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

Natalia Prado de Abreu
LNLS Accelerator Physics Group

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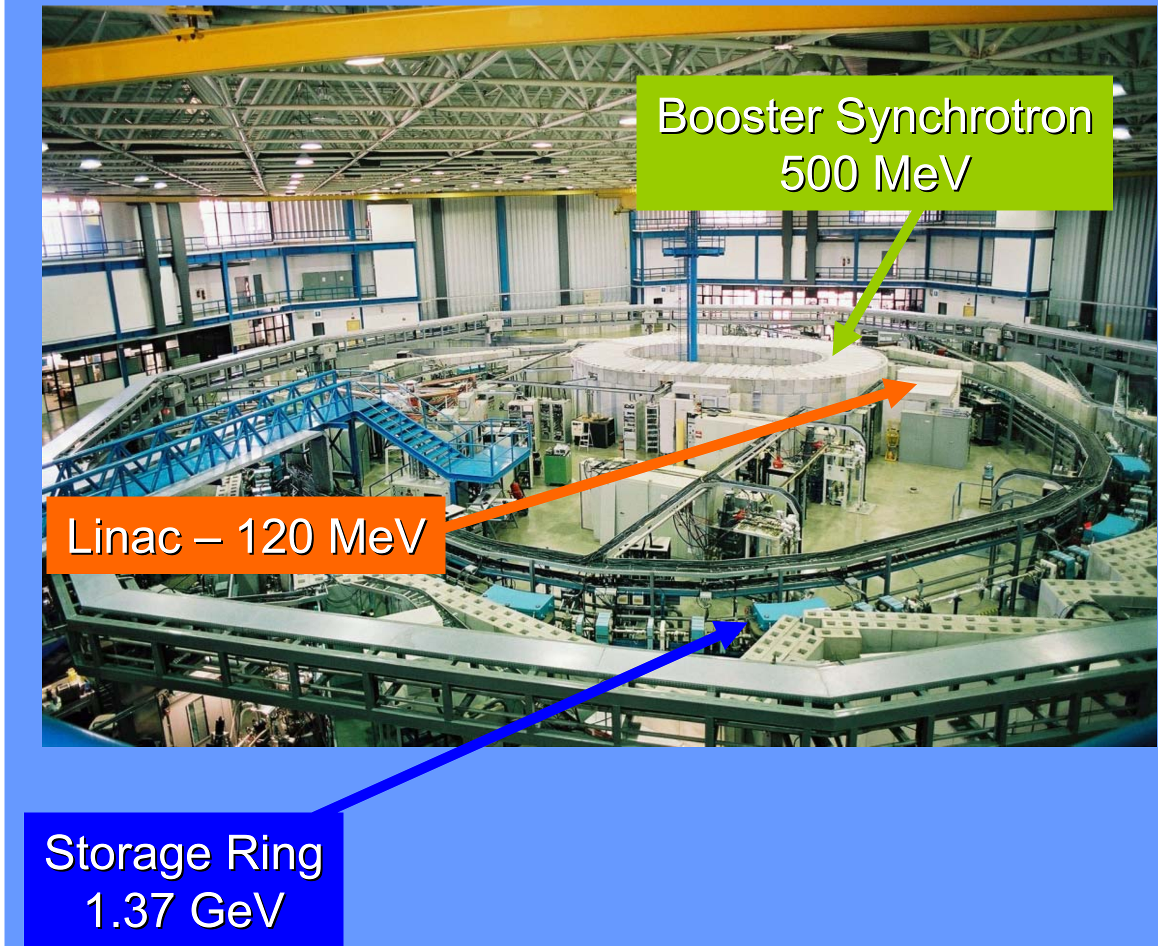
# Summary

