Electron cloud effects in positron and proton rings

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Fermilab

Thanks to Y. Alexahin, A. Valishev, R. Zwaska and V. Shiltsev
Electron cloud effects in positron rings

- Large yield of photo-emission,
- Flat beam,
- Short bunch length
Threshold of the strong head-tail instability (Balance of growth and Landau damping)

\[ U_i \equiv \frac{\sqrt{3r_p c/\beta_i} \lambda_e K Q L}{4\pi \gamma \nu_s \omega_e \sigma_z \sigma_i (\sigma_x + \sigma_y)} = \frac{\sqrt{3r_p c/\beta_i} \lambda_e K Q}{2\gamma \omega_e \eta \sigma \Delta_p / p \sigma_i (\sigma_x + \sigma_y)} = 1 \]

- Stability condition for \( \omega_e \sigma_z / c > 1 \)

\[ \omega_e = \sqrt{\frac{\lambda_p r_e c^2}{\sigma_y (\sigma_x + \sigma_y)}} \]

- Since \( \rho_e = \lambda_e / 2\pi \sigma_x \sigma_y \),

\[ \rho_{e,th} = \frac{2\gamma \nu_s \omega_e \sigma_z / c}{\sqrt{3KQr_0 \beta L}} \quad \text{Origin of Landau damping is momentum compaction} \]

\[ 2\pi \nu_s \sigma_z = \eta \sigma \Delta_p / p L \]

- \( Q = \min(Q_{nl}, \omega_e \sigma_z / c) \)
- \( Q_{nl} \) depends on the nonlinear interaction.
- \( K \) characterizes cloud size effect and pinching.
- We use \( K = \omega_e \sigma_z / c \) and \( Q_{nl} = 7 \) for analytical estimation.
### Parameters for $e^+$ machines

Table 1: Basic parameters of the positron rings

<table>
<thead>
<tr>
<th>Lattice</th>
<th>KEKB</th>
<th>CESR-TA</th>
<th>PETRA-III</th>
<th>SuperKEKB</th>
<th>SuperB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>$L$ (m)</td>
<td>3,016</td>
<td>768</td>
<td>2304</td>
<td>3016</td>
</tr>
<tr>
<td>Energy</td>
<td>$E$ (GeV)</td>
<td>3.5</td>
<td>2.5</td>
<td>6</td>
<td>4.0</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$N_+ (10^{10})$</td>
<td>8</td>
<td>2</td>
<td>0.5</td>
<td>9</td>
</tr>
<tr>
<td>Beam current</td>
<td>$I_+ (A)$</td>
<td>1.7</td>
<td>-</td>
<td>0.1</td>
<td>3.6</td>
</tr>
<tr>
<td>Emittance</td>
<td>$\varepsilon_x (\text{nm})$</td>
<td>18</td>
<td>2.3</td>
<td>1</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>$\varepsilon_y (\text{nm})$</td>
<td>0.18</td>
<td>0.023</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>$\alpha (10^{-4})$</td>
<td>3.4</td>
<td>68</td>
<td>12.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z (\text{mm})$</td>
<td>6</td>
<td>6.8</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>RMS energy spread</td>
<td>$\sigma_E/E (10^{-3})$</td>
<td>0.73</td>
<td>0.8</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>$\nu_s$</td>
<td>0.025</td>
<td>0.067</td>
<td>0.049</td>
<td>0.0256</td>
</tr>
<tr>
<td>Damping time</td>
<td>$\tau_T (\text{ms})$</td>
<td>40</td>
<td>56.4</td>
<td>16</td>
<td>43</td>
</tr>
</tbody>
</table>

Table 2: Threshold of the B factories positron rings and others

<table>
<thead>
<tr>
<th>Lattice</th>
<th>KEKB (no sol.)</th>
<th>KEKB (50 G sol.)</th>
<th>CESR-TA</th>
<th>PETRA-III</th>
<th>SuperKEKB</th>
<th>SuperB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch population</td>
<td>$N_+ (10^{10})$</td>
<td>3</td>
<td>8</td>
<td>2</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>Beam current</td>
<td>$I_+ (A)$</td>
<td>0.5</td>
<td>1.7</td>
<td>-</td>
<td>0.1</td>
<td>3.6</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>$\ell_{sp} (\text{ns})$</td>
<td>8</td>
<td>7</td>
<td>4-14</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>Electron frequency</td>
<td>$\omega_e/2\pi (\text{GHz})$</td>
<td>28</td>
<td>40</td>
<td>43</td>
<td>35</td>
<td>150</td>
</tr>
<tr>
<td>Phase angle</td>
<td>$\omega_e\sigma_z/e$</td>
<td>3.6</td>
<td>5.9</td>
<td>11.0</td>
<td>8.8</td>
<td>18.8</td>
</tr>
<tr>
<td>Threshold</td>
<td>$\rho_e (10^{12} \text{ m}^{-3})$</td>
<td>0.63</td>
<td>0.38</td>
<td>1.7</td>
<td>1.2</td>
<td>0.27</td>
</tr>
</tbody>
</table>
KEKB: measurement and simulation of fast head-tail instability

Beam size blow up observed, and simultaneously synchro-beta sideband observed.

