RF & BPM data can be linked by Shot ID

Short Term RF Stability

KLY HV stability : 0.3% pk-pk (0.05% rms)

Estimation of RF stability from KLY HV

Amplitude stability

$\Delta A/A(\%) = 5/4\ \Delta V/V(\%) =$ 0.063% rms

Phase stability

$\Delta\theta = 4\text{deg} * \Delta\ V/V(\%) =$ 0.2 deg rms

(from -4deg/%)

Consistent

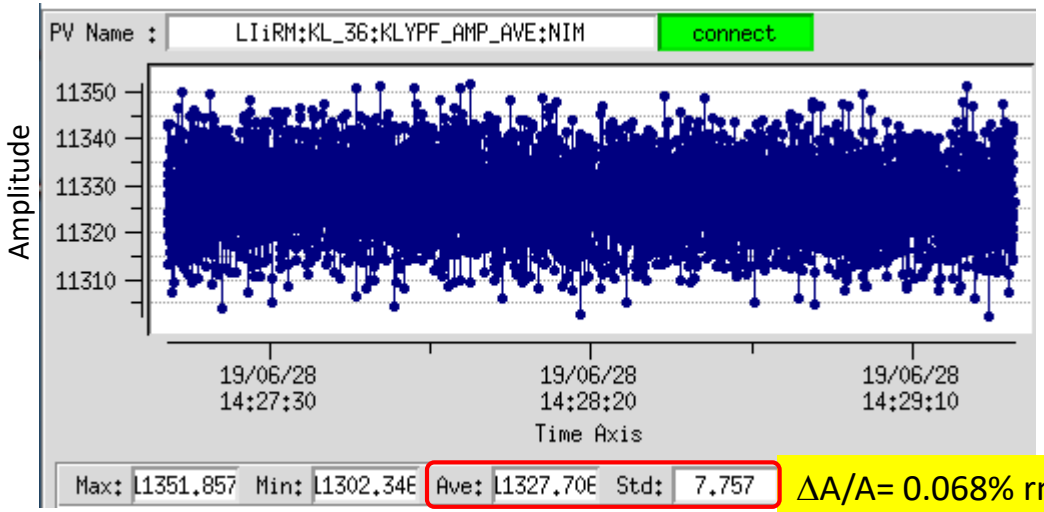
$K(\text{Perveance}) = I/V^{3/2}$

$P = \eta IV = \eta\ KV^{3/2}V = \eta\ KV^{5/2}$.

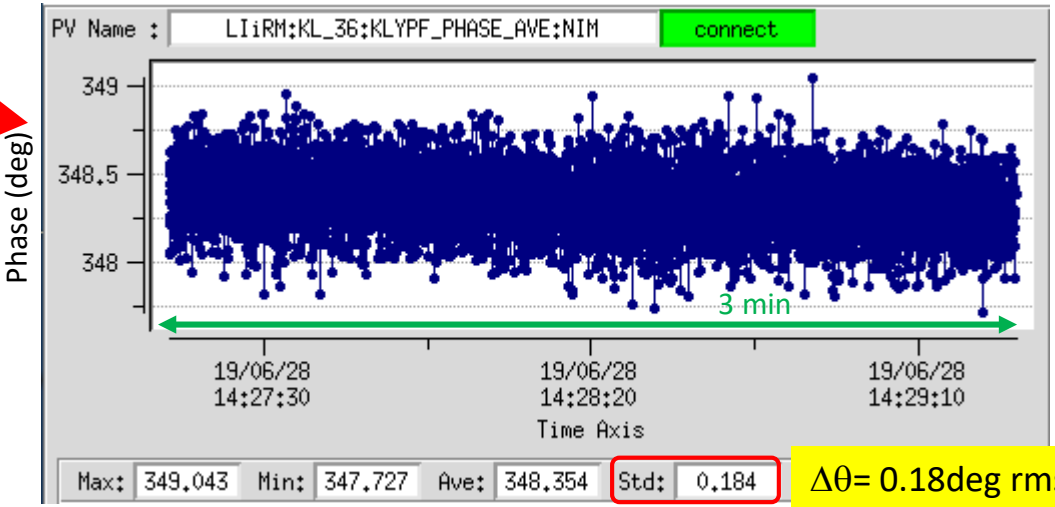
$\Delta P/P = 5/2\ \Delta V/V$.

