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Beam loading compensation for optimal bunch lengthening with harmonic cavities

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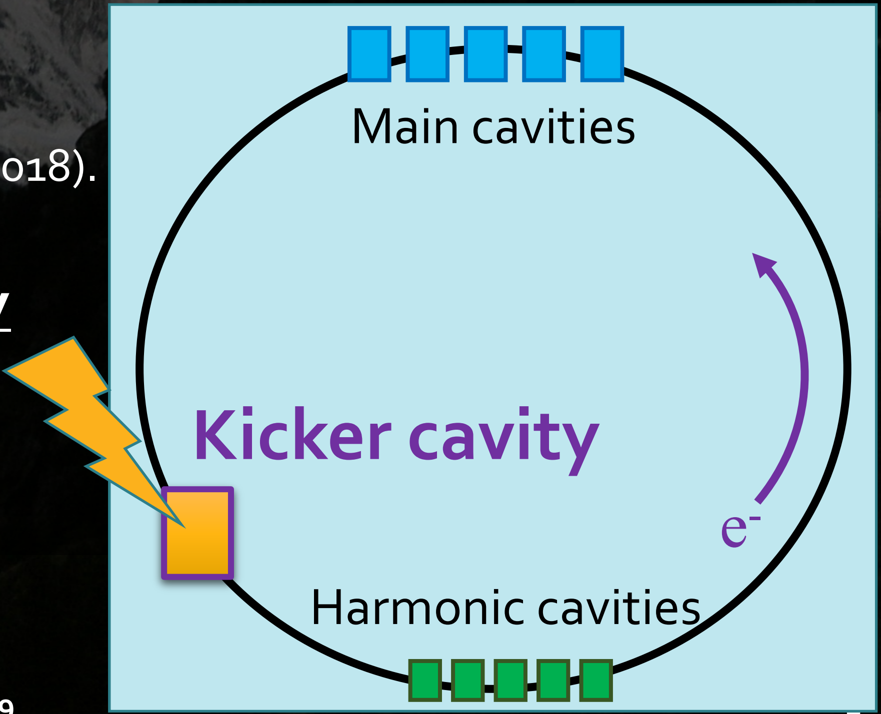
OUTLINE

- Harmonic (double) RF system
  - Introduction
  - Physics
- Reduction of Transient beam loading effect
  - Transient beam loading effect
  - Reduction of the effect
- Compensation of Transient effect

  *N. Yamamoto, et al., PRAB 21, 012001 (2018).
  - Basic idea
  - Compensation with <u>a kicker cavity</u>
  - Numerical estimation
- Summary



Introduction of harmonic RF system

- Extreme low emittance storage ring, which aim at achieving the beam emittances of < 100 pmrad, are being actively designed as future ring-based synchrotron light sources.
- In such rings, **emittance growth & small beam lifetime due to intrabeam scattering** are serious concerns.

http://kekls.kek.jp

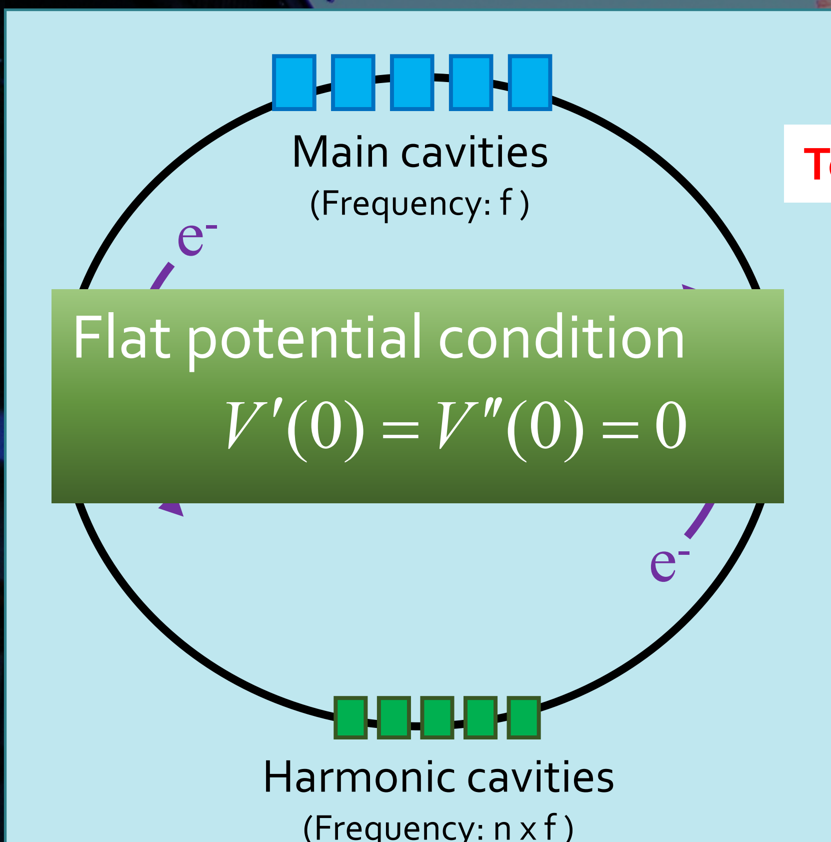
KEK-LS parameter

Electron energy	E_0 [GeV]	3		
RF frequency	f_{RF}[MHz]	500.07		
RF voltage	V_{RF}[MV]	2.5		
Beam current	[mA]	**0**	**200**	**500**
Hor. emittance	[pmrad]	**132.5**	**230.5**	**314.74**
Touschek lifetime	[h]	**–**	**2.9**	**1.8**

- One of solutions to such adverse effects is to lengthen beam bunches (reducing the electron densities).
- **For this purpose, the harmonic RF system is employed.**

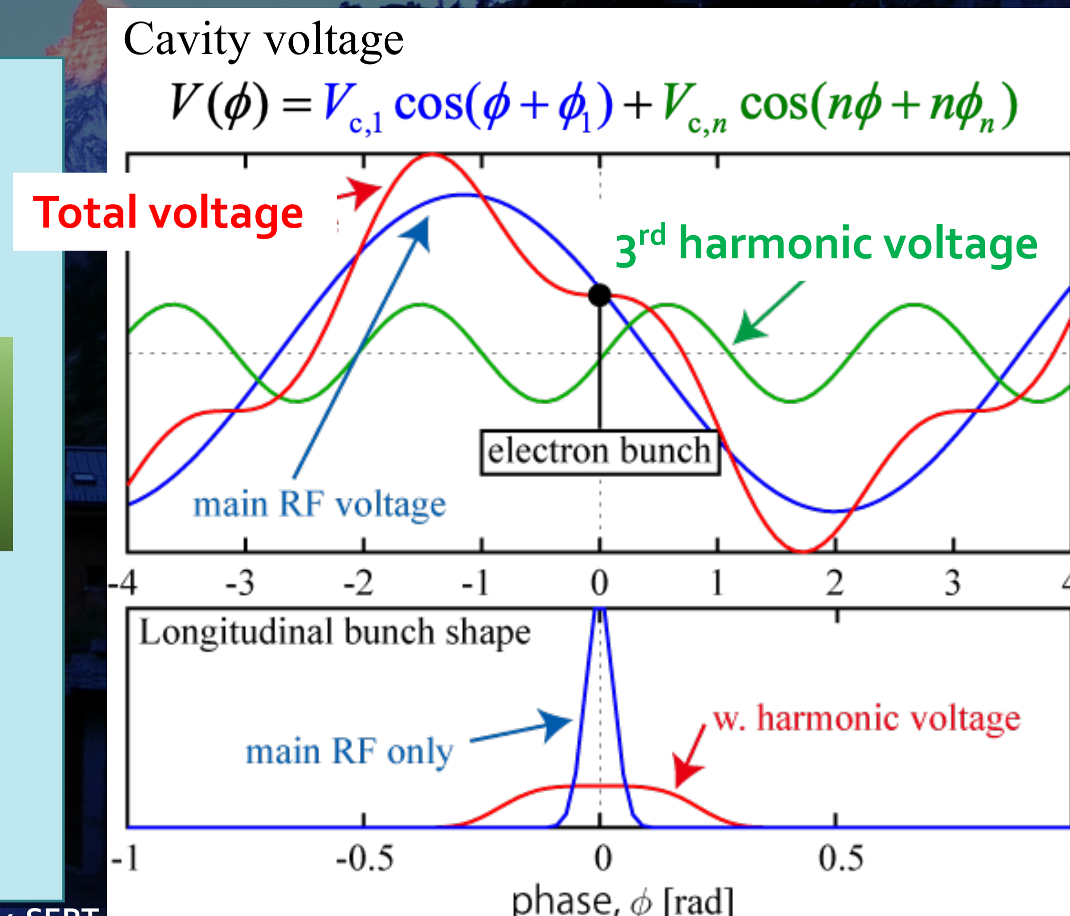
Physics of harmonic RF system

- Storage ring main cavity is used to replace energy lost through synchrotron radiation.
- **By adding *n*th harmonic voltage (cavity), we can shape the bunch longitudinally.**



Flat potential condition

$$V'(0) = V''(0) = 0$$



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Transient beam loading effect

- When the gaps (i.e. unoccupied RF buckets) are introduced in the fill pattern of the ring, the bunch gaps induce considerable variations in both amplitude and phase in the RF voltage.
- The higher frequency (> 1.5GHz) cavity, the effect is more serious.