Simulation (PEHTS)
HEADTAIL gave similar results (E. Beneditto showed large cloud gave nice sideband signal)

Measurement at KEKB

Betatron sideband
Tail of train $\nu_s > V_s$
Head of train

$\rho_{e,th} = 0.8 \times 10^{12} \text{m}^{-3}$
Bunch by bunch Feedback does not suppress the sideband

Bunch by bunch feedback suppress only betatron amplitude.

FIG. 2. Averaged spectra of all bunches with the feedback gain (a) high, (b) low, and (c) set to zero. The vertical betatron peak is visible at 0.588, and the sideband peak can be seen around 0.64.

Sideband signal is Integrated over the train
• Simulation $\rho_{\text{th}}=2.2 \times 10^{11}$ m$^{-3}$.  
• Analytic $\rho_{\text{th}}=2.7 \times 10^{11}$ m$^{-3}$.  
• Take care of high $\beta$ section. Effects are enhanced.

$$\int \rho_e/\beta_y ds/L = 10^{11} \times 10 \text{ m}^{-2}$$

Vacuum system designed to be $\rho_e=1 \times 10^{11}$ m$^{-3}$
• No ante-chamber.
• The threshold current is very low. $N_+ = 0.5 \times 10^{10}$/bunch.
• Upper sideband like KEKB has been observed.

$\rho_{e,\text{th}} = 1.2 \times 10^{12}\text{m}^{-3}$
**Vertical emittance blow up (640 bunches)**

*640 bunches, 8 ns bunch spacing + gap*
639 x 8 ns = 5112 ns, gap 2568 ns

Bunch current:

Harmonic number: \( h = 3840 \)
Revolution time: \( T = 7.68 \) micro sec
Bunch positions: 960 (8 ns bunch spacing)

\[ v_s = 6.4 \text{kHz} \]

measured emittance on May 11, 2010
Horz. 1.38 nm, total current 65 mA
Vert. 128 pm

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Tune spectrum, bunch position #274

upper side band

head of train vert. tune \( f_y = 30 \) kHz

tail of train

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Courtesy of R. Wanzenberg
Cesr-TA

• 5 GeV high emittance 40nm, $\omega_e\sigma_z/c=3.2$
• 2GeV low emittance 2nm, $\omega_e\sigma_z/c=11$

• Threshold of the instability is $\rho_e=1\times10^{12}$ m$^{-3}$ in CesrTA 2GeV experiment (ECLOUD10, G. Dugan)
• Both sideband upper and lower are seen.
CesrTA 2 and 5 GeV

\[ \rho_{th} = 0.8 \times 10^{12} \text{ cm}^{-3} \]

- High(2GeV) and
- low(5GeV) \[ \omega_e \sigma_z/c. \]

\[ \rho_{th} = 4 \times 10^{12} \text{ cm}^{-3} \]
Simulated Unstable spectra

- Lower sideband is dominant for high $\omega_e \sigma_z / c$ (low emittance).
- Upper sideband is dominant for 5GeV

H. Jin et al., JJAP, 50, 026401 (2011)
Estimation of cloud density and coupled bunch instability in SuperKEKB

• Ante-chamber, $\delta_{2,max}=1.2$ without special structure like groove

\[ \rho_e=2.2 \times 10^{11} \text{ m}^{-3} \]

• Wake field and growth rate of the coupled bunch instability.

• Suetsugu-san estimates the density based on measurements and is designing the chamber to achieve density.

Growth time is 40 turns. It should be suppressed at $\rho_e=1 \times 10^{11} \text{ m}^{-3}$. 
Multi-bunch instability in KEKB

Beam dancing with electron cloud

- Drift space
- Electrons move one way
- Bunch by bunch correlation is short, very low Q.
Multi-bunch instability in KEKB

- Beam dancing with electron cloud
  - In solenoid magnets
  - Electrons move along the chamber surface.

"ec307t.f11" index θ matrix

KEKB

- Solenoid-ON
- Simulation
  - Solenoid-10 G
    - Horizontal
    - Vertical
  - Mode: 0, 200, 400, 600, 800, 1000, 1200, 1400
  - Mode: 0, 1, 2, 3, 4, 5

Graph showing beam intensity and distribution in KEKB.
Summary for positron rings

- Electron cloud effects have been seen many positron rings. All machines are photo-emission dominant.

- Synchrotron sideband due to electron cloud instability has been observed in many machines. The behaviors well agree with simulations.

- Coupled bunch instability has observed many rings and analyzed in detail. The behaviors well agree with simulations.

- Simulations for SuperKEKB should be reliable.

