ESLS RF & HarmonLIP Workshop 2025
Oct.24, ALBA Synchrotron

Experimental demonstration of the compensation of the transient beam loading caused by a long bunch gap in the KEK-PF 2.5 GeV ring

Naoto Yamamoto, D. Naito, S. Sakanaka,
T. Takahashi, A. Motomura
RF-Group, ACC 6th division, KEK

30 minutes, including questions

Insight through Accelerators.
KEK

Introduction

- The transient beam loading effect affects the bunch lengthening performance with harmonic rf system.
- A compensation method using the fundamental/harmonic cavity or a broadband longitudinal kicker cavity are one method to recover the bunch lengthening performance (*PRAB 21, 012001, 2018*).

Fig.1 Schematic of bunch lengthening by using harmonic cavity with the flat potential.

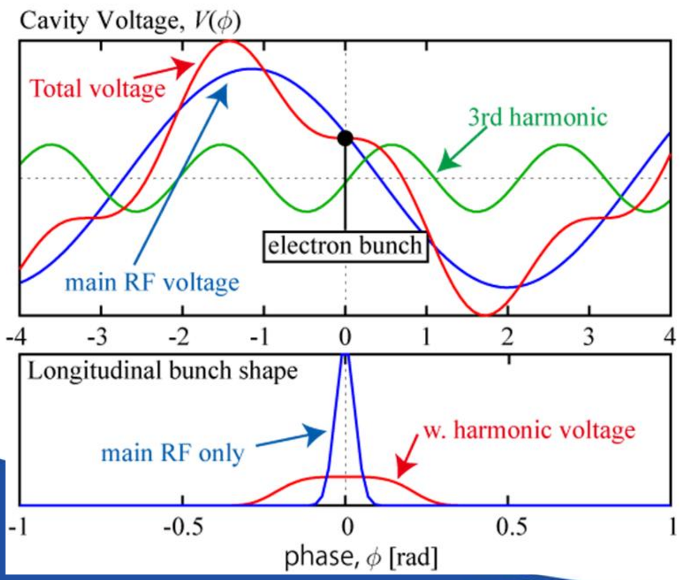


Fig.2 TBL Mitigation with NC TM020 cavity

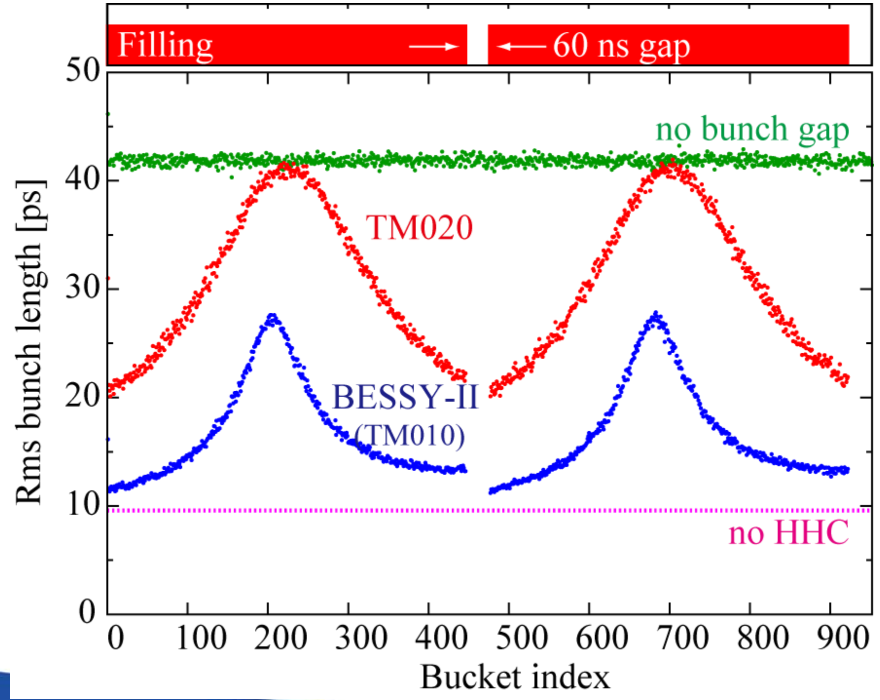
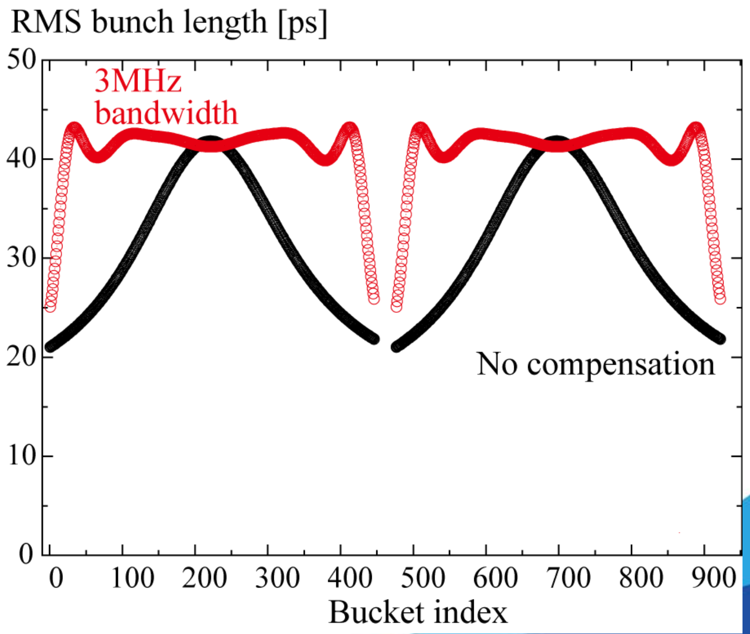


Fig.3 TBL compensation with a broadband kicker cavity.



Concept of TBL compensation

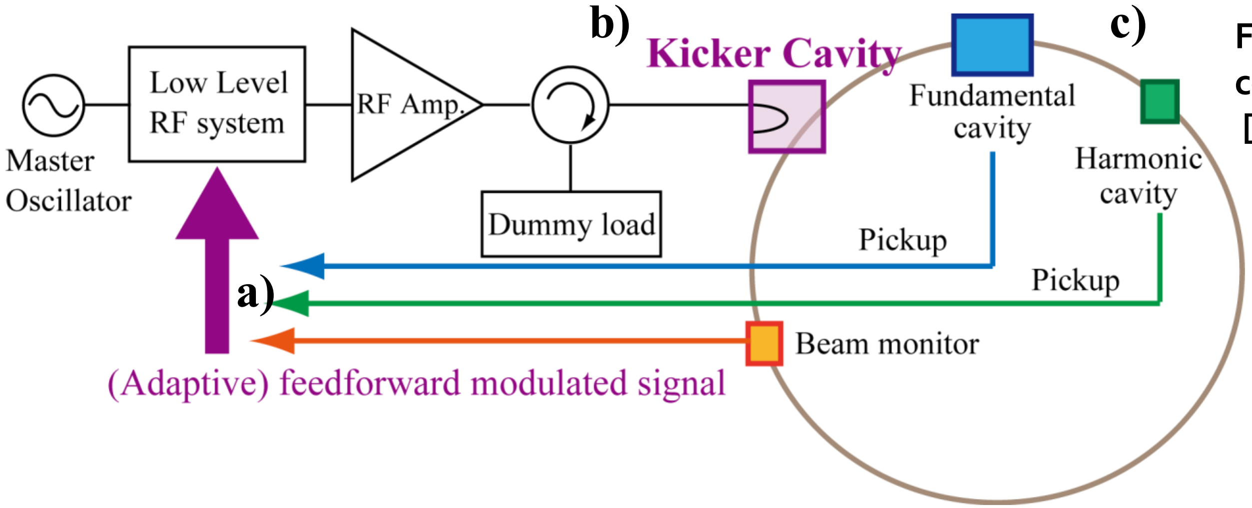
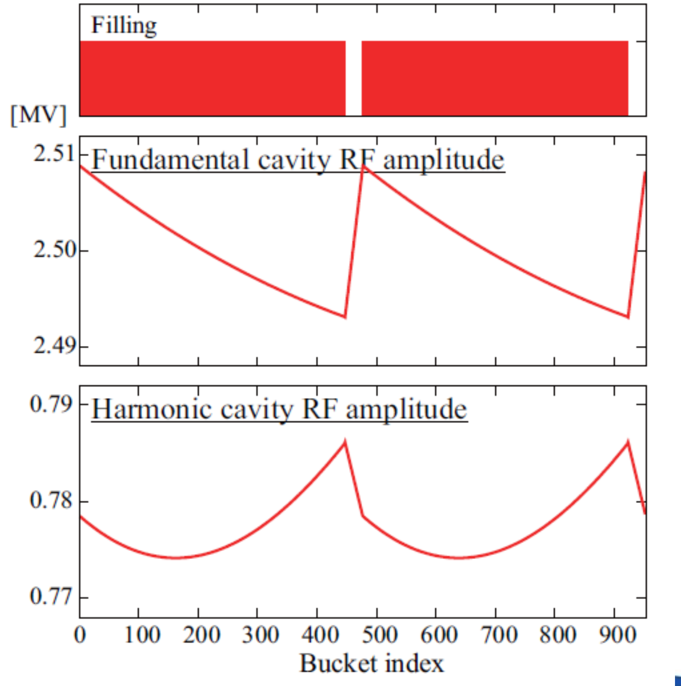


Fig. Concept of active compensation for TBL [Proc. of MCBI2019]

