Compensation of transient RF voltage in a double RF system using a kicker cavity

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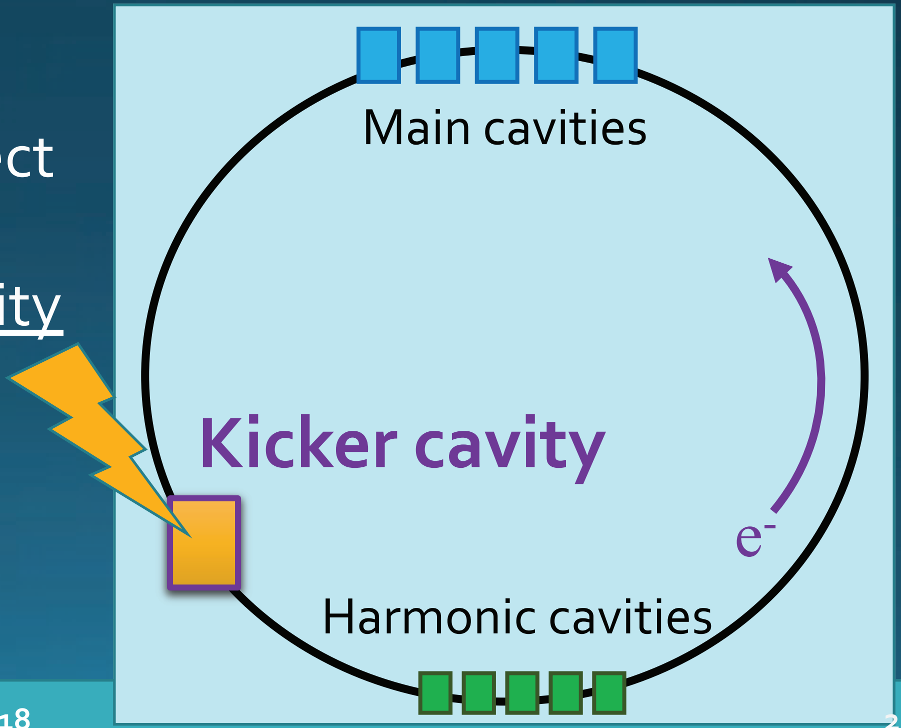
Outline

*N. Yamamoto, et al., PRAB 21, 012001 (2018).

- Double RF system
  - Motivation
  - Physics
  - Existing double RF system
- Reduction of Transient beam loading effect
  - Transient beam loading effect
  - Reduction of the effect
  - Normal-conducting TM020 cavity
- Compensation of Transient effect
  - Basic idea
  - Compensation with a kicker cavity
  - Numerical estimation
- Summary



Motivation for double RF system

- Quasi diffraction-limited synchrotron light sources, which aim at achieving the beam emittances of ~/< 100 pmrad are being actively designed.
- In such ultralow-emittance rings, **emittance growth due to intrabeam scattering** are serious concerns.

http://kekls.kek.jp

KEK-LS parameter

nominal electron energy	E0 [GeV]	3		
circumference	[m]	570.72		
RF frequency	f_{RF}[MHz]	500.07		
harmonic number	h	952		
RF voltage	V_{RF}[MV]	2.5		
energy loss per turn (max. with ID loss)	[MeV]	0.298 (0.851)		
momemtum compaction factor	α_c	2.1893×10^{-4}		
damping time x,y,z	[ms]	29.25, 38.28, 22.63		
beam current	[mA]	**0**	**200**	**500**
hor. emittance (not including ID)	[pmrad]	**132.51**	**230.5**	**314.74**
ver. emittance	[pmrad]		8.1	8.2
Touschek lifetime	[h]	**–**	**2.9**	**1.8**
energy spread	$\times 10^{-4}$	6.42	7.24	8.22

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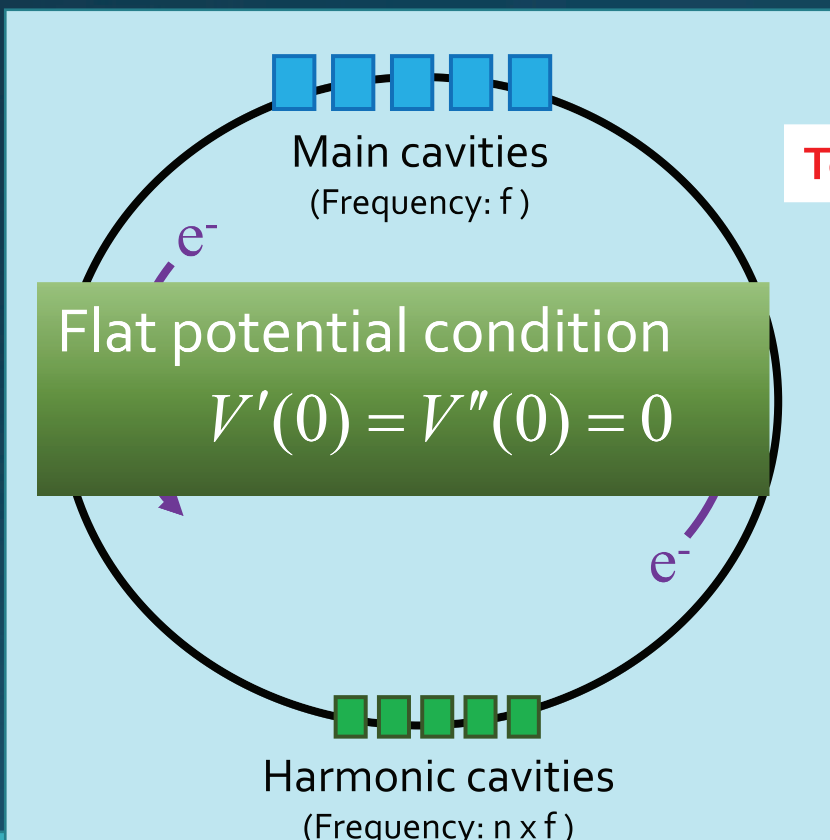
Touschek lifetime	[h]	**–**	**2.9**	**1.8**

- One of solutions to mitigate such adverse effects is to reduce the electron densities of the bunches.
- **For this purpose, the double RF system is installed.**

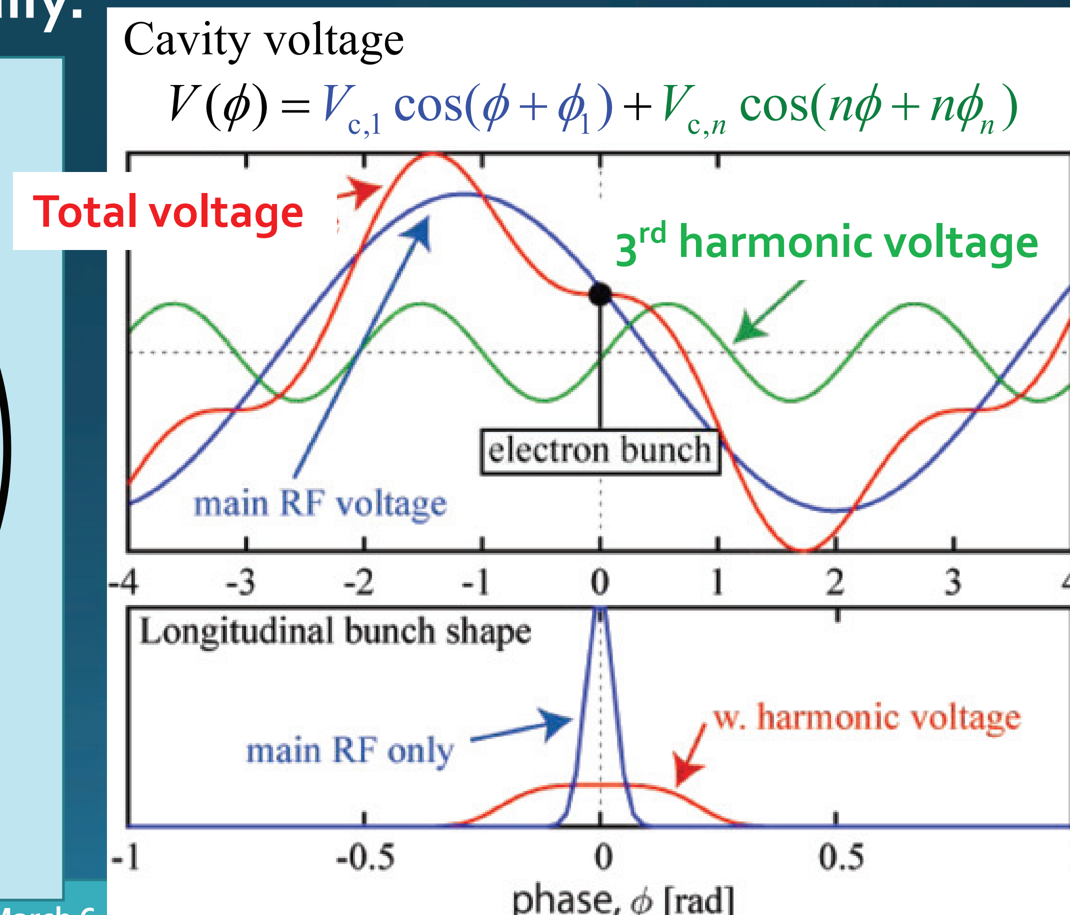
Physics of double RF system

- 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

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



Physics of double RF system (cont.)

- The bunch shape can be calculated from the total RF voltage.

Total RF voltage

$$V(\phi) = V_{c,1}\cos(\phi+\phi_1) + V_{c,n}\cos(n\phi+n\phi_n)$$

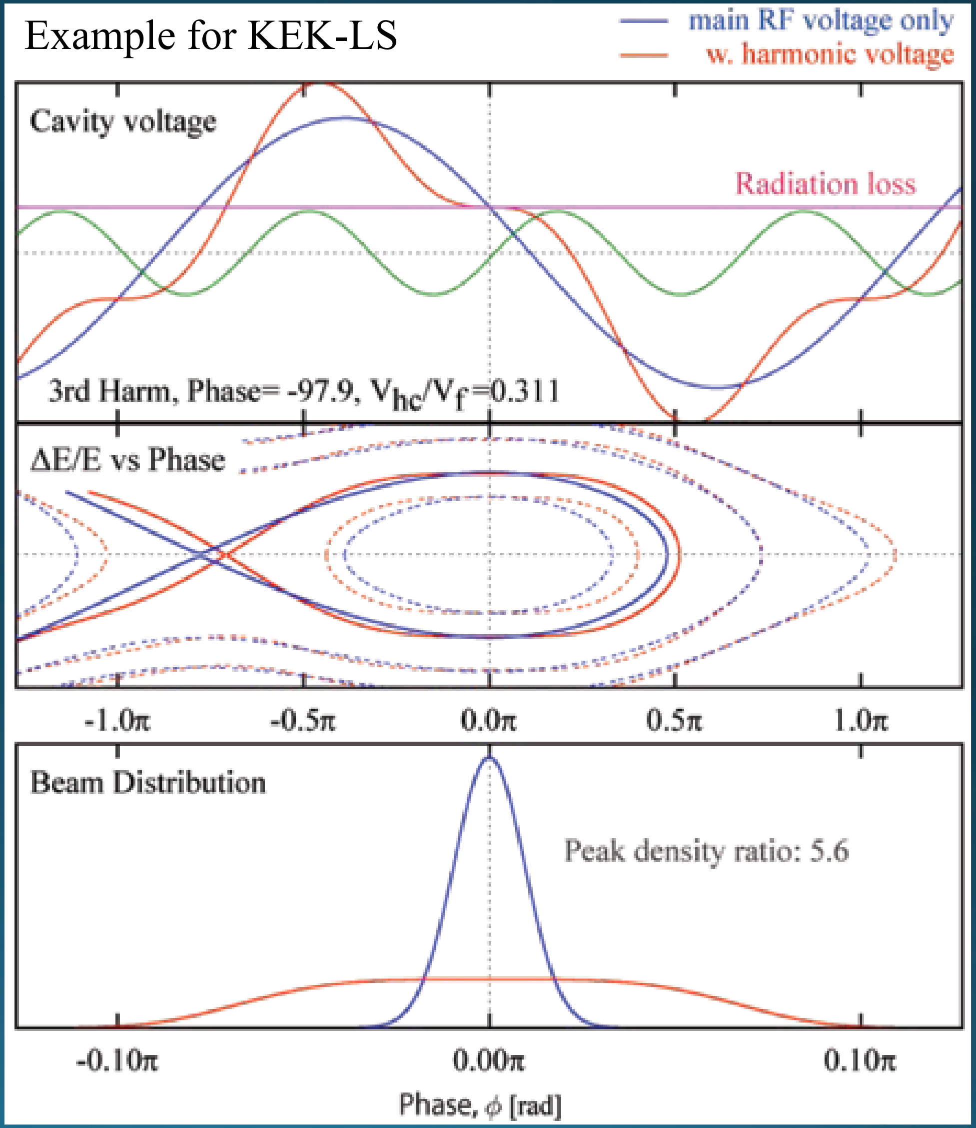
Electron distribution

$$\rho(\phi) = \rho\exp\left(-\frac{1}{\alpha_c{}^2\sigma_\varepsilon{}^2}\Phi(\phi)\right)$$

where

$$\Phi(\phi) = \frac{-\alpha_c}{2\pi h E_0}\int_0^\phi \{e_0 V(\phi') - U_0\}\,d\phi'$$

α_c : momentum compaction
h : harmonic number
σ_ε : relative energy spread
E_0 : nominal beam energy
U_0 : turn radiation loss



Existing double RF systems

- Double RF systems have been installed in several 3rd generation light sources, and they have been successfully operated to lengthen beam bunches. (ALS, BESSY-II, SLS, ELETTRA, MAX-IV, …)

[1] J. M. Byrd, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 455, 271 (2000).
[2] M. Georgsson, et al., Nucl. Instrum. Methods Phys. Res., Sect. A 469, 373 (2001).
[3] W. Anders and P. Kuske, in Proceedings of PAC 2003, (2003) p. 1186.
[4] M. Pedrozzi, et al., in Proceedings of SRF03 (2003) p. 91
[5] G. Penco and M. Svandrlik, Phys. Rev. Accel. Beams 9, 044401 (2006).
[6] N. Milas and L. Stingelin, in Proceedings of IPAC'10 (2010) p. 4719.
[7] P. F. Tavares, et al., Phys. Rev. Accel. Beams 17, 064401 (2014).

