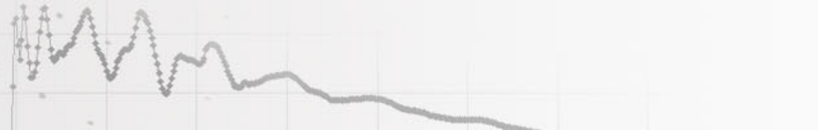
Impact of a Harmonic Cavity Flattened Potential on Multibunch Coherent Instabilities

Francis Cullinan, Ryutaro Nagaoka
(Synchrotron SOLEIL, St. Aubin, France)
Galina Skripka, Pedro Fernandes-Tavares
(MAX IV, Lund, Sweden)

Low Emittance Ring Workshop, ESRF, Grenoble, September 2015



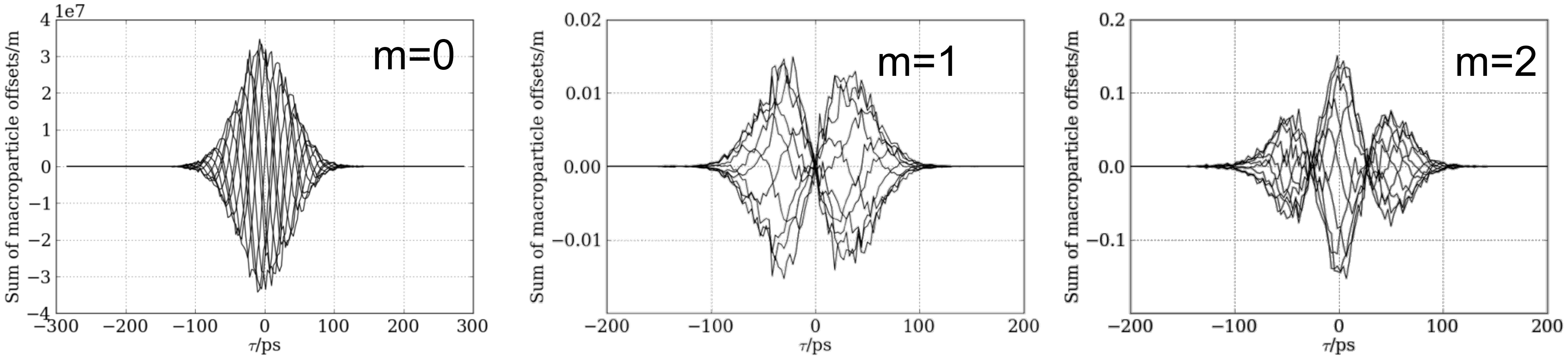
Introduction

- Interpretation of results from simulations of MAX IV with and without a harmonic cavity flattened potential
- Large increase in threshold current for coupled bunch transverse instabilities
- Harmonic cavities are essential for achieving design current
- Must better understand the physical mechanism responsible

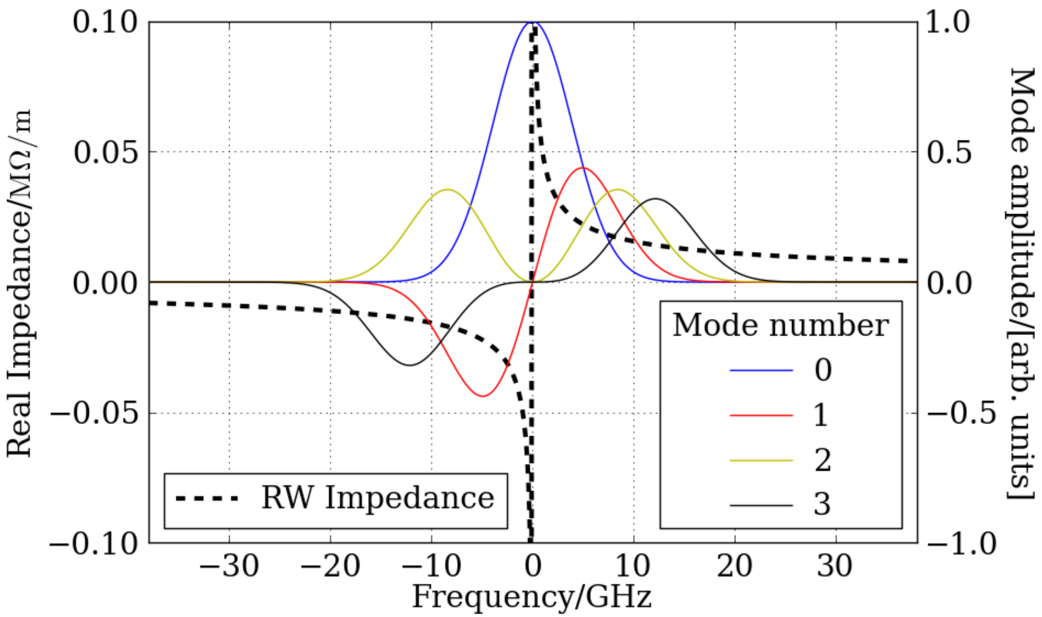
Outline

- Brief explanation of head-tail modes
- Effect of harmonic cavity potential on head-tail modes
- Multibunch simulations of MAX IV 3 GeV ring
- Modal analysis of results and interpretation

