Impedance issues in KEKB and SuperKEKB

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Outline

➤ Introduction
  ● KEKB and SuperKEKB

➤ Impedance model and Single-bunch effects
  ● Impedance calculations, impedance budget, ...
  ● Bunch lengthening, MWI, beam tilt, TMCI, ...

➤ Coherent synchrotron radiation (CSR)
  ● Its role in KEK’s projects
  ● Code developments and impedance calculations
  ● CSR driven MWI
  ● CSR field dynamics

➤ Summary
1. Introduction

<table>
<thead>
<tr>
<th></th>
<th>LER</th>
<th>HER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SKEKB</td>
<td>KEKB*</td>
</tr>
<tr>
<td>$E$ (GeV)</td>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>$I_b$ (mA)</td>
<td>1.44</td>
<td>1.03</td>
</tr>
<tr>
<td>$\varepsilon_x$ (nm)</td>
<td>3.2</td>
<td>18</td>
</tr>
<tr>
<td>$\varepsilon_y$ (pm)</td>
<td>8.64</td>
<td>180</td>
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<tr>
<td>$\alpha_p$ ($10^{-4}$)</td>
<td>3.25</td>
<td>3.31</td>
</tr>
<tr>
<td>$\sigma_\delta$ ($10^{-4}$)</td>
<td>8.08</td>
<td>7.73</td>
</tr>
<tr>
<td>$\sigma_z$ (mm)</td>
<td>5</td>
<td>4.6</td>
</tr>
</tbody>
</table>

[Image of the KEKB accelerator complex with labels for LER and HER.]
2. Impedance model: KEKB

- Y. Cai’s model for KEKB
  - VFP solver
  - 3-parameter broadband resonator model
  - Fit the measured bunch lengthening and profile
  - Determine the MWI threshold and compare with physics data

Y. Cai et al., PRST-AB 12, 061002 (2009)
2. Impedance model: KEKB

➤ Pseudo-Green function wake calculation

- Geometric wakes, resistive wall, CSR, CWR

<table>
<thead>
<tr>
<th>Component</th>
<th>Number</th>
<th>Software</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARES cavity</td>
<td>20</td>
<td>GdfidL</td>
</tr>
<tr>
<td>Movable mask</td>
<td>16</td>
<td>GdfidL</td>
</tr>
<tr>
<td>SR mask (arc/wiggler)</td>
<td>1000 (905/95)</td>
<td>GdfidL</td>
</tr>
<tr>
<td>Bellows</td>
<td>1000</td>
<td>GdfidL</td>
</tr>
<tr>
<td>Flange gap</td>
<td>2000</td>
<td>GdfidL</td>
</tr>
<tr>
<td>BPM</td>
<td>440</td>
<td>MAFIA</td>
</tr>
<tr>
<td>Pumping port</td>
<td>3000</td>
<td>GdfidL</td>
</tr>
<tr>
<td>Crab cavity</td>
<td>1</td>
<td>ABCI</td>
</tr>
<tr>
<td>FB kicker/BPM</td>
<td>1/40</td>
<td>GdfidL</td>
</tr>
<tr>
<td>Tapers</td>
<td>4/2/2/2</td>
<td>GdfidL</td>
</tr>
<tr>
<td>ARES/CRAB/ABORT/INJECTION IR(IP/QCSL/QCSR)</td>
<td>6(2/2/2)</td>
<td>GdfidL</td>
</tr>
<tr>
<td>Gate valves f94/f150/94x150</td>
<td>26/13/2</td>
<td>GdfidL</td>
</tr>
</tbody>
</table>

D. Zhou et al., ICAP09, TH2IOpk02
2. Impedance model: KEKB

Simulations using Pseudo-Green function wake

- Estimate loss factors and compare with measurements and prediction of broadband resonator model

![Graph showing loss factor vs. bunch length](image)

- Measurement: $k_r = 892 \sigma^{2.67}$
- Calculated wake: $k_r = 475 \sigma^{1.63}$
- Resonator model: $k_r = 2983 \sigma^{3.1}$