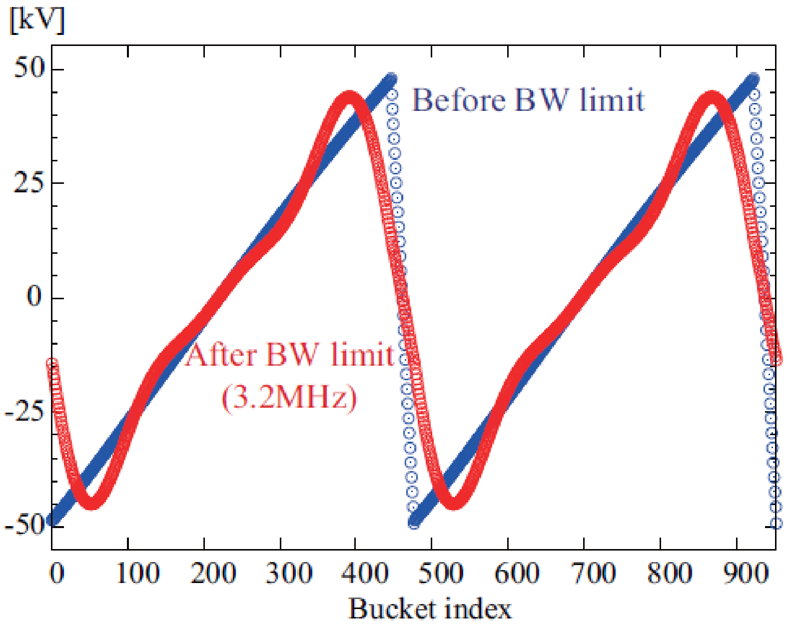
Tab. Kicker cavity parameter

Frequency	500 MHz
R/Q	175 Ω
Unloaded-Q	40000
Cavity number	1
Cavity coupling	199
Loaded-Q	200
3dB bandwidth	2.5 MHz

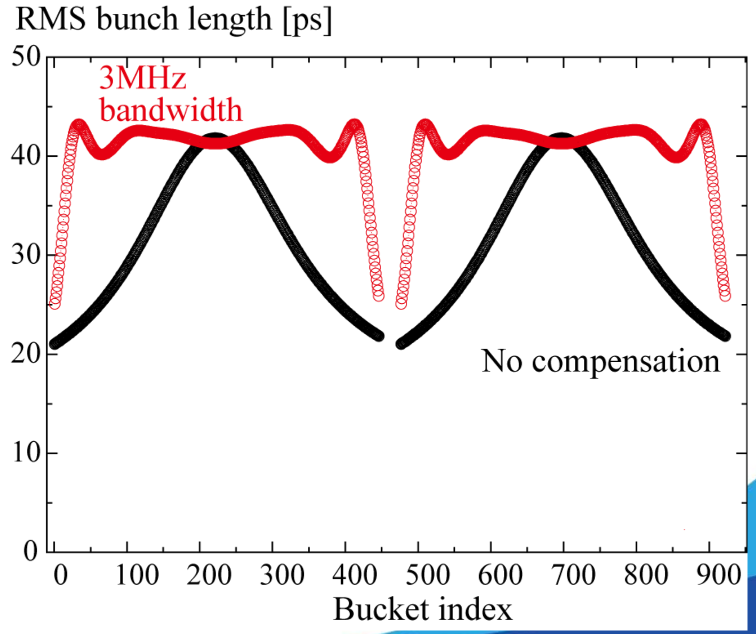
a) Monitor Signal from pickup/BPM



b) Input signal to Kicker cavity



c) Bunch length along the train w/wo. Compensation signal



Concept of TBL compensation

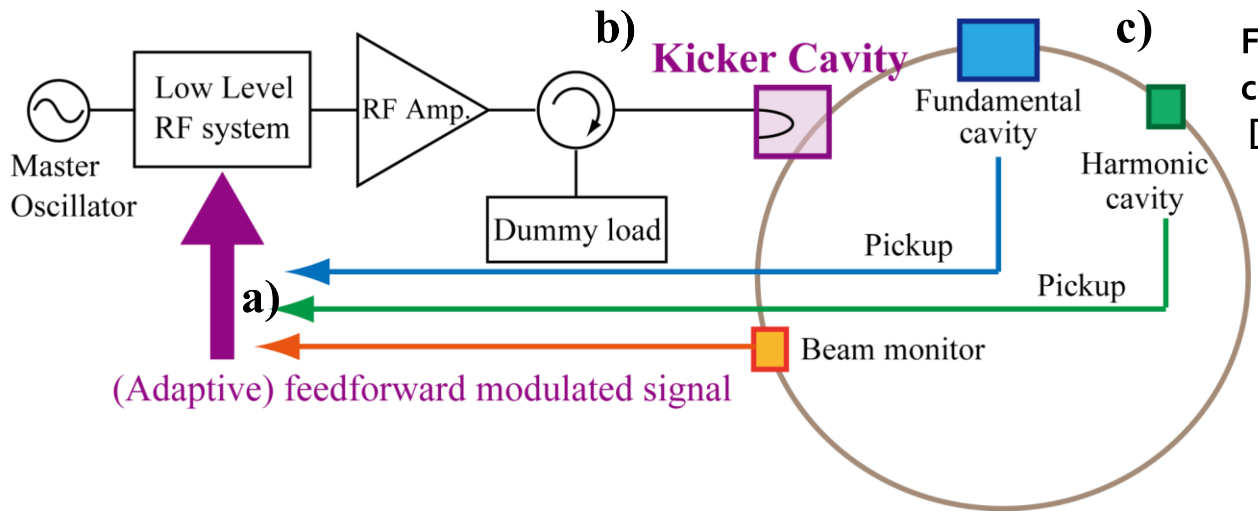


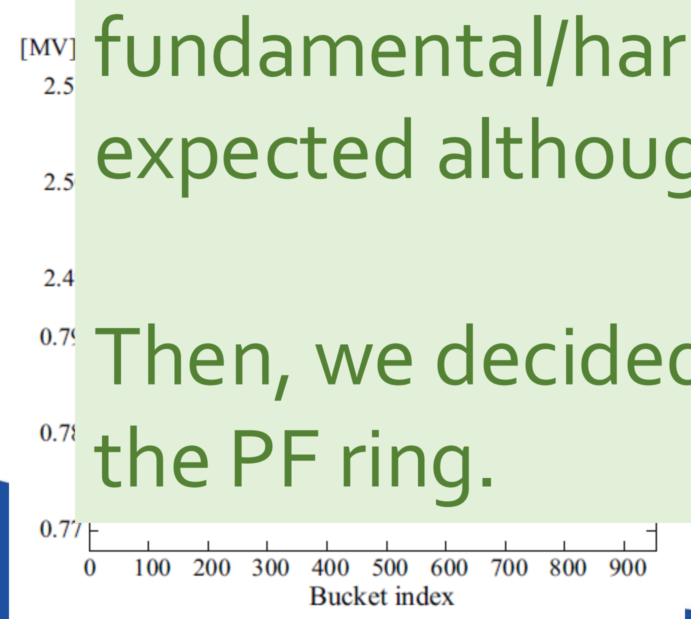
Fig. Concept of active compensation for TBL [Proc. of MCBI2019]

Tab. Kicker cavity parameter

Frequency	500 MHz
R/Q	175 Ω
Unloaded-Q	40000
Cavity number	1
Cavity coupling	199
Loaded-Q	200
3dB bandwidth	2.5 MHz

c) Bunch length along the train

a) M



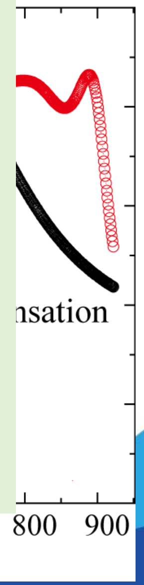
In the calculation, the improvement using fundamental/harmonic cavities instead of the kicker cavity is expected although the effect is limited.

Then, we decided to confirm the feasibility of this method at the PF ring.

0 100 200 300 400 500 600 700 800 900

Bucket index

ignal



D. Naito et al., IPAC2025, WEFN1

Concept of TBL compensation at PF ring

No kicker or Harmonic cavity at the PF ring!!