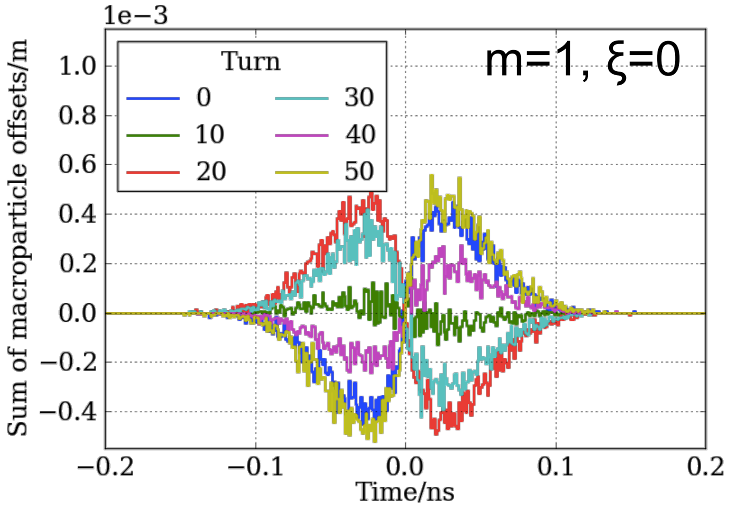
Transverse Head-Tail Modes

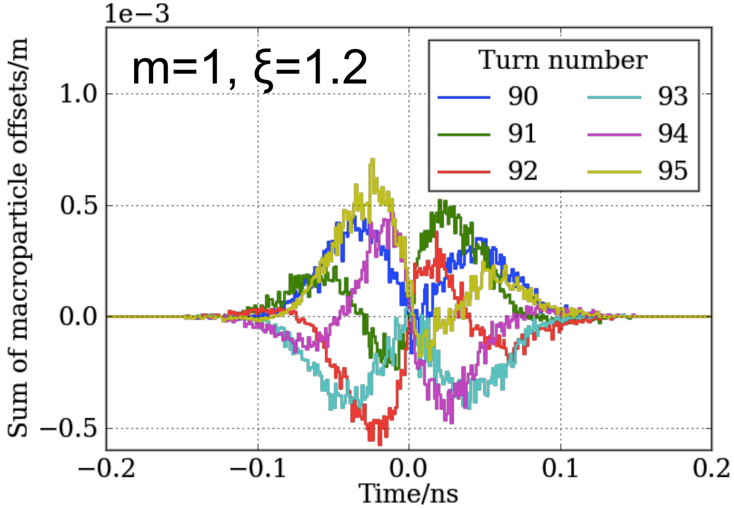


- Head tail modes are excited due to machine impedance
- Positive chromaticity adds modulation to dipole (m=0) mode but introduces dipolar component to higher modes
- Bunch centroid oscillation at synchrotron sideband
- In frequency domain, spectra are shifted towards positive chromaticity

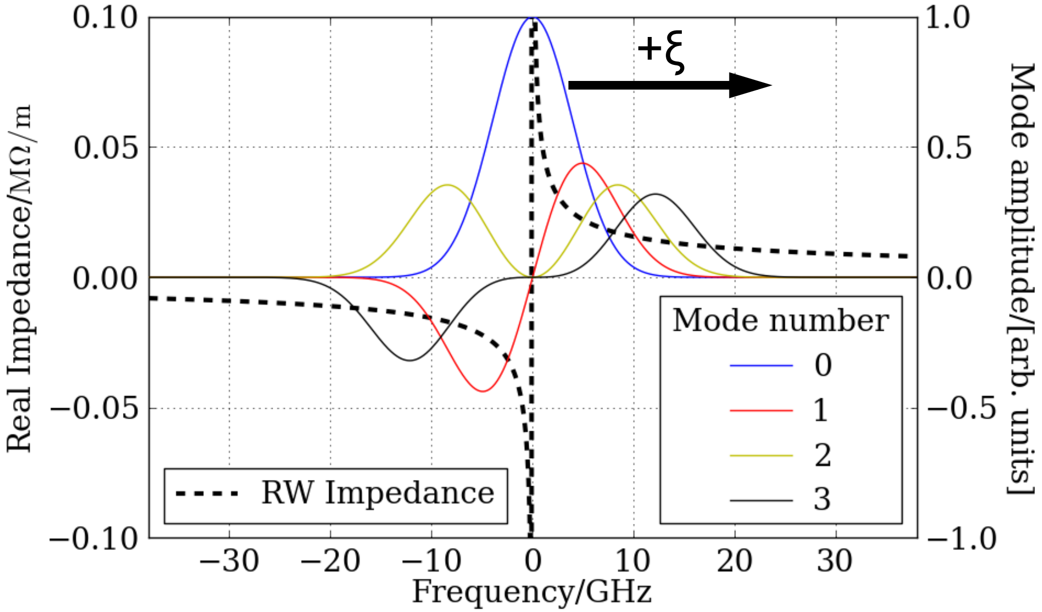


Transverse Head-Tail Modes





- Head tail modes are excited due to machine impedance
- Positive chromaticity adds modulation to dipole (m=0) mode but introduces dipolar component to higher modes
- Bunch centroid oscillation at synchrotron sideband
- In frequency domain, spectra are shifted towards positive chromaticity



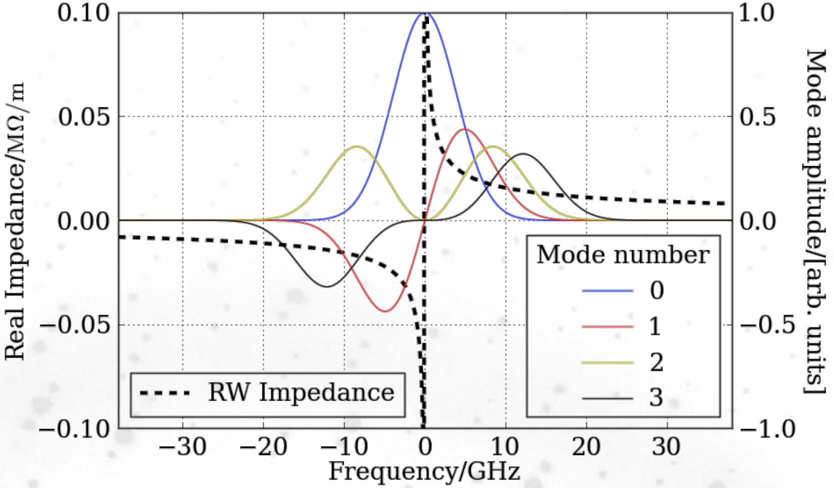
Effect of Harmonic Cavity Flat Potential

Two effects of a bunch lengthening harmonic cavity likely to have a large impact on threshold currents:

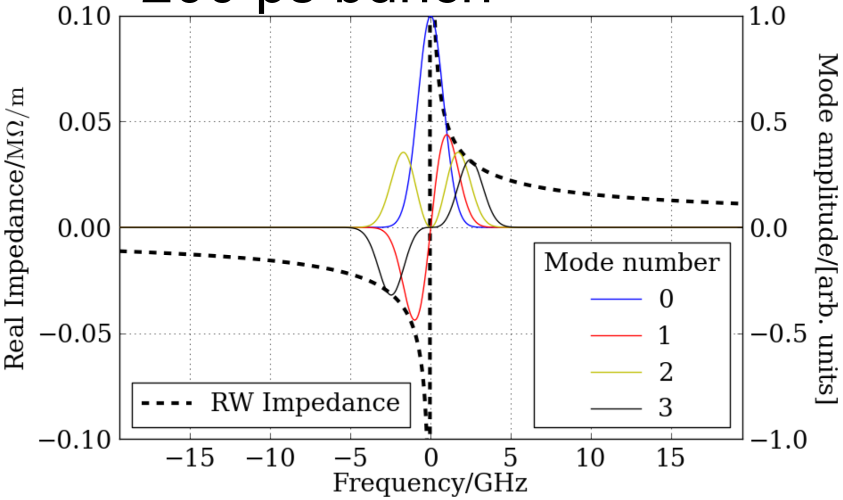
- Longer bunch
- Synchrotron tune spread