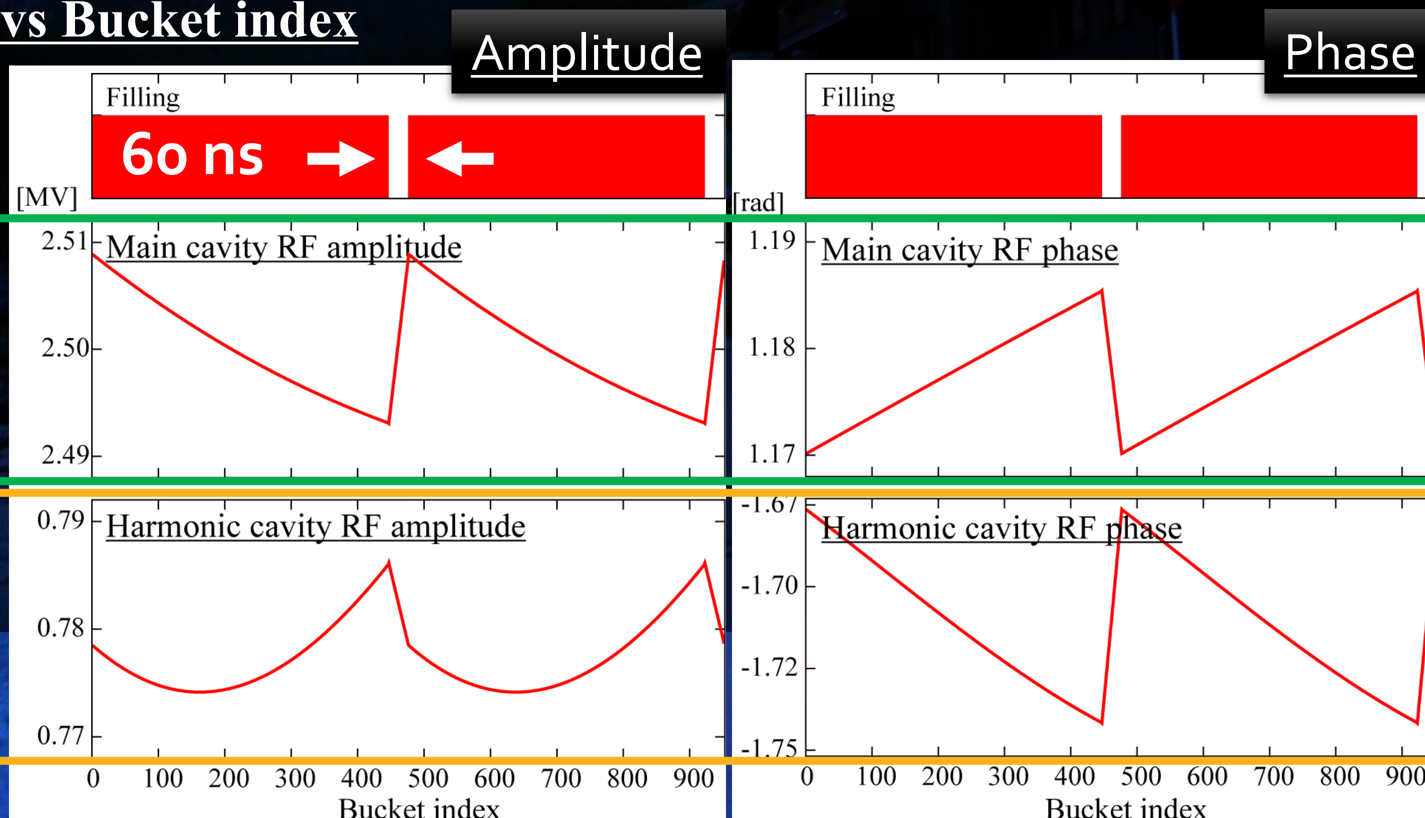
Cavity voltage vs Bucket index
(60 ns gap, KEK-LS)

Main cavity (500MHz)

$$|\Delta \tilde{V}_c| / |\tilde{V}_c| = 1.6\ \%$$

Harmonic cavity (1.5GHz)

$$|\Delta \tilde{V}_c| / |\tilde{V}_c| = 7.1\%$$



Naoto Yamamoto, KEK

Transient beam loading effect

• … pied RF buckets) … am, the bunch ga… voltage.

• The high… more serious.

Cavity vol…
(60 ns gap…
KEK-I…

Main cavity (500MHz)

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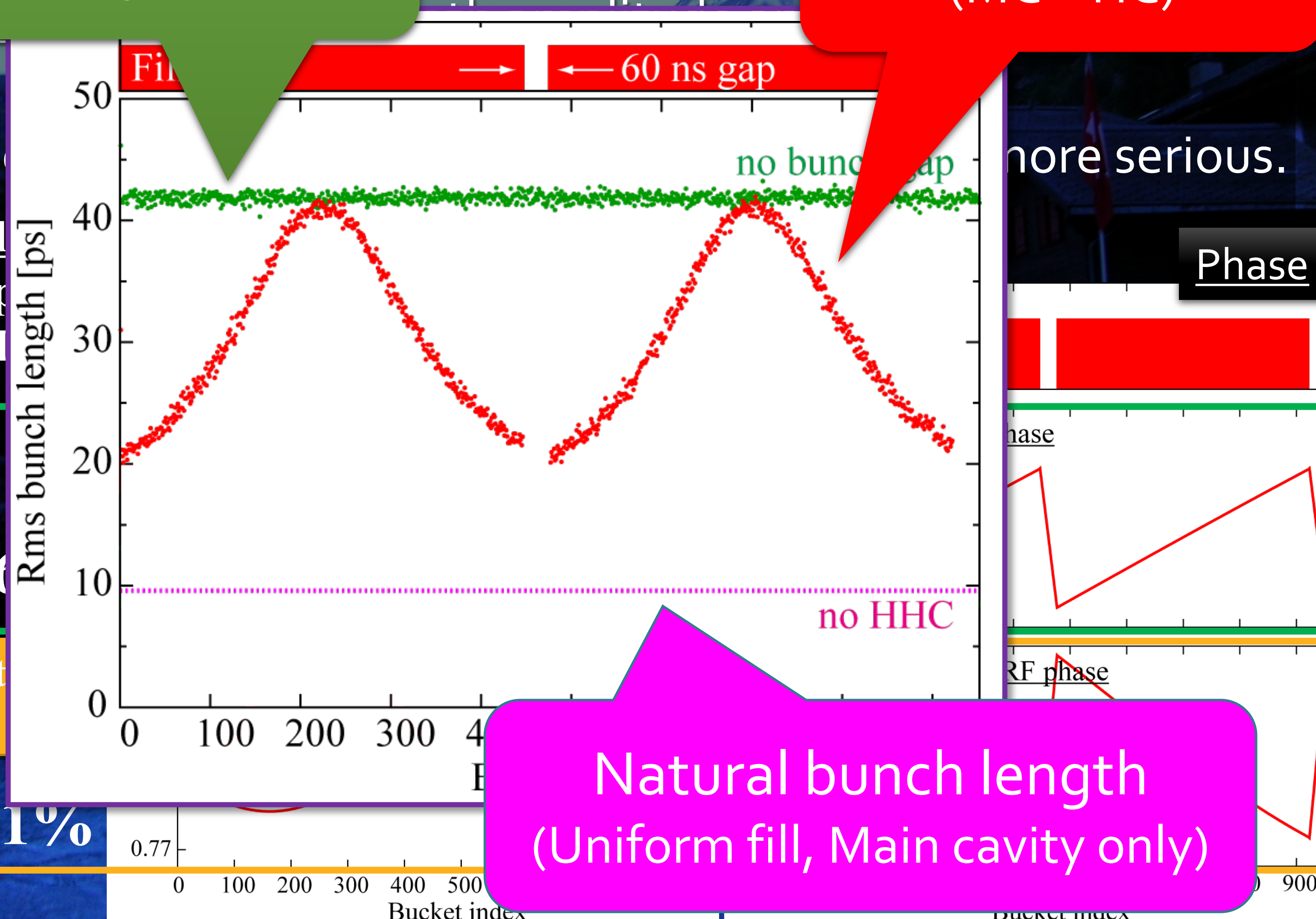


