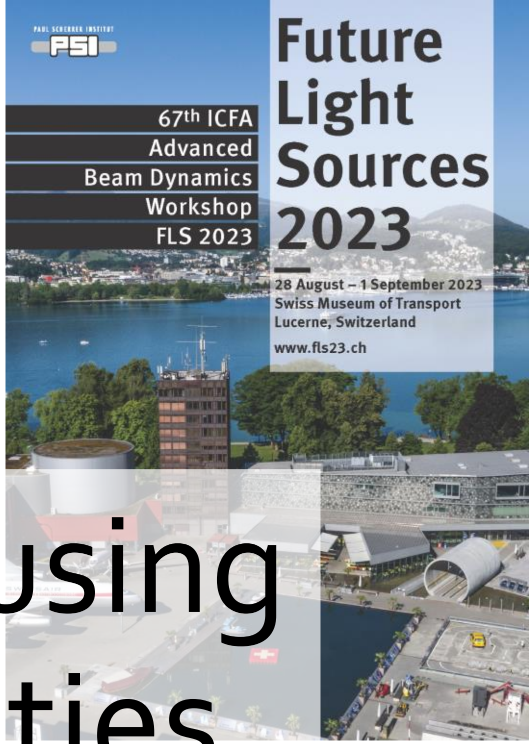
Future light sources 2023
MO3B3 :Working Group B, Storage Ring Light Sources
ID2061

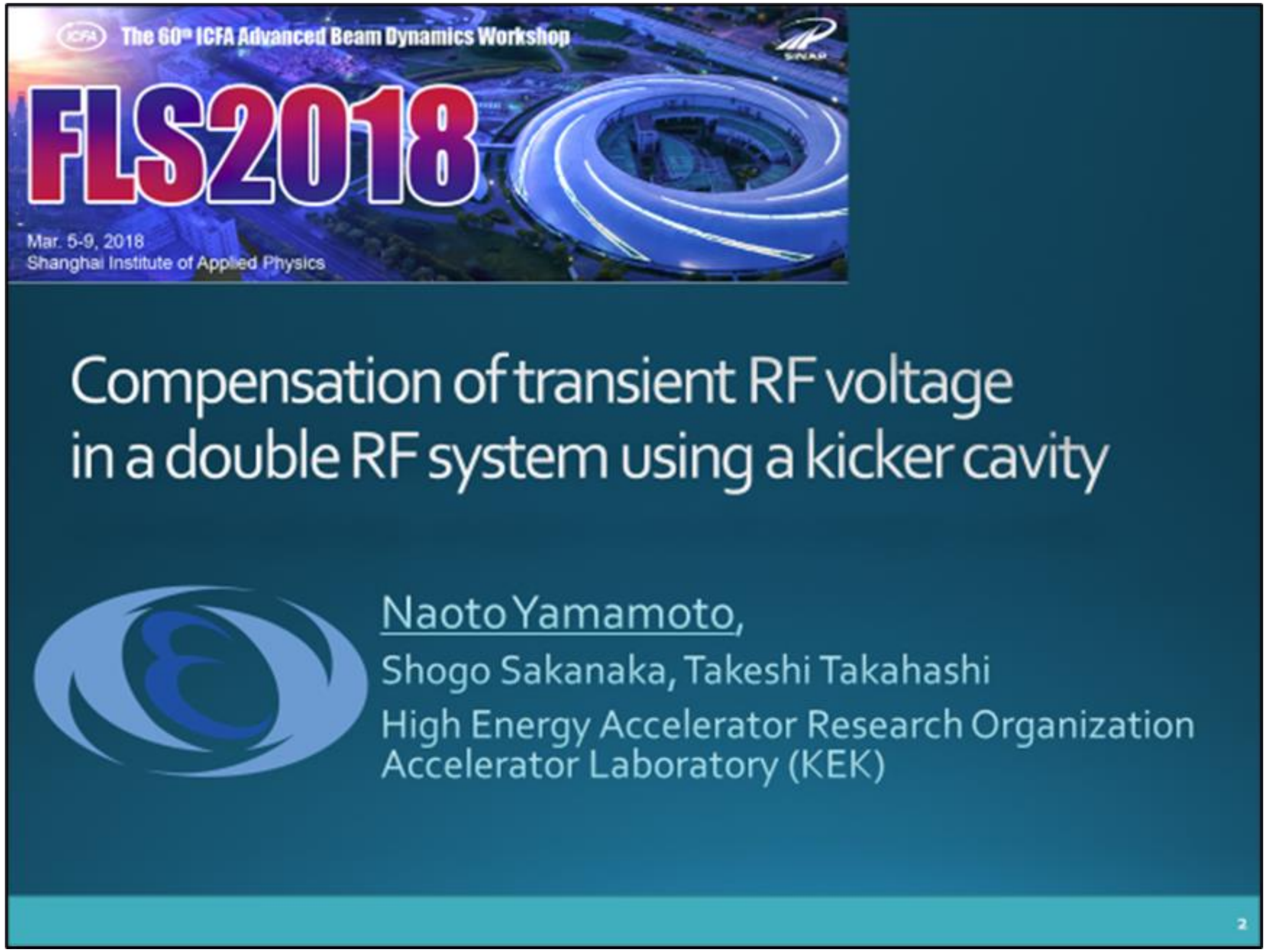


Bunch-lengthening RF system using active normal-conducting cavities

Naoto Yamamoto
Daichi Naito, Shogo Sakanaka, Takaaki Yamaguchi
(KEK, Ibaraki Japan),
Alexis Gamelin, Patrick Marchand, Ryutaro Nagaoka
(SOLEIL, Gif-sur-Yvette France)

Insight through Accelerators.
KEK

Introduction



At FLS2018,

a proposal for a bunch lengthening system concept using a normal-conducting cavity are made.

Based on this idea, we continue to design and develop the system.

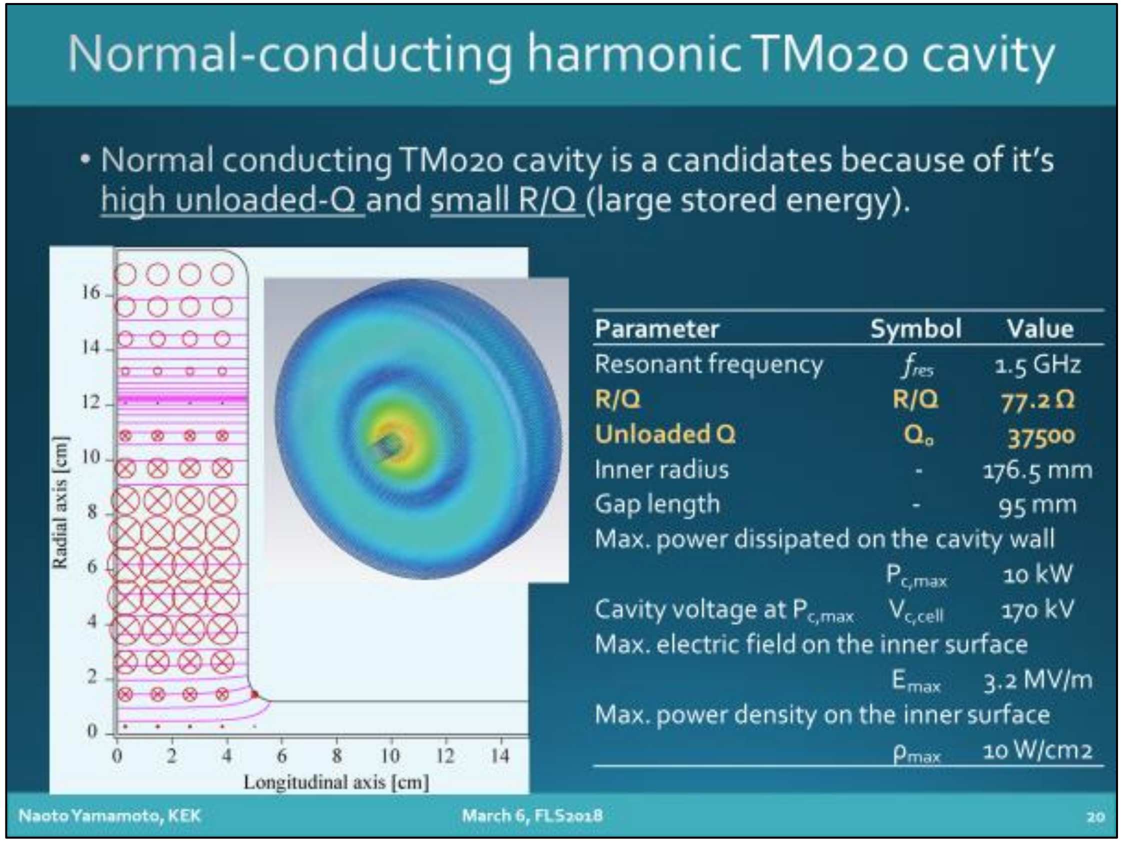
Today, I would like to report the progress on these developments.