Bunch Lengthening

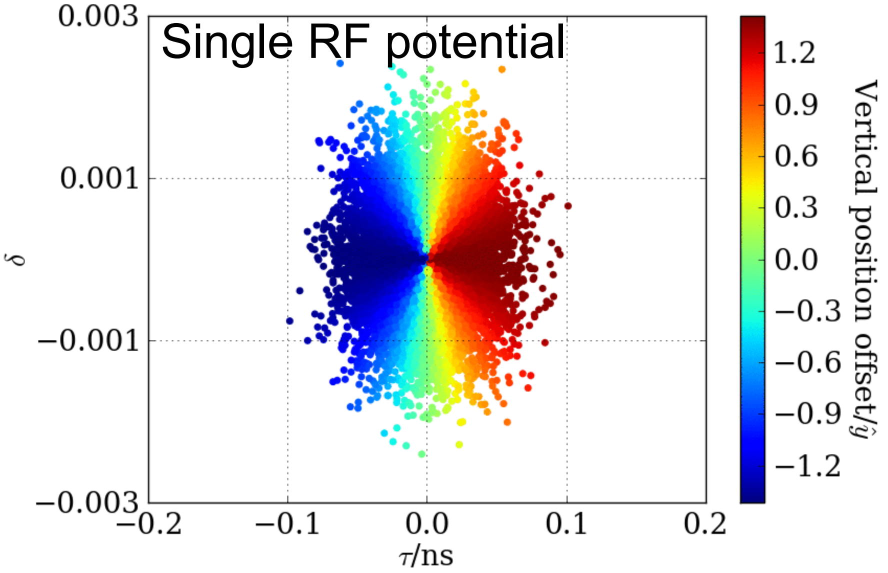
40 ps bunch

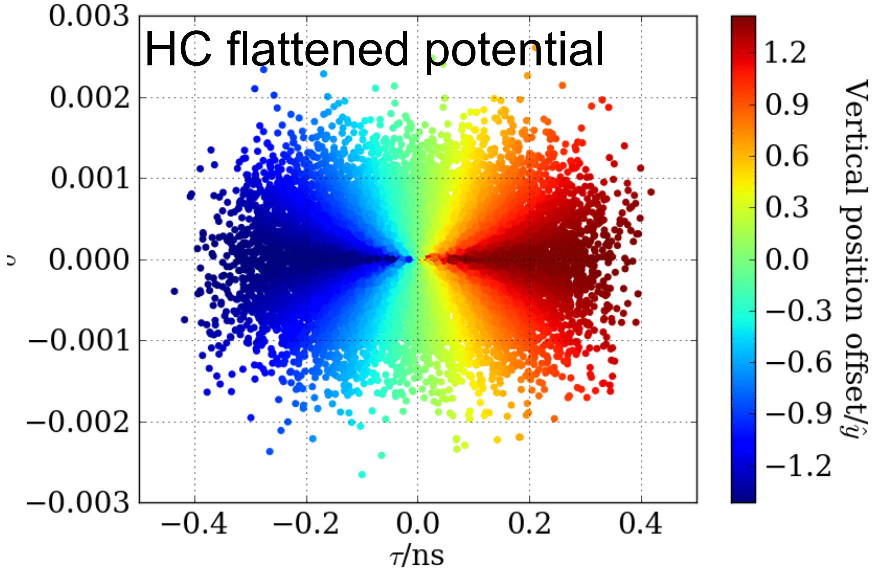


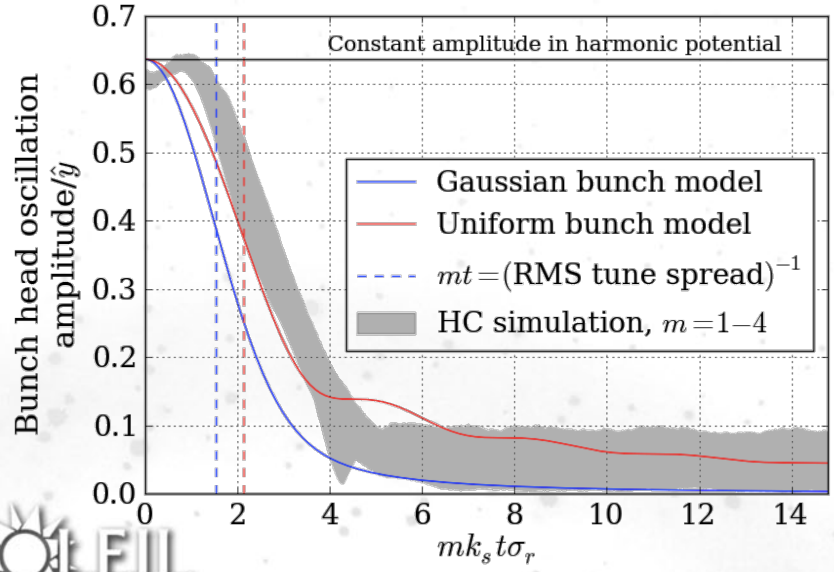
200 ps bunch



Synchrotron Tune Spread



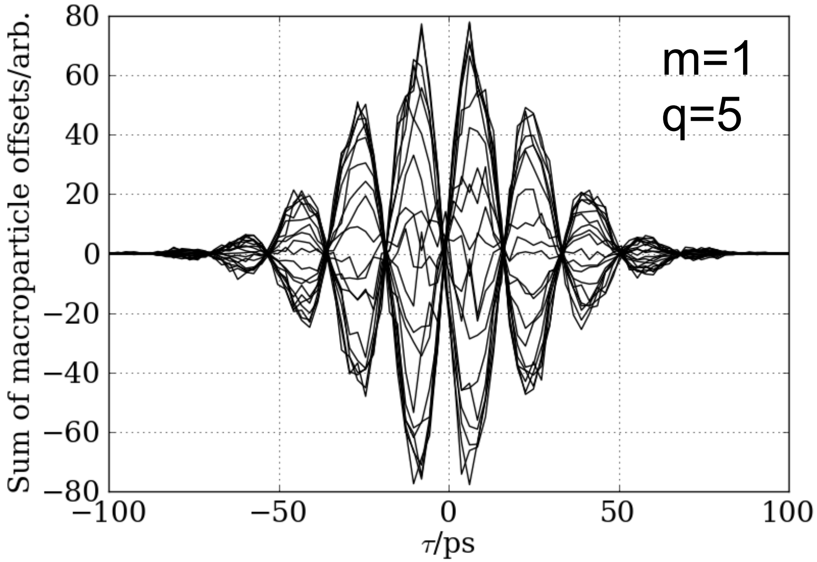


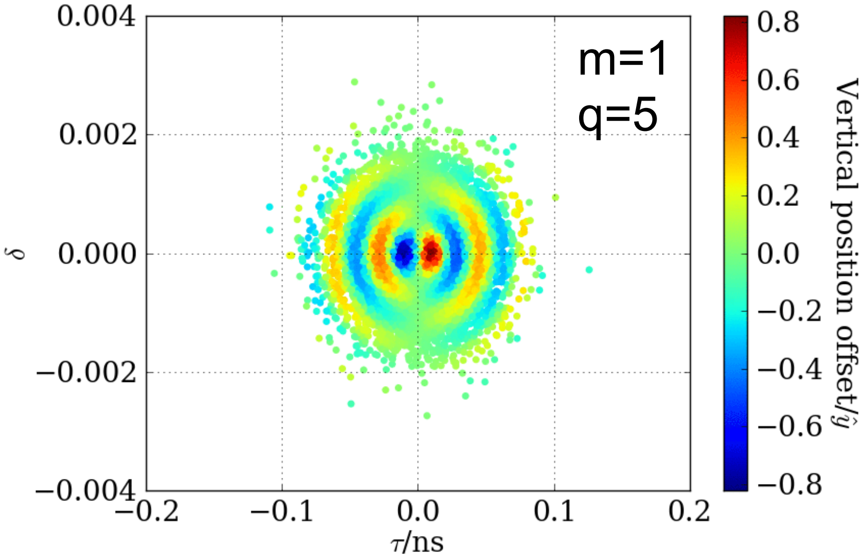


- Synchrotron tune spread leads to break up of m>0 head-tail modes
- Lifetime is around the inverse RMS synchrotron tune spread
    - For MAX IV, <1/9th of the radiation damping time