- 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

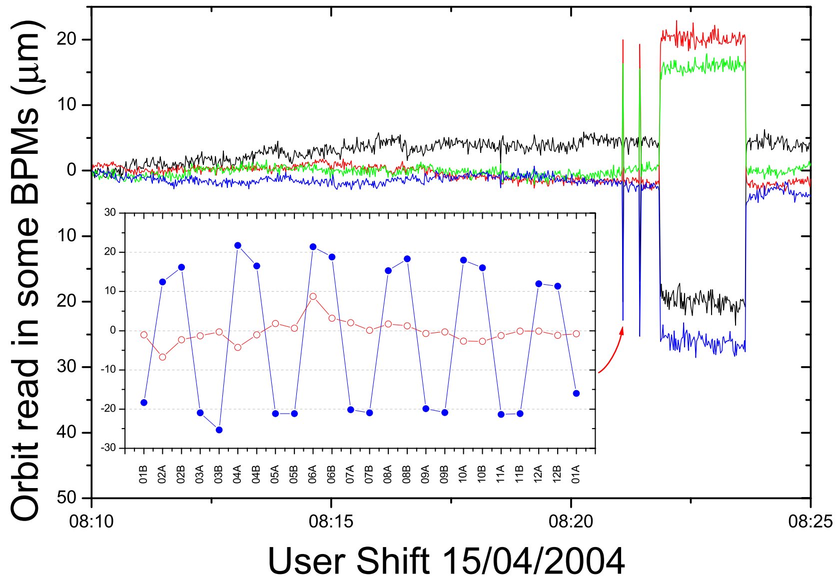
# The LNLS Electron Storage Ring

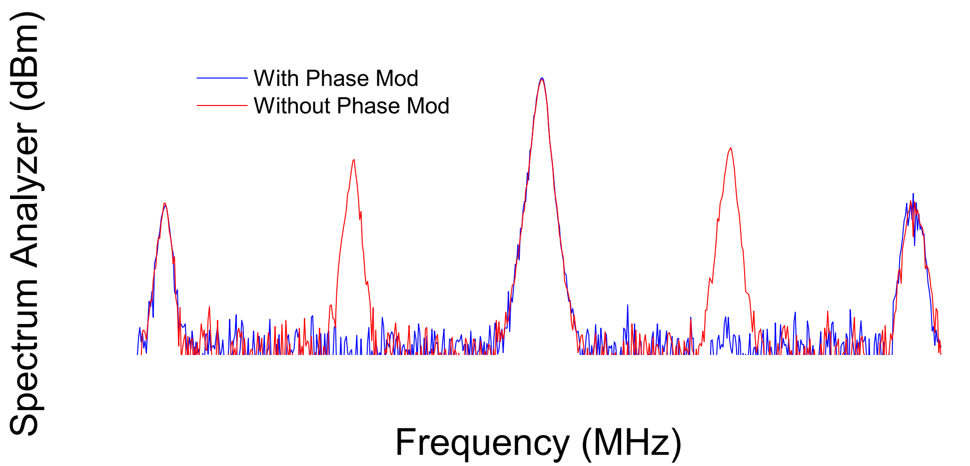



| Parameter | Value |
|---|---|
| Initial Current in user shifts | 250 mA |
| Energy Spread | $5.4 \times 10^{-4}$ |
| Circunference | 93.2 m |
| RF Frequency | 476.066 MHz |
| Synchrotron Frequency (500 kV) | 25.5 kHz |
| Synchronous Phase (500 kV) | 166.8 º |
| Harmonic Number | 148 |
| Momentum Compaction | $8.3 \text{ X } 10^{-4}$ |
| 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 longitudial Hamiltonian around the second harmonic resonance and performing a time average:

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

Expand around $J_0$ and $\Psi_0$

Dynamics around fixed points :

$$H(J,\Psi) = \frac{A}{2}\delta^2 + \frac{B}{2}\phi^2 - \frac{\omega_s \sqrt{2J_o}}{16}\phi^3 - \frac{\omega_s}{16}\left(\frac{\phi^4 + \delta^4}{4}\right) - \frac{\omega_s \varepsilon}{24}\left(\frac{\phi^4 - \delta^4}{4}\right)$$

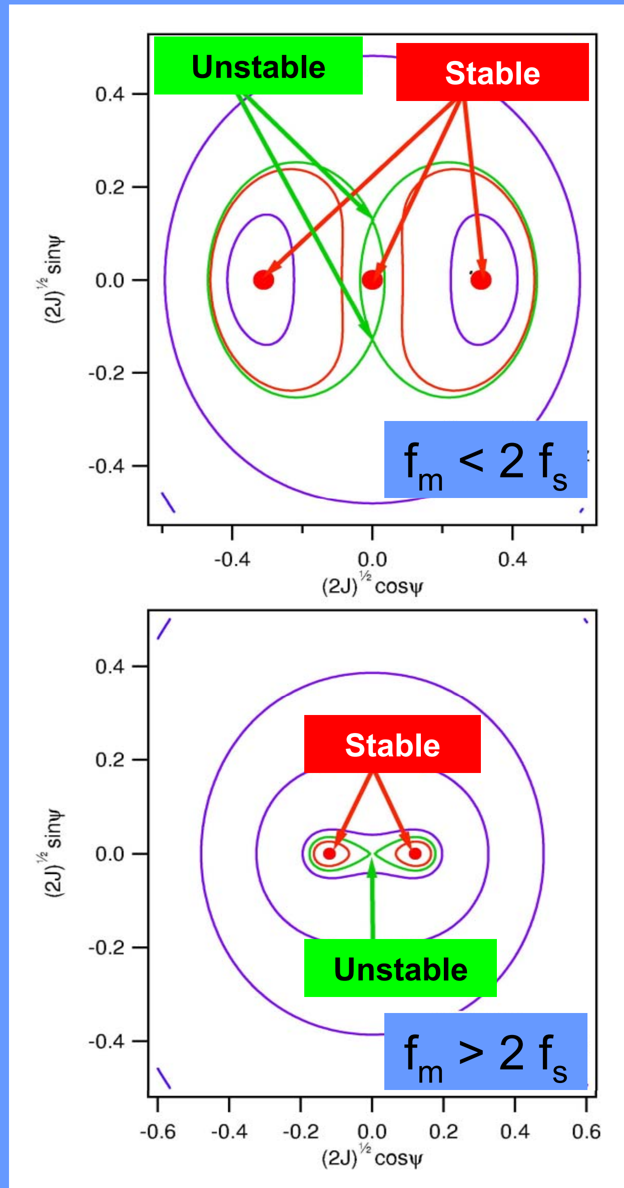
$$\omega(\hat{\phi}) = \omega_o\left(1 - \frac{3\omega_s}{16}\frac{A^2 + B^2}{A^2|B|}\frac{\hat{\phi}^2}{8}\right)$$