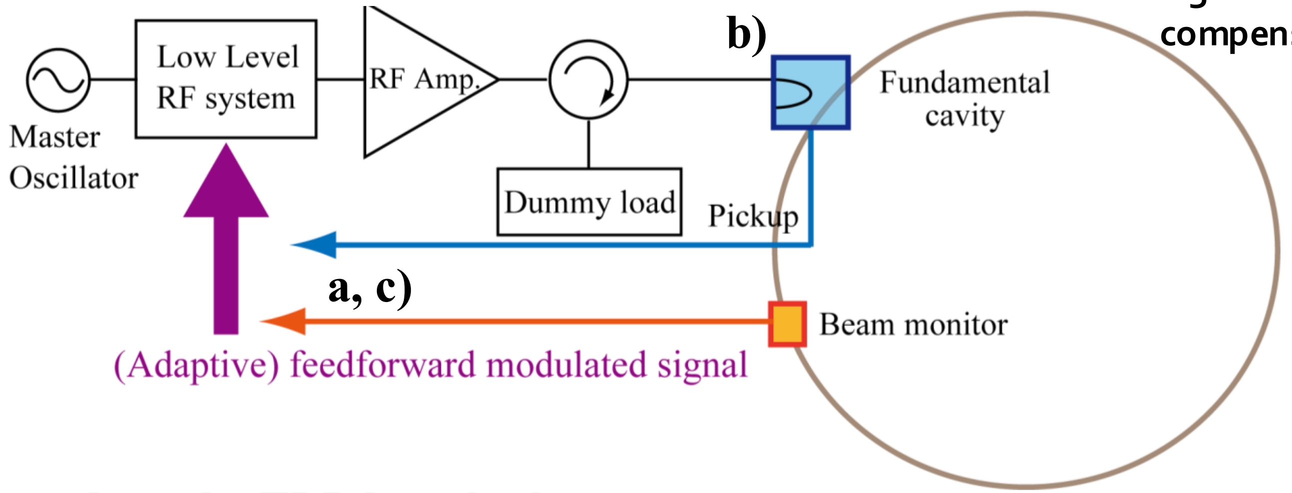
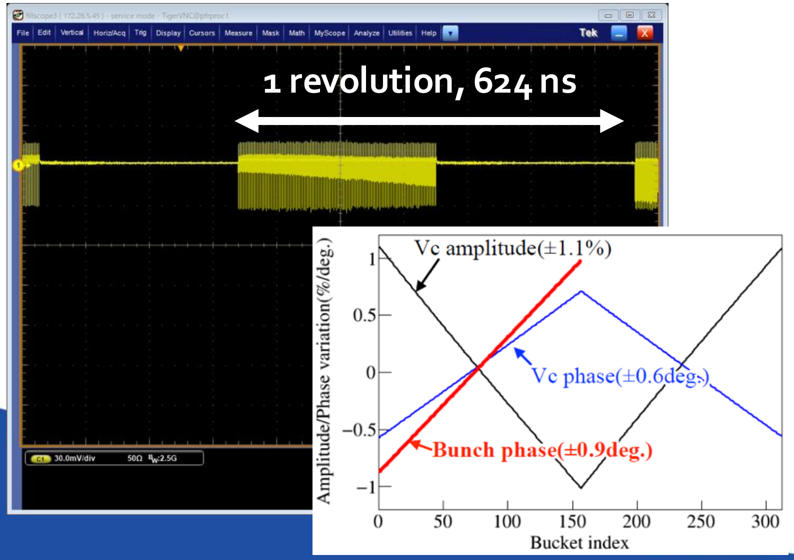


Fig. Concept of active compensation for TBL at PF ring

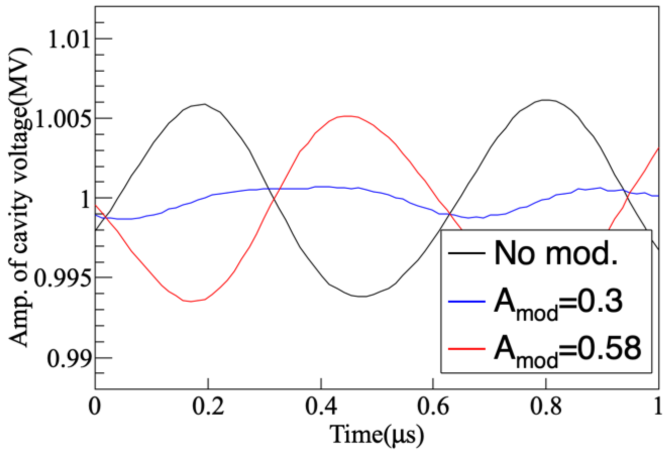
Tab. PF ring parameter

Parameter	Value
Energy	2.5 GeV
Natural emittance	34.6 nm·rad
Radio frequency	500.1 MHz
Number of cavities	4
Harmonic number	312
Number of bunches	156
Beam current	0.1 A
Total cavity voltage	1 MV

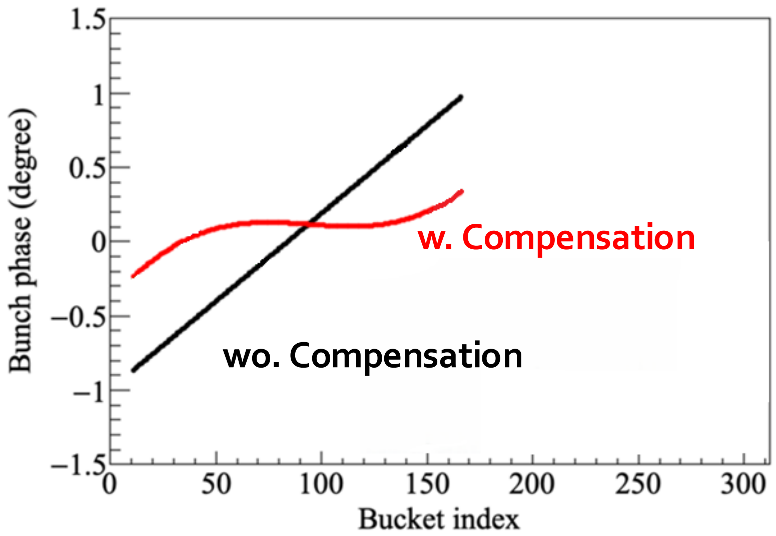
a) Introduce the TBL bunch phase shift using large bunch gap



b) Added modulation signal from the input of the Fundamental cavity



c) Bunch phase along the train w/wo. Compensation signal



Setup of the experimental "demonstration"

D. Naito et al., IPAC2025, WEFN1

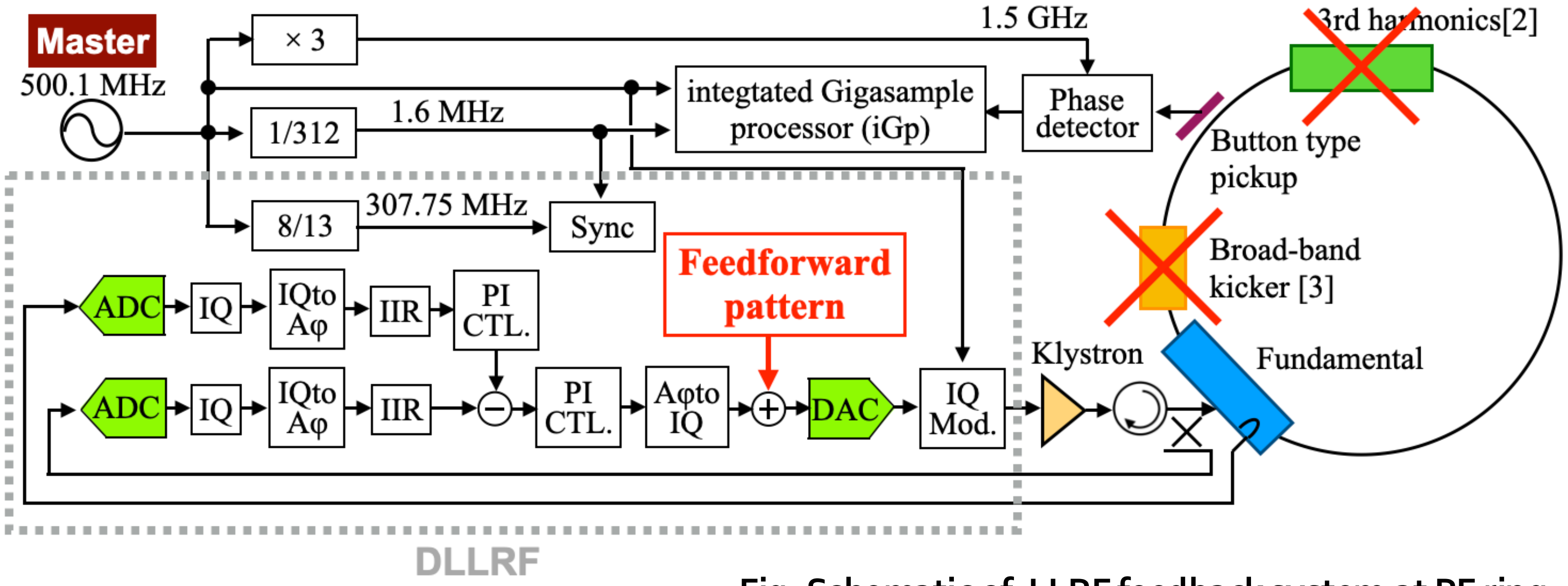


Fig. Schematic of LLRF feedback system at PF ring

Tab. PF ring parameter

Parameter	Value
Energy	2.5 GeV
Natural emittance	34.6 nm·rad
Radio frequency	500.1 MHz
Number of cavities	4
Harmonic number	312
Number of bunches	156
Beam current	0.1 A
Total cavity voltage	1 MV

- Use of the fundamental cavity and it's Digital LLRF system
  - ➢ The DLLRF system was introduced to the PF ring in 2023.
- Bunch signal monitored by button-type pickup is processed using the integrated Giga-sample processor (iGp) as an average of 40,000 turns bunch by bunch (*R.Takai, DIPAC09, pp. 59-61*).
- The FPGA-based Digital LLRF system was used to modulate the rf generator signal.