Reduction of the loading effect

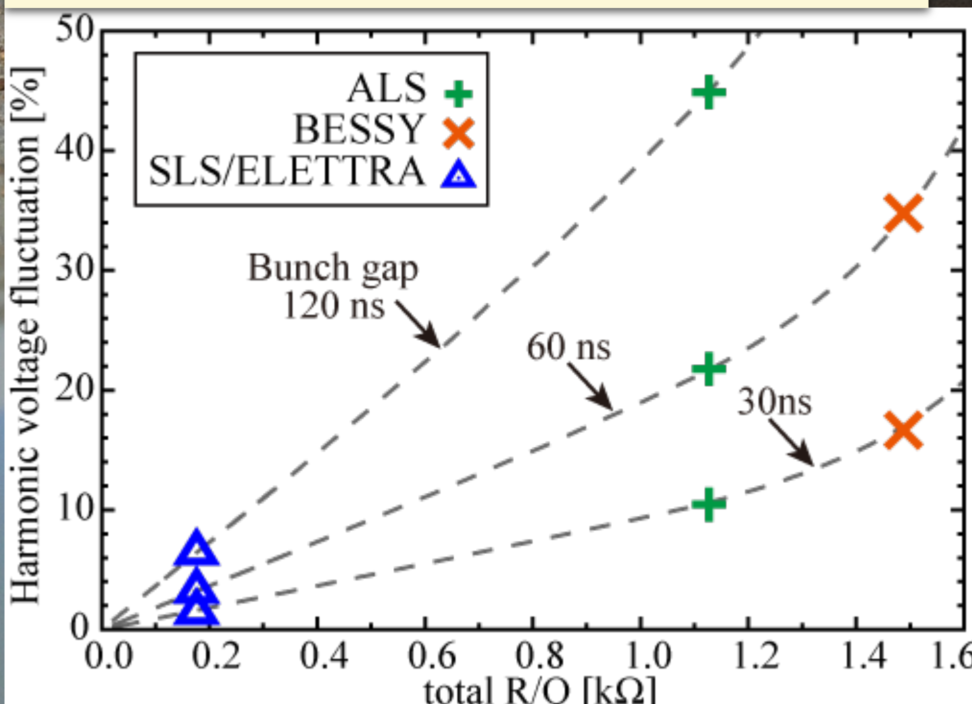
- **The transient effect depends on the total R/Q values.**

$$\Delta V_{max} / V_{ave} \cong e^{-n_g \alpha} - 1$$

For passive cavity (without generator)

$$\alpha = \pi \left(\frac{R}{Q}\right)_n \frac{m(m^2-1)}{U_0} I_0 \cos^2\psi_n (1 - i\tan\psi_n)$$

Harmonic voltage fluctuation vs Total R/Q (analytical calculation for KEK-LS ring)



		SLS/ ELETTRA	ALS	BESSY-II
R/Q	Ω	176	161	124
Unloaded-Q		2.0E+08	21000	13900
Coupling	β	3099	1.08	0.82
Loaded- Q		64514	10088	7631
Fill time	µs	13.7	2.1	1.6
Cav. number		1	7	12
total R/Q	Ω	176	1127	1488
V_{hc} / cav.	kV	777	111	65
Pc / cav.	kW	0.0	3.6	2.4
$\Delta V_c/V_c$(60ns)		3.2%	22.0%	35.0%

Transient beam loading effect for SC-cavity

- **SC harmonic cavity**

The effect is mitigated as compared to NC-cavity, but considerable effects (bunch phase shift & length modulation) still remain.

→ Additional treatments are needed !

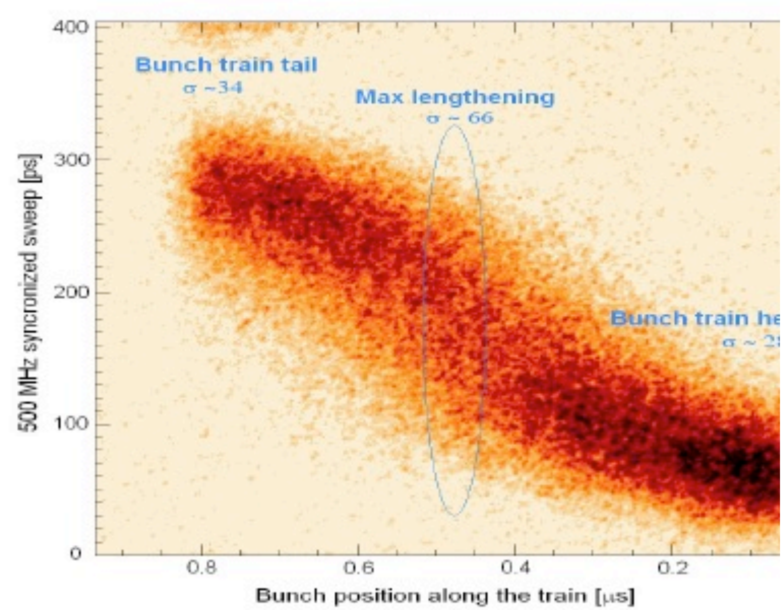
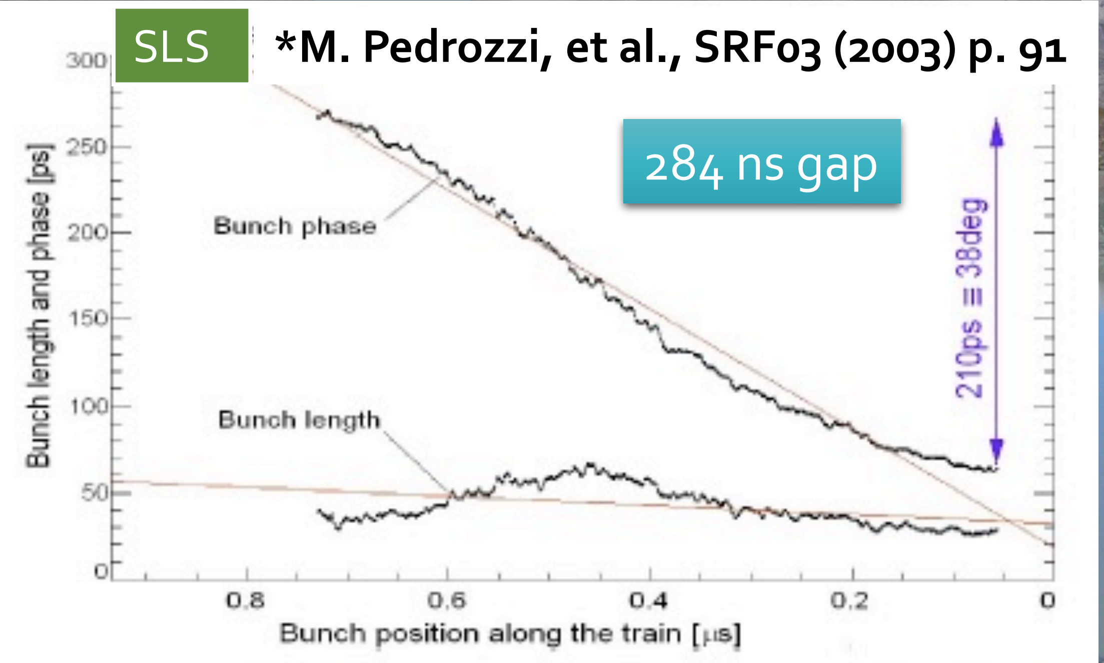


Figure 4: Streak camera snapshot at 320mA. Bunch σ and phase in ps versus position in the bunch train.



