Electron Cloud Studies at the SPS
Beam Stability Issues

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• LHC beam in the SPS
• Electron cloud effects on the beam
• Electron Cloud Instability in the SPS
• Cures for the Electron Cloud Instability
• Summary and Outlook
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum [GeV/c]</td>
<td>26</td>
<td>450</td>
</tr>
<tr>
<td>Revolution period [μs]</td>
<td>23.07</td>
<td>23.05</td>
</tr>
<tr>
<td>Tunes (H/V)</td>
<td>26.18/26.13</td>
<td></td>
</tr>
<tr>
<td>Gamma transition</td>
<td>22.8</td>
<td></td>
</tr>
<tr>
<td>Max. n. of batches</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>n. bunches/batch</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>Nominal $N_{\text{bunch}}$ [$10^{11}$ p]</td>
<td>1.15</td>
<td></td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>24.97/74.91</td>
<td>24.95/74.85</td>
</tr>
<tr>
<td>Full bunch length [ns]</td>
<td>4</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Batch spacing [ns]</td>
<td>224.7</td>
<td>224.6</td>
</tr>
<tr>
<td>r.m.s. $\epsilon^*_H, V$ [μm]</td>
<td>&lt;3</td>
<td>&lt;3.5</td>
</tr>
<tr>
<td>$\epsilon_L$ [eV s]</td>
<td>0.35</td>
<td>&lt;0.8</td>
</tr>
</tbody>
</table>
E-cloud effects on the beam

H & V emittance blow-up mainly in the tail of the batch (few ms after inj.)

Beam losses mainly affecting the tail of the batch (few ms after inj.)
About 70% of the SPS circumference filled with bends and threshold for electron multipacing $N_{th}$ is lower in dipole field regions than in field-free sections (after scrubbing $N_{th} \sim 0.8 \times 10^{11}$ p in the arcs, $N_{th} \geq 1.1 \times 10^{11}$ p in the straight sections) ➔ the behaviour of the electron cloud in the arcs determines the characteristics of the ECI.

$N_{th}=0.2 \times 10^{11}$ p $< N_{bunch} < 0.5 \times 10^{11}$ p

$N_{th}<0.5 \times 10^{11}$ p $< N_{bunch} < 1.1 \times 10^{11}$ p

Above $1.1 \times 10^{11}$ a third central stripe appears
Horizontal ECI in the SPS

\( N_{\text{bunch}} = 0.3 \times 10^{11} \text{ p} > N_{\text{th}} = 0.2 \times 10^{11} \text{ p} \) – Linear machine - TFB OFF

Bunch-by-bunch centroid position meas.

• One central electron stripe
• Coupled bunch instability (low order modes)
• \( \tau_{\text{ECI-H}} \sim 40 \) turns
• Second mode (+0.025) appearing in the tail of the batch (> bunch #50)

Detuning with amplitude of oscillation
Horizontal ECI in the SPS

$N_{\text{bunch}} = 1.1 \times 10^{11} \text{ p} > N_{\text{th}} = 0.8 \times 10^{11} \text{ p}$ - Linear machine - TFB OFF

- Three electron stripes
- $\tau_{\text{ECI-H}} \sim 40$ turns
- CB instability mainly affecting bunch $> 15$
- Positive detuning for low amplitudes and negative detuning for higher amplitudes
- Non-linear forces coupling bunches

**Energy dependence**

<table>
<thead>
<tr>
<th>Momentum [GeV/c]</th>
<th>$\tau_{\text{ECI-H}}$ [turns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>40</td>
</tr>
<tr>
<td>55</td>
<td>200</td>
</tr>
<tr>
<td>450</td>
<td>1500</td>
</tr>
</tbody>
</table>

Injection

Bunch #25
Linear coupling force \( F \):
\[
F = -\frac{e \rho_{ec}}{\varepsilon_0} \left( x_{j+1} - x_j \right) \chi(j - n)
\]

F depends on \( N_{\text{bunch}} \) via \( \rho_{ec} \) ➔ mild dependence on \( N_{\text{bunch}} \) above threshold. Only the number of bunches affected increases with \( N_{\text{bunch}} \).

For \( N_{\text{bunch}} < 5 - 6 \times 10^{10} \) p e-cloud ➔ vertical ribbon of uniform density starting from a given bunch n.

B-field freezes H-motion of the electrons ➔ no distortion of the e-cloud distribution ➔ e-cloud can couple only subsequent bunches.

For \( N_{\text{bunch}} > 5 - 6 \times 10^{10} \) p > \( N_{\text{th}} \) the above approx. is no more valid ➔ non-uniform density ➔ non linear behaviour of the coupling force.
Vertical ECI in the SPS

Single bunch instability (~700 MHz) affecting only the trailing bunches (after bunch 15)

V electron motion is not frozen by the dipole field \(\Rightarrow\) electron cloud is pinched during the bunch passage and couples the head and the tail of the bunches.

<table>
<thead>
<tr>
<th>(N_{\text{bunch}} [10^{11} \text{ p}])</th>
<th>(\tau_{\text{ECI-V}} [\text{turns}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>500</td>
</tr>
<tr>
<td>0.5</td>
<td>100</td>
</tr>
<tr>
<td>1.1</td>
<td>40</td>
</tr>
</tbody>
</table>
Cures for ECI

Horizontal instability
Can be cured by the Transverse Feedback:
• enough gain and bandwidth up to nominal intensity
• essential for scrubbing

New working point below the half integer:
• Reduced resistive wall growth rate
• Wider resonance-free space in tune diagram

Vertical Instability
• Cannot be cured by the TFB
• Chromaticity ($\xi_v > 0.4$) used to control ECI
• Limited blow-up (~30%) in 40 s at SPS injection energy during last scrubbing run.
With these cures LHC beam with nominal intensity and longitudinal emittance and with transverse emittances close to nominal ($\varepsilon_H^* < \varepsilon_{\text{nominal}}^*$ and $\varepsilon_V^* \approx 1.2 \varepsilon_{\text{nominal}}^*$) has been accelerated up to the SPS extraction energy in 2003.

Drawbacks of high $\xi_V$:
- **Limited lifetime** ($\sim 20$ min) at 26 GeV/c for large $\Delta p/p$ ($>2 \times 10^{-3}$): $\xi_V$ + diffusion process in the longitudinal plane; very likely RF noise.

Other solutions being investigated:
- **Coupling** as a tool to stabilize the vertical ECI (with working point close to the coupling resonance). Preliminary results are encouraging → Reduction of the chromaticity.
- **Measurement and correction of second order chromaticity** to minimize detuning with $\Delta p/p$
ECI properties determined by the behaviour of the e-cloud in the dipoles ➔ expect the same in the LHC at low energy.

**Horizontal ECI**
Cure: Transverse Feedback ➔ Crucial for the scrubbing in the SPS and LHC.

**Vertical ECI**
Cure: high $\xi_V$
Need to study energy dependence and long term emittance blow-up with coasts at 26 GeV/c and 270 GeV/c (input for LHC scrubbing scenario) ➔ started in 2003 ➔ part of the MD planning 2004.
Investigation of possible other solutions (e.g. coupling) being pursued.