- Existing 1.5GHz harmonic cavity (3rd harm. of 500MHz main cavity)

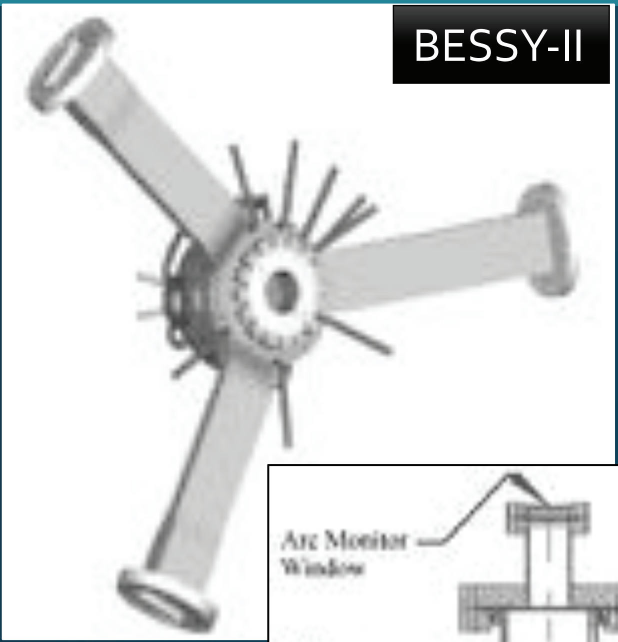
		BESSY-II	ALS	SLS/ELETTRA
NC or SC		NC	NC	SC
R/Q	Ω	124	161	176
Unloaded-Q (Q_0)		**13,900**	**21,000**	**2.0E+08**
Shunt impedance (R)	MΩ	1.72	3.38	35200

$$R \equiv V_c^2 / P_c$$

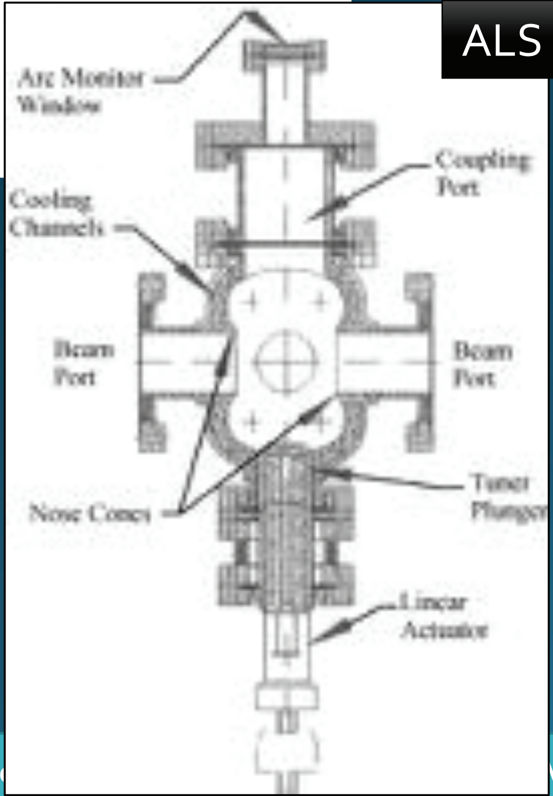
*NC: Normal conducting
SC: Super conducting

Existing harmonic cavities (cont.)

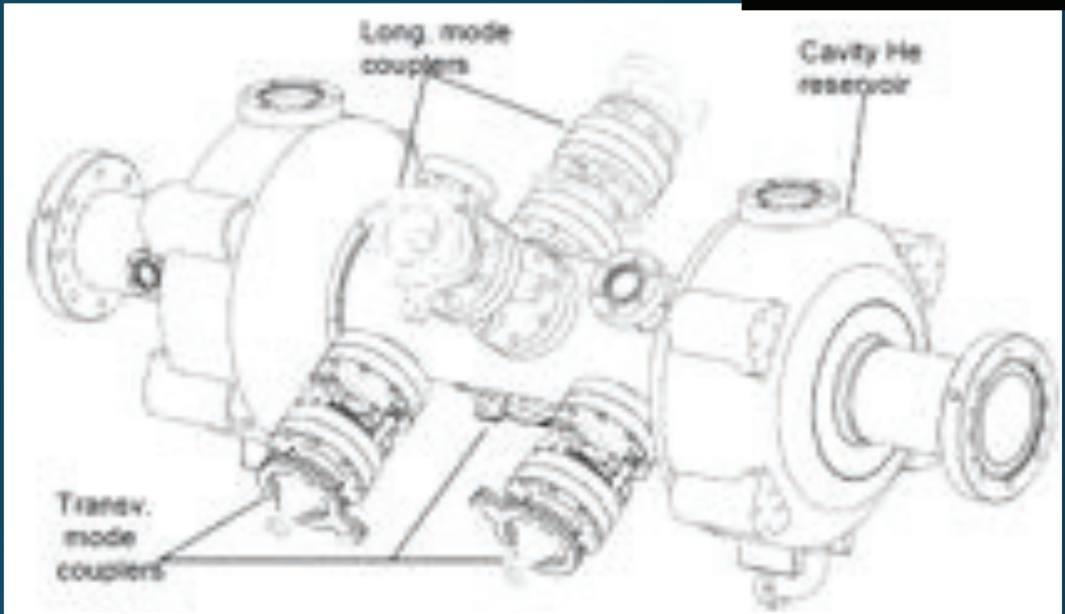
BESSY-II



ALS



SLS/ELETTRA



		BESSY-II	ALS	SLS/ELETTRA
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Bessy-II : W.Anders, et .al., Proc. PAC (2003) TPAB004
ALS : J. Byrd, et. al., NIM A, 439 (2000) pp.15-25
SLS: N. Milas. et.al., Proc. IPAC'10 (2010) THPE084

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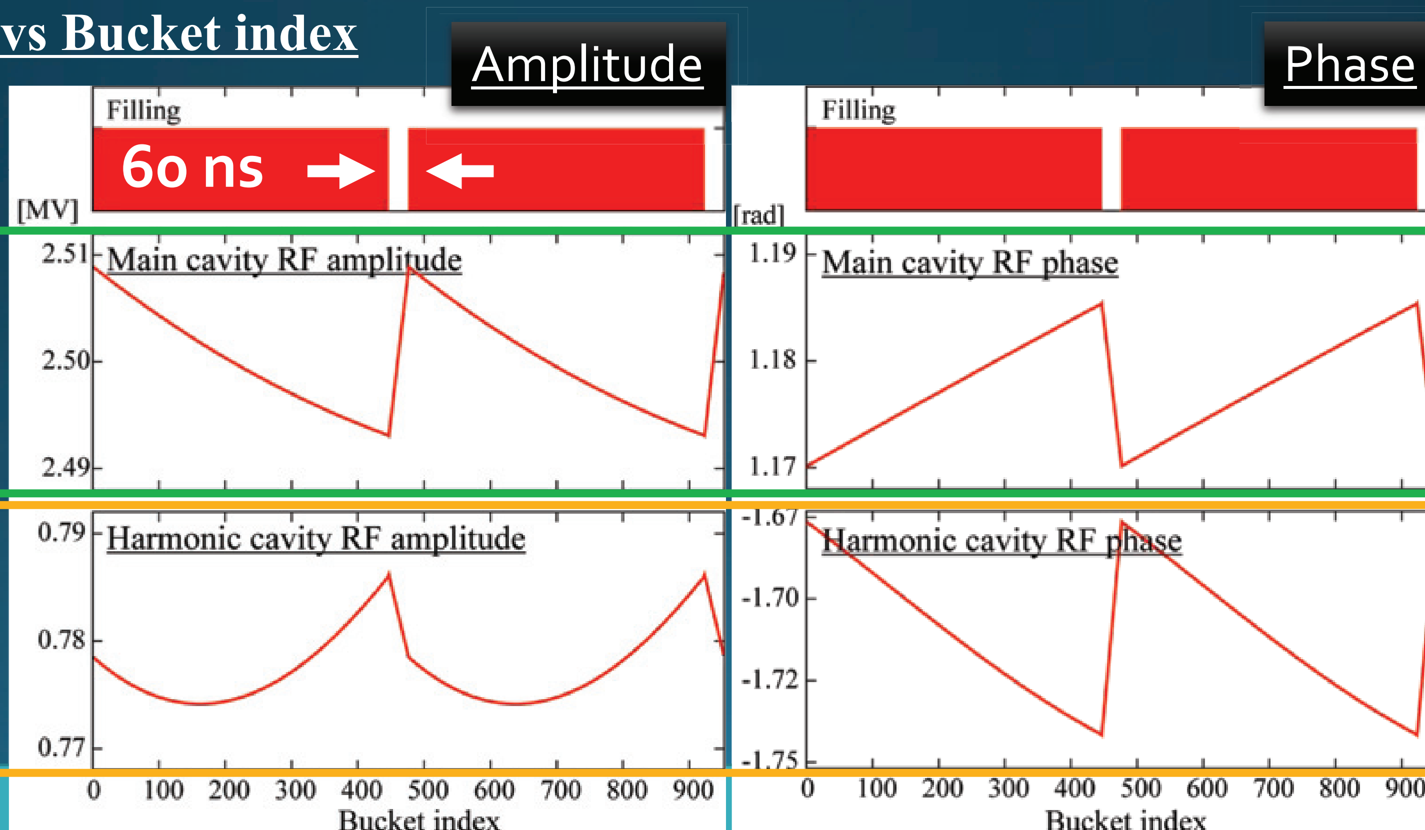
- Double RF system
  - Motivation
  - Physics
  - Existing double RF system
- Reduction of Transient beam loading effect
  - Transient beam loading effect
  - Reduction of the effect
  - Normal-conducting TM020 cavity
- Compensation of Transient beam loading effect
  - Basic idea
  - Compensation with a kicker cavity
  - Numerical estimation
- Summary

Transient beam loading effect

- When the gaps (i.e. unoccupied RF buckets) are introduced in the fill pattern of the stored beam, 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)