FPGA-based Digital LLRF system

D. Naito et al., IPAC2024, THPG71

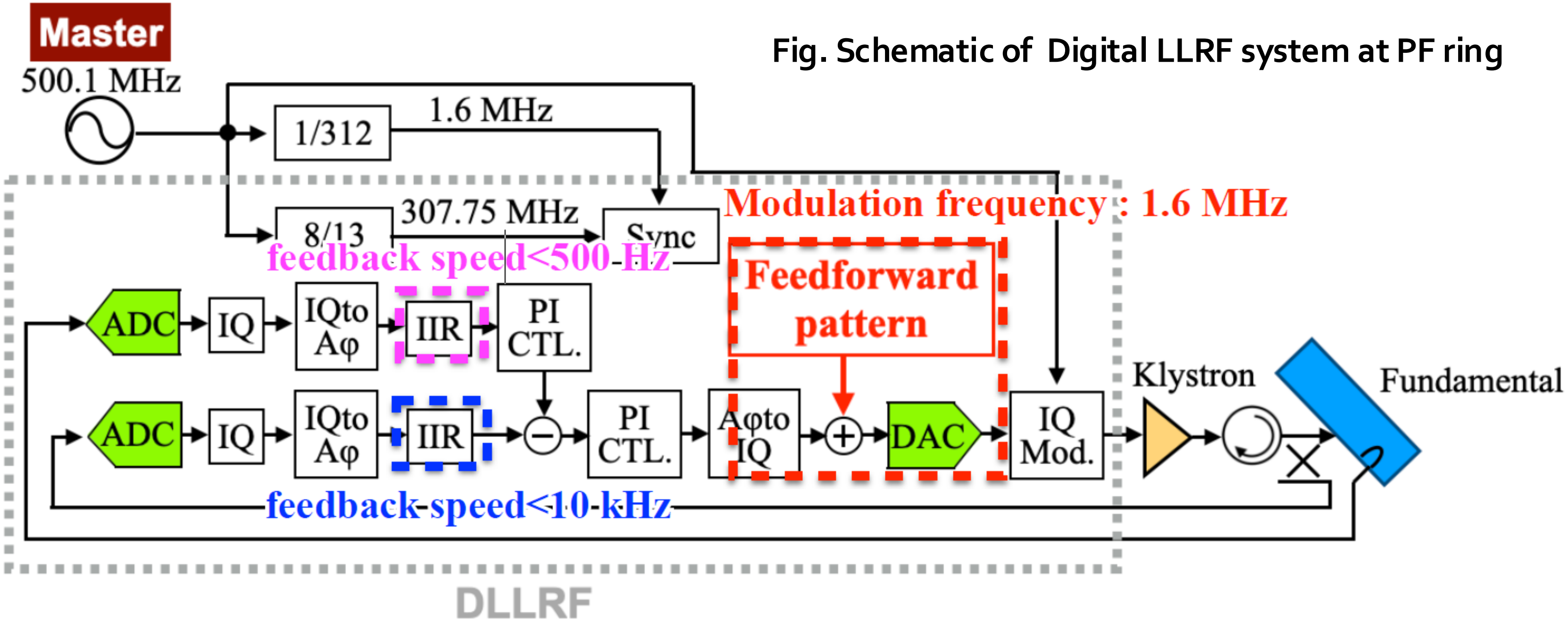
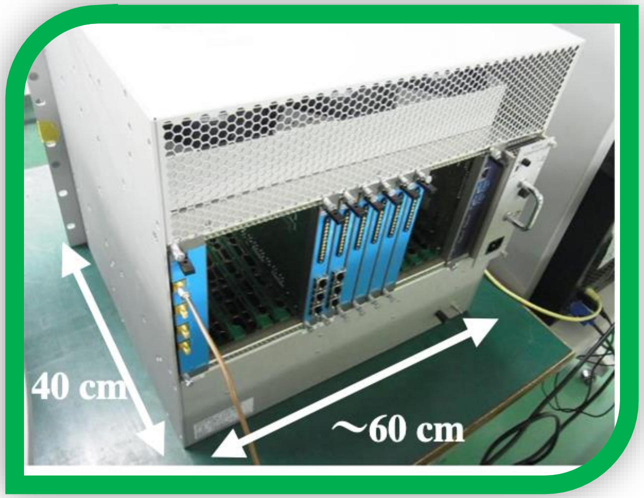


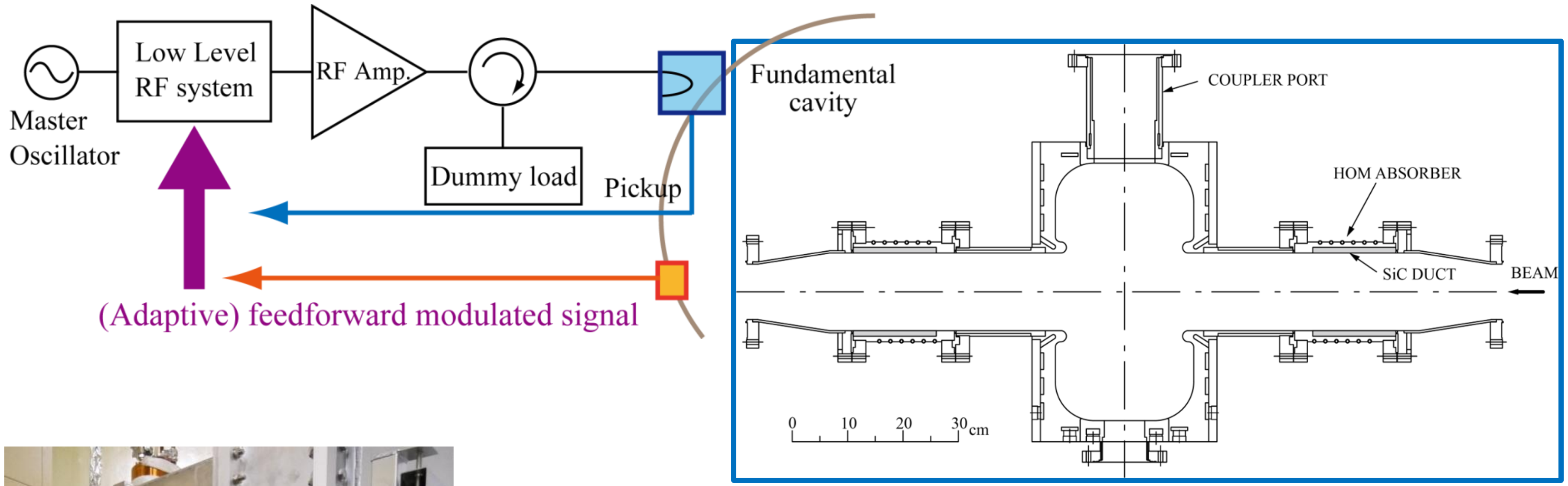
Fig. Schematic of Digital LLRF system at PF ring



- The cavity voltage is controlled by a double feedback loop.
- A FPGA-based Digital system is used to modulate the rf generator signal.
- Arbitrary feedforward pattern of the generator voltage synchronized with the beam revolution can be outputted.
- Thanks to IIR filters in the loop, the feedforward modulation does not affect the feedbacks.

Fundamental cavity

T. Koseki et al., RSI, 66, 1926-1929, 1995



Parameter	Value
Cavity number	4
R/Q, $R=V_c^2/P_C$	174 Ω
Unloaded Q	39,000
Loaded Q	11,818
3dB Bandwidth	21.2 kHz
Filling time	7.5 μs

- Enlarged beam tube structure for HOM damping (higher than cutoff frequency)
- 4 cavities are installed and used for user operation
- 3dB-band width is 21.2 kHz, while the revolution frequency is 1.6 MHz for PF ring

→ When the 1.6MHz modulated signal is inputted, almost power is reflected.

attenuation of the cavity is ~ 32 dB at 1.6 MHz.

modulation amplitudes are limited by the dummy load, ~30 kW.

RF amplifier; Klystron

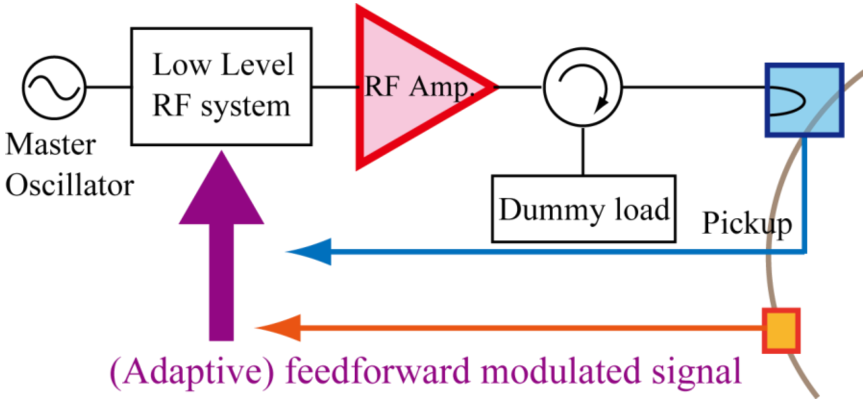
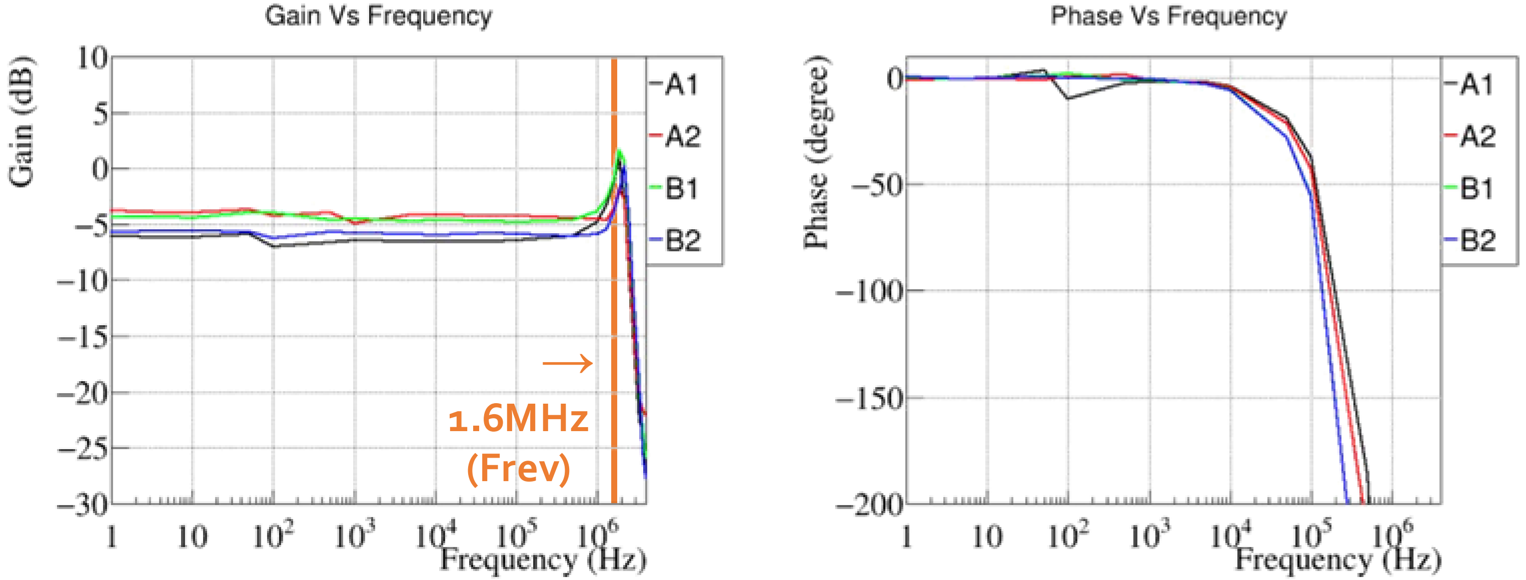


