Mini-workshop on WP2 of the collaboration on RF

MBTRACK calculation results of bunch lengthening operation at SOLEIL-U ring

2021/06/23. Naoto Yamamoto （KEK）

Content

1. Transient beam loading effect and it's compensation
   - SOLEIL-U 3/4Fill with harmonic and kicker cavities
2. Low current limit of bunch lengthening operation
   - SOLEIL-U single bunch with HC
3. Other possible equipment to affect the bunch-lengthening beam dynamics (Direct RF feedback)
   1. Benchmark result with PF/KEK-B experiments.
   2. Impact for SOLEIL-U uniform/single-bunch operation

Today, the calculation results, assuming SOLEIL-U ring, obtained in this two years are shown.

1. SOLEIL-U 3/4Fill with harmonic and kicker cavities

- In this calculation, the transient beam loading effect is investigated in the 3/4 filling at SOLIEL-U, which corresponds to hybrid filling; a bunch train including 312 bunches train and an isolated single bunch.
- The behavior of the single bunch is not focused and is not reported in this talk, because the purpose of this investigation is to evaluate the TBL effect for the bunch train from such a large bunch gap of 295 ns (104 bunch x 2.84 ns)
- The feasibility of the TBL compensation with a single kicker cavity is also investigated.

- The calculations were carried out by using a MBTRACK code in 2020.

1. SOLEIL-U 3/4Fill with harmonic and kicker cavities

Calculation parameters

SOLEIL-U ring

- Electron energy = 2.75 GeV
- Machine circumference = 354.1 m
- Vc = 1.7MV
- Momentum compaction = 9.4e-5
- Uo = 682 keV/Turn, Tau_e = 11.9 ms
- Energy spread = 8.6e-4
- Stored current = 450 mA

Cavity setup

- Main Cavity
  - NC (Qo = 34000, Rs = 19.6 MΩ) or
  - SC (Qo = 1e9, Rs = 45 GΩ)
    - → SC (Qo = 2e9, Rs = 180 GΩ); existing one
- Harmonic Cavity
  - 3^{rd} or 4^{th}, SC, Rs = 4.5 GΩ or 9.0 GΩ
- Kicker Cavity
  - 352MHz, Qo=40000, Rs = 3.5 MΩ, Δf/f = 5MHz

Some parameters are no longer correct, comparing with the latest design of the SOLEIL-U ring

1. SOLEIL-U 3/4Fill with 3rd harmonic and no kicker cavities

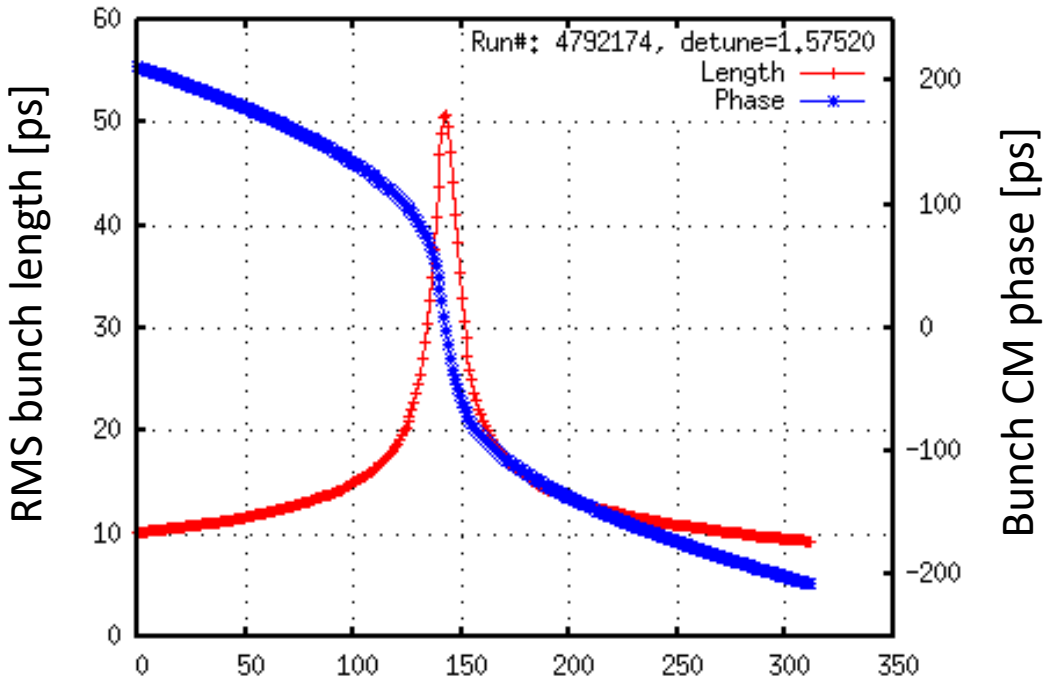
Calculation result

MC: **Rs = 19.60 [MOhm], Qzero = 34000.0 , Qload = 6000.00,**

Cavity Voltage = 1.70 [MV], Phase = 1.10255 [rad]

3rdHC: **Rs = 4500.0 [MOhm], Qzero = 1e8 , Qload = 1e8, detune = 1.57052 [rad]**

No kicker cavity



Phase shift (peak to peak) :	419 ps
Bunch length	
average :	14.8 ps
max :	50.7 ps
min :	9.3 ps

Natural bunch length : 8.1 ps

1. SOLEIL-U 3/4Fill with 4th harmonic and no kicker cavities

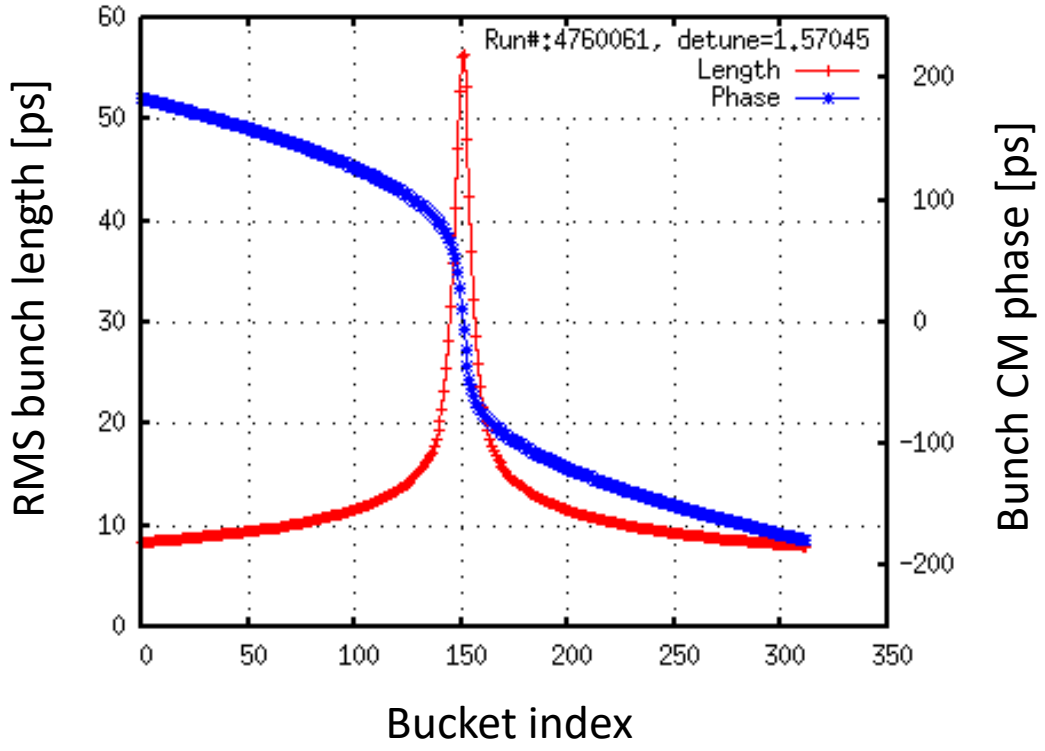
Calculation result

MC: **Rs = 19.60 [MOhm], Qzero = 34000.0 , Qload = 6000.00,**

Cavity Voltage = 1.70 [MV], Phase = 1.12860 [rad]

4thHC: **Rs = 4500.0 [MOhm], Qzero = 1e8 , Qload = 1e8, detune = 1.57045 [rad]**

No kicker cavity



Phase shift (peak to peak) :	362 ps
Bunch length	
average :	12.4 ps
max :	56.4 ps
min :	8.9 ps

Natural bunch length : 8.1 ps

1. SOLEIL-U 3/4Fill with harmonic and no kicker cavities

Calculation result

MC	HC	HC.Rs [MΩ]	Phase shift [ps]	Average BL [ps]	Max BL [ps]	Min BL [ps]	HC detune [kHz]	HC.Vc [MV]
NC	4	9000	385.0	11.3	26.3	7.3	42.4	0.477
NC	4	4500	362.0	12.4	56.4	8.9	20.3	0.476
SC	4	9000	283.7	14.2	21.2	9.8	92.3	0.417
SC	4	4500	253.8	18.9	40.5	11.5	45.1	0.429
NC	3	9000	468.4	13.1	41.7	8.3	30.0	0.605
NC	3	4500	419.0	14.8	50.7	9.3	19.1	0.573
SC	3	4500	282.0	24.4	53.9	14.2	30.0	0.546

Comment:

1. The phase shifts are larger than 250 ps even if the SC MC & SC HC are employed.
2. Average bunch lengths are smaller than 25 ps even if the SC MC & SC HC are employed.
   - Very severe TBL effect for 3/4 fill pattern of SOLEIL-U.

3. SC > NC, for both of the phase shifts and bunch lengths.
4. 3^{rd} > 4^{th}, for the bunch lengths
   - The bunch lengths is limited due to large TBL effect for 4^{th} HC (higher freqency) system.
5. Comparing with the Rs, Smaller one is preferred.

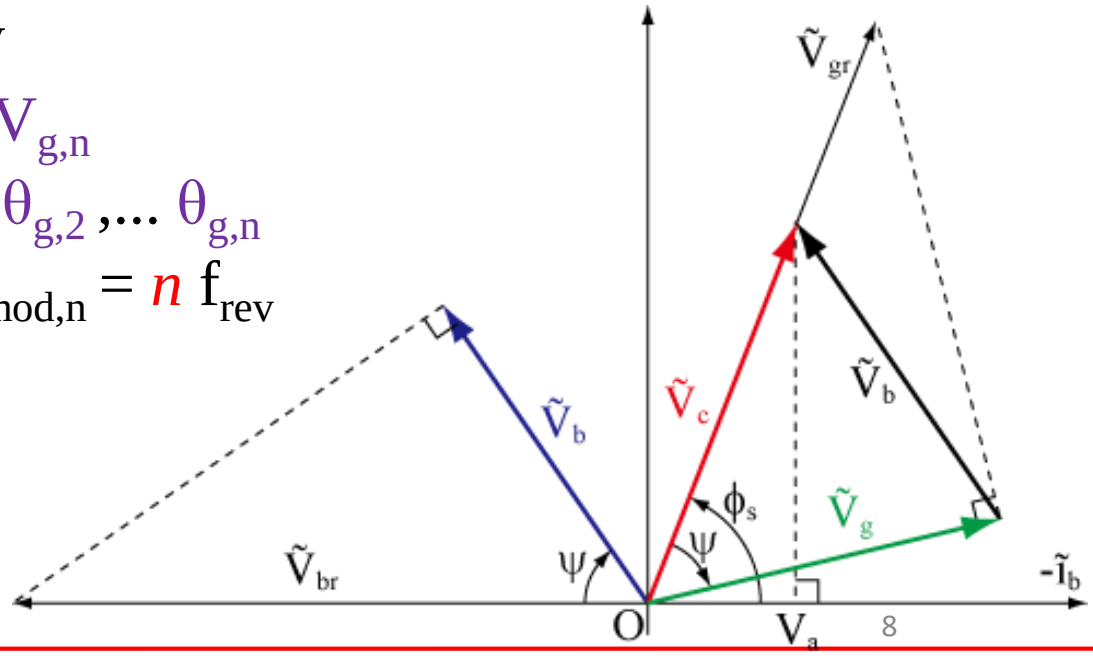
1. SOLEIL-U 3/4Fill with harmonic and kicker cavities

How to introduce the kicker cavity compensation

- Generator voltage seen from *m*-th bunch:
  - ➢Summation of *n*-th cosine functions along the revolution

$$\mathrm{Re}[V_g] = \Sigma\, \mathrm{Re}[V_{g,n,m}]$$
$$\mathrm{Re}[V_{g,n,m}] = V_{g,n}\cos[2\pi n/h(m+\theta_{g,n})+\Delta\tau]$$