T. Ieiri and H. Koiso, 14th SAST 2003
2. Impedance model: KEKB

- Simulations using Pseudo-Green function wake
  - Use VFP solver to simulate bunch lengthening and MWI
  - CSR plays a role but seems not serious
  - Missing impedance sources? CSR/CWR/RW not well modelled in MWI simulations? NOT clear yet

![Graph showing σ_z vs. l_b and σ_p vs. l_b](image-url)
2. Impedance model: SuperKEKB

➢ Upgrade LER
  ● \( \phi94\text{mm} \Rightarrow \phi90\text{mm} \text{ w/ antechamber} \)
  ● New Ecloud suppression devices
  ● Bellows: Finger-type => Comb-type
  ● Movable masks => PEP-II type collimators

➢ HER almost no changes

LER typical (~90%)  
 Aluminum w/ antechamber

HER typical (~70%)  
 Copper w/o antechamber

Y. Suetsugu and K. Shibata
2. Impedance model: SuperKEKB: LER

Bellows

Comb-type: Unique for SuperKEKB

MO-type flange

Pumping port

ARES RF cavity

T. Abe and K. Shibata
2. Impedance model: SuperKEKB: LER: Bellows

• Bellows chamber with comb-type RF shield will be used in SKEKB.
  – There is no radial step on the inner surface.
    (There is a small step (~1 mm) in a conventional bellows chamber.)
  – RF is shielded by nested comb teeth.
    length: 10 mm
    radial thickness: 10 mm
2. Impedance model: SuperKEKB: LER: Bellows

- **Loss factor** ($\sigma_z = 6$ mm)
  \[ k = 2.2 \times 10^{-3} \text{ V/pC} \]
  - 1000 pieces in one ring
  \[ k_{\text{total}} = 2.2 \text{ V/pC} \]

- **Impedance**
  It was found that there are trapped modes at 7.5 GHz and 25 GHz (over cut-off frequency (2.5GHz)). Effects of these trapped modes on the beams will be investigated.

---

K. Shibata
2. Impedance model: SuperKEKB: LER

Collimator (PEP-II type)

BPM

SR mask

T. Ishibashi, M. Tobiyama, and K. Shibata
2. Impedance model: SuperKEKB: LER

Clearing electrode

Grooved surfaces

From T. Ishibashi

Tested in KEKB

Ref. Y. Suetsugu et al., NIMA 598 (2009)

Ref. Y. Suetsugu et al., NIMA 604 (2009)
2. Impedance model: SuperKEKB: HER

SCC (ABCI)

Movable mask (KEKB type)

Bellows

ARES RF cavity

T. Abe, Y. Morita, and K. Shibata
2. Impedance model: SuperKEKB: HER

Pumping port

Flange

BPM

SR mask

K. Shibata and M. Tobiyama
2. Impedance model: SuperKEKB: LER

Pseudo-Green wake function

- $\sigma_z=0.5\text{mm}$
- CSR and CWR: CSRZ code with rectangular chamber
2. Impedance model: SuperKEKB: HER

- Pseudo-Green wake function
  - $\sigma_z = 0.5\,\text{mm}$
  - CSR: CSRZ code with rectangular chamber
  - CWR not considered yet
2. Impedance model: SuperKEKB: Budget

- Impedance budget with $\sigma_z = 5/4.9\text{mm}$:
  - Loss factors, resistance and inductance are calculated at nominal bunch lengths with input of Pseudo-Green function wakes.