*M. Pedrozzi, et al., SRF03 (2003) p. 91

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Basic idea of the compensation

- Two measures;

  (a) compensation on the main and harmonic cavities,

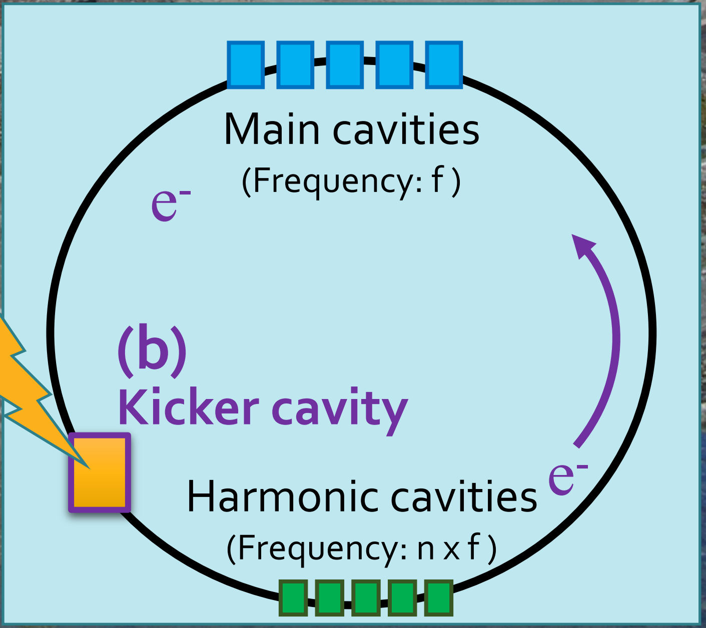
  <u>**(b) compensation using a separate kicker cavity.**</u>

Advantage of the method (b)

- Input RF power is minimized by optimizing the cavity bandwidth.

Disadvantage

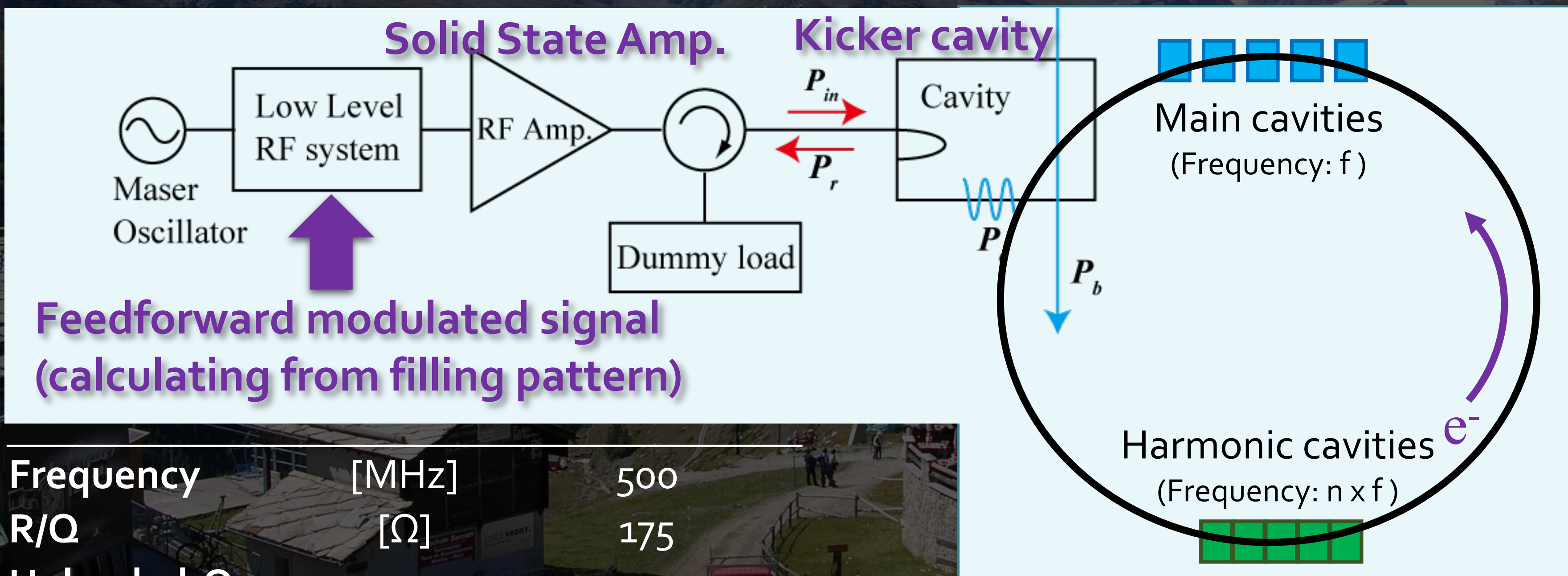
- Another space in the ring, RF system (low level system, RF amp …)



Compensation with a kicker cavity

System overview

We consider to use an active feedforward low level control, a kicker cavity having the wide bandwidth and a Solid state amplifier.



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

← assumed kicker cavity parameters (not optimized)