Fig. Klystron responses as a function of input signal frequency



Canon E3774 Klystron
500MHz, 180kW

- 4 x 180kW klystrons are used for user operation
- There is an amplitude resonance around 2MHz (due to the resonant frequency of one of the middle cavity of the klystron)

→ An 1.6MHz modulated signal is used for the TBL compensation.

The klystron response should be taken in account.

Analytical estimation of Modulation signal for generator

Fig.1 Cavity voltage and bunch phase with uniform filling

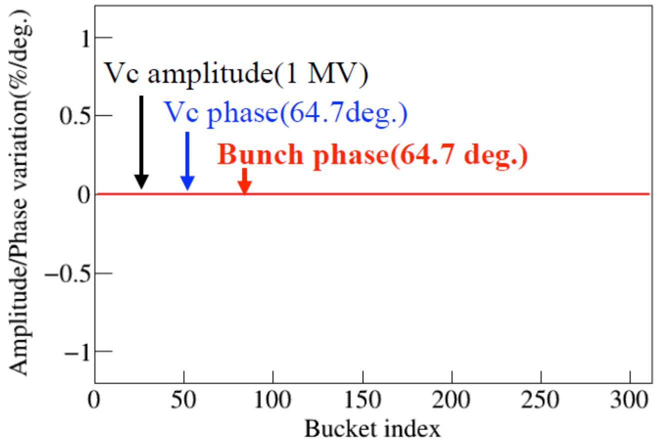


Fig.2 With 156 unoccupied bunch.

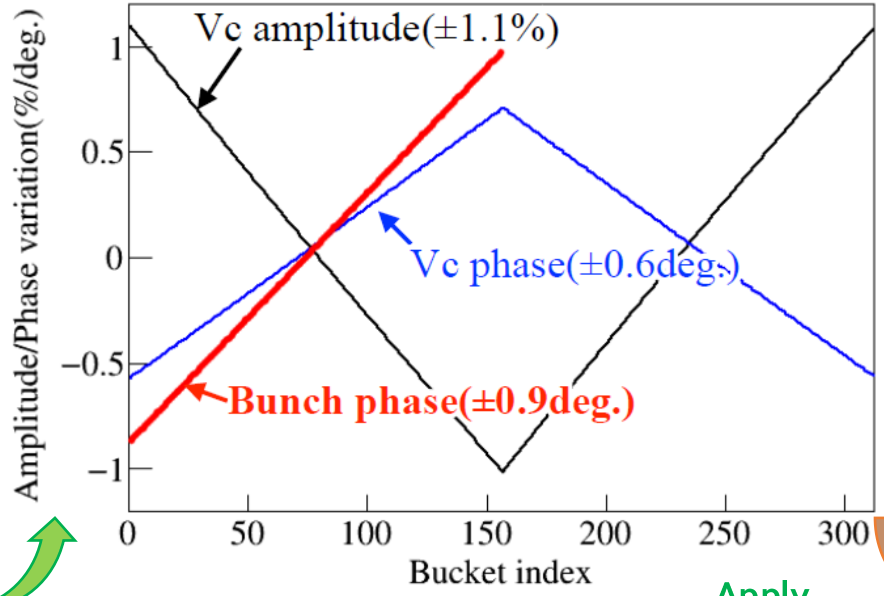
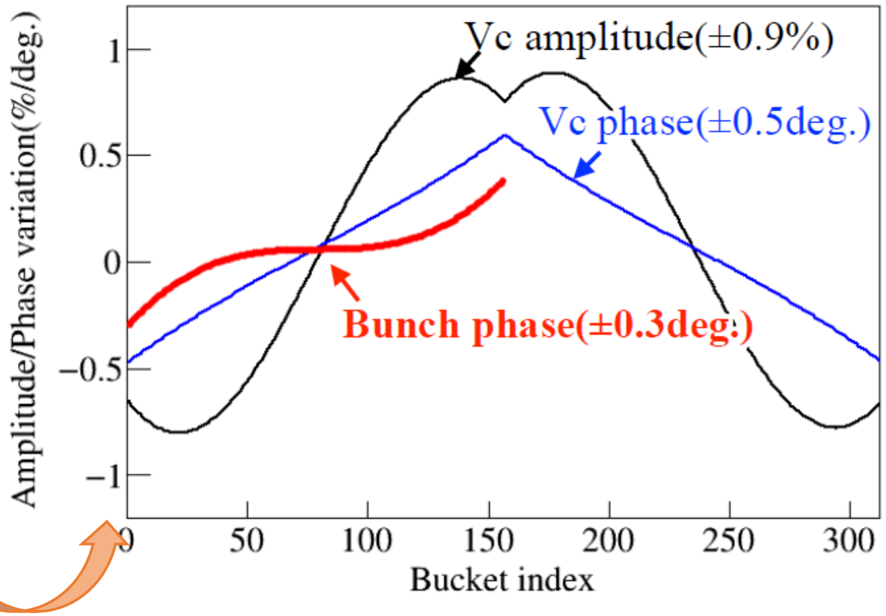


Fig.3 With mod. signal (Amod, θdelay) = (0.014,0) .



Introducing unoccupied 156 buckets

Apply Modulation signal for generator voltage

- Feedforward signal to modulate the amplitude of the generator induced voltage

$$|V_g(t)| = |V_{const}|\left(1 - A_{mod}\cos\left(2\pi f_{rev} t + \theta_{delay}\right)\right)$$

  - Add cosine wave with a revolution frequency (f_{rev} = 1.6 MHz)
  - Clock of the FPGA, resolution of ***t***, is 13 ns (76.94 MHz = 500.1 MHz x 2 / 13)

Analytical estimation of Modulation signal for generator with Klystron

Feedforward signal to the generator induced voltage

$$|V_g(t)| = |V_{const}| \left(1 - A_{mod}\cos(2\pi f_{rev} t + \theta_{delay})\right)$$

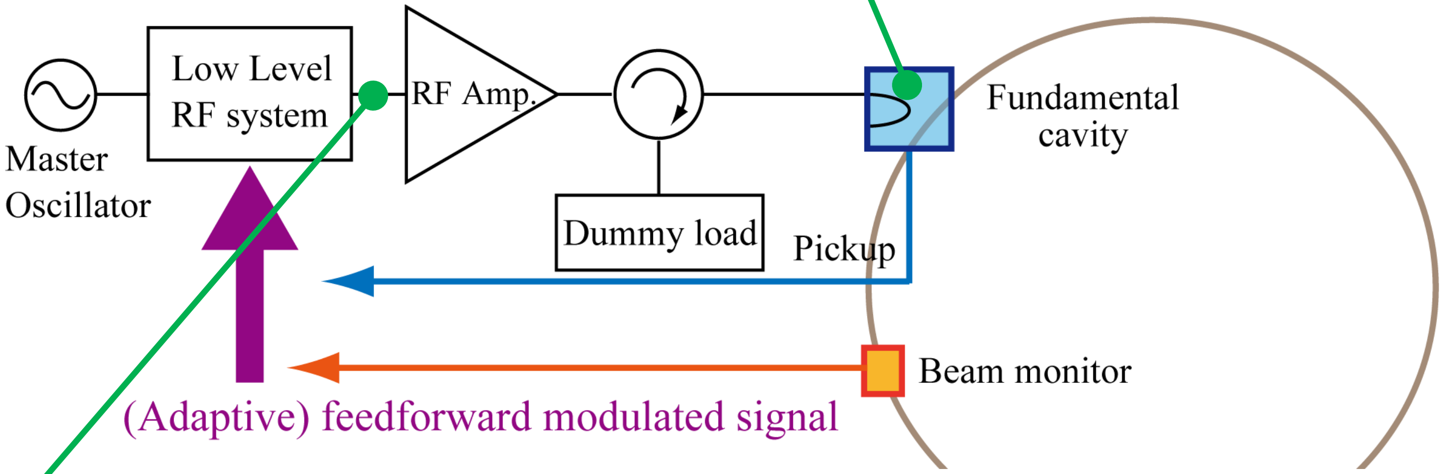
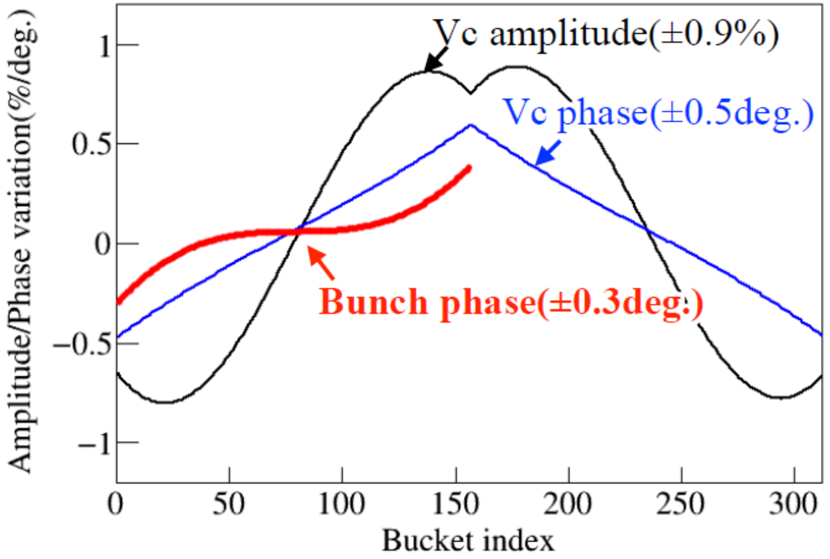