| Component       | LER $k_{||}$ | LER $R$ | LER $L$ | HER $k_{||}$ | HER $R$ | HER $L$ |
|-----------------|--------------|---------|---------|--------------|---------|---------|
| ARES cavity     | 8.9          | 524     | -       | 3.3          | 190     | -       |
| SC cavity       | -            | -       | -       | 7.8          | 454     | -       |
| Collimator      | 1.1          | 62.4    | 13.0    | 5.3          | 309     | 10.8    |
| Res. wall       | 3.9          | 231     | 5.7     | 5.9          | 340     | 8.2     |
| Bellows         | 2.7          | 159     | 5.1     | 4.6          | 265     | 16.0    |
| Flange          | 0.2          | 13.7    | 4.1     | 0.6          | 34.1    | 19.3    |
| Pump. port      | 0.0          | 0.0     | 0.0     | 0.6          | 34.1    | 19.3    |
| SR mask         | 0.0          | 0.0     | 0.0     | 0.4          | 21.4    | 6.6     |
| IR duct         | 0.0          | 2.2     | 0.5     | 0.0          | 2.2     | 0.5     |
| BPM             | 0.1          | 8.2     | 0.6     | 0.0          | 0.0     | 0.0     |
| FB kicker       | 0.4          | 26.3    | 0.0     | 0.5          | 26.2    | 0.0     |
| FB BPM          | 0.0          | 1.1     | 0.0     | 0.0          | 1.1     | 0.0     |
| Long. kicker    | 1.8          | 105     | 1.2     | -            | -       | -       |
| Groove pipe     | 0.1          | 5.7     | 0.9     | -            | -       | -       |
| Electrode       | 0.0          | 2.2     | 2.3     | -            | -       | -       |
| **Total**       | **19.2**     | **1141**| **33.4**| **29.0**     | **1677**| **62.1**|

Table 2: Key parameters of SuperKEKB main rings for MWI simulations.

Ref. D. Zhou et al., IPAC14, TUPRI021
## 2. Impedance model: Budget

➤ **Compare LER of KEKB and SuperKEKB**

<table>
<thead>
<tr>
<th>Component</th>
<th>Super-LER</th>
<th>KEKB-LER</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$k_{</td>
<td></td>
</tr>
<tr>
<td>ARES cavity</td>
<td>8.9</td>
<td>524</td>
</tr>
<tr>
<td>Crab cavity</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Collimator</td>
<td>1.1</td>
<td>62.4</td>
</tr>
<tr>
<td>Res. wall</td>
<td>3.9</td>
<td>231</td>
</tr>
<tr>
<td>Bellows</td>
<td>2.7</td>
<td>159</td>
</tr>
<tr>
<td>Flange</td>
<td>0.2</td>
<td>13.7</td>
</tr>
<tr>
<td>Pump. port</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>SR mask</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>IR duct</td>
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<td>2.2</td>
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<tr>
<td>BPM</td>
<td>0.1</td>
<td>8.2</td>
</tr>
<tr>
<td>FB kicker</td>
<td>0.4</td>
<td>26.3</td>
</tr>
<tr>
<td>FB BPM</td>
<td>0.0</td>
<td>1.1</td>
</tr>
<tr>
<td>Gate valve</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Taper</td>
<td>0.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Long. kicker</td>
<td>1.8</td>
<td>105</td>
</tr>
<tr>
<td>Groove pipe</td>
<td>0.1</td>
<td>5.7</td>
</tr>
<tr>
<td>Electrode</td>
<td>0.0</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>19.2</td>
<td>1142</td>
</tr>
</tbody>
</table>
2. Impedance model: SuperKEKB: LER: MWI

- Simulations with input of Pseudo-Green wake:
  - Use Warnock-Cai’s VFP solver
  - Collimators are important sources in bunch lengthening
  - Simulated $\sigma_z \approx 5.9\,\text{mm}$ @Design bunch current
  - Simulated MWI threshold is around $NP_{\text{th}} = 1.2E11$
  - Interplay between CSR and conventional wakes?
2. Impedance model: SuperKEKB: HER: MWI

- Simulations with input of Pseudo-Green wake:
  - Use Warnock-Cai’s VFP solver
  - Simulated $\sigma_z \approx 5.8\text{mm}$ @Design bunch current
  - Simulated MWI threshold is around $NP_{th}=1.7\times10^{11}$
  - CSR and CWR are likely to be not important.
2. Impedance model: Transverse: Beam tilt

 setBackgroundColor

Transverse beam tilt:

- To be a concern in low emittance rings
- Asymmetric protrusion (if exists)

\[
\Delta \epsilon_y = \frac{1}{4 \sin^2(\pi \nu_y)} \beta_y \theta_{\text{rms}}^2
\]

\[
\theta_{\text{rms}} = \frac{N e^2}{\gamma m_0 c^2} \sqrt{\langle (W_y - \langle W_y \rangle)^2 \rangle}
\]

\[
\langle W_y \rangle = \int_{-\infty}^{\infty} W_y(s) \lambda(s) ds
\]