- The vacuum chamber is designed to satisfy the requirement $\rho_e \sim 1 \times 10^{11} \text{m}^{-3}$ in SuperKEKB.
Proton rings

- LHC, SPS
- J-PARC and neutron sources
- Proton machines in Fermilab
Electron source

- Ionization \( Y_i = 10^{-8} / \text{proton.meter} \)

- Proton loss \( 100 / \text{proton loss} \)
  - PSR \( Y_L = 10^{-6} / \text{proton.meter} \)
  - J-PARC MR (1kW) \( Y_L = 10^{-8} / \text{proton.meter} \)

- Photo-emission
  - LHC \( Y_e = 10^{-3} / \text{proton.meter} \)
  - KEKB \( Y_e = 10^{-2} / \text{positron.meter} \)

- Field emission...
Threshold of the strong head-tail instability
LHC, SPS, Fermi MI

- Stability condition for $Q \sim \omega_e \sigma_z / c > 1$

$$U_i \equiv \frac{\sqrt{3} r_p c \beta_i \lambda_e K Q L}{4 \pi \gamma \nu_s \omega_e \sigma_z \sigma_i (\sigma_x + \sigma_y)} = \frac{\sqrt{3} r_p c \beta_i \lambda_e K Q}{2 \gamma \omega e \eta \sigma \Delta_p / p \sigma_i (\sigma_x + \sigma_y)} = 1$$

- Since $\rho_e = \lambda_e / 2\pi \sigma_x \sigma_y$

$$\rho_{e,th} = \frac{2 \gamma \nu_s \omega_e \sigma_z / c}{\sqrt{3} K Q r_0 \beta L}$$

- Origin of Landau damping is momentum compaction
  $$2 \pi \nu_s \sigma_z = \eta \sigma \Delta_p / p L$$

- $Q = \text{min}(Q_{nl}, \omega_e \sigma_z / c)$
- $Q_{nl}$ depends on the nonlinear interaction.
- $K$ characterizes cloud size effect and pinching.
- We use $K = \omega_e \sigma_z / c$ and $Q_{nl} = 7$ for analytical estimation.

The same formula as positron machine
Threshold of the strong head-tail instability

J-PARC and neutron sources

- Stability condition for $\omega_e \sigma_z / c >> Q >> 1$

$$\omega_e = \sqrt{\frac{\lambda_e r_e c^2}{\sigma_y (\sigma_x + \sigma_y)}}$$

$$U_i \equiv \frac{\sqrt{3} r_p c \beta_i \lambda_e Q L}{4\pi \gamma \nu_s \omega_e \sigma_z \sigma_i (\sigma_x + \sigma_y)} = \frac{\sqrt{3} r_p c \beta_i \lambda_e Q}{2\gamma \omega_e \eta \sigma \Delta p / p \sigma_i (\sigma_x + \sigma_y)} = 1$$

- $i=\{x,y\}$
- $\lambda_e$ is now electron line density, since all electrons are gathered near the beam.

- $Q = Q_{nl} = 7$
- Threshold for the neutralization factor

$$f_{th} = \frac{\lambda_e}{\lambda_p} = \frac{2\gamma \omega_e \eta \sigma \Delta p / p \sigma_i (\sigma_x + \sigma_y)}{\sqrt{3} r_p c \lambda_p \beta_i Q}$$

2$\pi \nu_s \sigma_z = \eta \sigma \Delta p / p L$
# Electron cloud effects in LHC

## Table 1: Parameter list of LHC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Injection</th>
<th>Top</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy (TeV)</td>
<td>0.45</td>
<td>7</td>
</tr>
<tr>
<td>Circumference (m)</td>
<td>26,658</td>
<td>26,658</td>
</tr>
<tr>
<td>Bunch population</td>
<td>1.15x10^{11}</td>
<td>1.15x10^{11}</td>
</tr>
<tr>
<td>Emittance x/y (m)</td>
<td>7.3x10^{-9}</td>
<td>5.1x10^{-10}</td>
</tr>
<tr>
<td>Bunch length (m)</td>
<td>0.112</td>
<td>0.0755</td>
</tr>
<tr>
<td>Energy spread (10^{-4})</td>
<td>3.06</td>
<td>1.13</td>
</tr>
<tr>
<td>Synchrotron tune ν_s</td>
<td>0.0055</td>
<td>0.0019</td>
</tr>
<tr>
<td>Bending field (T)</td>
<td>0.535</td>
<td>8.33</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

ω_eσ_z/c                                  3.4      11

Analytic          ρ_{e,th} (m^{-3})  2.2x10^{11}  5.7x10^{11}  
Simulation (bend) ρ_{e,th} (m^{-3})  6x10^{11}  3x10^{12}  
Simulation (drift) ρ_{e,th} (m^{-3})  3x10^{11}  1x10^{12}  