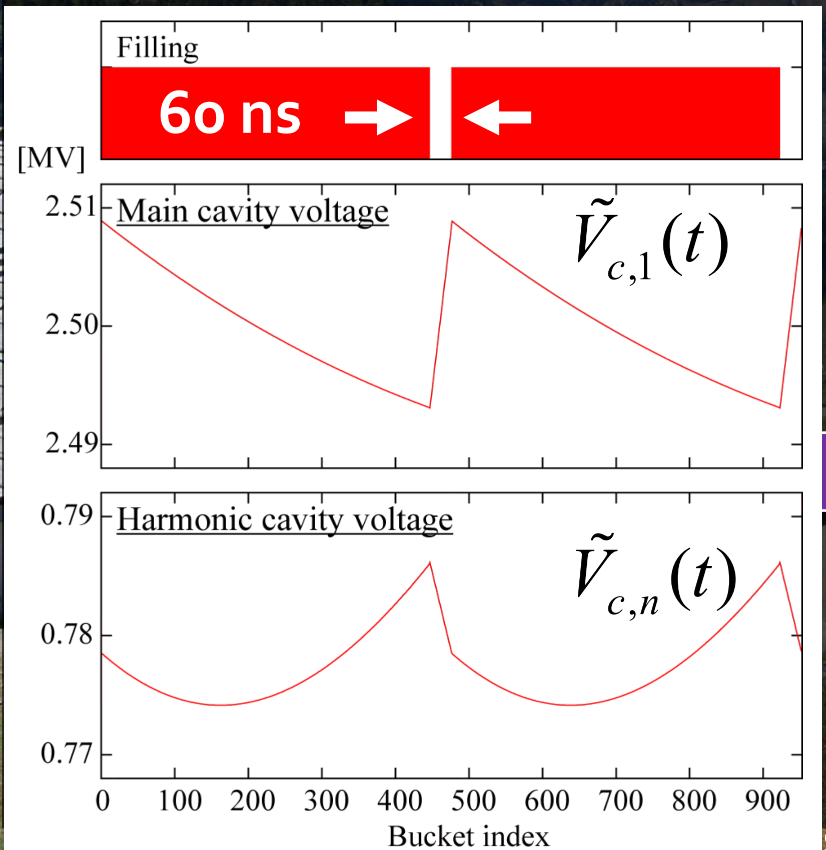
Compensation with a kicker cavity

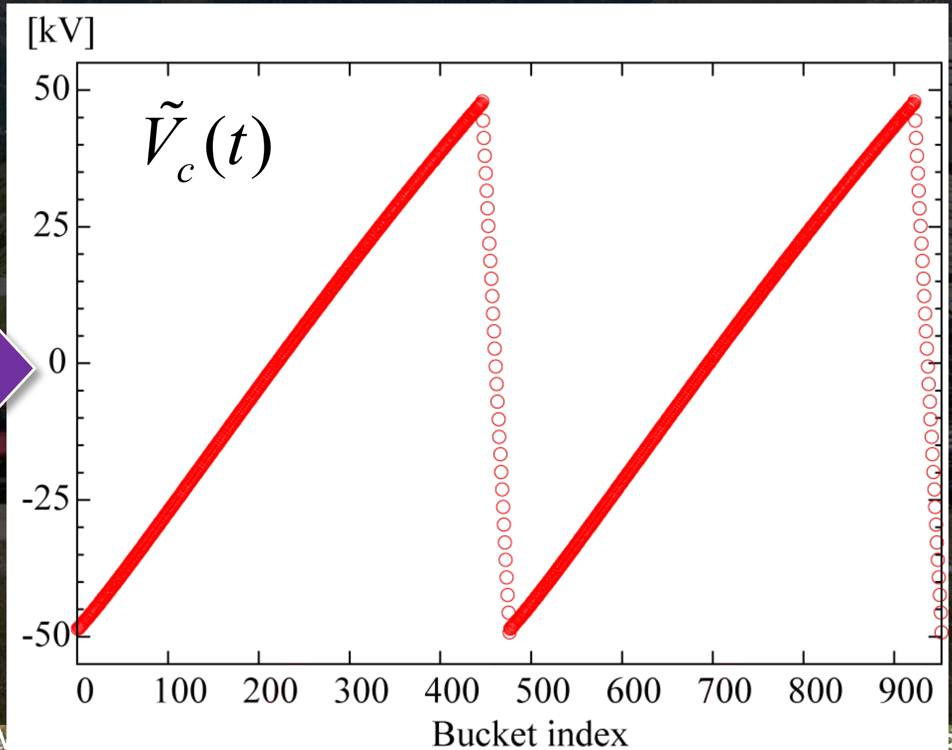
How to obtain the feedfoward signal

1. **The RF voltage of the kicker cavity can be decided to suppress phase shifts of the bunches along the train.**

* Main and harmonic voltage can be evaluated from the fill pattern.

$$\tilde{V}_c(t) = -\left(\mathrm{Re}\left[\tilde{V}_{c,1}(t) + \tilde{V}_{c,n}(t)\right] - U_0\right)$$

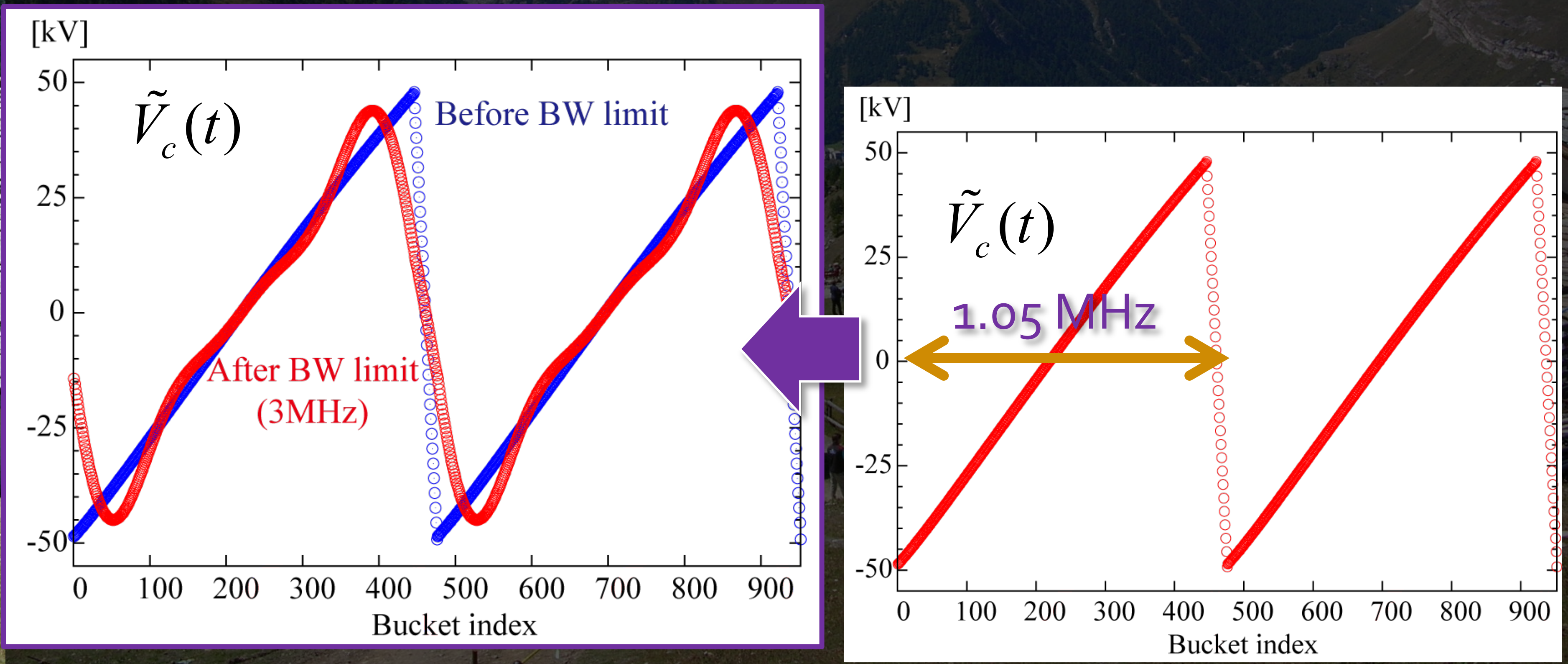




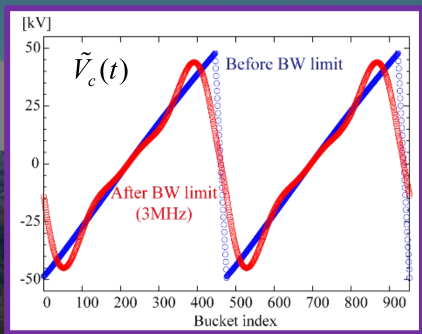
Compensation with a kicker cavity

<u>How to obtain the feedfoward signal</u>

1. Evaluate the kicker cavity voltage
2. **Apply the bandwidth limitation, where the bandwidth should be wider than the repetition frequency of the bunch train.**