F. Cullinan et al., IPAC 2015, Richmond, Virginia, MOPWA011.

Radial Dimension





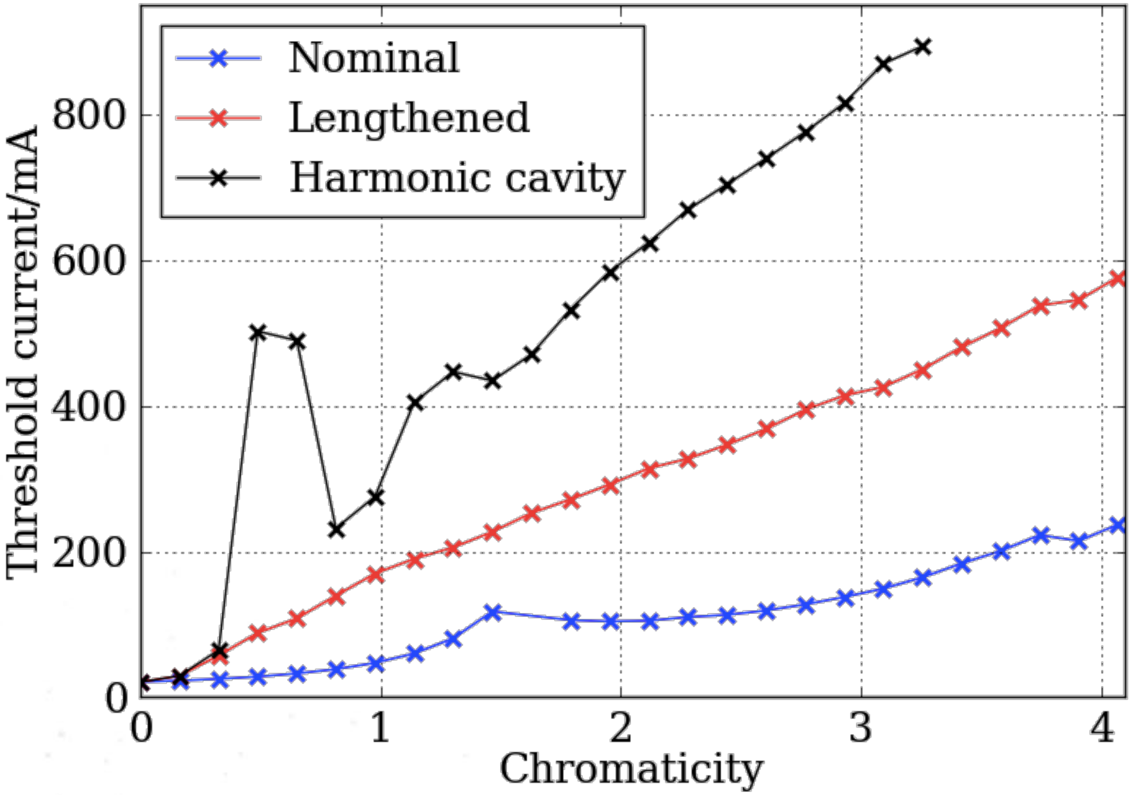
- Head-tail mode with a radial component, betatron amplitude is dependent on synchrotron amplitude
- Bunch has similar profile to higher order azimuthal mode but bunch oscillates at frequency of the azimuthal mode present
- Radial components of m=0 mode ➔ higher order modes that are not broken up by synchrotron tune spread