Simulations are showed letter
Electron source

• Ionization, \(2 \times 10^{-7} \text{ Pa}, N_{pe}/L=8 \times 10^{-9} \text{ m}^{-1}\) at injection

• Photo-emission \(\gamma=7463, N_{pe}/L=0.0019 \text{ m}^{-1}, u_c=30 \text{ eV}\) at top energy

• Cyclotron motion in bending magnet.
  * \(\text{Inj 0.535 T, } \omega_c\sigma_z/c=35, \rho_c/\sigma_x=0.12 \text{ (300eV)}\)
  * \(\text{Top 8.33T, } \omega_c\sigma_z/c=369, \rho_c/\sigma_x=0.03 \text{ (300eV)}\)
  * Neglect cyclotron motion in this presentation, electrons move along magnetic flux line.
Electron line density

- injection
- top energy

Since multipacting is dominant in injection, the density is almost independent of initial yield.

Used cylindrical pipe $r=2\text{cm}$

- 100 time worse vacuum
Simulation results (PEHTS)

- injection
  - $\rho_{e,th} = 6 \times 10^{11} \text{m}^{-3}$

- top energy
  - $\rho_{e,th} = 3 \times 10^{12} \text{m}^{-3}$

- dispersion 1.5m, no remarkable effects

in Bend
Electron density and the threshold in Bend

• Injection

\[ \rho_{e,\text{th}} = 2 \times 10^{12} \text{ m}^{-3} \]

\( \rho_e \): electron density just interacting with beam

• Top energy

\[ \rho_{e,\text{th}} = 2 \times 10^{12} \text{ m}^{-3} \] is determined by simulation in previous slide
Electron density and the threshold in Drift space

\[ \rho_{e, \text{th}} = 3 \times 10^{11} \text{ m}^{-3} \]

\[ \rho_{e, \text{th}} = 1 \times 10^{12} \text{ m}^{-3} \]
SPS

- $E = 26$ GeV, $\varepsilon = 1.01 \times 10^{-7}$, $\beta_x = 33.85$ m, $\beta_y = 71.87$ m
- $\sigma_z = 0.229$ m, $\sigma_E = 0.19\%$, $\alpha = 1.92 \times 10^{-3}$, $\nu_s = 0.00564$

- $\omega_e / 2\pi = 355$ MHz, $\omega_e \sigma_z / c = 1.7$
- $\rho_{e,\text{th}} = 1.4 \times 10^{11}$ m$^{-3}$. (use the formula)

$$\rho_{\text{th}} = \frac{2 \gamma \sqrt{\varepsilon} \omega_e q_e / c}{\sqrt{3} K Q r_c \beta_y L}$$
Electron cloud instability in drift

- **Note** $\sigma_x < \sigma_y$

- Instability signal is clear near the threshold.

- Incoherent (artifact) effect is strong in high density. $\rho_{th} = 1 \sim 2 \times 10^{11} \text{ m}^{-3}$. 
J-PARC and neutron sources

- J-PARC
- LINAC 181 MeV -> 400 MeV
- Rappid Cycle Synchrotron (RCS)
  400(181) MeV -> 3 GeV  25 Hz  1 MW
- Main Ring (MR)
- 3 GeV -> 30 GeV  0.3-0.2 Hz  0.75 MW
## Old work

K. Ohmi et al., PRST(2002)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>3 GeV</th>
<th>50 GeV</th>
<th>PSR</th>
<th>ISIS</th>
<th>SNS</th>
<th>AGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>$L$ (m)</td>
<td>348.3</td>
<td>1567.5</td>
<td>90</td>
<td>163</td>
<td>248</td>
<td>800</td>
</tr>
<tr>
<td>Relativistic factor</td>
<td>$\gamma$</td>
<td>1.4</td>
<td>4.2</td>
<td>4.2</td>
<td>54</td>
<td>1.85</td>
<td>1.07</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$N_p(\times10^{13})$</td>
<td>4.15</td>
<td>4.15</td>
<td>4.15</td>
<td>4.15</td>
<td>3</td>
<td>1.25</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>$n_b$</td>
<td>2</td>
<td>8</td>
<td>8</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>$H$</td>
<td>2</td>
<td>9</td>
<td>9</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>rms beam sizes</td>
<td>$\sigma_r$ (cm)</td>
<td>1.9</td>
<td>1.2</td>
<td>1.1</td>
<td>0.5</td>
<td>1.0</td>
<td>3.8</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\ell_p$ (m)</td>
<td>110</td>
<td>82</td>
<td>82</td>
<td>16</td>
<td>65</td>
<td>60</td>
</tr>
<tr>
<td>rms energy spread</td>
<td>$\sigma_{SE/E}$ (%)</td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
<td>0.25</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Slippage factor</td>
<td>$\eta$</td>
<td>-0.48</td>
<td>-0.047</td>
<td>-0.058</td>
<td>-0.0013</td>
<td>-0.187</td>
<td>-0.83</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>$\nu_s$</td>
<td>0.0058</td>
<td>0.0005</td>
<td>0.0026</td>
<td>0.0001</td>
<td>0.0003</td>
<td>0.0036</td>
</tr>
<tr>
<td>Beam pipe radius</td>
<td>$R$ (cm)</td>
<td>12.5</td>
<td>12.5</td>
<td>6.5</td>
<td>6.5</td>
<td>5</td>
<td>8</td>
</tr>
</tbody>
</table>
Trailing edge Multipacting