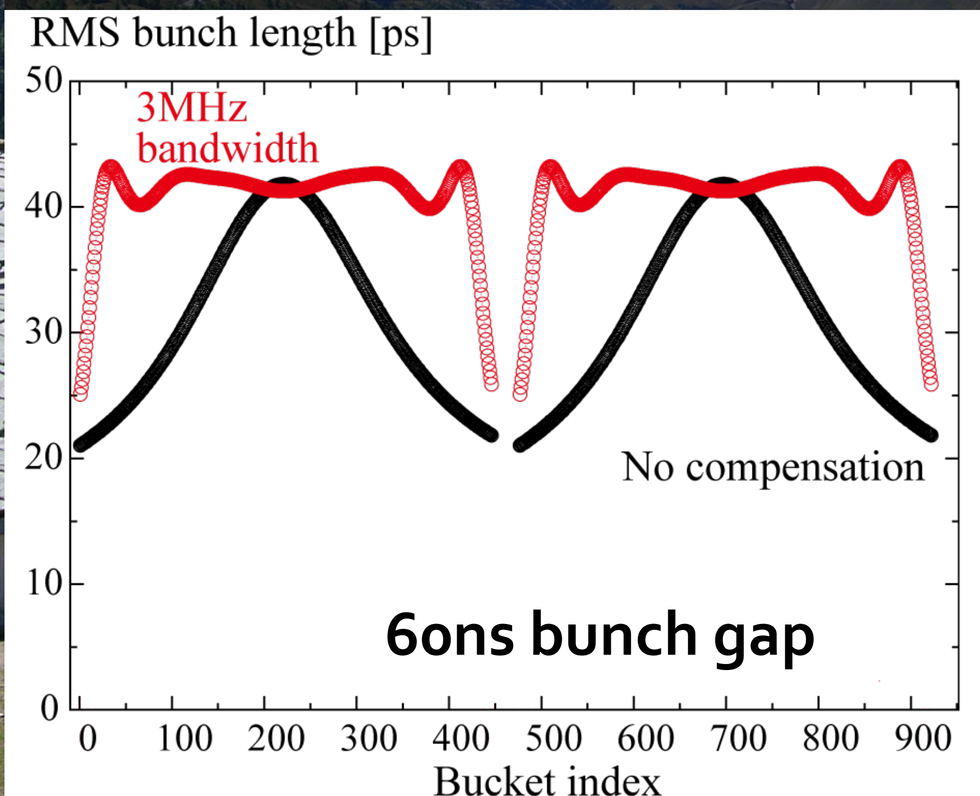


Compensation with a kicker cavity

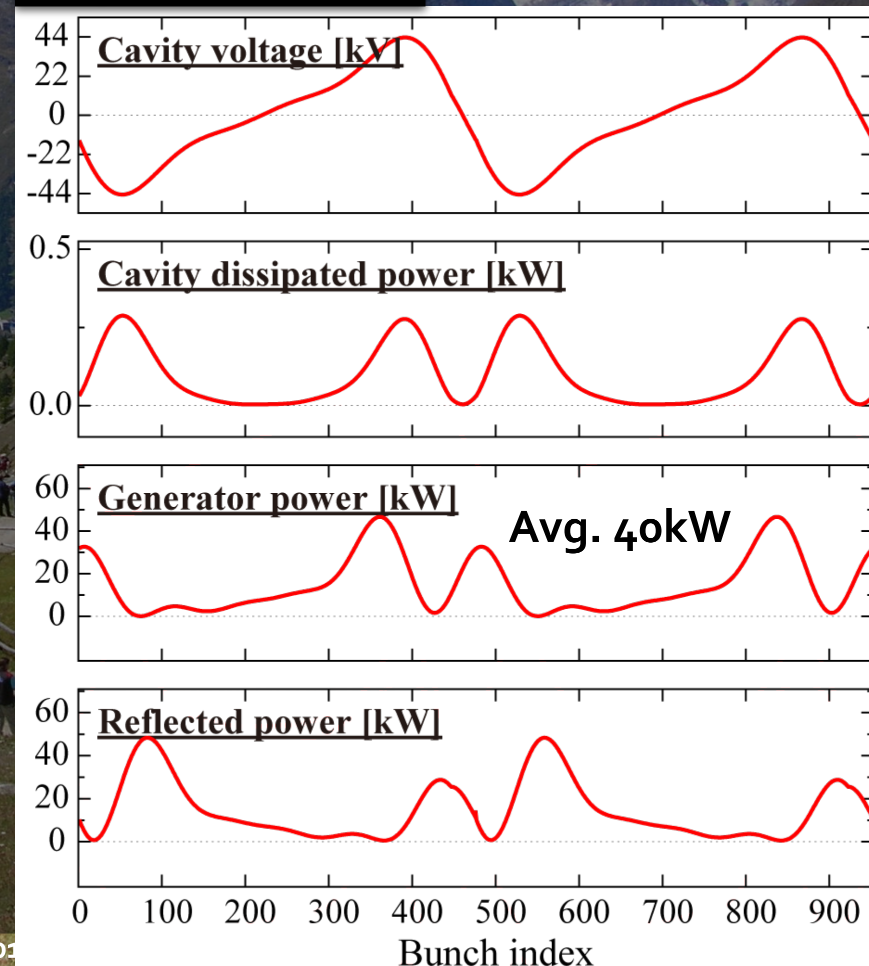


Adding Kicker cavity field in Analytical calculation

Beam energy 3GeV
Main RF voltage 2.5MV
RF frequency 500MHz

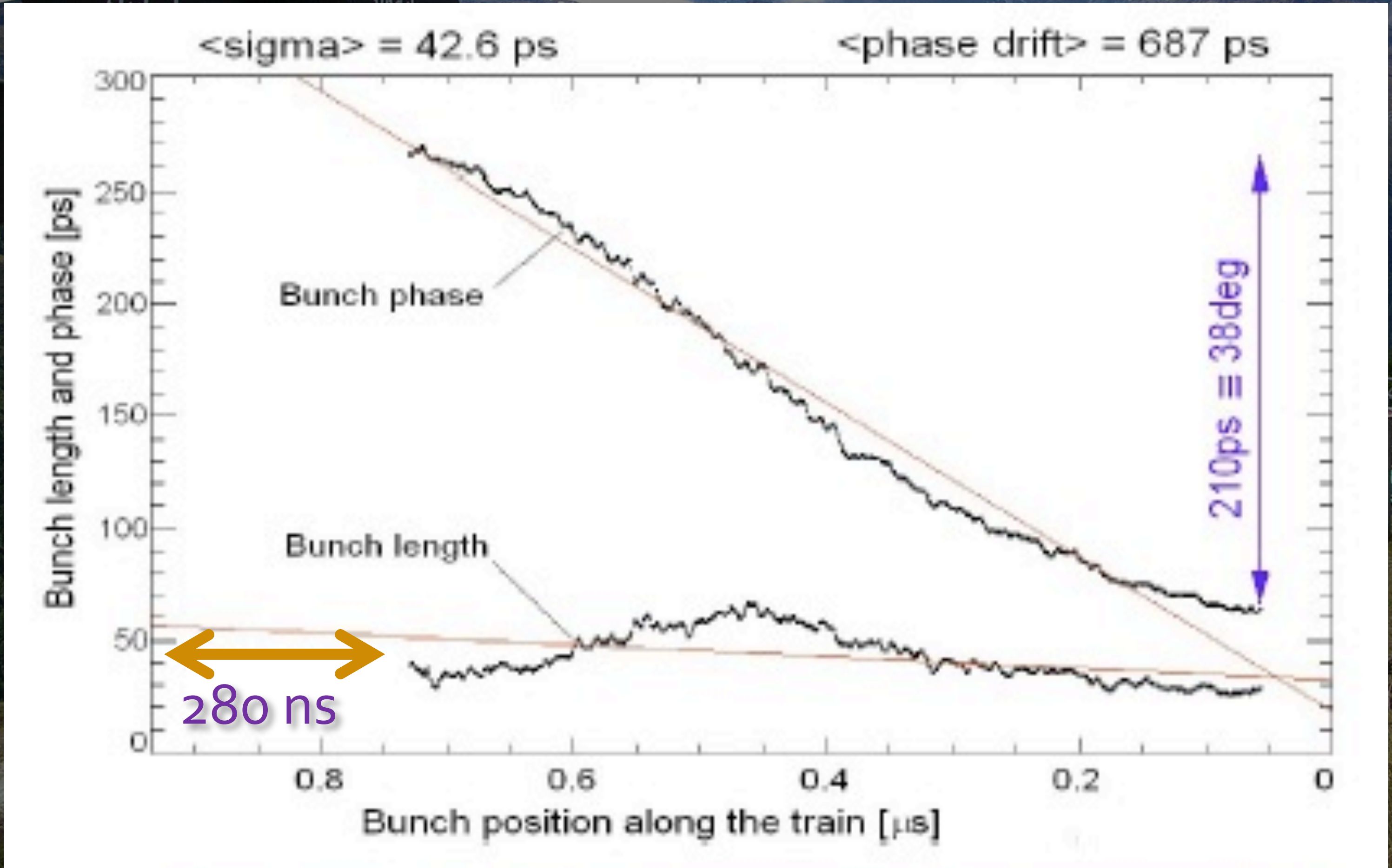


RF power valances

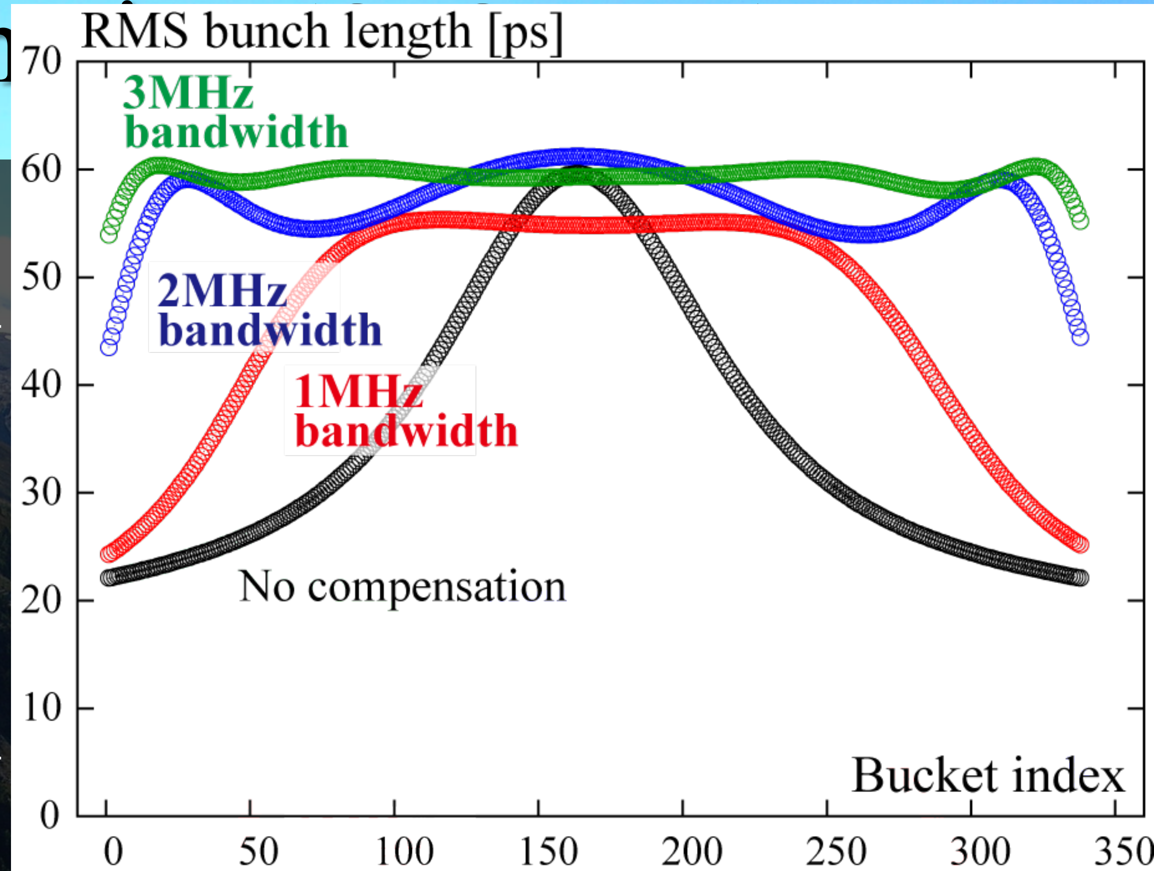


Analytical estimation (SLS case)

*M. Pedrozzi, et al., SRF03 (2003) p. 91



Analytical estim



Kicker cavity parameter

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

Compensation bandwidth	Average Bunch length	Peak Generator Power	Average Generator Power
[MHz]	[ps]	[kW]	[kW]
—	35.8	—	—
1	46.3	25.8	16.8
2	56.9	84.1	35.6
3	59.3	98.3	39.1

Macro particle simulation for SOLEIL-U