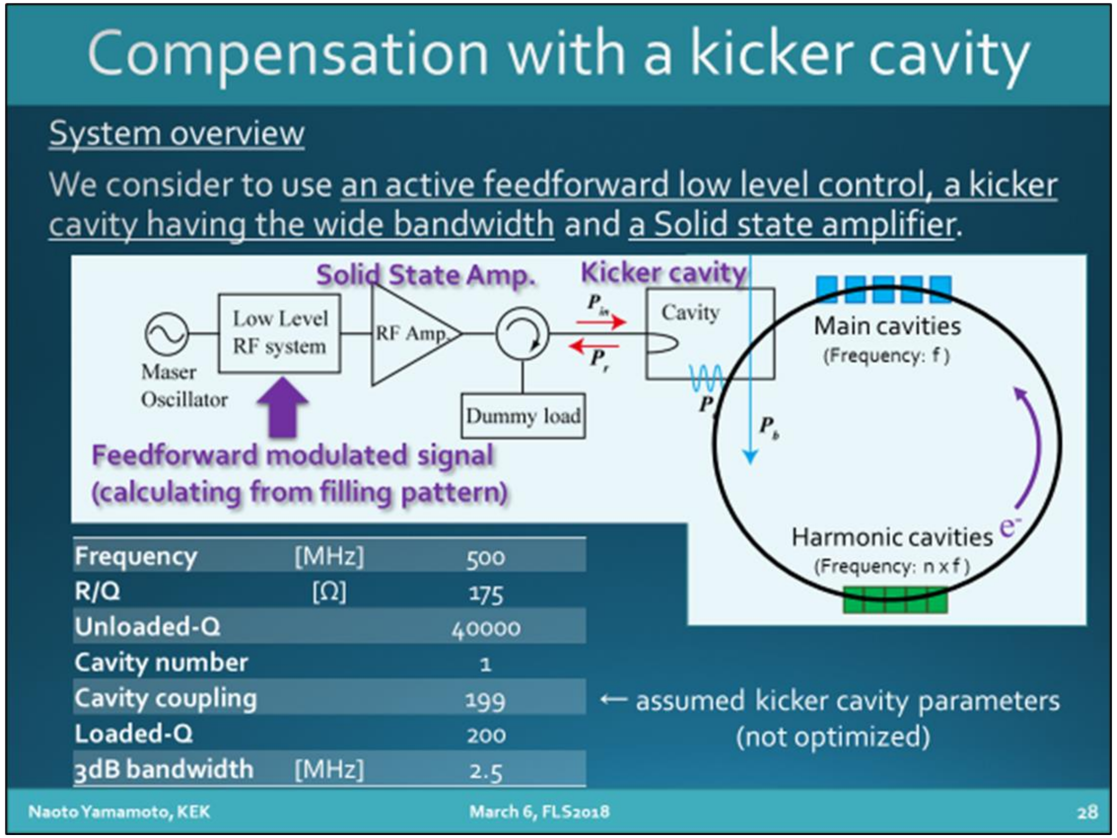
Outline

- Active Normal-conducting bunch-lengthening system
  - Proposal of system configuration
    - ☐Harmonic cavities with small total R/Qs.
    - ☐NC harmonic cavities having rf external generator
    - ☐Advanced LLRF control & a broadband kicker cavity

- Hardware developments
  - 1.5GHz-TM020 Harmonic cavity
  - Broadband Kicker cavity
  - Bunch Phase monitor

Proposal of system configuration (cont.)





- Harmonic cavities with small total R/Qs.
- NC harmonic cavities having rf external generator
- Advanced LLRF control & a broadband kicker cavity

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Harmonic cavities with small total R/Qs

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- ☐NC harmonic cavities having rf external generator
- ☐Advanced LLRF control & a broadband kicker cavity

Lower total R/Qs for RF cavities mitigate the Transient beam loading and the beam instability “Periodic transient beam loading (PTBL)”.

Harmonic cavities with small total R/Qs

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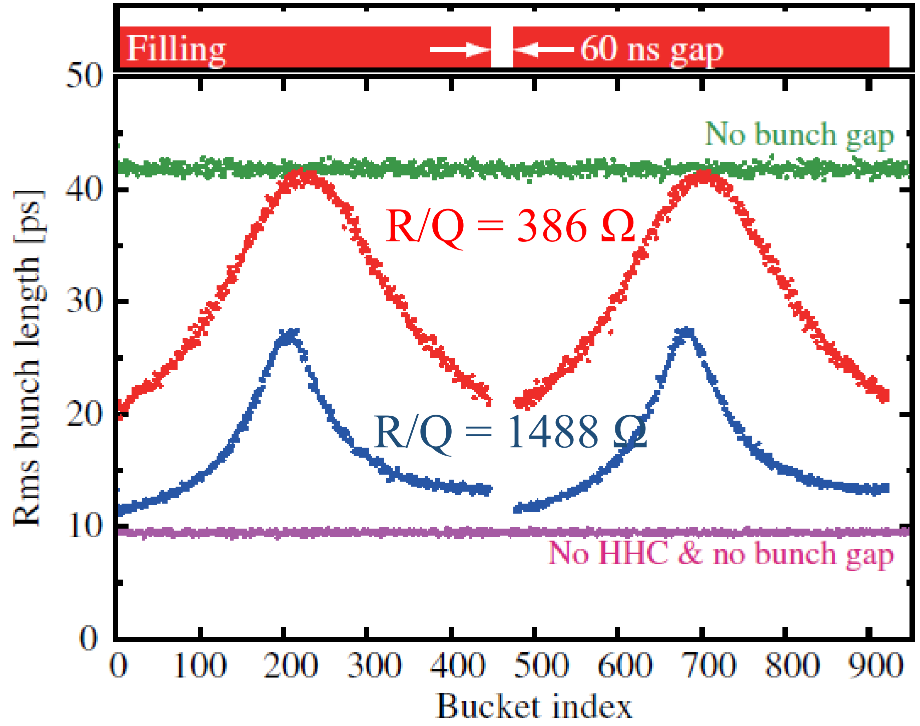
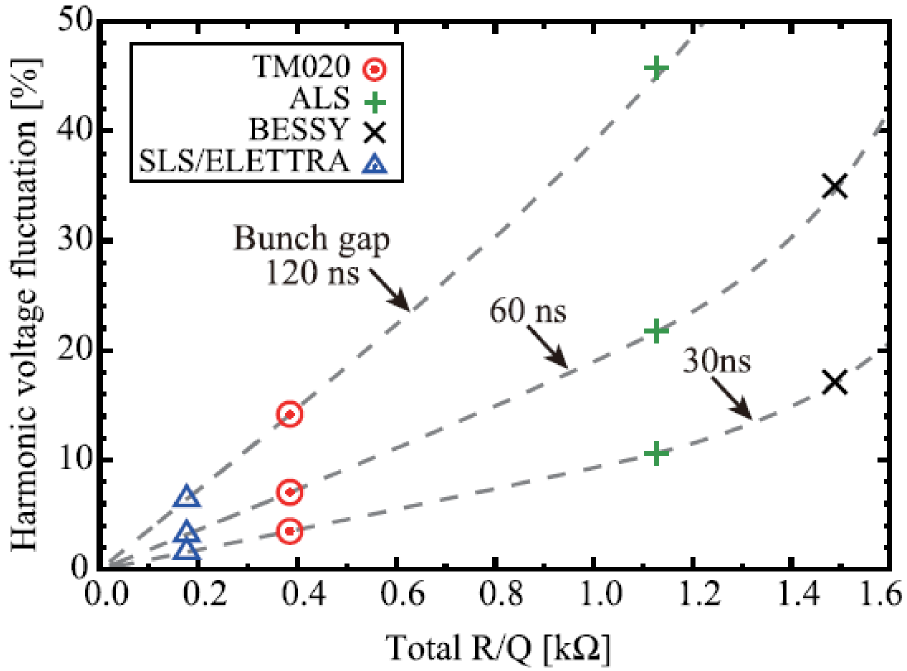
*N. Yamamoto, et al., "Reduction and compensation of the transient beam loading effect in a double rf system of synchrotron light sources", PRAB 21, 012001 (2018).

Bunch length along the bunch index
Fig. 3 of Ref.1



Voltage fluctuation vs Total R/Q;
Fig. 7 of Ref.1 (analytical estimation)



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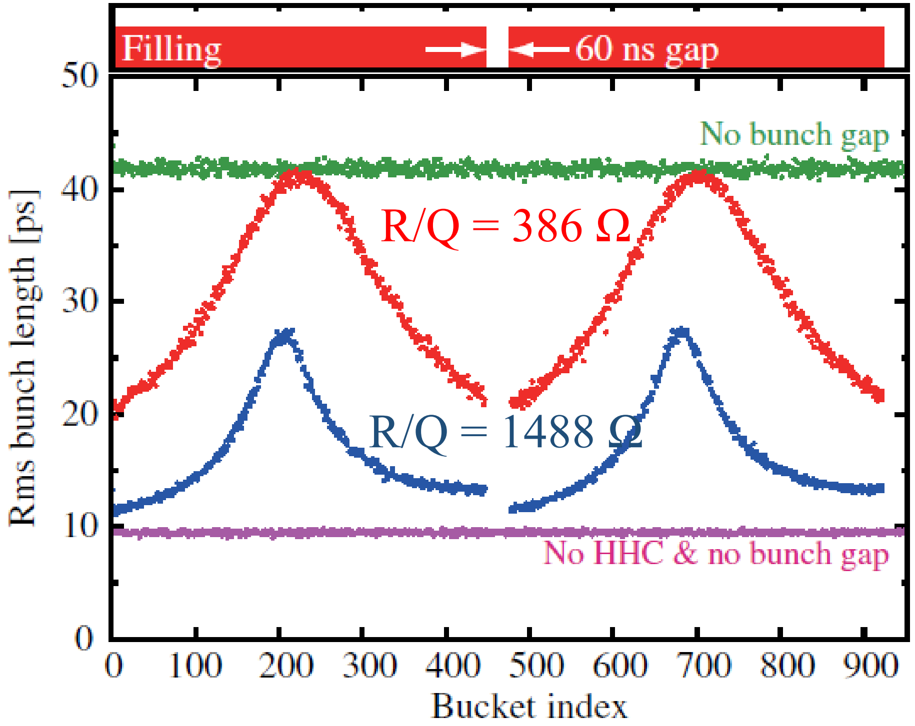
Harmonic cavities with small total R/Qs

Lowe… …he Transient beam loading and the beam insta… …ng (PTBL)".

It is known that the bunch-lengthening performance is limited when the bunch gaps are introduced in the fill pattern.

N. Yamamoto, et al., "Reduction and compensation of the transient beam loading effect in a double rf system of synchrotron light sources", PRAB 21, 012001 (2018).