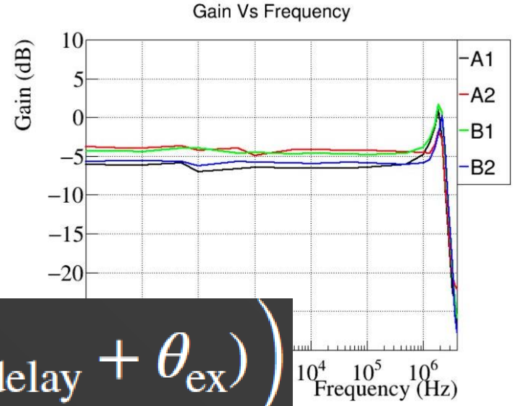
Fig.3 With mod. signal (Amod, θdelay) = (0.014,0) .

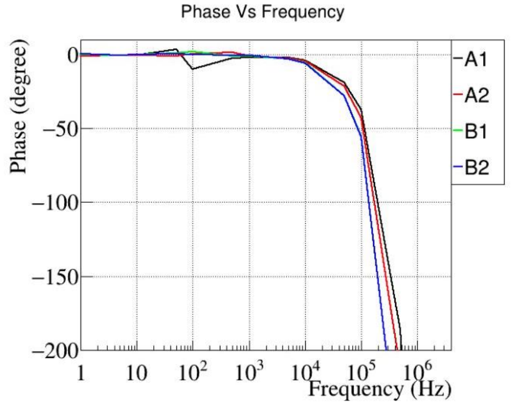


- At the exit of the LLRF system , responses of the cavity and klystron should be considered.
  - ➢ Attenuation due to bandwidth of the cavity (32 dB)
  - ➢ Amplitude-to-Phase conversion in the klystron

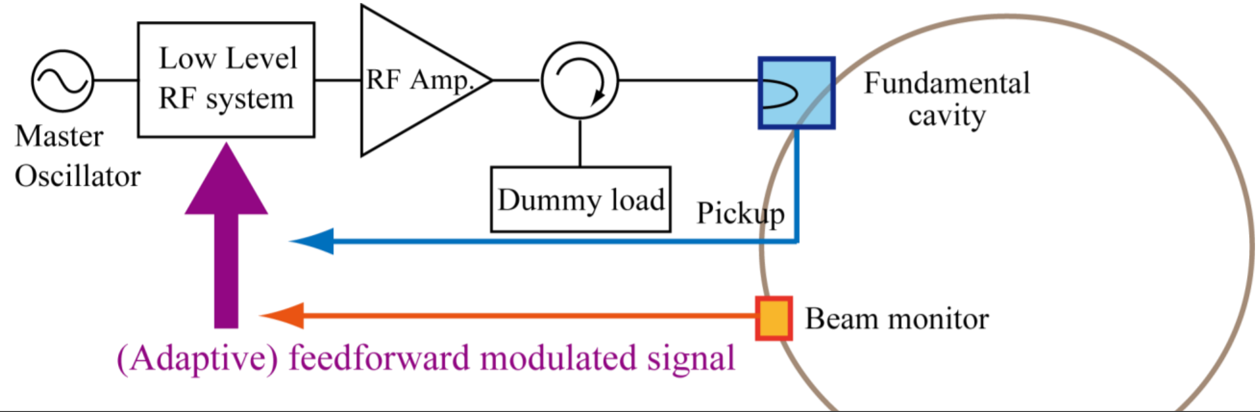
$$V_g(t) = |V_{const}| \left(1 - A_{mod}\cos(2\pi f_{rev} t + \theta_{delay})\right)$$

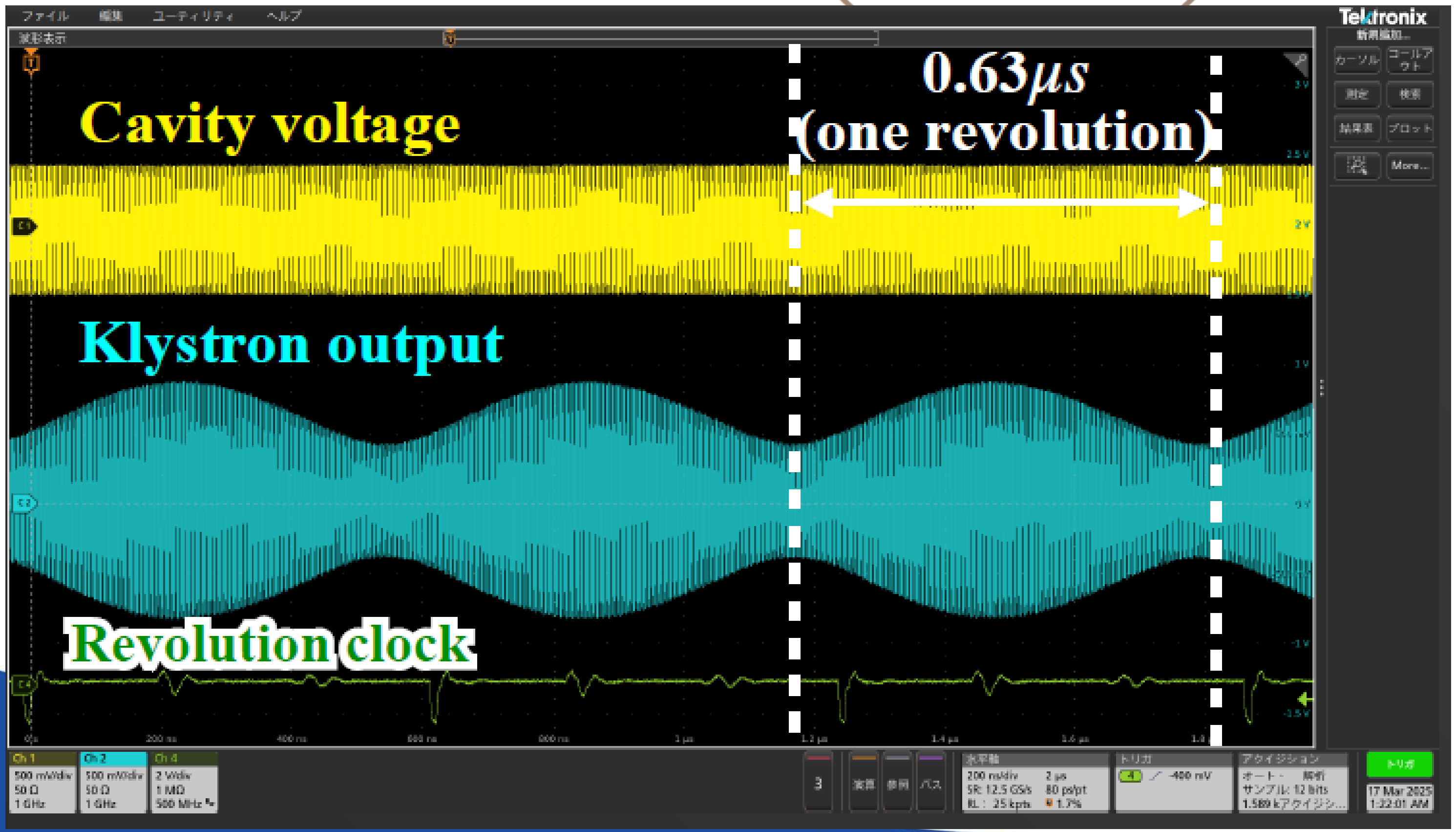
$$\cos\left(2\pi f_{RF} t - P_{ex}\cdot A_{mod}\cos(2\pi f_{rev} t + \theta_{delay} + \theta_{ex})\right)$$





Experimental result





Parameter	Value
Energy	2.5 GeV
Natural emittance	34.6 nm·rad
Radio frequency	500.1 MHz
Number of cavities	4
Harmonic number	312
Number of bunches	156
Beam current	0.1 A
Total cavity voltage	1 MV

Selected To enhance the TBL effect

Nominal values are 0.45mA and 1.7MV.