  - ➢Each harmonic component is characterized by
    - Generator Amplitude : $V_{g,0}$, $V_{g,1}$, $V_{g,2}$,... $V_{g,n}$
    - Angle of generator voltage from $-i_b$: $\theta_{g,1}$, $\theta_{g,2}$,... $\theta_{g,n}$
    - Harmonic number (Modulation frequency) : $f_{mod,n} = n\, f_{rev}$



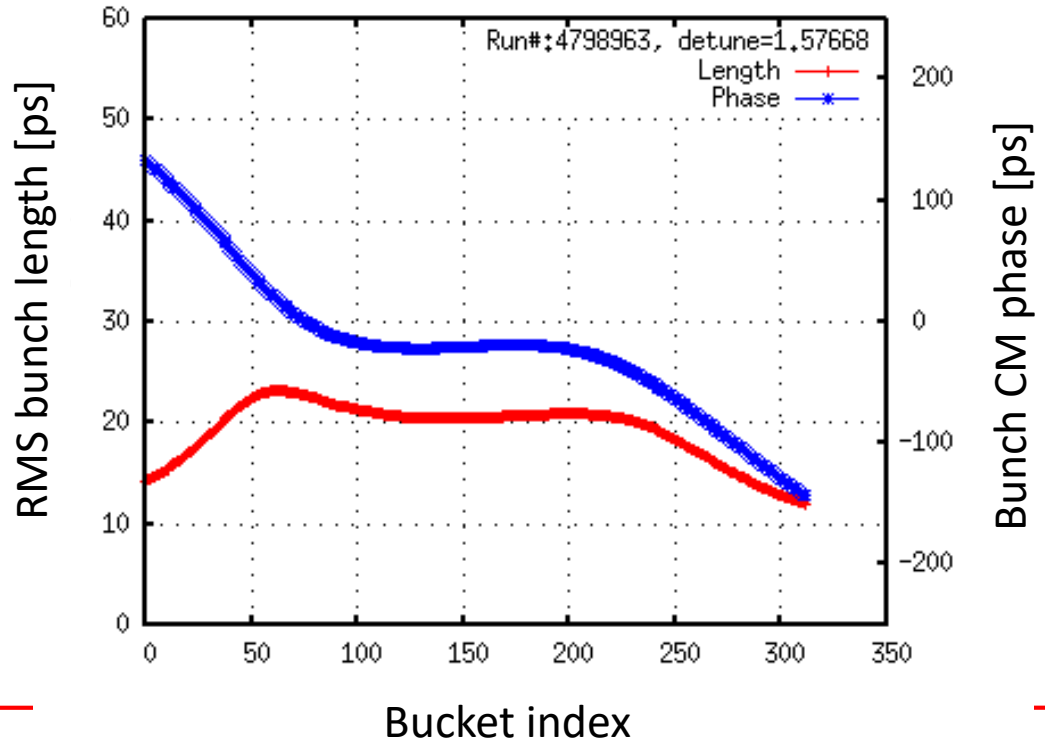
1. SOLEIL-U 3/4Fill with 3rd harmonic and kicker cavities

Calculation result, Modulated by 1 revolution period

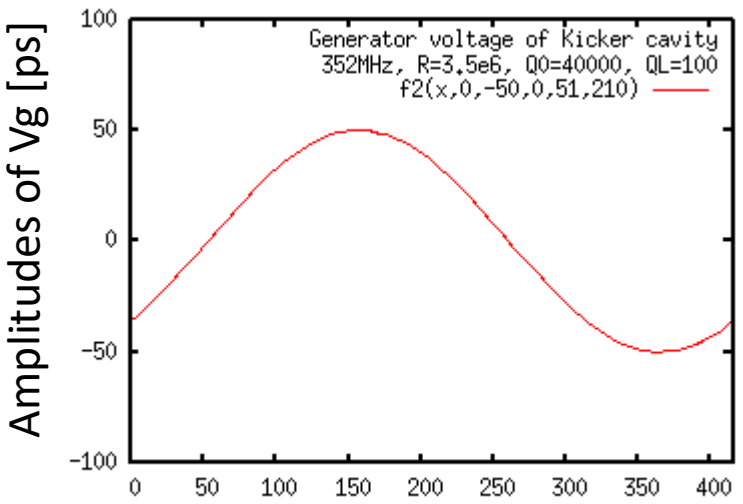
MC: **Rs = 19.60 [MOhm], Qzero = 34000.0 , Qload = 6000.00,**
Cavity Voltage = 1.70 [MV], Phase = 1.10255 [rad]

3rdHC: **Rs = 4500.0 [MOhm], Qzero = 1e8 ,**
Qload = 1e8, detune = 1.570668 [rad]

Kicker cavity: **352MHz, Rs = 3.5e6, Qzero = 40000, F_{mod}=1 x F_{rev}**



|Vg| of Kicker cavity



Phase shift (peak to peak): 276 ps
Bunch length
average : 19.3 ps
max : 23.2 ps
min : 12.0 ps
Generator Power (kicker cavity)
Peak : 35.8 kW
average : 18 kW
(R=3.5MΩ, βc=399)

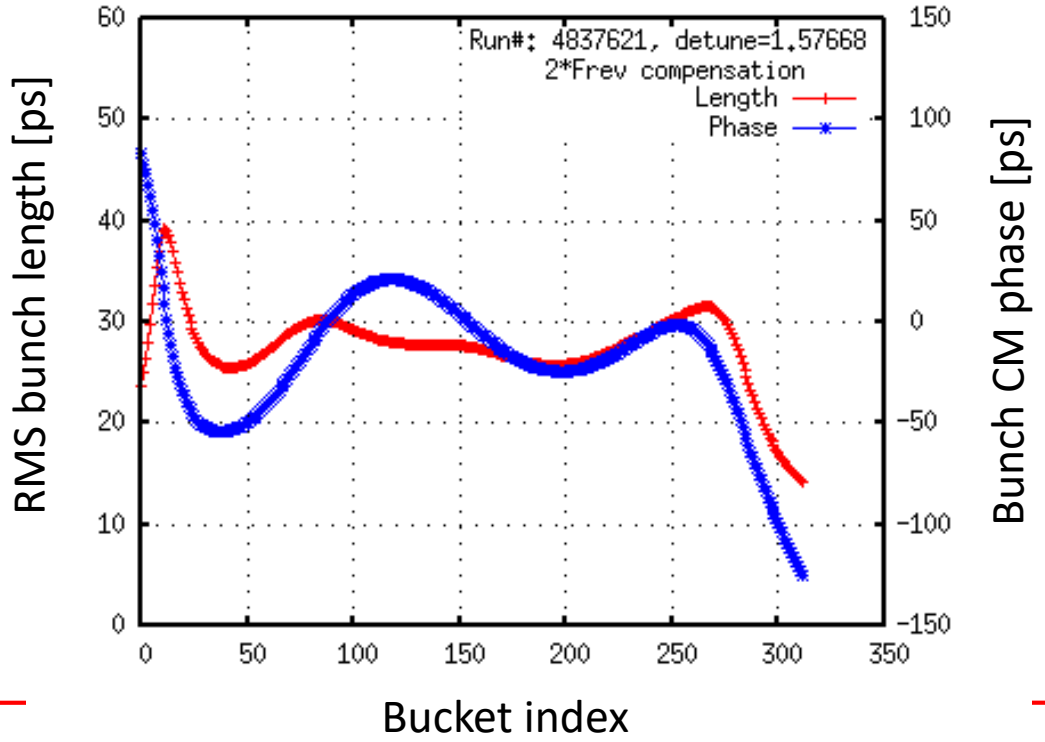
1. SOLEIL-U 3/4Fill with 3rd harmonic and kicker cavities

Calculation result, Modulated by (1+2) revolution frequencies

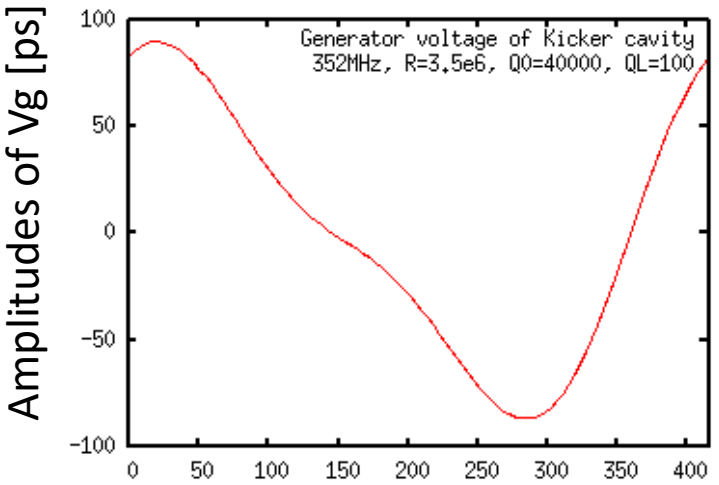
MC: **Rs = 19.60 [MOhm], Qzero = 34000.0 , Qload = 6000.00,**
Cavity Voltage = 1.70 [MV], Phase = 1.10255 [rad]

3rdHC: **Rs = 4500.0 [MOhm], Qzero = 1e8 ,**
Qload = 1e8, detune = 1.570668 [rad]

Kicker cavity: **352MHz, Rs = 3.5e6, Qzero = 40000, F_{mod}= (1+2) x F_{rev}**



|Vg| of Kicker cavity



Phase shift (peak to peak): 208 ps
Bunch length
average : 27.5 ps
max : 39.3 ps
min : 14.2 ps
Generator Power (kicker cavity)
Peak : 115 kW
average : 57 kW
(R=3.5MΩ, βc=399)

1. SOLEIL-U 3/4Fill with harmonic and kicker cavities

Calculation result

MC	HC	HC.Rs [MΩ]	Kicker Cavity F_{mod}	Peak KC Power [kW]	Avg. KC Power [kW]	Phase shift [ps]	Average BL [ps]	Max BL [ps]	Min BL [ps]
NC	4	4500	-	-		362.0	12.4	56.4	8.9
NC	4	4500	1 x F_{rev}	46.5	23.3	322.0	25.2		
NC	4	4500	(1 + 2) x F_{rev}	83.0	41.5	273.1	31.3	49.9	10.1
SC	4	9000	-	-		283.7	14.2	21.2	9.8
SC	4	9000	1 x F_{rev}	18.6	9.3	234.4	20.0	24.6	11.1
SC	4	9000	(1 + 2) x F_{rev}	26.4	13.2	223.3	19.7	23.6	11.6
SC	4	4500	-	-		253.8	18.9	40.5	11.5
SC	4	4500	1 x F_{rev}	4.1	2.1	240.5	33.2	50.3	11.6
SC	4	4500	(1 + 2) x F_{rev}	7.8	3.9	195.3	38.3	54.1	13.7
NC	3	4500	-	-		419.0	14.8	50.7	9.3
NC	3	4500	1 x F_{rev}	35.8	17.9	276.0	19.3	23.2	12.0
NC	3	4500	2 x F_{rev}	10.4	5.2	402.5	18.1	32.0	9.5
NC	3	4500	(1 + 2) x F_{rev}	115.4	57.7	208.0	27.5	39.3	14.2
SC	3	4500	-	-	-	282.0	24.4	53.9	14.2
SC	3	4500	1 x F_{rev}	2.4	1.2	238.6	37.7	50.9	15.4
SC	3	4500	(1 + 2) x F_{rev}	6.6	3.3	137.2	46.0	54.2	19.3

2nd performance

Shown plot

Best performance

Comment:

1. By using the KC, the improvements for phase shifts &bunch lengths are expected.
2. However, the improvements for phase shift are limited.

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   - **SOLEIL-U single bunch with HC**
3. Other possible equipment to affect the bunch-lengthening beam dynamics (Direct RF feedback)
   1. Benchmark result with PF/KEK-B experiments.
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2. SOLEIL-U single bunch with HC

- In this calculation, the single bunch current limit is investigated for SOLIEL-U ring. For the passive harmonic system, there is a lower current limit to achieve “flat potential condition.”
- The current limit may be given by longitudinal mode coupling or AC Robinson.