Tracking code : *mbtrack* **N.Yamamoto et al., IPAC2019 (2019) MOPGW039*

Tracking with

Long-range wake fields due to RF cavity impedances

(Main SC cavity, passive 3rd-HC cavity, NC Kicker cavity)

* other impedance sources & intra-beam scattering were not taken account

Energy	2.75 GeV
Emittance (H,V)	50 pmrad
Circumference	354 m
RF frequency	352 MHz
Momentum compaction	1.47e-4
Energy spread	8.53e-4
Damping time	23.9 ms
Radiation loss / turn	0.5 MeV
RF Voltage	2.5 MV
Stored Current	450 mA
Filling pattern	3/4 , 295 ns gap

Main cavity

Unloaded-Q	1×10^{10}
Loaded-Q	50000
total R/Q	360 Ω

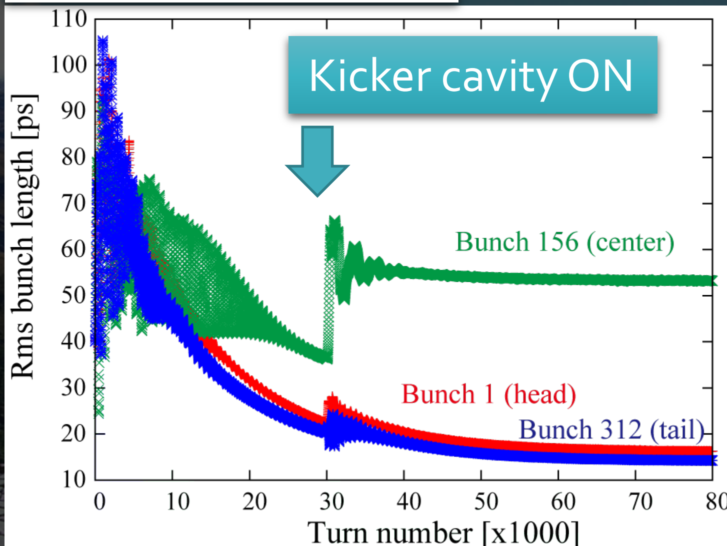
3rd Harmonic cavity

Unloaded-Q	1×10^{8}
Loaded-Q	1×10^{8}
total R/Q	180 Ω

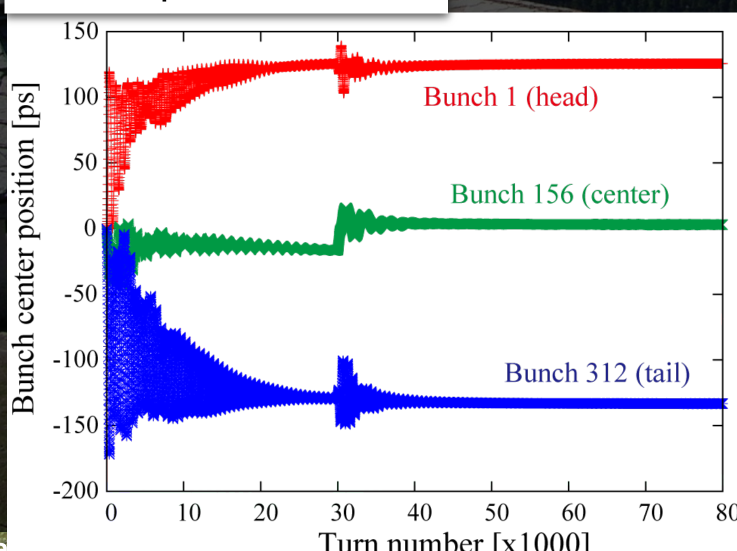
\+ NC Kicker cavity (352MHz)