$\Delta A/A = 5/4\ \Delta V/V$

Measurement result of short-term KLYPF RF stabilities



$\Delta A/A = 0.068\%$ rms

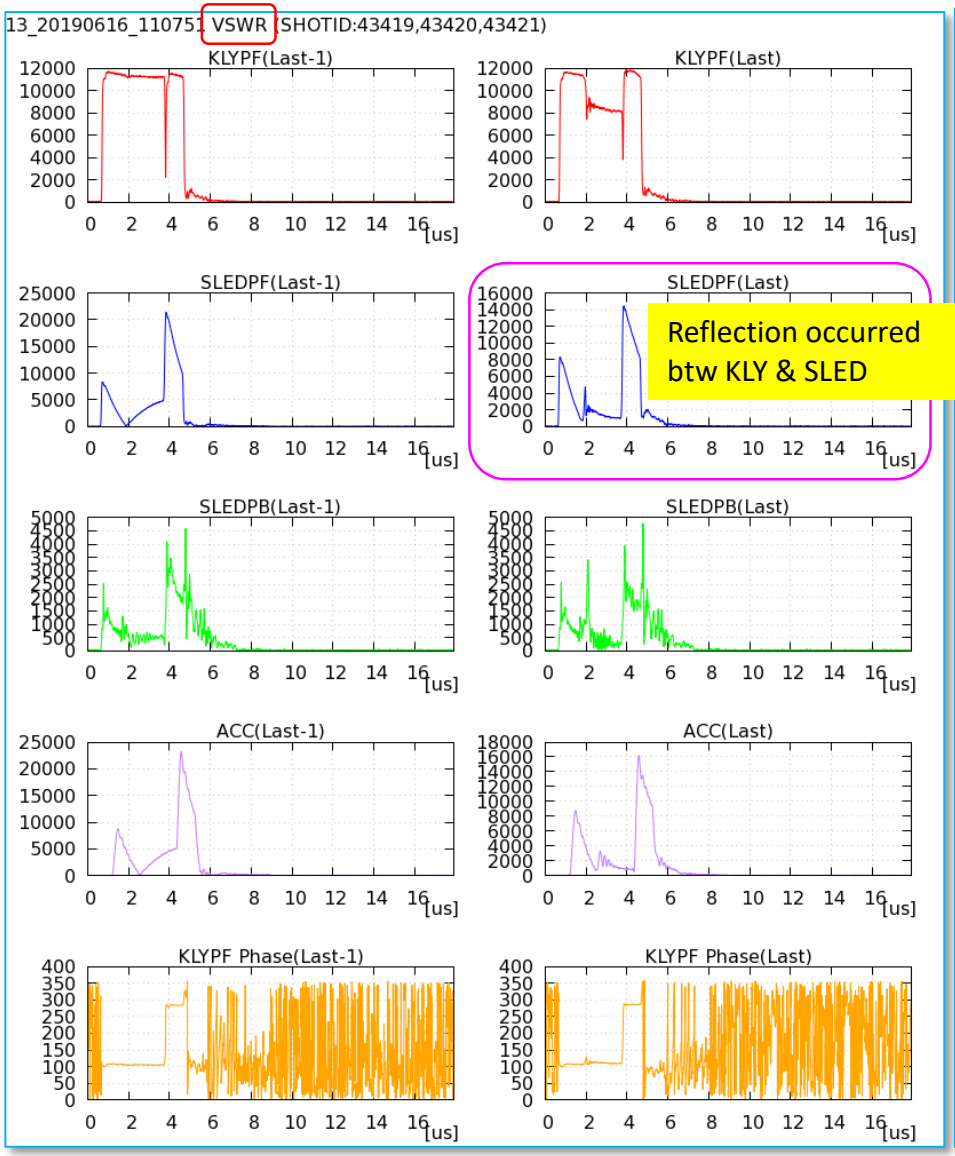


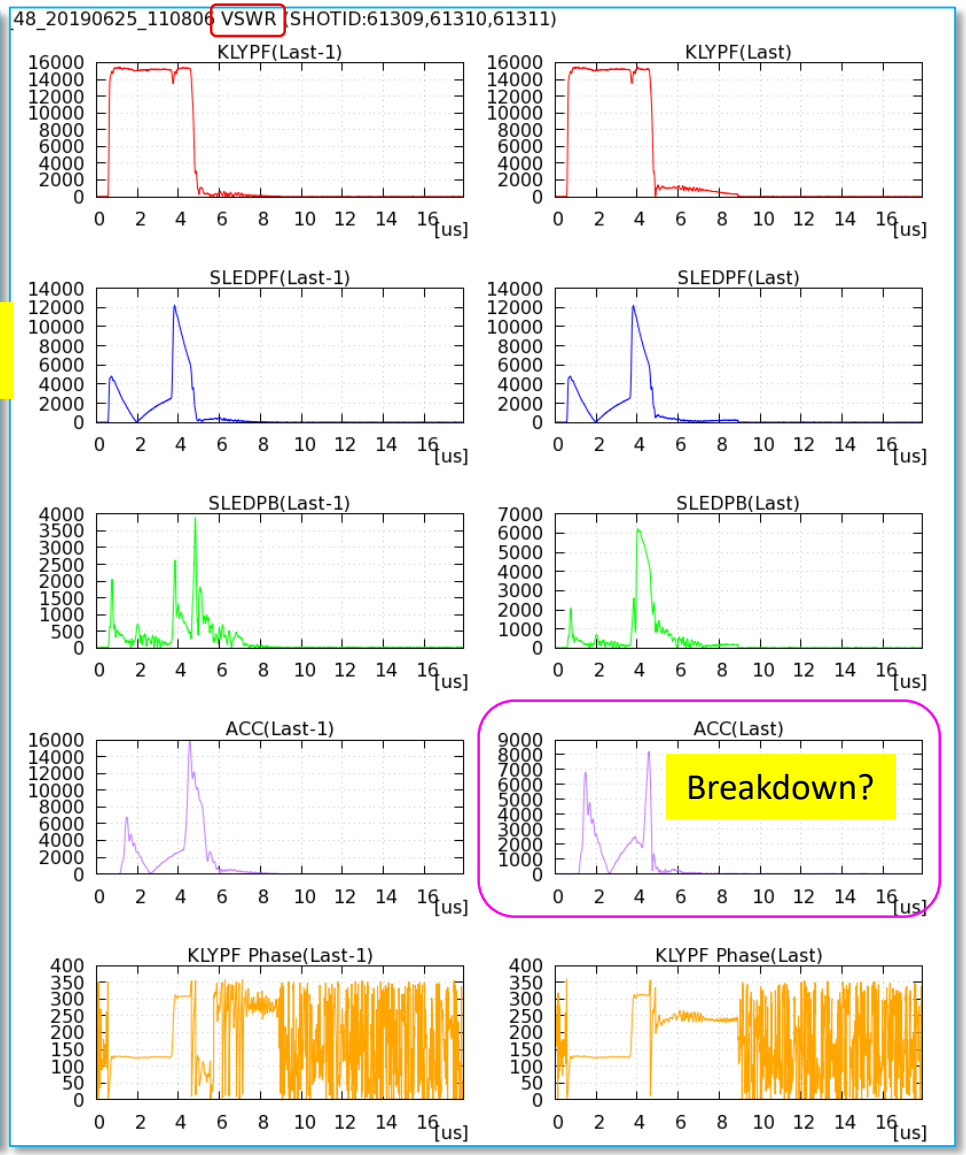
$\Delta\theta = 0.18$deg rms

Application of RF monitor

The Last Waveform Saving at Klystron Interlock

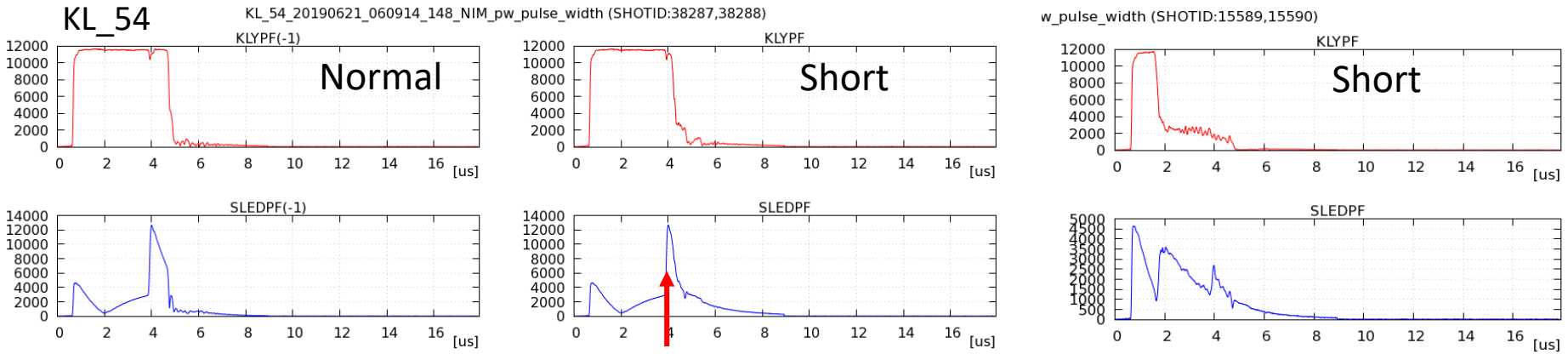
The cause of interlock is identified from the last RF waveform.