- For the high charge single-bunch operation, it is considered that the bunch lengthening due to the ring impedance can not be ignored.
- In the following result, the ring impedance is not included. In a positive momentum compaction machine, additional bunch lengthening thanks to the ring impedance will be expected. (In this case, the flat potential can be achieved with relatively lower harmonic voltage, ref)

- The calculations were carried out by using a MBTRACK code in 2020 and 2021.

2. SOLEIL-U single bunch with HC

Calculation parameters

SOLEIL-U ring

- Electron energy = 2.75 GeV
- Machine circumference = 354.1 m
- Vc = 1.7MV
- Momentum compaction = 9.4e-5
- Uo = 770 keV/Turn, Tau_e = 11.9 ms
- Energy spread = 8.6e-4
- Stored current = 10,20 mA

Cavity setup

- Main Cavity
  - NC (Qo = 34000, Rs = 19.6 MΩ)
- Harmonic Cavity
  - 4^{th}, SC, Rs = 9.0 GΩ, Q= 1e8 (passive)

Some parameters are no longer correct, comparing with the latest design of the SOLEIL-U ring

2.SOLEIL-U single bunch 20 mA with HC

Calculation result

Every 60k Turn,
detunRad is decreased by 0.0001
Start value = 1.56990 (7.86 kHz)

single peak -> double peak -> loss

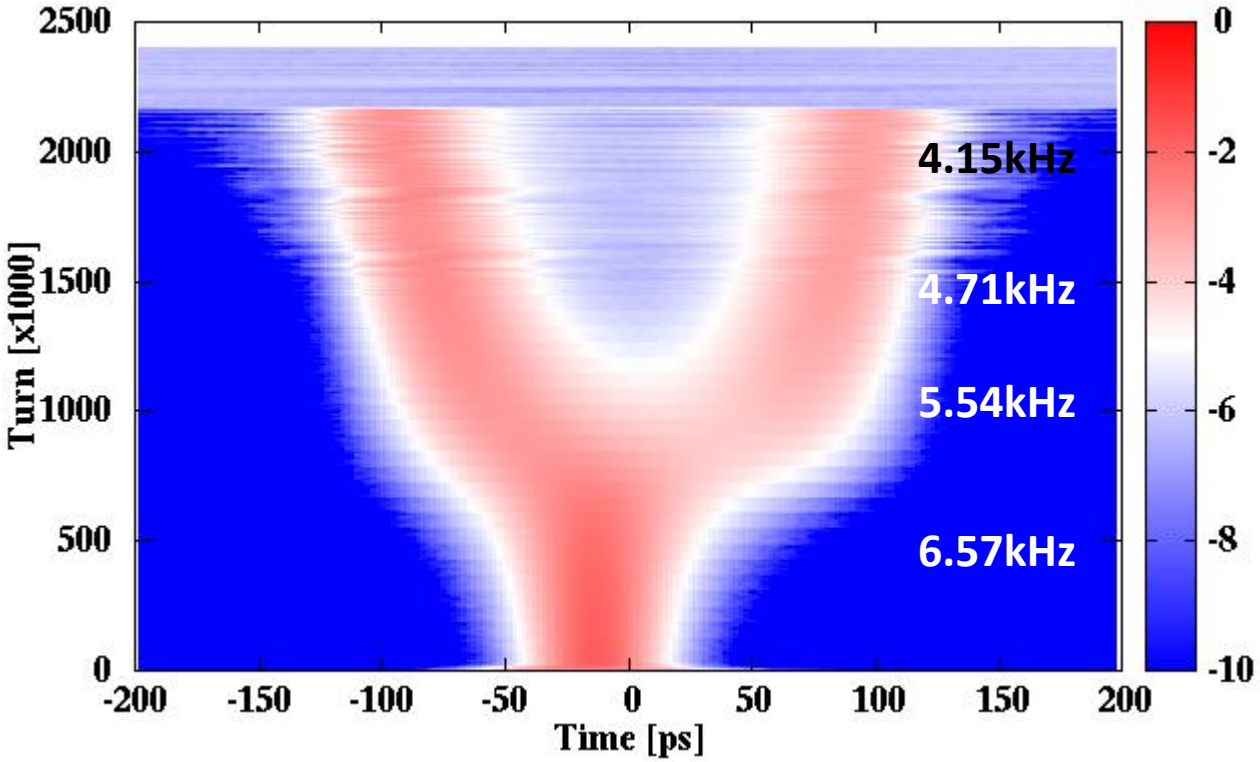


Fig. Evolution of particle distribution

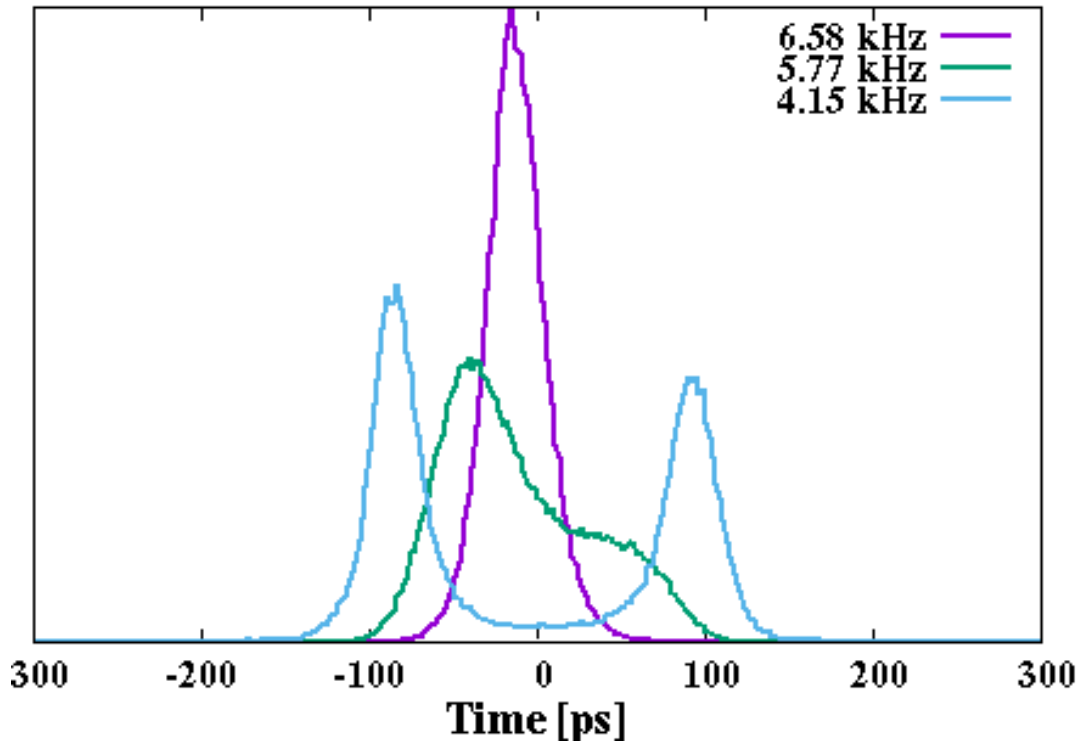
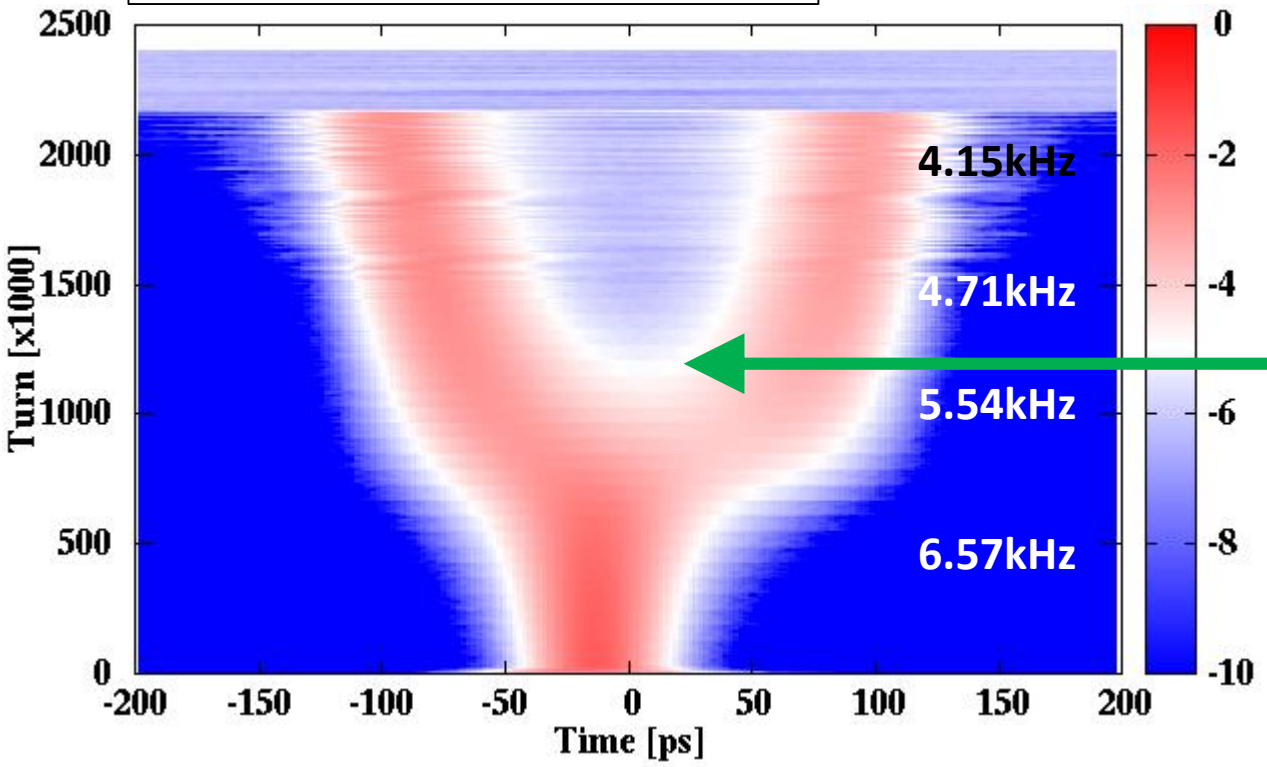


Fig. Bunch profiles at 4.15, 5.77 and 6.58 kHz detuning

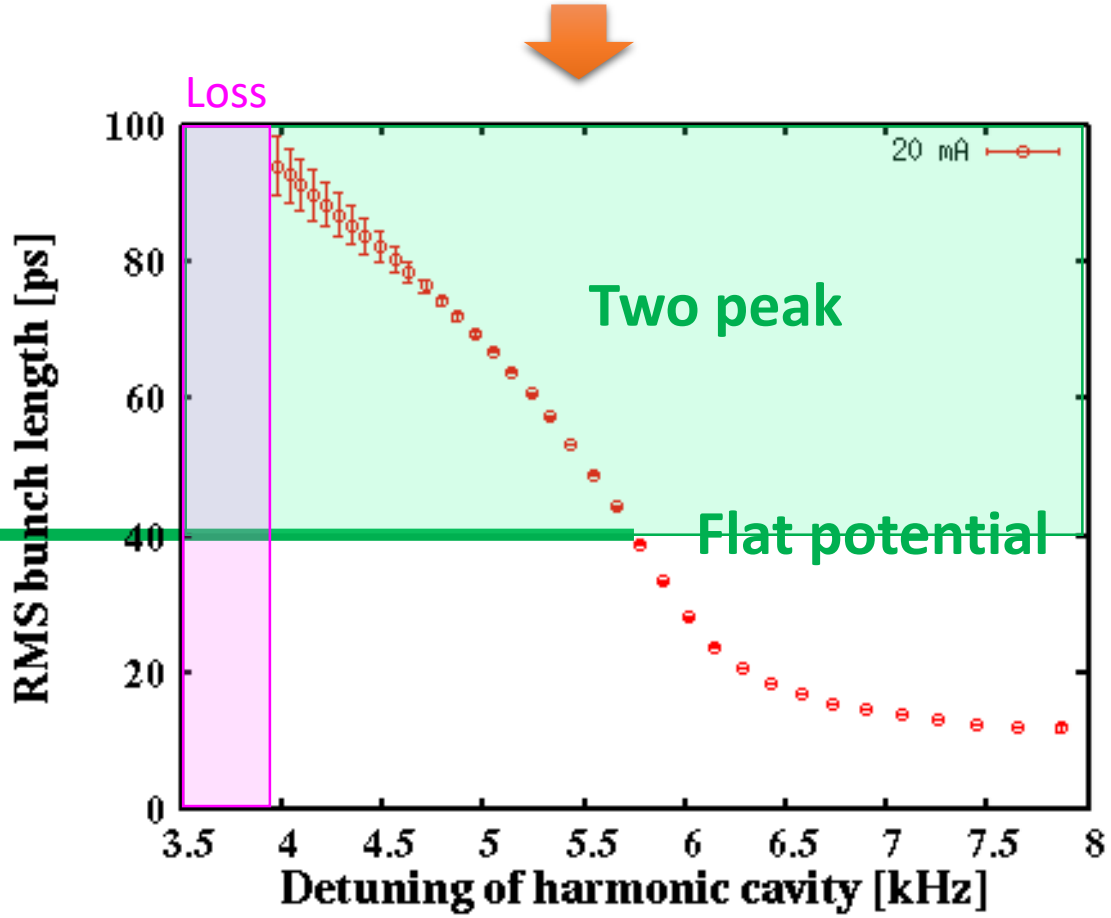
2.SOLEIL-U single bunch 20 mA with HC

Calculation result

Every 60k Turn,
detunRad is decreased by 0.0001
Start value = 1.56990 (7.86 kHz)



Error bar represents unstable beam motion inside of the bunch.