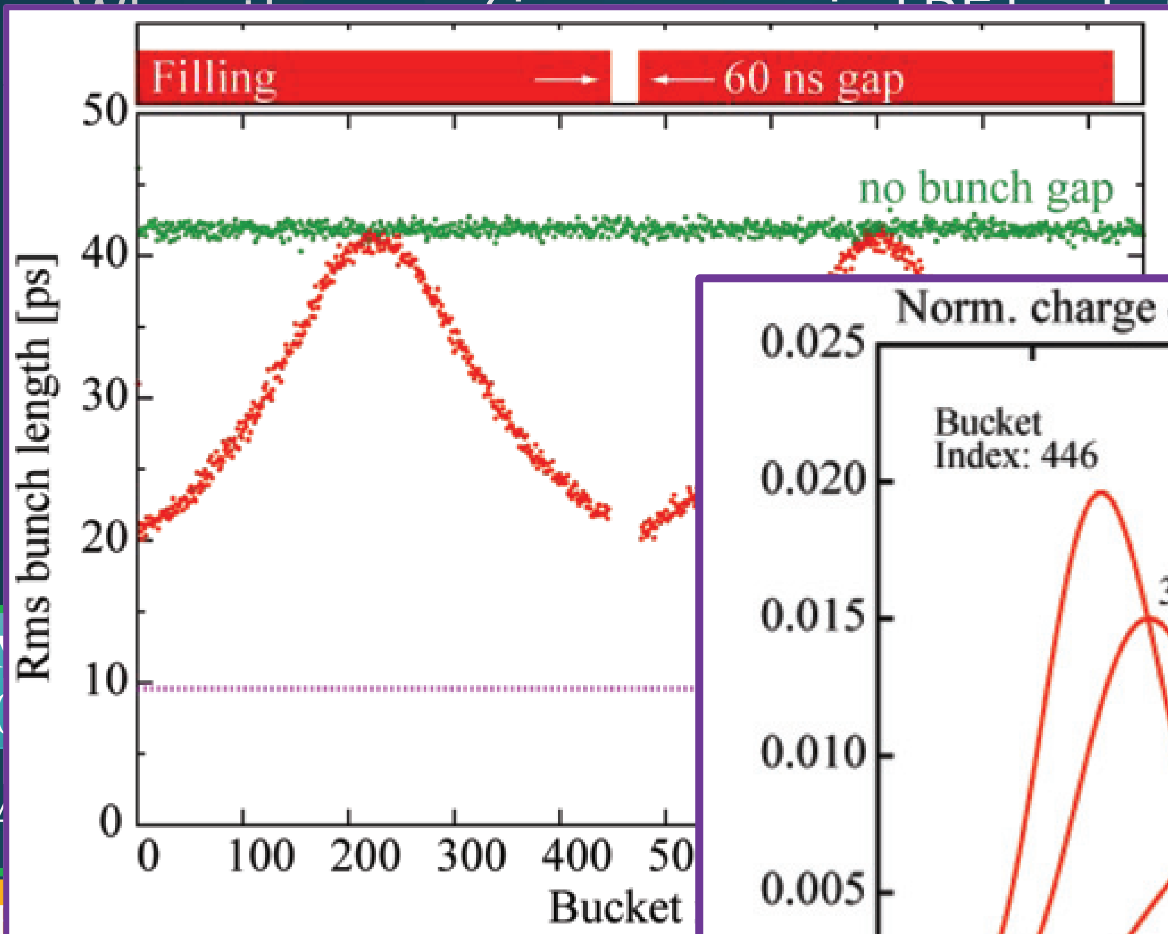
$|\Delta \tilde{V}_c| / |\tilde{V}_c| = 1.6\ \%$

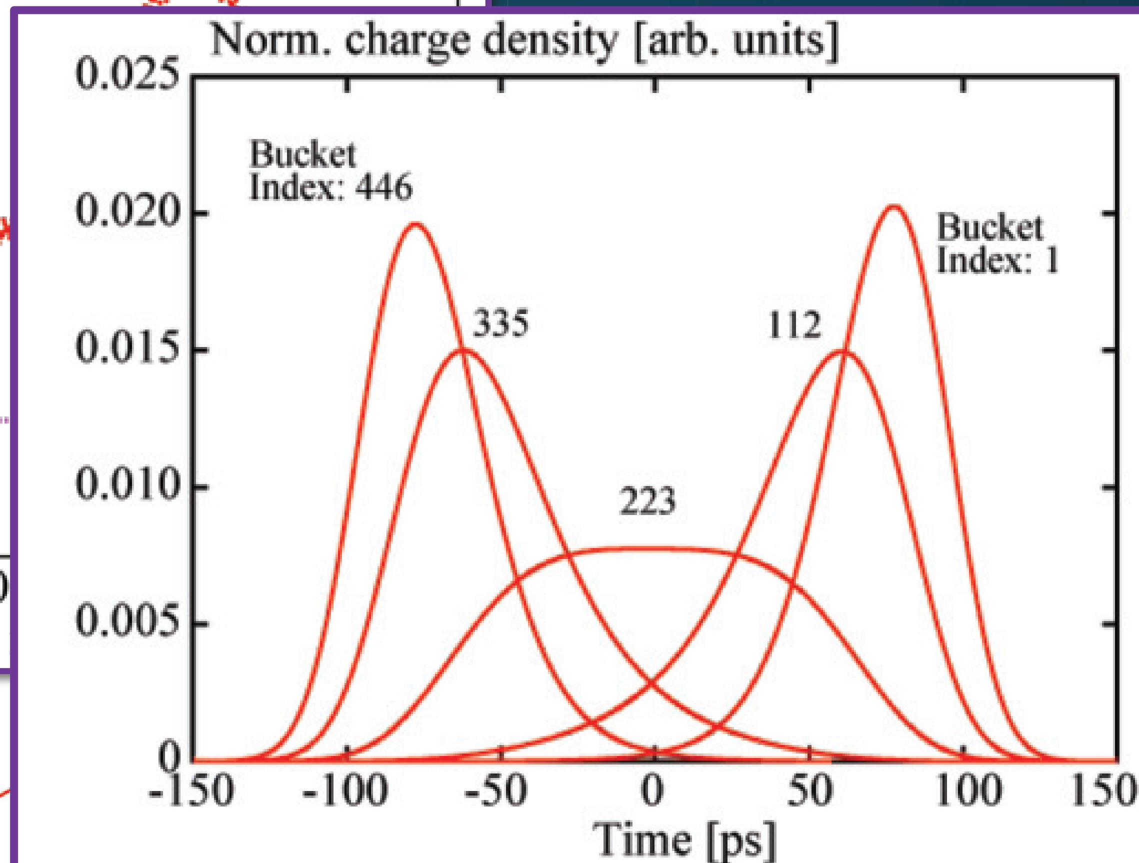
Harmonic cavity (1.5GHz)

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

Transient beam loading effect

s) are introduced in the
gaps induce
and phase in the RF





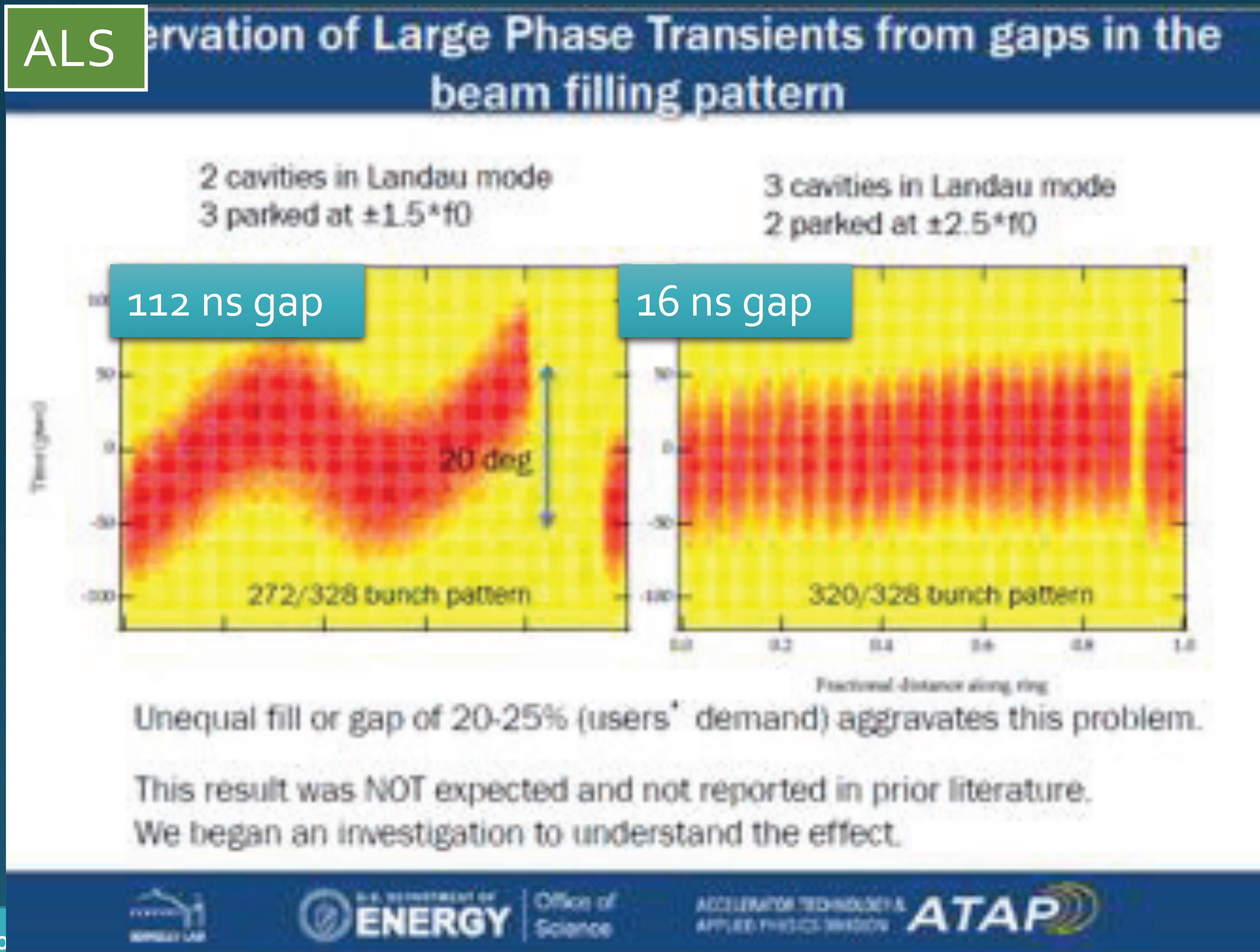
(1.5GHz)

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

Transient beam loading effect (cont.)

- **NC harmonic cavity**

*J. Byrd's presentation on ALERT, Sep. 2016
*J. M. Byrd, et al., NIM A 455, 271 (2000).



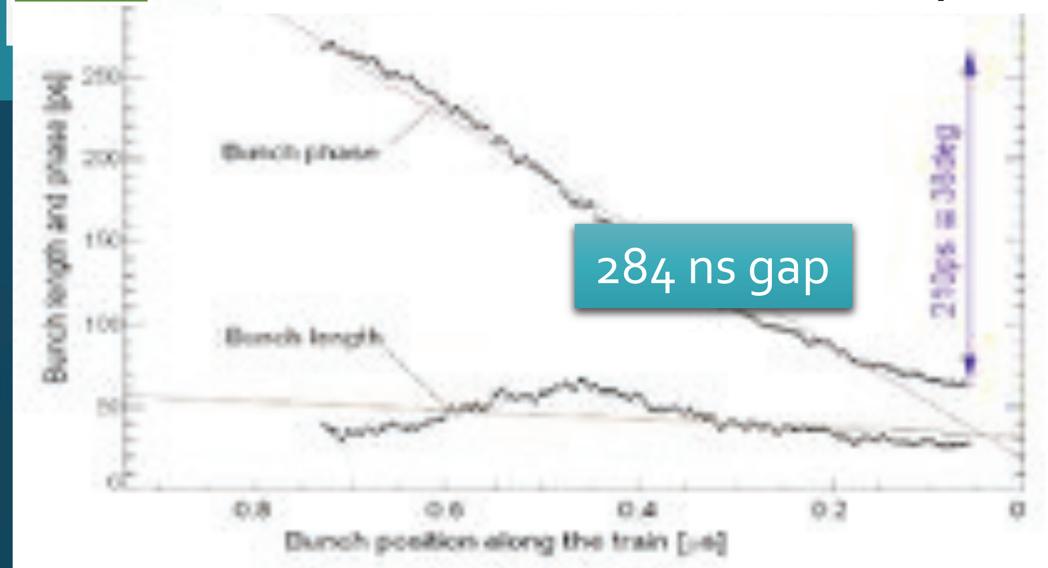
Transient beam

- **SC harmonic cavity**

better than NC-cavity,
but the considerable effect.

SLS

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



ELETTRA

*G. Penco and M. Svandrlik, PRAB 9, 044401 (2006).

