Simulation of instability at transition energy with a new impedance model for CERN PS

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Outline

• Overview of the vertical instability in PS at transition energy

• Instability measurements with TOF beam

• Macroparticle simulations with PyHEADTAIL
Overview of the vertical instability in PS at transition energy

• In the PS, the beam has to cross the transition energy:
  • The synchrotron motion of the particles are frozen
  • The beam is particularly sensitive to perturbations, such as wakefield

• With increasing the beam intensity, a fast vertical instability was observed near transition energy.

• Many studies have been done with TOF beam.

References:

Overview of the vertical instability in PS at transition energy

- Instability observation with LHC-INDIV beam.
  - Beam intensity: 50E10
  - Longitudinal emittance: 0.264eVs
  - Fast vertical instability and beam losses are observed near transition energy

Guido Sterbini
How this instability will affect the LIU-PS beam

• Beam characteristic (https://espace.cern.ch/liu-project/Shared%20Documents/Beam_Characteristics_v2.pdf)

<table>
<thead>
<tr>
<th>PSB extraction</th>
<th>PS extraction</th>
<th>SPS extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>p/ring [\times 10^{11}]</td>
<td>(\varepsilon_{h/v}) [(\mu\text{m})]</td>
<td>nb bunches</td>
</tr>
<tr>
<td>32</td>
<td>1.8</td>
<td>4 + 2</td>
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</tbody>
</table>

• Motivation of this study
  • Reproduce the instability with TOF beam
  • Benchmark the measurements with simulations based on the new PS impedance model
  • Try to identify whether this instability would be a limitation for the LIU-PS beam
Instability measurements with TOF beam

- Measurement setting up
  - Single bunch beam
  - Without gamma transition jump
  - Zero chromaticity plateau are programmed in the vertical plane

- Bunch oscillations are measured by the WCM
- Development of the instability

- FFT on each trace of the $\Delta y$ signal $\rightarrow$ frequency spectrum (instability centered at 600-700MHz)

- The particles close to the peak density become unstable near transition.
- The amplitude of the particle increases rapidly until the beam is lost.
- At intensity of $1.4E12$ and emittance of $2.25eVs$, the instability growth time of 0.1ms.
• Dependence on beam intensity and longitudinal emittance

By scanning the emittance from 1.9 to 2.9eVs
  • For a certain emittance, the growth rate increases linearly with beam intensity
  • Threshold intensity increases from 90E10 to 170E10
  • The slope of the growth rate vs. intensity decreases from 0.4 to 0.2 [kHz/E10]

Faster instability
Macroparticle simulations with PyHEADTAIL

• Transverse impedance and wake

\[ W_{x,y}(x, y, x_0, y_0, z)[V/C] = -\frac{1}{q_0 q} \int_0^L F_{x,y}(x, y, s, x_0, y_0, z) ds \]

\[ Z_{x,y}(\omega)[\Omega/m] = j \int_{-\infty}^{\infty} W_{x,y}(z) e^{-j \omega z / v} dz / v \]

• The transverse impedance and wake function can be expanded into a power series in the offsets of source and test particle.

\[ W_x = W_x^{\text{dip}} x_0 + W_x^{\text{quad}} x \]
\[ Z_x = Z_x^{\text{dip}} x_0 + Z_x^{\text{quad}} x \]
\[ W_y = W_y^{\text{dip}} y_0 + W_y^{\text{quad}} y \]
\[ Z_y = Z_y^{\text{dip}} y_0 + Z_y^{\text{quad}} y \]

• Wake act back to the beam as transverse kick

\[ \Delta x' \propto W_x(z) = W_x^{\text{dip}}(z)x_0 + W_x^{\text{quad}}(z)x \]
\[ \Delta y' \propto W_y(z) = W_y^{\text{dip}}(z)y_0 + W_y^{\text{quad}}(z)y \]
• Both dipolar and quadrupolar impedance below 2GHz are dominated by the kickers.
• As a first estimate, we consider only the kicker impedance in the simulation.
Introduction to PyHEADTAIL

- PyHEADTAIL is a macroparticle tracking code designed to simulate collective effects in circular accelerators.

\[ M = \left( \begin{array}{cc} \sqrt{\beta_1} & 0 \\ \frac{a_1}{\sqrt{\beta_1}} & \frac{1}{\sqrt{\beta_1}} \end{array} \right) \left( \begin{array}{cc} \cos \mu & \sin \mu \\ -\sin \mu & \cos \mu \end{array} \right) \left( \begin{array}{cc} \frac{1}{\sqrt{\beta_0}} & 0 \\ \frac{a_0}{\sqrt{\beta_0}} & \frac{1}{\sqrt{\beta_0}} \end{array} \right) \]