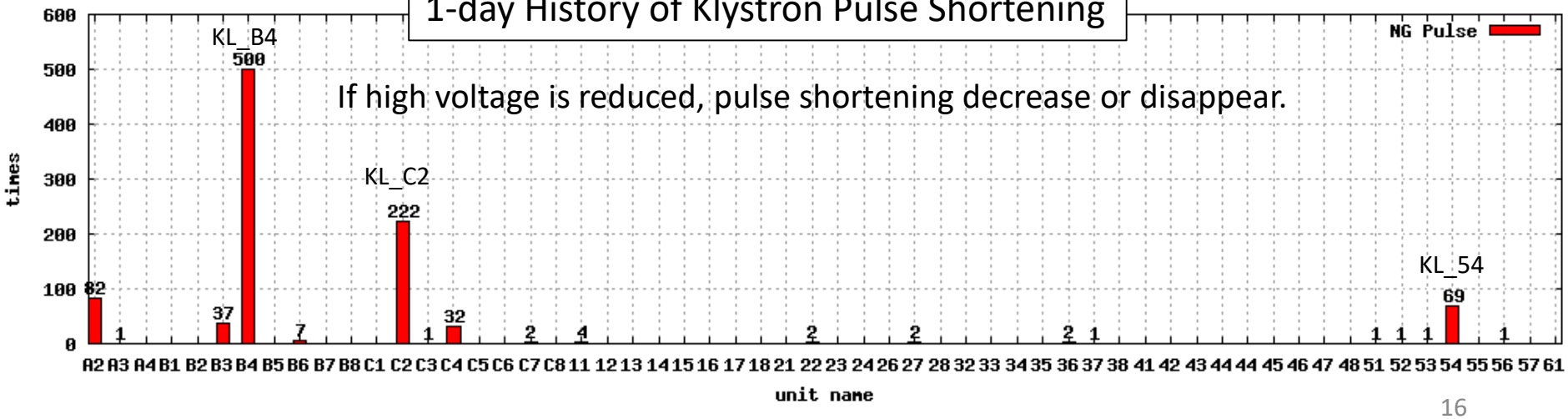
Klystron Pulse Shortening Detection

Klystron pulse-shortening events detected by using RF monitor data



Beam might be injected the MR

1-day History of Klystron Pulse Shortening



Beam Induced RF Monitor

Motivation

Monitored RF phase is affected temperature drift of cable and monitor system.
By comparing the phase of driving RF and beam induced RF in the accelerating structure, we can expect to get the beam phase against RF without system drift error.