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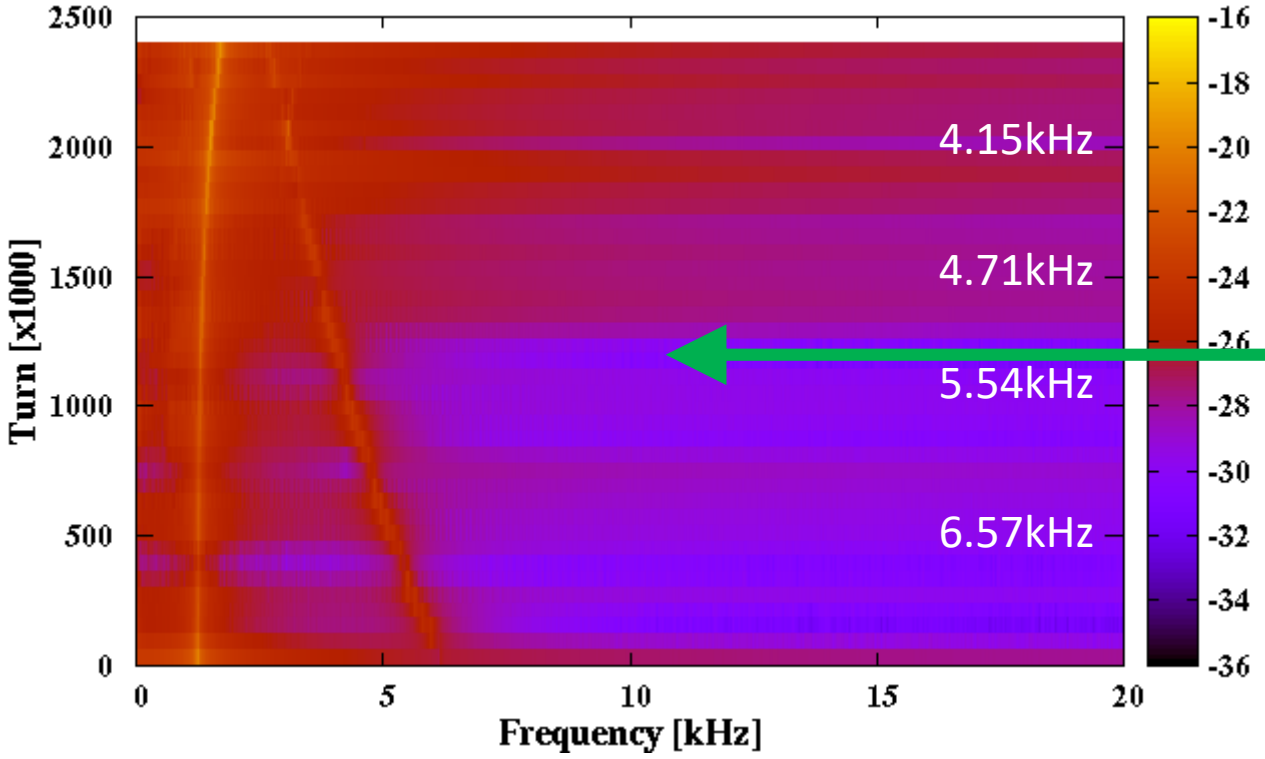
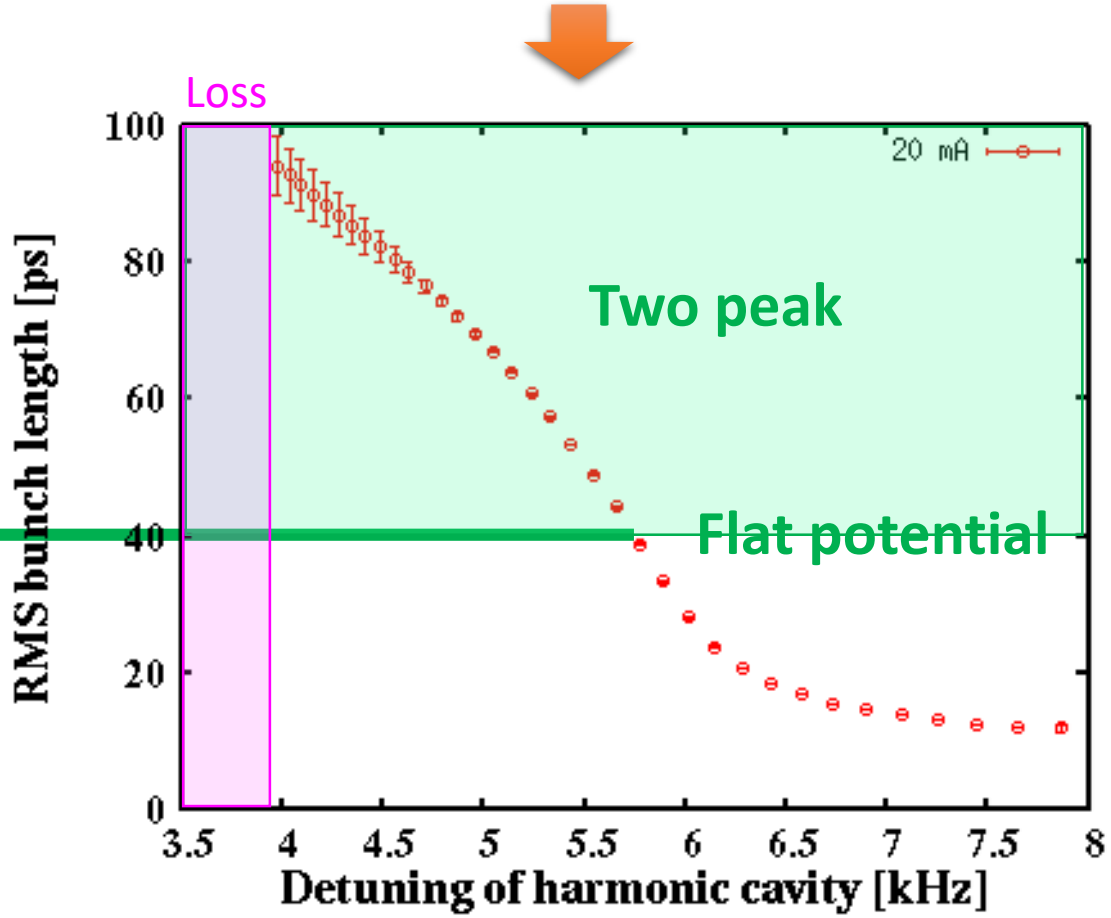


Error bar represents unstable beam motion inside of the bunch.



2.SOLEIL-U single bunch 10 mA with HC

Calculation result

Every 60k Turn,
detunRad is decreased by 0.0001
Start value = 1.56950 (5.43 kHz)

Beam loss before the flat potential condition.