Bunch length along the bunch index
Fig. 3 of Ref.1



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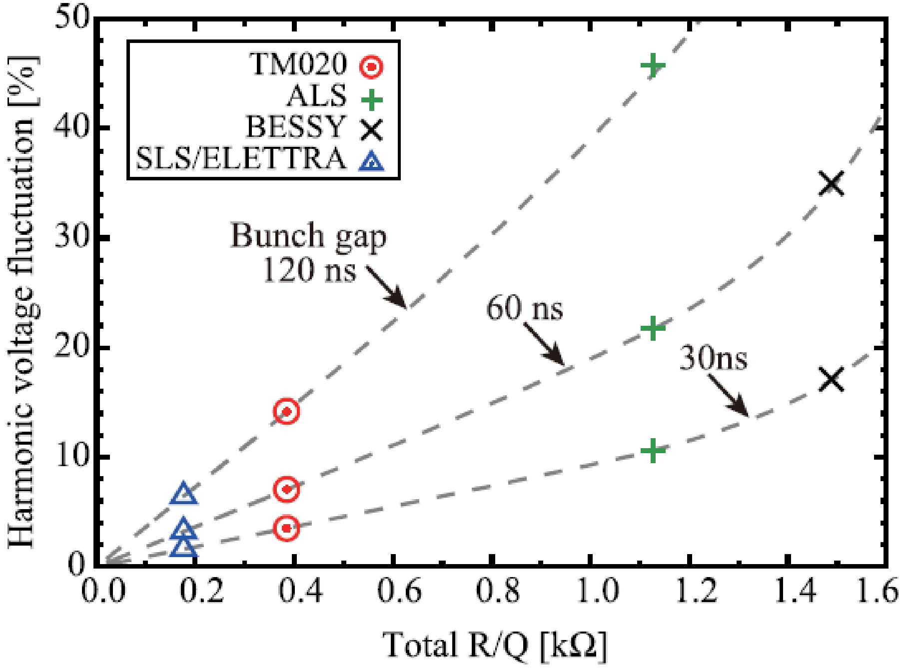


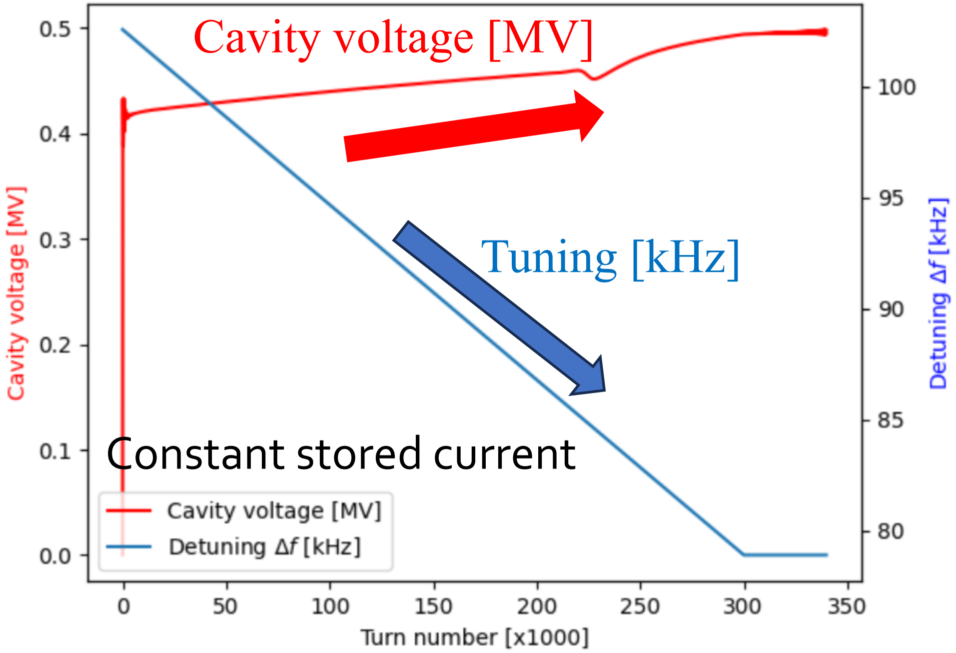
Harmonic cavities with small total R/Qs

Lower total R/Qs for RF cavities mitigate the Transient beam loading and the beam instability "Periodic transient beam loading (PTBL) ".[*1,2]

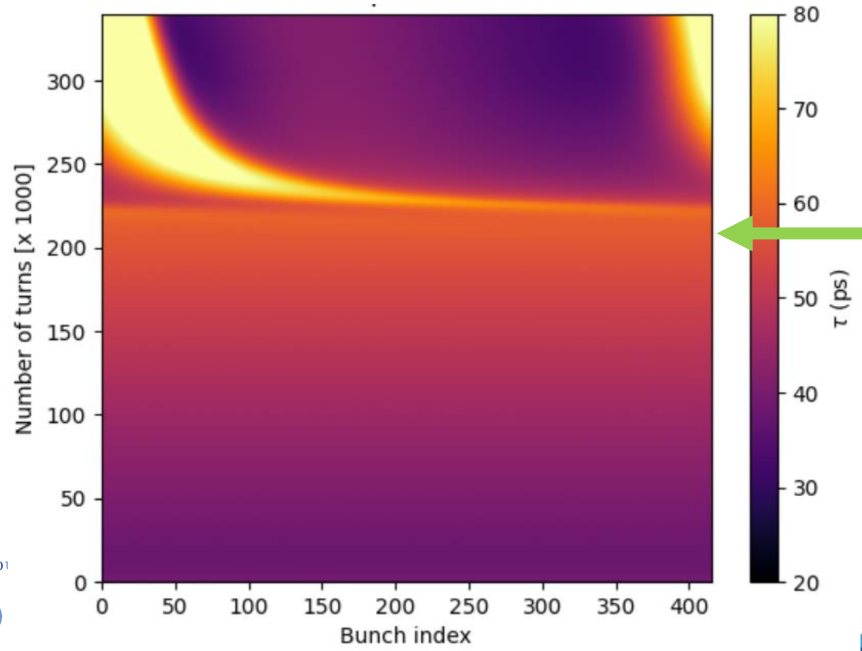
*1 M. Venturini, *PRAB* 21, 114404, 11 2018.
*2 T. He *et al.*, *PRAB* 25, 024401, 2 2022

Typical behavior of PTBL (MBTRACK2 Tracking simulation result)

Turn number vs HC detuning &voltage



Bunch length evolution with turn number



Threshold detuning.

Har… small total R/Qs

It is known that this instability prevent from reaching the flat-potential condition at high beam current.

Low… …he Transient beam loading and the beam instability “Periodic transient beam loading (PTBL) “.[*1,2]

*1 M. Venturini, *PRAB* 21, 114404, 11 2018.
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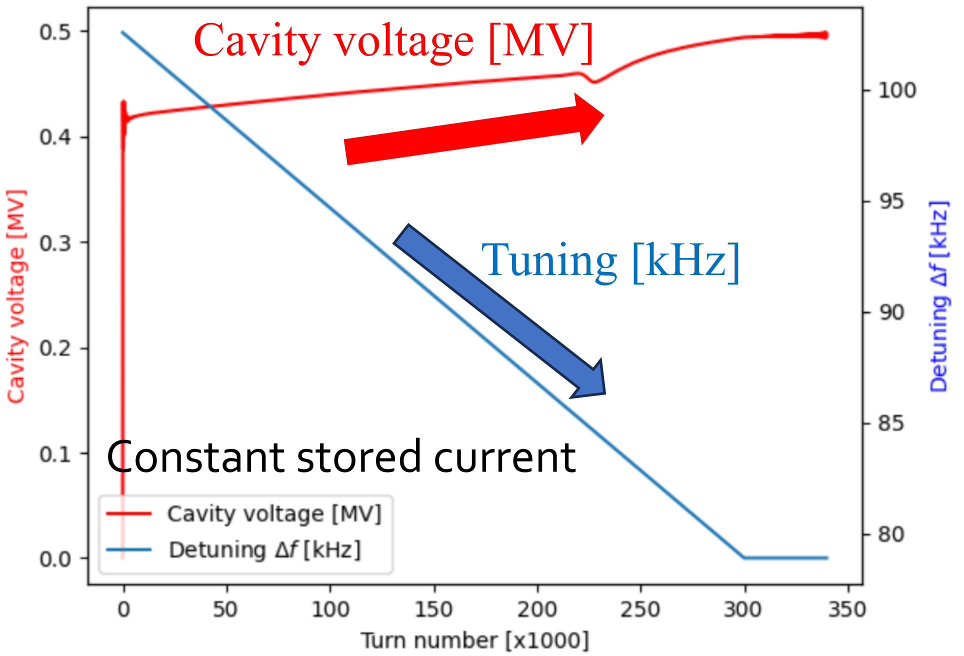

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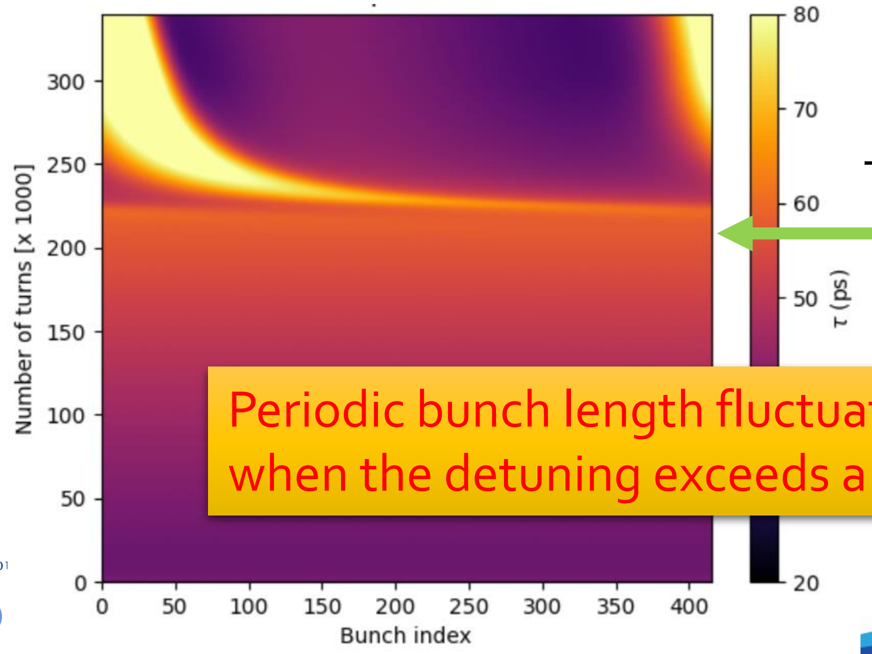

Threshold detuning.

Periodic bunch length fluctuation begins when the detuning exceeds a certain threshold.