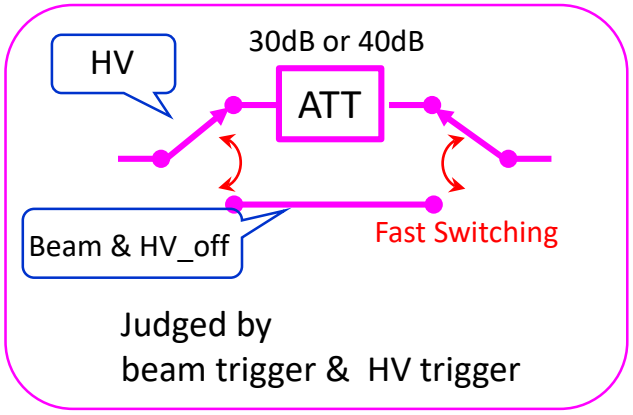
Amplitude estimation

ACC Grad : 20 MV/m

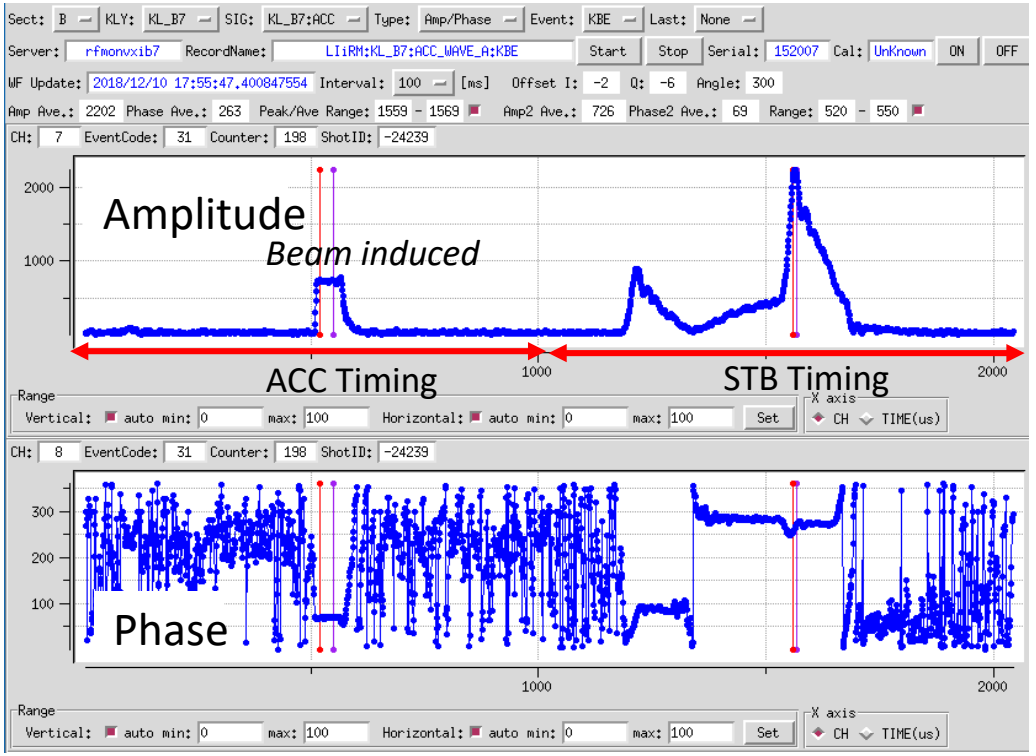
-40.9 dB
small

Beam Induced:
180 kV/m @ 2nC, 3.3ps

Fast ATT switching module



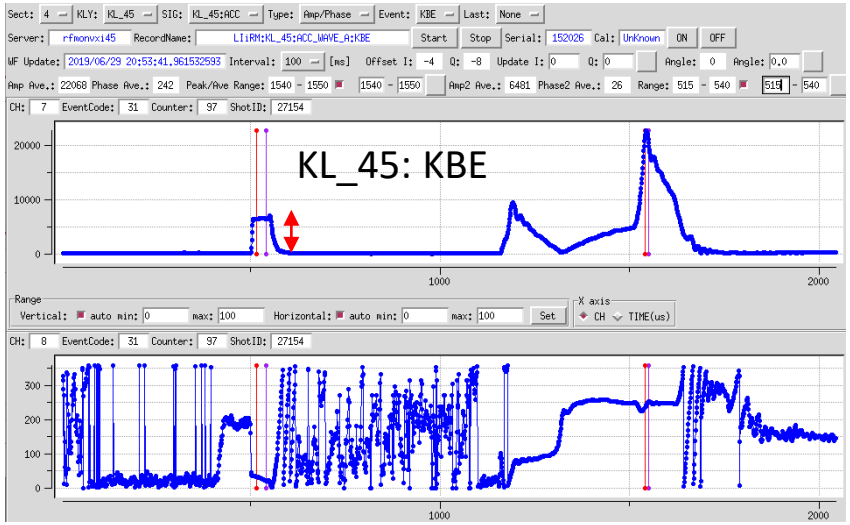
Judged by
beam trigger & HV trigger



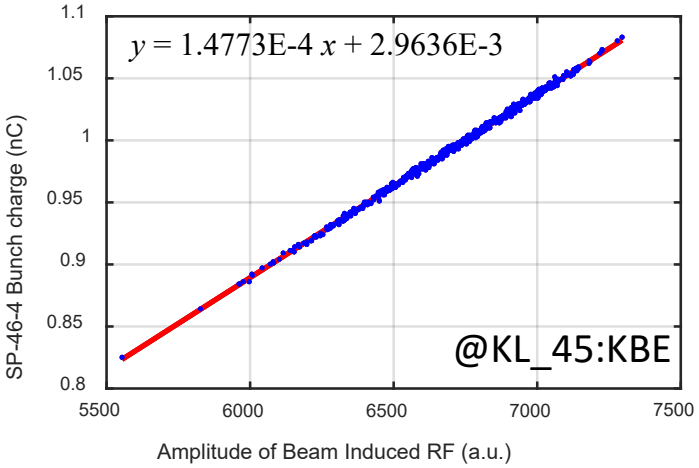
2018/12/10

Installed Unit : A2, B7, C1, 12, 22, 38, 45, 53, 57

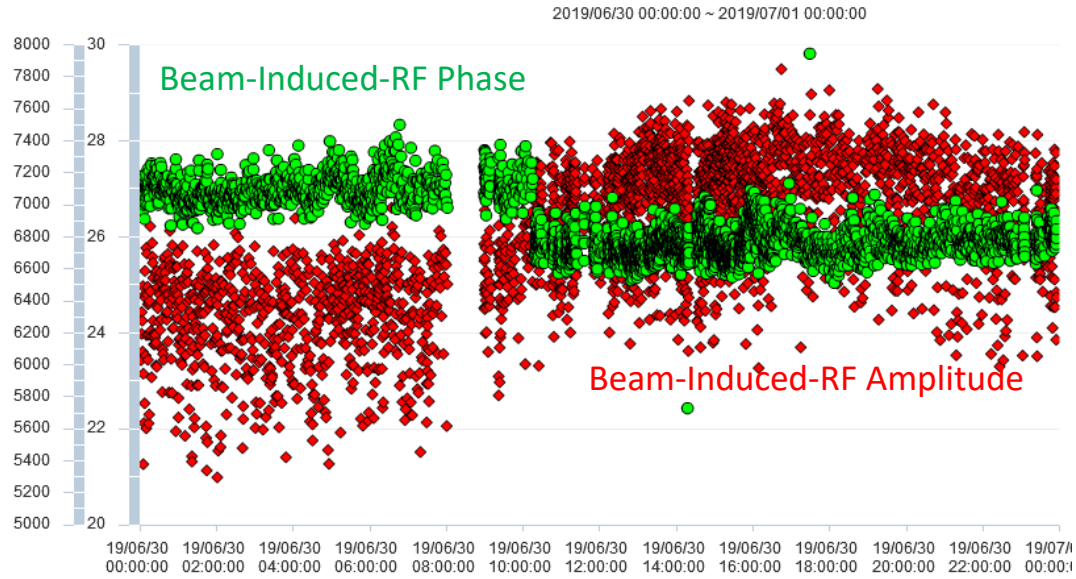
Measurement of Beam Induced RF



Amplitude of Beam Induced RF vs. Bunch charge



Amplitude of beam induced RF is proportional to bunch charge. (plotted at the same shot ID)



KL_45: KBE

When beam phase changed @2019/6/30 10:18, beam charge increased.

LIiRM:KL_45:ACC2_AMP_AVE:KBE:10S

LIiRM:KL_45:ACC2_PHASE_AVE:KBE:10S

Summary

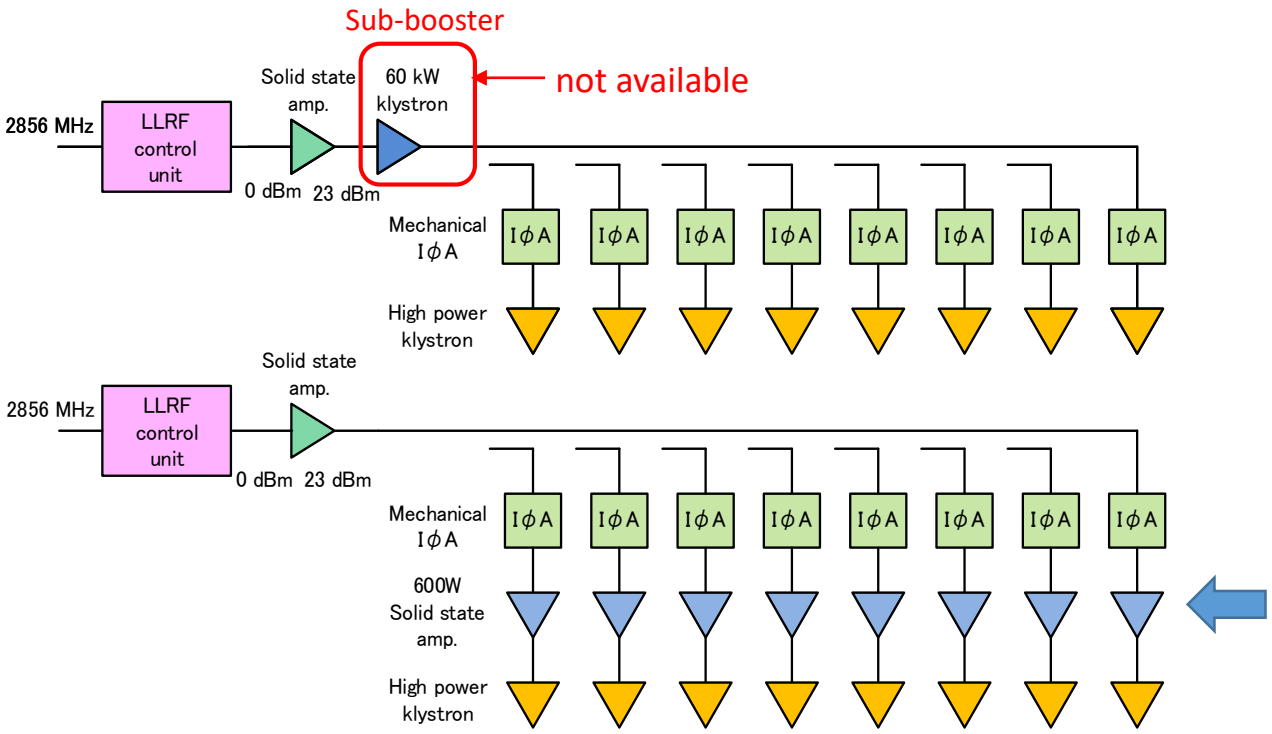
- Linac reference RF control system are almost established by installing injector MOPS, S-band PS, and MO phase drift compensation system.

- RF monitors are installed for all RF power sources.
  Not only stability confirmation, they are utilized the investigation of interlock event and the klystron pulse-shortening detection.

- Beam induced monitor is currently under development.
  Beam phase information is so useful to confirm the operating condition.

Future Work

- Amplitude & phase controllers with digital mode are required for SHB1/SHB2.
- Replacement of old coaxial cable in RF distribution line is necessary due to contact failure.
- Change RF drive line from sub-booster drive to SSA drive (Sect 1: already done)