+ Focker-Planck

Island energy and phase spread :

$$\sigma_\delta = \sqrt{\frac{\kappa}{\gamma_d}} \qquad \sigma_\phi = \sqrt{\frac{A}{B}}\sigma_\delta = \sqrt{\frac{A\kappa}{B\gamma_d}} ,$$

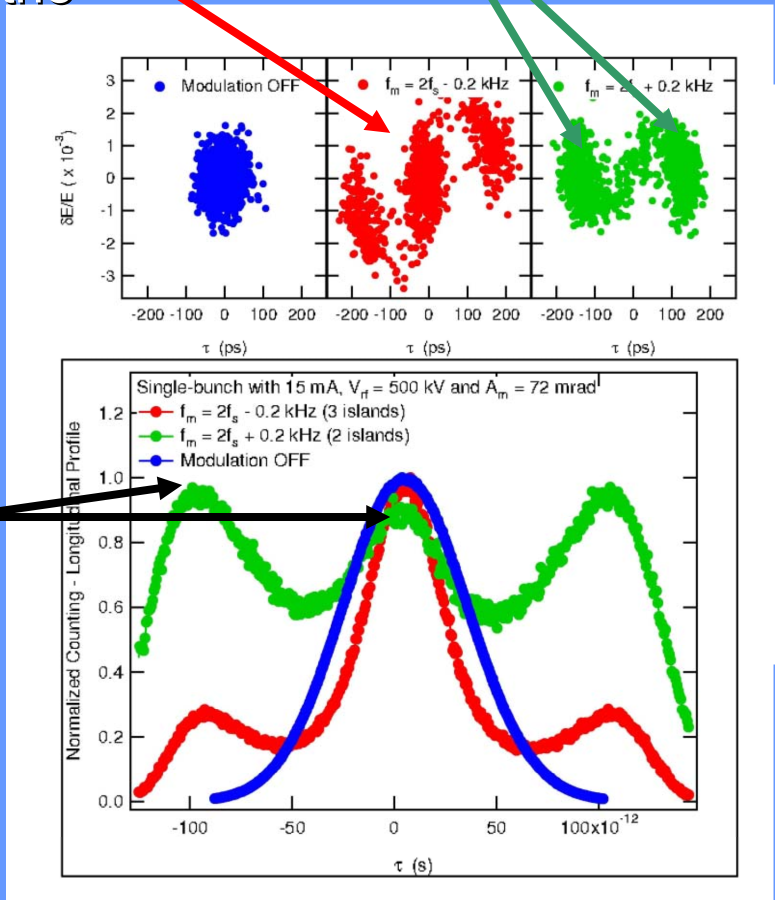
$$\kappa = 4\times 10^{-4}\, s^{-1} \qquad \gamma_d = 250\, s^{-1}$$

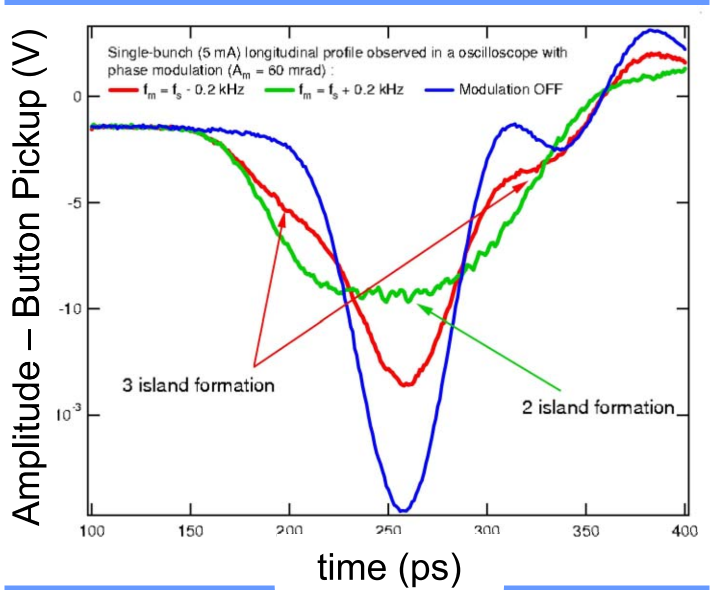


# Single Bunch Simulations and Measurements

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.