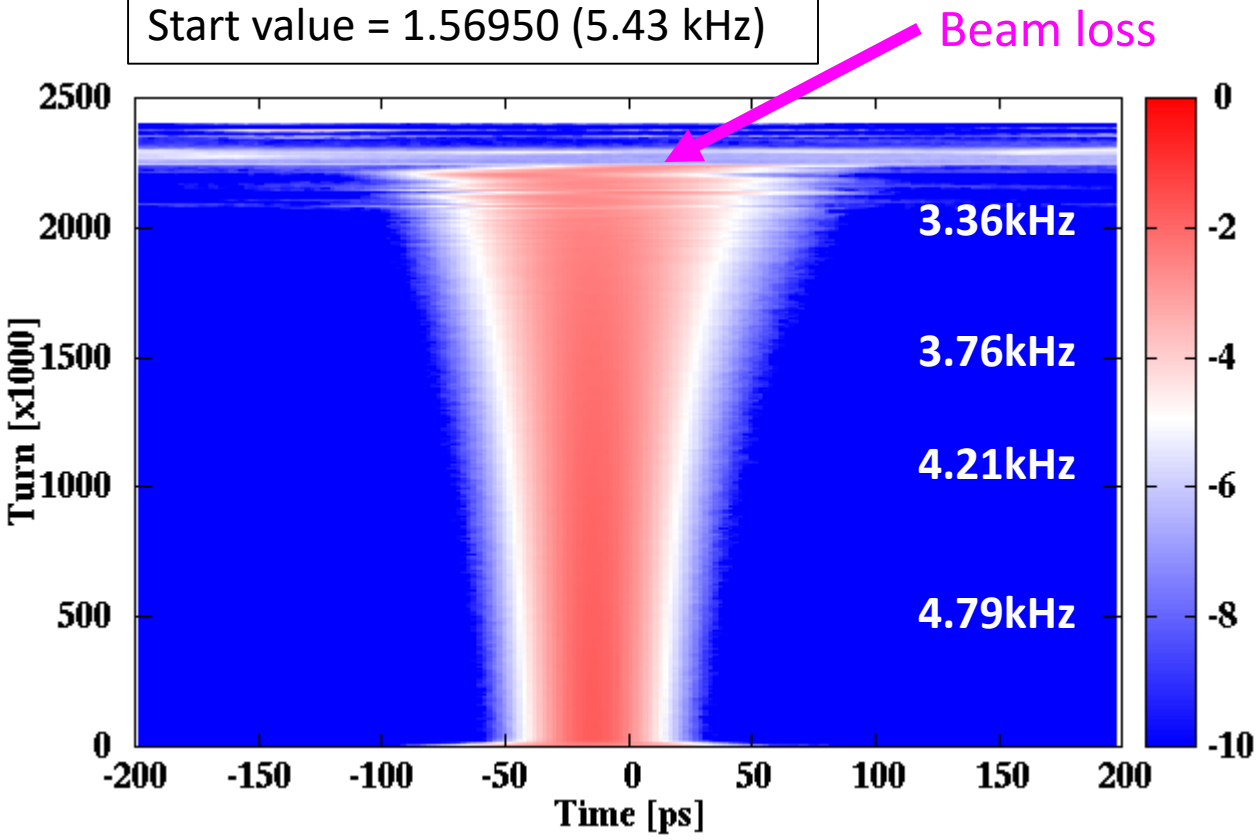


Fig. Evolution of particle distribution

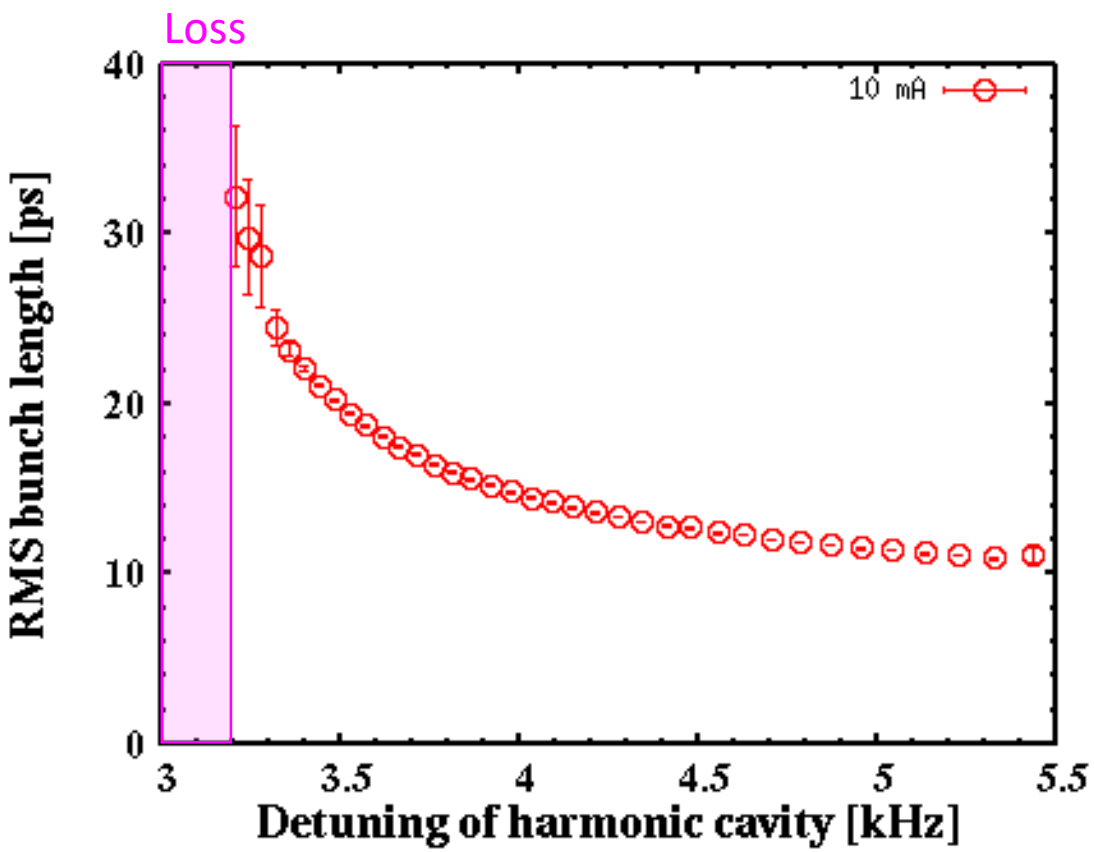


Fig. RMS bunch length vs Harmonic cavity detuning

2.SOLEIL-U single bunch 10 mA with HC

Calculation result

Every 60k Turn,
detunRad is decreased by 0.0001
Start value = 1.56950 (5.43 kHz)

Beam loss

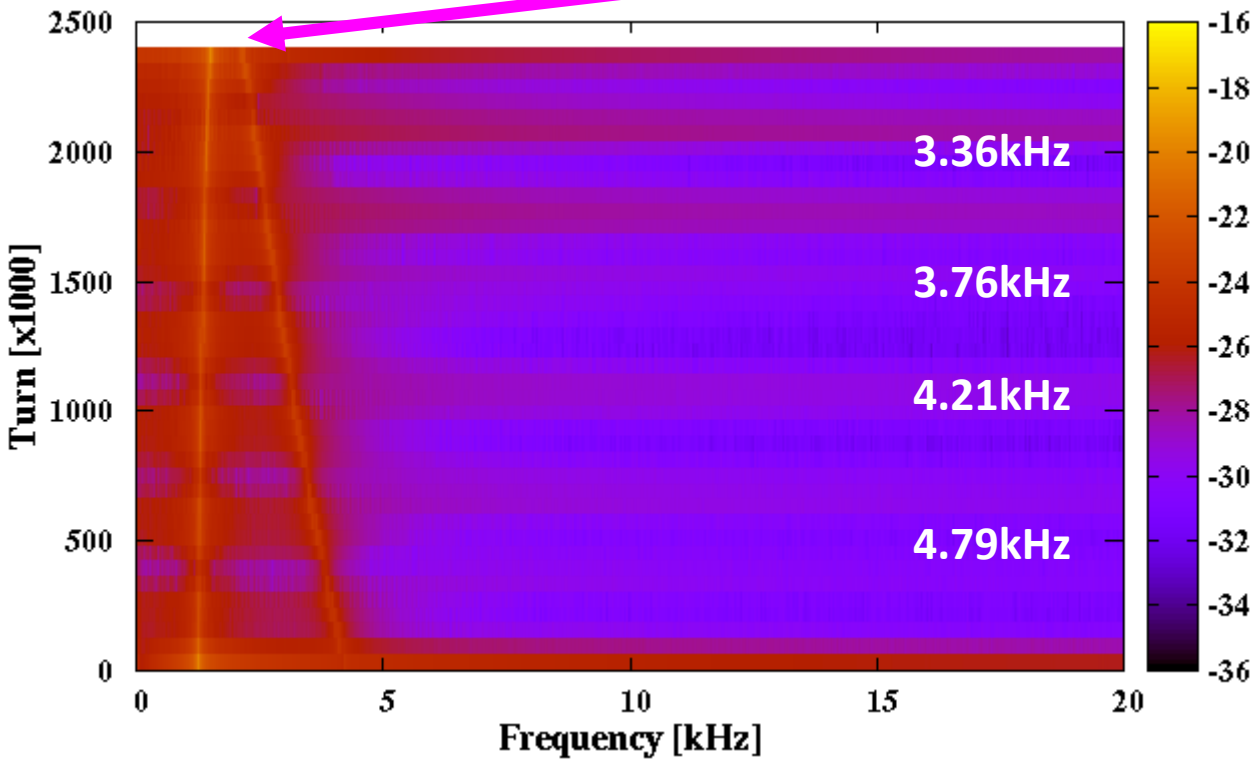
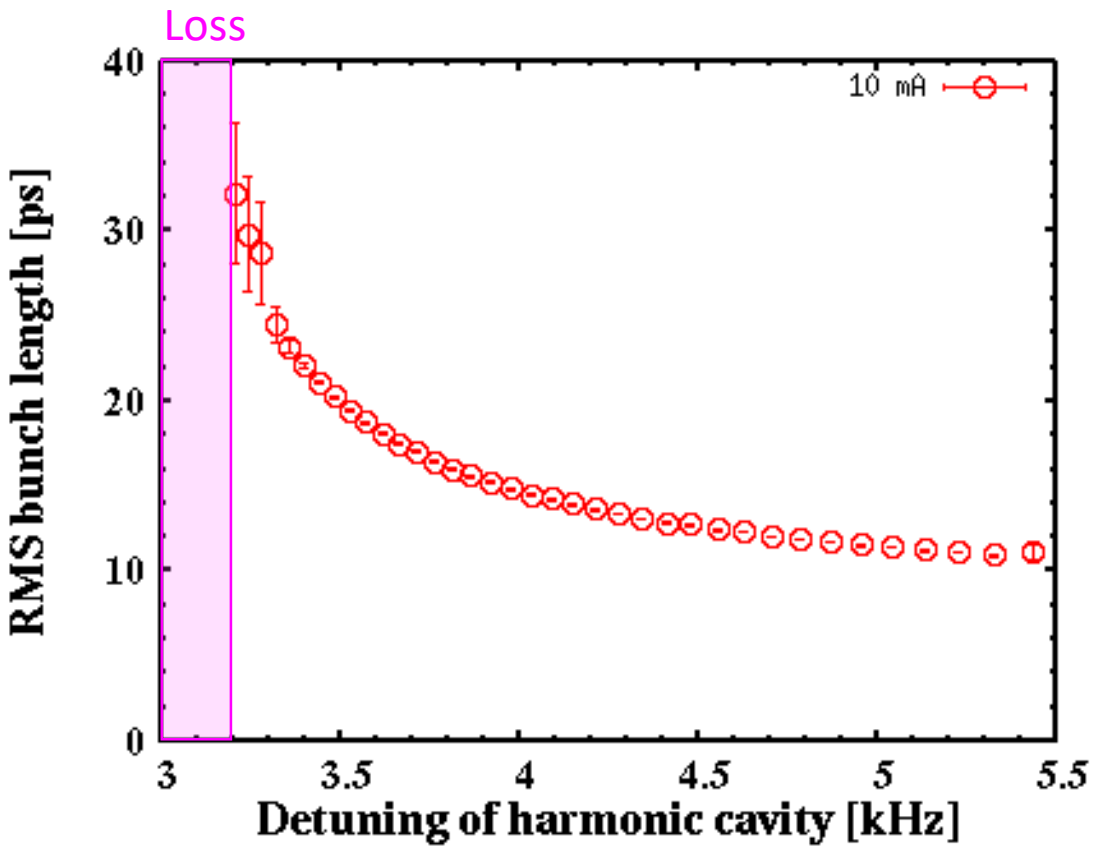


Fig. FFT spectra map along Turn number

Beam loss before the flat potential condition.



2.SOLEIL-U single bunch with HC

Calculation result

20 mA : single bunch Gaussian -> (close to the flat potential) -> double peak shape (over stretch) -> beam loss

Beam loss due to large separating of two stable points (?)

(We can tune the harmonic cavity detuning to obtain adequate bunch length.)

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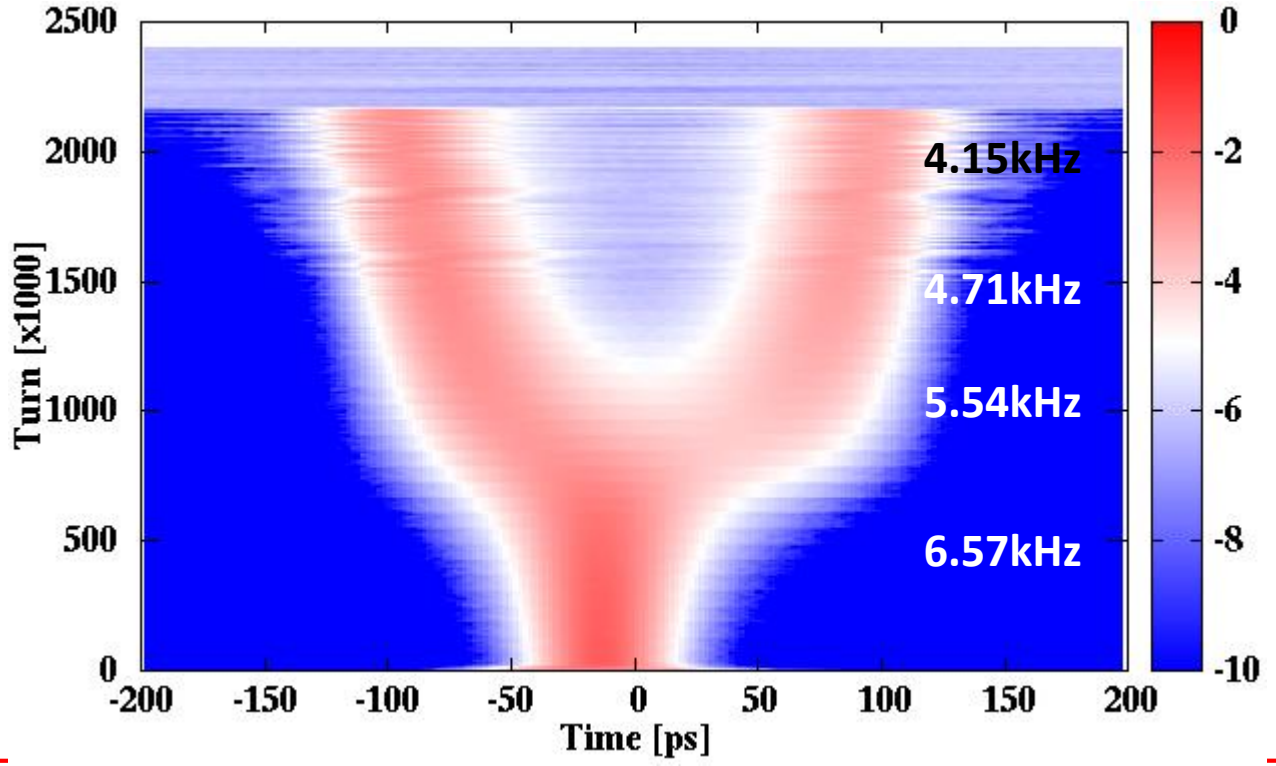
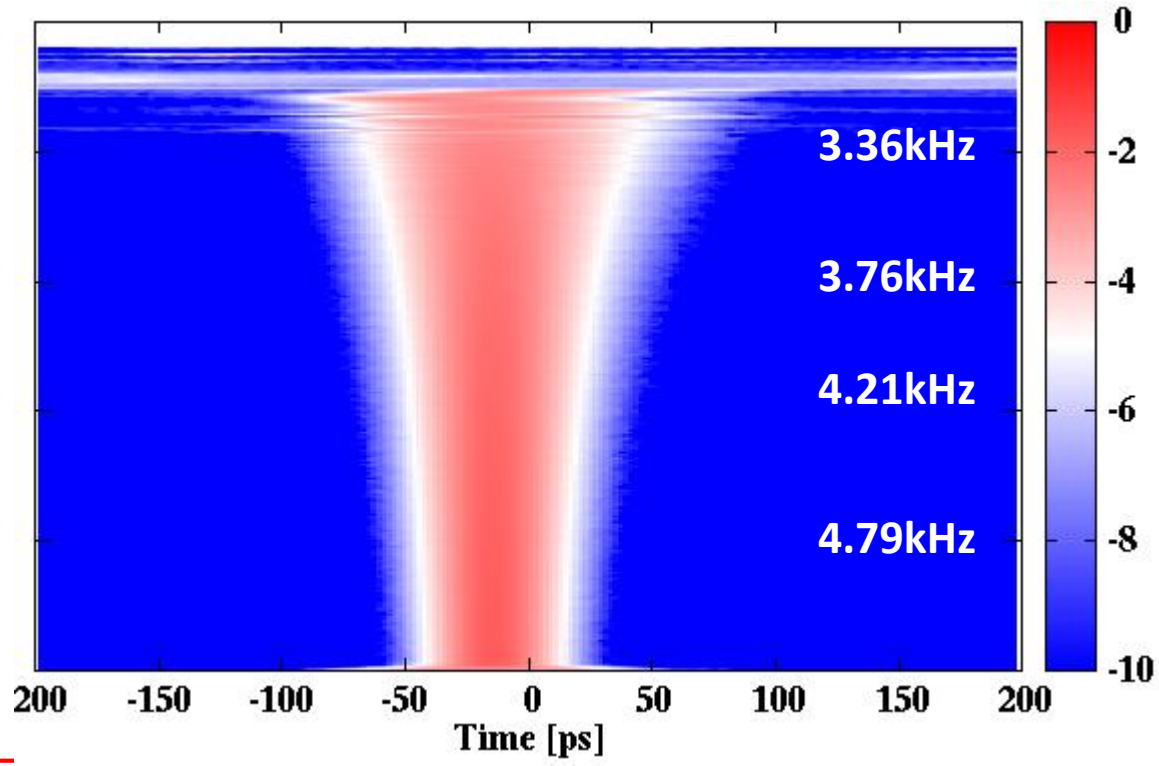
10 mA : single bunch Gaussian -> beam loss (before the flat potential condition)