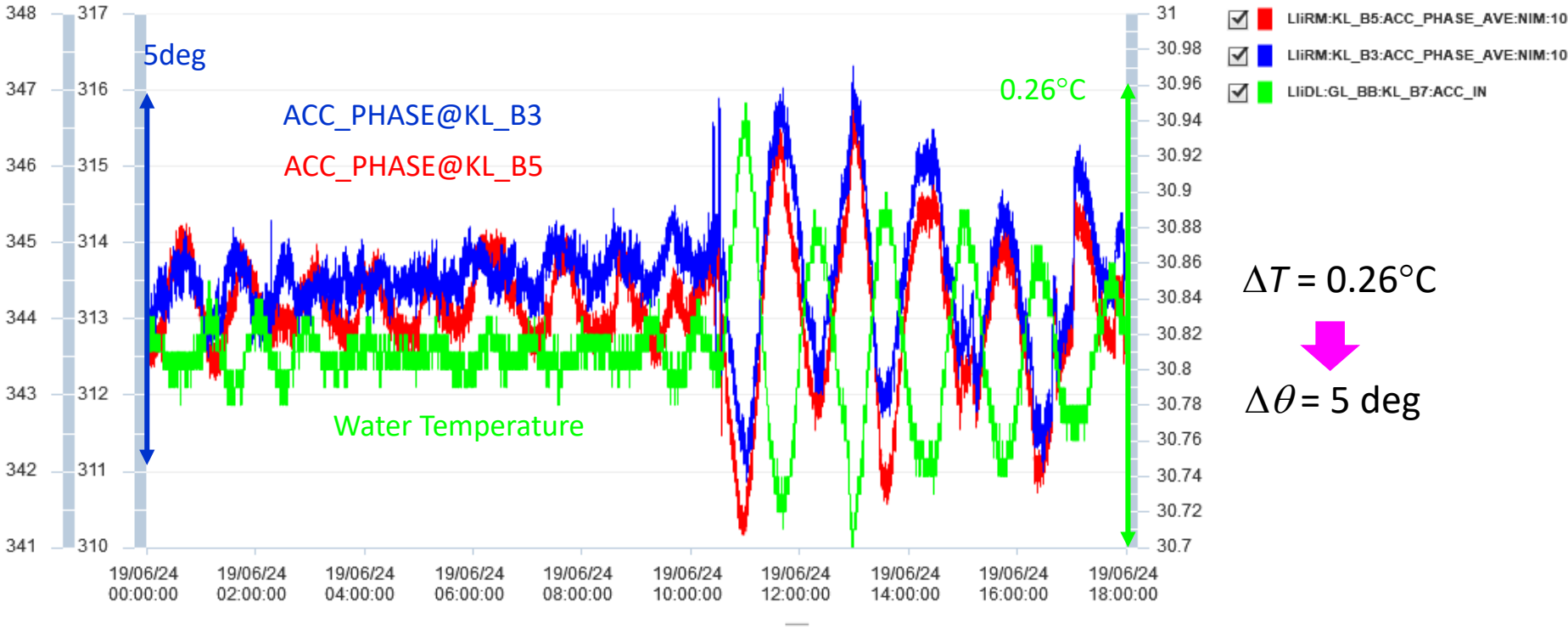


Instead of sub-booster, 600W SSA will be installed in each unit.

Back up

Diagnostics of RF Stability by RF Monitor

Water Temperature vs. RF Phase of ACC Structures



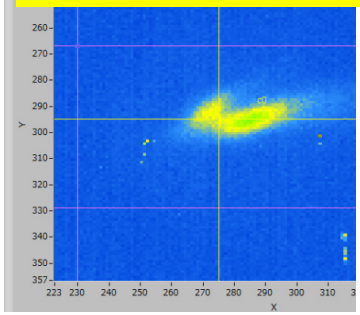
ΔT = 0.26°C

$\Delta\theta$ = 5 deg

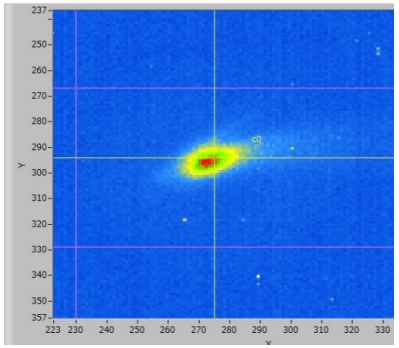
Cooling Water Temperature fluctuation is causing RF phase fluctuation

Beam Phase Confirmation for Energy Spread Tuning

Beam Energy Profile

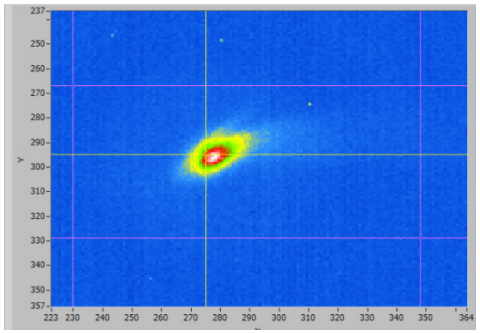


(1) Beam energy is split @screen (SC61H1)

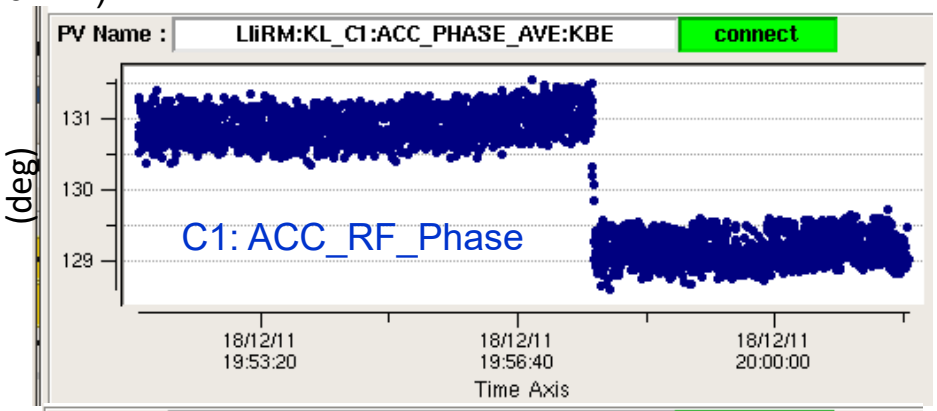


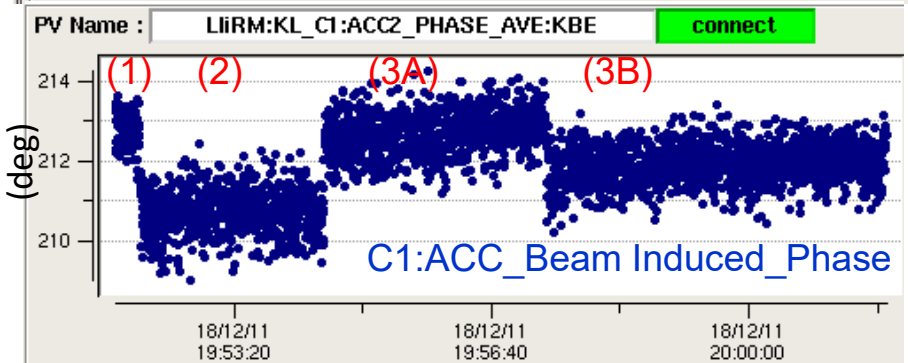
(2) SHB1(114MHz) +1.5deg
Beam phase: -2deg

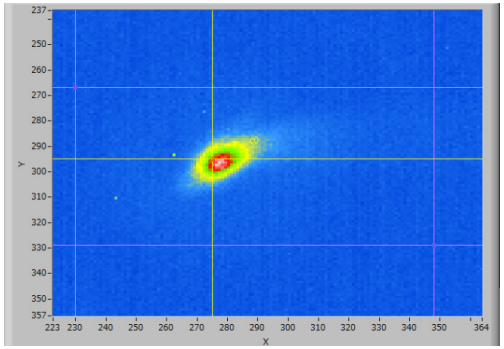
Beam tail correction



(3A) Buncher +1deg.
Beam phase: recovered
Correct procedure







(3B) All S-band RF -2deg
(except for buncher)