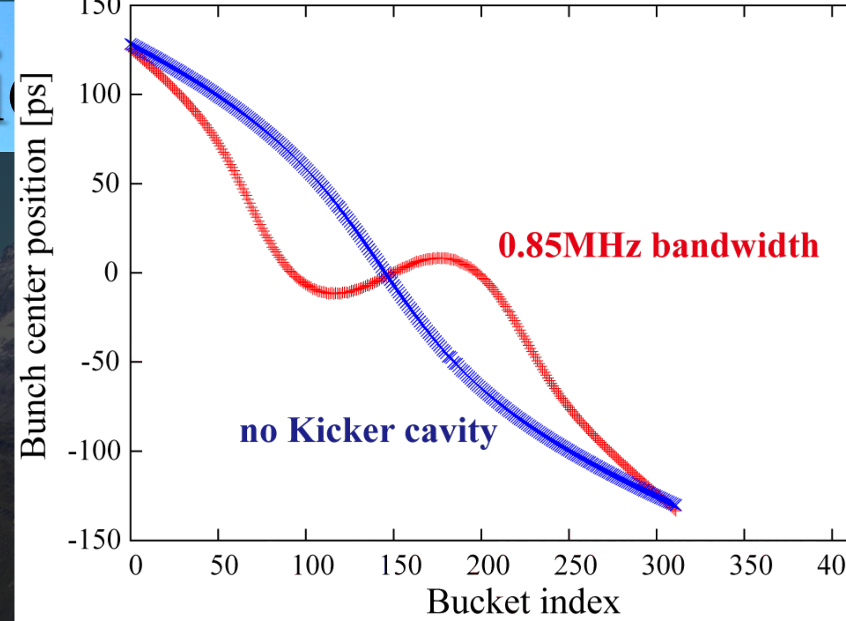
Macro particle simulati

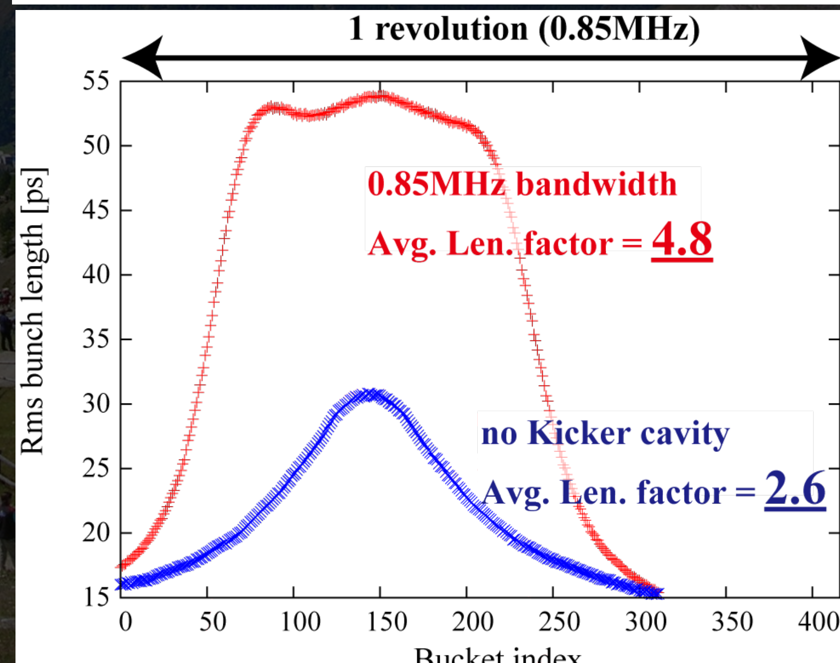
Bunch length vs Turn



Bunch phase vs Turn





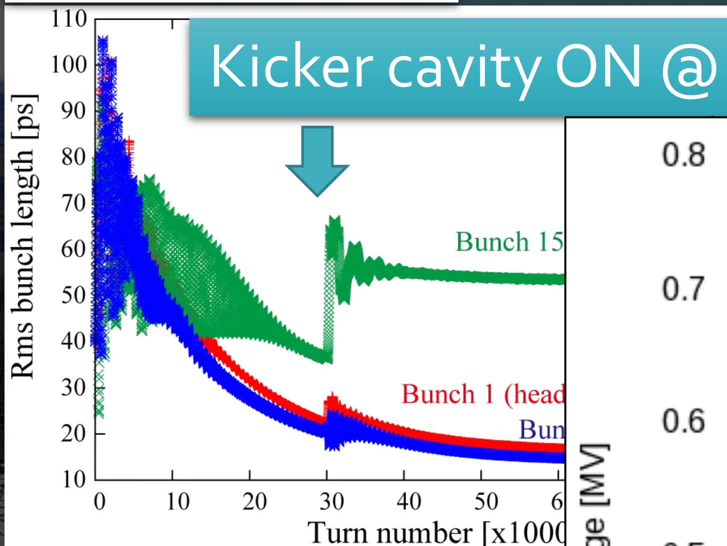


Kicker Cavity Power

$P_{in,avg}$= 13.0 kW, $P_{in,max}$=19.5 kW

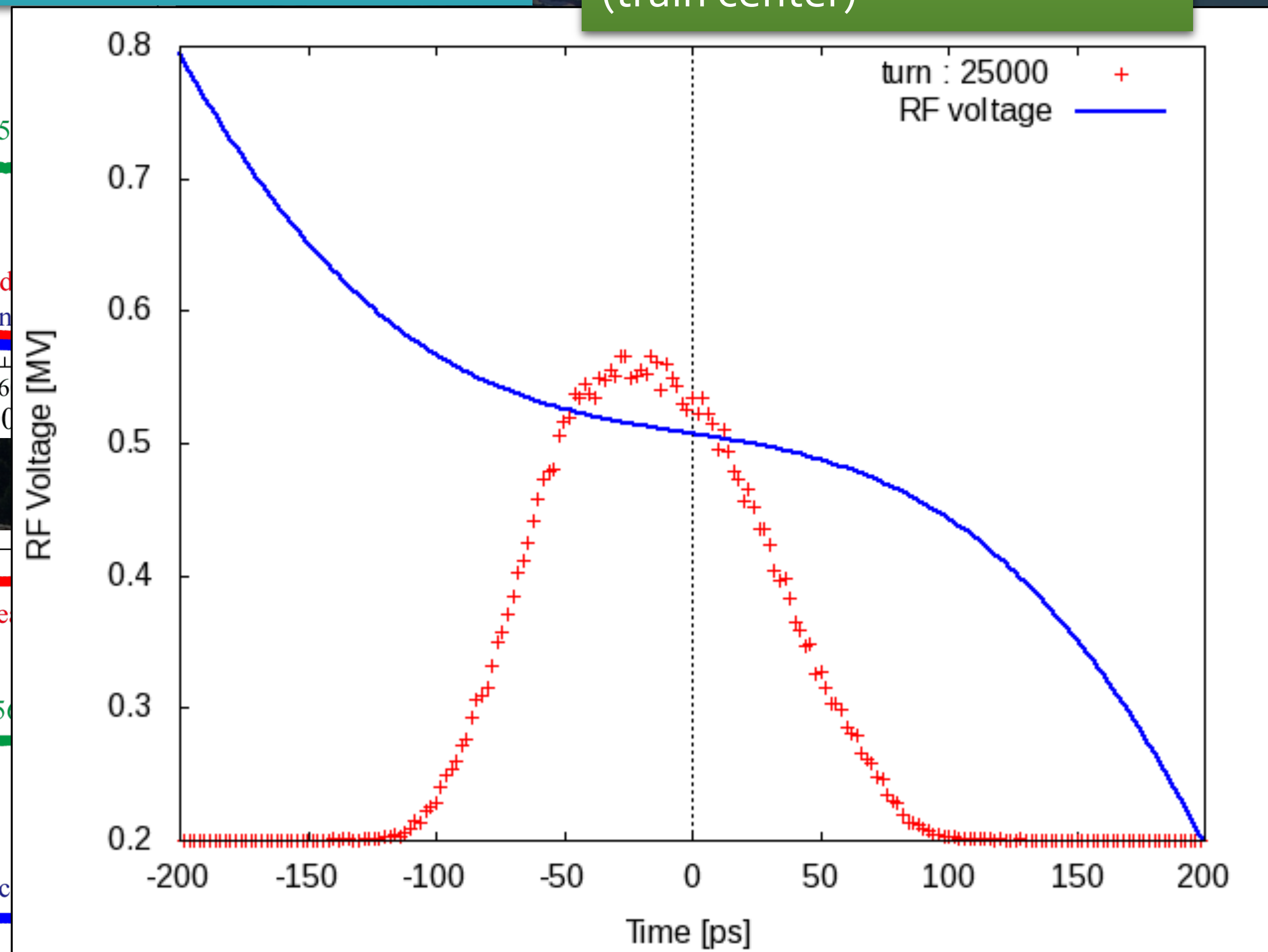
Macro particle simulation for SOLEIL-U

Bunch length vs Turn

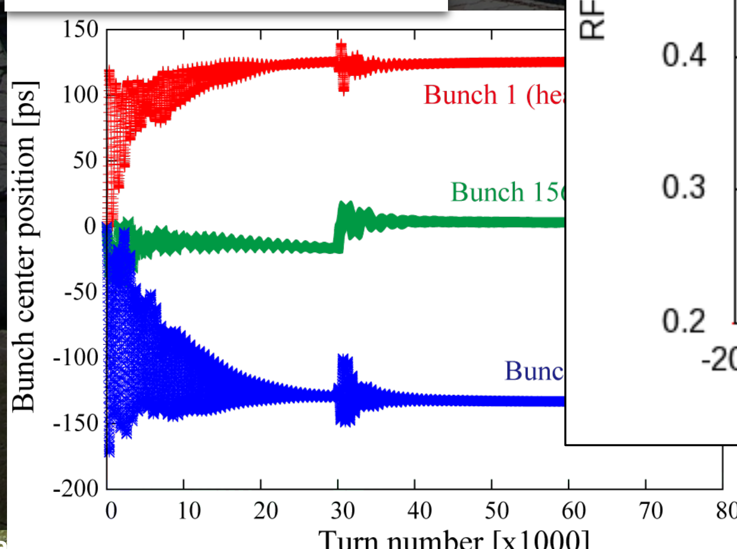


Kicker cavity ON @ 30,000 turns

156th Bunch shape evolution (train center)



Bunch phase vs Turn



Summary

- Harmonic RF system is essential in ring based future light source.
- The performance is very sensitive to the Transient beam loading.
- By using single kicker cavity with active feedfoward LLRF system, the beam loading effect can be mitigated.

<u>To realize kicker cavity compensation,</u>

We (SOLEIL, ESRF, SLS and KEK) are working together on …

- ➢ Beam dynamics study in bunch lengthening operation
  - Unstable Beam motion caused by cavity impedances;
    AC/DC Robinson, coupled-bunch, …
  - Beam dynamics including other impedances such as resistive wall
- ➢ Design of HOM-damped Kicker cavity
- ➢ Design of (adaptive) feedforward Low level RF system


Thank you
for your attention!