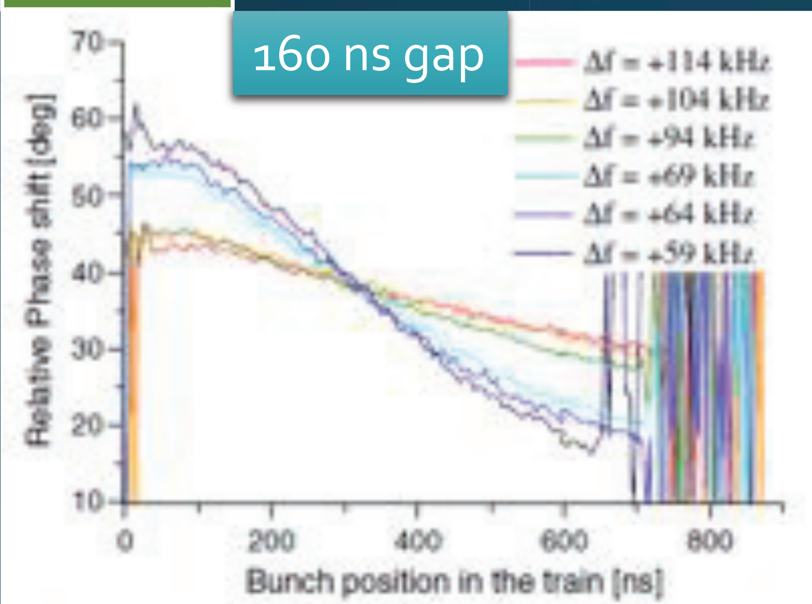


FIG. 6. (Color) Relative stable phase along the bunch train vs the 3HC detuning, for a 80% filling: $I_{beam} = 315$ mA, $E = 2.0$ GeV.

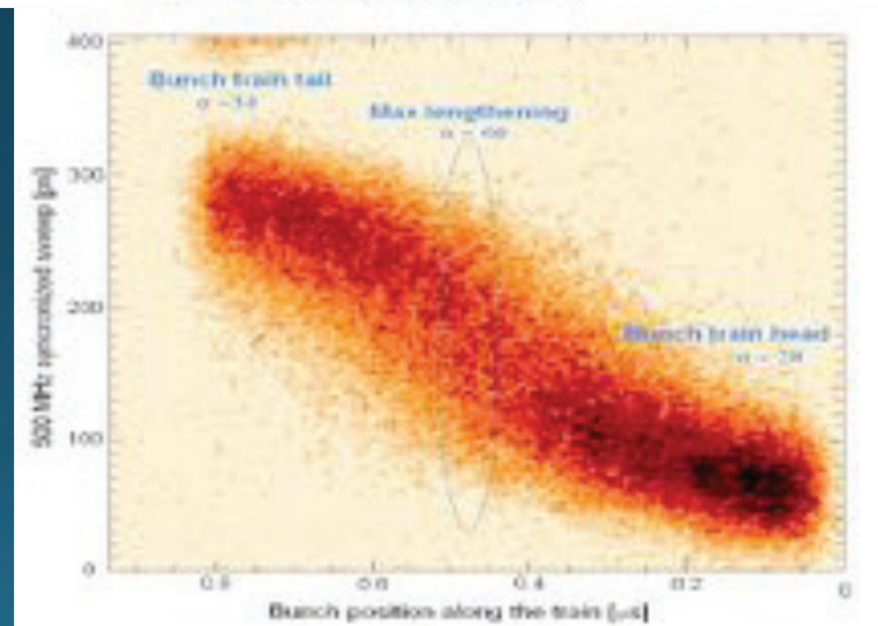
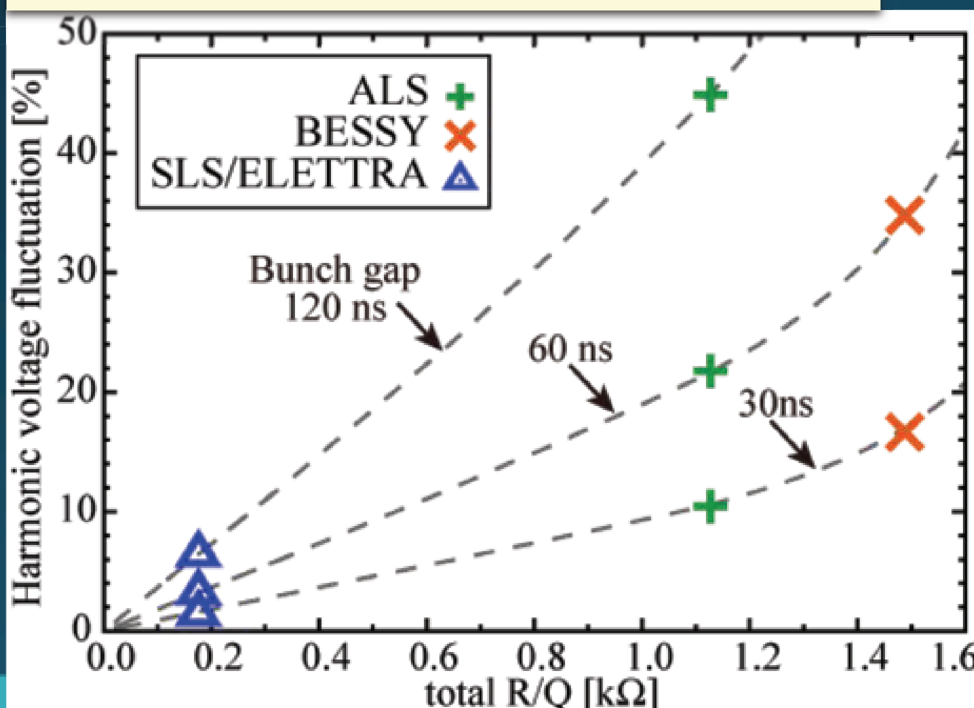


Figure 4: Streak camera snapshot at 320mA. Bunch σ and phase in ps versus position in the bunch train.

Reduction of the effect

- Such transient effects were well-investigated by J. Byrd, et al. .
- It was reported that the reduction of a <u>total *R/Q*</u> of harmonic cavities is essential to alleviate such transient effects.

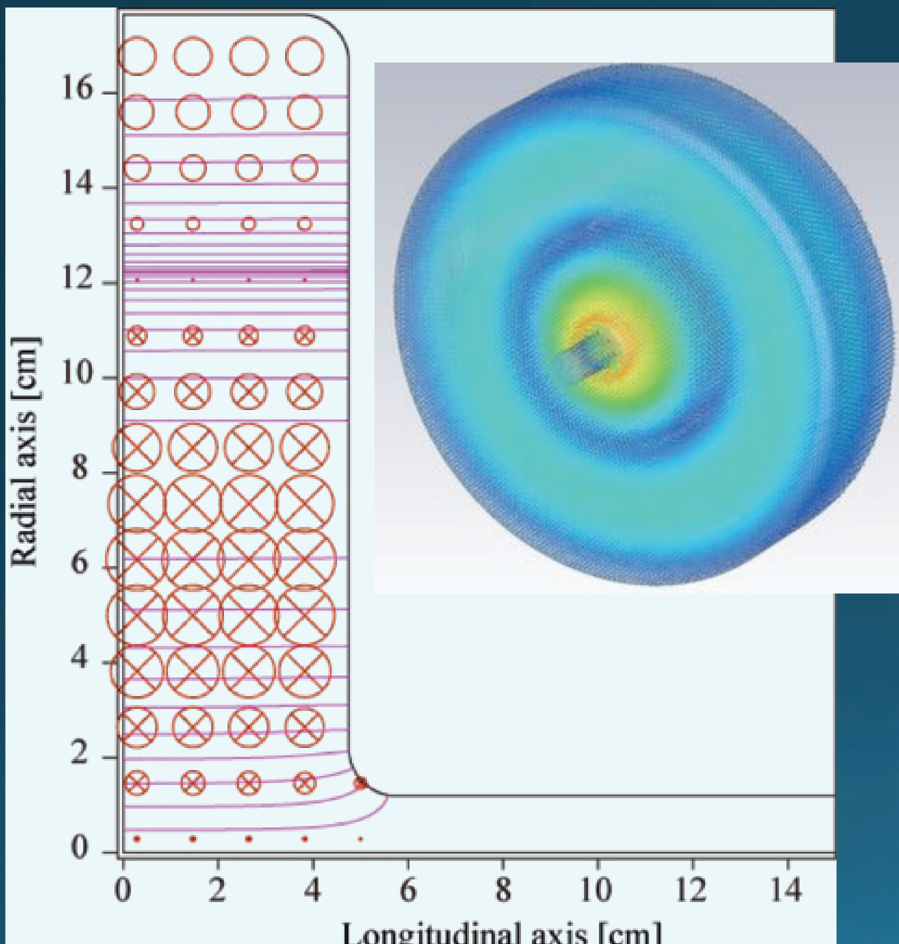
Harmonic voltage fluctuation (KEK-LS) vs Total R/Q



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

Normal-conducting harmonic TM020 cavity

- Normal conducting TM020 cavity is a candidates because of it's <u>high unloaded-Q</u> and <u>small R/Q</u> (large stored energy).



Parameter	Symbol	Value
Resonant frequency	f_{res}	1.5 GHz
R/Q	**R/Q**	**77.2 Ω**
Unloaded Q	**Q_0**	**37500**
Inner radius	-	176.5 mm
Gap length	-	95 mm
Max. power dissipated on the cavity wall	$P_{c,max}$	10 kW
Cavity voltage at $P_{c,max}$	$V_{c,cell}$	170 kV
Max. electric field on the inner surface	E_{max}	3.2 MV/m
Max. power density on the inner surface	ρ_{max}	10 W/cm2

HOM-Damped TM020 cavity (508MHz)

* H. Ego, et. al., PASJ11, (2014) MOOL14

- This type cavity was pioneered by Dr. Ego and was developed as a accelerating cavity for the “Spring-8 II” storage ring.

Table 1: RF Properties of the TM020 Mode

Shunt impedance (R_a) [MΩ]	6.8
Unloaded Q (Q_a)	60,300
R_a/Q_a	113
Accelerating voltage [kV]	900

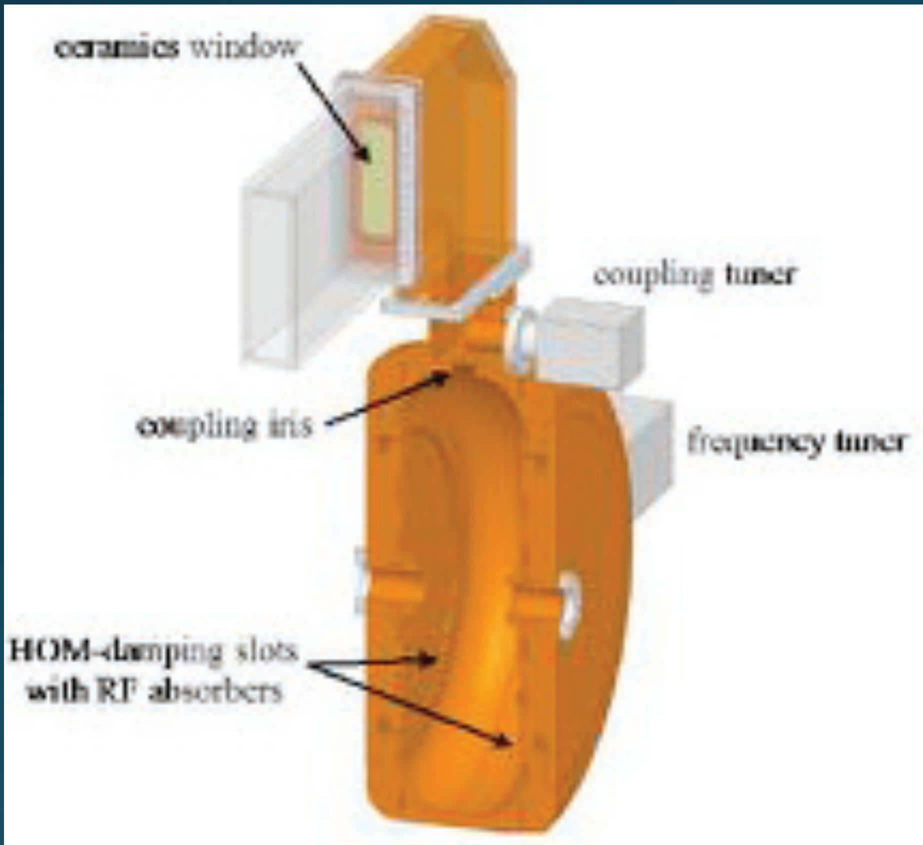


Figure 1: Structure of the new HOM-damped cavity.