<table>
<thead>
<tr>
<th>TABLE II. Emittance increase in LER of SUPERKEKB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrugation depth $h$ (cm)</td>
</tr>
<tr>
<td>$\theta_{\text{rms}}$ (nrad)</td>
</tr>
<tr>
<td>$\Delta \epsilon$ (pm)</td>
</tr>
</tbody>
</table>

2. Impedance model: Transverse: Beam tilt

- **Transverse beam tilt:**
  - Symmetric 3D structure (like collimator) with orbit offset
  - D02V1 in LER as an example: d=-2/2mm, $\beta_y=104.6$ m
  - COD DY < 0.2 mm required

\[
\Delta \epsilon_y = \frac{1}{4 \sin^2 (\pi \nu_y)} \beta_y \theta_{\text{rms}}^2
\]

\[
\theta_{\text{rms}} = \frac{N e^2 \Delta y}{\gamma m_0 c^2} \sqrt{\langle (W'_y - \langle W'_y \rangle)^2 \rangle}
\]
2. Impedance model: Transverse: TMCI: LER

- **TMCI in LER**
  - We estimated the threshold of the Transverse Mode Coupling Instability using actual $\beta$ value at location of each collimator with $\sigma_z = 6$ mm.
  - D02V1 is the main impedance source because it would be used with the narrow aperture ($d = \pm 2$ mm).
  - The threshold is about 1.71 mA/bunch (Design value: 1.44 mA/bunch) in the latest collimator design.

<table>
<thead>
<tr>
<th></th>
<th>All Closed</th>
<th>Actual apertures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>1.41</td>
<td>13.15</td>
</tr>
<tr>
<td>Vertical</td>
<td>1.32</td>
<td>1.71</td>
</tr>
</tbody>
</table>

$I_{thresh} = \frac{C_1 f_s E/e}{\sum_i \beta_i \kappa_{\perp_i} \sigma_z}$

- $C_1$: constant $\approx 8$
- $f_s$: synchrotron frequency
- $E$: beam energy
- $\beta$: beta function
- $\kappa_{\perp_i}$: kick factor

**Collimator Aperture List (mm)**

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>D06H1</td>
<td>-16.0/+17.0</td>
</tr>
<tr>
<td>D06H2</td>
<td>-16.0/+16.0</td>
</tr>
<tr>
<td>D06H3</td>
<td>-16.0/+15.0</td>
</tr>
<tr>
<td>D06H4</td>
<td>-13.0/+13.0</td>
</tr>
<tr>
<td>D03H1</td>
<td>-21.0/+20.0</td>
</tr>
<tr>
<td>D03H2</td>
<td>-18.0/+20.0</td>
</tr>
<tr>
<td>D03V1</td>
<td>-9.0/+9.0</td>
</tr>
<tr>
<td>D03V2</td>
<td>-9.0/+9.0</td>
</tr>
<tr>
<td>D02H1</td>
<td>-10.6/+12.0</td>
</tr>
<tr>
<td>D02H2</td>
<td>-16.0/+20.0</td>
</tr>
<tr>
<td>D02H3</td>
<td>-18.0/+21.0</td>
</tr>
<tr>
<td>D02H4</td>
<td>-13.0/+9.0</td>
</tr>
<tr>
<td>D02V1</td>
<td>-2.0/+2.0</td>
</tr>
</tbody>
</table>
3. CSR: SuperKEKB design

➤ High-current scheme
- CSR driven MWI in LER was very serious

| $N$ (design) | $11.7$ | $10^{10}$ |
| $\sigma_{z0}$ | $3$ | mm |
| $\sigma_{\varepsilon 0}$ | $7.1$ | $10^{-4}$ |
| $\nu_z$ | $-0.022$ | |

K. Oide, et al., MO3RAI01, PAC’09 (2009)
3. CSR: SuperKEKB design

Simple estimation of CSR instability threshold [Stupakov and Heifets (2002)] ...