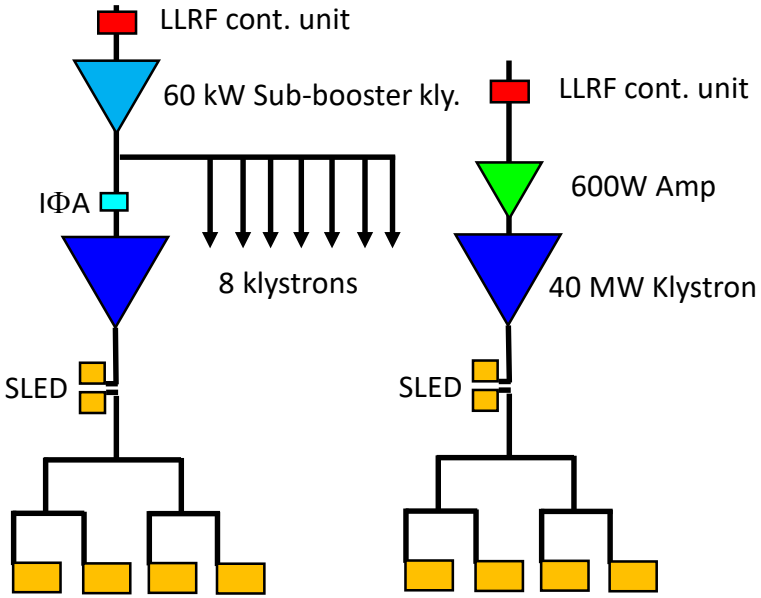
Crest phase => shift

LLRF Control Unit

presented in KEKB Review2014
IPAC2018, WEPAK018

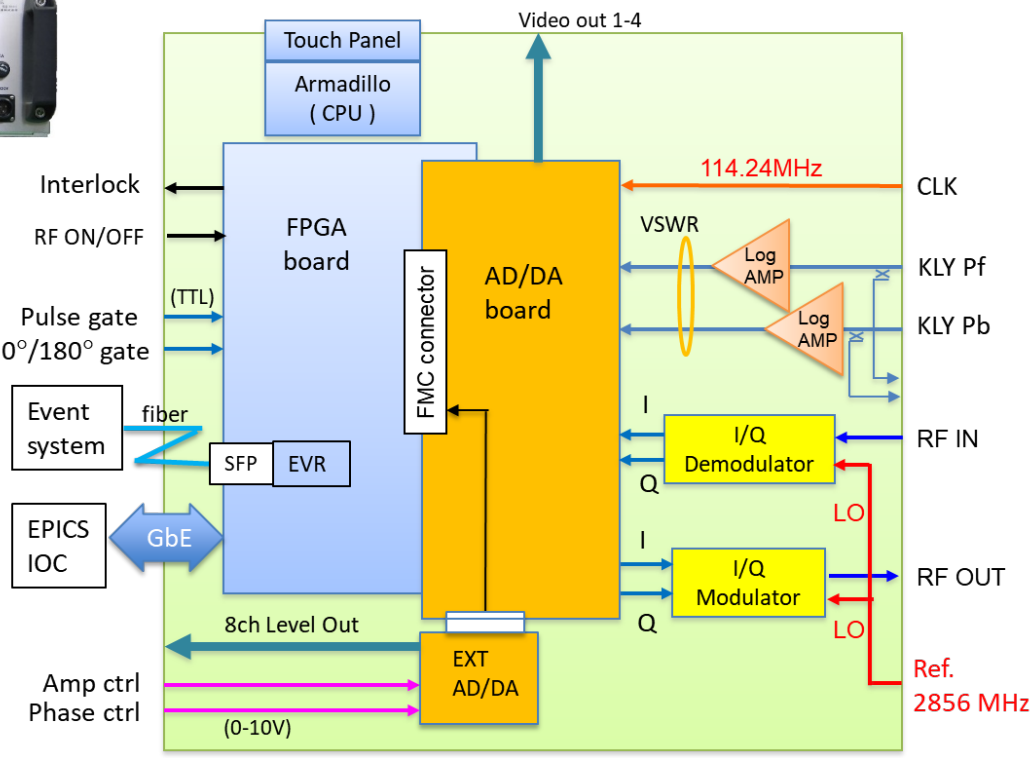
Front

Rear



Driveline by sub-booster klystron(left) and independent driveline (right)

Frequency	2856 MHz
RF output level	+10 dBm (100%)
Linearity of amp.	0.3% rms and max < ±0.5%
RF pulse rise time	< 35 ns (0 - 90%)
Phase setting-range	0 – 400°

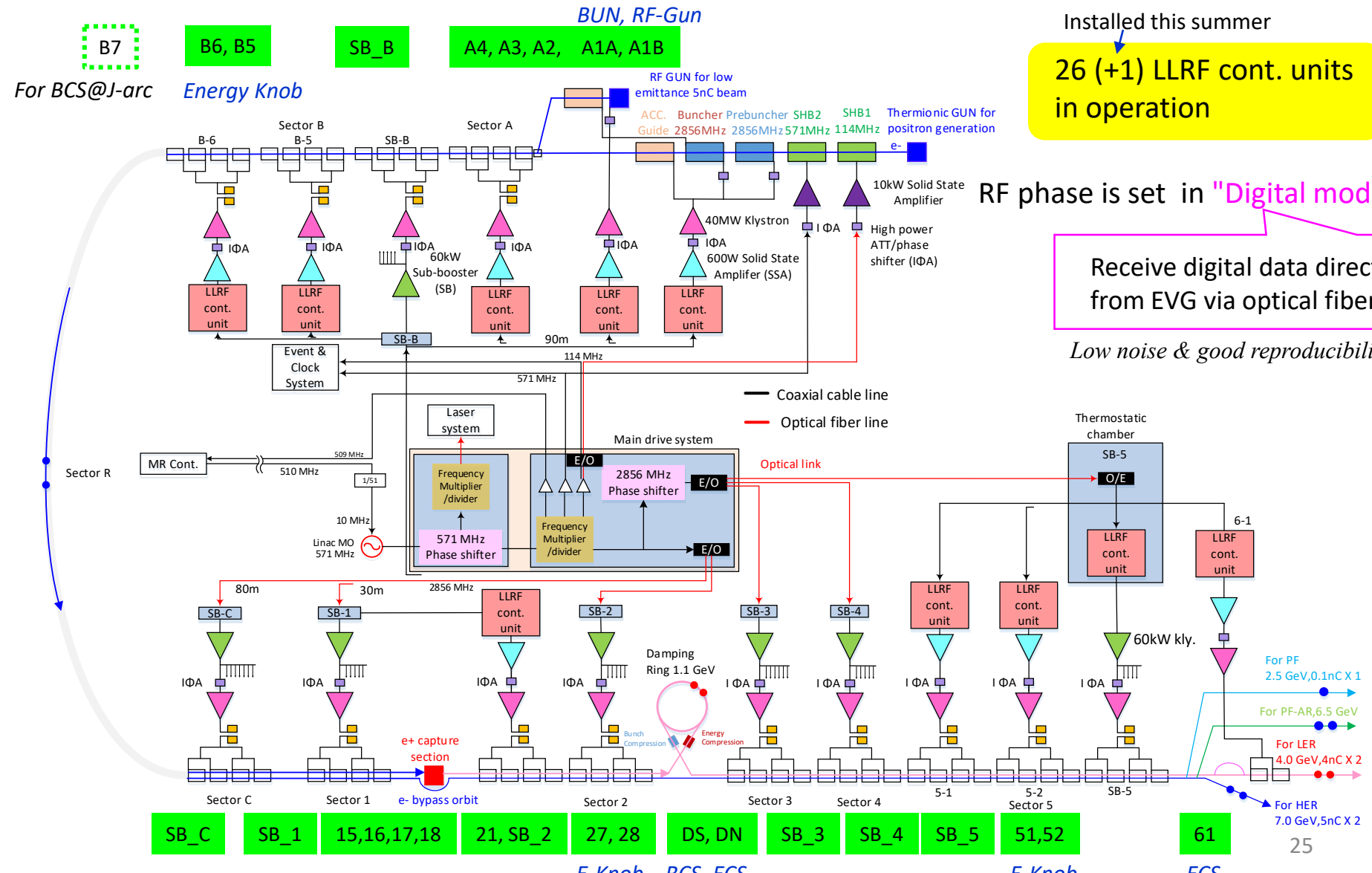


< Functions of LLRF control unit >

- Pulse modulation (AMP & Phase)
- VSWR meter (Power detection)
- 1ch RF monitor
- Event receiver
- Pulse shortening detection