Formation of only
2 islands as predicted by theory

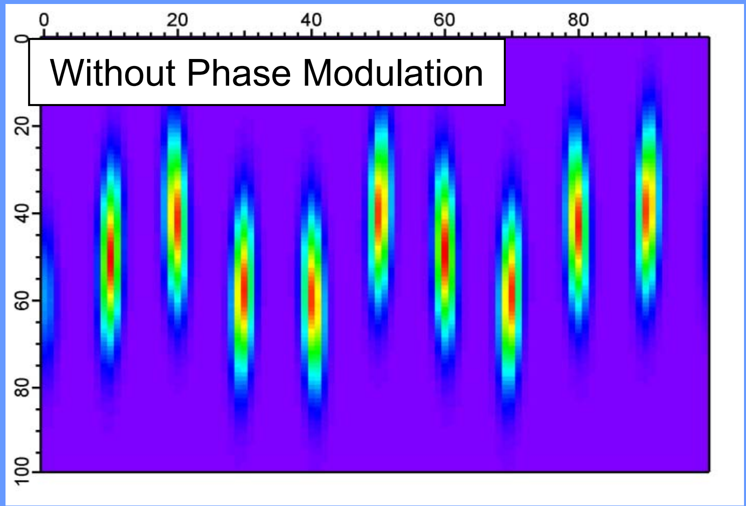


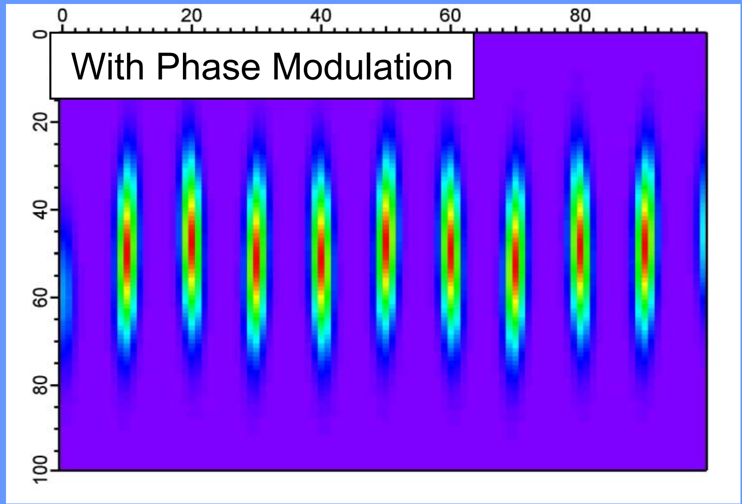




200 ps

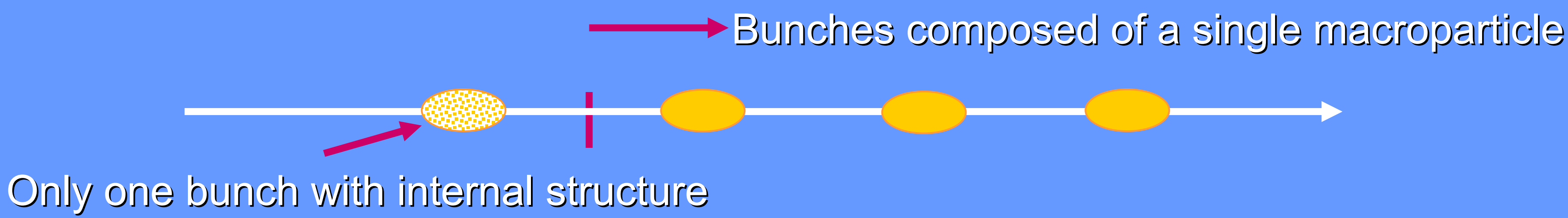
The oscilloscope can not resolve between the peaks of the longitudinal profile