$A_e = \frac{N_e}{N_{e,0}}$: Amplification of electron

**FIG. 2.** Electron amplification factor. The proton beam profiles are plotted by the dashed lines in the pictures with arbitrary units. Electrons are produced at the chamber surface. (a) 3 GeV injection; (b) 3 GeV extraction; (c) 50 GeV injection; (d) 50 GeV extraction; (e) PSR; (f) ISIS; (g) SNS; (h) AGS.
Summary for simulation results

- **Neutralization factor**

  K. Ohmi et al., PRST(2002)

  TABLE II. Electron cloud buildup of the proton rings.

<table>
<thead>
<tr>
<th>Variable</th>
<th>J-PARC</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 GeV</td>
<td>50 GeV</td>
<td>PSR</td>
<td>ISIS</td>
<td>SNS</td>
<td>AGS</td>
<td></td>
</tr>
<tr>
<td>$A_e$ (bottom)</td>
<td>42.0</td>
<td>18.0</td>
<td>9.4</td>
<td>0.13</td>
<td>118</td>
<td>12.9</td>
<td>7.8</td>
</tr>
<tr>
<td>$A_e$ (peak)</td>
<td>87.6</td>
<td>62</td>
<td>136</td>
<td>6.9</td>
<td>236</td>
<td>17.5</td>
<td>286</td>
</tr>
<tr>
<td>$f$ (bottom)</td>
<td>0.020</td>
<td>0.067</td>
<td>0.0035</td>
<td>0.0001</td>
<td>0.034</td>
<td>0.003</td>
<td>0.007</td>
</tr>
<tr>
<td>$f$ (peak)</td>
<td>0.042</td>
<td>0.023</td>
<td>0.05</td>
<td>0.0005</td>
<td>0.067</td>
<td>0.005</td>
<td>0.25</td>
</tr>
</tbody>
</table>

- **Stability,**

  TABLE III. Wake field and stability for electron cloud instability.

<table>
<thead>
<tr>
<th>Variable</th>
<th>J-PARC</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 GeV</td>
<td>50 GeV</td>
<td>PSR</td>
<td>ISIS</td>
<td>SNS</td>
<td>AGS</td>
<td></td>
</tr>
<tr>
<td>$Z(\omega_e)_{1,L}/Q$ (MΩ/m)</td>
<td>0.29</td>
<td>0.24</td>
<td>0.68</td>
<td>0.019</td>
<td>0.46</td>
<td>0.0051</td>
<td>0.03</td>
</tr>
<tr>
<td>$Z(\omega_e)_{1,H}/Q$ (MΩ/m)</td>
<td>0.61</td>
<td>0.83</td>
<td>9.7</td>
<td>0.96</td>
<td>0.90</td>
<td>0.0085</td>
<td>1.23</td>
</tr>
<tr>
<td>$\omega_e \epsilon_p/c$</td>
<td>133</td>
<td>182</td>
<td>199</td>
<td>276</td>
<td>166</td>
<td>27</td>
<td>272</td>
</tr>
<tr>
<td>$U_L$</td>
<td>0.07</td>
<td>0.23</td>
<td>0.11</td>
<td>0.02</td>
<td>1.6</td>
<td>0.007</td>
<td>0.10</td>
</tr>
<tr>
<td>$U_H$</td>
<td>0.15</td>
<td>0.78</td>
<td>1.6</td>
<td>1.2</td>
<td>3.2</td>
<td>0.012</td>
<td>4.0</td>
</tr>
</tbody>
</table>

SNS is serious only tail part shown in previous slide.
## Latest works (2006)