To increase power margin of the input signal and to reduce the cavity reflection power

Experimental result

- As predicted by the semi-analytical calculation, the bunch phase shift along the bunch index can be successfully mitigated by adding the modulation signal.

Parameter	Value
Energy	2.5 GeV
Natural emittance	34.6 nm·rad
Radio frequency	500.1 MHz
Number of cavities	4
Harmonic number	312
Number of bunches	156
Beam current	0.1 A
Total cavity voltage	1 MV

Fig.1 Observed bunch phase shift w/wo. modulation signals

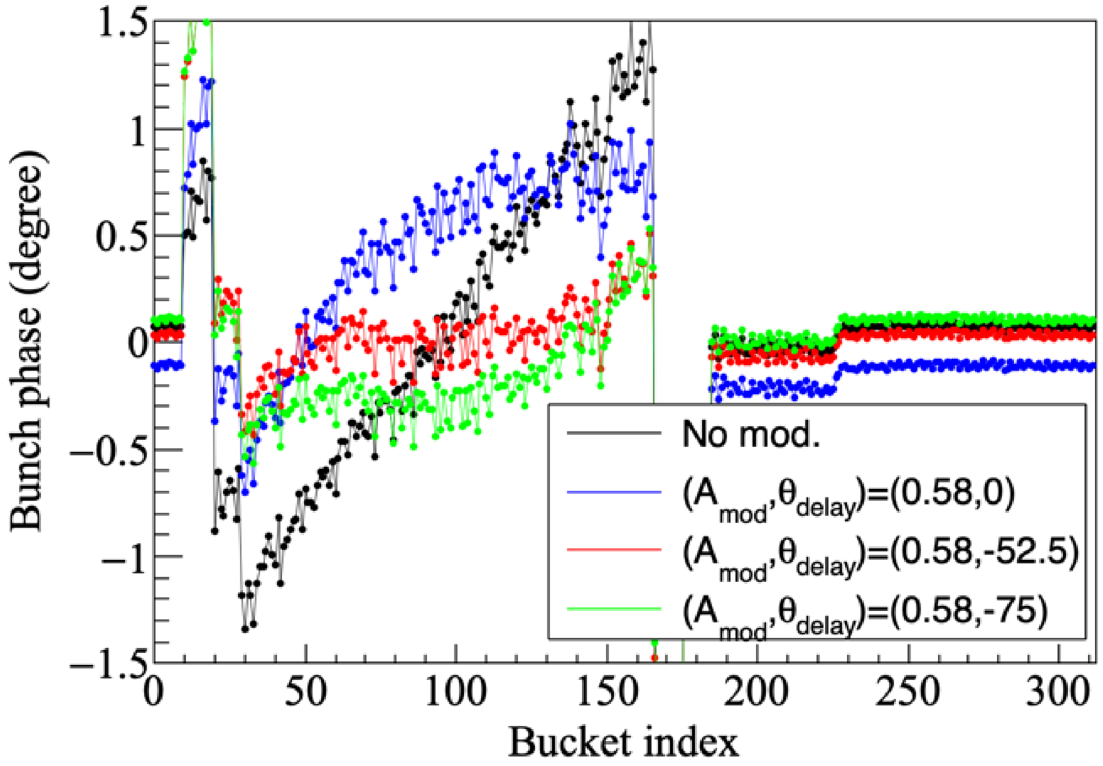
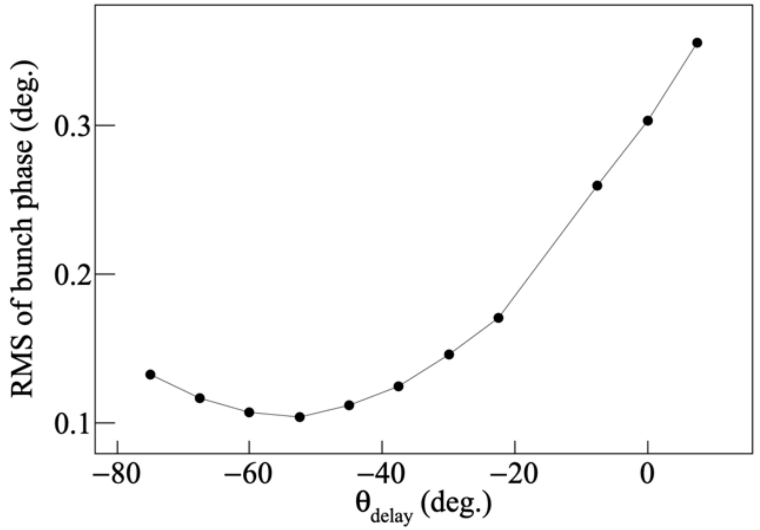


Fig.2 RMS bunch phase within 40 and 150 buckets



Experimental result vs Analytical estimation

- The analytical calculation reproduce the observed results well.

Fig.1 Observed bunch phase shift w/wo. modulation signals

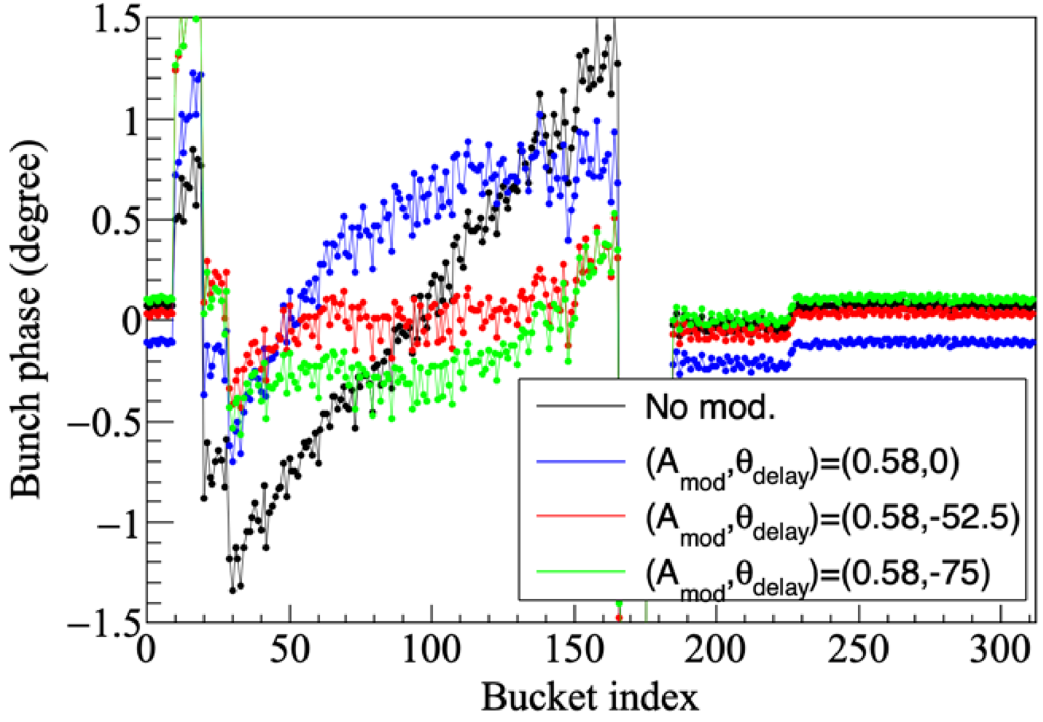
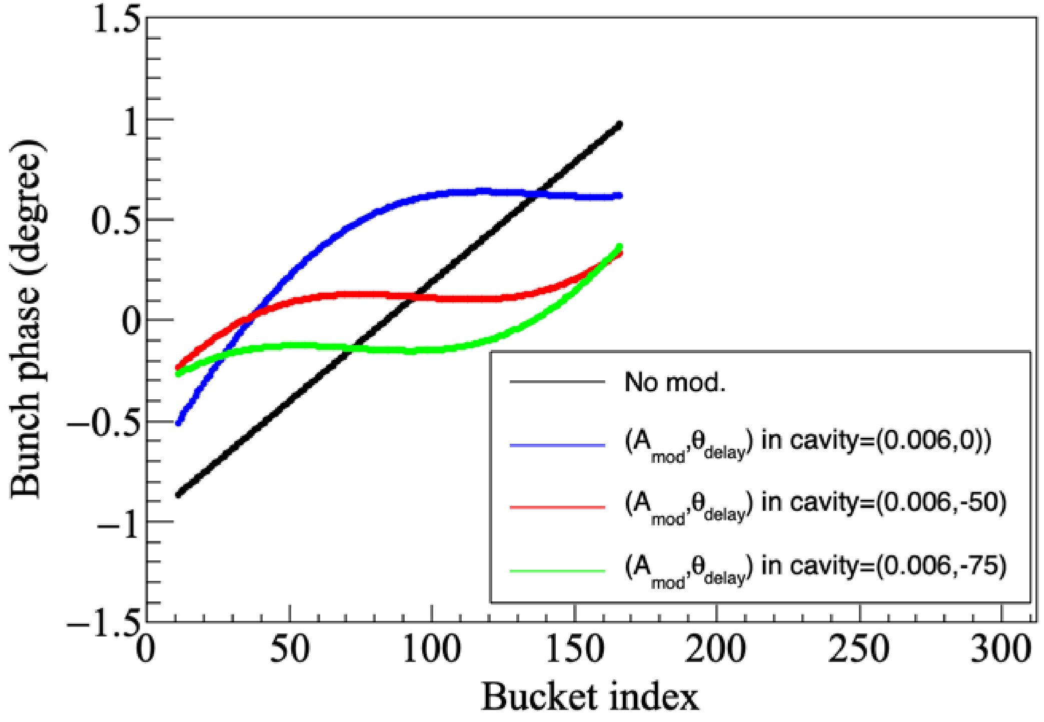


Fig.2 Analytical calculation w/wo. modulation signals



Experimental result vs Analytical estimation

- The analytical calculation suggests better results.
- However, it could not be tested due to the limitation of the dynamic range of the LLRF output and the power of cavity reflection.