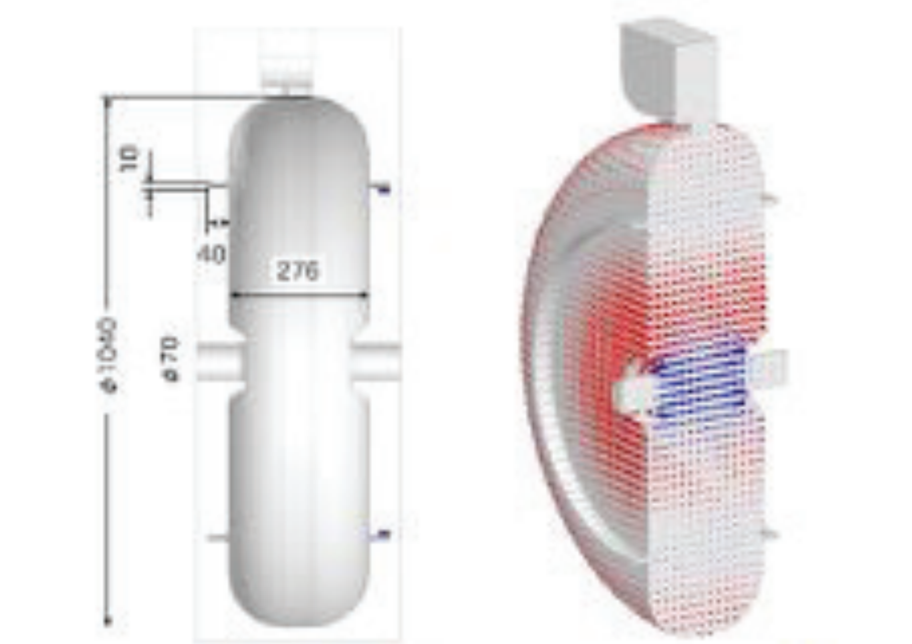


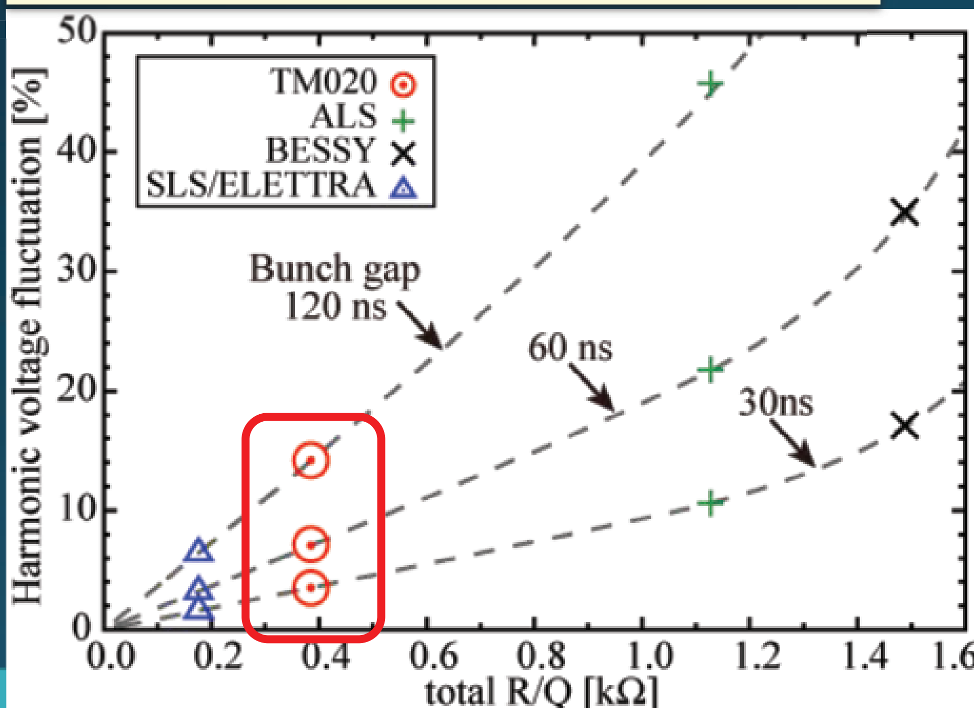
Figure 3: Inner shape of the cavity and the TM020 field distributions. Blue and red arrows show electric and magnetic fields, respectively.

Normal-conducting TM020 cavity

*N. Yamamoto, et al., PRAB 21, 012001 (2018).

- Normal conducting TM020 cavity is a candidates because of it's high unloaded-Q and small R/Q (large stored energy).

Harmonic voltage fluctuation (KEK-LS) vs Total R/Q



		TM020	ALS	SLS/ ELETTRA
R/Q	Ω	77	161	176
Unloaded-Q		37449	21000	2.0E+08
Coupling	β	0.27	1.08	3099
Loaded-Q		29411	10088	64514
Fill time	us	6.2	2.1	13.7
Cav. number		5	7	1
total R/Q	Ω	385	1127	176
V_{hc} / cav.	kV	155	111	777
Pc / cav.	kW	8.4	3.6	0.0
$\Delta V_c/V_c$(60ns)		7.1%	22.0%	3.2%

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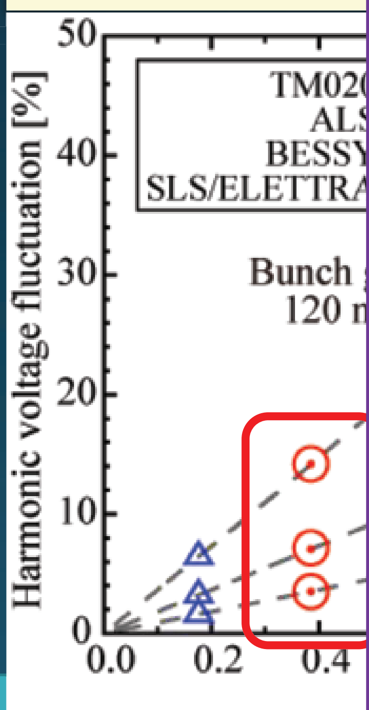
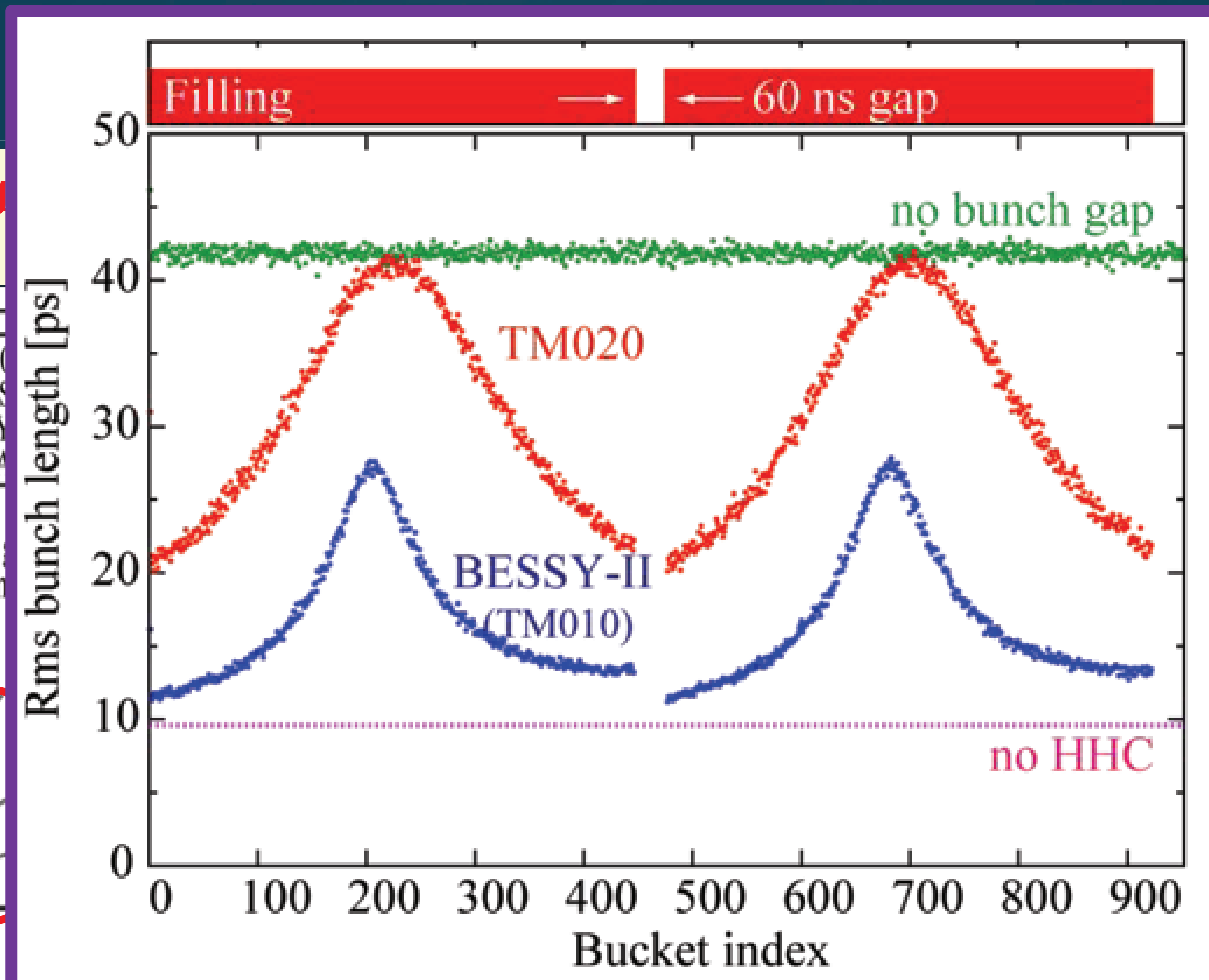




LS	SLS/ ELETTRA
61	176
000	2.0E+08
08	3099
088	64514
.1	13.7
7	1
127	176
11	777
.6	0.0
.0%	3.2%

Outline

- Double RF system
  - Motivation
  - Physics
  - Reviews of existing double RF system
- Reduction of Transient beam loading effect
  - Transient beam loading effect
  - Key parameter for the reduction of the effect
  - Normal-conducting TM020 cavity
- Compensation of Transient beam loading effect
  - Basic idea
  - Compensation with a kicker cavity
  - Numerical estimation
- Summary

Basic idea of the compensation

- If the voltage fluctuation is small, we can further reduce the transient effect using an active compensation technique.
- We have investigated two measures;

  (a) compensation on the main and harmonic cavities,

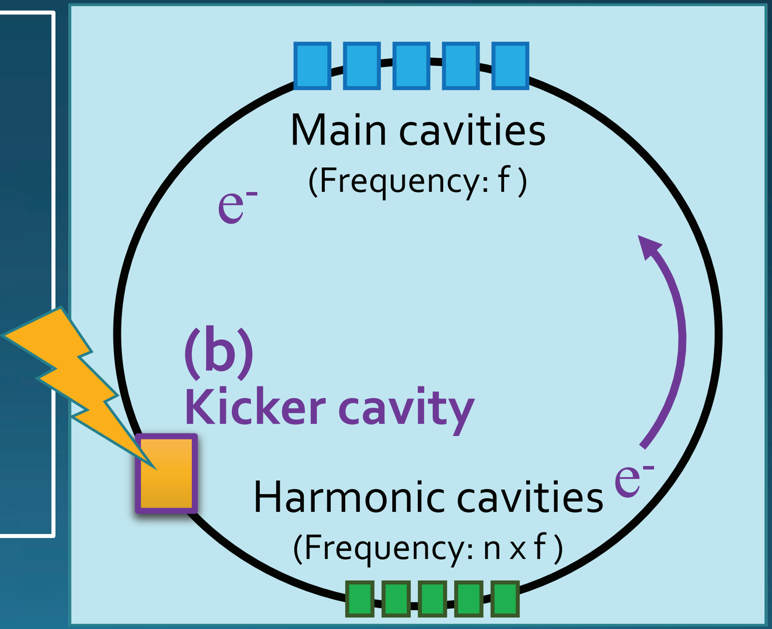
  (b) compensation using a separate kicker cavity.

