Measurements of Longitudinal Coupled bunch growth rates in the CERN PS Booster

Active damping, growth rates, BTF and Landau damping.

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Outline

Main RF parameters of the PS Booster
Modes and line spectrum
Active frequency domain mode by mode feedback system
Tracking mode analyser and mode excitation
Growth rates vs. energy and frequency
BTF and stability diagram
Growth rates vs. intensity.
Summary and conclusion
Main RF parameters of the CERN PS Booster

High intensity four ring proton synchrotron
Harmonic number $h = 5$, Energy $T = 50$ MeV - 1 GeV
Revolution frequency $f_0 = 0.6$ to $1.66$ MHz ($\beta = 0.3 - 0.83$)
RF frequency $f_{RF} = 3.0$ to $8.3$ MHz
Design intensity $N = 2.5 \times 10^{12}$ protons per ring
Achieved intensity $N = 10^{13}$ protons per ring
Space charge (negative inductance) is dominating longitudinal impedance
Long bunches: $\sim 180$ to $270$ RF degrees!
Modes and Line Spectrum

Within-bunch modes \( m = 1 \) to 4, coupled-bunch mode pattern \( n = 4 \). a) Mountain range display of one synchrotron period; b) Superimposed; c) Phase space

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Modes and Line Spectrum

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Envelope of Line spectrum

Observed spectrum for mode \( n = 3, \ m = 4 \). Sweep speed 2 msec/div, bandwidth 300 kHz, range 0 - 50 MHz, linear scale, bunch length \( \tau_L = 66 \) nsec.

Synchrotron frequency sidebands around 12 \( f_0 \) showing mode \( m = 4 \).

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The form factor $F_m$ which enters in Sacherer's formulae is related to the normalised power spectrum of the mode spectrum envelope.
Form factors are favourable for \( m = 1 \) and \( m = 2 \) at the 6\(^{th}\) and 7\(^{th}\) harmonic. Some damping of \( m = 3 \). Filters designed for correct phase for \( m = 1, 2 \) and 3.
Implementation of Active Filters

\[ a_1 = e^{j\omega_c t} \quad \text{Mixers} \]
\[ a_2 = e^{j(\omega_c t + \varphi)} \quad \text{G(s)} \]
\[ \omega_c = k\omega_0, \quad k = 6,7 \]

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## Tracking Mode Analyser Response

<table>
<thead>
<tr>
<th>n</th>
<th>m = 1 ((sec^{-1}))</th>
<th>m = 2 ((sec^{-1}))</th>
<th>m = 3 ((sec^{-1}))</th>
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<tr>
<td>1,4</td>
<td>370</td>
<td>400</td>
<td>60</td>
</tr>
<tr>
<td>2,3</td>
<td>140</td>
<td>175</td>
<td>50</td>
</tr>
</tbody>
</table>

![Amplitude vs. \(\%\omega_0\) diagram]

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A chosen mode is excited to a well-defined initial amplitude by using the active damping system and the appropriate mode sideband frequency. The growth rate can be determined from the mode amplitude slope on a log scale.
Growth Rates vs. Energy and Frequency

Fig. 9: Growth and damping rates for dipole and quadrupole modes (Ring 4 with $3.2 \times 10^{12}$ protons)

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Beam Transfer Function of Dipole Mode

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Stability Diagram of Dipole Mode

Fig. 11 Stability diagram for $n = 3$ dipole mode with damping on.
Incoherent and Coherent Frequencies vs. Intensity

By measuring BTF's at different intensities, incoherent frequency range (Landau damping) and coherent frequencies vs. intensity can be determined.
Growth Rate vs. Intensity

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Conclusion and Summary

For dipole modes, Landau damping is lost for $N > 2.0 \times 10^{12}$ protons/ring.

Threshold for loss of Landau damping for higher order modes are higher: $N > 2.8 \times 10^{12}$ for $m = 2$.

Very large space charge shifts ($1/\tau > 2000$ sec$^{-1}$) move the coherent frequency out of the stable region such that Landau damping is lost.

Once Landau damping is lost, relatively small resistive impedances of a few hundred ohms are harmful ($1/\tau < 50$ sec$^{-1}$).

The active damping system for coupled bunch modes damps all coupled bunch modes $n = 1, 2, 3$ and $4$ and $m = 1, 2,$ and $3$.

It has been in successful operation for 20 years, and will be decommissioned by the end of 97.