Beam loss due to Longitudinal mode coupling or AC Robinson (too low detuning is required) (?)

20 mA



10 mA



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2. Low current limit of bunch lengthening operation
   - SOLEIL-U single bunch with HC
3. **Other possible equipment to affect the bunch-lengthening beam dynamics (Direct RF feedback)**
   1. **Benchmark result with PF/KEK-B experiments.**
   2. **Impact for SOLEIL-U uniform/single-bunch operation**

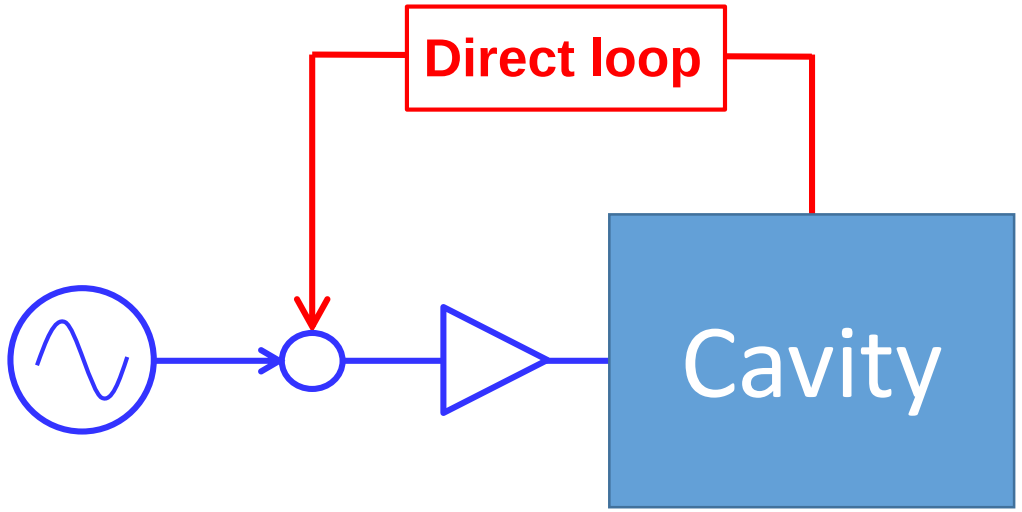
3. Direct RF feedback

- A direct RF feedback system and CBI Mode damper has been employed as an additional function of low level RF system in recent storage rings.
- A direct RF feedback system reduces the cavity impedance as seen by the beam, and allows us to avoid driving coupled-bunch instabilities and reduction of the coherent synchrotron frequency.
- For the purpose to investigate the impact of a direct RF system to the bunch lengthening operation, a function of direct RF feedback system has been introduced to the beam tracking code MBTRACK. (CBI Mode damper has been already introduced.)

- In this presentation, the preliminary calculation results are shown.
- Some results shown here were presented at IPAC2021.

3. Direct RF feedback

By subtracting a sample of the cavity voltage to the RF drive signal, the cavity impedance as seen by the beam is reduced.



Reducing the accelerating mode impedance is beneficial to avoid driving coupled-bunch instabilities and reduction of the coherent synchrotron frequency.

Direct RF feedback for the KEK-B system

*K. Akai et al., PASJ2020, WEPP35

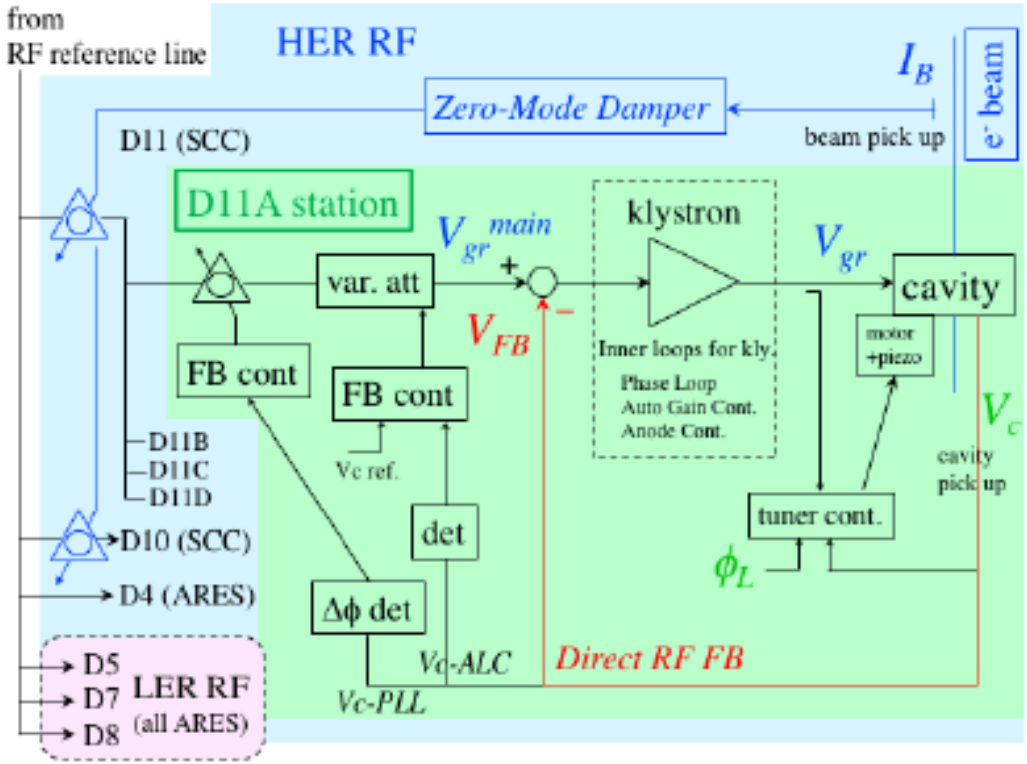


Figure 1: Schematic view of LLRF system for SupeKEKB. Green colored part is for one SCC station in HER. Blue (red) colored region shows HER (LER).

3. Direct RF feedback in the MBTRACK code

Characteristic parameter for DRFB
- Gf : Feedback gain,
- ΦF : RF phase shift
- ΔT : Loop delay (turn number)

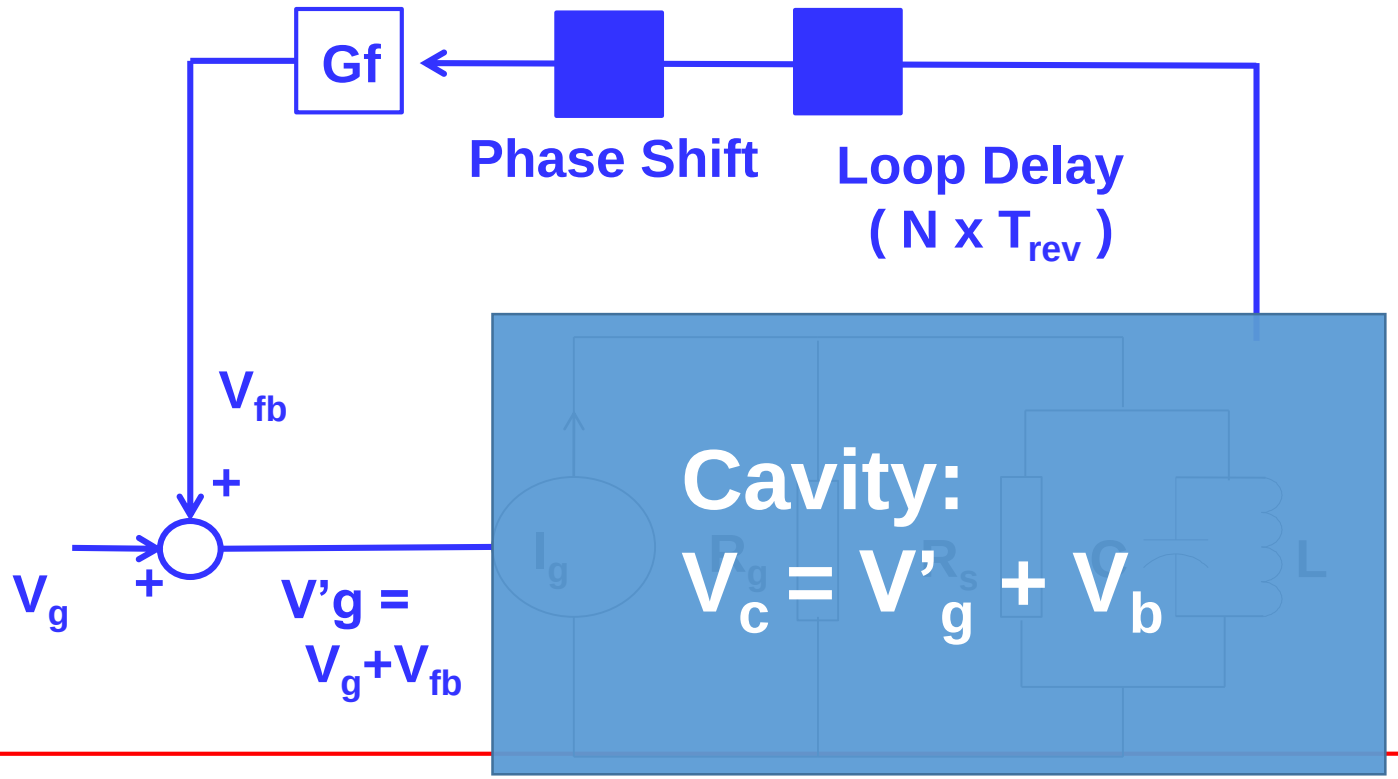
$$V_{g,fb} = G_f \cdot V_c(\Delta T)$$

$$\angle V_{g,fb} = \angle V_c(\Delta T) + \phi_F$$

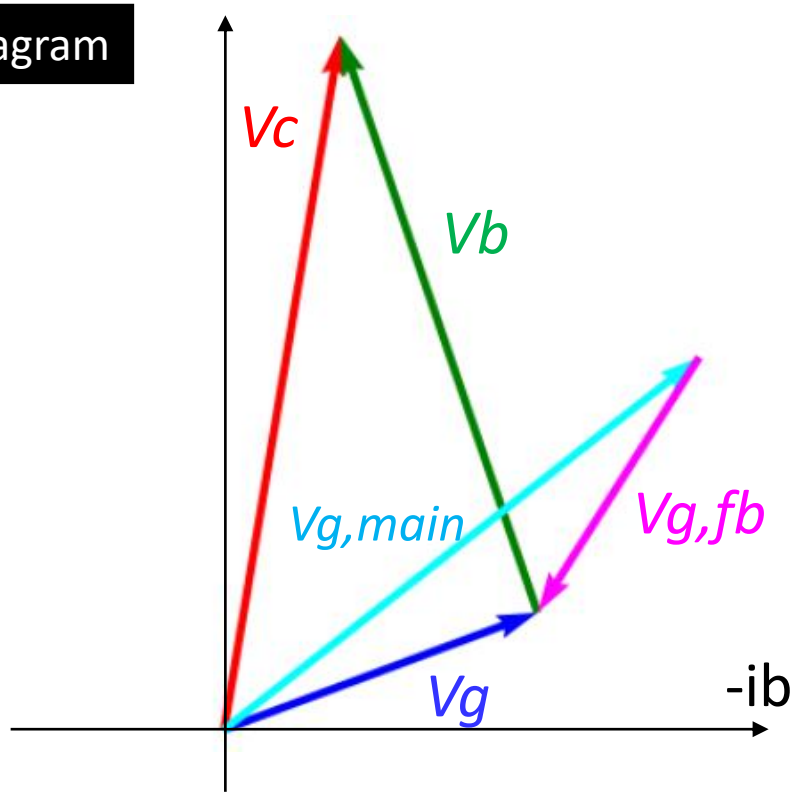
$V_c(N)$: V_c before N turns

Note: In this definition, ΦF is not applied to the drive RF signal but the induced voltage in the cavity.