Advantage of the method (b)

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

Disadvantage

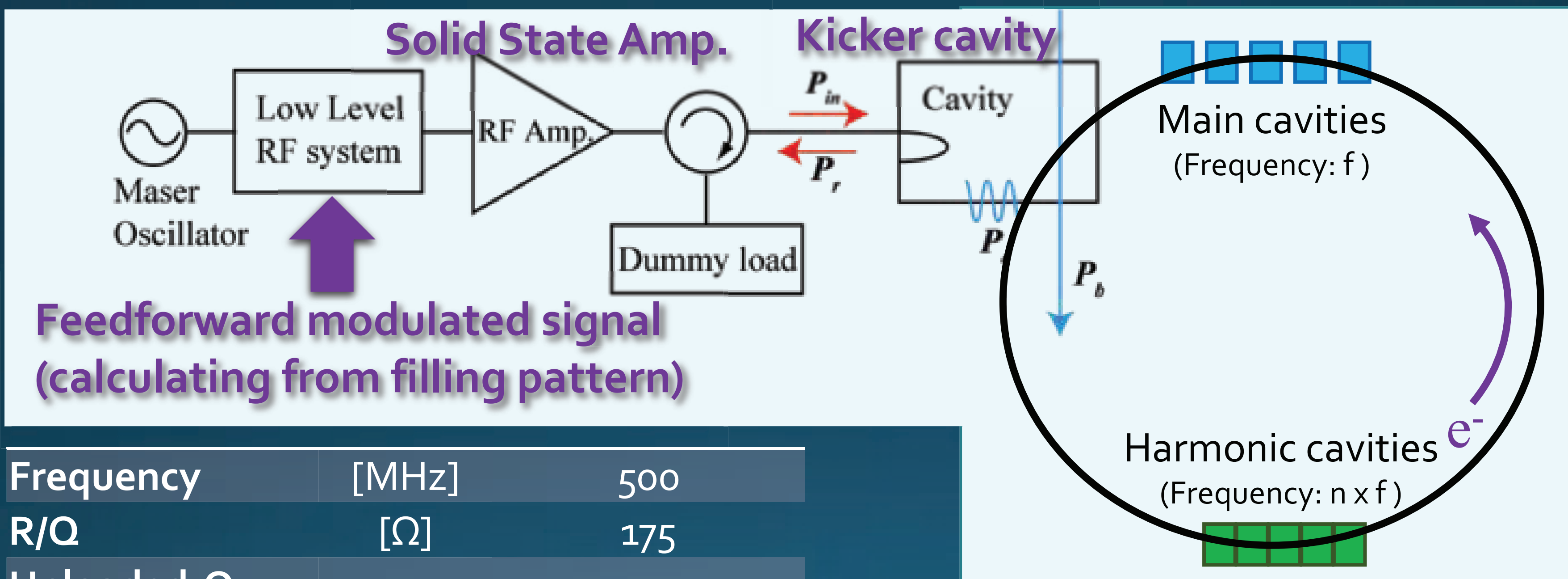
- Another space in the ring, RF system (low level system, RF amp …)



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

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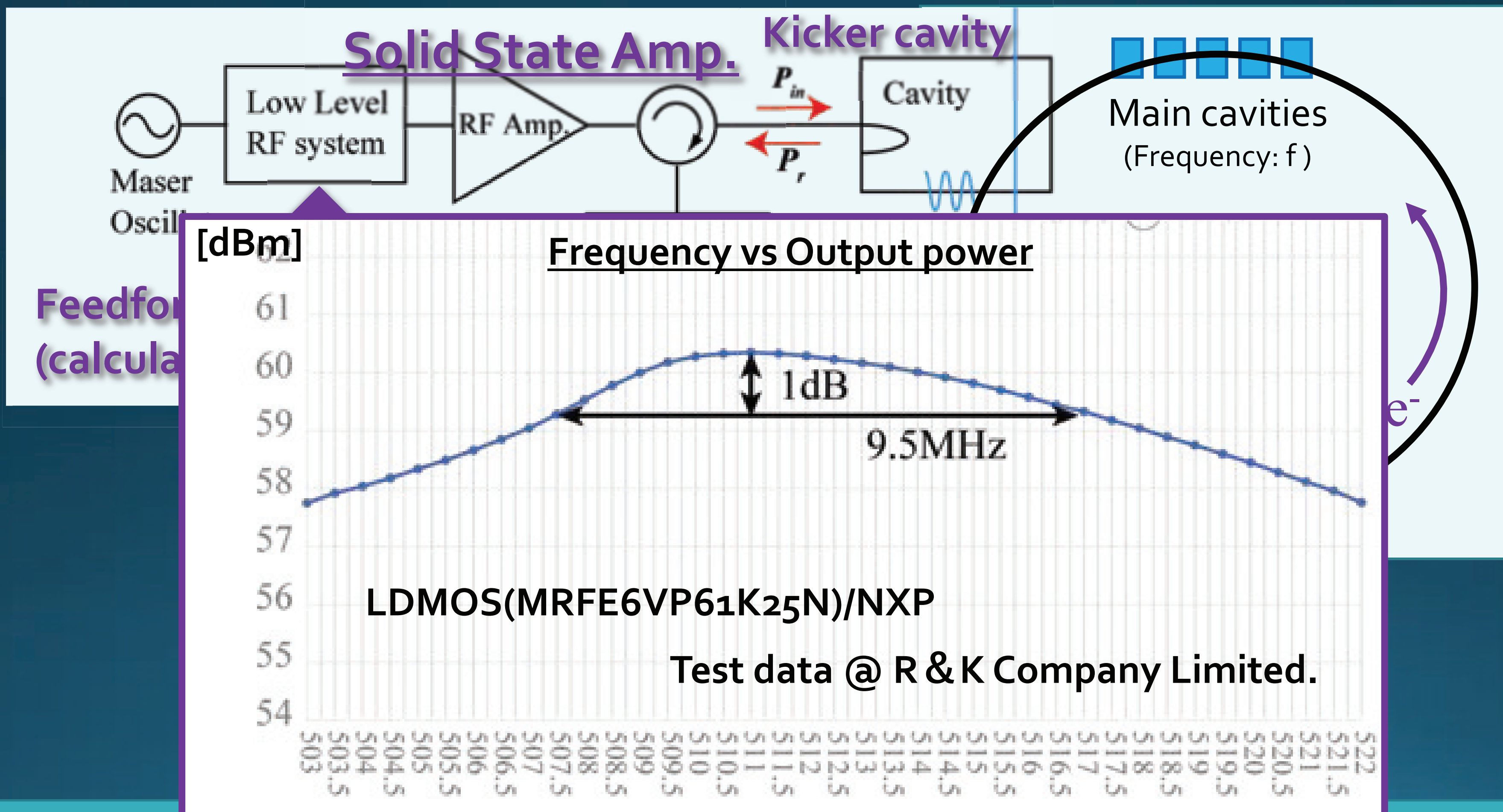


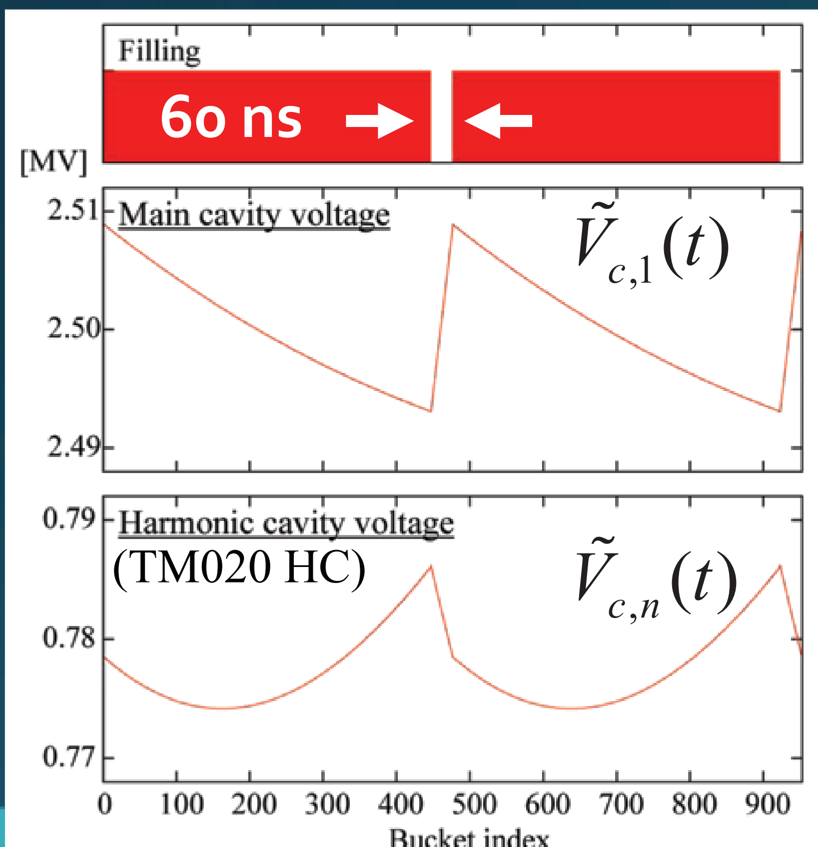
Numerical estimation (KEK-LS)

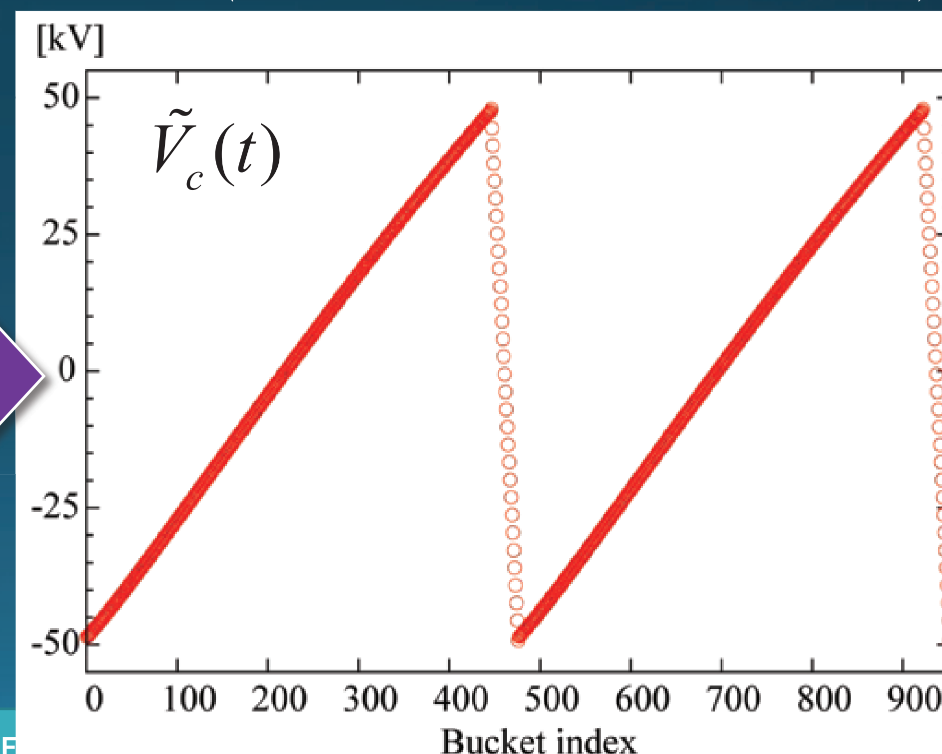
How to obtain the feedfoward signal

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.

