Development of a New Beam-Energy-Spread Monitor Using Multi-Stripline Electrodes

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**KEKB Accelerator Complex**

**KEKB Accelerators Complex**

**KEKB Collider Rings**

- **High Energy Ring (HER):** $e^-$ 8.0 GeV
- **Low Energy Ring (LER):** $e^+$ 3.5 GeV

**Photon Factory**

$E_{e^+} = 3.5$ GeV

$E_{e^-} = 8$ GeV

Tsuyoshi Suwada  
/KEKB Injector Linac  
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Introduction

Purpose
Well-controlled operation of the KEKB injector linac is strongly required

- for keeping the injection rate as high as possible,
- and for maintaining stable operation.

Beam Feedback Controls

- Beam position feedback [LINAC2000, pp.633-635]
- Beam energy feedback [ICALEPCS’99, pp.248-250]
- Beam energy-spread feedback

Motivation

- A nondestructive energy-spread monitor contributes toward further stable operation/injection of the linac.

→ We developed a new beam energy-spread monitor with multi-stripline electrodes.
Beam Energy-Spread Monitor with Eight Stripline-Type Electrodes

• This work was strongly motivated by a pioneering work of R. H. Miller, et al. [HEAC’83, pp.602-605].
  → They showed that a stripline-type BPM with four pickups could be utilized as a nonintercepting emittance monitor.

• Also our previous work using similar stripline-type BPMs [Jpn.J.App.Phys. 40 (2001), pp.890-897] demonstrated that the higher-order (second- and third-order) moments of an electron beam were directly measured depending upon the transverse beam sizes.
Multi-Stripline Energy-Spread Monitor: Mechanical Design Parameters

Stripline electrodes

$\alpha$

$R_1$

$R_2$

$t$

$L$

**TABLE I: Mechanical design parameters of the BESM.**

<table>
<thead>
<tr>
<th>Mechanical parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius $R_1$ (mm)</td>
<td>20.6</td>
</tr>
<tr>
<td>Outer radius $R_2$ (mm)</td>
<td>23.4</td>
</tr>
<tr>
<td>Electrode angular width $\alpha$ (deg)</td>
<td>15</td>
</tr>
<tr>
<td>Electrode thickness $t$ (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Electrode length $l$ (mm)</td>
<td>132.5</td>
</tr>
<tr>
<td>Total length $L$ (mm)</td>
<td>283</td>
</tr>
</tbody>
</table>
Multipole Analysis of the Electromagnetic Field Generated by a Charged Beam

The image charge density distribution by a line charge for a conducting round duct is formulated by,

\[ j(r, \phi, R, \theta) = \frac{I(r, \phi)}{2\pi R} \left[ 1 + 2 \sum_{n=1}^{\infty} \left( \frac{r}{R} \right)^n \cos(n(\theta - \phi)) \right]. \]

Assuming the transverse \( r \)-distribution \( \rho(r) \) of a traveling charged beam, the total image charge \( J \) is formulated by,

\[ J(R, \theta) = \int_{0}^{R} \int_{0}^{2\pi} j(r, \phi, R, \theta) \rho(r) r \, dr \, d\phi. \]

It is easily expanded by the power series,

\[ J(R, \theta) = \frac{I_b}{2\pi R} \left[ 1 + \frac{2}{R} \left( \langle x \rangle \cos \theta + \langle y \rangle \sin \theta \right) \right. \]
\[ + \frac{2}{R^2} \left( \langle x^2 \rangle - \langle y^2 \rangle + \langle x \rangle^2 - \langle y \rangle^2 \right) \cos 2\theta + 2 \langle xy \rangle + \langle x \rangle \langle y \rangle \sin 2\theta \]
\[ + \text{higher orders} \].
Multipole Analysis of 8-Electrode BESM

The multipole moments are defined by using the pickup voltages($V_i$)

- for the 1st-order (dipole) moments,

\[
J_{dx} = \frac{\langle x \rangle}{R} = \frac{2\pi}{\pi} \int J(R,\theta) \cos \theta R d\theta = \sum_{i=1}^{3} \frac{V_i \cos \theta}{\sum_{i=1}^{3} V_i},
\]

\[
J_{dy} = \frac{\langle y \rangle}{R} = \frac{2\pi}{\pi} \int J(R,\theta) \sin \theta R d\theta = \sum_{i=1}^{3} \frac{V_i \sin \theta}{\sum_{i=1}^{3} V_i},
\]