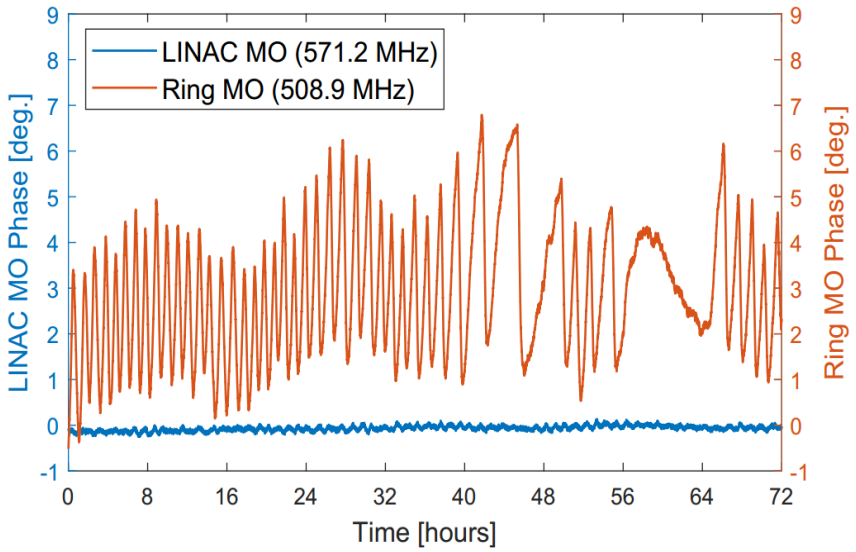
Installation of LLRF Control Unit

KEKB Review2014
IPAC2018, WEPAK018



Phase Drift between Linac MO & Ring MO

Monitored phase with the clock based on Linac MO



Phase drift between Linac MO and Ring MO

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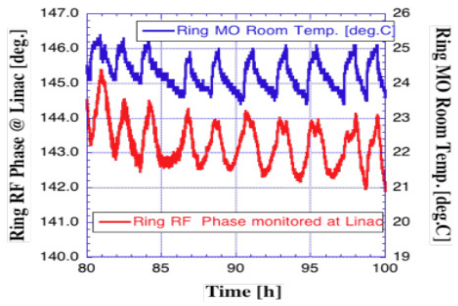
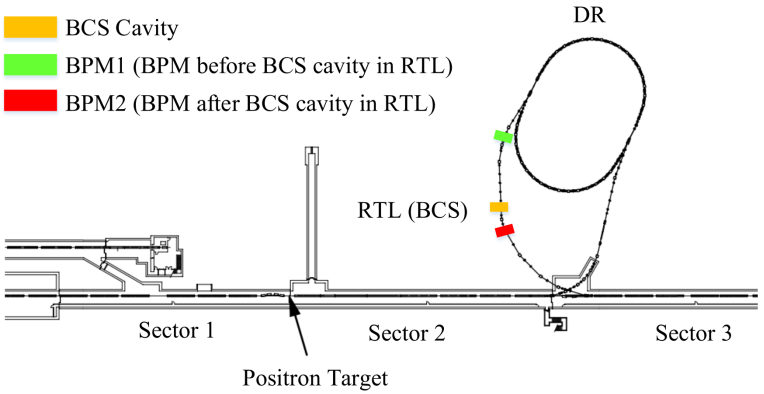
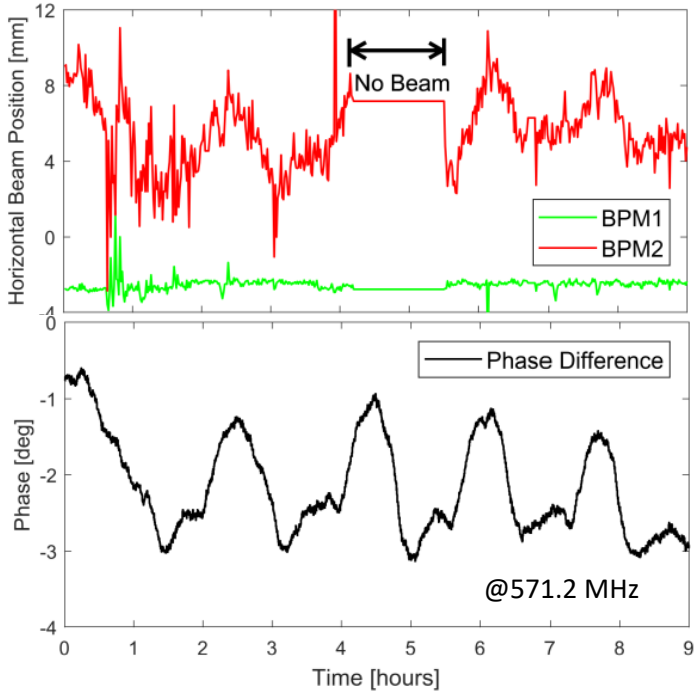
  BCS RF : 2856 MHz (Linac MO x 5)
- Drift of MR injection phase

Strong correlation with Ring MO Room Temp.
(by T. Kobayashi)