Harmonic cavities with small total R/Qs

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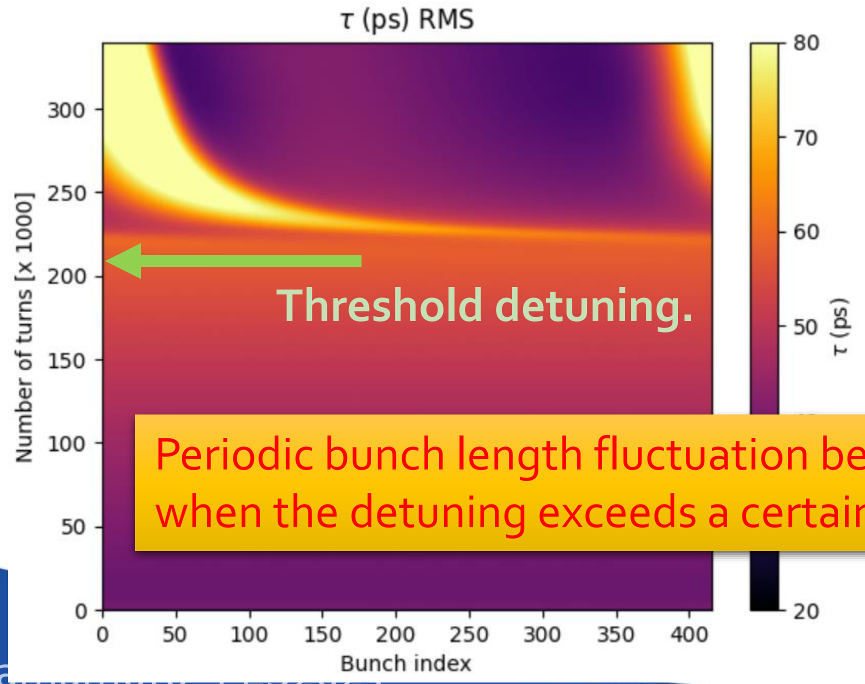
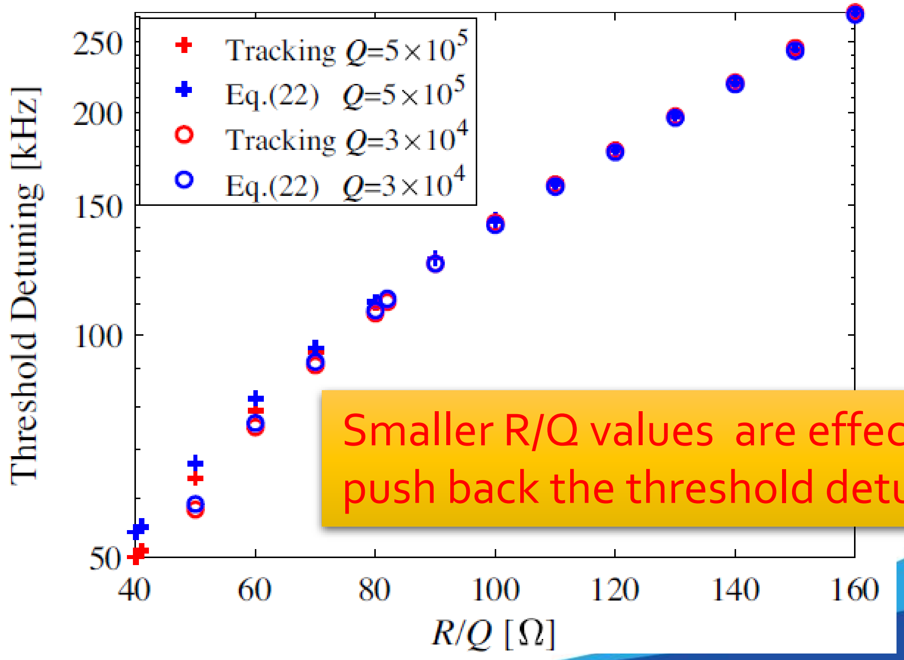


Periodic bunch length fluctuation begins when the detuning exceeds a certain threshold.

Fig. Threshold detuning vs Total R/Q
T. He et al., PRAB 25, 094402, 9 2022



Smaller R/Q values are effective to push back the threshold detuning .

Insight through Accelerators. KEK

NC harmonic cavities having rf external generator

- Harmonic cavities with small total R/Qs.

➢NC harmonic cavities having rf external generator

☐Advanced LLRF control & a broadband kicker cavity

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The external generator of an active HC can provide sufficient voltage to lengthen the bunches even at a low stored current (operation with a single or few bunches)

I believe this is important to maintain a wide use of the synchrotron radiation in the future light sources by preserving all the operating modes available in third-generation light sources.

NC harmonic cavities having rf external generator

The external generator of an active HC can provide sufficient voltage to lengthen the bunches even at a low stored current (operation with a single or few bunches)

Feasibility study of an active HC for the SOLEIL-II ring
(MBTRACK2 Tracking simulation result)

The relevant bunch lengthening factors (BLFs) can be achieved for all the operating modes without special RF feedback.

Table 3: Summary of Bunch Lengthening Performance

HC setup	Bunch length	BLF
Multi bunch 500 mA		
one HC	33.6 ps	4.0
one Passive HC ($\beta = 0$)	34.2 ps	4.0
Single bunch 20 mA		
one HC	38.8 ps	4.6
8-bunch 100 mA		
one HC	30.0 ps	3.5

High Current

Low Current

Table 1: SOLEIL Upgrade Parameters (v0356)

Parameter	Unit	Value
Energy, E_0	GeV	2.75
RF frequency	MHz	351.6
Energy loss per turn (no ID), U_0	keV	458
Main RF voltage, $V_{c,1}$	MV	1.80
Energy spread		8.9×10^{-4}
Momentum compaction factor, α		1.1×10^{-4}
Longitudinal damping time, τ_e	ms	12.2
Synchrotron frequency w/o. HC	kHz	1.78
Natural rms bunch length	ps	8.5

Table 2: Cavity Parameters of the Double Rf System

Parameter	MC	HC (2 cell)
Harmonic number, n	1	4
Shunt Impedance, $R_s = V_c^2/2P_c$	5.0 MΩ	2.4 MΩ
Unloaded-Q, Q_0	35,000	27,000
Cavity coupling coefficient, β	5.0	1.0
Cavity number	4	1~3

EU-cavity

ESRF-type TM020 cavity

Detailed in N. Yamamoto et al., PASJ2022, WEP059, 2022.

Advanced LLRF system & a broadband kicker cavity

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Countermeasures for performance degradations due to Transient beam loading effect and unstable beam motion, such as PTBL.

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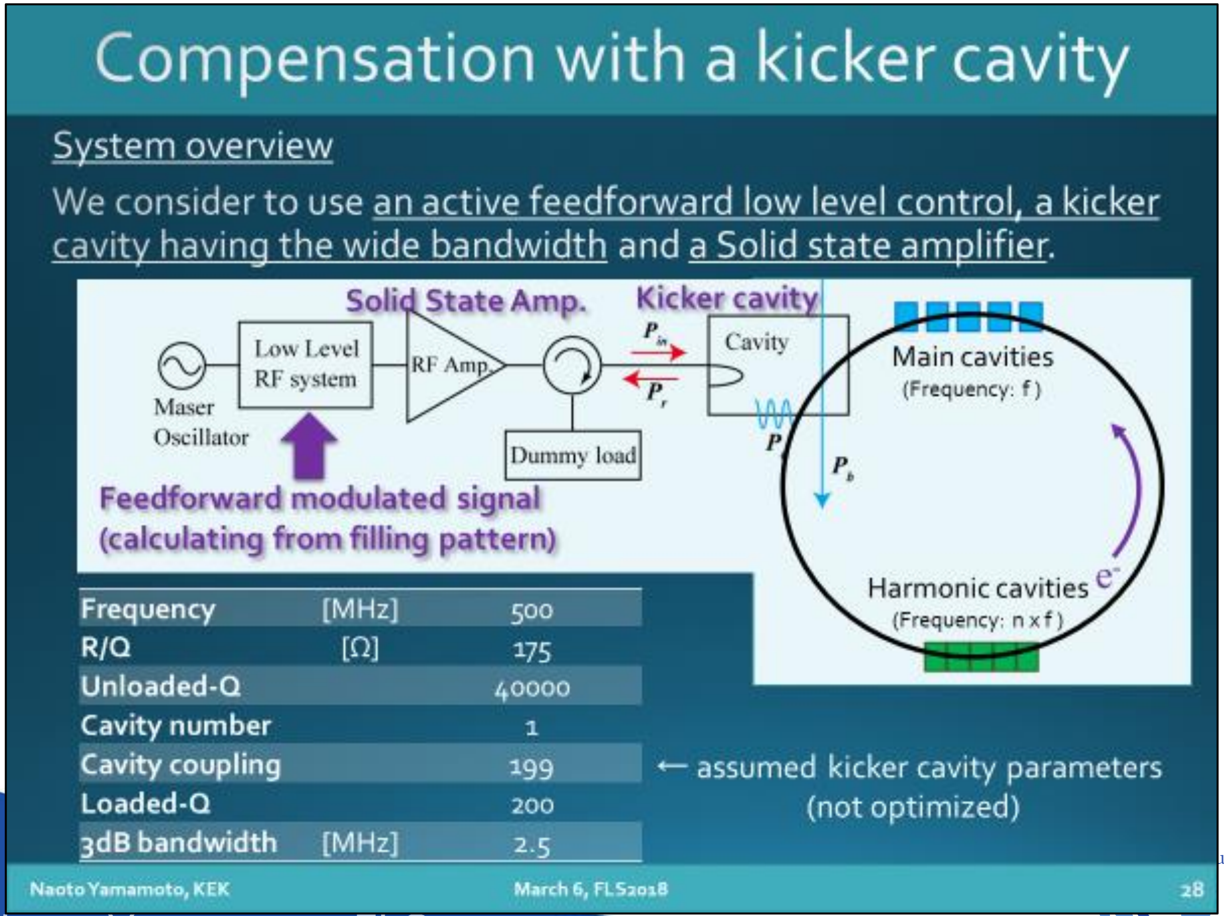
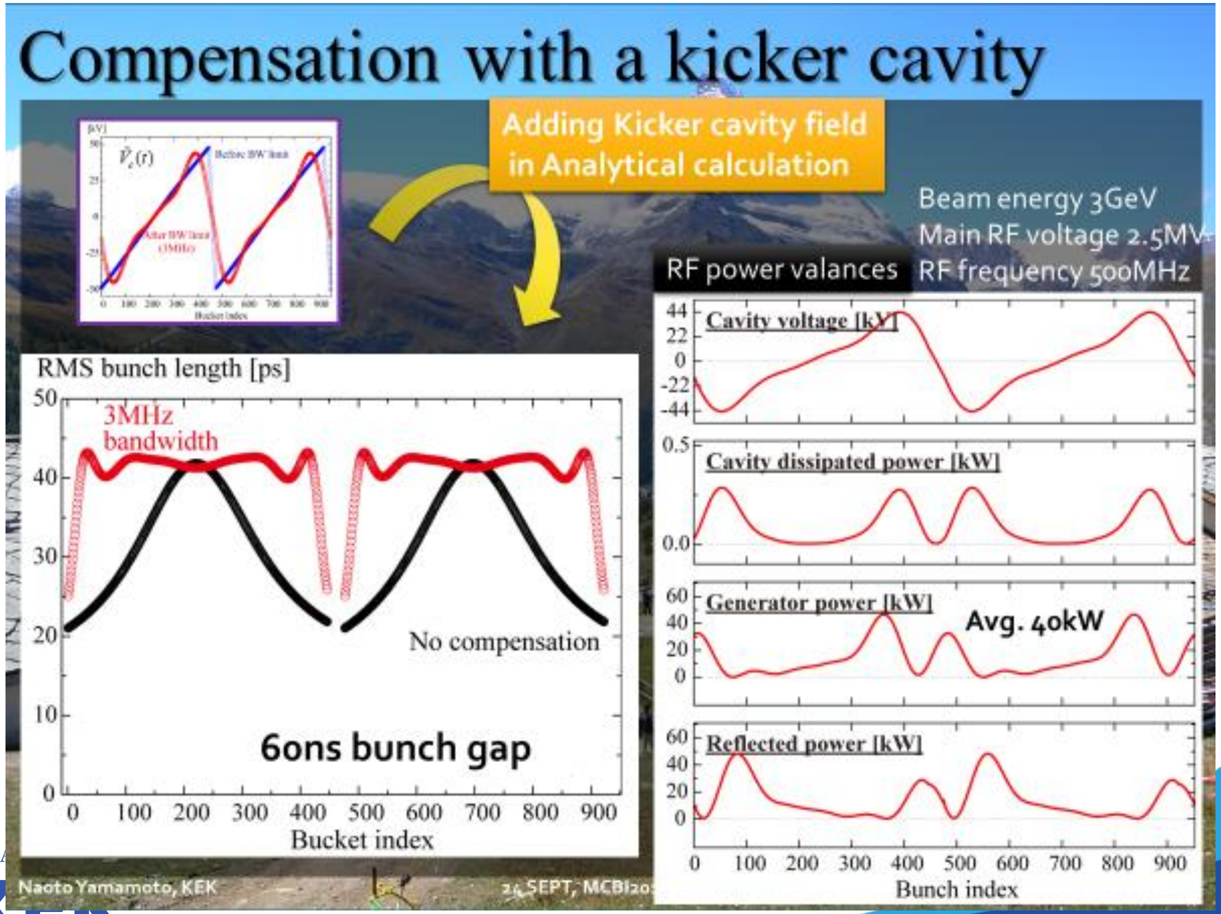