\[ I_b > \frac{\pi^{1/6}}{\sqrt{2}} \frac{e c}{r_0 \rho^{1/3}} \gamma \alpha_p \delta_0^2 \sigma_z \frac{1}{\lambda^{2/3}} \]

SuperKEKB LER (High-current scheme)

SuperKEKB DR (Version 1.140)

Shielding threshold:

\[ \lambda_c = 2 \sqrt{b^3 / R} \]


J. Byrd, et al., PRL 89, 22, Nov. 2002

3. CSR: SuperKEKB

➤ **DR design**
- **Optics**: CSR-optimized
- **Vacuum chamber and RF system**

➤ **Collaboration**
- **SLAC**: Y. Cai, G. Stupakov, L. Wang et al.
- **CERN**: F. Zimmermann

➤ **Intensive CSR impedance calculations**
- **Benchmark**: 5 codes (Agoh, Oide, Zhou, Stupakov, L. Wang)
- **Single-bend and multi-bend**
- **Rectangular and arbitrary cross-section of chamber**

➤ **Intensive simulations of MWI**
- **Macro-particle tracking**: SAD
- **Vlasov solver**: SAD, Warnock-Cai’s code
3. CSR: SuperKEKB

- Y. Cai’s theory on CSR effects in rectangular chamber
  - Steady-state CSR model
  - Square chamber lowers MWI threshold [Surprise!]
  - Chamber aspect ratio >2 preferred

\[ N_{th} = \frac{C I_A}{c e} \frac{\alpha_p \gamma \sigma_\delta^2}{\sigma_z} \frac{\sigma_z^{4/3}}{R^{1/3}} \xi_{th} \]

\[ I_A = 4\pi \varepsilon_0 \frac{m_e c^3}{e} \quad \chi = \sigma_z \sqrt{\frac{R}{b^3}} \]

**Parallel plates:**
\[ \xi_{th} = 0.5 + 0.34\chi \]

**Rectangular chamber:**
\[ \xi = \xi_{th}(\chi, A = \frac{a}{b}, \frac{1}{\omega_s \tau_d}) \]

Ref. Y. Cai, PRST-AB 17, 020702 (2014)
3. CSR: SuperKEKB

➤ Y. Cai’s theory on CSR effects in *rectangular chamber*

<table>
<thead>
<tr>
<th></th>
<th>DR</th>
<th>LER</th>
<th>HER</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (GeV)</td>
<td>1.1</td>
<td>4</td>
<td>7.007</td>
</tr>
<tr>
<td>$N_P (10^{10})$</td>
<td>5</td>
<td>9.04</td>
<td>6.53</td>
</tr>
<tr>
<td>$b$ (mm)</td>
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<td>90</td>
<td>50</td>
</tr>
<tr>
<td>$a$ (mm)</td>
<td>34</td>
<td>90</td>
<td>104</td>
</tr>
<tr>
<td>$R$ (m)</td>
<td>2.7/3</td>
<td>74.7</td>
<td>106</td>
</tr>
<tr>
<td>$\chi$</td>
<td>1.49</td>
<td>1.67</td>
<td>2.16</td>
</tr>
<tr>
<td>$\alpha_p (10^{-4})$</td>
<td>141</td>
<td>3.25</td>
<td>4.55</td>
</tr>
<tr>
<td>$\sigma_\delta (10^{-4})$</td>
<td>5.5</td>
<td>8.08</td>
<td>6.37</td>
</tr>
<tr>
<td>$\sigma_z$ (mm)</td>
<td>6.6</td>
<td>7.8</td>
<td>11</td>
</tr>
<tr>
<td>$\xi_{th}^{old}$</td>
<td>1.49</td>
<td>1.67</td>
<td>2.16</td>
</tr>
<tr>
<td>$N_{th}^{old} (10^{10})$</td>
<td>4.4</td>
<td>5.2</td>
<td>7.6</td>
</tr>
<tr>
<td>$\xi_{th}^{new}$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$N_{th}^{new} (10^{10})$</td>
<td>1.5</td>
<td>1.6</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Ref. Y. Cai, PRST-AB 17, 020702 (2014)
3. CSR: Field dynamics