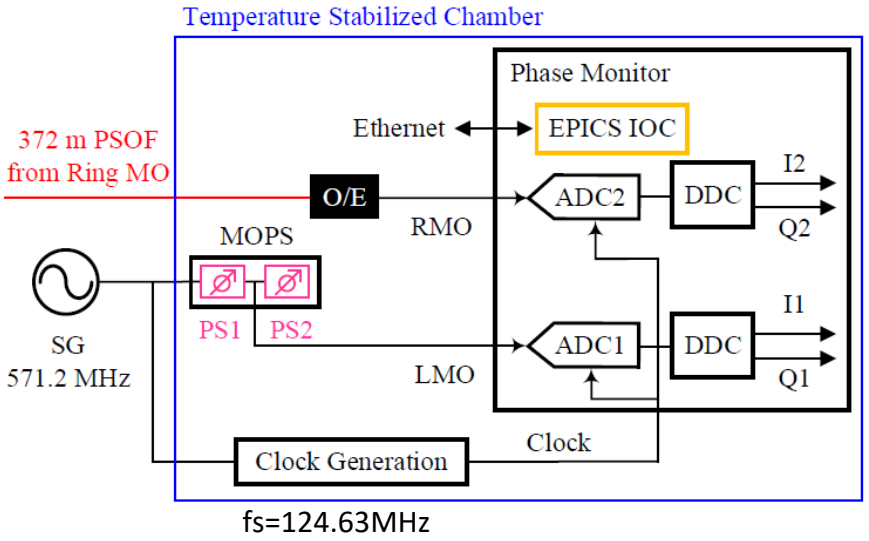


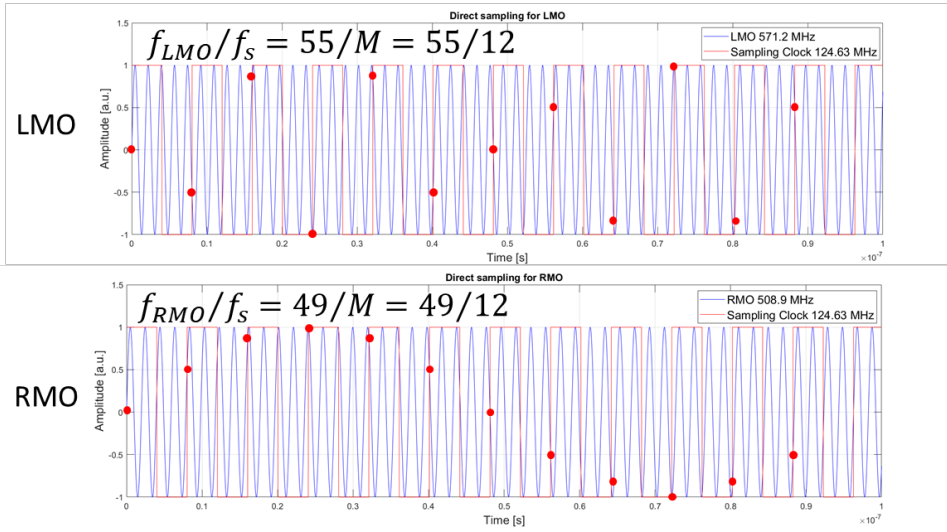




Under-sampling Technique for Linac MO & Ring MO

LMO(571.2 MHz):RMO(508.9 MHz)=55:49

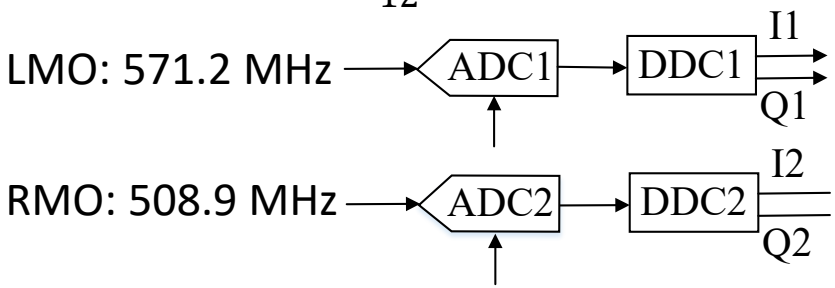




$$f_s = \frac{f_{LMO}}{4 + \frac{7}{12}}$$

$$I = \frac{2}{M}\sum_{n=0}^{M-1} x[n]\cos\left(\frac{2\pi \cdot N}{M}\cdot n\right)$$

$$Q = -\frac{2}{M}\sum_{n=0}^{M-1} x[n]\sin\left(\frac{2\pi \cdot N}{M}\cdot n\right)$$



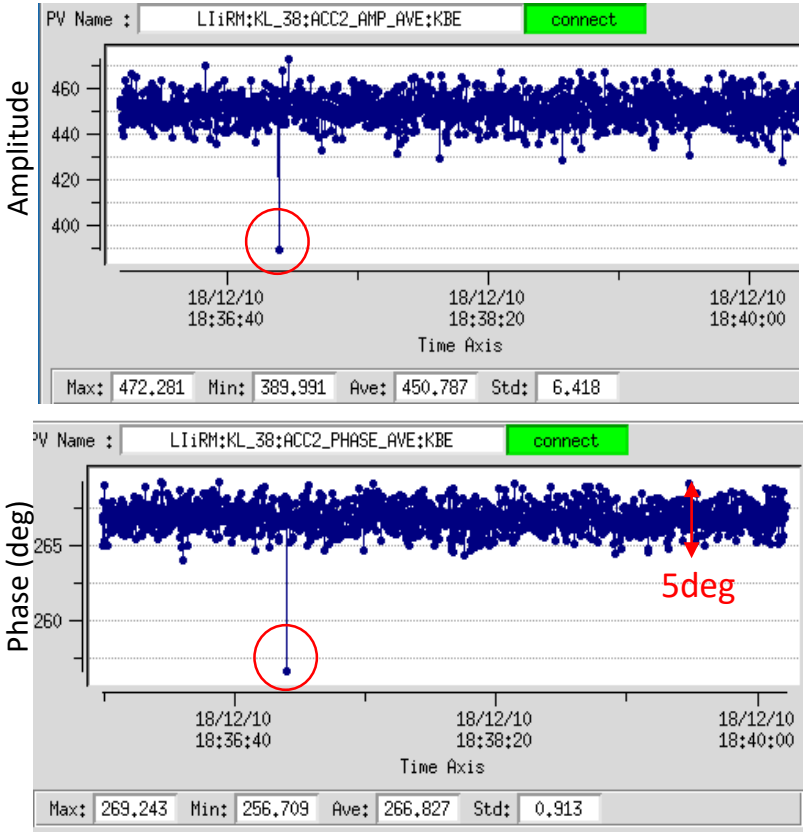
M1=12
N1=7

M2=12
N2=1

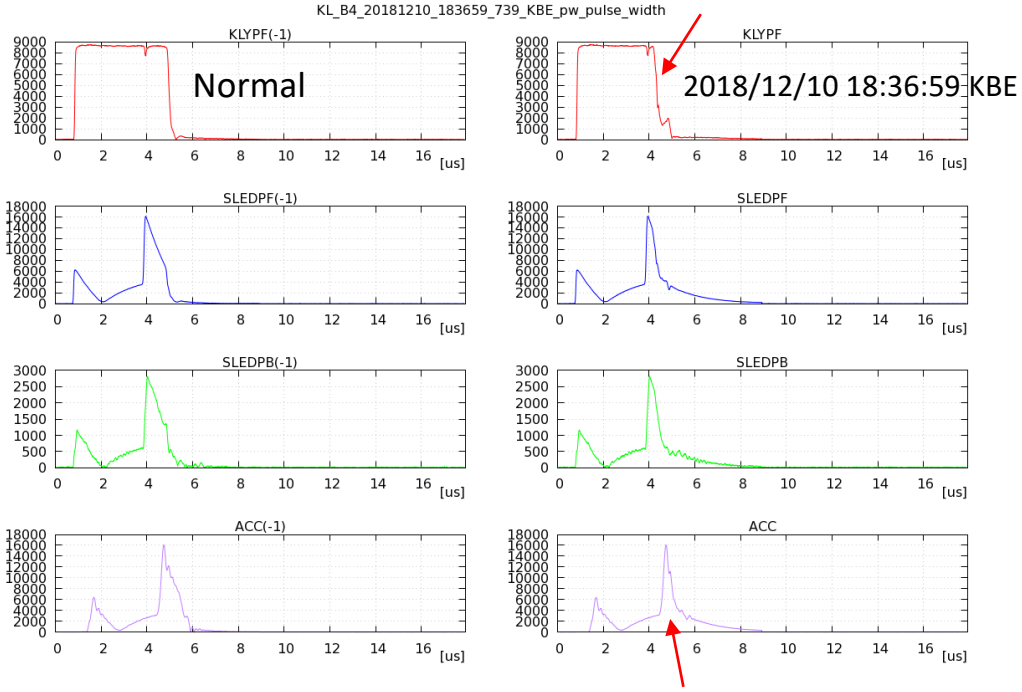
$$\varphi_{LMO} = \tan^{-1}(Q_1/I_1)$$
$$\varphi_{RMO} = \tan^{-1}(Q_2/I_2)$$

Measurement of Beam Induced RF

Trend graph of beam induced RF @KL_38:KBE



Pulse shortening @KL_B4



Peak amplitude was almost the same, but pulse width became shorter.

Amplitude is not so high.
Phase jitter (error) is 5 deg pk-pk.

For more high precision, parameters of attenuator and amplifier will be revised.

Linac RF System