**Estimation of electron yield (Toyama et.al.)**

<table>
<thead>
<tr>
<th></th>
<th>Proton loss</th>
<th>electron yield</th>
<th>$Y_1$ (/m.p)</th>
<th>Cure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RCS</strong> Charge exchange carbon foil (140 W)</td>
<td>-</td>
<td>1.7 x 10^{14}/500 µs</td>
<td>1.1 x 10^{-5}</td>
<td>electron catcher</td>
</tr>
<tr>
<td><strong>Second stripping foils</strong>&lt;br&gt;H^0&lt;br&gt;H^-&lt;br&gt; &lt; 400 W</td>
<td>-</td>
<td>5 x 10^{11}/500 µs</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Halo collimator</strong>&lt;br&gt;181 MeV&lt;br&gt;400 MeV</td>
<td>&lt; 5.5 x 10^{12}&lt;br&gt; &lt; 2.5 x 10^{12}</td>
<td>5.5 x 10^{14}/500 µs&lt;br&gt;2.5 x 10^{14}/500 µs</td>
<td>8.2 x 10^{-5}&lt;br&gt;2.8 x 10^{-5}</td>
<td>solenoid solenoid</td>
</tr>
<tr>
<td><strong>Uncontrolled loss</strong>&lt;br&gt;181 MeV&lt;br&gt;400 MeV</td>
<td>&lt; 1.1 x 10^{11}&lt;br&gt; &lt; 5 x 10^{10}</td>
<td>1.1 x 10^{13}&lt;br&gt;5 x 10^{12}</td>
<td>1.6 x 10^{-6}&lt;br&gt;5.6 x 10^{-7}</td>
<td>-</td>
</tr>
<tr>
<td><strong>MR</strong> Hallo collimator&lt;br&gt;(450 W)</td>
<td>&lt; 6.6 x 10^{11} x 5</td>
<td>6.6 x 10^{13} x 5</td>
<td>-</td>
<td>solenoid</td>
</tr>
<tr>
<td><strong>Uncontrolled loss for fast extraction</strong>&lt;br&gt;(1.37 kW)</td>
<td>1.65 x 10^{13}/0.6 s</td>
<td>1.65 x 10^{15}/0.6 s</td>
<td>2.8 x 10^{-8}</td>
<td>-</td>
</tr>
<tr>
<td><strong>Uncontrolled loss for slow extraction</strong>&lt;br&gt;(7.5 kW)</td>
<td>5.2 x 10^{12}/s</td>
<td>5.2 x 10^{14}/s</td>
<td>5.4 x 10^{-9}</td>
<td>-</td>
</tr>
</tbody>
</table>

$Y_1$: Normalized electron yield, electron created by a proton per meter.
These neutralization levels are less than the threshold given by analytic theory.
Tracking simulation for long proton beam

- Solve both equations of beam and electrons simultaneously and self consistently.
- Electrons are produced and tracked with the exact initial condition.

\[
\frac{d^2x_{p,a}}{ds^2} + K(s)x_{p,a} = \frac{2r_p}{\gamma} \sum_{j=1}^{N_i} F_G(x_{p,a} - x_{e,j}; \sigma(s))\delta(s - s_j)
\]

\[
\frac{d^2x_{e,j}}{dt^2} = 2N_p r_e c^2 F_G(x_{e,j} - x_{p,a}; \sigma(s))\delta(t - t(s_{e,j}))
\]

Electron cloud

Landau damping is not taken into account, since no slippage.
Stability for the instability

- Landau damping is well-known phenomenon.
- The stability is estimated by considering Landau damping.
- Criteria, $U > 1$ unstable  $U < 1$ stable

$$ U = \frac{\sqrt{3} T_0 / \tau_G}{v_s \omega_e \sigma_z / c} = 1 $$

$T_0 / \tau_G$ : Growth rate

$$ \frac{v_s \omega_e \sigma_z / c}{\sqrt{3}} : $Landau damping rate$

- Analytic formula for resonator model

$$ \frac{T_0}{\tau_G} = \frac{\lambda_p r_0 \beta}{\gamma} \left| Z_\perp (\omega_e) \right| $$

$$ \frac{Z(\omega_e)}{Z_0} = \frac{1}{4\pi} \frac{\lambda_e L}{\sigma_y} \frac{Q}{\sigma_x + \sigma_y} $$
Landau damping in a simulation

- Landau damping due to energy spread (slippage).
- Landau damping works very well as is expected!

Green $\nu_s = 0.0002 (U = 1.07)$
Red $\nu_s = 0$ or $0.0001 (U = 2.14)$
Results of the tracking simulation (RCS)

3GeV RCS inj.  Extraction
(kicker section is dominant)

Comparison of the growth with the Landau damping rate gives information whether stable or not.

These growths do not arise due to Landau damping.
Results of the tracking simulation (MR)

- Length of Ferrite section is $\sim 20$ m, 1.3 % of the circumference.
- Neutralization factor at $\delta_{2\text{max}}=4-5$ is 100 times that at $\delta_{2\text{max}}=2.1$.
- Contributions to instability of high and low multipactoring sections are similar.
- The density (neutralization factor) is less than the threshold given by analytic formula.