- and for the 2nd-order (quadrupole and skew) moments,

\[
J_q = \frac{1}{R^2} \left( \langle x^2 \rangle - \langle y^2 \rangle + \langle x \rangle^2 - \langle y \rangle^2 \right) = \frac{2\pi}{\pi} \int J(R,\theta) \cos^2 \theta R d\theta = \sum_{i=1}^{3} \frac{V_i \cos 2\theta}{\sum_{i=1}^{3} V_i},
\]

\[
J_s = \frac{1}{R^2} \left( \langle xy \rangle + \langle x \rangle \langle y \rangle \right) = \frac{2\pi}{\pi} \int J(R,\theta) \sin 2\theta R d\theta = \sum_{i=1}^{3} \frac{V_i \sin 2\theta}{\sum_{i=1}^{3} V_i},
\]

- the skew angle (x-y coupling) of the beam is formulated by

\[
\theta_{skew} = J_s / 2 J_q,
\]

- and the beam energy spread is also formulated using the optics parameters and transverse emittances by

\[
\langle x^2 \rangle - \langle y^2 \rangle = \beta_x \varepsilon_x + \left( \frac{\Delta E}{E} \right)^2 - \beta_y \varepsilon_y + g,
\]

where $g$ is the parameter due to the gain imbalance and the geometrical errors of the pickups.
Beam Test at the 180-degree J-arc section of the injector linac
Beam Test: Experiment and beam condition

1. Beam Conditions:
   • single bunch (KEKB) electron and high-current e-/e+ production beam (bunch width=12ps, bunch charge=0.9 and 8nC, repetition rate=25Hz)
   • beam energies ($E_b=1.7\text{GeV}$) at the linac J-arc.

2. Second-order moments (quadrupole and skew moments) were measured by the BESM depending upon the rf phase of the booster klystron and the transverse beam positions.

3. Beam-size calibration was performed by a fluorescent screen monitor with a high-resolution image processing system.

4. Data-acquisition system of the BESM comprises a signal-digitizing system of a fast oscilloscope (LeCroy WavePro 950) with a sampling rate of 8-GS/s (BW=1GHz) and a PC/Linux-based computer with a Pentium IV microprocessor at 2.2GHz.
Experimental Results:

Variations of the horizontal and vertical beam-position dependence of $J_{quad}$

**Horizontal**

Position-corrected $J_{quad}$

**Vertical**

Position-corrected $J_{quad}$
Experimental Results:
Variations of $J_{\text{quad}}$ and the energy spread depending on the rf phase (0.9 and 8-nC e- beams)

Variations of $J_{\text{quad}}$

Energy Spread

- Gaussian distribution
- Parabolic distribution

8-nC $e^-$

0.9-nC $e^-$

$\langle x \rangle - \langle y \rangle$ [mm]

$\langle x^2 \rangle - \langle y^2 \rangle$ [mm$^2$]

$\langle x \rangle - \langle y \rangle$ [mm]

$\langle x^2 \rangle - \langle y^2 \rangle$ [mm$^2$]

$\Delta E/E(\%)$

8-nC $e^-$

0.9-nC $e^-$

$0.264 \pm 0.004\%$ $0.150 \pm 0.007\%$
Experimental Results:
Time trend of the quadrupole moment and the rf phase of the booster klystron

![Graph showing time trend of quadrupole moment and rf phase](image)
Conclusions

• Result of the beam-size measurement by the BESM is
  • consistent well with that obtained by the fluorescent screen monitor system, and the 2nd-order moments need to be corrected with the transverse beam positions.

• Beam energy spreads were
  • $0.150 \pm 0.007\%$ for the 0.9-nC electron beam,
  • and $0.264 \pm 0.004\%$ for the 8-nC e- beam, and the resolution is on the order of $10^{-3}$ depending upon the beam charge and the rf phase.

• Good agreement between the rf phase of the booster klystron and the 2nd-order moment by the BESM for the variation of the time trend is a clear demonstration of the principal function of the BESM, and it is an important step towards the stable operation of the injector linac.

