Instabilities
simulation and observation


21-th KEKB Accelerator Review Committee

KEK, 13-15 June, 2016
Contents

• Beam size blow-up due to Electron cloud
• Coupled bunch instability due to electron cloud
• Coupled bunch instability in HER
• Tune shift measurement and transverse impedance
• Bunch length measurement
Beam size blow-up in LER

- Beam-size blowup observed in KEKB has been seen in early stage of SuperKEKB commissioning

1. Threshold I~300mA in Apr 19 (Y. Funakoshi)
2. Electron cloud has been monitored at AL chamber w and w/o TiN coating (Y. Suetsugu).
3. Beast study threshold I~600mA, N_{bunch}=1576 in May 17 (Nakayama et al)
4. Systematic study in 1 June (H. Fukuma et al.)
5. Permanent magnets are set at aluminum bellows.(Y. Suetsugu et al.)
6. Systematic studies in 8 July (H. Fukuma et al.)

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June 1, 2016
4 train x150 bunches, N_{bunch}=600

Threshold beam current 160, 200, 260, 500 mA for 2, 3, 4, 6 bucket spacing

H. Fukuma et al.,
Instability simulation at SuperKEKB design stage

- Using code PEHTS

Simulation, \( \rho_{\text{eth}} = 3.8 \times 10^{11} \text{ m}^{-3} \).

\[
\rho_{\text{e,th}} = \frac{2 \gamma \nu_s \sigma_0 \sigma_z / c}{\sqrt{3} K Q r_e \beta_y L} = 2.2 \times 10^{11} \text{ m}^{-3},
\]

where \( K = \omega_e \sigma_z / c = 17 \) and \( Q = \min(\omega_e \sigma_z / c, 10) \)

Design target for vacuum system: \( \rho_{\text{e}} < 10^{11} \text{ m}^{-3} \) in average of whole ring
Simulation studies using beam study condition

Threshold of the electron density
\( \varepsilon_x = 2\text{nm}, \varepsilon_y = 15\text{pm}, \sigma_z = 6\text{mm}, \nu_s = 0.019 \)

Np=1.6x10\(^{10}\)
I\(_{th}\)=160mA, 4ns spacing

Np=2.7x10\(^{10}\)
I\(_{th}\)=260mA, 8ns spacing

Np=2.1x10\(^{10}\),
\( \varepsilon_y = 100\text{pm} \)

Np=2.1x10\(^{10}\)
I\(_{th}\)=200mA, 6ns spacing

Np=5.2x10\(^{10}\)
I\(_{th}\)=500mA, 8ns spacing

Np=2.4x10\(^{10}\),
\( \varepsilon_y = 100\text{pm} \)
Simulated threshold electron density (condition before solenoid installation)

- \( N_b = 600, \ \varepsilon_x = 2\text{nm}, \ \varepsilon_y = 15\text{pm}, \ \sigma_z = 6\text{mm}, \ \nu_s = 0.019 \)

<table>
<thead>
<tr>
<th>spacing</th>
<th>( I_{p,\text{th}} ) (mA)</th>
<th>( N_{p,\text{th}} ) ((10^{10}))</th>
<th>( \omega_e/2\pi ) (GHz)</th>
<th>( \omega_e\sigma_z/c )</th>
<th>( \rho_{\text{eth}} ) (Q=10) ((10^{11}\text{m}^{-3}))</th>
<th>( \rho_{\text{eth}} ) (Q=6) ((10^{11}\text{m}^{-3}))</th>
<th>( \rho_{\text{eth}} ) (Simu) ((10^{11}\text{m}^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 (4ns)</td>
<td>160</td>
<td>1.6</td>
<td>61</td>
<td>7.7</td>
<td>1.91</td>
<td>2.45</td>
<td>3.4</td>
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<tr>
<td>3 (6ns)</td>
<td>200</td>
<td>2.1</td>
<td>71</td>
<td>8.9</td>
<td>1.65</td>
<td>2.45</td>
<td>3.4</td>
</tr>
<tr>
<td>4 (8ns)</td>
<td>260</td>
<td>2.7</td>
<td>80</td>
<td>10.1</td>
<td>1.47</td>
<td>2.45</td>
<td>3.8</td>
</tr>
<tr>
<td>6 (12ns)</td>
<td>500</td>
<td>5.2</td>
<td>111</td>
<td>14.0</td>
<td>1.47</td>
<td>2.45</td>
<td>5.0</td>
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<tr>
<td>3.06</td>
<td>500</td>
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<td>37</td>
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\[
\rho_{e,\text{th}} = \frac{2\gamma \nu_s \omega_e \sigma_z/c}{\sqrt{3KQr_0\beta L}}
\]

\[
K = \frac{\omega_e \sigma_z/c}{Q}
\]

\[
Q = \min(\omega_e \sigma_z/c, 6)
\]

\( N_b = 1576, \ \varepsilon_y = 100\text{pm} \)
Electron cloud measurement

- Retarding bias, V=500V or 0V, select electrons with E>500eV or all, respectively.

