Impedance Optimization for EIC

Alexei Blednykh
Accelerator Physicist

SuperKEKB: Challenges for the high luminosity frontier. January 30, 2020

Electron Ion Collider – EIC at BNL
Outlook

• Introduction
• Comparison with PEP-II and SuperKEKB
• Vacuum Chamber Profile Optimization
• IR Chamber Design
• RF Shielded Bellows
• Notable Risks
Introduction to e⁻-Ring

- **Bunch Charge**  
  \( \text{Ne} \)  
  48.4nC

- **Number of Bunches**  
  \( M \)  
  660

- **Bunch Length**  
  \( \sigma_s \)  
  12mm

- **Single Bunch Current**  
  \( I_0 = \frac{\text{Ne}}{T_0} \)  
  3.8mA

- **Peak Bunch Current**  
  \( I_p = \frac{N e}{\sqrt{2\pi\sigma_t}} \)  
  483A for \( \sigma_t = 40\text{ps} \)  
  ignoring bunch lengthening

- **Average Current**  
  \( I_{av} = \frac{M N e}{T_0} \)  
  2.5A
Comparison Between EIC, SuperKEKB, PEP-II

<table>
<thead>
<tr>
<th></th>
<th>EIC</th>
<th>PEP-II*</th>
<th>SKEKB*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>10</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td>Average Current (A)</td>
<td>2.5</td>
<td>2</td>
<td>2.6</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>660</td>
<td>1658</td>
<td>1576</td>
</tr>
<tr>
<td>RMS Bunch Duration (mm)</td>
<td>12</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>Power Loss, $P_{loss} = k_{</td>
<td></td>
<td>}(\sigma_s)I_{av}^2T_0/M$</td>
<td>$k_{</td>
</tr>
<tr>
<td>Vertical Aperture (mm)</td>
<td>20</td>
<td>33</td>
<td>25</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>3834</td>
<td>2199</td>
<td>3016</td>
</tr>
<tr>
<td>RF Frequency (MHz)</td>
<td>591</td>
<td>476</td>
<td>508.9</td>
</tr>
<tr>
<td>RF Voltage (MV)</td>
<td>41</td>
<td>5.9</td>
<td>15</td>
</tr>
<tr>
<td>Mom. Compaction ($x10^{-4}$)</td>
<td>10.4</td>
<td>24.1</td>
<td>4.55</td>
</tr>
<tr>
<td>Horiz. &amp; Ver. Emittances (nm &amp; pm)</td>
<td>20 &amp; 1</td>
<td>48 &amp; 1.9</td>
<td>4.4 &amp; 1.5</td>
</tr>
</tbody>
</table>

*S. HEIFETS, ..., SLAC PUB 6989, Impedance Study for the PEP-II B-Factory

*http://www-superkekb.kek.jp/index.html

- Resistive Wall: $k_{||} \approx 1.2 \frac{cZ_0}{4\pi} \frac{L}{\sqrt{2\pi b} \sqrt{Z_0} \sqrt{\sigma_{con}} \sigma_s^{3/2}}$
- High conductivity and bunch lengthening can help to reduce RW impedance
Vacuum Chamber Profile Concept

Dipole Chamber

- 82mm
- 40.00 mm

Straight Section Chamber

- Ø62mm

● The cutoff frequency for the longitudinal $E_{01}$-Mode:

- GdfidL: $f_c = 4.36\,GHz$ – for standard octagonal chamber

\[ f_c = \frac{2}{\sqrt{\left(\frac{1}{a}\right)^2 + \left(\frac{1}{b}\right)^2}} = 4.19\,GHz \] – for rectangular chamber

\[ f_c = \frac{c2.405}{2\pi b} = 3.7\,GHz \] – for circular chamber

- Standard Cu tubing – readily available
Tapered Transition

Vacuum Chamber Profile

382m each straight section: Total 6
- RF straight section
- IR straight section
- Injection Straight Section

- 180mm tapered transition was chosen for numerical simulations. It can be longer.
Vacuum Chamber Proposal

- Easy for BPM Button installation
- Lower RW loss factor $k_{\text{loss}} = 0.5V/pC$ for $L=3\times382m=1145m$ of Cu with $b=31mm$

- Lower cutoff frequency for $E_{01}$ mode, $f_c = \frac{c2.405}{2\pi b} = 3.7GHz$ – for circular chamber with $b=31mm$
- HOM’s generation due to cavity transition
- Heat load and beam instability
- Tune shift $v_{x,y}$ dependence on the average current $I_{av}$ (Quadrupole impedance $Z_Q$)

- Advantages/Disadvantages of both options from synchrotron radiation protection need to be analyzed
- Total cost of both options needs to be evaluated.