MAX IV 3 GeV Ring Multibunch

Multibunch simulations in mbtrack – 10000 macroparticles per bunch

Simulation at 100 mA then threshold current determined from growth rate

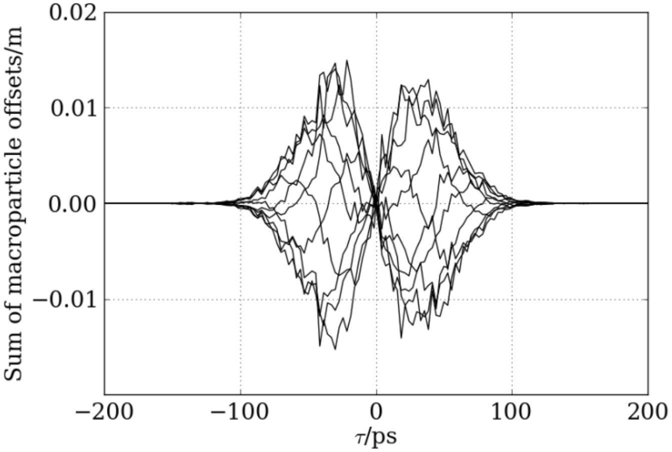
Resistive wall impedance only

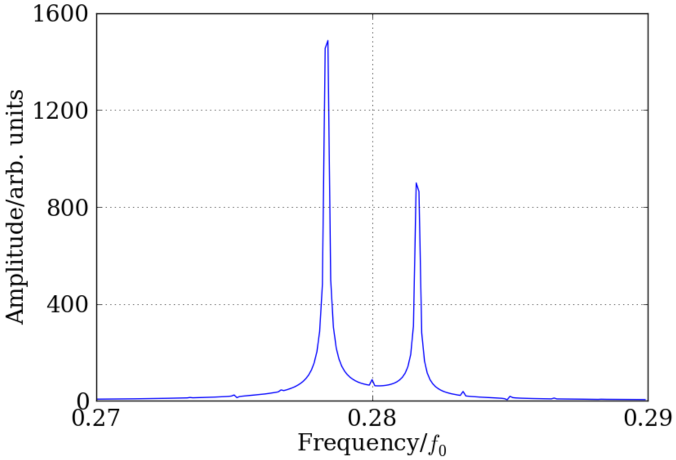


Lengthened case:

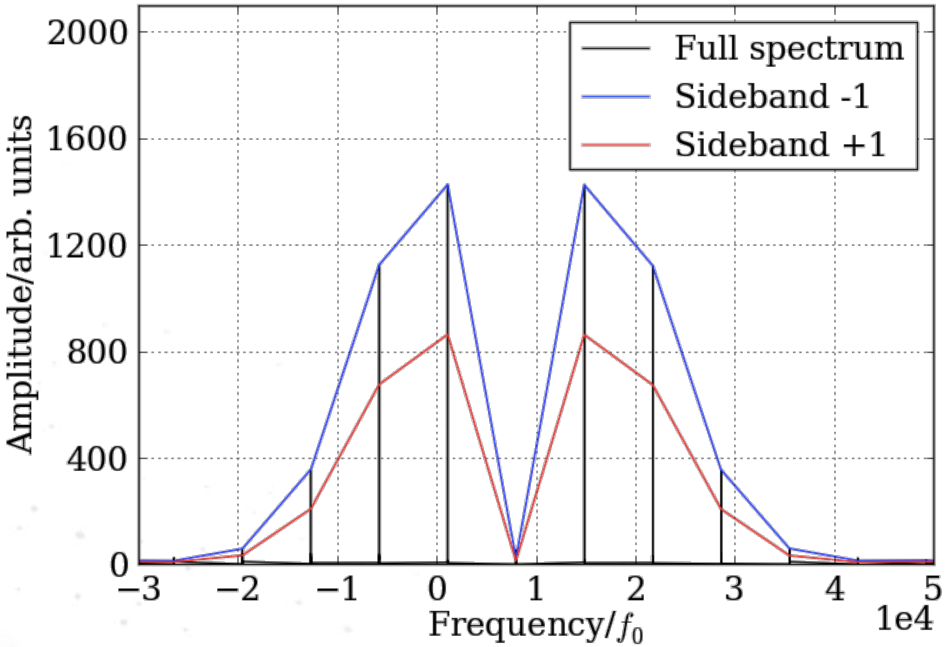
- Same energy spread as other two cases
- Lower synchrotron tune – via RF voltage and radiation loss
- Unlike Harmonic Cavity case, no synchrotron tune spread

Modal Analysis



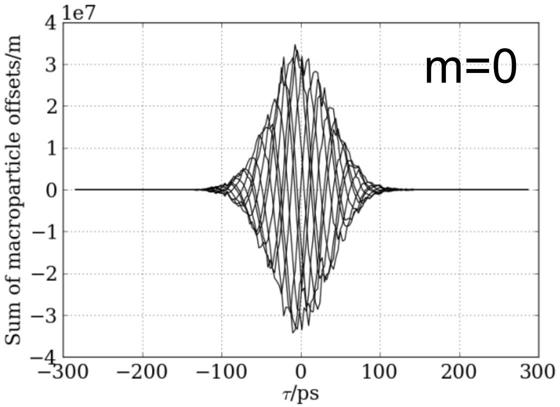


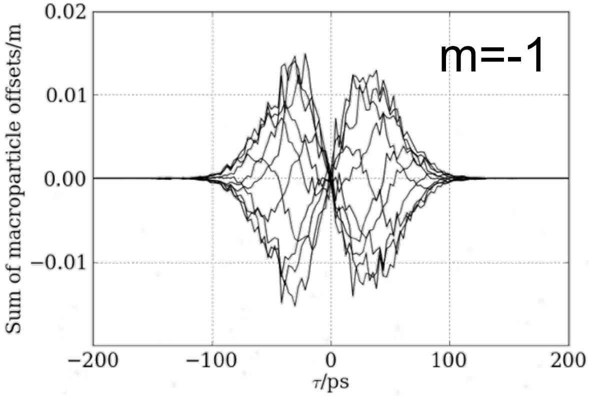
- Track final particle distribution over 10000 turns
- Take turn by turn profiles of single bunch
- Put them end to end separated by revolution time
- Fourier transform (only partial summation needed because of many zeros)
- Link up synchrotron side bands to reconstruct head-tail spectrum

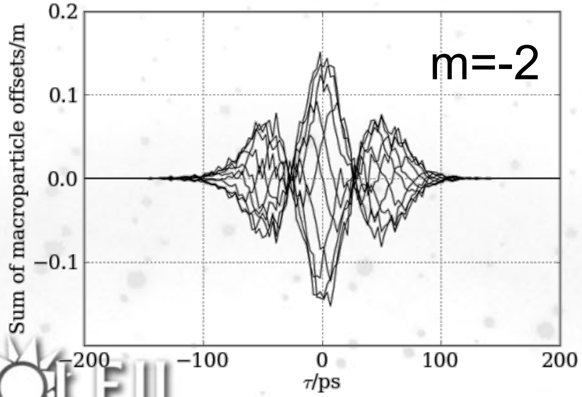


As described in PhD thesis of Philippe Kernel, ESRF and University Joseph Fourier, Grenoble, October 2000.