- Electron E=500eV, \( v = 1.3 \times 10^7 \text{m/s} \). \( R/v = 3.8 \text{ns} \), \( R = 5 \text{cm} \), density can be estimated considering volume with energy gain 500eV from a bunch. 500eV may be critical for 2 (4ns) spacing.

- For V=0V, electron rate production including secondary is detected.
Measured electron current

For \( V = 0 \text{V}, 1 \mu\text{A} \), electron production rate is \( 0.3 \times 10^9 \text{ m}^{-1}/\text{bunch} \)
Electron density at the blow-up threshold

- Simulated electron density at the threshold current
- Measured threshold current and density

Only Al part

Simple formula $Q=6$
After installation of permanent solenoid at Al bellows

\[ Q = 6 \]

\[ I_{th} = 200 \text{ mA} \]
\[ I_{th} = 330 \text{ mA} \]
\[ I_{th} > 600 \text{ mA} \]

Simulated electron density at the threshold current

Simple formula \( Q = 6 \)
Threshold of electron cloud density after solenoid attach

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<td>91</td>
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<td>2.45</td>
<td>2.45</td>
<td>4.8</td>
</tr>
<tr>
<td>4 (8ns)</td>
<td>&gt;600</td>
<td>&gt;6.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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Simulated electron cloud build up in Drift

$N_p = 2.5 \times 10^{10}$, $I = 240 \text{ mA}$ for $N_b = 150 \times 4 = 600$

$N_p = 4 \times 10^{10}$, $I = 380 \text{ mA}$ for $N_b = 600$

$N_p = 9.4 \times 10^{10}$, $I = 900 \text{ mA}$ for $N_b = 600$

Beam current: Slightly higher than measured threshold

$\rho_e(r=0) \sim \lambda_e \times 1000$

$Y_1 = \text{Photon number} \times 0.1 \times 0.01$
$d_{\text{max}} = 1.0$

$E$ cloud buildup

$N_p = 3.13 \times 10^{10}$,
Density $R < 4\,\text{mm}$

$Y_1 = \text{Photon number} \times 0.1 \times 0.01$
quantum eff. antechamber

$\delta_{\text{max}} = 1.0$ 計算を打ち切った。
Coupled bunch instability caused by electron cloud
- Electron cloud motion reflects coupled bunch instability mode.
- Electrons in drift, short range wake $\sim$10ns
- Electrons in solenoid, slow rotation around chamber surface.
Unstable mode (before solenoid installation)

• Typical signal of coupled bunch instability caused by drift electrons

M. Tobiyama
Mode spectrum

By 2 ver

300mA

Solenoid origin

400mA

Drift origin

By 4 ver

350mA

Solenoid origin

600mA

Solenoid origin
Unstable mode (after solenoid installation)

• Typical mode caused by electrons in solenoid is seen.
• Mode seems to change to those of drift origin at high current.
Coupled bunch instability in electron ring (HER)

- Ion?

\[
\omega_{i,x}^2 = \frac{2\lambda_e r_A c^2}{A_f \Sigma_x (\Sigma_x + \Sigma_y)}
\]
\[
\omega_{i,y}^2 = \frac{2\lambda_e r_A c^2}{A_f \Sigma_y (\Sigma_x + \Sigma_y)}
\]
\[
\Sigma_{x(y)} = \sqrt{\sigma_{e,x(y)}^2 + \sigma_{i,x(y)}^2}
\]

Mode = 5120 - \frac{\omega_{i,xy}}{\omega_0}

Beam current Nb
Apr.1 174mA 1163
Apr.2 174 1163
Apr.5 225 953
Apr.6 240 953
Apr.8 280 953
Apr.9 280 1163
Apr.10 280 1163
Apr.12 340 1163
Apr.22 520 1394
May.30 738 1576

Resistive wall
5120-1=5119
Impedance estimation - transverse

- Tune shift as function of bunch current

\[ \Delta \nu_x = \frac{1}{4\pi^{3/2}} \frac{N_r e}{\gamma} \frac{L}{\nu_x \sigma_z} \frac{iZ_{eff}}{Z_0} \]

\[ iZ_{eff}(k\Omega) = 33.3 \frac{\Delta \nu_x}{I(mA)} \]

LER \[\frac{\Delta \nu_x}{I(mA)} = 58.2\]

LER: 0.0034mA, 81kW/m, 33-46 kΩ/m

Her \[\frac{\Delta \nu_x}{I(mA)} = 58.2\]