Injection

Simulation shows slower growth than Landau damping. Instability does not arise.

extraction
J-PARC operation start from 2008

AN EXPECTED BEAM POWER CURVES FOR RCS AND MR FAST BEAM EXTRACTION

$P_{MR} (8\text{-bunch}\@30\text{GeV}) = 1.6 \times \frac{P_{RCS}}{MRCYCLE}$

( ): Beam transfer ratio from RSC to MR

- RCS POWER FOR MR
- Linac energy upgrade
- MR POWER AT 30GeV
- (maximum cycle with existing power supply)
Instability observed in J-PARC MR
T. Toyama, ATAC2011

- Transverse instabilities
  - Physics runs are operated with
    \( \xi_x, \xi_y \sim -7 - -5, \)
    BxB feedback ON,
    \( N_B \sim 8 \times 10^{13} \) ppp / 8 bunches, \( P \sim 120 \) kW.
    \( \rightarrow \) No fatal instability
  - studied:
    \( \xi_x, \xi_y \sim -3, -1.5, -0.75, 0, 0.75, 1.5, 3 \)
    \( \xi_x \sim -6, \xi_y \sim +6 \)
    Instability is observed.
### Parameters of proton rings

<table>
<thead>
<tr>
<th></th>
<th>RCS-inj1</th>
<th>RCS-inj2</th>
<th>RCS-ext</th>
<th>MR-inj</th>
<th>MR-ext</th>
<th>MR-inj 2011Feb</th>
<th>MR-ext</th>
<th>SNS</th>
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</thead>
<tbody>
<tr>
<td>L (m)</td>
<td>348</td>
<td>348</td>
<td>348</td>
<td>1567</td>
<td>1567</td>
<td>1567</td>
<td>1567</td>
<td>248</td>
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<tr>
<td>γ</td>
<td>1.19</td>
<td>1.4</td>
<td>4</td>
<td>4</td>
<td>50.9</td>
<td>4</td>
<td>30.9</td>
<td>2.02</td>
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<tr>
<td>N_p(10^{13})</td>
<td>2.5</td>
<td>4.15</td>
<td>4.15</td>
<td>4.15/2.5</td>
<td>4.15/2.5</td>
<td>1</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>n_{bunch}</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>8/17</td>
<td>8/17</td>
<td>8</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>9/18</td>
<td>9/18</td>
<td>9</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>σ_r(cm)</td>
<td>1.9</td>
<td>1.9</td>
<td>1.2</td>
<td>1.1</td>
<td>0.35</td>
<td>1.4</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>l_p(m)</td>
<td>110</td>
<td>110</td>
<td>82</td>
<td>82/40</td>
<td>16/8</td>
<td>30</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>η</td>
<td>-0.48</td>
<td>-0.48</td>
<td>-0.047</td>
<td>-0.058</td>
<td>-0.0013</td>
<td>-0.058</td>
<td>-0.002</td>
<td>-0.204</td>
</tr>
<tr>
<td>ν_s</td>
<td>0.0058</td>
<td>0.0058</td>
<td>0.0005</td>
<td>0.0026</td>
<td>0.00007</td>
<td>0.0026</td>
<td>0.0001</td>
<td>0.0004</td>
</tr>
<tr>
<td>ω_e/2π (MHz)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ω_e l_p/c</td>
<td>133</td>
<td>182</td>
<td>199/99</td>
<td>276/138</td>
<td>50.4</td>
<td>153</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ν_s ω_p/3^{1/2}c</td>
<td>0.45</td>
<td>0.45</td>
<td>0.053</td>
<td>0.30</td>
<td>0.011</td>
<td>0.065</td>
<td>0.035</td>
<td></td>
</tr>
<tr>
<td>F_{th} (%)</td>
<td>28.0</td>
<td>28.0</td>
<td>3.0</td>
<td>3.1</td>
<td>0.04</td>
<td>2.7</td>
<td>6.5</td>
<td></td>
</tr>
</tbody>
</table>

ω: electron freq. in beam, ν_s ω_p/3^{1/2}c: Landau damping rate/turn, f_{th}: threshold electron neutralization factor given by analytic formula.
Δ-signal turn-by-turn plot, after injected

Sextupole ~ -4.5 (-15%)
$N_B = 115 \text{ kW}$
1st bunch

100 - 110 turns
300 - 310 turns
500 - 510 turns

200 - 210 turns
400 - 410 turns
600 - 610 turns
Summary for J-PARC

- If beam loss (electron yield) is well controlled, electron cloud instability should be weak in simulations. (chicken or egg)

- Horizontal instability has been observed in J-PARC MR. Frequency ~60MHz or lower.

- Electron frequency is ~80MHz, somewhat different.

- Single bunch effect, independent of total current.

- This instability seems to limit the intensity.