Nominal Case







- For nominal case, head-tail modes are clear in both time and frequency domain
- Bunch spectra are very similar to shaker modes:

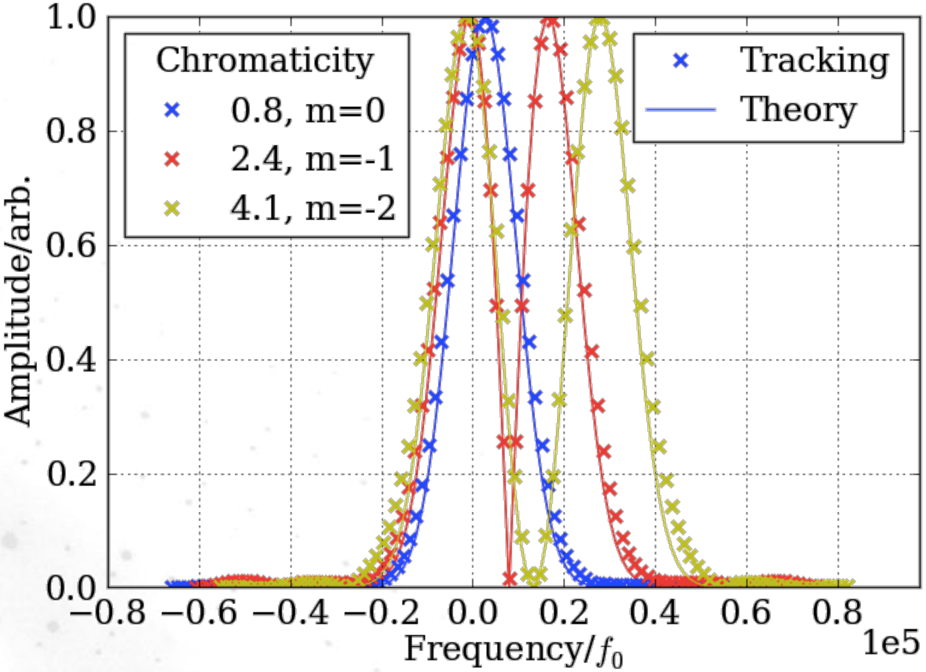
Bunch length

$$s[\omega_p] = I_m[\omega_q(\omega_p - \omega_\xi)\sigma_\tau^2] \exp\left(-\frac{\omega_q^2\sigma_\tau^2 + (\omega_p - \omega_\xi)^2\sigma_\tau^2}{2}\right)$$

radial frequency

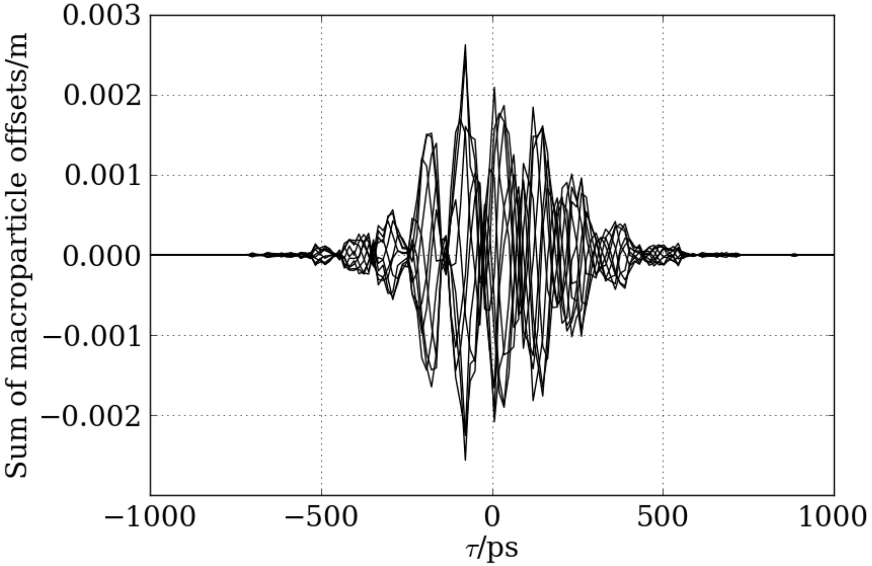
Revolution harmonic

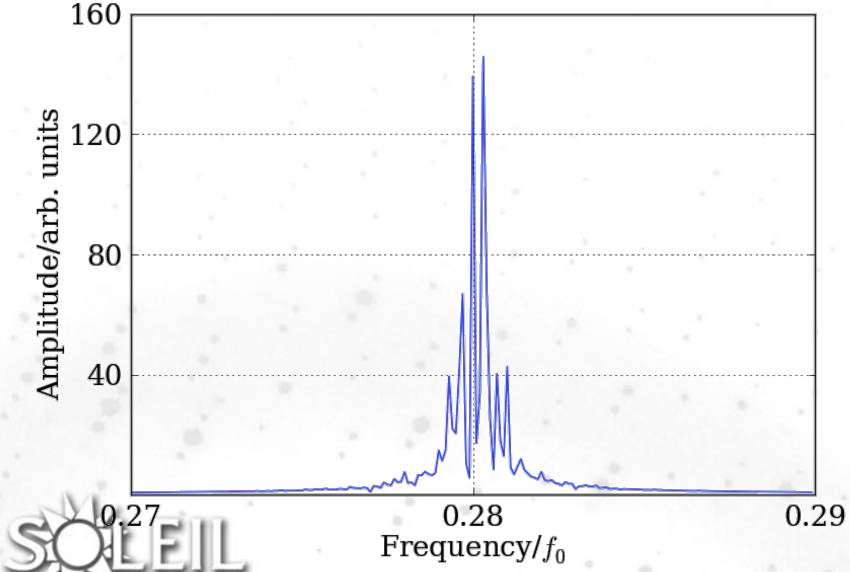
Chromatic frequency

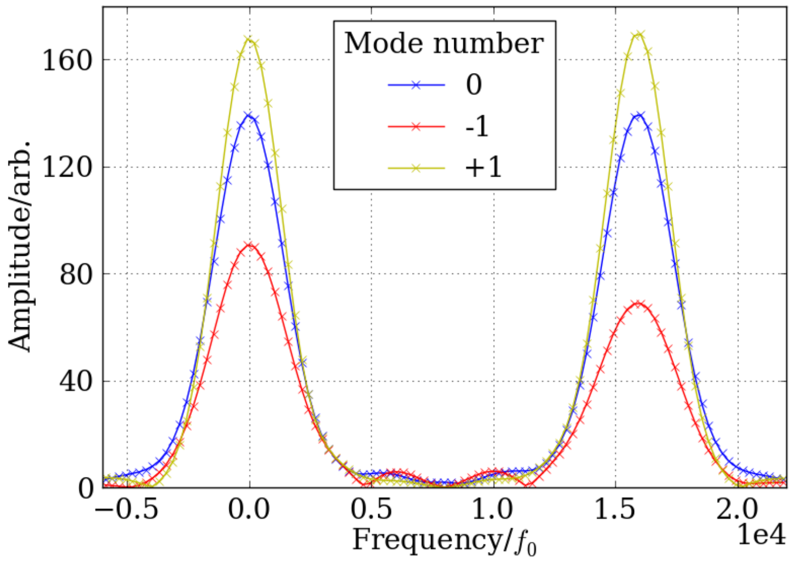


Lengthened Bunch – ξ =2.4

- Head-tail mode is clear but many low order sidebands present
- Dipole (m=0) mode spectrum is double-peaked
- Frequency separation of two peaks is the same for all modes
- Lower frequency peak centred at zero for all modes