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

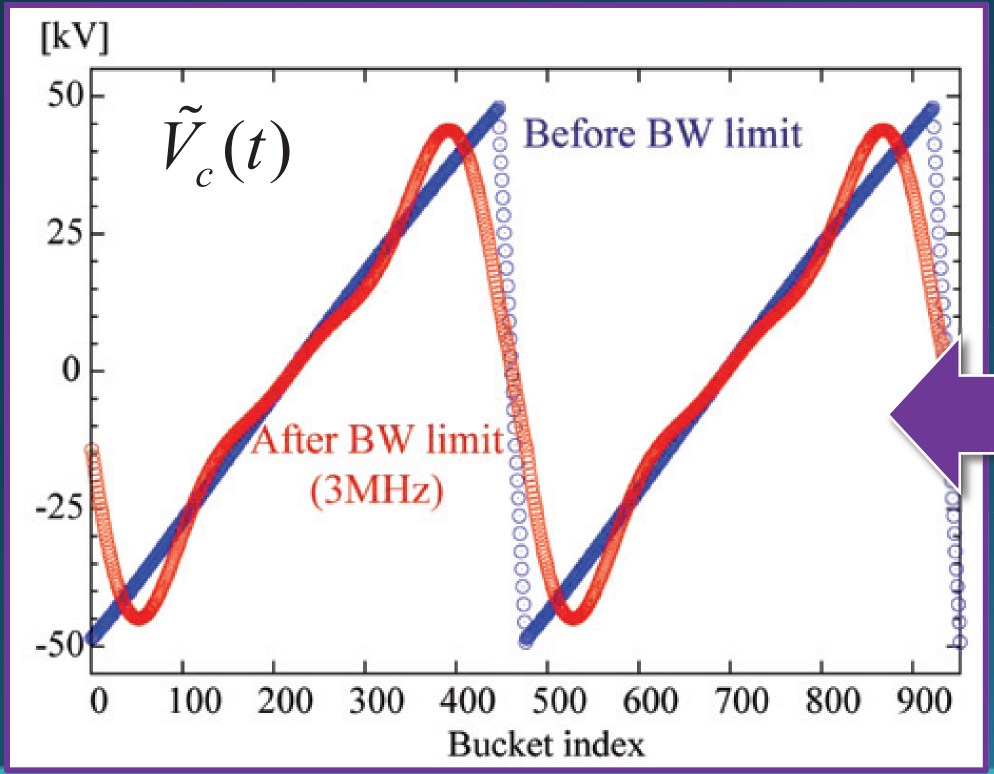


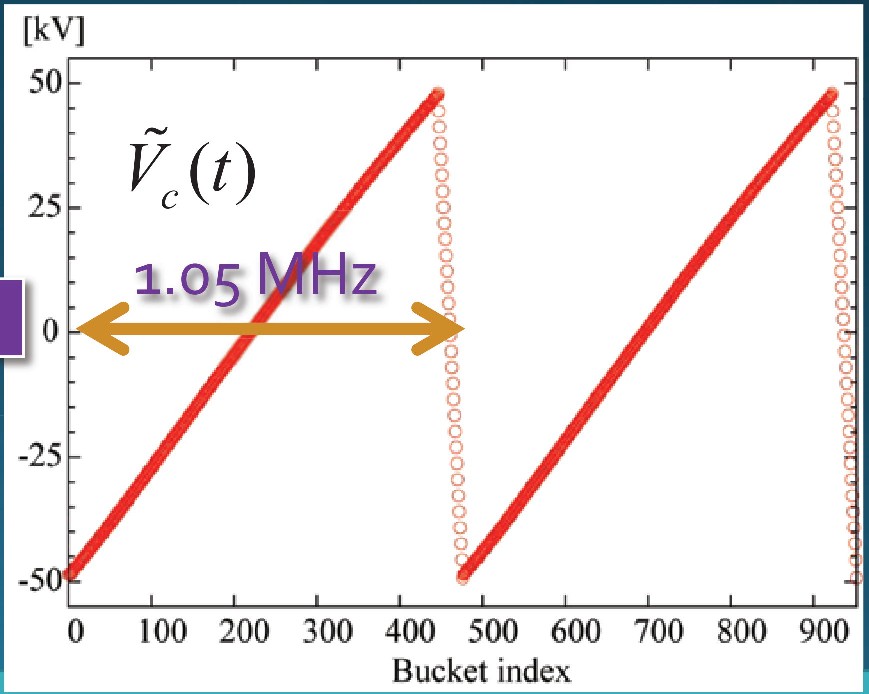


Numerical estimation (KEK-LS)

How to obtain the feedfoward signal

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.**





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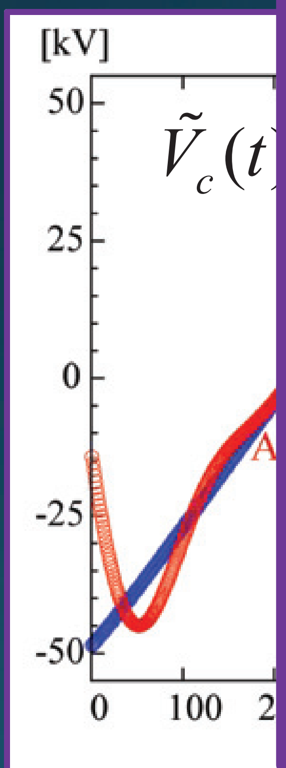
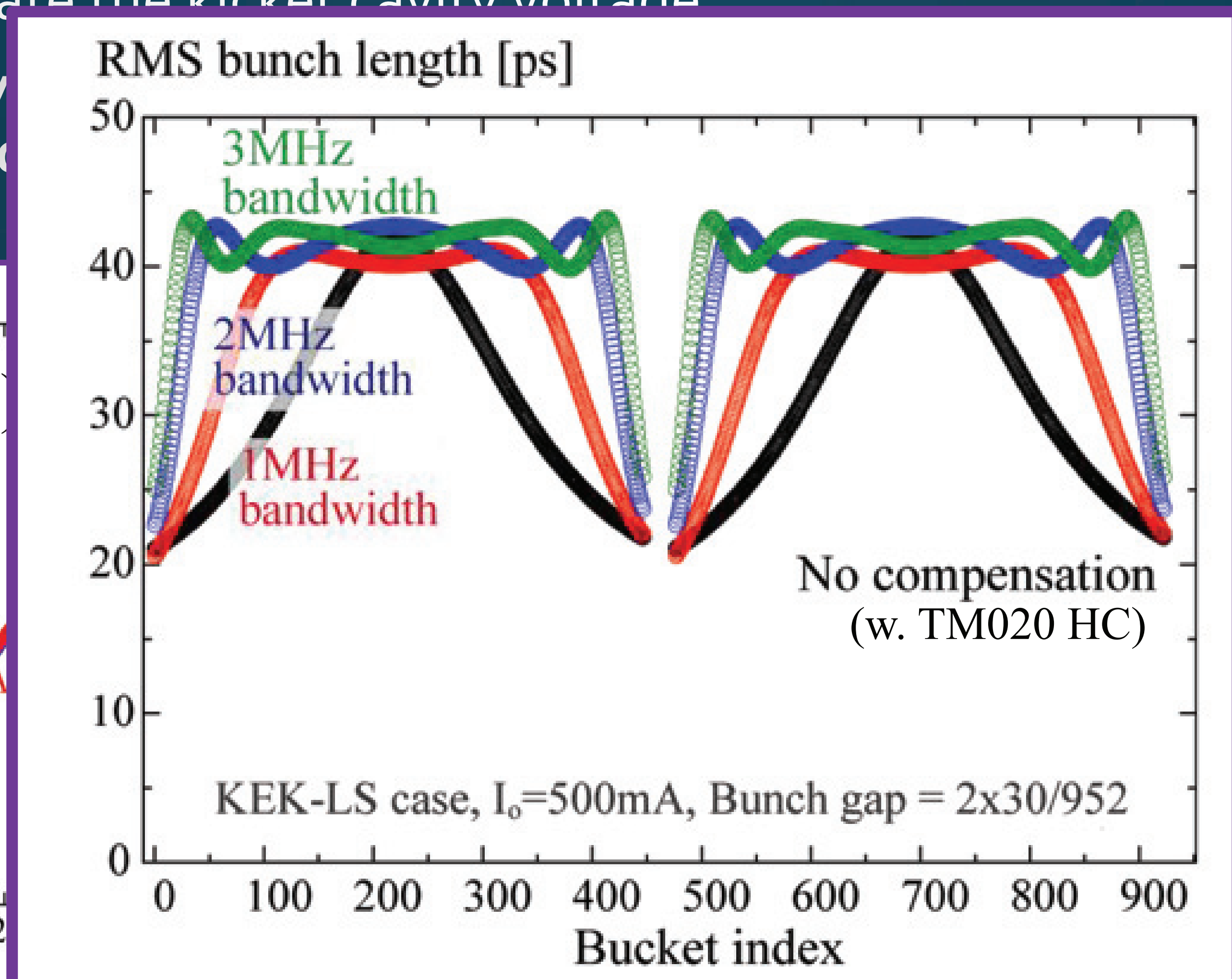
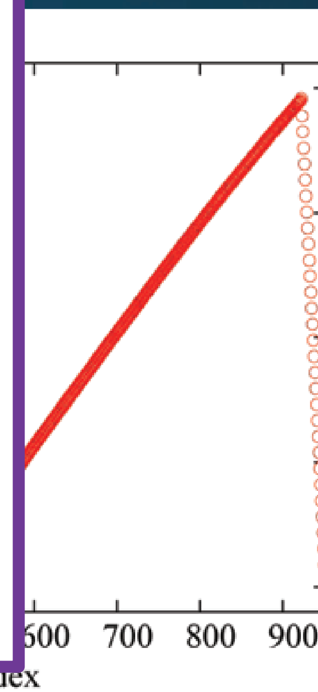






Numerical estimation (KEK-LS)

How to obtain the feedfoward signal

1. Evaluate the kicker cavity voltage
2. Apply the bandwidth limitation, considering the repetition frequency of the bunch train.

※ **Input RF power can be estimated, taking into account the cavity and amplifier responses.**

skip

$$\tilde{V}_g(t) = \left(\tilde{V}_c(t)\right)_{\text{target}} - \tilde{V}_b(t)$$

$$k\,\tilde{i}_g(t) = \frac{d\tilde{V}_g(t)}{dt} + \frac{1}{\tau_{\mathrm{f}}}\tilde{V}_g(t)$$

$\tilde{i}_g$: generator current of kicker cavity
k : loss parameter of kicker cavity
R : shunt impedance of kicker cavity
β : cavity coupling coefficient

$$\tilde{V}_g^{\text{limit}}(t) = \left[\tilde{V}_g^{\text{limit}}(-\infty) + k\int_{-\infty}^{t} \tilde{i}_g(t')e^{-t'/\tau_{\mathrm{f}}}\,dt'\right]\cdot e^{\alpha/\tau_{\mathrm{f}} t},\; P_g(t) = \frac{R}{16\beta}\left|\tilde{i}_g^{\text{limit}}(t)\right|^2$$

*N. Yamamoto, et al., PRAB 21, 012001 (2018).

Numerical estimation (KEK-LS)

How to obtain the feedfoward signal

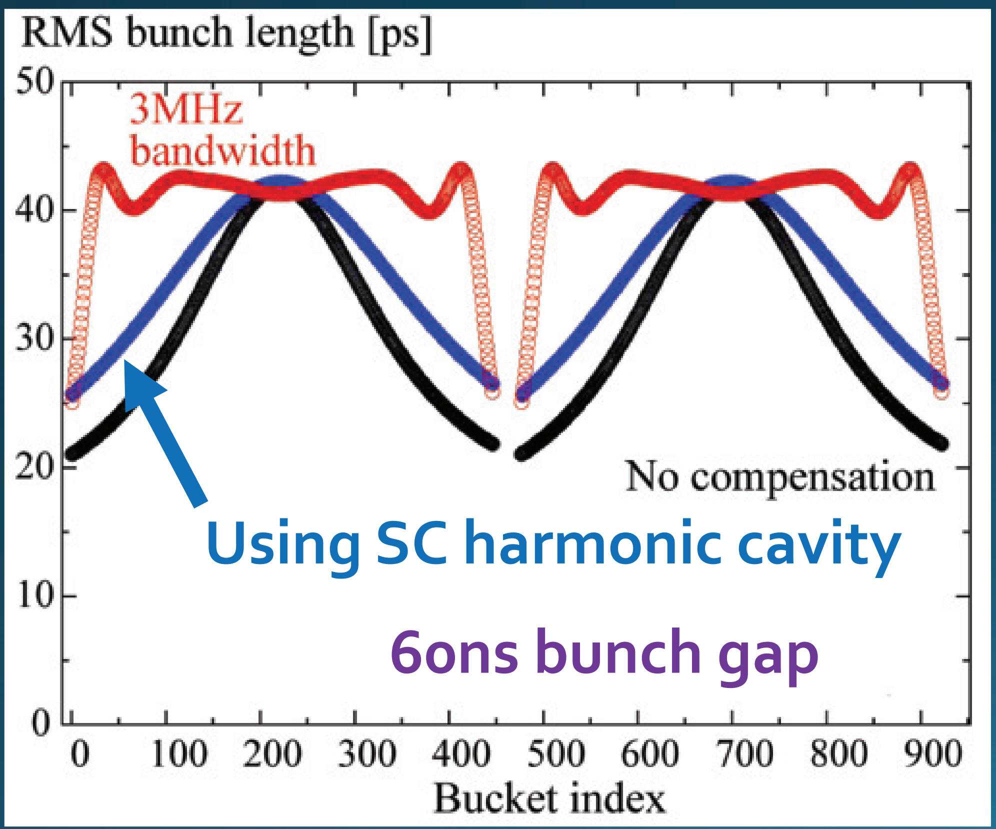
1. Evaluate the kicker cavity voltage
2. Apply the bandwidth limitation, considering the repetition frequency of the bunch train.