• We have a plan to investigate beam characteristics of two beam bunches in the two-bunch injection scheme.
Multipole Analysis of the Electromagnetic Field Generated by a Charged Beam: Wall current formula and its multipole expansion (cont’d)

The multipole moments are defined for the 1st-order moment,
\[ \langle x \rangle = \int x j(x, y) \rho(x, y) \, dx \, dy \]
\[ \langle y \rangle = \int y j(x, y) \rho(x, y) \, dx \, dy \]
for the 2nd-order moment,
\[ \langle x^2 \rangle = \int x^2 j(x, y) \rho(x, y) \, dx \, dy \]
\[ \langle y^2 \rangle = \int y^2 j(x, y) \rho(x, y) \, dx \, dy \]
and for the xy coupling term,
\[ \langle xy \rangle = \int xy j(x, y) \rho(x, y) \, dx \, dy \]
Multipole Analysis of the Electromagnetic Field Generated by a Charged Beam:
Wall current formula and its multipole expansion (cont'd)

Assuming a gaussian function for the transverse charge distribution, the total image charge is formulated by,

\[ J(R, \theta) = \frac{l_b}{2\pi\sigma_x\sigma_y} \int \int \frac{j(r, \phi, R, \theta)}{I(r, \phi)} \exp\left[\frac{-(x-x_0)^2}{2\sigma_x^2}\right] \exp\left[\frac{-(y-y_0)^2}{2\sigma_y^2}\right] dx dy \]

\[ J(R, \theta) = \frac{l_b}{2\pi R} \left\{ 1 + 2\left[ \frac{x_0}{R} \cos \theta + \frac{y_0}{R} \sin \theta \right] \right. 
\[ + 2\left[ \left( \frac{\sigma_x^2 - \sigma_y^2}{R^2} + \frac{x_0^2 - y_0^2}{R^2} \right) \cos 2\theta + 2 \frac{x_0 y_0}{R^2} \sin 2\theta \right] \right. 
\[ + 2 \left[ \frac{x_0}{R} \left( \frac{3(\sigma_x^2 - \sigma_y^2)}{R^2} + \frac{x_0^2 - 3y_0^2}{R^2} \right) \cos 3\theta + \frac{y_0}{R} \left( \frac{3(\sigma_x^2 - \sigma_y^2)}{R^2} + 3x_0^2 - y_0^2 \right) \sin 3\theta \right] 
\[ + \text{higher orders} \]
Multi-Stripline Energy Spread Monitor: Charge Simulation Method

![Graph 1]

![Graph 2]
Multi-Stripline Energy Spread Monitor: $J_{\text{quad}}$-Sensitivity Calculation
Experimental Results:
phase=0deg (0.9-nC e-beam)
Experimental Results:
\[ \text{phase} = +3\text{deg} \ (0.9\text{-nC} \ e^{-} \text{ beam}) \]
Experimental Results:
Beam-size measurement by the screen monitor system depending on the rf phase (0.9-nC e-beam)
Experimental Results:
Variations of the skew angles depending upon the rf phase (0.9 and 8-nC e- beams)

The obtained skew angles in average are

- 21 and 20 mrad for the 0.9- and 8-nC e- beam over the measured region of the rf phase.
Experimental Results:
Variations of $J_{\text{quad}}$ and the rf phase resolution depending on the rf phase (0.9 and 8-nC e-beams)

Variations of $J_{\text{quad}}$  rf phase resolution
Experimental Results: Variations of the beam energy spread depending upon the rf phase

The obtained beam energy spreads were

- $0.150 \pm 0.007\%$ for the $0.9\text{-}nC\ e^-$,
- and $0.264 \pm 0.004\%$ for the $8\text{-}nC\ e^-/e^+\ production\ at\ the\ rf\ phase\ of\ the\ energy-spread\ minimum$

The resolution of the measurement is on the order of $10^{-3}$ depending upon the beam charge and the rf phase.
Conclusions

• Result of the beam-size measurement by the BESM is consistent well with that obtained by the fluorescent screen monitor system, where the 2nd-order moments need to be corrected with the transverse beam positions.

• RF phase resolutions were
  • less than 1 deg. for the high-current primarily electron (8-nC) beam, and less than 1 deg. over the region of ±1 deg. apart from the rf phase at the energy-spread minimum.

• Beam energy spreads were
  • $0.150 \pm 0.007\%$ for the 0.9-nC electron beam,
  • and $0.264 \pm 0.004\%$ for the 8-nC e-beam, and the resolution is on the order of $10^{-3}$ depending upon the beam charge and the rf phase.

• Skew angles of the electron beam were
  • 21 and 20 mrad in average over the measured region of the rf phase for the 0.9- and 8-nC electron beam, respectively.