Lengthened Bunch - Radial Modes

- Set the radial frequency to the chromatic frequency (ω_q=ω_ξ)
- Observed spectra look very similar to shaker modes

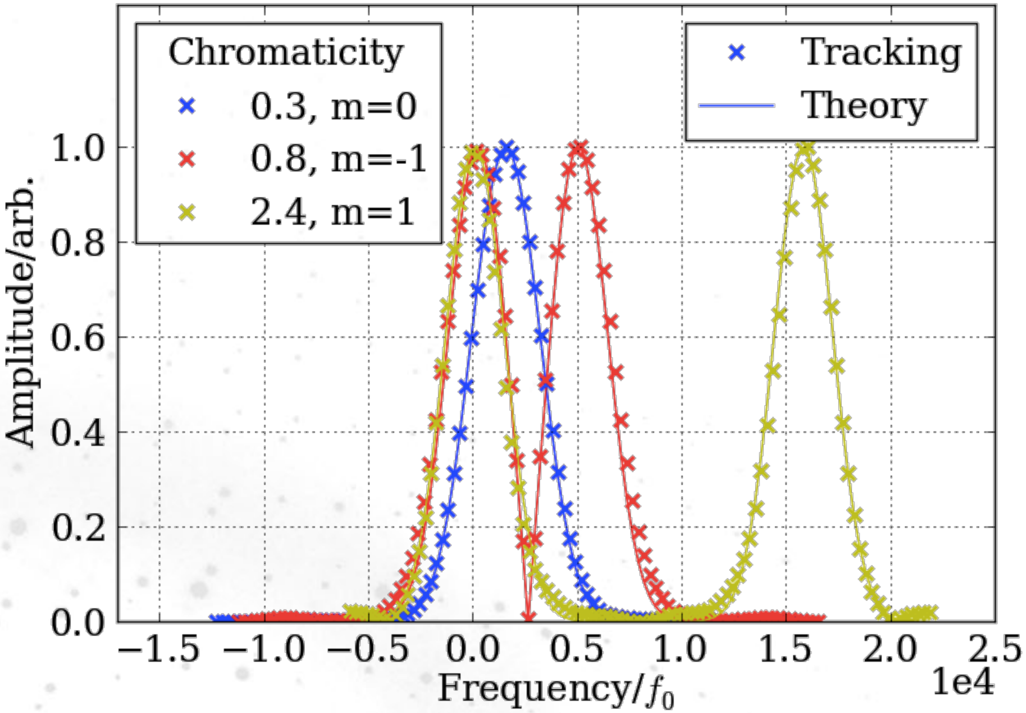
Bunch length

$$s[\omega_p] = I_m[\omega_q(\omega_p - \omega_\xi)\sigma_\tau^2] \exp\left(-\frac{\omega_q^2\sigma_\tau^2 + (\omega_p - \omega_\xi)^2\sigma_\tau^2}{2}\right)$$