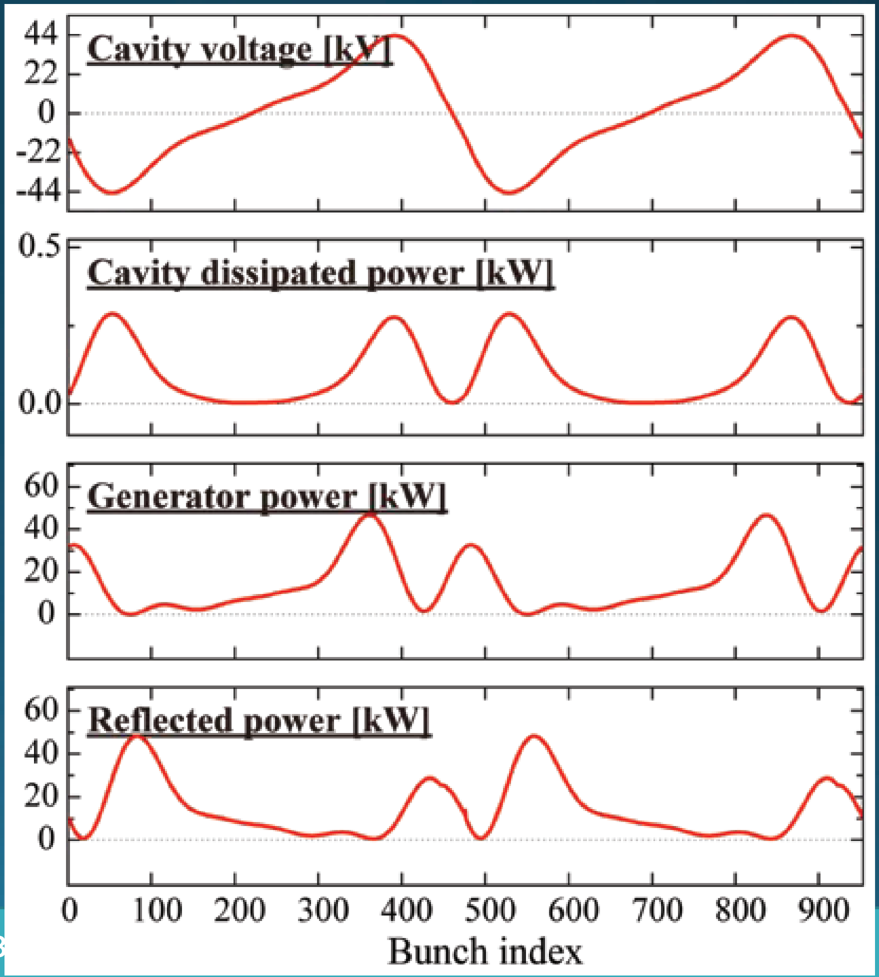
※**Input RF power can be estimated, taking into account the cavity and amplifier responses.**

Compensation bandwidth [MHz]	Average Bunch length [ps]	Peak Generator Power [kW]	Average Generator Power [kW]
—	31.1	—	—
1	35.6	11.1	5.6
2	39.6	31.6	11.1
3	**40.9**	**46.7**	**14.7**

Numerical estimation (KEK-LS)

Compensation bandwidth [MHz]	Average Bunch length [ps]	Peak Generator Power [kW]	Average Generator Power [kW]
3	40.9	46.7	14.7

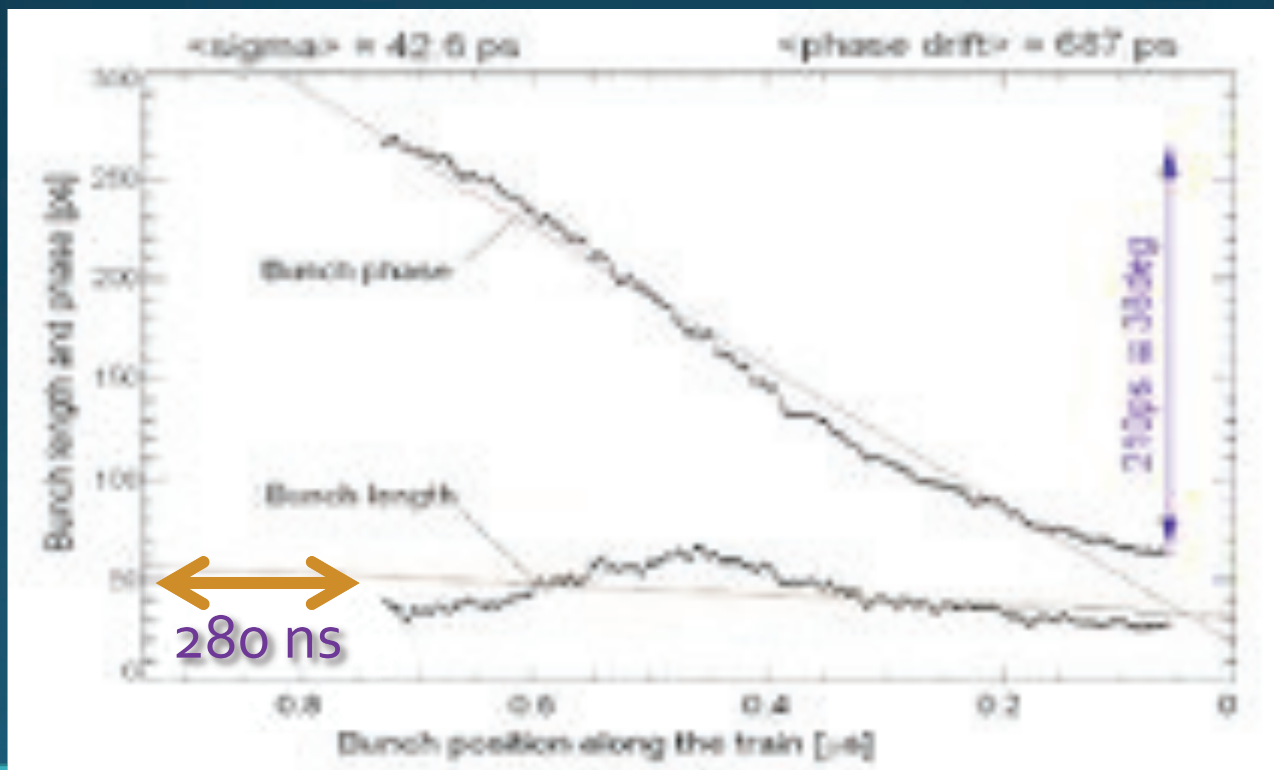




Numerical estimation (SLS)

- Such compensation scheme can be applied to the SC harmonic system.
- At SLS, when the bunch gap was around 280 ns, considerable transient effect was observed.

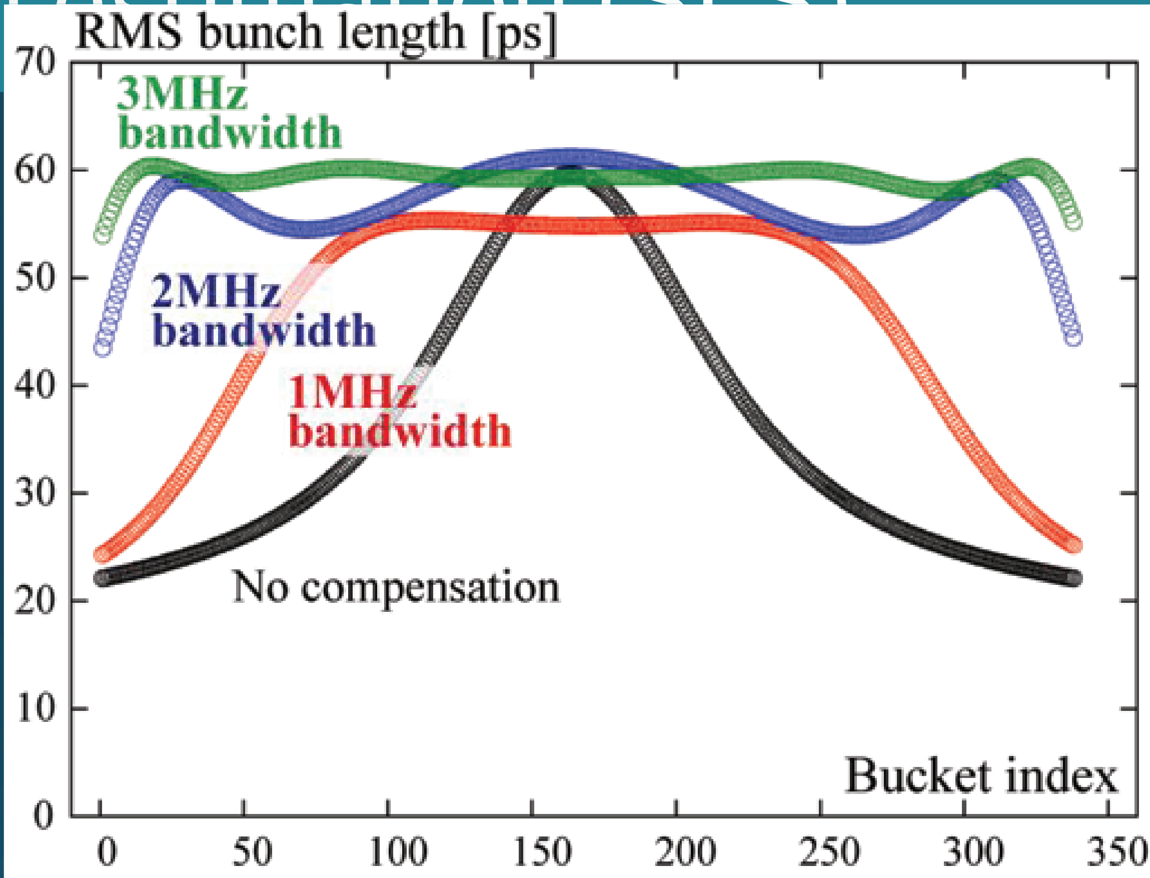
*M. Pedrozzi, et al., SRF03 (2003) p. 91



Numerical estimation (SLS)

Kicker cavity parameter
(not optimized)

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

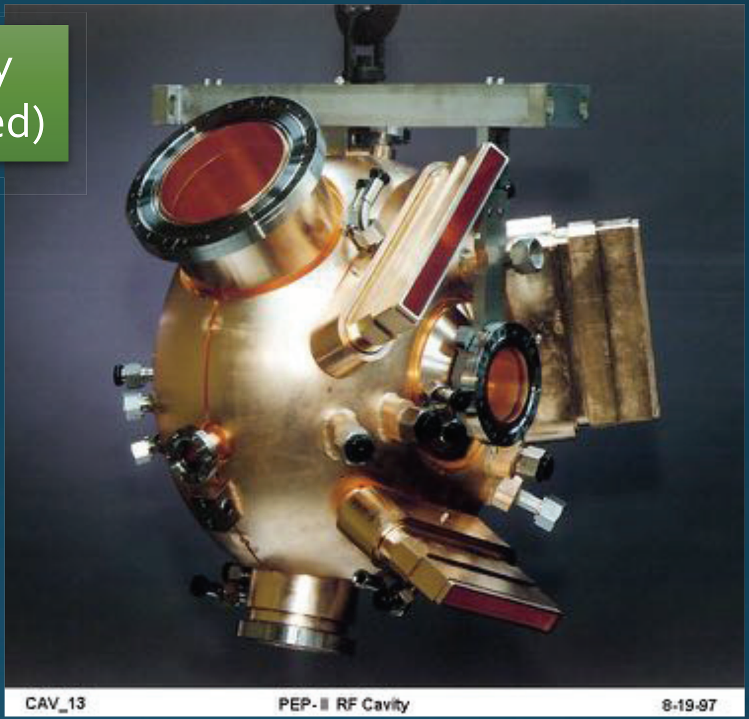
Numerical estimation (SLS)

* R.A. Rimmer, LBL-33360, UC-414 (1992); and related papers.

Kicker cavity parameter (not optimized)

Frequency	[MHz]	500
R/Q	[Ω]	230
Unloaded-Q		30000
Cavity number		1
Cavity coupling		149
Loaded-Q		200
3dB bandwidth	[MHz]	2.5

PEP-II cavity (HOM-damped)



Compensation bandwidth	**Average Bunch length**	**Peak Generator Power**	**Average Generator Power**
[MHz]	[ps]	[kW]	[kW]
–	35.8	–	–
3	59.3	~~98.3~~ -> 81.5	~~39.1~~ -> 31.6

Summary

- Double RF system is essential in ring based future light source.
- Normal conducting TM020 cavity is a candidates for harmonic cavities because of it's high unloaded-Q and small R/Q (large stored energy).
- By using single kicker cavity with active feedfoward LLRF system, the beam loading effect for the double RF system can be minimized and avoided.

(This technique can be applied to not only NC but also SC systems.)

<u>Future tasks</u>

- Concrete designs of
  - ➢ the HOM-damped/high-coupling kicker cavity
  - ➢ the (adaptive) feedforward Low level RF system
  - ➢ Several tens kW level solid state amp. with wide bandwidth.