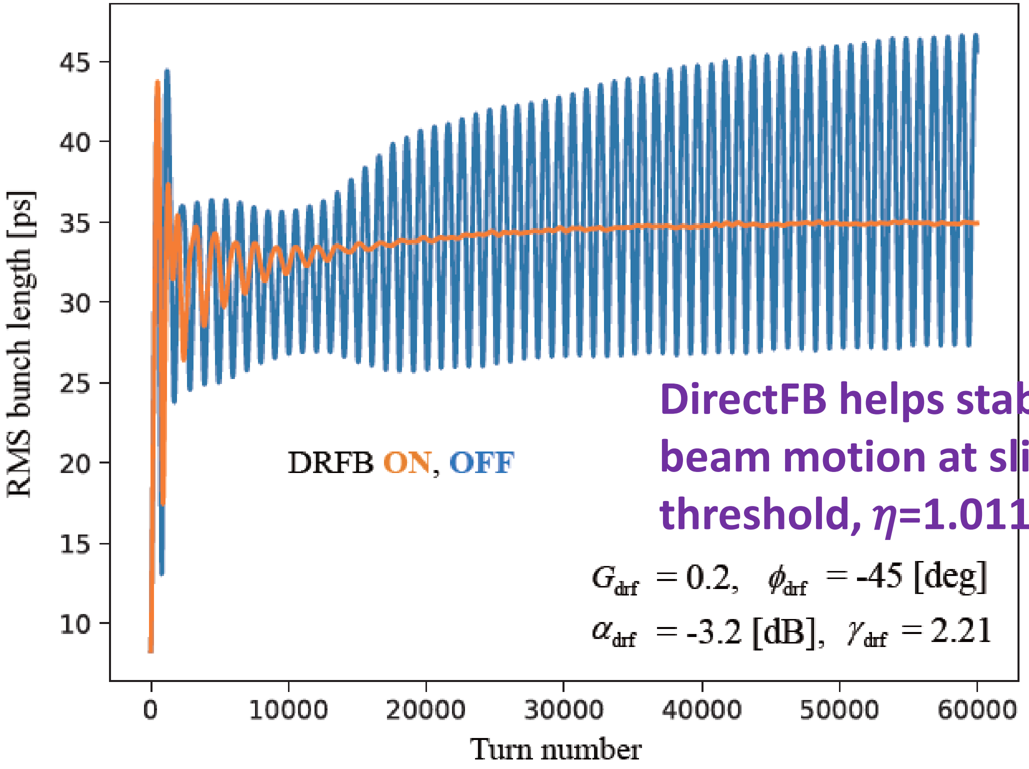


Advanced LLRF control & a broadband kicker cavity

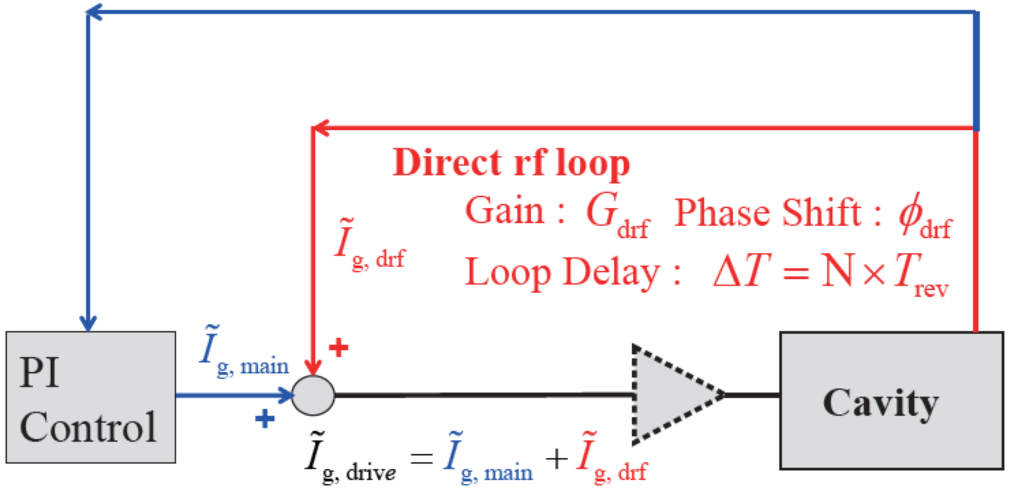
Countermeasures for performance degradations due to Transient beam loading effect and unstable beam motion, such as PTBL.

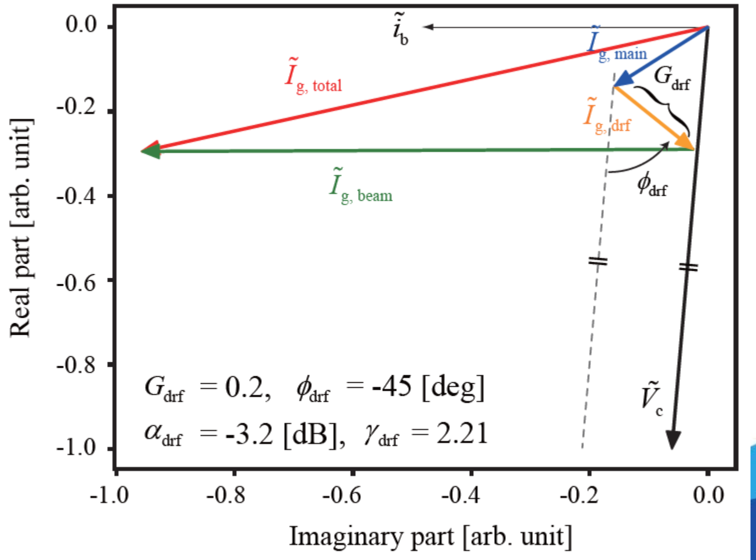
Stability survey with Direct FB loops of HC for the SOLEIL-II ring
(MBTRACK2 Tracking simulation result)

Detailed in N. Yamamoto et al., IPAC2023, WEPL161.



DirectFB helps stabilize the unstable beam motion at slightly above PTBL threshold, η=1.011.





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Hardware developments

Code development & Tracking Simulation study (MBTRACK2)

- Harmonic cavities with small total R/Qs.
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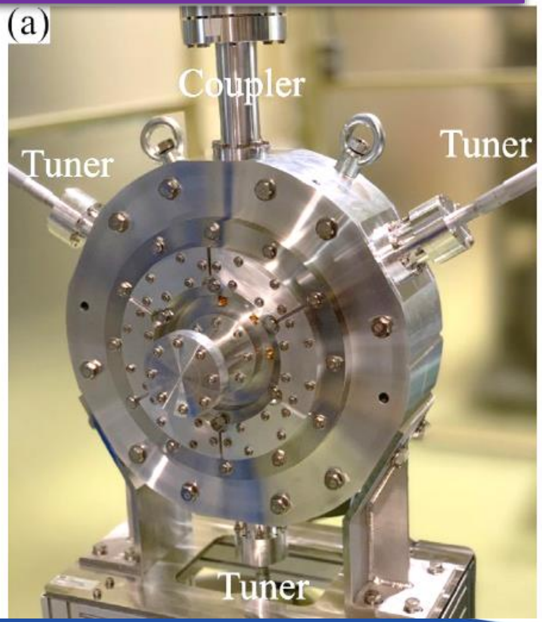
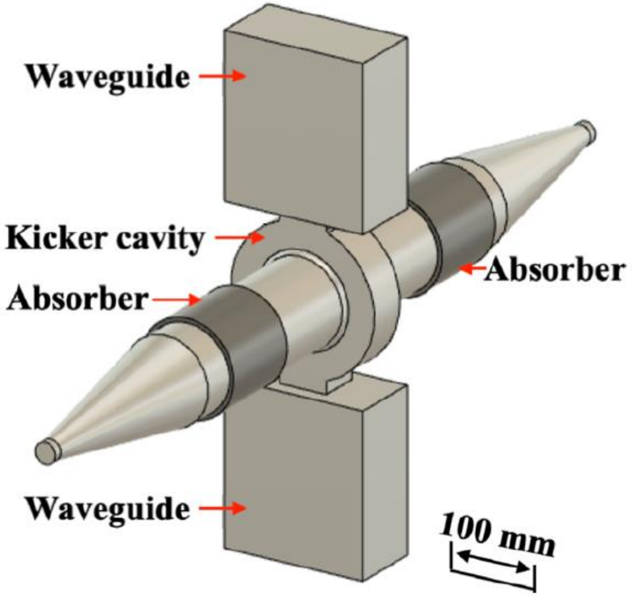
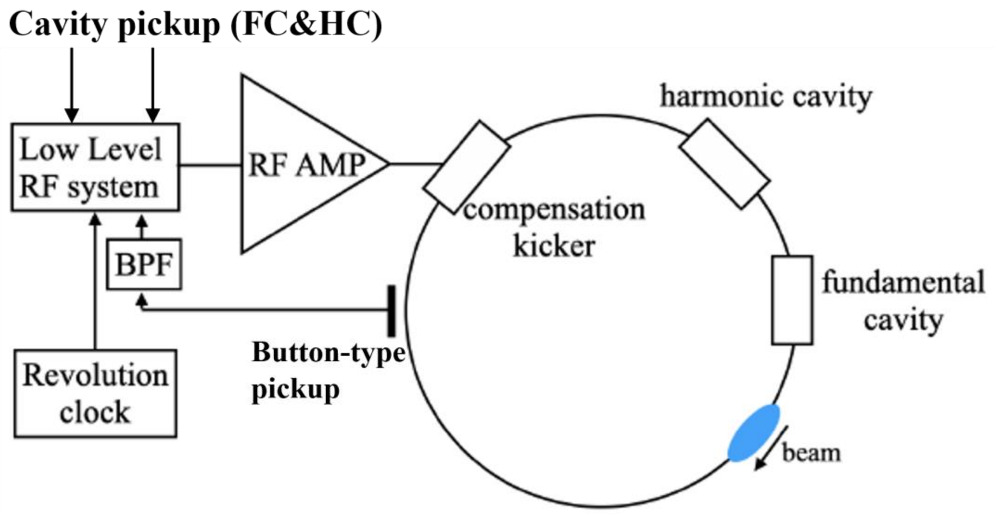
- Advanced LLRF control & a broadband kicker cavity

Development of
1.5GHz-TM020 cavity



Development of
a broadband cavity & Integrated Bunch phase monitor





KEK

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  - Proposal of system configuration
    - ✓Harmonic cavities with small total R/Qs.
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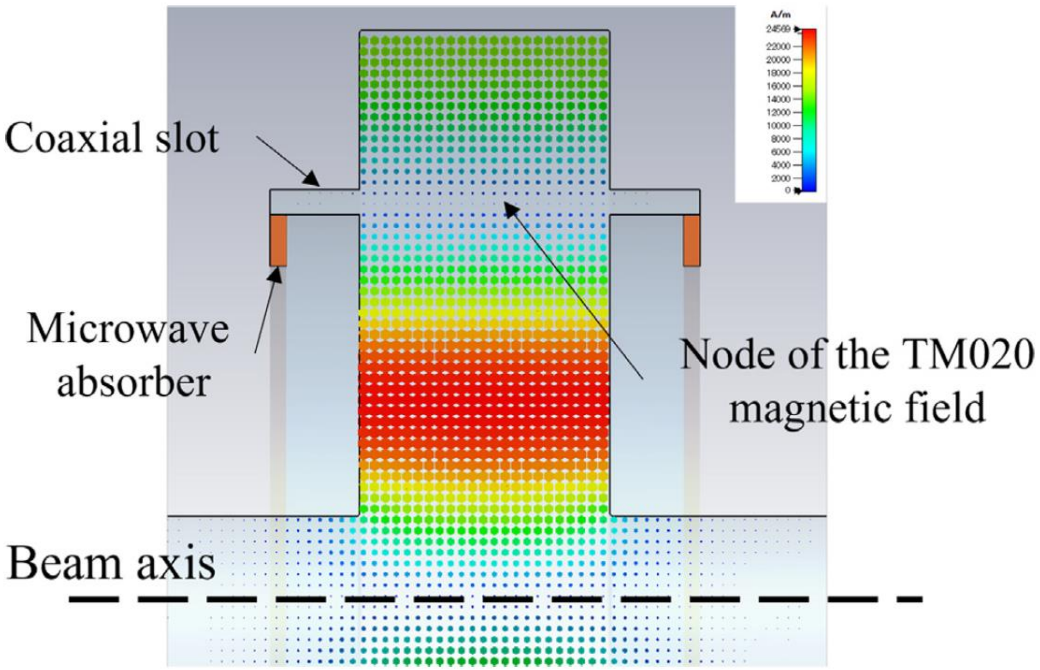
- Hardware developments
  - 1.5GHz-TM020 Harmonic cavity
  - Broadband Kicker cavity
  - Bunch Phase monitor

Development of 1.5GHz-TM020 cavity

- TM020 cavity was originally developed for the SPring-8-II project; *H. Ego, et. al., PASJ11, (2014) MOOL14*, and oral presentation will be given tomorrow by Prof. Ego; *TU3 WG-D Tuesday, Aug. 29*
- A similar 1.41GHz-TM020 cavity is also being developed at ESRF; *A. D'ELia et al., 25th ESLS RF Meeting, 2021.*

Magnetic field of the TM020 mode
Fig.1 of T. Yamaguchi et al, NIM A 1053 (2023) 168362



TM020 cavity;

a higher TM020 resonant mode is used for beam acceleration instead of the lowest TM010 mode.

Advantages:

A lower R/Q (appox. 40% compared to TM010 mode)

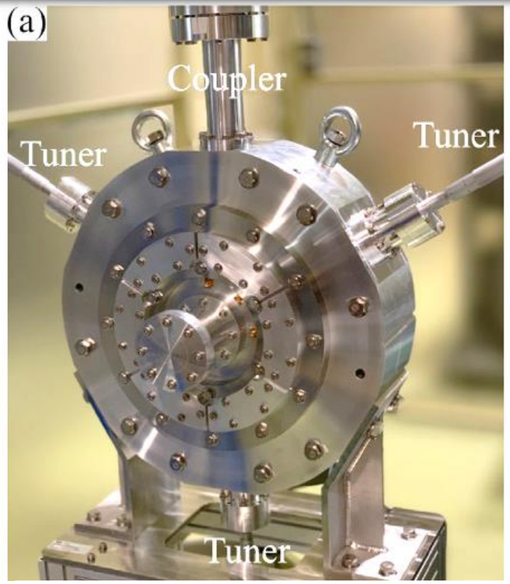
Compact parasitic-mode damped structure;

- coaxial slots and microwave absorber.

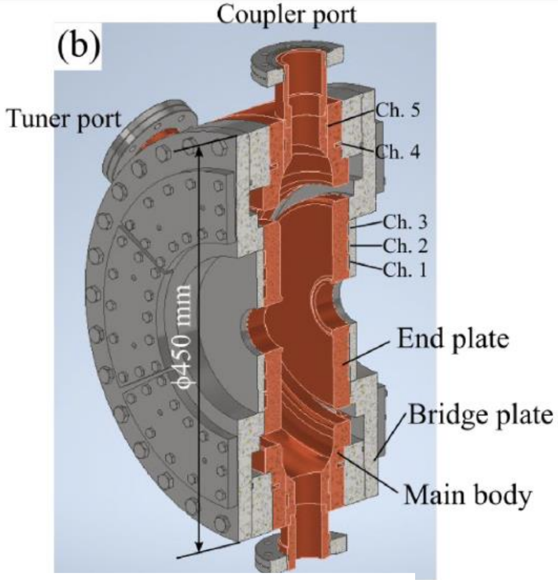
Development of 1.5GHz-TM020 cavity

- At KEK, the design of the high-power model is almost completed; *T. Yamaguchi et al, NIM A 1053 (2023) 168362.*

a) Picture of low power cavity model



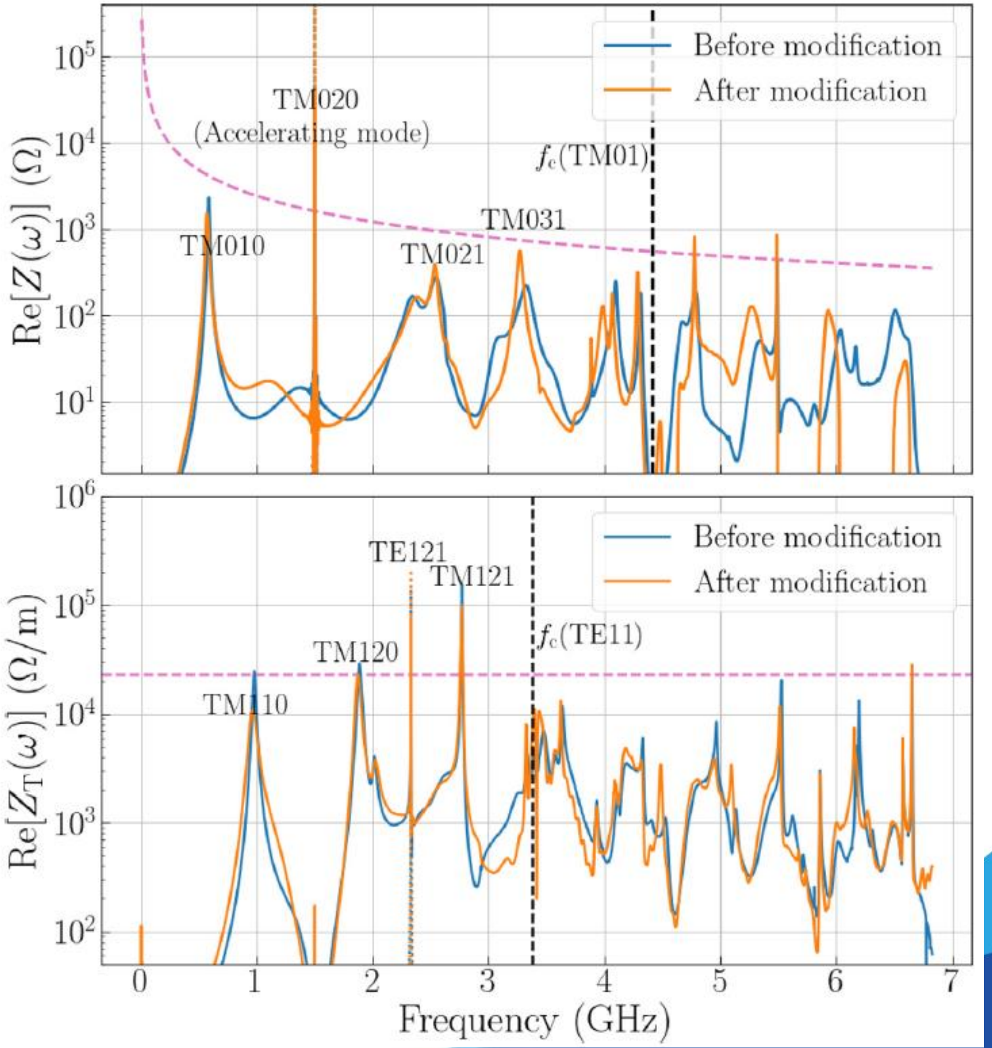
b) Schematic of high power model



Parameter	Value
Resonant frequency	1.5 GHz
R/Q, $(R_s = V_c^2/2P_c)$	34.0 Ω
Unloaded Q	31400
Tuning range, $(P_{abs}/P_{wall})^1 < 2\%$	-0.5 ~ 0.5 MHz

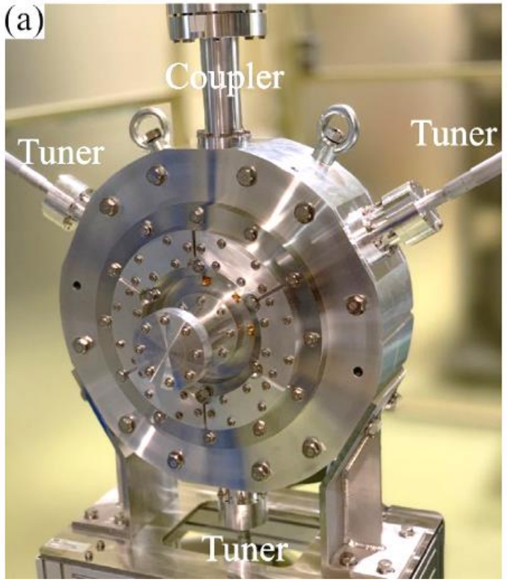
The challenge was to ensure sufficient frequency tuning range while maintaining acceleration mode performance.

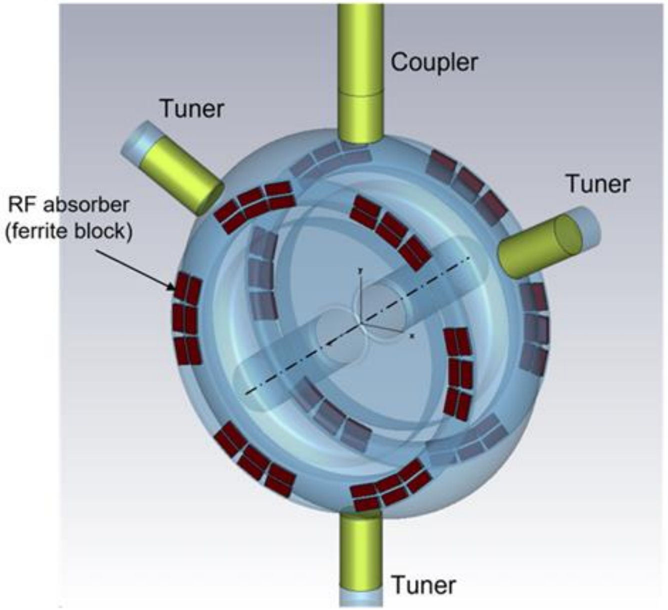
Coupling impedance of one cavity



Development of 1.5GHz-TM020 cavity

- In the early stages of the study, we were faced with the problem of losing acceleration mode performance with only a slight tuning in frequency.
- As a result of investigations, we found that maintaining the axial symmetry of the cavity is essential for minimizing the leakage power of the accelerating mode into the coaxial slots.





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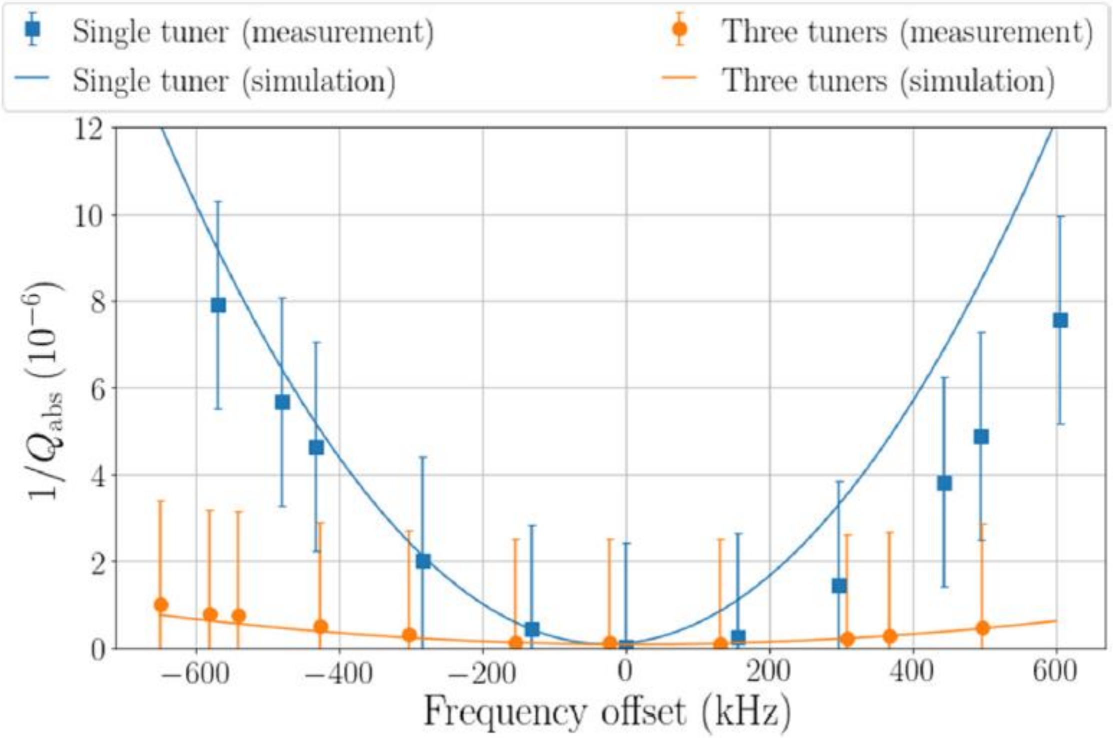
Measurement result of the accelerating mode power loss ($1/Q_{abs}$) at RF absorber.



Development of a broadband Kicker cavity

- A broadband cavity as a countermeasure of transient beam loading is being designed ;
  D. Naito et al., IPAC2023, WEPA119.

Schematic & Parameters of the designed cavity
Fig. & table from N. Naito et al, IPAC2023, WEPA119

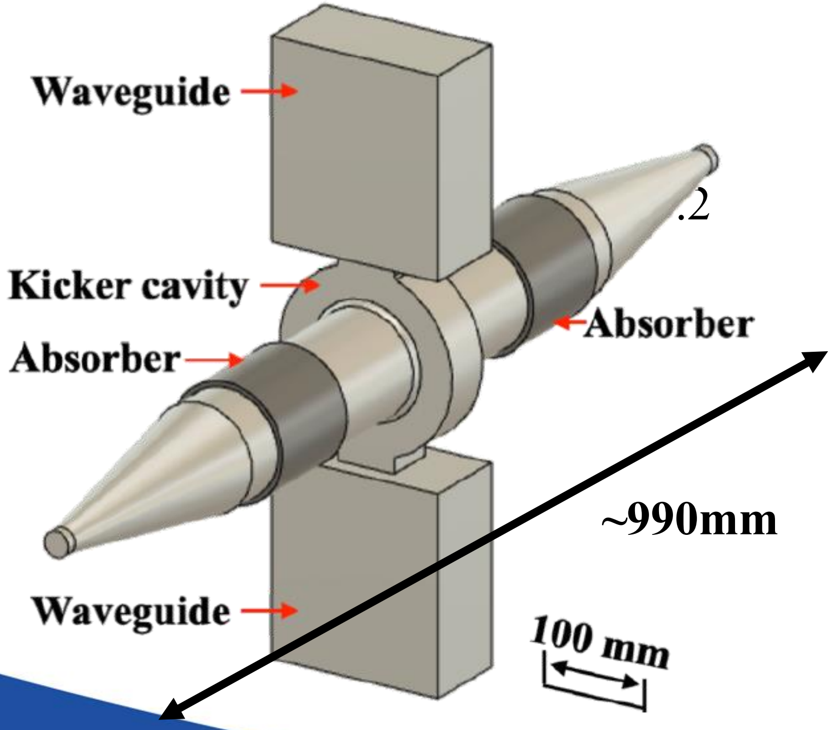


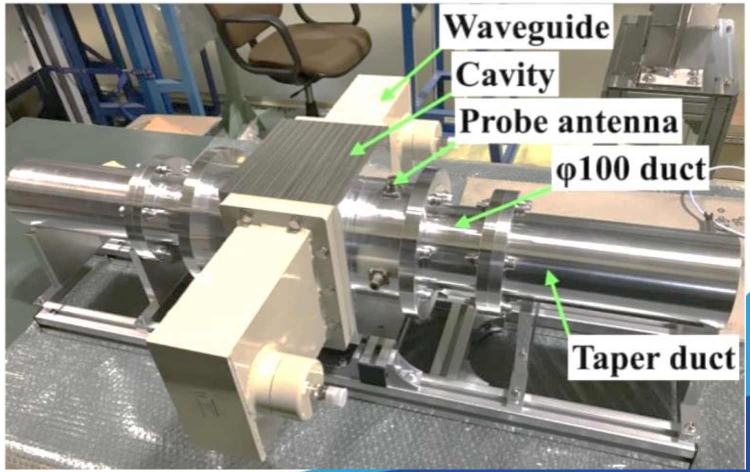
Table 1: The parameters of the kicker cavity

Parameter	Value
Resonant frequency	1.500 06 GHz
R/Q	60.38 Ω
Q_0	17937
Q_L	292.41
Synchronous phase	0 degree
Generator voltage	53 kV
Cavity voltage	44.2 kV
Generator power	40.4 kW
Power loss in cavity	2.59 kW
Reflecting power	15.7 kW
Max power density	21.7 W/cm^2
Absorber loss	3.38 %

- A single-mode cavity concept
- Strongly loaded by means of two external wave-guides, connected through large coupling

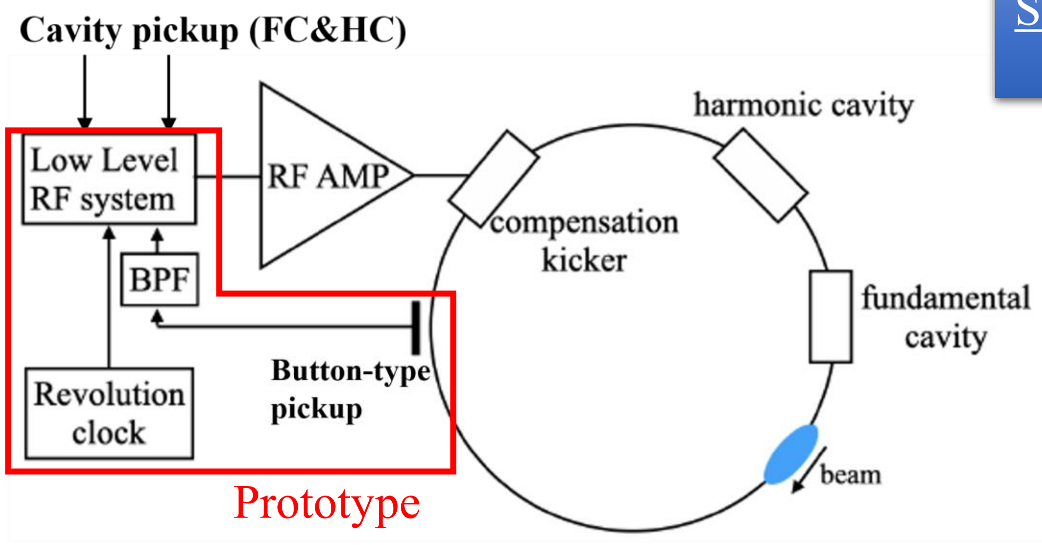
3dB-bandwidth : 5.1 MHz

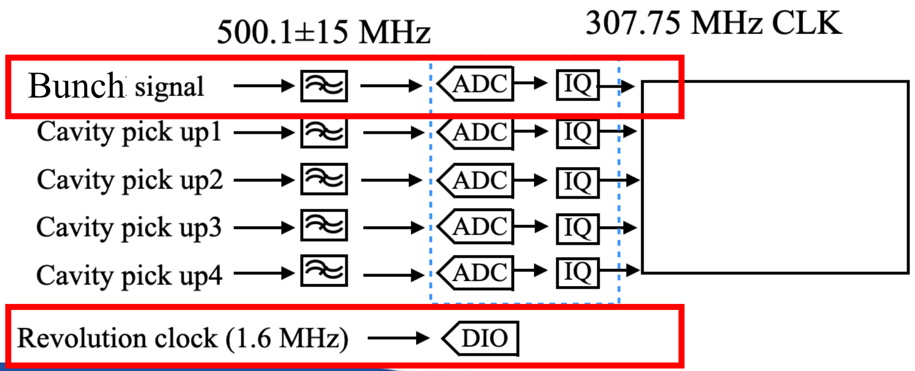
Low power model



Development of Bunch Phase Monitor

- To realize adaptive feedback for transient beam loading compensation, a LLRF control system with integrated bunch phase monitor is being developed and tested at KEK-PF; *D. Naito et al., PASJ2021, THOA01.*





Schematic of the Bunch Phase Monitor
will be presented at LLRF2023

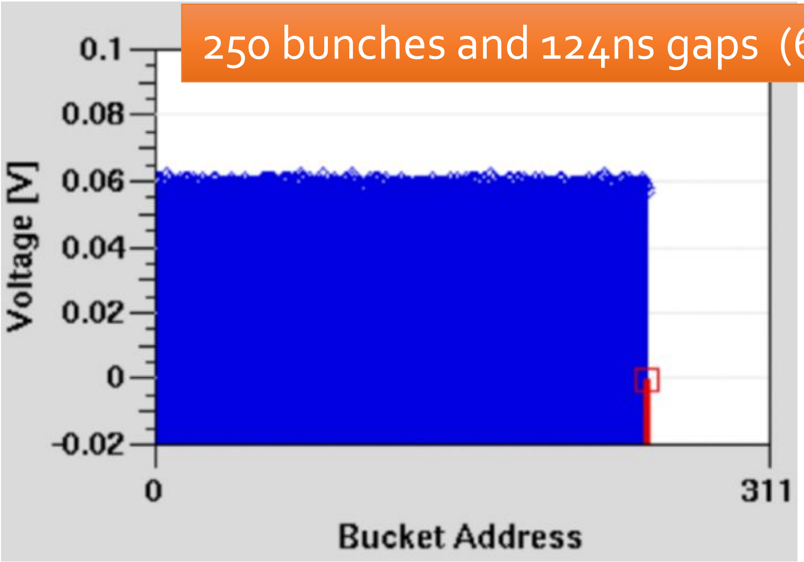
Prototype for the test at KEK-PF

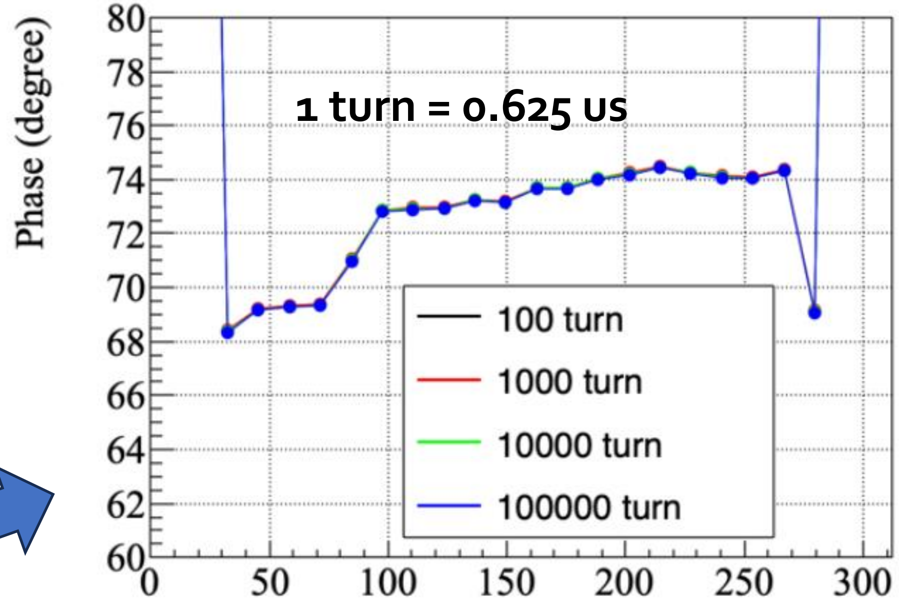
- MTCA.4 technology
- Direct Sampling method
- Synchronized to Revolution clock (1.6MHz)
- Sampling frequency = 307.75 MHz, F_{rf} x 8/13
- Data rate = ~ 1kHz

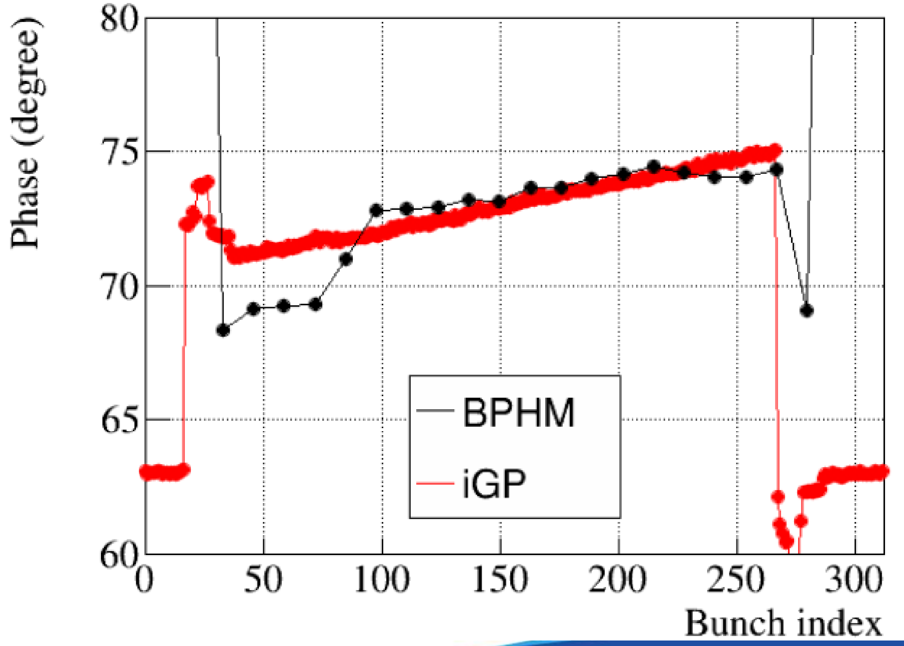
The IQ sampling was performed every 13 bunches, and 24 samples were obtained during one revolution period.

*KEK-PF: Harmonic = 312 , RF frequency = 500.1 MHz

Preliminary result of the bunch phase monitor (BPhM) at KEK-PF







The bunch phase shift in the bunch train could be monitored with only 100-turn averaging data.

Comparison with the bunch phase from the iGP (red) , which is signal processors used for bunch-by-bunch feedback.

iGP : 40kTurn average with a synchronous detection at 1.5GHz

Although the measured bunch phase slopes are slightly different, we expect that it is good enough for a TBL compensation.

Summary

- We are considering to realize "Active Normal-conducting bunch-lengthening system" with
  - Small total R/Q system to mitigate the transient beam loading and beam instability
  - Active harmonic cavity to improve the bunch lengthening performance even at low current
  - Advanced LLRF control system & a broadband kicker cavity

- Hardware developments are proceeding.
  - 1.5GHz-TM020 Harmonic cavity
  - Broadband Kicker cavity
  - Bunch Phase monitor

Thank you for your attention!