- No cavity transition and related HOM’s effects
- Higher cutoff frequency, $f_c = \frac{c2.405}{2\pi b} = 5.7GHz$ - for $b=20mm$.
- Cancelation effect of low frequency $Z_Q$ and hence $v_{x,y}(I_{av})$.

- Small cavity openings around the BPM Buttons
- Smaller diameter, 40mm, contribution of the resistive wall will be larger, by a factor of 1.55.
- $k_{\text{loss}} = 0.7V/pC$ for $L=3\times382m=1145m$ of Cu with $b=20mm$
Cutoff Frequency

- The cutoff frequency $f_{c,E01}$ for $E_{01}$-mode vs. the circular vacuum chamber radius $b$

- Higher cut-off frequency and longer bunch length can reduce the beam-induced heating of the vacuum components.

- The circulating bunch length needs to be larger than the radius $b$ of the vacuum chamber, $\sigma_s > b$, to reduce beam-induced heating.

The cutoff frequency $f_{c,E01}$ for $E_{01}$-mode vs. the circular vacuum chamber radius $b$

Real part of the longitudinal impedance for the EIC IR chamber

Real part of the longitudinal impedance for the APS-U BPM Button

APS-U Project, Preliminary Design Report, September, 2017
The crossing angle is 22 mrad.

The IR-chamber has a complex geometry in crossing location of two beam pipes, electron and proton rings.

Merging beam pipes on the hadron forward side is the main impedance source.
IR Chamber Design (Cont.)

Version 3

- The electron beam pipe was extended all the way to the center of the detector chamber
- An opening on the side of the electron beam pipe is large enough for the forward moving collision particles
- Impedance has been reduced since there is no cavity formed between the 2 beam pipes.
- Coupling Impedance of a long oval hole
- Synchrotron radiation masking is outside of the central detector pipe.

Version 2

C. Hetzel
Longitudinal Wakefield/Impedance Analysis

The longitudinal wakepotential simulated for a $\sigma_s = 0.3\text{mm}$ bunch length

The imaginary part of the longitudinal impedance divided by $n = \omega/\omega_0$, where $\omega_0 = 2\pi \times 78.186\text{kHz}$.

- Beam–Induced Heating: $ReZ_{||}$ up to 8.5GHz for $\sigma_s = 12\text{mm}$
- Microwave Instability: Short-Range $W_{||}(s)$ for $\sigma_s = 0.3\text{mm}$ (Pseudo-Green’s Function)
- Bunch Lengthening: $ImZ_{||}$ at low frequencies.
The wake field almost follows the shape of a bunch. That corresponds to creation of the additional bunch self electromagnetic field in the pipe of a larger size.

Special designed HOM Absorber can be implemented for damping of HOM.

Detailed impedance comparison is in progress.

S. Novokhatski
Bellows Choice – Conventional Design

**NSLS-II (500mA)**

\[ M = 1205, \sigma_s = 5\text{mm} \]

- RF contact fingers need to be well compressed
- Localized heating can appear due to poor contact between the RF fingers and the sleeve.

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**APS-U (200mA)**

\[ M = 48, \sigma_s = 15\text{mm} \]

- Conventional bellows needs to be with an effective water-cooling design/ Engineering Effort / Cost increase / Under Development

**HHC**

\[ V_{RF} = 3\text{MV} \]

**BLW10**

**NSLS-II Experimental Data**
Bellows Choice – Comb-Type Design

Racetrack bellows chamber with comb-type RF shield

Y. Suetsugu, K. Kanazawa, N. Ohuchi, K. Shibata, M. Shirai, KEK, Tsukuba, Japan, Proceedings of 2005 Particle Accelerator Conference, Knoxville, Tennessee

- Comb-Type Bellows Design Experience in SuperKEKB
- Advantages and Disadvantages?
- Impedance, HOM, Max. temperature limit, Mechanical Difficulties, Cost
- Long Term Operation Experience

The loss factor as a function of bunch length.

Demin Zhou, Collective Effects in SuperKEKB CLASSE Seminar, Aug. 6, 2014
Notable Risks

- Transverse oscillations are damped by beam–beam tune spread.
- Longitudinal feedback is needed due to RF HOM.
- Since protons have no radiation damping the residual electron oscillations are a concern.
- Localized IP heating.
- Beam gas interaction inside the detector.
- Reliability of vacuum components.
- Viability of Higher Harmonic Cavity (HHC).
- Ion instabilities and vacuum requirements.
- We are calculating the detailed impedance of the EIC vacuum components.
- The instability thresholds will be estimated via particle tracking simulations, applying the calculated impedance budget.
- IR chamber is critical component.
Acknowledgments

- **BNL/EIC**

- **BNL/NSLS-II**
  C. Hetzel, V. Smaluk, T. Shaftan, G. Bassi

- **SLAC**
  A. Novokhatiski, K. Bane

- **SuperKEKB**
  K. Shibata, D. Zhou, Y. Suetsugu