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
  - Basic idea
  - Compensation with a kicker cavity
  - 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.

- 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.

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<table>
<thead>
<tr>
<th>KEK-LS parameter</th>
<th>Electron energy $E_0$ [GeV]</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency $f_{RF}$ [MHz]</td>
<td>500.07</td>
<td></td>
</tr>
<tr>
<td>RF voltage $V_{RF}$ [MV]</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td><strong>Beam current</strong> [mA]</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td><strong>Hor. emittance</strong> [pmrad]</td>
<td>132.5</td>
<td>230.5</td>
</tr>
<tr>
<td><strong>Touschek lifetime</strong> [h]</td>
<td>–</td>
<td>2.9</td>
</tr>
</tbody>
</table>

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http://kekls.kek.jp
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.

Main cavities (Frequency: $f$)

Harmonic cavities (Frequency: $n \times f$)

Flat potential condition

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

Cavity voltage

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

Total voltage

3$^{rd}$ harmonic voltage

Longitudinal bunch shape

main RF only

w. harmonic voltage
Harmonic (double) RF system
- Introduction
- Physics

Reduction of Transient beam loading effect
- Transient beam loading effect
- Reduction of the effect

Compensation of Transient effect
- Basic idea
- Compensation with a kicker cavity
- Numerical estimation

Summary

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.
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 is more serious.

### Cavity voltage vs Bucket index

- **Main cavity (500MHz)**
  - \[ |\Delta \tilde{V}_c| / |\tilde{V}_c| = 1.6 \% \]

- **Harmonic cavity (1.5GHz)**
  - \[ |\Delta \tilde{V}_c| / |\tilde{V}_c| = 7.1 \% \]

### Optimum condition

- **60ps bunch gaps** (MC + HC)

#### More serious:

- **Natural bunch length** (Uniform fill, Main cavity only)
Reduction of the loading effect

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

\[
\frac{\Delta V_{\text{max}}}{V_{\text{ave}}} \approx e^{-n_g \alpha} - 1
\]

For passive cavity (without generator)

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

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

<table>
<thead>
<tr>
<th>R/Q</th>
<th>Ω</th>
<th>SLS/ELETTRA</th>
<th>ALS</th>
<th>BESSY-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloaded-Q</td>
<td>2.0E+08</td>
<td>21000</td>
<td>13900</td>
<td></td>
</tr>
<tr>
<td>Coupling</td>
<td>β</td>
<td>3099</td>
<td>1.08</td>
<td>0.82</td>
</tr>
<tr>
<td>Loaded- Q</td>
<td>64514</td>
<td>10088</td>
<td>7631</td>
<td></td>
</tr>
<tr>
<td>Fill time</td>
<td>μs</td>
<td>13.7</td>
<td>2.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Cav. number</td>
<td>1</td>
<td>7</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>total R/Q</td>
<td>Ω</td>
<td>176</td>
<td>1127</td>
<td>1488</td>
</tr>
<tr>
<td>(V_{hc}/\text{cav.})</td>
<td>kV</td>
<td>777</td>
<td>111</td>
<td>65</td>
</tr>
<tr>
<td>(P_c/\text{cav.})</td>
<td>kW</td>
<td>0.0</td>
<td>3.6</td>
<td>2.4</td>
</tr>
<tr>
<td>(\Delta V_c/V_c(6\text{ns}))</td>
<td>%</td>
<td>3.2</td>
<td>22.0</td>
<td>35.0</td>
</tr>
</tbody>
</table>
**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!

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*SLS 284 ns gap*

![Graph](image-url)

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*
• Double RF system
  • Motivation
  • Physics

• Reduction of Transient beam loading effect
  • Transient beam loading effect
  • Reduction of the effect

• Compensation of Transient effect
  • Basic idea
  • Compensation with a kicker cavity
  • Numerical estimation

• Summary
Basic idea of the compensation

- 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 ...)

- Main cavities
  - Frequency: $f$
- Haromic cavities
  - Frequency: $n \times f$
- Kicker cavity
  - Frequency: $f$

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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.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>500 MHz</td>
</tr>
<tr>
<td>R/Q</td>
<td>175 Ω</td>
</tr>
<tr>
<td>Unloaded-Q</td>
<td>40000</td>
</tr>
<tr>
<td>Cavity number</td>
<td>1</td>
</tr>
<tr>
<td>Cavity coupling</td>
<td>199</td>
</tr>
<tr>
<td>Loaded-Q</td>
<td>200</td>
</tr>
<tr>
<td>3dB bandwidth</td>
<td>2.5 MHz</td>
</tr>
</tbody>
</table>

← assumed kicker cavity parameters (not optimized)
Compensation with a kicker cavity

How to obtain the feedforward 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.

\[ \tilde{V}_c(t) = - \left( \text{Re} \left[ \tilde{V}_{c,1}(t) + \tilde{V}_{c,n}(t) \right] - U_0 \right) \]
Compensation with a kicker cavity

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.

\[ \tilde{V}_c(t) \]

<table>
<thead>
<tr>
<th>[kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
</tr>
<tr>
<td>25</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>-25</td>
</tr>
<tr>
<td>-50</td>
</tr>
</tbody>
</table>

Before BW limit

After BW limit (3MHz)

\[ 1.05 \text{ MHz} \]
Compensation with a kicker cavity

Adding Kicker cavity field in Analytical calculation

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

RMS bunch length [ps]

3MHz bandwidth

No compensation

6ons bunch gap

RF power valances

Cavity voltage [kV]

Cavity dissipated power [kW]

Generator power [kW]

Avg. 40kW

Reflected power [kW]
Analytical estimation (SLS case)

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

<table>
<thead>
<tr>
<th>Kicker cavity parameter</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [MHz]</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>R/Q [Ω]</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td>Unloaded-Q [Ω]</td>
<td>40000</td>
<td></td>
</tr>
<tr>
<td>Cavity number</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Cavity coupling [199]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loaded-Q</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>3dB bandwidth [MHz]</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Compensation bandwidth [MHz]</th>
<th>Average Bunch length [ps]</th>
<th>Peak Generator Power [kW]</th>
<th>Average Generator Power [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35.8</td>
<td>25.8</td>
<td>16.8</td>
</tr>
<tr>
<td>2</td>
<td>46.3</td>
<td>84.1</td>
<td>35.6</td>
</tr>
<tr>
<td>3</td>
<td>59.3</td>
<td>98.3</td>
<td>39.1</td>
</tr>
</tbody>
</table>

RMS bunch length [ps]

Bucket index

No compensation

3MHz bandwidth

2MHz bandwidth

1MHz bandwidth
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

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

| Main cavity             |                |
| Unloaded-Q              | $1 \times 10^{10}$ |
| Loaded-Q               | 50,000         |
| total R/Q              | 360 Ω          |

| 3rd Harmonic cavity     |                |
| Unloaded-Q              | $1 \times 10^8$ |
| Loaded-Q               | $1 \times 10^8$ |
| total R/Q              | 180 Ω          |

+ NC Kicker cavity (352MHz)
Macro particle simulation

Bunch length vs Turn

Kicker cavity ON

Bunch length [ps]

Bunch 156 (center)
Bunch 1 (head)
Bunch 312 (tail)

Turn number [x1000]

Bunch phase vs Turn

Bunch 1 (head)
Bunch 156 (center)
Bunch 312 (tail)

Turn number [x1000]

0.85 MHz bandwidth

Avg. Len. factor = 4.8

Kicker Cavity Power

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

Bunch 156th shape evolution (train center)

RF Voltage [MV]

Time [ps]
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.

To realize kicker cavity compensation, 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!