Linear transfer map

\[ \Delta y_i' \propto -\frac{N e^2}{m \gamma \beta^2 c^2} \sum_{j=0}^{n_{slices}} (\Delta z_j \rho(z_j)) W(z_i - z_j) \]

Wakefield

Wake kick

Bunch slices
Main parameters used in the simulation

- Single bunch: 3D Gaussian distribution (longitudinal cut to $3\sigma$)
- Tracking energy range: $\gamma=4$~7
- With zero chromaticity
- Without transition gamma jump
- Constant momentum step per turn ($\mathbf{Bdot}=20\text{Gs/ms}$)
- Without aperture restriction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Circumference [m]</td>
<td>628.3</td>
</tr>
<tr>
<td>$N_b$ [1E12]</td>
<td>1.4</td>
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<tr>
<td>$n_b$</td>
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<tr>
<td>$\varepsilon_{z,rms}[\text{eV}\cdot\text{s}]$</td>
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<td>$Q_x/Q_y$</td>
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<td>$Q_{px}/Q_{py}$</td>
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<tr>
<td>$h$</td>
<td>8</td>
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<tr>
<td>$V$ [kV]</td>
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<tr>
<td>$\alpha_p$</td>
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<td>$N_{\text{macroparticle}}$</td>
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<tr>
<td>$N_{\text{slice}}$</td>
<td>4096</td>
</tr>
</tbody>
</table>
Simulation results

- The instability cantered at frequency of 600MHz ~ 700MHz.
- At intensity of $1.4 \times 10^{12}$ and emittance of $2.25 \text{eVs}$, the instability growth time of 0.05ms.
Comparison between simulation and measurement - I

- Np=1.4E12, \( \varepsilon_L=2.25\text{eVs} \)
- Measurement
  - fr: 600~700MHz
  - growth time 0.1ms
- Simulation
  - fr: 600~700MHz
  - growth time 0.05ms
Comparison between simulation and measurement - II

- **Np=0.95E12, \( \varepsilon L = 1.94\text{eVs} \)**

- **Measurement**
  - \( f_r \): 600~700MHz
  - growth time 0.2ms~0.3ms

- **Simulation**
  - \( f_r \): 600~700MHz
  - growth time 0.07ms
Comparison between simulation and measurement - III

• Np=1.25E12, εL=2.34eVs

• Measurement
  • fr: 600~700MHz
  • growth time 0.3ms-0.7ms

• Simulation
  • fr: 600~700MHz
  • growth time 0.06ms
Intensity Scan (Preliminary results)

- $\epsilon_L = 2.34\text{eVs}$
- $\epsilon_L = 1.94\text{eVs}$

- Higher growth rate in simulation
  - Less stabilizing factors (space charge, chromaticity, nonlinear optics)
  - Gaussian distribution beam

- A factor of 2 or 3 lower slope in simulation
  - Smaller effective impedance (only kicker impedance considered)
Contribution from a single kicker

• Try to identify how much we can benefit by removing one or several kickers
• Impedance contribution: PE.KFA71>PI.KFA45>PE.KFA79=PE.KFA21=PE.KFA13
• Two cases that is possible to happen
  • Case1: remove BFA09S, BFA21P, BFA21S
  • Case2: remove KFA04, KFA13, KFA21

The instability growth rate decreased by ~10% for case1 and ~20% for case2.

Further studies are needed to include total impedance model and more realistic beam distribution.

<table>
<thead>
<tr>
<th></th>
<th>With all kickers</th>
<th>Case1</th>
<th>Case2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_p = 1.4 \times 10^{12}, \varepsilon_L = 2.25 \text{eVs} )</td>
<td>0.052ms</td>
<td>0.057ms</td>
<td>0.067ms</td>
</tr>
<tr>
<td>( N_p = 0.95 \times 10^{12}, \varepsilon_L = 1.94 \text{eVs} )</td>
<td>0.070ms</td>
<td>0.077ms</td>
<td>0.093ms</td>
</tr>
<tr>
<td>( N_p = 1.25 \times 10^{12}, \varepsilon_L = 2.34 \text{eVs} )</td>
<td>0.055ms</td>
<td>0.065ms</td>
<td>0.072ms</td>
</tr>
</tbody>
</table>
Summary

• The fast vertical instability at 700MHz near transition is reproduced by measurement with TOF beam. The instability growth rate and threshold intensity are measured for different longitudinal emittance.

• Simulation studies based on the new PS impedance model shows considerably good agreement with the measurements. Kickers are proved to be the dominate contribution to the instability.

• Simulations show that we can benefit 10% of growth rate by removing BFA kickers (BFA09S, BFA21P, BFA21S) and about 20% by removing KFA04, KFA13 and KFA21.

• Further studies are needed to include total impedance model, more realistic beam distribution and gamma transition jump.
Thank you for your attention!