Parabolic equation (PE) in Frenet-Serret coordinate system:

\[
\frac{\partial \vec{E}_\perp}{\partial s} = \frac{i}{2k} \left[ \nabla^2 \vec{E}_\perp - \frac{1}{\varepsilon_0} \nabla \rho_0 + 2k^2 \left( \frac{x}{R(s)} - \frac{1}{2\gamma^2} \right) \vec{E}_\perp \right]
\]

Longitudinal field and impedance:

\[
E_s = \frac{i}{k} \left( \nabla \cdot \vec{E}_\perp - \mu_0 c J_s \right) \quad Z(k) = -\frac{1}{q} \int_0^\infty E_s(x_c, y_c) ds
\]

Contributors:
➤ G. Stupakov and I.A. Kotelnikov (Mode expansion, PRST-AB 2003, 2009)
➤ D.R. Gillingham and T.M. Antonsen (Time-domain PE, PRST-AB 2007)
➤ K. Oide (Mesh + Eigen solver, PAC 2009)
➤ D. Zhou (Mesh + Finite difference, JJAP 2012)
➤ L. Wang (Mesh + Finite element, 2012)
➤ D.A. Bizzozero (Mesh + Discontinuous Galerkin method, PRL 2015)
➤ R. Warnock
3. CSR: Field dynamics

CSRZ code: Uniform rectangular cross-section

Field separation:

\[ \vec{E}_\perp = \vec{E}_\perp^r + \vec{E}_\perp^b \]
\[ \frac{\partial \vec{E}_\perp^r}{\partial s} = \frac{i}{2k} \left[ \nabla^2 \vec{E}_\perp^r + 2k^2 \left( \frac{x}{R(s)} - \frac{1}{2\gamma^2} \right) (\vec{E}_\perp^r + \vec{E}_\perp^b) \right] \]

The curvature is variable (Single dipole, soft fringe, a series of dipoles, wiggler, etc.):

Single dipole

Wiggler - “Wiggling pipe”
3. CSR: Field dynamics: Eigenmodes

Resonance poles = Eigen modes
a/b=60/30 mm, L_{bend}=8 m, R=5 m

\[ E_x(x, y) = E_{x0} \Lambda i \left( k_y^2 \kappa^2 - x/\kappa \right) \sin \left[ k_y(y + b/2) \right] \]

Freq. & index
\[ k = 4930 \text{ m}^{-1} \]
\[ (m, p) = (3, 1) \]

Im. \( E_x^r \):

Re. \( E_x^r \):

Mode pattern:

Overtaking fields

G. Stupakov and I. Kotelnikov, PRST-AB 6, 034401 (2003).
3. CSR: Field dynamics: Eigenmodes

Arbitrary cross-section: Finite element technique + parabolic equation (L. Wang)

![Graphs showing field dynamics](image-url)
3. CSR: Field dynamics: Optical model

Outer-wall reflection can be well approximated by optical model [Derbenev (1995), Carr (2001), Sagan (2009), Oide (2010)]

Critical length (Catch-up distance):

\[ L_c = 2R\theta_c \approx 2\sqrt{2Rx_b} \]

\[ \theta_c = \arccos \left( \frac{R}{R + x_b} \right) \approx \sqrt{2x_b/R} \]

Path difference:

\[ \Delta s = 2R(\tan(\theta_c) - \theta_c) \approx \frac{4}{3} \sqrt{\frac{2x^3}{R}} \]

Condition of neglecting outer wall:

\[ \Delta s \gg \sigma_z \]

D. Sagan et al., PRST-AB 12, 040703 (2009).
K. Oide, Talk at CSR mini-workshop, Nov. 08, 2010.
3. CSR: Field dynamics: Multi-bend interference

➤ SuperKEKB DR

- CSR impedance: Forest of “narrow-band” spikes
- Multi-bend interference: Modify the measured power spectrum in CSR

**DR layout**

**Bend:**
- $\rho_{\text{bend}} \approx 2.7/-3$ m
- $L_{\text{bend}} \approx 0.7/0.3$ m
- $a/b \approx 24/34$ mm
- $L_{\text{drift}} \approx 0.9$ m