Fig.1 Analytical calculation w/wo. modulation signals

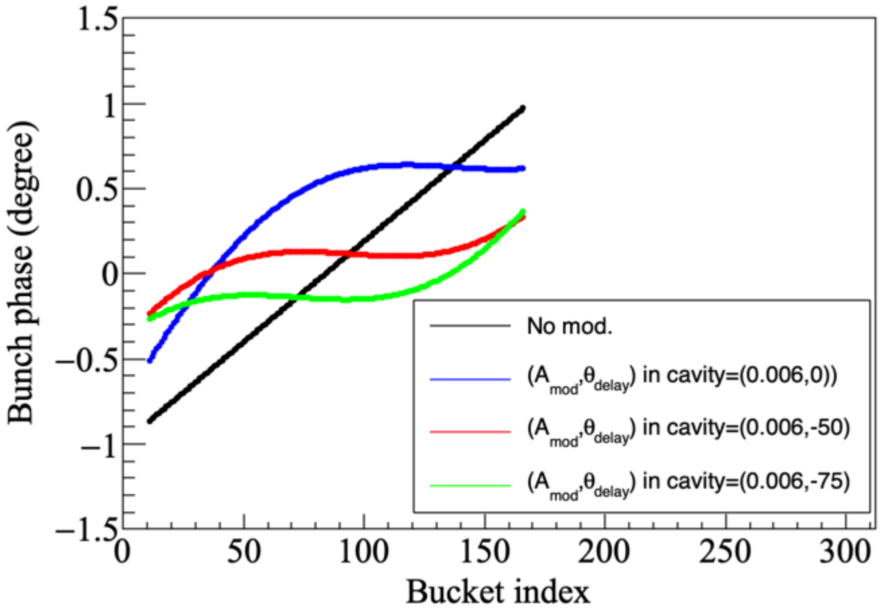
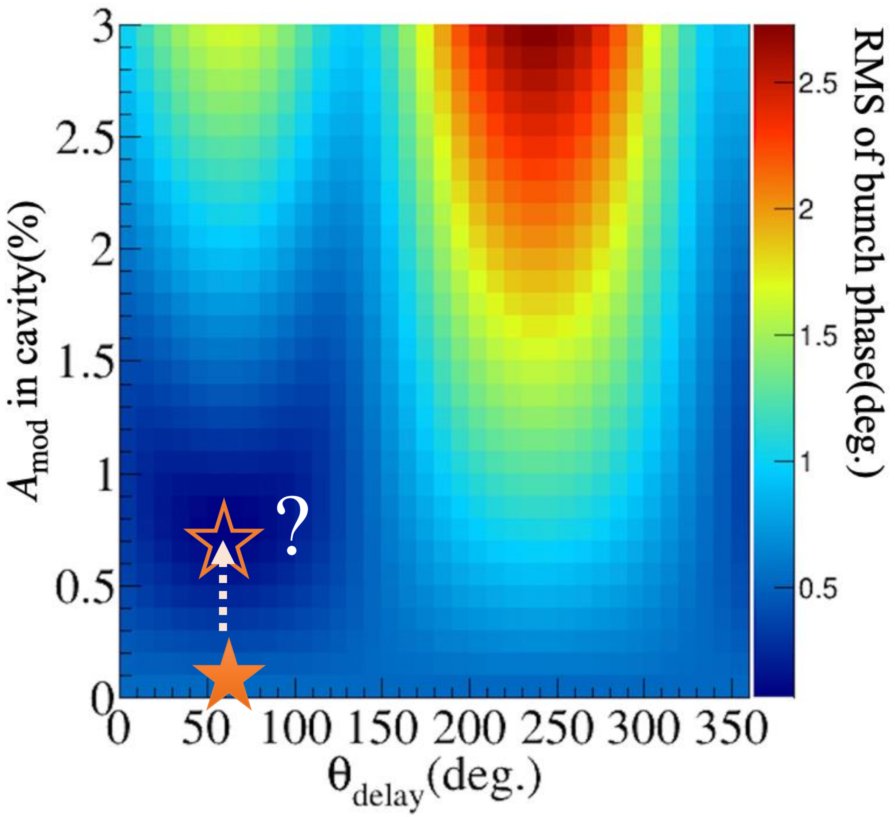
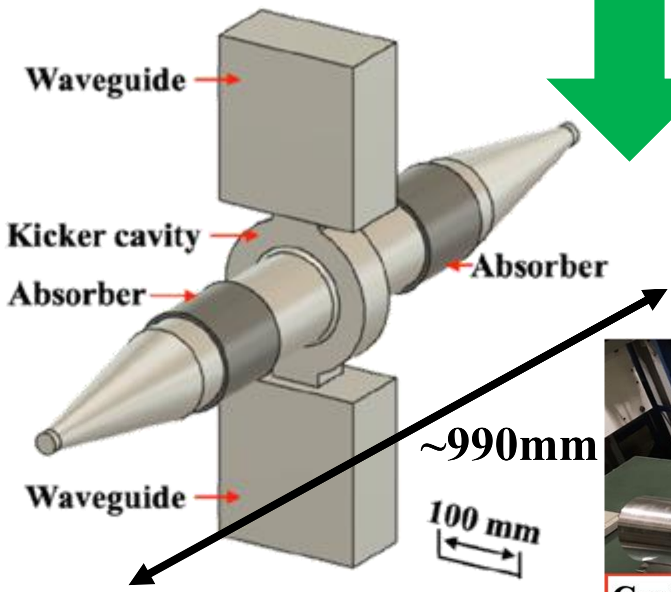


Fig.2 Rms bunch phase dependence on the parameter of the signals (analytical calculation)



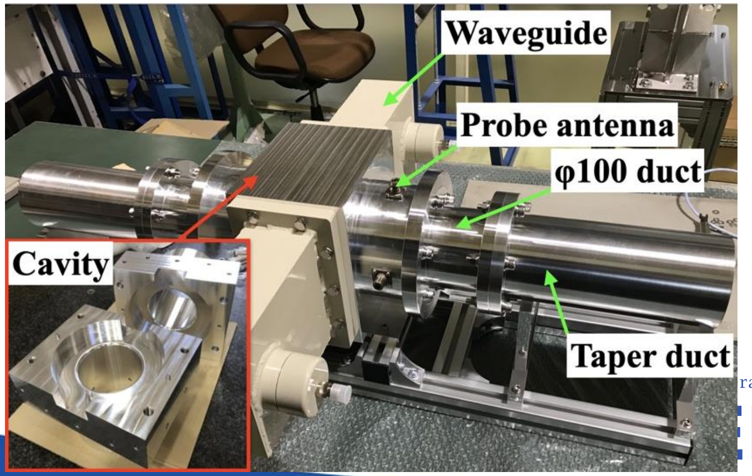
Toward further improvement

- TBL mitigation with a harmonic cavity having low R/Q and high Q.
- A broadband kicker cavity
- Advanced LLRF system with integrated bunch phase monitor



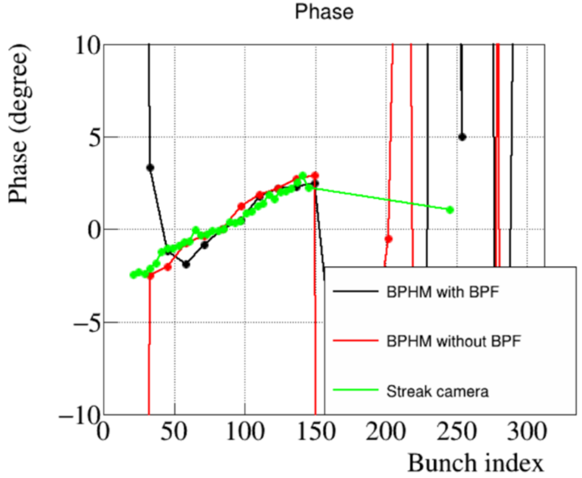
Fres = 1.500GHz
R/Q = 60Ω
Qo = 17,937
QL = 292

Low power model



D. Naito et al., PRAB, (accepted on 2025 Oct 22)

Integrated Bunch Phase Monitor (iBPhM)



Configuration of KEK-PF Digital LLRF system
- μTCA.4 technology
- Non-IQ Direct Sampling method
- Sampling frequency = 307.75 MHz, F_{rf} x 8/13
- Synchronized to Revolution clock (1.6MHz, PF)
- BPhM Data rate = ~ 1kHz (average 100-turn)

D. Naito et al., PASJ2021, THOA01.

Summary

- To improve the bunch lengthening performance, TBL compensation method by using an adaptive feedback are considered.
- As a first step, feasible study using a fundamental cavity and FPGA-based LLRF was performed at the PF 2.5 GeV ring.
    - ➢ The TBL compensation was successfully demonstrated, and the bunch phase variation was reduced from $\pm 1.5^{\circ}$ to $\pm 0.4^{\circ}$.
    - ➢ Considering the klystron and cavity responses, the behaviors can be reproduced by analytical calculations.

- A broad band kicker cavity, fast bunch phase monitor and harmonic cavity having low R/Q are also being developed.

Gracias por su atención.