# Multibunch Simulation



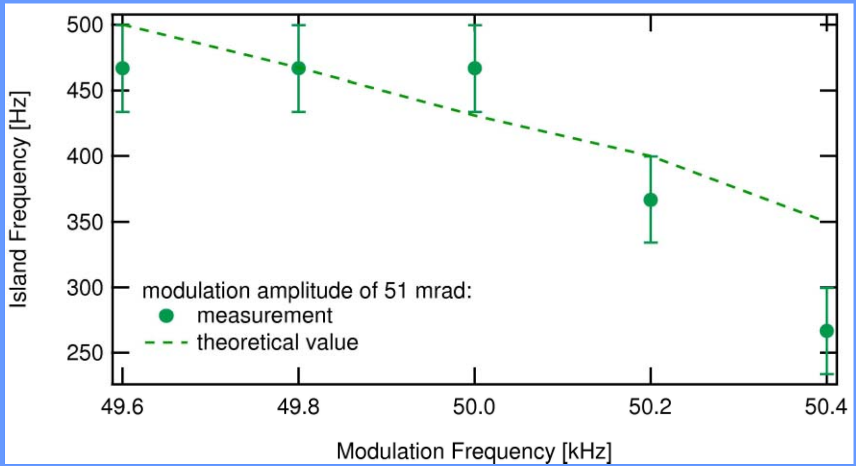



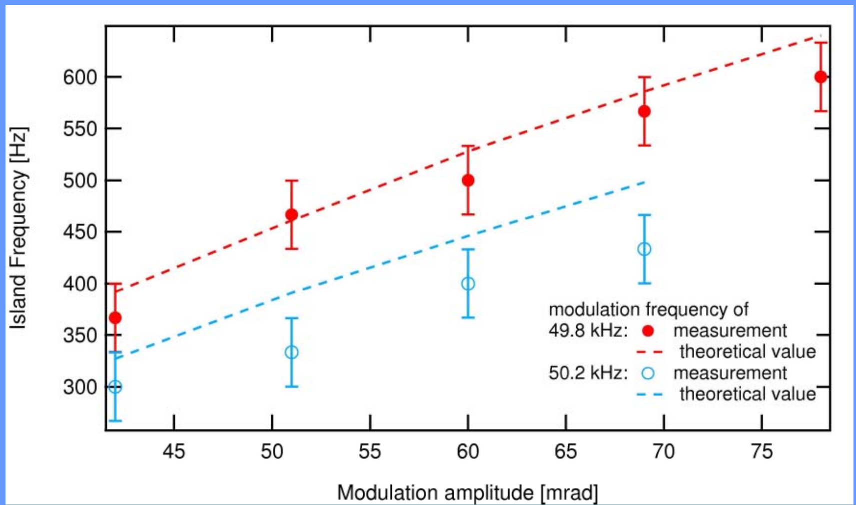

- Stabilization of CBM oscillations driven by the HOM of the new cavity (L1 mode)
- Main idea of the simulation code:



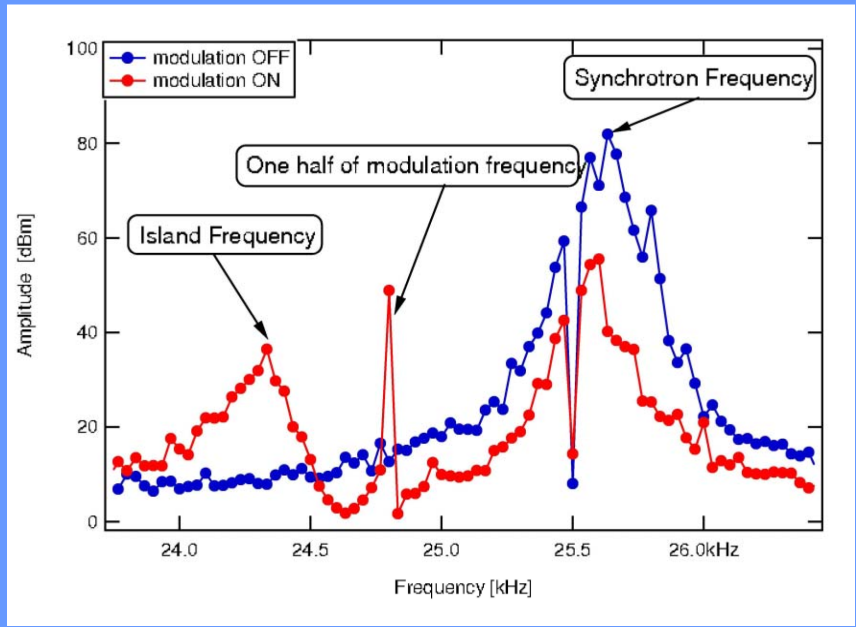
# Measurements

## Measurements of the island frequency




## Observation of the island frequency



# 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 $\Omega$

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

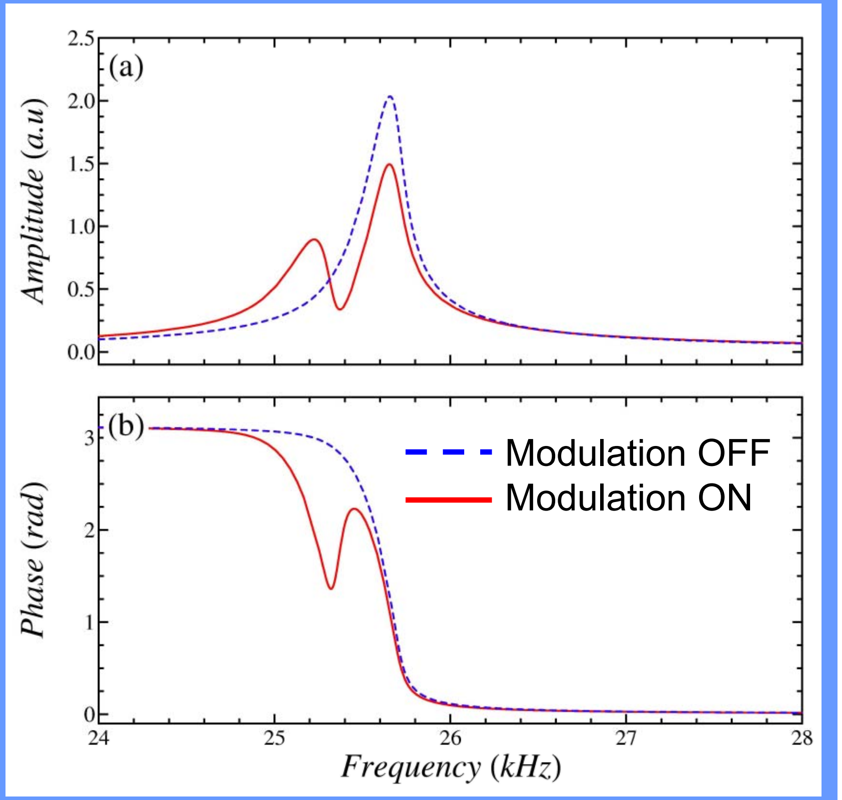
$$\underbrace{\Psi(r,\theta,t) = \Psi_0(r) + \Psi_1(r) e^{j(\Omega t - \theta)}}$$

$$\Downarrow$$

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

$$\bar{\tau}(t) = \frac{F_0}{2\omega_c} e^{-j\Omega t} \underbrace{\left[ N_c I_c(\Omega) + N_i \frac{\omega_c}{\omega_i} I_i(\Omega) \right]}_{\text{Beam Transfer Function -}I(\Omega)}$$

$$I_n(\Omega) \equiv \pi \int_0^{\infty} \frac{r^2 dr}{\Omega - \omega(r)} \frac{\partial \Psi_0(r)}{\partial r} \quad \text{and} \quad N_c + N_i = 1$$

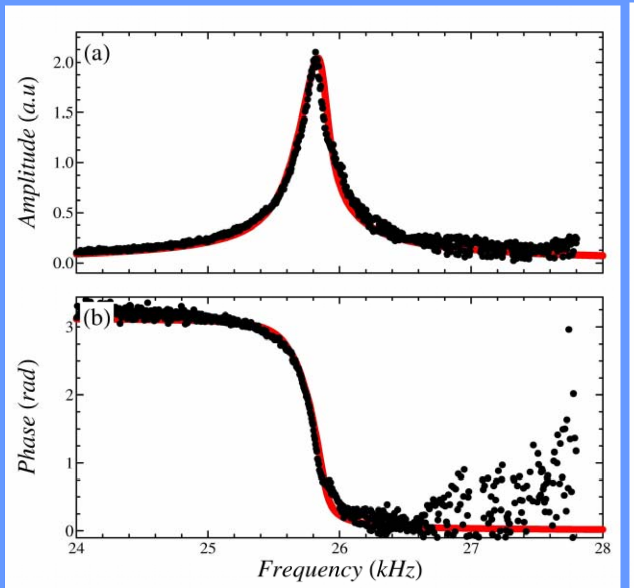


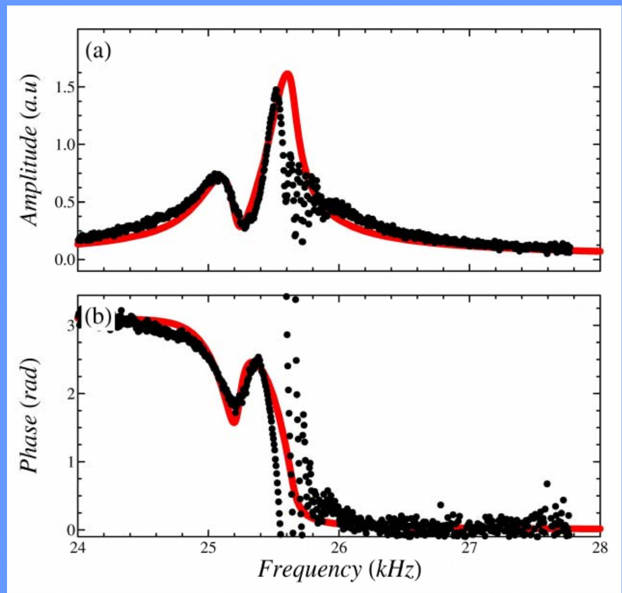

(a) BTF Amplitude - $|I(\Omega)|$
(b) BTF Phase- $\arg[I(\Omega)]$

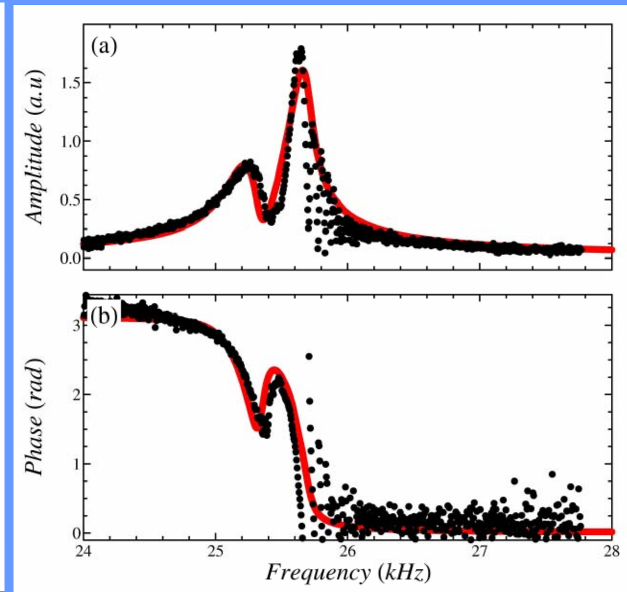
# BTF Measurements

- All parameters, but Nc, 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 controled and acurately measured (modulation frequency and amplitude).

| Phase Modulation OFF | $f_m$ = 50.8 kHz<br>$A_m$ = 50 mrad<br>$N_c$ = 0.5 | $f_m$ = 51 kHz<br>$A_m$ = 50 mrad<br>$N_c$ = 0.3 |
|---|---|---|



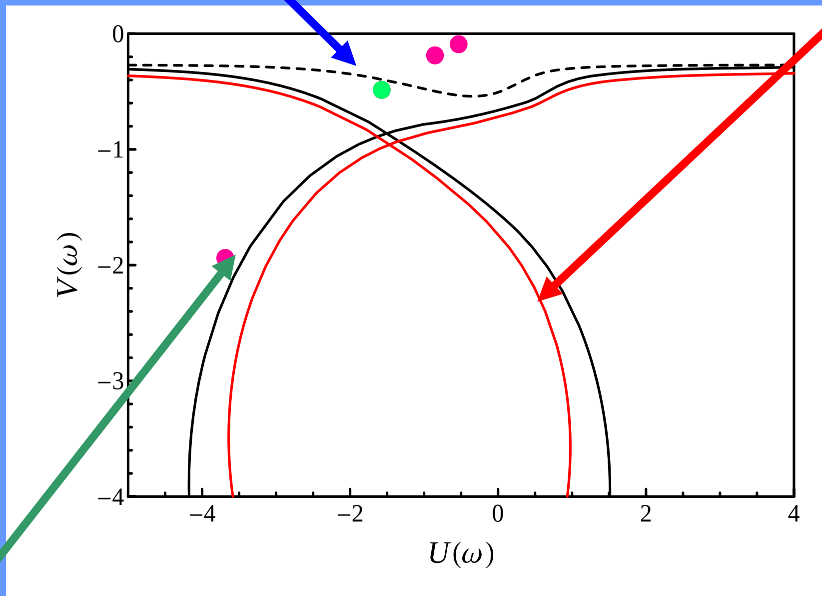




BTF Amplitude - $|I(\Omega)|$
BTF Phase- $\arg[I(\Omega)]$

# Stability Diagram and Landau Damping

Longitudinal Stability Diagram
without
phase modulation

Longitudinal Stability Diagram
with phase modulation and
Im[Ω]>0 – Unstable condition




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

$$\Delta\omega_{coh} \cong \Omega - \omega_0 = -\frac{je^2N\eta\omega_{rev}}{2\omega_0 EC^2} Z_{//}$$

$\mathrm{Im}[\Omega] \leq 0 \Rightarrow$ Stability

Longitudinal Stability Diagram
with phase modulation

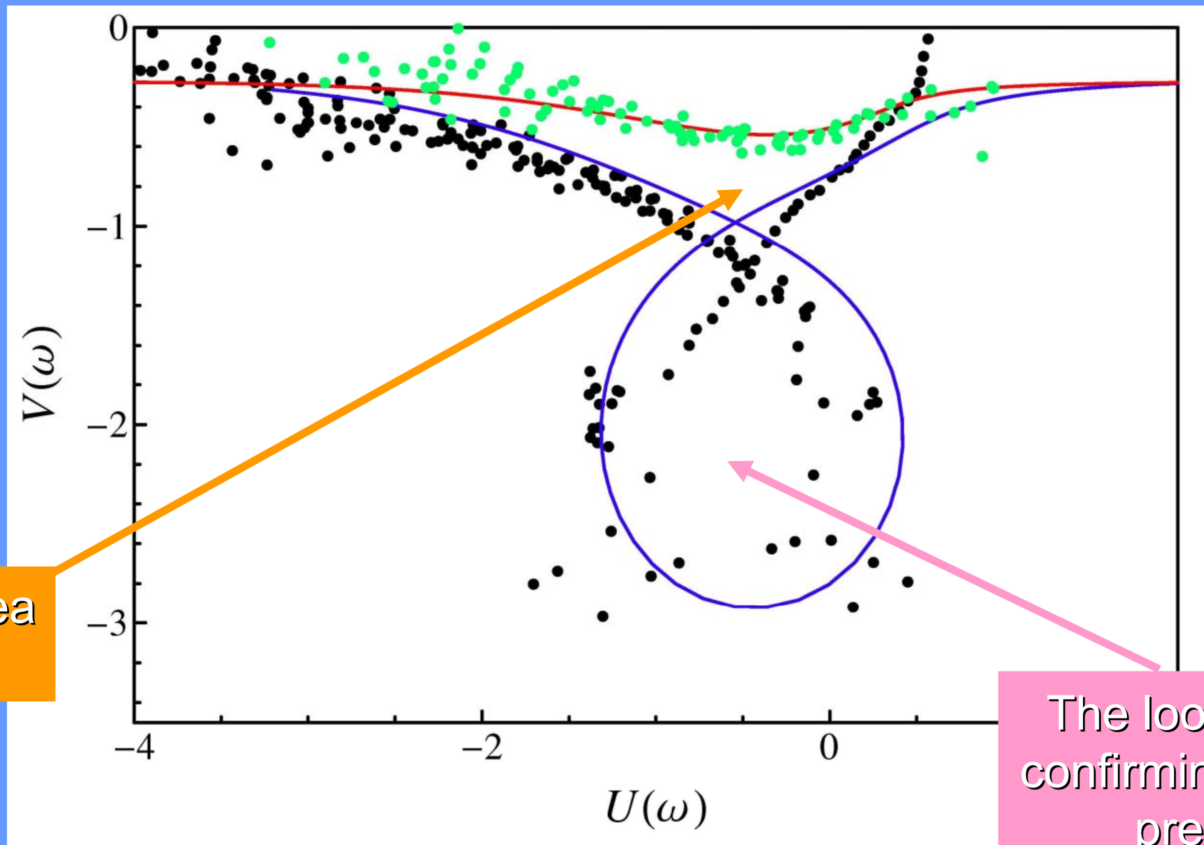
As the spread in frequencies inside the bunch increases the stable area in the U-V plane also increases.

# Experimental Stability Diagram

**Legend:**

1) Without RF Phase Modulation
- Theory
- Experimental Result

2) With RF Phase Modulation
- Theory
- Experimental Result




The stable area is increased

The loop is present confirming the theory predictions

# Final Remarks

- Phase modulation can effectivelly 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.

# Aknowledgements

- The LNLS Accelerator, Radiofrequency and Diagnostic groups;

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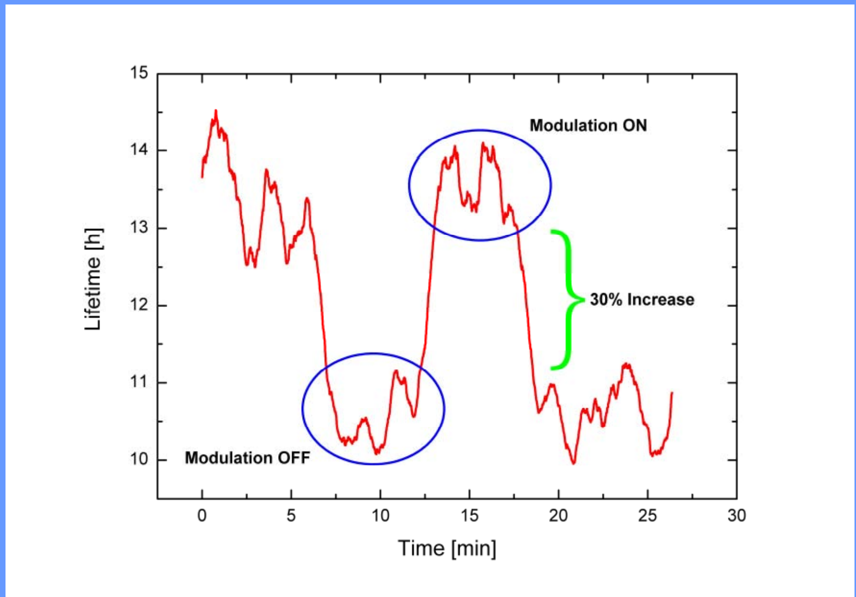
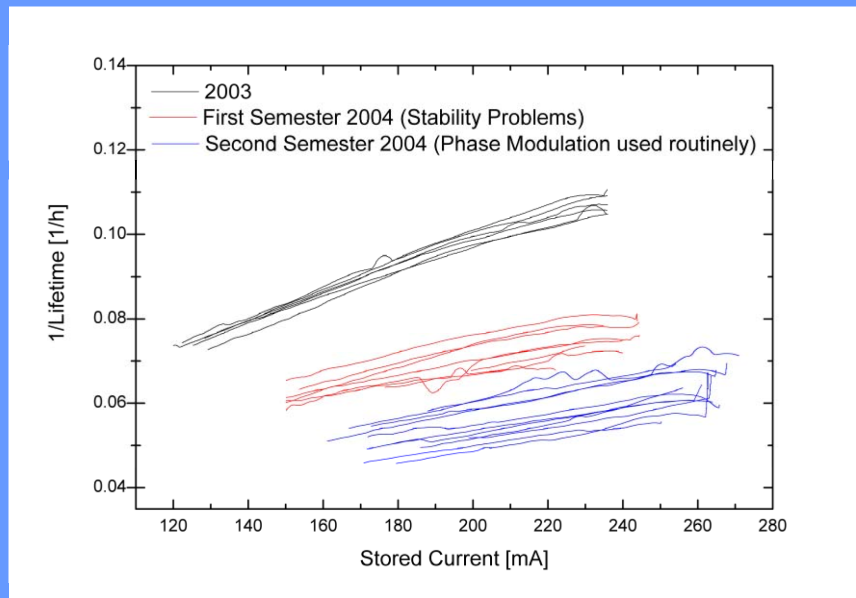
# Increase of Beam Lifetime




Improvement in Single Bunch Lifetime

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



# Experimental Setup