**Impedance**
3. CSR: Field dynamics: Waveguide modes

R. Warnock’s idea: Similarity of steady-state CSR and whispering gallery modes

Ref. R. Warnock, in ICFA beam dynamics Newsletter 63 (2014)
3. CSR: Field dynamics: Measurements

CSR measurements at NSLS VUV ring

Observation of coherent synchrotron radiation from the NSLS VUV ring

G.L. Carr\textsuperscript{a}, S.L. Kramer\textsuperscript{a}, J.B. Murphy\textsuperscript{a}, R.P.S.M. Lobo\textsuperscript{b}, D.B. Tanner\textsuperscript{b}

Microbunching@Streak Camera

S. Kramer, EPAC 2002
3. CSR: Field dynamics: Measurements

CSR measurements at NSLS VUV ring
\[ \frac{a}{b} = 80/42 \text{ mm}, \quad L_{\text{bend}} = 1.5 \text{ m}, \quad R = 1.91 \text{ m} \]

Chamber cross section

Model for calculation

Excellent agreements in peak positions and widths.
The discrepancy in amplitude at low- and high-frequency parts is attributed to the transfer function of the detection system.

Blue solid: SR impedance
Red dashed: Measured ISR spectrum
(Data provided by S.L. Kramer)
3. CSR: Field dynamics: Measurements

➤ High-resolution CSR measurements at CLS
Since the interesting wavelength of CSR is much smaller than the chamber geometry (\(\lambda << b\)), we can safely do ray-tracing for even complicated geometry.

3. CSR: Field dynamics: Measurements

Figure 10: Vacuum chamber of CLS at dipole where IR is extracted

R. Warnock
3. CSR: Field dynamics: Measurements

➤ High-resolution CSR measurements at CLS

FIG. 4 (color online). rf diode measurements in the time domain (oscilloscope traces) with a 50–75 GHz detector. Diode mounting and polarization: 1—backward horizontal; 2—backward vertical; 3—forward horizontal (with adjustment of time base). For clarity the curves have been separated vertically.

FIG. 5 (color online). Simulated $E_x^2$ at backward port vs $ct$, after a low pass filter to account for detector response. The origin of time $t$ is when the bunch is 5 cm before the entrance to the bend. Only the lowest mode in $y$ is included.

B.E. Billinghurst et al., PRL 114, 204801 (2015)
4. Summary

➤ Impedance model and single-bunch effects
  • Pseudo-Green function wakes obtained for KEKB and SuperKEKB rings
  • Sources of bunch lengthening and MWI in KEKB are not well understood yet
  • Beam tilt and TMCI are potentially important in SuperKEKB

➤ CSR
  • CSR effect is still a concern in SuperKEKB
  • CSR calculations based on parabolic equations well investigated
  • CSR fields calculation/measurement with 3D chamber is a very interesting subject to be investigated
4. Summary

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  ● CSR effect is still a concern in SuperKEKB
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➤ SuperKEKB started beam commissioning on Feb. 1st
  ● Beam measurements to be delivered
  ● Welcome to follow the experiences of SuperKEKB
Thanks for your attention!
2. Impedance model: KEKB: LER

➤ Use Zotter’s equation

\[
\left( \frac{\sigma_z}{\sigma_{z0}} \right)^3 - \frac{\sigma_z}{\sigma_{z0}} - \frac{\alpha I_b \text{Im} \left\{ \frac{Z_{ij}}{n} \right\}_{eff}}{\sqrt{2\pi}(E/e)\nu_{s0}^2} \left( \frac{R}{\sigma_{z0}} \right)^3 = 0
\]

Ref. J. Corbett, TUPP028, EPAC08

\[
L_{\parallel \text{eff}} \approx 34\text{nH}
\]
3. CSR: SuperKEKB: Damping ring

➤ Findings: Multi-bunch instability

• Long-range CSR wake extend to distance of \(~0.1\ m\)

• Not considered in CSR impedance calculation: Resistive wall and chamber discontinuities

• Likely no multi-bunch CSR instability

\[ \sigma_z = 0.2\text{mm} \]

Freq. < 1.4THz

L. Wang and D. Zhou