HER: 0.0034mA, 81kW/m, 33-46 kΩ/m

\[ iZ_{eff} = 31 \ (x) \ 53 \ (y) \ k\Omega/m \]

\[ iZ_{eff} = 43 \ (x) \ 145 \ (y) \ k\Omega/m \]

KEKB-LER: -0.0034mA^{-1}, 81kΩ/m

coll. open 33-46 kΩ/m

T. Ieiri, EPAC00
Longitudinal impedance issue - Bunch length measurement

\[ f_1(l_b) = 4.0 + 2.5l_b \]
\[ f_2(l_b) = 4.4 + 2.0l_b \]
\[ f_3(l_b) = 3.5 + 3.2l_b \]

Measured by a Streak camera

The behaviors are similar as KEKB for both of LER and HER. Bunch lengthening is stronger than that of simulation.
Summary

• Beam size blow-up has been observed since early stage of SuperKEKB commissioning.
• Electron density at Al bellows part (5% of circumf.) is high ($\rho_e > 10^{12}$ m$^{-3}$). Simulations show the electrons can cause fast head-tail instability.
• Coupled bunch instability caused by electron cloud has also been observed as is predicted.
• Installation of Permanent solenoid reduced the blow up. It is possible to operate with 1A, 4 bucket spacing at present condition.
• Tune shift as function of bunch current was measured to estimate transverse impedance. It was 30-50k$\Omega$/m, similar as KEKB.
• Bunch length was measured by a streak camera. Bunch lengthening, which was similar as KEKB, was observed, 7-8 mm at the design current, while no bunch lengthening in prediction.
Thank you for your attention
Rough estimation of Electron density

- Electron current, $I_e=1\mu\text{A}$.
- Acceptance of the electron detector, $S_{\text{mon}}=1\ \text{cm}^2$.
- Number of electron absorbed (=produced) at chamber wall, $d=10\text{cm}$.

$$n_e = \frac{10^{-6} \times 0.1\pi}{1.6 \times 10^{-19} \times 10^{-4}} = 2 \times 10^{16} \text{ m}^{-1}\text{s}^{-1}$$

- Electron stay time in the chamber, $\tau_e=100\text{ns}$. Electron density

$$\rho_e = \frac{2 \times 10^{16} \times 10^{-7}}{0.05^2\pi} = 2.5 \times 10^{11} \text{ m}^{-3}$$
Emittance dependence

• Vertical emittance knob

\[ \beta_y = 67 \text{m} \]
Design current & spacing

$N_p = 9.4 \times 10^{10}$, $I = 3600$ mA
金澤氏の式を使った電子密度の算出

\[
D = \frac{\mu(V_b)}{V_{obs}(V_b)}
\]

\[
\mu(V_b) = \frac{I_{obs}(V_b)}{en_b f_{rev}}
\]

\[
V_{obs}(V_b) = A \pi r_e^2 = 2 \pi A r_e^2 N_b^2 \frac{m_e c^2}{e V_b}
\]

\[
e = 1.602E-19 \text{ [C]}
\]

\[
f_{rev} = 1E5 \text{ [s}^{-1}\text{]}
\]

\[
r_e = 2.818E-15 \text{ [m]}
\]

\[
m_e = 9.109E-31 \text{ [kg]}
\]

\[
c = 3.0E8 \text{ [ms}^{-1}\text{]}
\]

\[n_b = \text{バンチ数}
\]

\[\pi A = \text{通過確率} = 0.0003 \times \frac{1}{4} = 7.5E-5
\]

\[V_b = \text{グリッド電圧} \text{ [V]}
\]

\[N_b = \text{バンチ内の} e^+ \text{の数}
\]

\[
N_b = \frac{I}{n_b f_{rev} e} \quad I = \text{ビーム電流} \text{ [A]}
\]

まとめると、

\[D = 2.630E13 \times \frac{I_{obs} n_b V_b}{I^2}
\]

例えば、2/150/3 \( V_r = -30 \text{ V} \), \( I = 200 \text{ mA} \), \( I_{obs} = 1E-7 \text{ A} \) の場合 (平均で)

\[n_b = 600, \quad V_b = 30 \quad D = 1.18E12 \text{ [e}^{-} \text{ m}^{-3}\text{]}
\]
Simulated electron cloud build up in Bend

N_p=2.5 \times 10^{10}, I=240 \text{ mA} \text{ for } N_b=600

N_p=4 \times 10^{10}, I=380 \text{ mA}

N_p=9.4 \times 10^{10}, I=900 \text{ mA}

Multipacting arises \gamma_{2\text{max}} \geq 1.5 \text{ at the threshold beam currents.}
KEKB

Solenoid-Off

Experiment

Simulation

Horizontal

Vertical

Su Su Win et al, (EC2002)