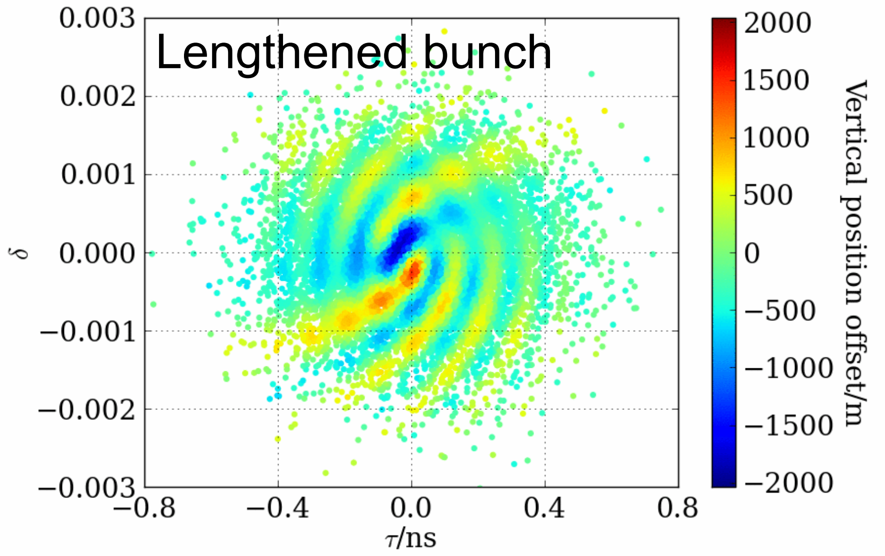
radial frequency

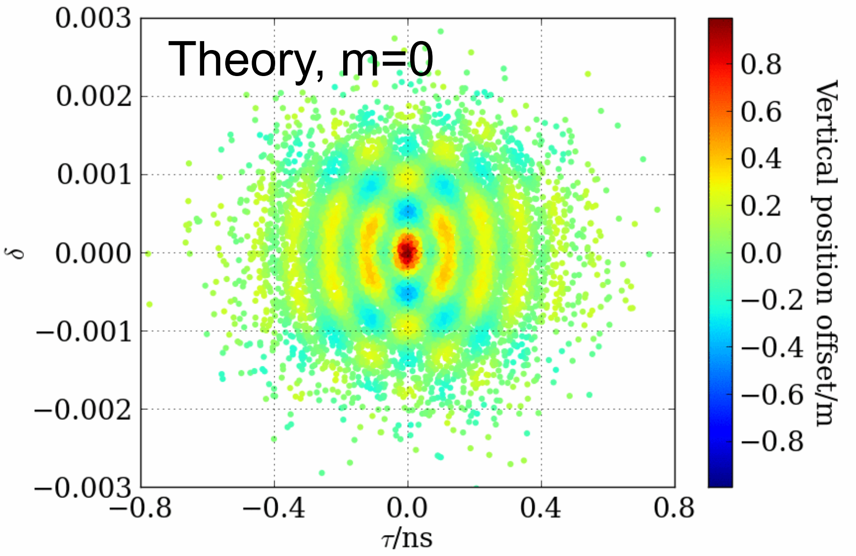
Revolution harmonic

Chromatic frequency



Bunch Distributions - ξ =2.4



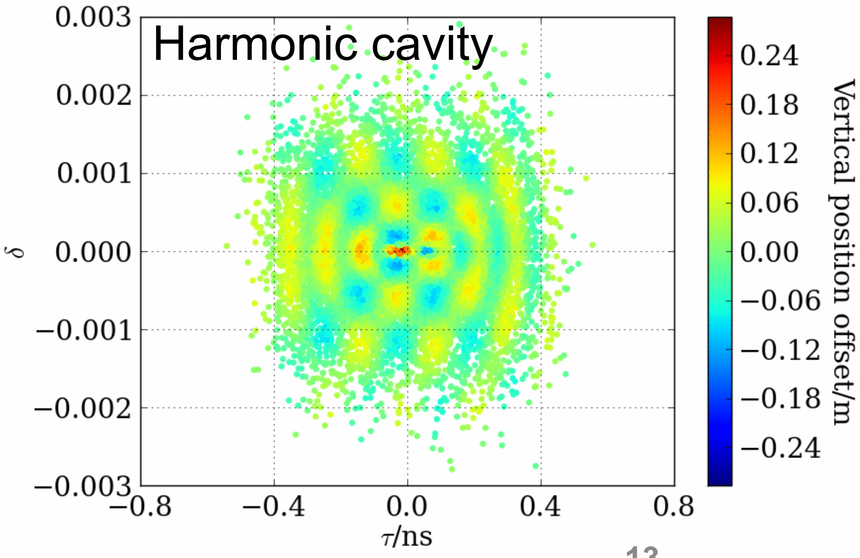


- Bunch distribution looks similar to the radial modes at times
- Also for the harmonic cavity case
- Theoretical mode given by:

$$y = \exp[i(m\theta + \omega_\xi r\cos\theta)]J_m(\omega_\xi r)$$

(r,θ) synchrotron amplitude, phase

Radial frequency
=
Chromatic frequency

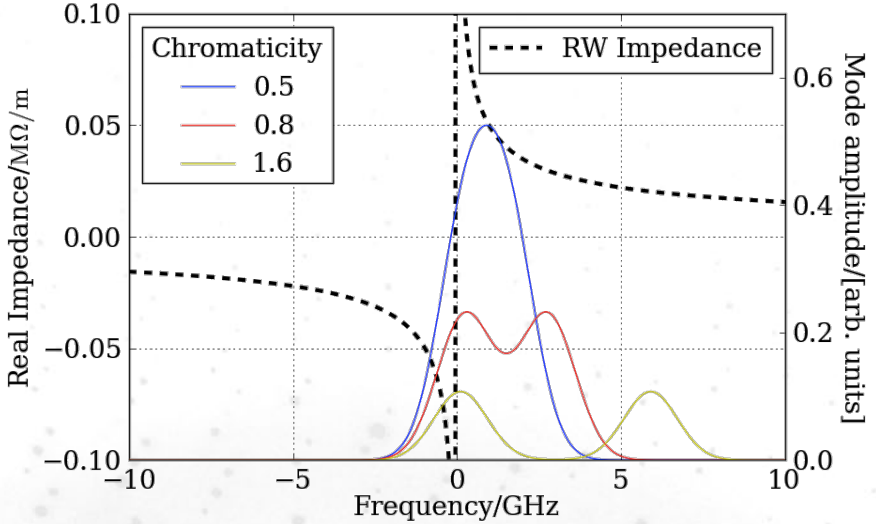


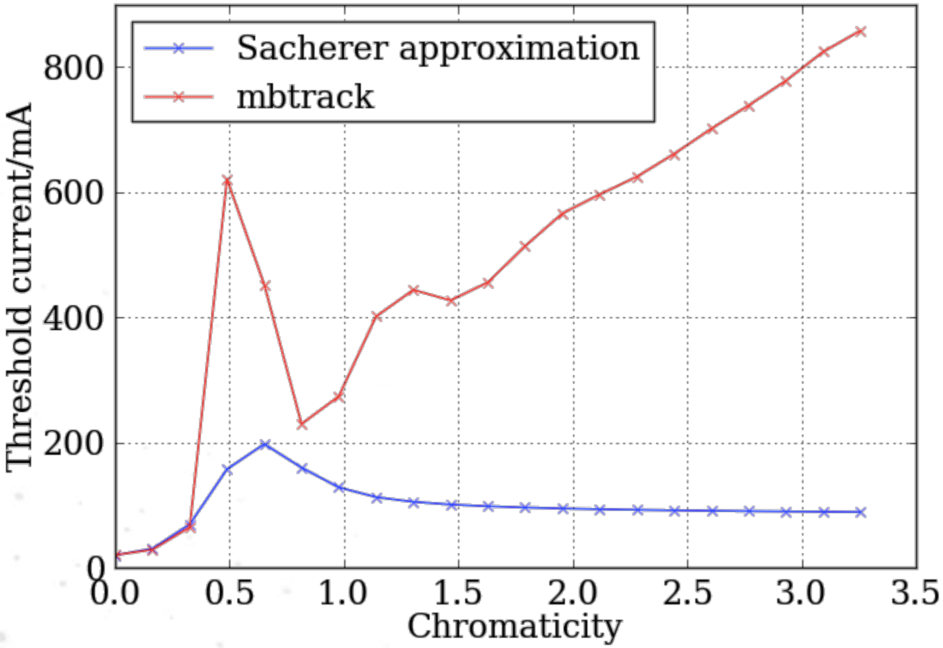
Harmonic Cavity – Sacherer Approximation

RWMBI – Frequency domain code benchmarked with mbtrack

Use the radial shaker modes (m=0) defined before ($\omega_q=\omega_\xi$) and determine the threshold currents using the Sacherer approximation

- Mode initially stabilised as with no radial component
- Smaller peak in threshold currents seen at same chromaticity





Conclusion

- In harmonic cavity flattened potential, higher than zeroth order head-tail modes are broken up by synchrotron tune spread
- Beam is not stabilised indefinitely with increased chromaticity
- Results show common behaviour with a lengthened bunch with no tune spread
- Radial head-tail mode component at the chromatic frequency seem to offer some explanation
  - Additional evidence from Sacherer approximation

Outlook

- Must simulate other machines (starting with MAX IV 1.5 GeV ring)
- Why do spectra for harmonic cavity potential case appear chaotic?
- What determines which modes are excited and with which amplitude?

Mbtrack Benchmarking

- RWMBI solves for eigenmodes of bunch-impedance system that each correspond to a different head-tail mode (azimuthal only)
- Alternatively, define the mode spectrum (shaker mode) and determine the growth rate using Sacherer's approximation
- With MAX IV 3 GeV ring parameters: