RF Phase Modulation Studies in the Brazilian Light Source (LNLS)

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Summary

- The LNLS Electron Storage Ring
- Motivation:
  - CBM Stabilization with Phase Modulation
  - Increase of Beam Lifetime
- Longitudinal Dynamics with Phase Modulation: Theory, Simulations and Experimental Results
- Beam Transfer Function and Landau Damping
- Final Remarks
The LNLS Electron Storage Ring

**Parameter** | **Value**
---|---
Initial Current in user shifts | 250 mA
Energy Spread | $5.4 \times 10^{-4}$
Circumference | 93.2 m
RF Frequency | 476.066 MHz
Synchrotron Frequency (500 kV) | 25.5 kHz
Synchronous Phase (500 kV) | 166.8 °
Harmonic Number | 148
Momentum Compaction | $8.3 \times 10^{-4}$
Radiation Loss Per Turn | 114 keV
CBM Stabilization with Phase Modulation and Increase of Beam Lifetime

- Installation of a new RF Cavity at the end of 2003;
- Instability driven by a longitudinal HOM of the new cavity;
- Attempts to shift the mode frequency by changing temperature (plunger position and axial deformation) without success;
- Active solution → Phase Modulation at the second harmonic of the synchrotron frequency.
- Lifetime Increase
  - Single-bunch: 30%
  - Multibunch: 15%
Longitudinal Dynamics with Phase Modulation

Expanding the longitudinal Hamiltonian around the second harmonic resonance and performing a time average:

\[
\langle H \rangle = \left( \omega_s - \frac{\omega_m}{2} \right) J - \frac{\omega_s J^2}{16} + \frac{\omega_m A_m \tan \phi J}{4} \cos 2\Psi
\]

Dynamics around fixed points:

\[
H(J, \Psi) = \frac{A}{2} \delta^2 + \frac{B}{2} \phi^2 - \frac{\omega_s}{16} \sqrt{2J_0} \delta^3 - \frac{\omega_s}{16} \left( \phi^4 + \delta^4 \right) - \frac{\omega_s}{24} \epsilon \left( \phi^4 - \delta^4 \right)
\]

\[
\omega(\hat{\phi}) = \omega_s \left( 1 - \frac{3\omega_s}{16} \frac{A^2 + B^2 \hat{\phi}^2}{A^2 B} \right)
\]

Island energy and phase spread:

\[
\sigma_\delta = \sqrt{\frac{\kappa}{\gamma_d}}, \quad \sigma_\phi = \sqrt{\frac{A}{B}} \sigma_\delta = \sqrt{\frac{A \kappa}{B \gamma_d}},
\]

\[
\kappa = 4 \times 10^{-4} \text{ s}^{-1}, \quad \gamma_d = 250 \text{ s}^{-1}
\]

Expand around \( J_0 \) and \( \Psi_0 \)

\( f_m < 2 f_s \) for Unstable, \( f_m > 2 f_s \) for Stable
Single Bunch Simulations and Measurements

Formation of 3 islands, as predicted by theory. There is also an increase in the energy spread of the bunch, as the islands rotate around the phase space origin.

The oscilloscope can not resolve between the peaks of the longitudinal profile.

Formation of only 2 islands as predicted by theory.

200 ps
Multibunch Simulation

- Stabilization of CBM oscillations driven by the HOM of the new cavity (L1 mode)
- Main idea of the simulation code:

Bunches composed of a single macroparticle

Only one bunch with internal structure
Beam Response to an External Excitation (BTF)

Considering that the electron distribution in each bunch is composed of gaussian functions centered at each stable fixed point and that it is excited by an external harmonic driving force with frequency $\Omega$

\[
\dot{\tau} + 2\gamma_d \dot{\tau} + \omega_0^2 \tau = F_0 e^{-j\Omega t}
\]

\[
\Psi(r, \theta, t) = \Psi_0(r) + \Psi_1(r)e^{j(\Omega t - \theta)}
\]

\[
\bar{\tau}(t) = \int_0^{2\pi} \int_0^\infty r^2 \cos \theta dr d\theta \Psi(r, \theta, t)
\]

\[
\bar{\tau}(t) = \frac{F_0}{2\omega_c} e^{-j\Omega t} \left[ N_c I_c(\Omega) + N_i \omega_c \omega_i I_i(\Omega) \right]
\]

\[
I_n(\Omega) \equiv \pi \int_0^\infty \frac{r^2 dr}{\Omega - \omega(r)} \frac{\partial \Psi_0(r)}{\partial r}
\]

and $N_c + N_i = 1$

(a) BTF Amplitude - $|I(\Omega)|$
(b) BTF Phase - arg[$I(\Omega)$]
BTF Measurements

- All parameters, but $N_c$, used to calculate the red curves (island frequency, island width and energy spread) come from the equations derived in theory or from parameters that could be externally controlled and accurately measured (modulation frequency and amplitude).

Phase Modulation OFF

<table>
<thead>
<tr>
<th>$f_m$</th>
<th>$A_m$</th>
<th>$N_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>51 kHz</td>
<td>50 mrad</td>
<td>0.3</td>
</tr>
<tr>
<td>50.8 kHz</td>
<td>50 mrad</td>
<td>0.5</td>
</tr>
</tbody>
</table>

BTF Amplitude - $|I(\Omega)|$
BTF Phase - $\text{arg}[I(\Omega)]$
Stability Diagram and Landau Damping

As the spread in frequencies inside the bunch increases, the stable area in the U-V plane also increases.

\[ U + jV = -j(\Delta \omega_{coh}) = \frac{j}{I(\Omega)} \]

\[ \Delta \omega_{coh} \equiv \Omega - \omega_0 = -\frac{je^2N\eta\omega_{rev}}{2\omega_0 EC^2} \]

\[ \text{Im}[\Omega] \leq 0 \Rightarrow \text{Stability} \]
Experimental Stability Diagram

Legend:
1) Without RF Phase Modulation
   - Theory (red line)
   - Experimental Result (green dots)
2) With RF Phase Modulation
   - Theory (blue line)
   - Experimental Result (black dots)

- The stable area is increased
- The loop is present confirming the theory predictions
Final Remarks

• Phase modulation can effectively damp CBM instabilities;
• Phase modulation accounts for the increase in beam lifetime;
• The measurements indicate that when phase modulation is turned on the bunch splits up into 3 or 2 bunchlets with slightly different frequencies;
• Measurements of BTF indicate that the spread in frequencies, created by phase modulation, is responsible for the damping of unstable motion of the beam via Landau Damping.
Acknowledgements

• The LNLS Accelerator, Radiofrequency and Diagnostic groups;
Increase of Beam Lifetime

After the installation of the second cavity there was a lifetime increase due to the Increase in gap voltage, however the beam suffered with constant instability outbreaks. After phase modulation was introduced the CBM was damped and lifetime was improved.

Improvement in Single Bunch Lifetime
Experimental Setup