- Beam studies just start now.
# Fermilab Main Injector

Table 1-1: Main Injector Parameter List

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>3319.419 m</td>
</tr>
<tr>
<td>Injection Momentum</td>
<td>8.9 GeV/c</td>
</tr>
<tr>
<td>Peak Momentum</td>
<td>150 GeV/c</td>
</tr>
<tr>
<td>Minimum Cycle Time (@120 GeV)</td>
<td>&lt; 1.5 s</td>
</tr>
<tr>
<td>Minimum Cycle Time (@150 GeV)</td>
<td>2.4 s</td>
</tr>
<tr>
<td>Number of Protons</td>
<td>$3 \times 10^{13}$</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>498</td>
</tr>
<tr>
<td>Protons/Bunch</td>
<td>$6 \times 10^{10}$</td>
</tr>
<tr>
<td>Max. Courant-Snyder Amplitude Function ($\beta_{\text{max}}$)</td>
<td>57 m</td>
</tr>
<tr>
<td>Maximum Dispersion Function</td>
<td>1.9 m</td>
</tr>
<tr>
<td>Phase Advance per Cell</td>
<td>90 degrees</td>
</tr>
<tr>
<td>Nominal Horizontal Tune</td>
<td>26.425</td>
</tr>
<tr>
<td>Nominal Vertical Tune</td>
<td>25.415</td>
</tr>
<tr>
<td>Natural Chromaticity (H)</td>
<td>-33.6</td>
</tr>
<tr>
<td>Natural Chromaticity (V)</td>
<td>-33.9</td>
</tr>
<tr>
<td>Transverse Admittance (@ 8.9 GeV)</td>
<td>$&gt;40,\text{p mm-mr}$</td>
</tr>
<tr>
<td>Longitudinal Admittance</td>
<td>$&gt;0.5 ,\text{eVs}$</td>
</tr>
<tr>
<td>Transverse Emittance (Normalized)</td>
<td>12p mm-mr</td>
</tr>
<tr>
<td>Longitudinal Emittance</td>
<td>0.2 eVs</td>
</tr>
<tr>
<td>Harmonic Number (@53 MHz)</td>
<td>588</td>
</tr>
<tr>
<td>RF Frequency (Injection)</td>
<td>52.8 MHz</td>
</tr>
<tr>
<td>RF Frequency (Extraction)</td>
<td>53.1 MHz</td>
</tr>
<tr>
<td>RF Voltage</td>
<td>4 MV</td>
</tr>
<tr>
<td>Transition Gamma</td>
<td>21.8</td>
</tr>
</tbody>
</table>

Thanks R. Zwaska
Threshold density for single bunch instability in Main Injector

- $\omega_e/2\pi=73$ MHz, $\omega_e\sigma_z/c=4.6$
- $\rho_{e,th}=2.2\times10^{11}$ m$^{-3}$.(use the formula)
- $\lambda_{e,th}=10^8$ m$^{-1}$, $f_{th}=0.005$, if all electrons are located near the beam.
- Landau damping rate, $\nu_s\omega_e\sigma_z/3^{1/2}c=0.012$
- The growth slower than $0.012^{-1}=80$ turn is stabilized.
Neutralization factor

- An example. $Y_{1,e} = 4 \times 10^{-4} / \text{p.m}$, 4 order higher than ionization. The neutralization factor $f$ linearly depends on the initial yield.
Growth of the transverse amplitude

$\varepsilon^{1/2} = 10^{-3}$

$Y_{1,e} = 4 \times 10^{-4} / \text{p.m}$

$Y_{1,e} = 4 \times 10^{-6} / \text{p.m}$
Bunch transverse motion

$\sigma_{x,y} \sim 3\text{mm}$
Higher secondary efficiency

\[ \varepsilon^{1/2} = 10^{-3} \]

\[ \delta_2 = 2.6-2.7 \text{ is critical value.} \]
Summary for proton rings

- Electron source is secondary emission, while it was photo-emission in present positron rings.
- The cloud build-up is very sensitive for secondary rate, bunch profile initial yield and ....
- Electron cloud instability for proton rings has not well understood yet in my impression.
- Ecloud effects should be understood toward high intensity in J-PARC and Fermi MI.
Thank you for your attention
Simulated beam spectra

- Lower sideband is seen for high $\omega_e \sigma_z/c$, 2GeV.
- Upper sideband is seen for low $\omega_e \sigma_z/c$, 5 GeV.
Incoherent effect in CesrTA

• Emittance growth due to nonlinear interaction with electron cloud

- Nonlinearity of beam-cloud interaction
- Integrated the nonlinear terms with multiplying $\beta$ function and $\cos (\sin)$ of phase difference

$$M = e^{-F_1}; e^{-F_2}; e^{-F_3}; e^{-F_4}; e^{-F_5}; e^{-F_6}; ... e^{-F_m};$$

$$\approx e^{-F_1}; \exp \left( - \sum_{i=1}^{n} \phi_i (e^{-F_i}; x) \right);$$

F: (non)linear lattice transformation
$\phi$: cloud interaction

$$k \chi^n \Rightarrow k \beta_i^{m/2} J^{m/2} \cos(m \Delta \psi_{11})$$
Slow growth lower than the threshold

2GeV

$\rho_{th} = 1.2 \times 10^{12}$

Slower than radiation damping time

5GeV

$\rho_{th} = 5 \times 10^{12}$
High frequency Feedback

- Feedback slice by slice, nonuniform 40 slices.

The feedback with <10GHz should give the same result, since high frequency component is not contained.