Schematic of feedback circuit



Phasor diagram



3. Direct RF feedback

Benchmark results,
Coherent frequency shift as a function of the beam current

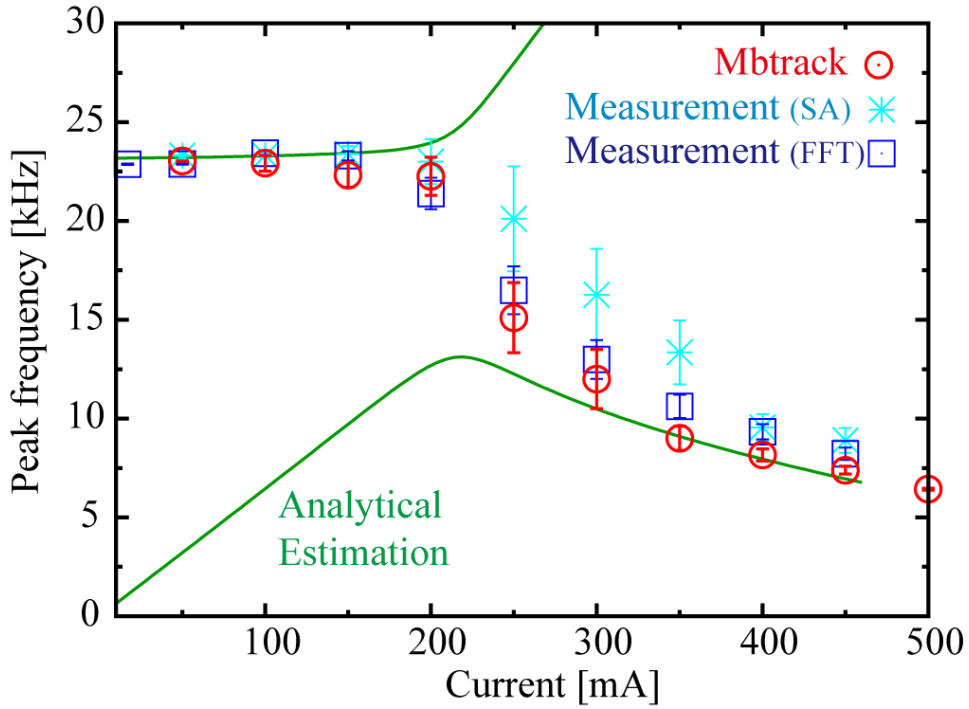


Fig. Frequency shits at PF-ring (measurement and calculation) , without harmonic cavity

Longitudinal coherent frequency shifts due to beam loading, where so-called static Robinson effects, are calculated by MBTRACK for KEK-PF ring, and compared with analytic/experimental results.

MBTRACK results are plotted on top of Figure.8

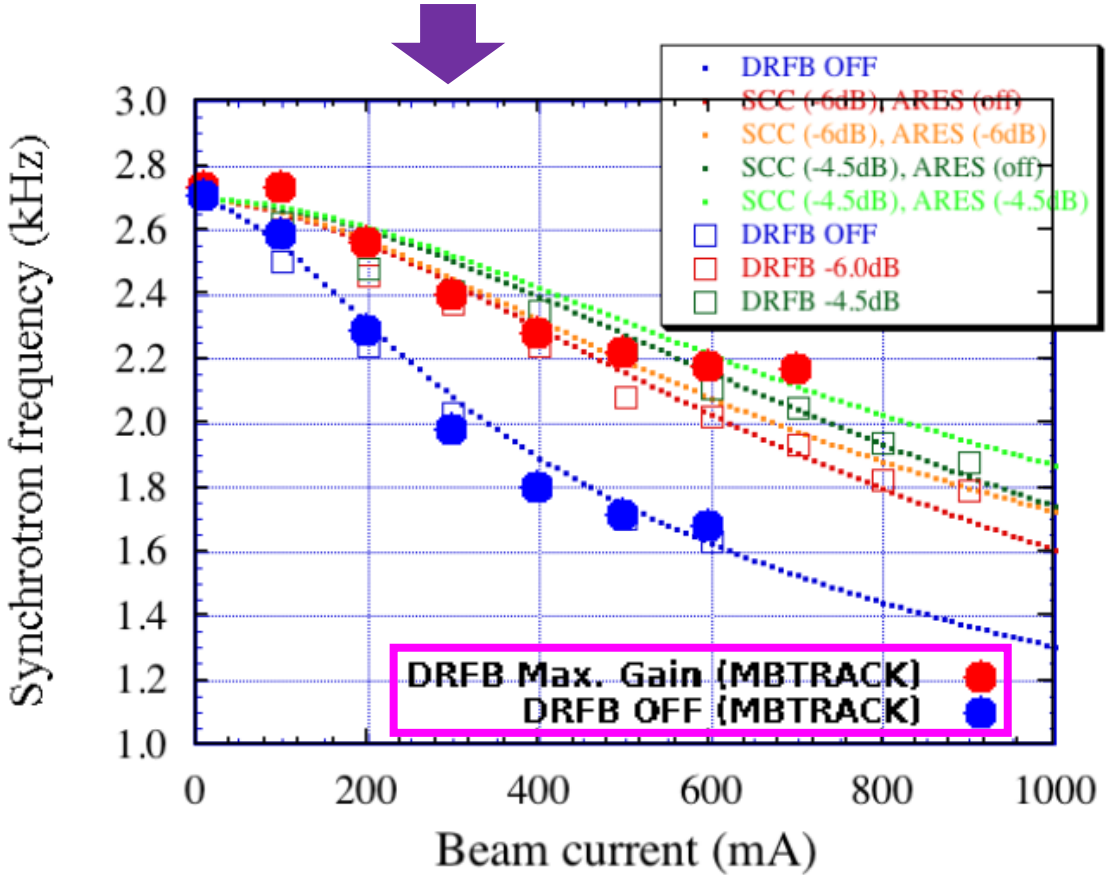


Figure 8: Calculated (dots) and measured (squares) frequencies of coherent synchrotron oscillation with SCC and ARES in HER for DRFB off, -6 dB and -4.5 dB.

*K. Akai et al., PASJ2020, WEPP35

3. Direct RF feedback, Multi-bunch

Calculation parameters

PARAMETER	
Beam energy	2.75 GeV
RF frequency	352.202 MHz
Revolution frequency	0.847 MHz
Stored current (uniform fill.)	450 mA
RF voltage	1.70 MV
Energy loss per turn	0.682 MeV
RF cavity	
Shunt Impedance	19.6 MΩ
Unloaded-Q	34000
Loaded-Q	6000

Direct RF feedback is applied only to main accelerating cavity.

Main cavity parameter (w. FB)		***4th SC harm. cavity***	***(w/o. FB)***
Shunt Impedance	19.6 MΩ	Shunt Impedance	9000 MΩ
Unloaded-Q	34000	Unloaded-Q	1e8
Loaded-Q	6000	Loaded-Q	1e8
Cavity voltage	1.70 MV	Cavity voltage	0.379 MV
		Detuning angle	145.8 kHz

Resulting bunch lengthening factor = 3.6

Some parameters are no longer correct, comparing with the latest design of the SOLEIL-U ring

3. Direct RF feedback, Multi-bunch

Calculation result

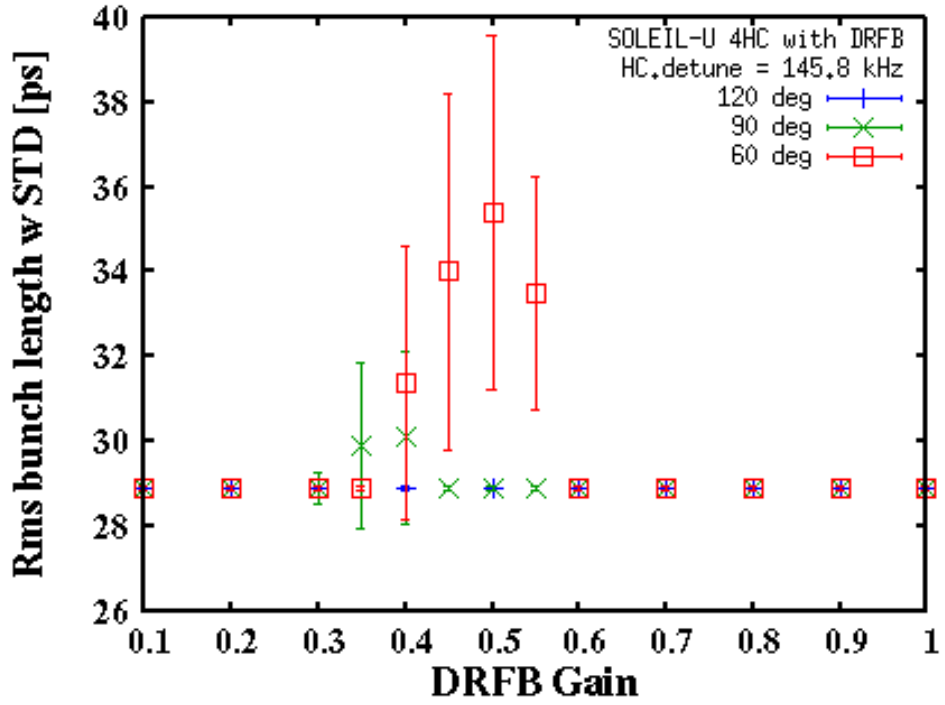


Fig. RMS bunch length and standard deviation as a function of the DRFB gain

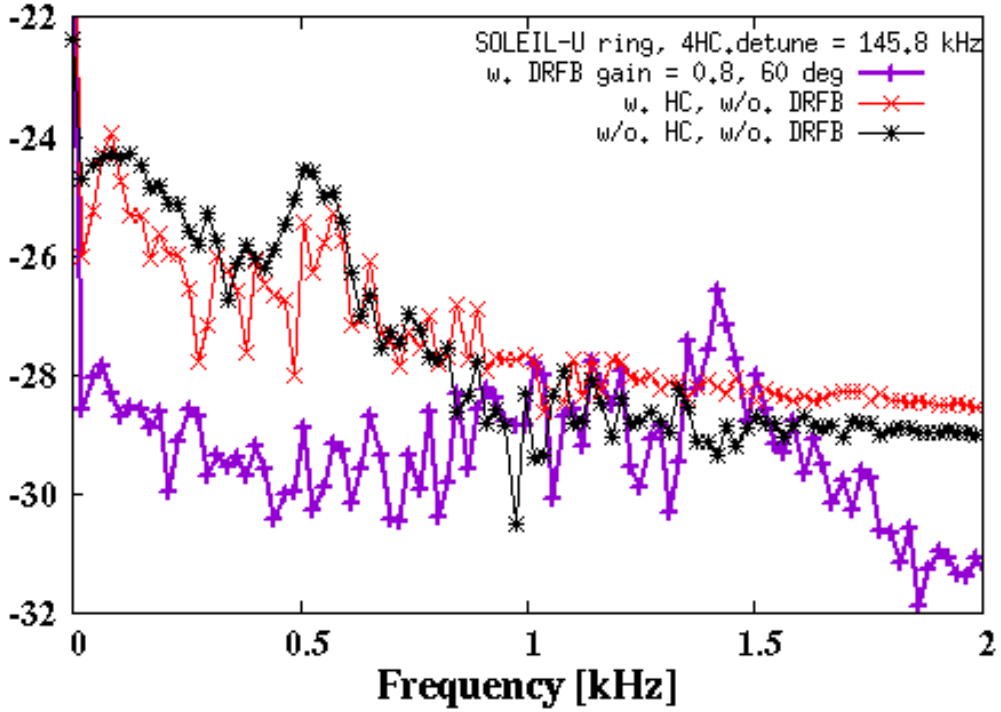


Fig. FFT spectra of beam center mass position

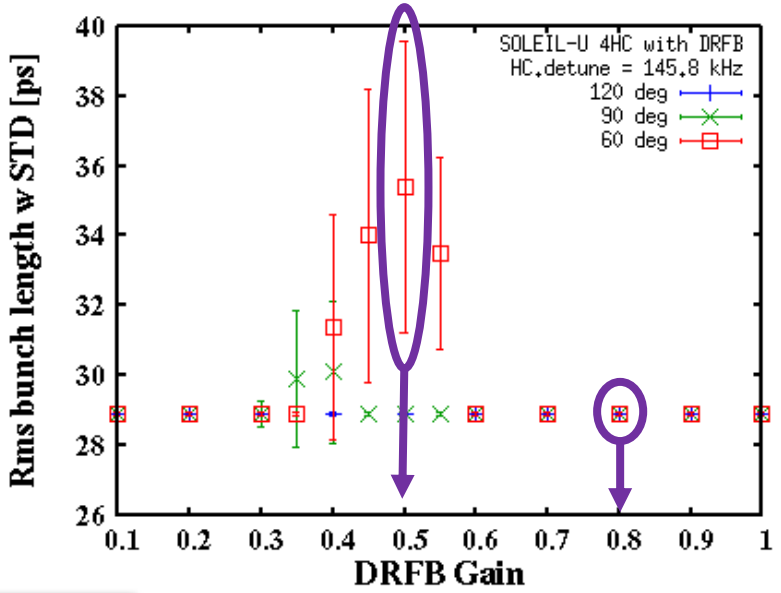
Unstable beam motions are observed at the gains between 0.4 ~ 0.55 for the phase shift of 60 deg and 0.3 ~ 0.45 for 90 deg.

Reduction of the coherent frequency shift is also observed even if bunch lengthening mode.

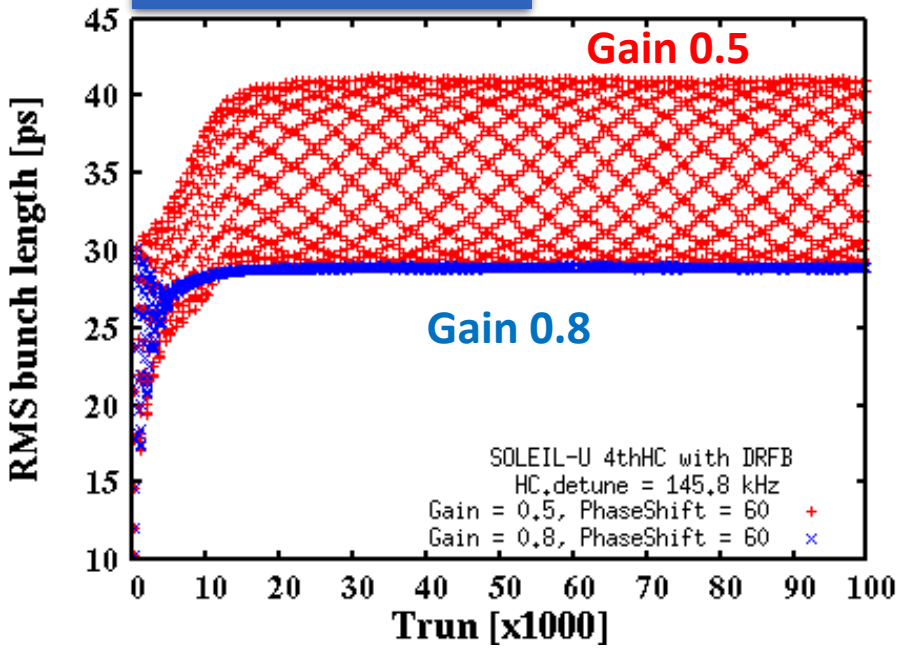
3. Direct RF feedback, Multi-bunch

Calculation result

Unstable beam motions are observed at the gains between 0.4 ~ 0.55 for the phase shift of 60 deg and 0.3 ~ 0.45 for 90 deg.



RMS bunch length



Cavity voltage

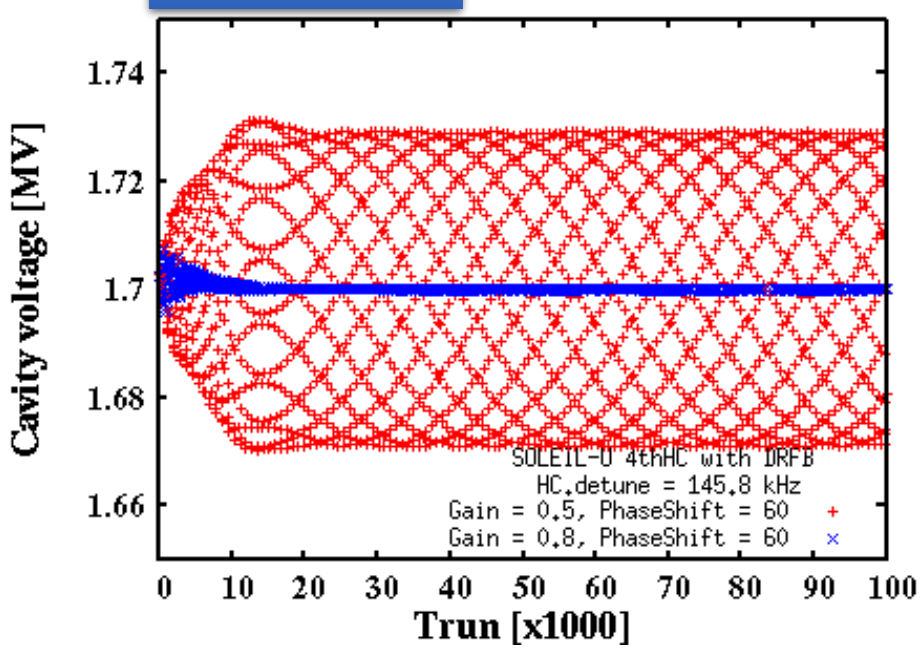
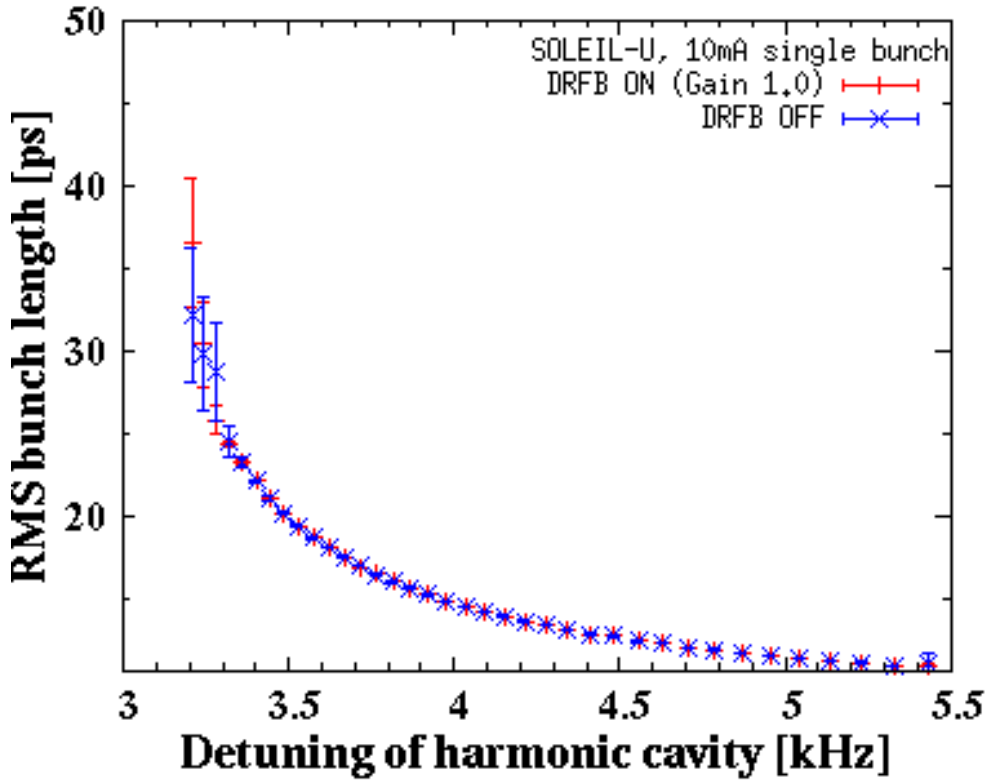


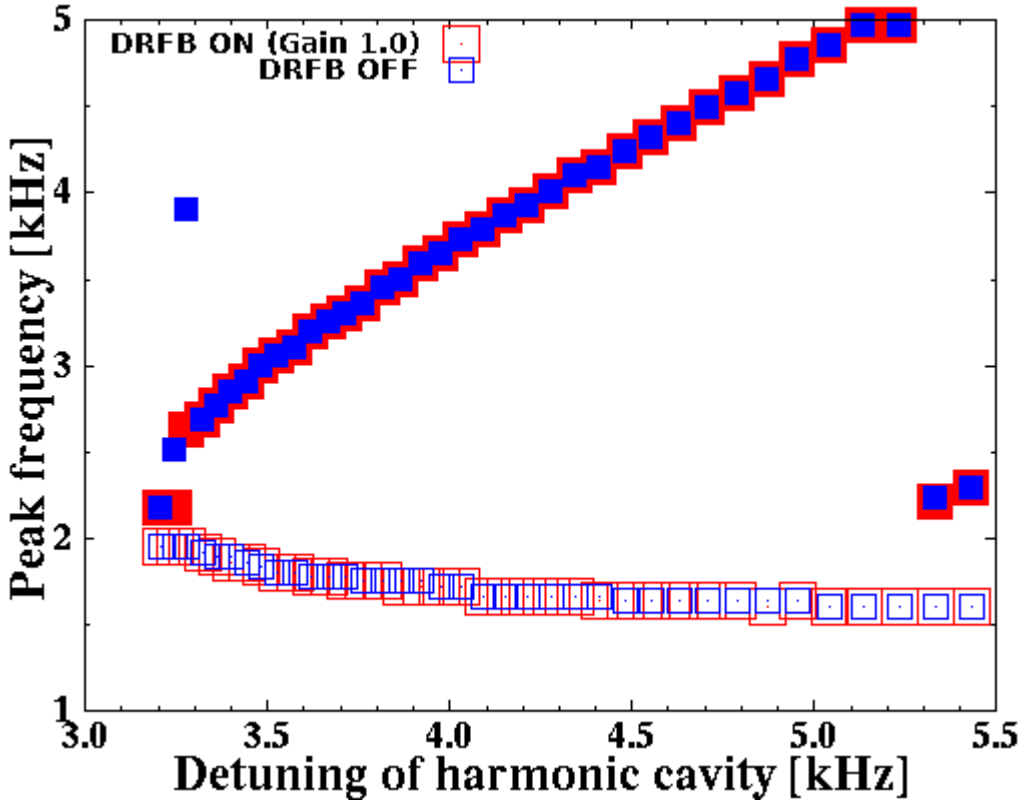
Fig. Comparison with the gain of **0.5** and **0.8** for the phase shift of 60 deg

3. Direct RF feedback, Single-bunch 10 mA

In single bunch case, beam load is small.
Then it seems that the impact of DRFB is very small.

Calculation result





Discussion

1. SOLEIL-U 3/4Fill with harmonic and kicker cavities
2. SOLEIL-U single bunch with HC
3. Direct RF feedback
    1. Benchmark result with PF/KEK-B experiments.
    2. Impact for SOLEIL-U uniform/single-bunch